

# Conceptual Aspects of Future High Voltage Direct Current (HVDC) Electrical Power Transmission Networks

Von der Fakultät für Maschinenbau, Elektro- und Energiesysteme  
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# Declaration of Authorship

I, Michael Samborsky, hereby declare that this thesis titled, 'Conceptual Aspects of Future High Voltage Direct Current (HVDC) Electrical Power Transmission Networks' and the work presented in it are my own. I confirm that:

- This work has been done wholly while in candidature for the degree of Doctor of Engineering at the Brandenburg University of Technology Cottbus-Senftenberg.
- Where I have consulted the previously published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of support.
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Date: November 30, 2017

Signed:



“For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.”

Richard P. Feynman

## Abstract

Michael Samborsky

### 'Conceptual Aspects of Future High Voltage Direct Current (HVDC) Electrical Power Transmission Networks'

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A continually growing demand for reliable energy supply makes existing power systems more heavily loaded and evokes engineers and experts to look for feasible immediate solutions in power energy transmission. One of these solutions might be a bulk power transmission network at extra high voltages based on direct current.

Currently, high voltage direct current (*HVDC*) transmission has been only realized in point-to-point systems and back-to-back arrangements. Thus, the next logical step in this development would be an *HVDC* network. In principle, it might have certain advantages over a conventional high voltage *AC* system, as it could be less closely meshed covering larger areas and transmit higher electric power with lower losses.

However, no well-grounded investigations concerning possible layout and operation of an *HVDC* network are publicly available. Experience from the *HVDC* lines does not allow to make substantial conclusions regarding the requirements for an *HVDC* network.

Therefore, some basic questions on the operation of an *HVDC* network need to be answered mainly from systems simulations.

Key words: HVDC, power transmission, transient process, energy system, high voltage

# Zusammenfassung

Michael Samborsky

## 'Konzeptionelle Aspekte für ein kommendes Hochspannungs-Gleichstrom-Übertragungsnetz (HGÜ)'

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Die ständig wachsende Nachfrage nach zuverlässiger Energieversorgung verursacht eine höhere Belastung vorhandener Energiesysteme und veranlasst Ingenieure und Experten, nach machbaren Lösungen in Energieübertragungssystemen zu suchen. Eine dieser Lösungen könnte ein leistungsstarkes Übertragungsnetz bei hohen Spannungen auf der Basis von Gleichstrom sein.

Hochspannungs-Gleichstrom-Übertragungen (HGÜ) werden bislang nur als Punkt-zu-Punkt-Systeme und als Kurzkupplungen ausgeführt. Prinzipiell würde jedoch ein HGÜ-Netz wesentliche Vorteile gegenüber einem Hochspannungs-Drehstromnetz bieten, da es weiträumiger gespannt und für die Übertragung höherer elektrischer Leistungen geeignet sein könnte.

Grundlegende Untersuchungen für die Gestaltung und den Betrieb eines HGÜ-Netzes liegen jedoch nicht vor. Erfahrungen aus dem Betrieb der HGÜ-Leitungsverbindungen ermöglichen keine wesentlichen Schlüsse auf die Erfordernisse eines Gleichspannungsnetzes.

Daher sind im Rahmen einer Netzsimulation im HGÜ-Netzbetrieb voraussichtlich auftretende Fragestellungen zu klären.

Schlüsselwörter: HGÜ, Energieübertragung, Übergangsprozess, Energiesystem, Hochspannung

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Michael Samborsky

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# Abbreviations

|                     |   |
|---------------------|---|
| <b>HV</b>           | <b>H</b> igh <b>V</b> oltage  |
| <b>AC</b>           | <b>A</b> lternating <b>C</b> urrent   |
| <b>DC</b>           | <b>D</b> irect <b>C</b> urrent  |
| <b>HVDC</b>         | <b>H</b> igh <b>V</b> oltage <b>D</b> irect <b>C</b> urrent   |
| <b>HVAC</b>         | <b>H</b> igh <b>V</b> oltage <b>A</b> lternating <b>C</b> urrent  |
| <b>MTDC System</b>  | <b>M</b> ulti <b>T</b> erminal <b>D</b> irect <b>C</b> urrent <b>S</b> ystem  |
| <b>LCC</b>          | <b>L</b> ine <b>C</b> ommutated <b>C</b> onverter   |
| <b>VSC</b>          | <b>V</b> oltage <b>S</b> ourced <b>C</b> onverter   |
| <b>CTL</b>          | <b>C</b> ascaded <b>T</b> wo <b>L</b> evel  |
| <b>MMC</b>          | <b>M</b> odular <b>M</b> ulti- <b>L</b> evel <b>C</b> onverter  |
| <b>STATCOM</b>      | <b>S</b> tatic synchronous <b>C</b> ompensator  |
| <b>FACTS</b>        | <b>F</b> lexible <b>A</b> C <b>T</b> ransmission <b>S</b> ystem   |
| <b>ATP-EMTP</b>     | <b>A</b> lternative <b>T</b> ransients <b>P</b> rogram - <b>E</b> lectromagnetic <b>T</b> ransients <b>P</b> rogram |
| <b>EMT-software</b> | <b>E</b> lectromagnetic <b>T</b> ransients - software   |
| <b>TACS</b>         | <b>T</b> ransient <b>A</b> nalysis of <b>C</b> ontrol <b>S</b> ystems   |
| <b>CL</b>           | <b>C</b> able <b>L</b> ine  |
| <b>OHL</b>          | <b>O</b> ver <b>H</b> ead <b>L</b> ine  |
| <b>EF</b>           | <b>E</b> arth <b>F</b> ault   |
| <b>FCL</b>          | <b>F</b> ault <b>C</b> urrent <b>L</b> imiter   |
| <b>SCFCL</b>        | <b>S</b> uper <b>C</b> onducting <b>F</b> ault <b>C</b> urrent <b>L</b> imiter                                      |
| <b>IGBT</b>         | <b>I</b> nsulated <b>G</b> ate <b>B</b> ipolar <b>T</b> ransistor   |
| <b>IGCT</b>         | <b>I</b> ntegrated <b>G</b> ate <b>C</b> ommutated <b>T</b> hyristor  |
| <b>GTO</b>          | <b>G</b> ate <b>T</b> urn- <b>O</b> ff thyristor  |
| <b>RMS</b>          | <b>R</b> oot <b>M</b> ean <b>S</b> quare  |
| <b>PWM</b>          | <b>P</b> ulse <b>W</b> idth <b>M</b> odulation  |

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|                 |   |
|-----------------|---|
| <b>SPWM</b>     | <b>S</b> inusoidal <b>P</b> ulse <b>W</b> idth <b>M</b> odulation   |
| <b>NBS</b>      | <b>N</b> eutral <b>B</b> us <b>S</b> witch  |
| <b>NBGS</b>     | <b>N</b> eutral <b>B</b> us <b>G</b> round <b>S</b> witch   |
| <b>MRTB</b>     | <b>M</b> etallic <b>R</b> eturn <b>T</b> ransfer <b>B</b> reaker  |
| <b>GRTS</b>     | <b>G</b> round <b>R</b> eturn <b>T</b> ransfer <b>S</b> witch   |
| <b>HSBS</b>     | <b>H</b> igh <b>S</b> peed <b>B</b> ypass <b>S</b> witch  |
| <b>SF6</b>      | <b>S</b> ulfur <b>H</b> exafluoride   |
| <b>RES</b>      | <b>R</b> enewable <b>E</b> nergy <b>S</b> ources  |
| <b>CIGRÉ</b>    | <b>C</b> onseil <b>I</b> nternational des <b>G</b> rands <b>R</b> éseaux <b>E</b> lectriques                      |
| <b>DKE</b>      | <b>D</b> eutsche <b>K</b> ommission <b>E</b> lektrotechnik  |
| <b>VDE</b>      | <b>V</b> erband <b>D</b> er <b>E</b> lektrotechnik  |
| <b>IEC</b>      | <b>I</b> nternational <b>E</b> lectrotechnical <b>C</b> ommission   |
| <b>CENELEC</b>  | <b>C</b> omité <b>E</b> uropéen de <b>N</b> ormalisation <b>E</b> lectrotechnique                                 |
| <b>ENTSO-E</b>  | <b>E</b> uropean <b>N</b> etwork of <b>T</b> ransmission <b>S</b> ystem <b>O</b> perators for <b>E</b> lectricity |
| <b>UPS/IPS</b>  | <b>U</b> nified <b>P</b> ower <b>S</b> ystem of <b>R</b> ussia / <b>I</b> ntegrated <b>P</b> ower <b>S</b> ystem  |
| <b>UCTE</b>     | <b>U</b> nion for the <b>C</b> o-ordination of <b>T</b> ransmission of <b>E</b> lectricity                        |
| <b>KBPD</b>     | <b>K</b> ilo (Thousand) <b>B</b> arrels <b>P</b> er <b>D</b> ay   |
| <b>GWh</b>      | <b>G</b> iga <b>W</b> att <b>h</b> our  |
| <b>CSP</b>      | <b>C</b> oncentrating <b>S</b> olar <b>P</b> ower   |
| <b>ASEA</b>     | <b>A</b> llmänna <b>S</b> venska <b>E</b> lektriska <b>A</b> ktiebolaget  |
| <b>BP</b>       | <b>B</b> ritish <b>P</b> etroleum   |
| <b>U.S. EIA</b> | <b>U</b> nited <b>S</b> tates <b>E</b> nergy <b>I</b> nformation <b>A</b> dministration                           |
| <b>CIS</b>      | <b>C</b> ommonwealth of <b>I</b> ndependent <b>S</b> tates  |

# Physical Constants

Speed of Light  $c = 2.997\,924\,58 \times 10^8 \text{ ms}^{-1}$  (exact)

Vacuum Permeability  $\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2 \approx 1.2566370614\dots \times 10^{-6} \text{ H/m}$

Vacuum Permittivity  $\epsilon_0 = 1/(\mu_0 \times c^2) \text{ F} \times \text{m}^{-1}$

The number  $\pi = 3.14159$

# Symbols

|          |                   |                        |
|----------|-------------------|------------------------|
| $a$      | coefficient       | non-dimensional value  |
| $P$      | power             | W                      |
| $I$      | current           | A                      |
| $U$      | voltage           | V                      |
| $R$      | resistance        | Ohm                    |
| $f$      | frequency         | Hz                     |
| $t$      | time              | s                      |
| $L$      | inductance        | H                      |
| $C$      | capacitance       | F                      |
| $\omega$ | angular frequency | rads <sup>-1</sup>     |
| sin      | sine              | trigonometric function |

*To the World with Love that is All Around*



# Chapter 1

## HVDC Grid Feasibility Study

### 1.1 Development of HVDC transmission. First steps.

Although *HVDC* technology nowadays is widely considered in a context of discussions on innovations, renewable energy and state-of-art breakthrough, in fact, it already has its own quite long history of emergence and development comparable with, what we consider nowadays conventional, more common alternating current (*AC*) transmission systems.

The first attempts were made in 1882 between Miesbach and Munich in Germany, where relatively long-distance (about  $50km$ ) an electric power transmission line with direct current was put into operation and transmitted some  $1.5kW$  at  $2kV$ .

Rotating direct current machines converted the voltage from low up to transmission level and back to reasonable consumer voltage which was at the moment the only possible way to do it.

Series-connected sets of rotating machines - generators/motors were capable of rising the voltage up to few tens kilovolts. Each set insulated from ground with up to  $5,000volts$  across each machine was driven by shafts from a prime mover.

Thury systems were in operation and developed until the 1930s, when this arrangement finally reached its natural limits. Moutiers–Lyon system was the most powerful *HVDC* transmission bipolar link with rotating machines ever built -  $4300kW$  at above  $60kV$  with overhead lines over  $190km$  and last  $10km$  in the hard-to-reach area in the vicinity of Lyon as paper insulated underground cable.

TABLE 1.1: Development of *HVDC* based on Thury Systems.

| Transmission link                   | Voltage    | Power       | Length          | Year |
|-------------------------------------|------------|-------------|-----------------|------|
| Miesbach - Munich, Germany          | 2 kV       | 2,5 kW      | 58 km           | 1882 |
| Laghi del Gorzente - Genoa, Italy   | 6 kV       | $\geq 1$ MW | $\approx 35$ km | 1889 |
| St. Maurice - Lausanne, Switzerland | 22 kV      | 3,7 MW      | 60 km           | 1899 |
| Lyon - Moutiers, France             | $\pm 75kV$ | 30 MW       | 200 km          | 1906 |

It is interesting to note that numerous cities kept using DC technology well into the 20th century. The old *DC* systems there retained mainly as contingency reserves and for some other sorted purposes. For example, a DC network in Helsinki was preserved in good working conditions until the late 1940's. Stockholm also phased out its *DC* network step by step, but it was still in operation until the 1960s. [1].

Costs of units, complexity, need for constant maintenance of rotating parts and high losses made these systems extremely expensive, less reliable and, thus, unable to compete with fast emerging alternating current systems already enjoying a breakthrough in technology and commercial success.

## 1.2 Mercury-arc and thyristor valves.

Development in mercury valves and especially thyristors gave *HVDC* a second wind. First proposed mercury-arc valves were typically able to transmit tens of MW up to a few hundred kV over a few hundred kilometers.

A buried single-core cable link with aluminum conductors known as the "Elbe-Project" was planned in 1941 to connect Vockerode lignite power station with Berlin's district - Marienfelde to deliver *60 megawatts* via symmetrical bipolar operating voltage  $\pm 200kV$ .

The system was never finished and after the World War II dismantled and put into service between Moscow and Kashira. The *125km* experimental link was operated either as a bi-pole at  $\pm 100kV$  or at *200kV* as a monopole with earth return.

In 1954 later *ASEA* introduced an *HVDC* connection from the island of Gotland to the Swedish mainland via under sea cable what immediately became yet another milestone in this rapid technical development and fierce competition.

Though, the experience collected on these *HVDC* stations with multiple mercury arc valves in series was useful and later in 1965 made it possible to build another already *475kilometers* long *HVDC* bipolar link between Volgograd and Donbass using mercury arc valves of entirely Soviet design with operating voltage of  $\pm 400kV$  and a maximum power of *750MW*, what was at that moment the highest top in the world, until the Nelson River Bipole 1 *DC* Transmission System (*895km*,  $\pm 450kV$  and *1620MW*) was put into operation.

TABLE 1.2: Development of HVDC-systems based on Mercury-arc.

| Transmission link                       | Voltage      | Power   | Length | Year |
|---|--------------|---------|--------|------|
| HVDC Zurich-Wettingen, Switzerland      | 50 kV        | 0.5 MW  | 20 km  | 1939 |
| Berlin Charlottenburg - Moabit, Germany | 100 kV       | 14 MW   | 4,6 km | 1942 |
| Elbe-Project, Germany                   | $\pm 200$ kV | 60 MW   | 115 km | 1945 |
| Cross-Channel, France – UK              | $\pm 100$ kV | 160 MW  | 65 km  | 1961 |
| SACOI 1 Suvereto-San Dalmazio, Italy    | $\pm 200$ kV | 200 MW  | 483 km | 1965 |
| Kontiskan 1, Denmark – Sweden           | 250 kV       | 250 MW  | 176 km | 1965 |
| Volgograd-Donbass DC scheme, USSR       | $\pm 400$ kV | 750 MW  | 475 km | 1965 |
| Nelson River Bipol 1*, Canada           | $\pm 450$ kV | 1620 MW | 895 km | 1971 |

\* The largest mercury arc rectifiers ever built. Poles converted to thyristors in 1993.

In the 70s of the XX century began the era of solid-state electronics devices giving birth, besides others, to thyristor valves now commonly known as line commutated converter or *LCC* for short. Thyristor based *HVDC* made another step forward pushing the limits to several thousand megawatts and kilometers e.g. project Cahora-Bassa - a scheme which was designed with thyristor valves was able to transmit *1920megawatts* at a voltage level of  $\pm 533kV$  over *1,420kilometers* as a bi-polar line with poles on separate towers in hard-to-reach regions in South Africa.

### 1.3 Present state of the HVDC transmission

Having reached already significant characteristic the development certainly has not stopped. Significant service limitations of line-commutated converters for *HVDC* systems, such as their inability to reverse voltage without interruption, a constant need for reactive power compensation, conversion process dependence on the *AC* system line voltage and others were drivers to look for solutions.

However, it is worth noting that most of the ultra long bulk power HVDC links at the moment are still operated on line-commutated converters (*LCC*).

The advent of reliable and economically advantageous power electronic devices such as insulated-gate bipolar transistors (*IGBTs*), integrated gate-commutated thyristors (*IGCTs*) and gate turn-off thyristors (*GTOs*) have brought on the market new types of converters. With voltage-source converters, or *VSC* for short, HVDC transmission systems have become not only more powerful, but rather more compact and economical.

TABLE 1.3: Development of *LCC* and *VSC* based HVDC-systems.

| Transmission link                       | Voltage      | Power             | Length  | Year |
|---|--------------|-------------------|---------|------|
| Skagerrak, Denmark - Norway             | $\pm 250$ kV | 500 MW            | 240 km  | 1977 |
| Cahora Bassa, Mozambique - South Africa | $\pm 533$ kV | 1920 MW           | 1420 km | 1979 |
| Itaipu 1, Brasil                        | $\pm 600$ kV | 3150 MW           | 785 km  | 1984 |
| Itaipu 2, Brasil                        | $\pm 600$ kV | 3150 MW           | 805 km  | 1984 |
| Nelson-River Bipol 2, Canada            | $\pm 500$ kV | 1800 MW           | 937 km  | 1985 |
| Intermountain HVDC, USA                 | $\pm 500$ kV | 1920 MW           | 785 km  | 1986 |
| Pacific DC Intertie, USA                | $\pm 500$ kV | 3100 MW           | 1362 km | 1989 |
| Quebec - New England, Canada            | $\pm 450$ kV | 2250 MW           | 1105 km | 1991 |
| Talcher - Kolar, India                  | $\pm 500$ kV | 2000 MW           | 1450 km | 2003 |
| Three Gorges – Changzhou, China         | $\pm 500$ kV | 3000 MW           | 940 km  | 2004 |
| Yunnan–Guangdong, China                 | $\pm 800$ kV | 5000 MW           | 1418 km | 2009 |
| Xiangjiaba–Shanghai, China              | $\pm 800$ kV | 6400 MW           | 2070 km | 2010 |
| Jinping - Sunan, China                  | $\pm 800$ kV | 7200 MW           | 2095 km | 2012 |
| Rio Madeira, Brasil                     | $\pm 600$ kV | 7100 MW           | 2375 km | 2013 |
| Xiluodo - West Zhejiang, China          | $\pm 800$ kV | 8000 MW           | 1680 km | 2014 |
| Terranora interconnector, Australia     | $\pm 80$ kV  | 180 MW            | 59 km   | 2000 |
| Murraylink, Australia                   | $\pm 150$ kV | 220 MW            | 180 km  | 2002 |
| Estlink, Estonia - Finland              | $\pm 150$ kV | 350 MW            | 105 km  | 2006 |
| NordE.ON 1, Germany                     | $\pm 150$ kV | 400 MW            | 203 km  | 2009 |
| Caprivi Link, Namibia                   | $\pm 350$ kV | 300 MW            | 950 km  | 2010 |
| Naoao Multi-terminal HVDC, China        | $\pm 160$ kV | 200 MW            | 32 km   | 2013 |
| Zhoushan Multi-terminal HVDC, China     | $\pm 200$ kV | 400 MW            | 134 km  | 2014 |
| SydVästlänken, Sweden                   | $\pm 300$ kV | $2 \times 720$ MW | 260 km  | 2016 |
| Nemo Link, UK-Belgium                   | $\pm 400$ kV | 1000 MW           | 140 km  | 2019 |

How it can be seen from the Table 1.3 tendency of development IGBT-based converter technology apparently grows towards higher voltage and power ratings.

At the moment, the leaders on *HVDC* markets world-wide are presumably able to deliver solutions designed for  $\pm 400$  kV -  $\pm 450$  kV and power of about 1200 MW. However, this should be beaten by the NSN Link, 730 km long between Norway and England with its 515 kV and 1400 MW already in 2020.

Several companies, central players in the *HVDC* area, have introduced their products designed on a *VSC* and *MMC* (Modular Multi-Level Converter) converter concepts.

In the present context in Europe and in the rest of the world, near term drivers seem to be to some extent contradictory. On the one hand, a search for highest possible *DC* power transmission applications to replace out-of-date thyristor-based systems undergoes agile development.

On the other hand high prices, legal issues and lack of space coupled with ever-growing power energy demand and explosive growth of green renewable generation dictate future *HVDC* applications to be very compact, robust, modular and not necessarily of ultra-high power and voltage.

The recent public presentations of compact gas-insulated *HVDC* solutions for off-shore platforms prove the sanity of this proposition again.

## 1.4 Why Do We Need HVDC Network?

Under an *HVDC* electrical network let us agree to understand a network interconnected or sometimes overlaid with *AC* intended for delivery of electricity from distant generation to end consumers. Here and further, at times the term grid instead of term network is used with the same meaning as it is not considered that grid implies only certain configuration, layout or limited in scale and etc.

An *HVDC* network may consist of generating capacities producing electrical power, high-voltage transmission lines and cables carrying power from remote generation sources to load centres, and, in the specific case of *HVDC*, converter stations responsible for current transformation from *AC* to *DC* and back.



FIGURE 1.1: Incorporation of HVDC into the Network.  
Source: renewableenergyfocus.com

Even though an *HVDC* network is just one possible variant of high voltage power transmission in future, potential benefits of such a solution are supposed to be several.

First of all, it is an optimization of power flow control resulting in lower cost of power delivery in all embraced regions what allows the interchange of power flows to be the most efficient.

Load variability and power station unreliability could be improved. A sound reduction of inefficient spinning reserve and standby that have to be supplied is also envisaged.

An *HVDC* network represents a flexible and logical solution for integration of renewable energy, mainly wind and solar energy, into the grid allowing the green generation to be very much distributed and up to some point stochastic.

Obviously, at one and the same time wind may blow in regions for hundreds or even thousands of kilometres away from each other while main load centres are more or less predictable.

Thus, a general consideration "it should always be windy somewhere" combined with solar irradiation volatility with the help of *HVDC* extra-long distance transmission may come into its own and become a reality.

The same refers to hydropower resources integration as well as to any other energy source in regions, where generation at some precise moment exceeds local needs.

Enlargement and consolidation would fight with power grid uncertainties on generation and transmission level, and facilitate the collective management of such a massive transmission system making it more operative to respond to vulnerabilities and disturbance.

From the operating standpoint, a continental *HVDC* network reveals rather new technical opportunities, that may give only consolidated power pool systems, and thus, *HVDC* transmission in practice becomes more reasonable and advantageous not only for a very long distance link, but also for more closely meshed interconnected systems to tie up lines of comparatively short length.

*HVDC* technology plays an integral role in meeting the challenge of accommodation within already existing transmission systems supporting a large amount of new "green" generation with constantly growing demand on energy supply from industry, infrastructure and households.

Addressing climate change problems and having in mind public opinion, which is normally set against any new power station or high voltage power line, *HVDC* might be the only option to level up the carrying capacity and enhancing the efficiency of existing transmission system thanks to its ability to provide backup power as well as grid stabilisation.

Any advances to the power grid shall support a robust and resilient transmission system, improve reliability and ensure high operating capabilities. Moreover, possible upgrade of a conventional grid to *HVDC* may reduce infrastructure investments in comparison with completely new lines construction.

However, at the present time there are several competing concepts and visions towards future grids. This process unfolds at this moment and particular results will be seen in the next few decades.

### 1.4.1 Advantages of HVDC Over Conventional HVAC

In the beginning of each large-scale project a question on comparative advantages and possible disadvantages requires special and careful attention.

Analysis and collected experience from many *HVDC* projects in operation have shown, that under certain conditions the *HVDC* transmission of a large amount of energy may profitably compete not only with the coal or natural gas transportation over extensive pipe lines, but also with such a mature and well-managed technology as *HVAC* transmission.

For transmitting large amounts of power *HVDC* is commonly chosen over *AC* due to less losses and, thus, more economical transfer of power especially in point-to-point links over long distances. Comparing with long distance *AC* transmission lines, high power *HVDC* transmission, as a rule, has lower losses and lower capital costs. All the most powerful transmission links in the world at the moment are *HVDC* and this tendency is just about to get stronger in years to come.

In slightly different terms it also refers to future *HVDC* networks, even taking into consideration intermediate power take-off and, therefore, increased number of converter stations.

Despite costly equipment at the *HVDC* converter stations, the total amount of capital cost saved may increase due to cost reduction on *HVDC* transmission lines. This margin becomes even more favourable with further increase of distance. The ground for it, an *HVDC* transmission line of the same capacity requires less space for right-of-way, may be less sophisticated in design and construction, needs fewer than a three phase *AC* line conductors and insulators.

*HVDC* technology is the only solution when it comes to long distance water crossing applications. Due to natural properties, namely to the inherent capacitance and inductance of high voltage cable, *AC* cable links suffer from significant reactive losses. These losses rise with an increase of cable length, what makes conventional long *AC* cable lines not viable from a technical and economical point of view.

In comparison, the only losses in a *DC* line are the active losses due to the natural resistivity of a metallic conductor. Whereas, capacitance and inductance show themselves only during transient processes.



The ability to connect several asynchronous *AC* grids with *HVDC* links represents serious technical benefits for the large interconnected power networks. An *HVDC* link or network may serve as a mediator to transmit significant amounts of power between separate distant *AC* networks.

Easier power flow control in *HVDC* could in real time support a weak *AC* system during transient-state or instability, what also adds on to substantial advantages of this technology. Furthermore, as a reliable mediator, an *HVDC* may unite several separate asynchronous *AC* systems in one super-grid or, when needed, may disrupt it back. Therefore, a collapse in one of the network would not lead to a collapse in the second.

Flexibility to operate separate asynchronous *AC* networks without a risk to loose either of them leads to a more smooth shift between different configurations. This enables to find a supply optimum of vast amounts of electricity providing stable and efficient transmission regimes in real time.

The integral technical-and-economic benefits of *DC* versus *AC* transmission often weight the scales on behalf of the former in overcoming a vexed problem with renewable generation. Resources employed in clean energy generation, like wind, solar and hydro, normally are very distributed, not simple to integrate into the grid and located far from load centres, where this energy is utilized.

The reasons to make a choice in favour of *HVDC* instead of *AC* are often numerous and to be considered in every particular project. Most of the reasons are based on technical, economical and environmental points of view.

### 1.4.2 Comparison and Estimation of Losses.

Although the conductors being used in modern transmission lines excel in low resistivity, they are still not perfect.

As it was mentioned in the previous section, power transmission links, either *AC* or *DC*, suffer from losses. The former has both - active and reactive losses, the latter only active and, thus, positively out-stands from conventional transmission technology.

Normally, in a *DC* system the total transmitted power is proportional to the voltage, when transmitted power of *AC* system is proportional to the *RMS* voltage value. For *AC* transmission the quadratic mean of Sine waveform  $y = a \sin(2\pi ft)$  can be determined without calculus:  $\frac{a}{\sqrt{2}}$ .

This is approximately equal to 0.7 of nominal value for a sine waveform. So, when all other factors held equal for both systems, *HVDC* is able to transmit more energy

than *AC*. In addition, losses in *HVDC* are less than typical average losses in an *AC* transmission and in relation to the voltage level.

In the planning stage, before the final decision is made, it is always better to have a preliminary assessment and at least profound understanding for how much losses one should expect in both - *AC* and *DC* cases.

Basically, it means that for a given length and amount of power to be transmitted in an overall power system, a comparative study of losses and related costs is to be made.

On the ground of reference conditions, we may consider that *DC* connections would cost less on wire due to decreased number and more efficient use of cross-section, the decreased number of insulators, and compact and simpler towers, but it would have more expensive equipment on converter stations at terminal points.

Consequently, we approach an intermediate conclusion that in the equation of *HVDC* effectiveness versus *AC*, inherent losses, line length and rank of transmitted power play a significant role.

Let's assume the power output is  $4000\text{MW}$  to be transmitted over  $500\text{km}$  of overhead line.

An output power is determined as  $P = I \times U$ . Then, the current drawn is  $I = P/U$

The line loss is given by  $P_{loss} = I^2 \times R$ , or, substituting for  $I$ ,

$$P_{loss} = \frac{P^2}{U^2} \times R ;$$

Evidently, the higher the transmission line voltage, the smaller the flowing current, and thus, the induced losses. Power is proportional to current, whereas line losses are proportional to current squared. Knowing the parameters of conductors in these three different options, we may quantify that loss through computation.

Let us assume, that for conventional  $400\text{kV}$  *AC* and *DC* line of the same voltage level quadruple bundle conductors are applied, and for  $800\text{kV}$  *DC* line six bundle conductors are applied.

Having taken from the table of conductors parameters the values needed, we are able now to calculate parameters of the line including estimated losses.

Resistance of the 400kV *DC* single line:  $R_{400kV} = 0,09 \times \left(\frac{1}{4}\right) \times 500 = 11,25\Omega$  ;

Resistance of the 800kV *DC* single line  $R_{800kV} = 0,09 \times \left(\frac{1}{6}\right) \times 500 = 7,5\Omega$  ;

As there is no reactive power in *DC* transmission it is very simple to calculate power losses there. Due to more complex nature of *AC* transmission actual calculations of power losses is more complicated. At this point we may accept only active resistive losses in calculation for *AC* and this would be a valid approximation for comparison.

Resistance of the 400kV *AC* one phase:  $R_{400kV} = 0,093 \times \left(\frac{1}{4}\right) \times 500 = 11,6\Omega$  ;

Then, losses with a conventional three-phase 400kV *AC* line are 12,9 %; with HVDC bipolar line at 400 kV, it is only 7,03 %, and at 800 kV it is just about 1,2 %.

Since *Resistance* is as small as one can make it in the planning stage and the *Power* needed by end-customers demand is usually fixed by the ability of generation and, consequently, cannot vary over a broad area, line losses depend strongly on the voltage level. They decrease sharply as the voltage increases and vice versa.

Additionally, from the same above reasoning, power transmission becomes less efficient during peaks of higher demand. On the other hand, produced and underutilized energy wastes into heating. So, losses in long lines especially may rise to 30 %. [2]

Thus, the most logical conclusion from these considerations is simply to keep the current as small as possible, in a way, rising the voltage in order to deliver the power with lower losses. However, there is a certain finite border to rise the voltage, as economic costs for insulation overgrow foreseen benefits from optimized power line losses.

As it can be found in many references and what has been proved by our estimation, the *HVDC* line transmission alone, in comparison with *AC* lines, may have in the most optimal for the *HVDC* cases up to 50 % fewer transmission losses.

Valve losses are the main contributor to overall *VSC HVDC* losses and, in principle, can be divided in switching and in conduction losses. Switching losses increase linearly with the switching frequency. Conduction losses depend on the threshold voltage and the resistance of the *IGBT's* and the diodes.

Converter losses can be decreased using multi-level *VSC* topologies versus two-level or three-level and/or by using optimal pulse width modulation (the optimal switching frequency), which cancels certain harmonics, what is an influencing factor in loss formation.

## 1.5 Where Do We Need HVDC?

There is always a big temptation to consider any new technology as a panacea for all woes. However, we all shall remember that any even comparatively robust solution has own advantages and disadvantages. Although *HVDC* adequately responses to many questions in modern transmission, there are some certain limits, which shall be defined for the *HVDC* technology, where it is applicable at most and where it still needs a significant development to compete on equal footing with other more mature technologies.

There are many reasons, as it was described earlier in this Chapter, to make a decision towards *HVDC* instead of *AC* transmission. Though, any technology has its applicability limits.

So, what are prerequisites to apply *HVDC* transmission technology at its best? First of all, *HVDC* transmission is of particular interest when it comes to where it may serve as a backbone for bigger *AC/DC* system or future super-grid.

In spite of high initial investments, the total operational costs may be significantly lower including reduced transmission losses, environmental excellence and relatively small footprint area required.

For another point, *HVDC* is a second-to-none solution for sub-sea electrical transmission as from a particular length of cable with high capacitance there is no any other option available at the moment.

*HVDC* is very well known and widely used to interconnect different asynchronous *AC* grids and networks with various operational frequency e.g. 50/60 Hz.

To all this should be added that *HVDC* perfect controllability is what very much desirable in big and complex systems from a technical point of view either as a supplement to *AC* transmission network or as a separate individual solution.

Taking into account all the specifics features of the technology it seems to be possible to name, in thoughtful details, a short list of applications where *HVDC* finds itself particularly suited. However, with fast technical development and coming of new energy era one may expect this list to grow far beyond its conventional wisdom.

### 1.5.1 Applications Most Suitable for HVDC.

As it has been shown before, *HVDC* technology may be a crucial point on the way to solve several important problems associated with long-distance bulk power transmission, reliability in large-scale renewable energy, robustness of big interconnected networks and in some other areas.

*HVDC* is able to handle a number of issues such as fault current reduction, voltage stability in adjoining *AC* power networks, optimized management of power flow and some others. Let us specify in which application an *HVDC* technology has an undeniable advantage.

- Underwater *HVDC* transmission systems.

*HVDC* transmission is indispensable for relatively long distance underwater connections. Due to natural limits, namely, inherent capacitance of cable, what makes electrical losses unacceptable and thus energy transmission ineffective and hardly possible, *AC* cable links cannot be longer than approximately 60 ~ 70 km. In accordance with the fundamental frequency of a network this capacitance recharges 50 or 60 times per second absorbing energy and making the whole transmission hardly feasible.

Thus, for bigger distances in such cases only *HVDC* underground or submarine cables may serve as the only option to overcome this obstacle. In this case, during operation an *HVDC* cable needs to be charged only once on switching the line and sometimes during transient processes. This in turn, decreases the total losses of the whole transmission scheme even taking into account converter losses on both sides.

This technological advantage makes sometimes *HVDC* cables economically preferable also at much shorter distances.

- Connecting of generation in remote and hard-to-reach regions.

Very often abundant energy sources are located hundreds or even thousands kilometres away from the end customer. In case of Germany, for example, wind generation is being rapidly developed on the German North - the Baltic Sea and the North Sea, while the main load centres are situated on the south of the country.

Moreover, *HVDC* technology can be used in rural areas, deserts or mountains getting through remote and hard-to-reach regions as *HVDC* transmission links can be quite compact, require less space comparing with conventional *AC* lines and is not limited to any distance when it comes to cable connections assuring reliable delivery of electricity with low losses.

- Several grids interconnections.

Liberalization of energy markets and acute needs for power flow between AC grids belonging to separate energy systems for stabilization purposes and to allow energy trading on the anticipated in the nearest future free energy markets create for *HVDC* technology very adorable environment.

Using *VSC* or *MMC* converters *HVDC* links obtain a desired flexibility and controllability in power flow control even dealing with unsynchronized systems or systems with different fundamental frequency.

- New generation energy sources integration into the grid.

Renewable energy sources, as it was mentioned above, are often placed far away from load centres. Due to more favourable natural conditions there, wind turbines need to be installed on a long distance off-shore.

Another specific feature of renewable energy sources on integration them into a common energy grid, is their very high volatility. This puts additional stresses on the network and may lead to overloading, instability and, when the total share of RES reaches the certain significant level, even black-outs.

*HVDC* technology resolves to some extend smooth the seemingly irrepressible conflict between the high volatility of ever-growing share of RES and the system stability requirements by providing good controllability and strengthening the network.

Some new generation energy sources of new type with considerably improved parameters in efficiency, higher power ratings and energy densities should be also considered as candidates to connect with end customers via *HVDC* power transmission links.

- Power supply from shore.

In most cases, we consider the need to transmit energy from off-shore to the mainland, however, there are some applications, where *HVDC* has definite advantages and offers more preferred technically and economically option.

Oil and gas platforms, construction sites or scientific research platforms in the shelf area have to use embedded generation, what is rather expensive and harmful for the environment and destructive to the health of working personnel. Instead, such remote platforms can be supplied from onshore via *HVDC* links not depending on the distance, allowing when needed bidirectional power flow. This application of *HVDC* is potentially able to decrease the overall costs, lower greenhouse gas emissions, improve working conditions and health safety.

- Strengthening of AC grids.

*HVDC* links that are in-built into AC grids can be successfully employed to raise the integrated stability of the entire transmission grid. Back-to-back connections between different energy systems promote fast and reliable regulation between regions with energy surplus and regions suffering from power shortages especially under demanding load conditions and during system disturbances.

The further development of an *HVDC* network from separate point-to-point connections to more complex multi-terminal configuration is seen as a remedy to improve transmission capacity and dissolve the most severe system bottlenecks.

- Cities in-feed. Hidden transmission.

According to World Urbanization Report made by the Department of Economic and Social Affairs of the United Nations Committee the world population will increase to 9.3 billion by 2050. At the same time urbanization, especially in developing countries is gaining momentum, passing from 3.6 billion in 2011 to projected 6.3 billion in 2050. [3]

The fast growing population of mega-cities and constant increase in energy demand will stress existing energy grid to the critical level and, thus, will require an entirely fresh perspective and new solutions.

*HVDC* transmission systems are ideal for supplying electricity to densely populated urban areas due to lower losses and increased capacity. The lack of space will dictate on compact arrangements and underground cable lines.

Hidden transmission through *HVDC* cables is also considered as a viable compromise with numerous environmental organization and groups of activists opposing the construction of new overhead lines also because of, from their point of view, unacceptable visual effect and disturbances to natural landscapes.

### 1.5.2 Limits of HVDC Transmission.

In spite of all advantages that were mentioned in the previous subsection, *HVDC* transmission has indeed its limits as well.

High competitiveness of *HVDC* consists in ability to connect remote energy resources and transmit this energy over vast distances at low losses and costs.

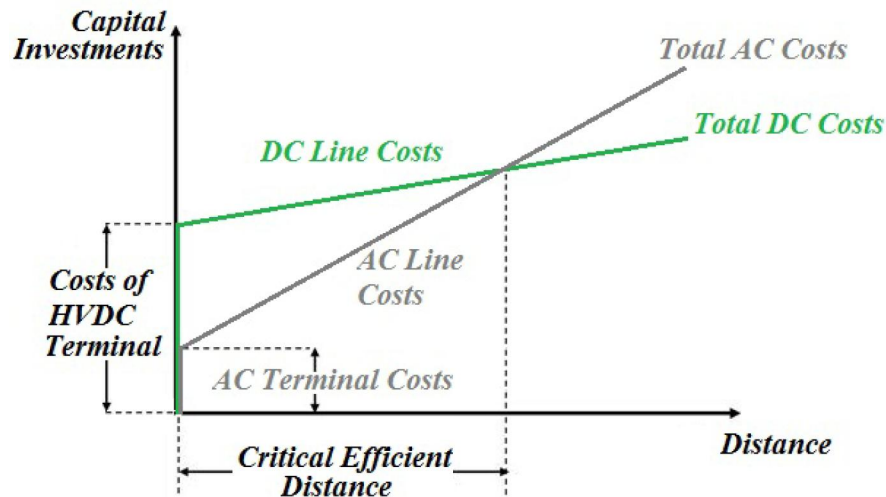


FIGURE 1.2: Competitiveness and Limits of HVDC.

A further step to increase competitiveness lays in the optimization of system variables, based, on the one hand, on the minimum costs of the transmitted energy and, on the other, on natural limits for huge transmission systems.

For the rapid evaluation of the competitiveness and limits a comprehensive technical and economic assessment would be reasonable. The details may vary depending on specific features of each project, the uniqueness of equipment, requirements and regulations, public acceptance etc.

Some studies, e.g. [4], at the same time, show that ultra-long distances do not represent a fundamental obstacle any more. From there, the longest cost-effective distance for *HVDC* transmission is determined as of 7,000 km.

For the bipolar direct current line of 800 kV from the estimations mentioned above the losses would be  $P_{loss} = 328,1MW$  or about 8,2% of total transmitted power.

However, at present all *HVDC* transmission lines in operation are substantially shorter than the mentioned distance. The longest *HVDC* link at the moment accounts "only" for one-third of it - 2375 kilometres in length.



This evident advantage will, however, disappear if we go to smaller distances. On the distance less or equal to 300-400 kilometres conventional and more accustomed AC transmission technology may already constitute a fierce competition. Though, even on short-range distances *HVDC* still may find own market niche as, for example, in the mentioned above underwater transmission or in compact applications for close to load-centre substations and densely populated areas.

Another severe limit, that should be considered, is a redundancy factor. To design a system with a given degree of reliability a redundancy (duplication) approach is widely used.

Reservation is understood as an application of some certain means and measures to ensure the operability of the system in case of failure.

Common and separate reservation are usually distinguished. The former approach aims to increase reliability by reservation (doubling) the system as a whole. The latter tends to backup the individual elements in the system.

Reservation can also be permanent, where reserve units are connected to the main ones at all times during the regular working regime thus dividing the load. And reservation by substitution, when backup units need to be switched fast into the circuit when the main element fails.

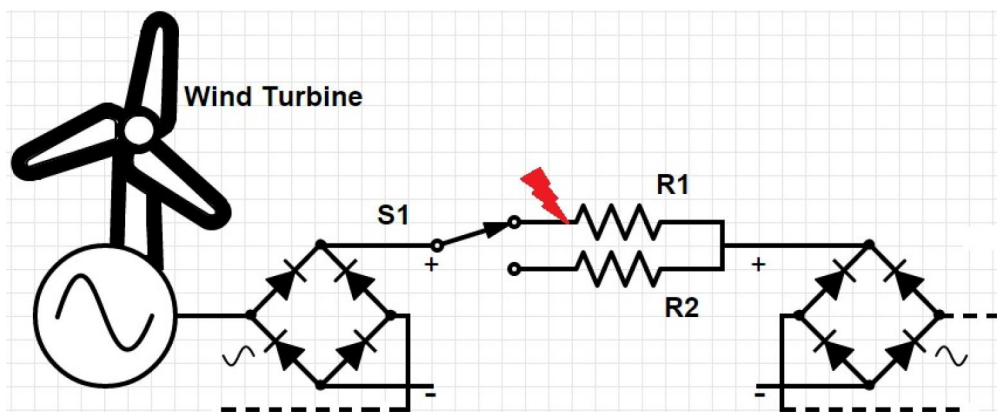


FIGURE 1.3: HVDC System with Reservation.

In systems with reservation applied there are primary and one or more backup isolated elements. The primary element is a part of the structure and in constant operation in normal regime.

Backup elements, just the opposite, being considered as additional redundancy measurements, do not belong to the default structure and are not in operation during the normal regime. In the case of primary element failure, the foreseen backup elements are to be turned on immediately to ensure the operability of the system, please, see Fig. 1.3.

On the other hand, in systems without reservation, the failure of the primary element leads to the loss of the whole system operability.

In the context of large backbone *HVDC* transmission line, where, compared to the rest of the energy system, a significant amount of power is transmitted, a complete reservation due to its cost is hardly feasible. Consequently, total system stability becomes very sensitive to any disturbances there. In turn, it means that transmission system operators would have to foresee adequate measures, e.g. additional capacity on power lines, in the case of contingency in the system to provide sufficient reliability.

No need to say, such a potentiality to shift the power flow in no time to other lines necessitates at least keeping these power lines underloaded in the normal regime of operation causing extra costs.

The complexity is another limiting factor for large *HVDC* transmission systems.

System simplification is a valid method to increase the system reliability by reducing the in-service failure rate and the number of failures. It very well correlates with general economy of scale tendency by applying simple design and construction of standard equipment, modularization and limiting the number of units, need for maintenance and required spare parts.

With an addition of new elements to the basic structure its complexity grows exponentially. When *HVDC* transmission technology development advances to the path of complex inter-zonal and large continental networks, super-sophisticated methods of control and management of such a system could be exceptionally challenging.

## 1.6 Disadvantages of HVDC Transmission Grid.

How it was described above, *HVDC* transmission technology clearly possess a number of sound advantages over AC transmission. Though, in some particular tasks or situations, it cannot, evidently, serve as a fully-featured replacement of AC transmission technology due to some known constraints and limitations.

Main bottlenecks of this technology are seen in conversion, switching, control etc. On conversion stage, for example, *HVDC* is believed less reliable mainly due to more sophisticated conversion equipment compared with conventional alternating current systems.

A more clear picture may give us an attempt to specify and itemize perspective bottlenecks in *HVDC* technology on the less theoretical case-by-case basis.

- Expensive. High Initial Substation Costs of *HVDC*.

For solutions based on *HVDC* technology the initial cost is substantially higher. First of all, an *HVDC* line necessitates converter stations at both the ends of the line for connection with AC power grid. These converter stations are much more expensive comparing with high voltage equipment for AC substations and high voltage overhead lines.

Bulk *HVDC* transmission at the moment uses line-commutated converters or *LCC* for short. These converters produce harmonics of various frequencies both on AC and DC side. On the AC side filters are used to absorb the harmonics, smoothing equipment on the DC side helps to remove DC output ripples. Thus, for a *LCC HVDC* link it becomes absolutely necessary to apply filtering and smoothing equipment on stations. These additional equipments and measures considerably increase the total investment costs of the *HVDC* system.

Only perspective savings from efficient power transmission, in the long run, may outweigh very high total investments at initial stage making *HVDC* economically advantageous.

- Availability

Availability of about 98.5% is considered good enough for single-pole systems, yet approximately one-third of the downtime, what is about two days per year, befalls unplanned due to faults.

More fault-tolerant bi-polar *HVDC* systems grant higher availability for the half of the full link capacity. Though, the availability at its full capacity is just about 97 - 98%.

- HVDC System Complexity

Converter substations are more complicated in design, installation and maintenance when compared to usual high voltage AC transmission substations. They imply not only additional equipment on converting stage, but also more sophisticated control and supervision systems.

Taking this into account, it becomes apparent that, in contrast to conventional AC power systems, design, construction and operation of large multi-terminal *HVDC* systems is a process of supreme complexity.

Power flow control and fault clearance ability in multi-terminal *HVDC* systems also require reliable constant real-time communication between all terminals and operators. Power flow control must be a proactive regulation process performed by a governing system itself and under no circumstances as a passive regulation measure seen in the inherent properties of the transmission lines.

The more complicated a future *HVDC* system shall become, the more parameters shall be continuously monitored and controlled, the quicker decisions have to be made and immediately put in action, the less endurance and error tolerance would be allowed. From the theory of guidance and control we know, that there is the certain upper limits of the number of guarded units or data and parameters in a system exist. The limits define how many parameters could be qualitative analysed and processed at the same time and thus, set certain boundaries to levels of system sophistication. Thus, to extend the system boundaries some routine operations could be given for unmanned outsourcing, automatically executable algorithms and adaptive self-learning control systems, if they are available and trusted.

- Limited Capacity

All types of converter stations in operation are not only expensive, but also have limited capacity and are very sensitive and restrictive to overloads. An optimum power balance in a network may require in some cases an elevated transmission voltage, what implies in turn, large power blocks to be converted and transmitted. The overall system response to the possible loss of converters or transmission links set quite strict limits on higher power levels.

Though the voltage rating progress is highly visible, there are still limitations on voltage and power capacity in semiconductor components. The highest pole voltage realized for *VSC* converters is 350 kV in Caprivi Link project in Namibia. (see Table 1.3) In the nearest future, this level is expected to rise over 500 kV. One project with comparable operational voltage level, namely, the Skagerrak 4 project - a link between Norway and Denmark, has been already under development and some more are being discussed.

- Need for Valve Cooling

Present *HVDC* converter valves are rather sophisticated units and need a complex cooling system. Generally, air insulated converter valves are cooled with water and mounted indoors in a thoroughly climate-controlled environment.

As losses in semiconductor devices can not be avoided and thus present an inherent part of the conversion process, the dissipation of energy shall be carried off by a cooling medium. In the function of such a medium due to economic and other reasons deionized water is broadly used.

A single cooling circuit normally includes gas scrubbers as de-aerification vessels, some extra pumps for redundancy, outdoor coolers and piping for all these units interconnection. [5]

A water treatment circuit with series connected ion exchangers and expansion vessels takes a small percentage of water from the main running stream to secure water volume changes with internal temperature variation. Expansion vessels are responsible also for leakage detection and oxygen removal.

This is already a pretty complex system of inter-conjugated units and parts, that are tied together by special software for management and protection of the cooling system. The software comprises several underlying concepts of different leakage detection to be precise enough to detect and control inconspicuous leakages of less than a liter per hour.

A limited thermal capacity is an inherent quality of valves, and thus, thermal security measurements shall be taken into account far in advance on the design stage.

The maximum temperature of a valve shall be satisfactory low to enable a valve to withstand short circuit failure without break-down. Thus the valve temperature during normal operation shall be kept lower this level respectively.

- Power Faults

In the *AC* power systems any short-circuits, that occur in a vicinity to connected *HVDC* converter stations, cause power vulnerability on the DC side of the transmission system of the same duration. In this case, converter substations undergo most hardships. Short-circuit faults at the rectifier side proportionate to the decrease of voltage. On the inverter side though short-circuit failure may cause a power fault of the whole transmission system.

- HVDC Circuit Breakers

The next step in *HVDC* system development from point-to-point connection to multi-terminal necessitates the presence of a circuit breaker. Advantageous in normal operation a low impedance of the *HVDC* system may be a real challenge in the case of short circuit fault because the easy propagation of fault into a system happens much faster and deeper.

To limit the fault penetration and possible damage and be able to isolate certain parts of an *HVDC* system a reliable and quick at switching operation *HVDC* breaker is of high demand.

Conventional mechanical breakers that already exist are insufficient as they operate within several tens of milliseconds, what might be too slow. Converter stations with semiconductor devices are endangered at most during faults. In order to minimize disturbances in converter operation, to avoid valves loss and overall system collapse it might be necessary to clear the fault within less than a few tens of milliseconds. *HVDC* breakers built of semiconductor devices are obviously faster than mechanical ones but lack effectiveness due to relatively large energy losses and still possess the same well-known problem with voltage withstand as regular converter station valves do.

Recently there are some new concepts of hybrid circuit breakers have been announced by a number of leading in *HVDC* technology producers. However, all of them are prototypes and have not yet been implemented into real projects. Moreover, all the concepts presented are bounded from above by the voltage level of approximately 300 kV what is already a passed chapter in *HVDC* technology at the moment aiming at levels above 800 kV.

It would not be amiss to mention that costs of DC circuit breakers are higher than conventional mechanical AC breakers. Moreover, throughout decades-long AC breakers operation, a lot of useful practical experience has been collected what is reflected in optimization of the AC breaker design and, consequently, in enhanced performance characteristics and costs. There is no such practical experience on *HVDC* breakers and, being put in the first operation, they would be apparently and gradually optimized and refined.

Still, it is evident that in the field of *HVDC* switching technology a lot of improvements need to be done and implemented into a reliably working standard.

- Need for Filters

Every *HVDC* converter station designed on thyristor element base is a source of voltage and current harmonics. In addition to it, the conversion process is followed necessitates a reactive power consumption.

For that very reason, filters are designed to minimize voltage distortion and electromagnetic interference in associated power grid. As a big inductance coil by its nature, a filter may also help in reactive power compensation support. And thus, known prerequisite conditions along with requirements from the adjacent network, environment and already existing transmission configuration may play a decisive role in case of filters and smoothing equipment connected to an *HVDC* transmission.

Filters and smoothing reactors being offered as a solution inevitable add to *HVDC* systems costs and complexity.

- Electromagnetic Interference

Producing a bunch of harmonics by converters can cause radio noise interference with the operational frequency used in communication channels. Although the interference is not destructive, communication asserted failures between grid operators can be expected and should be possibly avoided. As a consequence, electronic equipment sensitive to radio-noise interference may experience troubles what leads to data handling errors, data corruption and even to complete loss of data.

At most risks are exposed those communication lines and channels situated in proximity to valve converter station and *HVDC* lines. Installation of active filters helps to prevent high-frequency harmonics influence.

- Complex Grounding Measures

Grounding in high voltage transmission is applied to ensure the safety of personnel and reliability of the whole system and separate units the system consists of.

To avoid potential harm on electrical equipment due to the short current circuit and related to it hazards to health and life danger, a reliable and permanent connection between a protected unit and neutral earth should be securely established. Protective electrical earthing in the *HVDC* transmission presents a comprehensive set of measures to mitigate all the risks from accidental touching living parts or a dangerous “step voltage.” Grounding measurements are complex, require additional costs and high personnel qualification for accurate, precise installation.

A ground electrode might be in use as an active system reserve i.e. in continuous operation, for example, in the case of imbalance currents between bipolar overhead lines. Alternatively, it could operate for a limited duration of time for planned routine maintenance and in urgent cases of emergency at full current.

Inaccurate grounding may also be a reason for unwanted electromagnetic interferences bringing undesirable ruinous effects on the communication channels and the data being transmitted.

- Galvanic Electro-Corrosion.

Galvanic electro-corrosion becomes possible when at least two living parts - anode and cathode are closed into the electrical loop through a conductive medium, e.g. soil or water in the case of undersea cable line. As a result, conductive metallic structures in this electrical loop tend to lose mechanical properties and in the course of time eventually deteriorate.

Such an electrode line, when instead of metallic return for current flow, in an *HVDC* transmission system the sea floor or ground are used as a return path, evidently requires fewer capital investments.

However, in asymmetric transmission systems, e.g. in monopole overhead lines, electric current flows through conducting soil and may lead to electro-corrosion of underground pipelines and various mechanical structures. In many bipolar *HVDC* transmission systems electrodes are implemented in order to support system reliability.

In the case of one pole fault in bipolar systems, as the active resistance of the soil is not too high (usual values 10 to 1000  $\Omega \times m$ ), the current will immediately find its path through the conductive soil and allow the system to operate without interruption.

This optional solution gives a chance to avoid drastic consequences, when a fault of one pole would lead to the complete loss of the whole bipolar line and its capacity. Along with minimization of the full outage probability, such an arrangement allows for a short period of time to fix the faulty unit and bring it back into normal operation.

In undersea cable links, where sea water is used as a return path, it may cause corrosion of offshore platforms, bridge, port's onshore facilities.



- Visual Acceptability

In many countries it is especially hard to execute any large-scale ambitious project due to particular activity of groups, agencies and other organizations on nature or heritage protection. These groups on the various pretext are in opposition to any construction works and industrial development of defended location. Quite often this idea, being successfully pushed into public non-professional area of discussion and taken up by local communities, brings a complex and time-consuming negotiation process to a dead end.

If this location has no essential heritage to be proved or is not protected as a national park or preserved wildlife area, a key point in discussions might be a visual unacceptability of overhead lines and towers that possibly disturb people living in neighbourhood. In this way, a construction of an underground cable link as an alternative solution could be suggested. An HVDC cable transmission link being hidden underground easily passes to visual acceptability requirements and still able to carry considerable amount of power comparable to conventional three phase overhead high voltage lines. Though, it should be noted, this alternative brings along considerable additional installation costs, renders difficulties during maintenance, fault localization and, in the case of need, cable or other equipment replacement.

- Environmental Impact

The possible environmental impact caused by High Voltage Direct Current transmission systems should also be considered in Grid feasibility chapter. First of all, effects of electro-magnetic fields attribute to the most commonly discussed unavoidable characteristics of high voltage lines particularly related to the adverse influence on the environment.

Some of these weight factors are well-known and comparable with factors from HVAC transmission line exploitation. Some are different and are subject to further technical and scientific investigation. Based on results obtained in research centres all over the world, where such investigations are conducted on a long-term basis, it may be concluded, that *HVDC* transmission links do not present serious threats to the environment as well as to the life and health of human.

With use of the prototypical section of *HVDC* power line at *NIIPT* - the High Voltage Direct Current Power Transmission Research Institute in Saint-Petersburg, Russia a great number of experiments have been performed showing less pronounced influence on humans under a *HVDC* transmission line comparing with *HVAC*. The typical discomfort that humans normally felt under 50 Hz AC power lines, in the case of *HVDC* has not been observed. [6]

Safety regulations for people operating in *DC* electromagnetic field set certain limits, up to several hours, on the duration of EMF exposure and apply them by controlling the electrostatic field, a particular space charge level and ion current density.

The space charge level from *HVDC* lines may vary widely depending on many factors including weather conditions. As a result of its presence in the *HVDC* electrical field an ion current flux, which is also very changeable and can be evaluated by statistical parameters, is produced.

The DC line magnetic field alone has no notable effects and does not exceed the Earth's natural magnetic field. Since magnetic field exposure limits are prescribed in regulations and norms, there is no practical need to take extraordinary measures on *HVDC* line magnetic field restriction.

For reasons given above, we may supposedly come to the conclusion that *HVDC* electromagnetic fields are very limited and not obviously dangerous for living objects under *HVDC* overhead line. Thus, it is not necessary to foresee any special safety measures in addition to those that are normally implemented for conventional power transmission lines.

Taking into account most influencing on ambient environment technical characteristics of *HVDC* transmission links early in the planning stage can be lowered to the possible minimum. In this case, particular attention should be paid, for example, to transmission line routing, advisable remoteness of residential communities, technical features of power line towers etc.

Above mentioned possible disadvantages of *HVDC* transmission are not fixed and unsolvable problems. As the project condition vary, disadvantages may change or lose priority or certain cases even become an advantage. By all means, limiting factors may be solved with help of new technologies and fresh approach.

At the moment many companies, research centres and universities work on various kind of tasks to improve the area of responsibility in *HVDC* field. A number of technology breakthroughs, for example, are expected in the capacity increase of solid semiconductor devices, as well as in control and protection methods of *HVDC* transmission systems.

## 1.7 Summary.

Though *HVDC* technology nowadays is widely considered as something innovative in a context of discussions on renewable energy and state-of-art breakthrough, in fact, it already has own quite long history.

Development in mercury valves and especially solid semiconductors became a turning point in *HVDC* development, what was even intensified later with the advent of reliable and cost effective power electronic devices such as insulated-gate bipolar transistors (*IGBTs*), integrated gate-commutated thyristors (*IGCTs*) and gate turn-off thyristors (*GTOs*). During this technological breakthrough many new types of converters were discovered, thus, opening the way towards multi-terminal *HVDC* transmission network. However, at the present moment those electronic devices suffer from "infantile disease" in form limited capacity, voltage capability and some other crucial characteristics.

Thereby, the most of the ultra long bulk power *HVDC* links at the moment are still operated on thyristors' line-commutated converters (*LCC*).

There are several potential benefits of *HVDC* networks as a possible option for high voltage power transmission in the nearest future. An *HVDC* network represents a flexible and logical solution for integration of renewable energy and has a number of advantages over conventional *HVAC* technology. Thus, *HVDC* has a significant potential and certain exclusive niches where only *HVDC*-based solutions may beneficially operate.

Comparison and estimation of losses between *HVDC* and conventional *HVAC* is a non-trivial analysis, where many incoming specific factors on case-by-case ground shall be considered.

In spite of enormous initial investments, the total operational costs, in the long term, may become significantly lower with the improved power delivery, reduced transmission losses, environmental excellence and relatively small footprint area required.

The limits and possible disadvantages of *HVDC* transmission were also discussed in this Chapter. Still, above mentioned bottlenecks of *HVDC* transmission are not permanent and will be solved throughout further research and practical operation.

Constant and ever growing research and development in *HVDC* technology will gather headway, with its aim at solving existing and known puzzles, what will be done with the help of innovative technologies and new approaches.

Many technology breakthroughs in several important directions like the development of high capacity solid semiconductor devices or control and protection methods of *HVDC* transmission systems are expected to happen in the years ahead.

## Chapter 2

# HVDC Network Development. Issues and Opportunities.

In attempts to describe a concept of the future *HVDC* grid it is absolutely necessary to make a general survey of the current situation. Namely, what exact factors will most probably shape the future grid configuration, what kind of issues would be on the front-burner, what bottlenecks are to solve in the first instance and so forth.

Main features, decisive factors and requirements for long distance links and, of course, short connections between different synchronous areas, as well as, wind and solar power generation parks, which are at the present moment getting more and more impact on electricity system on the whole, should all be taken into account and described.

### 2.1 Possible Steps in Future Grid Development.

The ongoing transient shift to the post-industrial economy is characterized not only by the added value of ever increasing intellectual component in every product, but also, though becoming more energy efficient through the steep update in requirements, by still more and more power-consuming industry and households.

In the foreseeable future, the demand for electric energy will only increase this way bringing closer fore-handed renovation and further development of future energy grid.

In this chapter we will consider factual information with respect to existing trends, plans and visions for the future grid development and the various alternative power grid configurations, that may be applied in different regions of the world.

In a modern state *HVDC* transmission systems are seen as an intermediate connection between several separate high voltage AC systems by means of constant energy conversion of AC to DC and vice-versa.

This intermediate connection, as inbuilt solution approach, e.g. back-to-back converter stations, should contribute to a better stability of otherwise divided unsynchronized AC systems. Therefore, the possible configuration of *HVDC* networks on regional, national and international levels is mainly determined by the already existing grid outline and its expansion flexibility, regulations, practicability on the meet-the-needs basis.

Another possible approach implies stand-alone point-to-point or overlying separately-designed solutions with *HVDC* priority, where upgraded grid capacity is not limited by AC network nominal capacity, but, just the opposite, makes it possible to tap as much the power as certain AC transmission link could allocate.

Through the development process of future *HVDC* networks at the accelerated pace it is also expected that plenty of already known challenges involved will not only be successfully resolved, but at the same time, many of them will be simultaneously discovered and put on an agenda.

At the moment, there is no sound practical experience available on operating *HVDC* multi-terminal networks at the disposal. Comprehend value of many years' experience gained by many experts all over the world in AC system technology can only partially be applied to *HVDC* multi-terminal systems. From here it might be concluded, in order to avoid costly errors engineers and experts would have to rely, where it is possible and rational, on AC networks operation competencies and expertise, and collected experience from *HVDC* single lines projects to bring it to a more advanced level. Though, their position in many questions may be reinforced by *EMTP* simulations with as close as possible *HVDC* network parameters.

Several international research societies, e.g. *CIGRE*, *VDE*, *DKE*, *CENELEC* etc. consisting of many experts and scientists with keen interests in *HVDC* area aim to evaluate reasonable guidelines and recommendations on operation and standardization issues.

Thus, future improvements of components, which are employed in such networks whether in hardware, e.g. the converter stations, circuit breakers, line frequency filters, or in protection and control systems and algorithms might be needed.

To facilitate the execution of any proposed concept at first a good detailisation in a form of a timely delivered program and well-planned development steps of future *HVDC* should be achieved, broadly discussed and accepted.

Basically, there are three main grid levels which can be structurally separated out one from each other. Namely, regional, national and international conceptual levels, where *HVDC* technology will be naturally implemented. Still, such a division is nothing else than a mental model helping us to consider *HVDC* transmission possible benefits on various operational levels with essentially different adaptation and application for diverse groups of interests.

However, investment attractiveness, interlacing or even contradictory interests, mixed views on future grid development along with the overall profit for the same project on these three levels may differ in a very wide range of aspects and sometimes even come into severe conflict between all interested parties involved.

- Regional Level.

A regional network may consist of high voltage lines, cables and substations that connect different parts within one synchronized zone of operation. In such a case an energy region may exceed administrative borders of one administrative district or state covering considerably larger areas (see Fig.2.1).

On a regional level any regional transmission operator is highly interested in smooth and sustainable energy transmission over relatively large administrative divisions with the ability to monitor, control and coordinate the grid operation adding to reliability of the whole network infrastructure and performance.

Along with that, as main objectives activity could be named a policy on reducing electricity transmission costs, a limited budget and other resources, as well as disinclination towards large-scale infrastructure projects associated with large investments and risk.

To some extent a regional transmission operator enjoys flexibility in planning and configuration within regional limits but still lack the strategic sense of overall network development.

Relative independence and flexibility of a regional transmission operator are crucial for playing on energy markets in favour of an appropriate region. The scope of responsibilities and regional configuration have to be decided on this level.

A regional transmission operator shall also possess operational authority as an inescapable part of working actions to secure mid-term grid reliability and be able to control the transmission of energy.

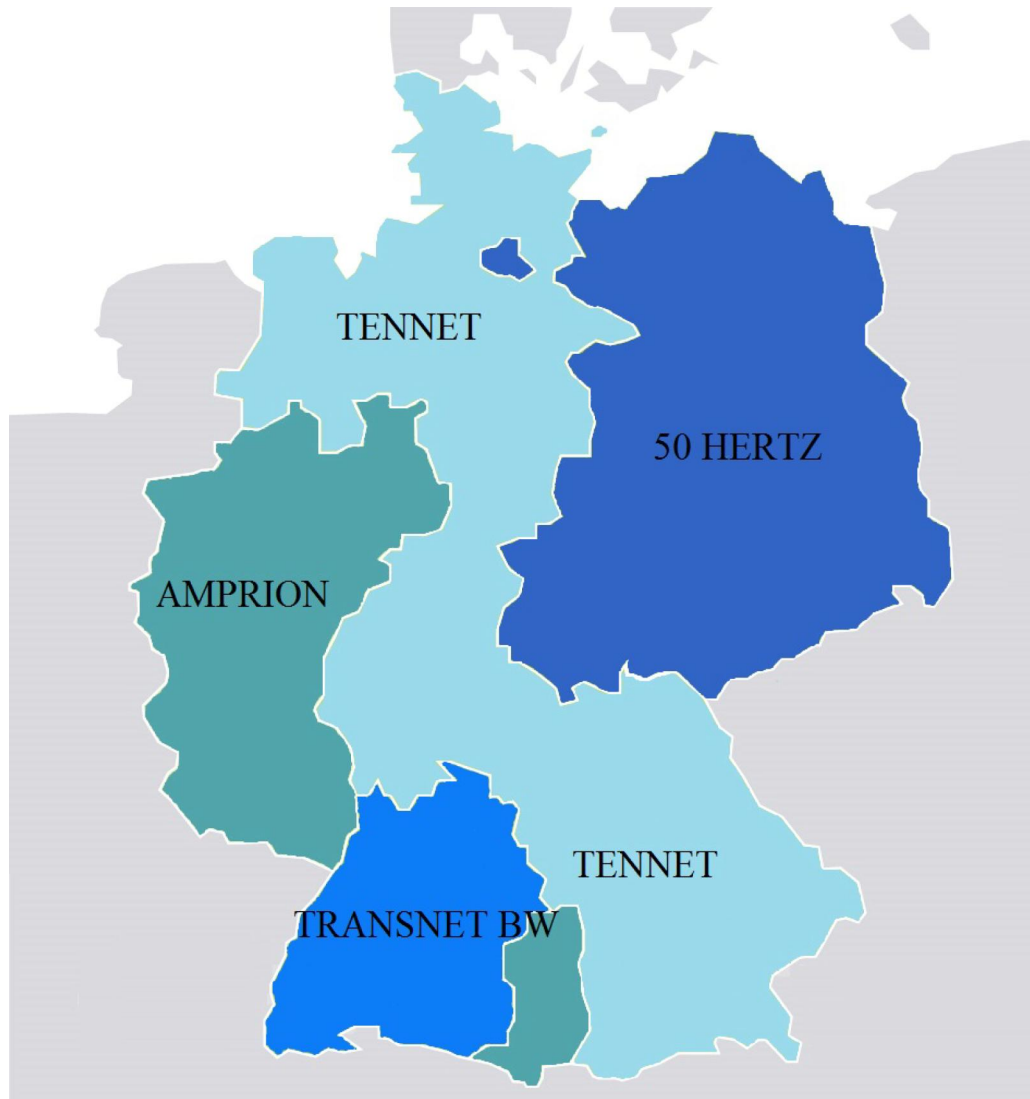


FIGURE 2.1: Regional Transmission Operators in Germany.

These and some others regional transmission operator interests fit well into a vision of future energy grids, where *HVDC* casts in the significant role. As it was mentioned before certain *HVDC* applications enhance overall performance, reliability and controllability of energy power transmission.

Special attention, as it is seen from now, shall be paid to *HVDC* technology as a stability factor to improve the whole system stability. It may also be considered as a viable solution owing to less demand for service and maintenance, less right-of-the-way and safety exclusion area due to rather moderate overall dimensions and upgraded security that is inherent to up-to-date manufacturing level, etc. The *HVDC* technology is very suitable for compelling needs of regional renewable generation integration. Low initial investment costs for transmission capacity upgrade, especially in the case of conversion of conventional three-phased *AC* lines into bipolar *DC* lines on the same pylons.

- National Level. Single Country Transmission System.

If we draw our attention one level up from regional grid, we will have to consider the next network configuration and consequently other groups of interests.

A national grid is committed to supplying sustainable and reliable power energy to end customers, communities and business inside the boundaries of one single country. This certainly marks a special own imprint on methods of financing, planning and management.

As a rule, national projects may rely on more flexible and abundant external financing sources. Using State resources more large-scale, complicated and long-lasting projects can be carried out.

National grid is already large enough to take advantage of the economies of scale in this way improving its applicability and economic efficiency.

At the same time, much higher total power energy shall be transported for considerably longer distances. This creates not only a favourable situation for *HVDC* technology, what is second to none in ultra-long transmission corridors and bulk power transfer, but also supplementary claims and additional specific requirements due to more parties with dispersed conflicting interests involved.

For example, a construction of some new *HVDC* transmission corridors on the national level, see Fig 2.2 may touch interests of not only primary players in the energy sector and main customers, but also various nature conservation and landscape protection organizations, environmentalists groups, host communities opposition, etc. Thus, the time needed to reach public consent and still keep the project on track, feasible economically and technically, increases dramatically, what becomes in many countries a sensitive issue.

During the planning stage, the National Energy Agency or any other similar institute provides with analysis on all current bottlenecks, issues and infrastructure gaps to be possibly fixed in transmission network on the national level. These reports and analysis supply the planning process with more broad many-sided vision, general idea or main direction of further development.

Inter-regional coordination and planning in interlinked and interdependent grids often have an ancillary supportive character, when power transmission management on national level serves as guidelines only, while full detailed elaboration and practical realisation of any certain project is delegated either in part or in whole to regional transmission counterparts.





FIGURE 2.2: HVDC Corridors in German Energy Grid Development. Source: www.netzausbau.de

As the main functions to monitor, control and coordinate both on regional and national levels have mutually-reinforcing nature, covering the larger geographic areas on the national level, the HVDC transmission may find its application in trunk line corridors.

Particularly useful it may be in merging several separated and unsynchronized regional grids into one nation-wide, which could not happen otherwise via conventional AC transmission connection.

Polling greater capacity improves system stability and affects favourably on transmission system ability in meeting demand fluctuations, load optimisation and lowering stresses on equipment and infrastructure. It also facilitates access to energy market for trading, bringing into the state of equilibrium total generation and prices.

Multi-terminal *HVDC* networks are already reasonably acceptable within one country or between two countries with the application of the *VSC* converter technology enabling flexible, compared to the *HVDC LCC*, system configuration, bi-directional power flow and intermediate power off-take.

Due to sensible mesh length of just a hundred or even less distance in kilometres it is not necessary to elevate voltage level any higher than 300 – 400kV. This voltage level is considered as a basis in some *HVDC* projects, that could potentially become a backbone for a future multi-terminal *HVDC* network. [7]

Moreover, for this voltage level all necessary equipment, including usually most limiting factors like power electronics devices and circuit breakers, are already available.[8]

Such an overlying network with several cross-boundary connections would also facilitate the access to the market of energy on the international level.

However, despite many evident advantages, the realization of such a large-scale and demanding project is not easy and a subject for further public and scientific discussion and corrections.

- International Level. Continental Network.

Although the idea with continental network is not new, until fairly recently it was unclear, that situation with available technologies (e.g. power electronic devices in *HVDC*), growing and penetration of renewable generation to the continent and ever-increasing demand for power, has come about to its possible direct realization as those above named factors admirably suit and complement each other almost perfectly.

On scaling up to international or continental level network with all cross-boundary connections a consolidated market for free energy trade becomes an integral logical part of this entire process. Latest rapid development in technologies applicable to *HVDC* energy transmission and their combination and complementarity allow us just only recently and for the first time, to raise a question about genuine overlying continental network linking through nations' energy grids.

This conceptually new network configuration will tie many countries' national grids into one single superstructure allowing deeper integration of renewable energy generation and adding to network resiliency and overall robust performance.

Geographically, such an *HVDC* network may embrace broad areas within large-scale economic agglomeration like the European Union or, as appropriate, take a swift step towards continental and even inter-continental network in the future.

One can easily guess, that such an expansion would lead to very fundamental changes in modern energy traffic connections and corridors with power flow directions and revolutionize energy trade market enabling inter-exchange of unprecedented high volumes of electricity across great distances on a global scale.

Developed on the national grids basis overlying *HVDC* network represents general integral means for rising transmission capacity and improving stability of all transmission systems involved. The idea of constructing long distance transmission system has been discussed already in the middle of the *20th* century as a probable solution to fast emerging unification of regional and national grids.

Understanding national grids as a basis and continental network as a superstructure will define its configuration. First of all, it may be assumed that proposed distances covering continental area would vary in a range from several hundred to few thousand kilometres.

Bi-directional power flow should be foreseen to facilitate power control between grids and zones and to intensify energy market interactions. To transmit high power capacity with the desired efficiency on distances from several hundred kilometres and more it is suggested to apply ultra-high voltage level from  $600 \div 800$  kV and even higher.

Transmission *HVDC* links with ultra high transmitting power ratio would serve as a backbone for a continental network, meaning at the same time that intermediate power take-off is delegated to national and regional grids functionality.

Further *HVDC* network up-growth dynamics may to some extent repeat the development of already accomplished gas or crude oil pipelines on the continent e.g. in Europe. Fig. 2.3 may well illustrate these similarities between the trans-European natural gas distributing network and the future inter-continental *HVDC* grid mainly due to their similar lengths, dimensions, involvement of many parties (e.g. governments, companies, local communities with various interests etc.), as well as, long-term character of planning and realisation of such a challenging project, in assumption, that way, of roughly similar scenarios of development.

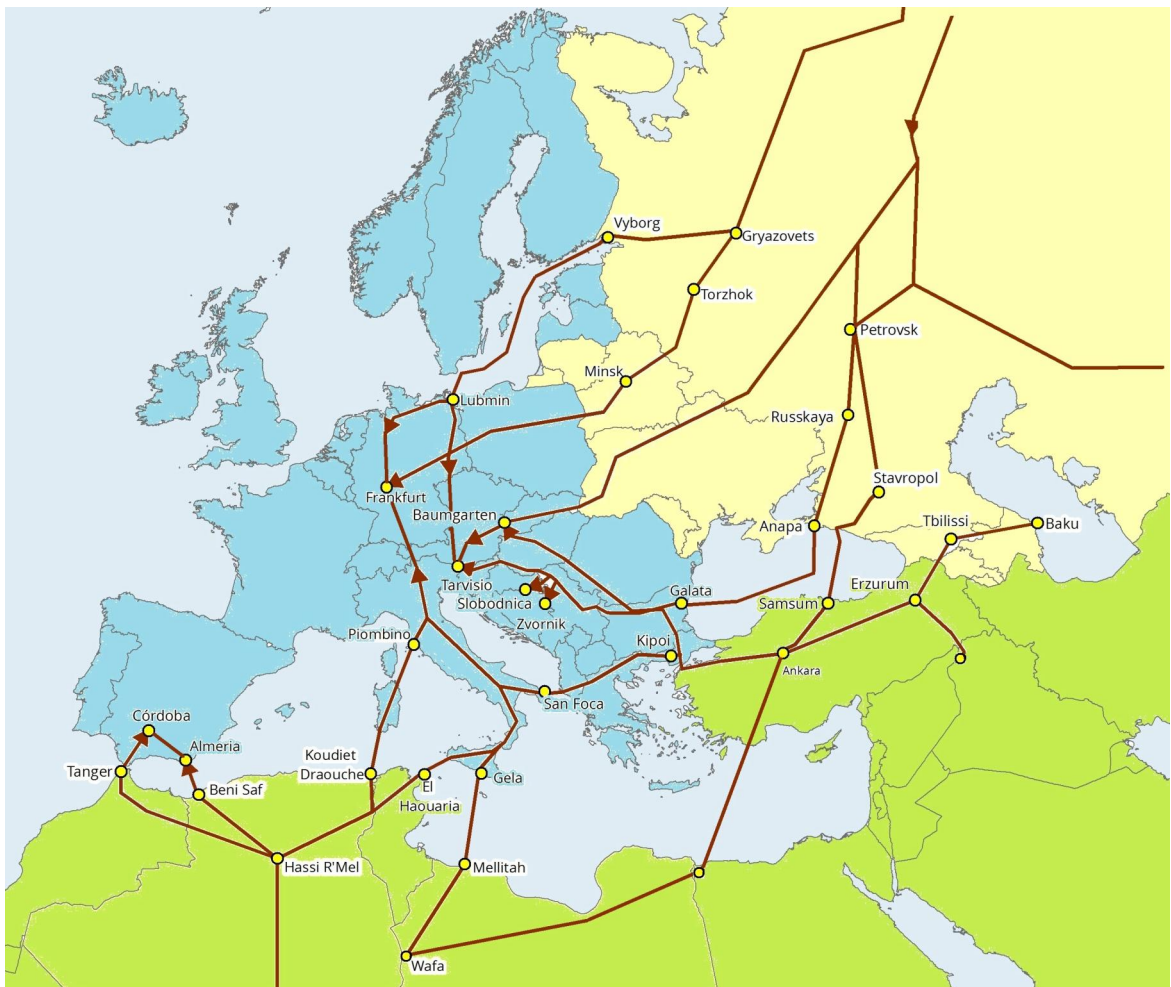


FIGURE 2.3: European Gas Pipelines Network as a Predecessor to HVDC Network.

However, it should be noted that the list of top 10 countries in electricity production, whose input is about two-thirds of the World Total generation, slightly differs from the top world oil producers, see Table 2.1.

TABLE 2.1: Top World Oil and Electricity Producers.

| Top World Oil Producers <sup>1</sup> |                   | Top World Electricity Producers <sup>2</sup> |                      |
|--------------------------------------|-------------------|--|----------------------|
| Country                              | Production (KBPD) | Country                                      | Production (GWh)     |
| Saudi Arabia                         | 11,726            | China  | $5,362 \times 10^3$  |
| United States                        | 11,119            | United States                                | $4,260 \times 10^3$  |
| Russia                               | 10,397            | India  | $1,103 \times 10^3$  |
| China                                | 4,372             | Japan  | $1,088 \times 10^3$  |
| Canada                               | 3,856             | Russia                                       | $1,069 \times 10^3$  |
| Iran                                 | 3,518             | Germany                                      | $634 \times 10^3$    |
| United Arab Emirates                 | 3,213             | Canada                                       | $627 \times 10^3$    |
| Iraq                                 | 2,987             | France                                       | $568 \times 10^3$    |
| Mexico                               | 2,936             | Brazil                                       | $557 \times 10^3$    |
| Kuwait                               | 2,797             | South Korea                                  | $535 \times 10^3$    |
| World Total                          | 84,951            | World Total                                  | $23,127 \times 10^3$ |

<sup>1</sup> Source: U.S. EIA [9] and <sup>2</sup> source: BP Workbook [10]

Thus, based on the information presented in Table 2.1 a reasonable assumption for the middle-term period could be made as following: top world electricity producers with electrical energy export interests are predetermined to become main movers and simultaneously important generation centres from where an *HVDC* network may be started.

Thereby, interconnections between them would add to the whole network robustness and ensure unbounded power flow in both directions, whereas bulk *HVDC* power transmission links leading to load centres would have a unidirectional character.

Along with this, as can be readily appreciated, further development of the continental *HVDC* network would become a powerful tool in a game of politics. Thus, next progress steps defining configuration and interconnection may greatly vary from desired engineering-and-economical performance in favour of one or another group of interest with significant influence.

Though, as compared to the regional or even national level possibilities e.g. for fund-raising, attraction of investments, specialists and experts and other resources, in spite of a kaleidoscope of contradictory interests and visions once having built a consensus, the international *HVDC* network as a project already on initial stage would command the widest possible support and significantly better chances for financing and other related resources to be accomplished in full and on time.

With *HVDC* technology it is not very obvious if the European grid unification shall take a path in synchronizing separately operating frequency zones.

Several important projects on the way towards the single European energy market have been recently completed. An *HVDC* link between France and Spain has been commissioned and ready for commercial operation since the middle of 2015 year. [11] Some other *HVDC* links are planned between *ENTSO – E* and Baltic countries, which are currently synchronized with UPS/IPS. [12]

High power capacity backbone links may connect remote synchronized grids without restrictions as the Continental *SuperGrid* vision proposed recently for North America, [13] and [14].

New approach with overlying *HVDC* network as a superstructure permits to operate various asynchronous grids from the Atlantic to the Pacific building in this way a massive unified network with given flexibility and power transmission potential.

In addition, flexibility in this context could also mean that such a grid covering the continent in part or in whole would be a solution to those bottlenecks in bulk energy transmission due to congestion issues and the lack in operational control over possible configuration.

### 2.1.1 Typical Values and Regularities.

The future *HVDC* transmission network is usually understood as a certain superstructure covering large areas and connecting several synchronous areas. However, as it has been shown above, *HVDC* transmission may have different scale, range of application and apply essentially different approaches.

Division into three considered layers, namely: regional, national and continental, is very relative, but reveals some regularities and typical features, that are inherent to one or another grid organization level.

In this approach, three separate layers differ from each other by some selected factors playing a significant role. However, sometimes the differentiation is not very clear and controversial, requiring more practical approach rather than theoretical generalizations.

Still, it is worth having a graphic presentation of possible *HVDC* grid development in the future with reservations to further discussions and corrections. In the Table 2.2 some important aspects of *HVDC* transmission are summarized and brought into comparison for analysis.

Key drivers for each level were already discussed above in Section 2.1 though it might be worth taking into consideration several factors presented in the Table 2.2.

First of all, drivers for implementation of various *HVDC* transmission solutions vary. On the regional level the main goal is to keep transmission stable, reliable and secure with regional operators on one side and end customers - households and local industry on the other side, as leading players.

One level above the number of actors increases with increasing significance of *HVDC* projects as they may affect interests of the much wider circle of groups and organizations including governmental agencies, official regulation bodies, ministries and corporations. On this level, the United national grid system becomes a powerful tool to manage power flows in order to consolidate the unity and increase economic and technical strengths along with effective climate and energy management policies of the whole national power system.

The next logical step is the international level where *HVDC* transmission is applied as overlying superstructure. Open energy market and possible profits from free energy trade become primary drivers for such an ambitious project, which would bring a tremendous effect on wide range of spectrum in energy industry and change our conceptions on how an energy system works. Main players from regional grids would give only verbal support and be replaced by governments, and transnational corporations.



TABLE 2.2: Typical Values and Configuration of HVDC Power Energy Systems.

|                 | <b>Regional</b>   | <b>National</b>   | <b>International</b>   |
|-----------------|---|---|--|
| Drivers         | <ul style="list-style-type: none"> <li>strengthening local systems;</li> <li>reliable uninterruptible power supply;</li> </ul>            | <ul style="list-style-type: none"> <li>increased transmission power and robustness</li> <li>united national grid system</li> </ul>              | <ul style="list-style-type: none"> <li>open trade energy market</li> <li>global energy system transformation</li> </ul>                              |
| Applications    | <ul style="list-style-type: none"> <li>city in-feed, "hidden" transmission</li> <li>on- and off-shore platforms</li> </ul>                | <ul style="list-style-type: none"> <li>asynchronous zones</li> <li>bulk power transmission corridors</li> </ul>                                 | <ul style="list-style-type: none"> <li>large interconnected systems</li> </ul>   |
| Configuration   | <ul style="list-style-type: none"> <li>back-to-back;</li> <li>point-to-point OHL, CL, GIL;</li> <li>FACTS, compensation units;</li> </ul> | <ul style="list-style-type: none"> <li>back-to-back;</li> <li>several point-to-point lines;</li> <li>ring/meshed <i>HVDC</i> network</li> </ul> | <ul style="list-style-type: none"> <li>overlying power network</li> <li>backbone transmission links</li> <li>submarine power transmission</li> </ul> |
| Length          | few 10s km  | up to few 100s km   | up to few 1000s km   |
| Capacity        | up to hundreds MW   | several hundreds MW   | thousands MW   |
| Voltage level   | up to 100 kV  | 100 ... 400 kV  | $\geq 600$ kV  |
| Interest Groups | Regional TSOs and DNOs  | Operator of Unified Energy System   | Energy Council for Continental Network Operation   |
| Functionality   | Local energy transmission and distribution  | United national grid operation  | International cooperation and coordination   |
| Implementation  | from months to few years  | several years   | up to few decades  |

To consider the next point, where *HVDC* transmission could be applied, it is necessary to have a clear picture of state-of-the-art in power transmission. In developed countries and areas the deployment of *HVDC* is likely to be in medium and higher voltage applications from approximately 20 kV up to 550 kV. On practise, in the already realized *VSC – HVDC* projects few steps of power/voltage relation are visible:  $\pm 150kV$  for 300 – 500MW,  $\pm 320kV$  for 500 – 1000MW and  $\pm 525kV$  for 1000 – 2000MW.



For the chosen voltage levels range several reasons can be named:

- In a case of retrofitting of conventional AC transmission lines and upgrading them with *HVDC* technology, for example, for higher transmission capacity, the same voltage level may be adopted, see Section 2.5. The voltage level of 400 kV is the highest one? that is commonly used in Europe nowadays. Thus, the same transmission towers can be applied, none or just few minor changes in isolation coordination would be required, what, in turn, would let to avoid additional investments on initial stage. This should be especially beneficial on switching from AC to DC long distance transmission.
- High voltage cables are considered as foundational part in *HVDC* off-shore network development. Cable technology at the moment offers high voltage products in the range from few tens to ca. 600 kV. Product ranging, in the first instance, is based oneself upon already known from *AC* voltage levels, and thus, inevitably affects *HVDC* grid development too.
- The very latest reports on *HVDC* breakers, being at the moment developed and tested, suggest us, that at least, few concepts of a *DC* breaker are capable to break *DC* current in power distribution and transmission grids [96], [97] and [104]. These solutions are available from medium voltages and limited now to 320–380kV. With great reserve and hope on further development, these solutions can be considered suitable for 400kV multi-terminal *DC* networks.
- The most suitable for *MT – HVDC* networks converter technology is Voltage Sourced Converter. Although, *VSC* is commonly promoted as a direct competitor to thyristor-based *LCC*, from its proven track records it becomes clear, that the *VSC* technology has not yet reached comparable voltage and power ratings. In other words, staying on firm ground *VSC* is broadly employed in the voltage range between 300–500kV [19].

However, the next voltage levels for *VSC* can be named as of 600kV (already tested and realised), followed by 800kV, especially taking into account rapid development in this area and acute need for higher voltages to cover larger distances in case of big countries and inter-continental configurations.

With the flexible power transmission advantage, whether it is cable "hidden" transmission in densely populated areas or undersea connections to on- and off-shore wind generation and oil platforms transferring power in either direction, where *VSC* technology should dominate. These *HVDC* applications would be able to meet demands and be realized in many projects to come.

In this case, length and capacity are expected in relatively small values - from few tens up to hundreds of kilometres and up to hundreds of Megawatts consequently.

However, if we have a closer look to developing parts of the world the above-mentioned *HVDC* applications and typical values may be very different. For example, at the current moment, the Chinese national power grid consists of seven large regional grids. *HVDC* transmission presents there mostly as point-to-point overhead bipolar lines with high power ratings at  $\pm 800$  kV and higher with capacity ratings of 4 – 6GW over long distances of e.g. 1000km.[15] *LCC* is, by all means, the key technology there, what will remain so in the nearest future.

Back-to-back converter stations is a good solution to tie asynchronous zones or separate grids with different operating frequency. On the national level the Japanese example best of all illustrates possible *HVDC* benefits. Due to historical reasons the Japanese power network has been divided into two quite independent regions - the North-East region, including Tokyo, is 50 Hz and the Southwestern part of Japan, including Nagoya, Kyoto and Osaka, functioning at a different frequency of 60 Hz. [16]

This congenital restriction in Japanese power network is overcome by applying *HVDC* converter station with back-to-back schemes at particular junction points. *VSC* converters here too are preferable solution as it could be necessary to supply *AC* grid with reactive power and prevent spreading blackouts beyond a certain area of occurrence.

Similarly, this could be done in other world regions, where it is required to enable an interconnection of several asynchronous zones or networks with absolutely different frequencies into a unified grid.

On the international level with help of *HVDC* technology most optimal results might be obtained through the long ago proposed unification of two tremendous in size, but not yet synchronized systems - the European *UCTE* and the Eurasian *IPS/UPS* power energy systems.

Evidently, that large interconnected systems should be able to transmit high power preferably in both directions. Here we run into the basic contradiction between two *HVDC* converter technologies in use that hopefully will be resolved in the nearest decade.

Line Commutated Converter (*LCC – HVDC*) technology with large industrial rectifiers and inverters is well known for transmitting bulk power over very long distance, but is complex and awkward as the need arises to change the power flow direction. This can be performed in *LCC* only by changing polarity of the converters with all ensuing consequences that implies such non-trivial procedure.

Voltage Source Converter (*VSC – HVDC*) technology is, just the opposite, born to manage power flows in both directions, but lacks at the moment sufficiently large voltage and power transmission ratings.

Still, this limitation is believed in many expert judgements relatively simple to solve and, thereby, to bridge the gap by technological advance in power electronic devices.

If this concept of overlying interconnected super grid to be carried out one day, we would likely see several backbone DC transmission links with the length up to few thousands of kilometres and few tens of Gigawatt of power capacity. In such a configuration national and regional power grid would be responsible for intermediate power take-off.

In conclusion, it is important to note that with a rise of scale-effect and overall importance of future *HVDC* transmission projects, the project implementation time also rises. For a common *HVDC* solution, in practice, the use of prefabricated modular equipment may shorten total project time from few years to few months.

Though, with scaling-up we enter an unfamiliar area where *HVDC* projects vary over a wide range, have own unique features and may differ over a broad area becoming in-adaptable to standard assembly-line production.

In this case, ordinary prefabricated units are of no help whereas design and production of specialized equipment becomes necessary, thus, extending project execution time to years.

Thereupon, working with unique properties of high-price *HVDC* equipment on the stage of design and production, it should be recognised early, that the wane from any mistake and defect is also very high.

## 2.2 Options for HVDC Grid Configuration.

The future *HVDC* grid is seen as a vigorous mean to transmit power from distributed remote locations with a deep incorporation of solar and on- and off-shore wind generation to load centres with high reliability and quality requirements. Therefore, a concept that suits these demands should embrace various solutions, where multi-terminal configurations are prevailing over separate point-to-point lines propositions. Multi-terminal configuration is a preferred alternative also in helping to offset power demand and supply and reinforcing reliability.

Talking about possible grid configuration, it shall be taken into account, that the question will be considered further in this Thesis mainly from national and international levels. Regional lines and medium voltage applications should be separated from *HVDC* transmission grid due to the same obvious reasons as city streets and country roads are distinctly separated from international transport corridors. Any acceptable universal generalisation seems here hard to reach.

There are just few regions on the Earth, where projects on transmission network development could be initiated from the scratch i.e. as green-field projects. In any other case, any network development would inevitably have interaction and natural constraints evoked by the already existing infrastructure. The higher the degree of the network development, the more intensive this interaction and the more fierce constraints on new projects could be exposed.

This results in a limited number of solutions acceptable as possible network configuration for further realisation. This could be either niche solutions or such a configuration that is flexible enough to integrate themselves into existing network. On the other side, the future *HVDC* grid would expand on the base of existing converter stations and separate single point-to-point links to radial and meshed networks on demand.

*HVDC* transmission may be configured in a broad various number of ways due to certain additional attendant circumstances and factors. Some of these possibilities are shown in Table 2.3.

TABLE 2.3: Options for *HVDC* Grid Configuration.

|                 |   |   |
|-----------------|---|---|
| Number of Poles | Monopolar   | <ul style="list-style-type: none"> <li>• earth return;</li> <li>• metallic return;</li> <li>• no return path (only bipolar systems);</li> </ul> |
|                 | Bipolar   |   |
| Converters      | LCC   | <ul style="list-style-type: none"> <li>• long distance;</li> <li>• bulk transmission;</li> </ul>  |
|                 | VSC (2, 3 Level) Half-Bridge                                  | <ul style="list-style-type: none"> <li>• easier power reverse;</li> <li>• black start facility;</li> </ul>                                      |
|                 | VSC-MMC Full-Bridge   | <ul style="list-style-type: none"> <li>• lower power ratings;</li> </ul>  |
| Scheme          | Asymmetric  | <ul style="list-style-type: none"> <li>• monopole is attractive for the cable systems;</li> </ul>   |
|                 | Symmetrical   | <ul style="list-style-type: none"> <li>• mainly used for VSC; (applicable to LCC as well);</li> </ul>   |
| Back to back    | Converter Station<br>Smoothing Reactors only,<br>(no DC yard) | Direct grids connection: <ul style="list-style-type: none"> <li>• different frequencies;</li> <li>• asynchronized zones;</li> </ul>             |
| Point to point  | Overhead lines  | <ul style="list-style-type: none"> <li>• long distances</li> <li>• low losses</li> </ul>  |
|                 | Cable lines   | <ul style="list-style-type: none"> <li>• undersea cable link;</li> <li>• hard-to-reach areas;</li> </ul>  |
|                 | GIL   | <ul style="list-style-type: none"> <li>• densely populated regions;</li> </ul>  |
| Radial Network  | Converter Station   | <ul style="list-style-type: none"> <li>• reliability and security-of-supply;</li> <li>• extra capacity margin;</li> </ul>                       |

As it follows here-from, the process of the *HVDC* network development would be both organic and symbiotic by its nature.

From that moment any development of a transmission network just cannot avoid conjugation and interaction with the already existing network infrastructure. The degree of this mutual penetration and interaction will have a symbiotic nature defining future *HVDC* power grid.

Let us consider several options as a starting point for *HVDC* grid development analysing their characteristics.

### 2.3 Back-to-Back HVDC Scheme

Up to date back-to-back operation of several asynchronous AC grids or grids with different frequencies, e.g.  $60\text{Hz}$  and  $50\text{Hz}$  was very complex, insufficient and problematic. With the help of *HVDC* technology such a systems can be coupled in a mutual operational regime.

The fundamental principle here is in the sequential conversion from *AC* current to *DC* by a converter station, and then back to another *AC* system, but with desired parameters like amplitude, frequency, angle etc. A part responsible for *AC* to *DC* conversion is called the rectifier and vice versa, from *DC* to *AC*, — inverter. Both parts are placed within the same converter substation area. See Fig. 2.4

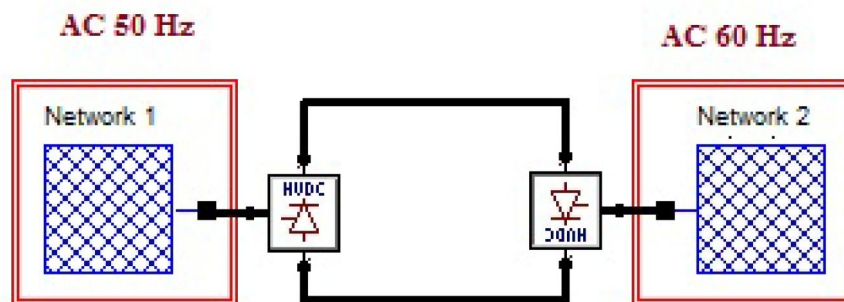


FIGURE 2.4: Back-to-Back HVDC Scheme.

Commonly thyristors-based current commutated converters are used. However, technological advance offers alternative solutions, where continuous bi-directional active and reactive power control is available.

The most advanced stations with voltage source converters and pulse-width modulation (*PWM*) allow a high degree of flexibility to control active and reactive power in all four quadrants. Moreover, every *VSC* unit on a converter station employing a reactive power control can also work as a *STATCOM*. This mode of operation permits independent *AC* voltage regulation at either terminal. [17]

The ability to integrate power systems via back-to-back connection improves network efficiency, reliability and avoids additional investments, for example, additional construction of overhead transmission lines or power plants.

Advantages of back-to-back configuration are numerous. First of all, power system stability rises owing to constant power flow management and timely appropriate control of voltage and frequency. It helps to damp peak oscillations during transient processes preventing outages and spreading of cascading faults in the *AC* networks.

The commonly used *HVDC* back-to-back schemes facilitate energy trade at times when prices in different regional networks are different, and thus, lower energy tariffs may be of great benefit to end-customer and serving utilities.

A sudden unexpected demand in large amounts of energy in one of the interconnected network consequently could be met by rapid power energy transfer from another interconnected network ensuring in this way overall system stability.

However, such a relatively simple scheme is just one of the first steps towards multi-terminal configuration.

## 2.4 Point-to-Point HVDC Scheme

The demand to reliably transmit more power from generation centre to end customers pushes the further development of transmissions network towards point-to-point *HVDC* solutions as they are considered more economical and able to carry considerably larger amounts of energy compared with conventional *AC* lines.

If we look at point-to-point scheme it is similar to back-to-back solution, but with the difference that rectifier and inverter parts are separated over a long distance with cable or overhead line in between. Usually, point-to-point transmission link connects high-capacity generation and load and, thus, is intended to transmit power mostly in one direction. See Fig. 2.5

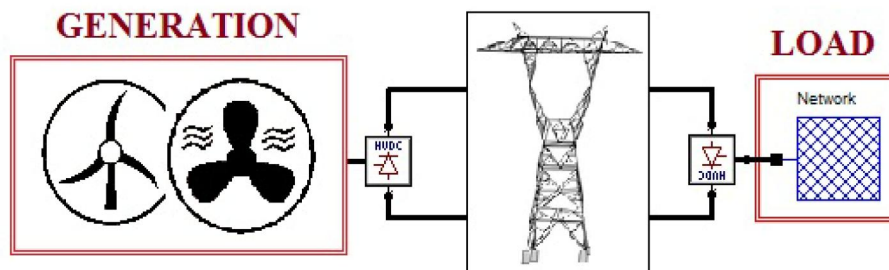


FIGURE 2.5: Point-to-Point HVDC Scheme.

Point-to-point *HVDC* connections ideally suit the needs to transmit large amount of electricity over very long distances. Point-to-point configuration may include cable links, overhead lines or a combination of them.

This solution becomes especially practical when the distance of transmission link exceeds break-even distance of ca. 400–500 km at a rating above 1 MW transmitted power. At the moment there is already an impressive list of successfully realized point-to-point *HVDC* connections both bulk transmission via overhead line and undersea cable links.

Nevertheless, several schemes for point-to-point configuration are possible.

Asymmetric monopole system with earth or metallic return.

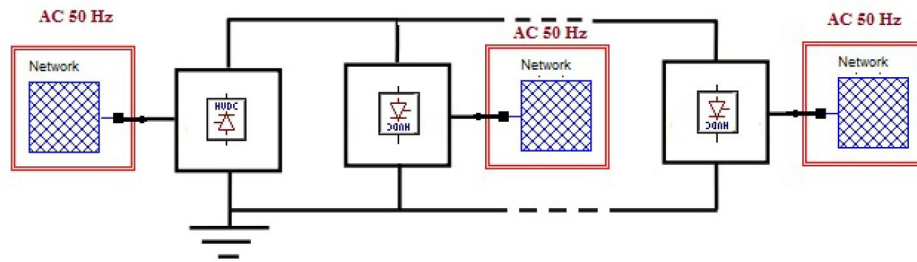


FIGURE 2.6: Asymmetric monopole system with metallic return.

Asymmetric monopole system is the simplest solution may consist of two or more converter stations with current loop via high-voltage conductor and, either earth return, or metallic conductor, as a return path, see Fig.2.6.

Mono-polar configuration with earth return may be attractive from economic point-of-view, for example, for cable links, where costs of cables compose the major part of initial investments. Thus, the possibility to avoid laying down additional cables may save a considerable amount of a project budget. Provided that, such configuration is acceptable by local regulation, which is not the case in many countries, where continuous current-flow via earth is not admissible for environmental or technical reasons.

By the contrast with earth return, asymmetric monopole system with metallic return uses low voltage conductor to loop the circuit and, as a result of this, excludes current flowing through the earth.

All converters in such system should have a connection between neutral points to only one directly earthed point of terminal to insulate neutral conductor and enable it to withstand voltage rise during faults.



In a symmetrical monopole configuration inverter and rectifier parts of *DC* converter stations are put together with two conductors of opposite voltage polarity, but the same magnitude.

The earthing in such a symmetrical configuration might be organized at the *AC* side reactors with high impedance, earthing of *DC* buses via high resistance, at *DC* capacitors middle points, see Fig.2.7. In this configuration under normal conditions there should be no current flowing through the earth loop.

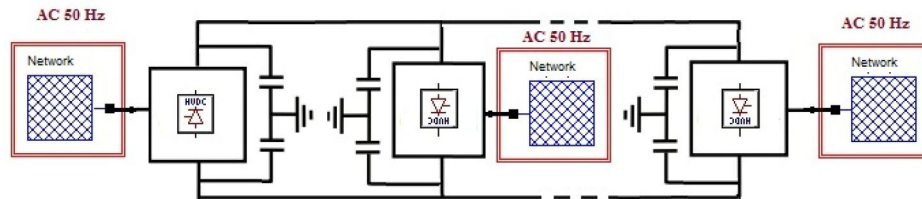


FIGURE 2.7: Symmetrical monopole system.

Even though two conductors of opposite polarity are foreseen to transmit power, still, they are interdependent from each other. In event of a fault of any conductor, the second unaffected one cannot keep on operating by closing the current loop through the earth, as a return path.

Both cable transmission and overhead lines are vulnerable to permanent and temporary faults. On the score of switching over-voltages or lightning strikes into the line, temporary faults are even more frequent. The clearance of temporary faults usually requires a restart of operation and a possibility to reconfigure the system during a short period of time.

Current/voltage imbalance in the case of an earth fault happened at one of two poles of a symmetrical monopole may even worsen the situation with automatic restart after a fault. So, it becomes essential at first to remove any voltage unbalance, what can be done by *DC* choppers in combination with discharge resistors.

Using the same number of conductors, that are able to withstand the full voltage, a symmetrical monopole scheme is less stable and reliable in comparison with normal bi-pole configuration.

Though, the symmetrical monopole configuration has own field of application. This scheme is applied mainly in *VSC HVDC* systems. [18] However, *LCC*-based point-to-point connections can be designed as a symmetrical monopole scheme too.

Bi-polar solutions for *HVDC* transmission provide even more pronounced economic effect as an alternative to conventional AC transmission since the same power link becomes able to transport more energy.

In addition to it, a bi-polar *HVDC* transmission has a higher level of endurance in the event of a fault at one pole or converter. Having lost one of two poles such configuration can still keep power transmission at a lower level with another healthy pole and low voltage conductor, that is used as a part for metallic return path under normal conditions.

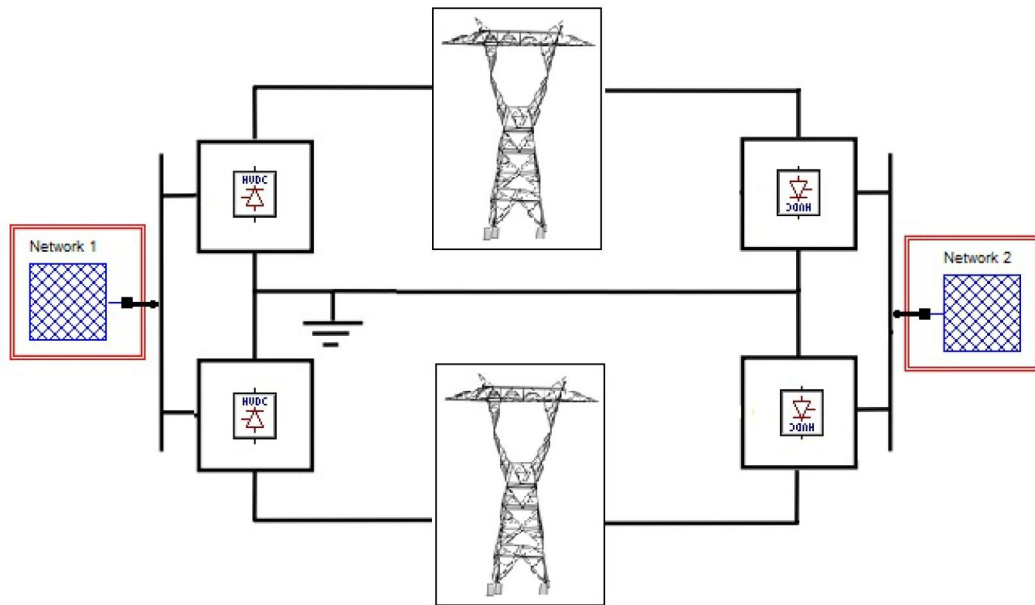


FIGURE 2.8: Symmetrical bipolar system.

In regular service a bipolar system, containing two poles at equal current ratings and potential, is symmetrical. This means, that *DC* currents flowing on both poles, are guided to the equal amplitude balance and the neutral current through the earth is about zero.

Under system's contingency the symmetry is immediately broken, *DC* currents that flow through the poles are not equal any more and, consequently, the neutral current also considerably distinguishes from zero. To prevent this, the earthing may be done at one point only, due to the lower earth resistance.

Based on economical and technical considerations and from a reliability point of view, a bipolar configuration with metallic return appears to be the most promising configuration for *HVDC* networks in the coming future. Moreover, as it has been already proved in practice, such scheme has a certain flexibility and may smoothly incorporate different *HVDC* technologies.

With the remaining controllability and the ability of voltage stabilization of the adjacent AC network, the classic line commutated converters based on thyristor technology can be successfully combined with voltage source converter *HVDC* transmission at an unreachable to this day voltage level of  $\pm 500kV$  and higher. [19]

For future *HVDC* networks a bipolar configuration with provided metallic return path appears to be the most suitable solution for further development and realization. Another viable solution is retrofitting the existing AC transmission line into *DC*, when *DC* lines are suited on the same power tower with three phase *AC* system, see Section 2.5.

### 2.4.1 Few HVDC Point-to-Point Lines.

First significant steps on the way to the future *HVDC* network are being taken in Germany. The key drivers for this action are, on the one hand, a very intensive deployment of renewable energy like solar and wind on the North of the country, and, on the other hand, the hard decision to phase out all nuclear generation, due to growing public concerns on the possible risks of failure.

National grid operators happen to be in a complicated situation: the ever growing demand of power energy in industrial centres located across southern Germany and urgent necessity get hold of large amount of power generated by off- and on-shore wind parks.

The existing power grid is already set under severe overloading and is stretched to its ultimate limits. Still, the country needs a lot more power in the coming years.

According to the expert estimation, to solve the conflict between existing demand and increasing share of volatile renewable generation it is required to build about 1000km of new high voltage overhead lines by the end of year 2015. [20]

Still, the business standard of lasting legislating approval, active and strong civil opposition etc. set serious longstops to any positive outcome.

To cut the impending danger of energy shortage and still be able to meet these challenges, a plan on the national power network development has been publicly introduced. According to this plan, the main role will be taken by *HVDC* transmission technology. Network operators find *HVDC* a less expensive and easier solution, than fixing *AC* network infrastructure.

All in all, the plan has foreseen the construction of at least four *HVDC* transmission lines within three main corridors, drawn from the energy abundant North to the industrial South, see Fig. 2.9

On the first stage, it is expected to start with a 660-kilometres long corridor A, which will be able to deliver 1 GW extra power from Emden - a connection point for offshore wind farms in the North Sea, to the AC grid hub near the nuclear power station in Philippsburg, some north-west from Stuttgart.

Offering increased power energy transfer, the *HVDC* link will connect regions as end points with already well-developed network infrastructure, where building new transmission lines meets public resistance.

*HVDC* is a pertinent answer to simultaneous changes that have put the transmission system at stress. Although a few sensitive issues such as limited power ratings of *VSC* converters and comparatively high switching losses of conventional *IGBTs* have been resolved by implementing novel *IGBT* modular multilevel converters, the last obstacle of *VSC* converters to the desired performance is still there owing to the impossibility of safe and reliable breaking of *DC* current.

Advance in power electronics industry may solve this issue very soon. At the moment, modular multilevel converters have already reached reasonable power transmission ratings from a few hundred megawatts to 1000 megawatts, while switching losses reduced to just few percent per each converter. [21]

The planned three *HVDC* corridors accommodate additional load in every of the four scenarios considered.

- Scenario A 2022

In comparison with the others, *ScenarioA2022* derived on the expectations of the lowest demand for overall power network expansion. The four DC transmission corridors should have a route length of approximately 1,800km and common transmission capacity in North-South direction of 10GW. The planned distance where AC operation will be substituted by DC makes up approximately 300km.

On- and offshore wind generation development in the federal states of Mecklenburg-Vorpommern, Schleswig-Holstein and Lower Saxony with around 27GW of the expected installed capacity is the main driver for the national network expansion needs.

- Scenario B 2022

The *ScenarioB2022* differs from the *ScenarioA2022* by a slightly higher network expansion needs, what turns into further *HVDC* transmission corridors extension. This Scenario provides with a vision on four DC transmission corridors approximately 2.100km long to transmit 10GW of power in North-South direction. The



FIGURE 2.9: The four HVDC corridors proposed for Germany's transmission grid. Scenario B 2032.

length where DC takes over AC transmission is planned equal to  $300\text{km}$ . In this Scenario the projected capacity to be installed is around  $32\text{GW}$ .

- Scenario B 2032

The *ScenarioB2032* is obtained from the *ScenarioB2022* as a possible enhancement of the latter and in comparison to the other scenarios requires the highest overall rate of total network expansion. A driving force for such an increase is

mainly resulted from significant boost of offshore wind power generation up to 54GW. Thus, with reference to the *ScenarioB2022* some additional *DC* lines of 1,000km are planned.

As the existing network infrastructure could not accommodate any additional load and with the further increase of the transmission ratings expected in the *ScenarioB2032* additional expansion of high power capacity *HVDC* corridors C up to 12GW and D up to 4 GW are introduced.

- Scenario C 2022

The *ScenarioC2022*, in comparison to the previous *ScenariosA2022* and *B2022*, stipulates major network expansion needs. In this Scenario wind power generation exceeds 44 GW and high capacity *HVDC* corridors are necessary. These *HVDC* corridors C and D should replace the expansion in the three-phase *AC* system, their total length may account 2400km with a transmission capacity of 18 GW in North-South direction.

Thereby, the vision of future grid development in Germany agrees with above-written considerations and practically should represent a feasible combination of underlying *AC* and overlying *DC* networks.

The measures planned in Network Development Plan with *HVDC* transmission involvement should be sufficient to manage the growth in renewable generation and accommodate all the generated power into the grid with lowest possible losses at delivery to remote load centres throughout the country.

Regardless of the fact that actual routes of the network expansion determined in the Plan depending on the scenario may vary in practice, it can be already concluded that a future power grid will have meshed configuration of intersecting *AC* and *DC* lines.

Since the transport requirements vary depending on each scenario, future network optimization may require the implementation of additional *DC* corridors to connect North-South *HVDC* links forming in this way a meshed *HVDC* network moving away from initial and straightforward point-to-point configuration.

The realization of this ambitious project may trigger still even more global hopes related with continental "supergrid" what may dwarf even setting a connection between *ENTSO – E* and *IPS/UPS*. [22]

Connecting earlier separated asynchronous networks into one is beneficial not only from an economical point of view due to numerous benefits from interstate energy trading and cooperation or in terms of increased reliability, but also when we consider bold plans to reach 80 percent of the renewable power supply by year 2050. To accommodate successfully such a big share of renewables into a network it is necessary to have a sufficient backup power and flexibility provided by *HVDC* transmission.

However, Germany is not the only country, where it is required to transmit large amounts of energy and where, due to structural prerequisites, *HVDC* transmission technology could be implemented to the benefit of both power network and the community. Many European, Asian, American and African countries consider it too and have more or less similar issues.

## 2.5 Retrofitting of Transmission Lines from AC to DC.

The continuous increase in electric power consumption dictates new reality for a concept of power network development. This process has significantly gained momentum during the last years. Obviously, this trend will last in the coming years.

Although new capacities of power generation are being constantly built, especially "green" renewable generation, a worn-out transmission network is forced to operate at stress, lack expansion and cannot accommodate new capacity at full. Existing power transmission lines are over saturated.

Therefore, construction new lines - the most logical solution in this situation, becomes a very urgent issue. However, in many countries new overhead lines construction may become impossible even on initial stages of rights of way ascertainment or transfer of territory for a new project. Environmental concerns also oppose to new transmission projects realization.

Design and construction of underground transmission may be an answer to some problems, but stay still very expensive.

In such circumstances, there is a clearly articulated need to search for possible alternative solutions to enable high power capacity transfer and, at the same time, to avoid large-scale construction activities.

The proposal of utilizing already existing *AC* lines and transforming them wholly or partly to high capacity *DC* transmission corridors represents a successful outcome in this

seemingly unsolvable puzzle. Retrofitting of *AC* lines that use earlier established right-of-way corridors, wiring and power line towers lets to save considerable investments and time.

Transformation from *AC* to *DC* backbone transmission in theory looks very simple and reliable - just run direct current through the already-built power lines instead of the three phase *AC* current. Nonetheless, this proposal has never yet been put into practice, and yet, is considered technically awkward and risky.

Still, the need to prove the proposal against reality drives experts in energy industry onto the field of real project implementation. It has been planned that a 400km long existing power transmission *AC* line will be re-equipped and converted into a hybrid one, e.g. on the same towers will be situated one circuit of three phase *AC* and *DC* simultaneously.

A pilot project by transmission operators *Amprion* and *TransnetBW* aiming to parallel *AC* and *DC* wires hanging on the same pylons within an experiment on an unused line. Before it started there were many uncertainties on electromagnetic fields that surround wires and their mutual coupling between *DC* and *AC* wires.[23]

However, preliminary computation and later experiments showed that should not be a problem. In a hybrid line where one circuit is represented by a typical three-phase *AC* and the second is upgraded to *DC* bipolar configuration with one positive, one negative and one wire as a neutral wire the conducted interference is expected to be very low.[24]

The only things that requires a change are the suspension line insulator, but this is a minor change demanding considerably less efforts and investments than a new line construction.

Applying this technology not only on regional but also on the national and international levels brings significant results and opens up new horizons of moving a large amount of electricity via *DC* backbone transmission. This, in turn, would increase capacity grid and its operational stability.

In addition to it and in the case of success of the first project that should have been completed already by 2019 year, the retrofitting technology should be able to reduce considerably the severe need for new lines construction and, what is of no small importance, to avoid cumbersome permit-granting procedures.

Retrofitting from *AC* to *DC*, especially on power towers with two circuits installed, could have different modifications. With use either conventional thyristors valves or *IGBTs* based converters capable for bi-directional transmission, or even a combination of both into one hybrid power line with so called tri-pole system configuration. See Fig. 2.10



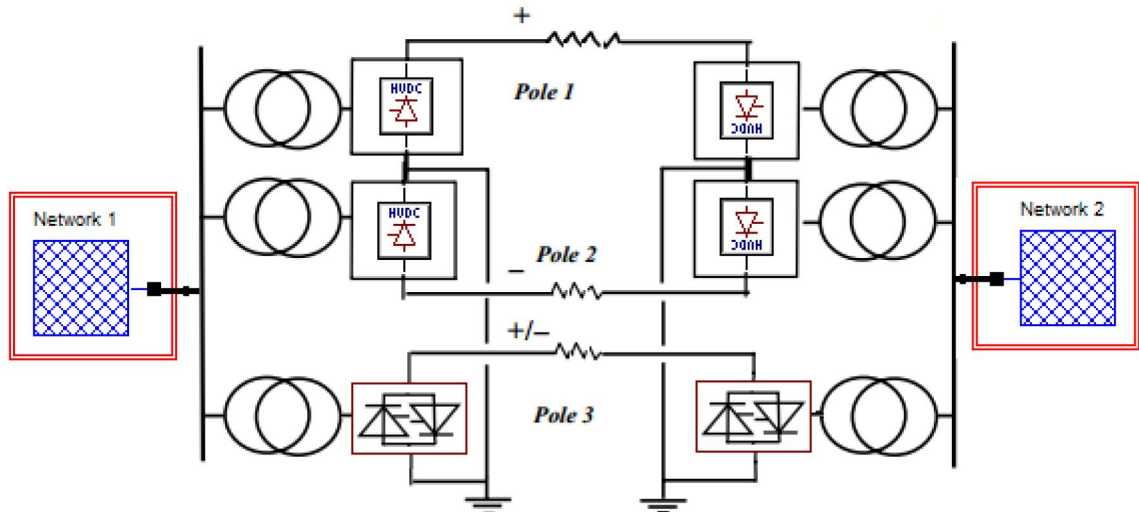


FIGURE 2.10: Tripole HVDC scheme with parallel bipole and monopole systems.

In such a configuration, as it can be seen on Fig.2.10, the three-phase AC system is turned into three DC poles with no earth current flowing both under normal operational conditions and under one pole fault. [25]

The tri-pole system configured in this way uses at full all three conductors and improves considerably high power transfer capacity along with the total system reliability. Due to the inherent internal redundancy, the DC tri-pole brings additional stability and robustness to the whole system. Well-known  $N - 1$  strategy could be even further enhanced, should the supposed AC circuit total loss be recognised as an equivalent just to the one DC pole loss, instead of the whole bi-polar power line fault. This presumption has all ground to be justified in case of bi-polar power line fault, where one of its poles still remains in operation. [26]

Accountable and recognized capabilities of DC transmission to operate longer periods of time under overload conditions, depending in turn on transmission lines and converter stations, would even broaden those criteria further.

In comparison with bi-pole scheme a tri-pole configuration obtains enhanced internal redundancy parameters and may considerably increase grid capacity helping to keep the balance between supply and demand, so that the daunting issue on building new transmission lines could be at least temporarily solved. Moreover, retrofitted power HVDC lines may serve as a foundation for the expected continental HVDC power grid.

## 2.6 Standards for Future HVDC Grids

In coming years a broad application of *HVDC* technology will become mainstream in high voltage bulk transmission technology. Though, there is just a few significant player on the market, and there is still a possibility for other technology companies to enter the pull of main *HVDC* players.

Very competitive market conditions and wrestling for regional and international markets control are getting more and more severe currently, what has already led to the advent of, in principle, very similar *HVDC* technologies, but still with the lack of practical interoperability between them.

Compatible and, when it is possible, even interchangeable modules from different producers may combine the complex *HVDC* grid piece by piece. The voltage levels, at which these modules should operate and be designed for, are also a vital task in extensive standardization process. [27]

A question of compatibility of high voltage equipment in the future multi-terminal interconnected *HVDC* system is of a great importance. The future harmonisation of *HVDC* grids is hardly possible without well-developed *HVDC* standards which should be addressed to manufacturers, transmission grid operators and end users.

Reliability of complex *HVDC* transmission network is strongly dependent on various grid configurations, what is also a subject to review and recommendations from standardization and unification authorities. All possible methodologies applicable to power flow control, fault detection and protection systems should also be carefully investigated.

On the other hand, clear and transparent standards and guidelines in *HVDC* field are potentially capable to lower various uncertainties along with the overall risks in future projects, improve current production processes at the early stage of planning and design, and later by construction, operation and maintenance of *HVDC* systems.

Considering current situation, some ground-breaking efforts shall be made towards the international standardization in the following fields related to *HVDC* technology and relevant equipment and systems, see Table 2.4.

TABLE 2.4: Existing *HVDC* Standards Established by IEC.

| Application                      | Standard                        | Title  |
|----------------------------------|---------------------------------|--|
| General technical standards      | IEC 60633 (2009-07)             | Terminology for high-voltage direct current ( <i>HVDC</i> ) transmission.  |
|                                  | IEC/TR 60919 Part 1, 2 and 3    | Performance of high voltage direct current ( <i>HVDC</i> ) systems with line-commutated converters.  |
|                                  | IEC 61803 (1999-02)             | Determination of power losses in high-voltage direct current ( <i>HVDC</i> ) converter stations.   |
| Design                           | IEC 62344 (2013-01)             | Design of earth electrode stations for high-voltage direct current ( <i>HVDC</i> ) links - General guidelines.                             |
| Technical criteria for equipment | IEC 62001 (2009-10)             | High-voltage direct current ( <i>HVDC</i> ) systems - Guidebook to the specification and design evaluation of A.C. filters.                |
|                                  | IEC/TR 62543 (work in progress) | High-voltage direct current ( <i>HVDC</i> ) power transmission using voltage sourced converters ( <i>VSC</i> ).                            |
|                                  | IEC/TR 62544 (work in progress) | Active filters in <i>HVDC</i> applications.  |
| Construction procedures          | IEC 61975 (2010-08)             | High-voltage direct current ( <i>HVDC</i> ) installations - System tests.  |
| Operation and maintenance        | IEC 60060 Part 1, 2 and 3       | High-voltage test techniques.  |
| Testing method for equipment     | IEC60700-1 (2008-11)            | Thyristor valves for high voltage direct current ( <i>HVDC</i> ) power transmission - Part 1: Electrical testing.                          |
|                                  | IEC 62501 (2009-06)             | Voltage sourced converter ( <i>VSC</i> ) valves for high transmission - Electrical testing - voltage direct current ( <i>HVDC</i> ) power. |
|                                  | IEC/TS 61245 (1993-10)          | Artificial Pollution Tests on High-Voltage Insulators to Be Used on <i>DC</i> Systems.   |

Even though the number of existing *HVDC* standards is already considerable, it is still far from being sufficient, as the field experiences an explosive growth and thus, the need for standards, guidelines and regulations stays also very sharp.

In the Table 2.5 below some crucial *HVDC* standards are presented. These *HVDC* standards is the primary responsibility area of joint working groups to develop jointly with other relevant Committees e.g. *CIGRE* working groups.

TABLE 2.5: *HVDC* Transmission Standards to be Established.

| No. | Title   |
|-----|---|
| 1.  | Reliability and availability evaluation of <i>HVDC</i> systems  |
| 2.  | Electromagnetic Environment Criterion for High-voltage Direct Current ( <i>HVDC</i> ) Overhead Transmission Lines |
| 3.  | Technical Report for Control and Protection Equipment of <i>HVDC</i> Power Transmission Systems                   |
| 4.  | Technical Report for test requirements for DC yard equipment  |
| 5.  | Technical Report for Guideline on Asset Management – <i>HVDC</i> Installation                                     |
| 6.  | DC side harmonics and filtering in <i>HVDC</i> transmission systems   |
| 7.  | Technical Report for Guideline of <i>HVDC</i> System Planning   |
| 8.  | Guideline for the system design of the <i>HVDC</i> transmission system  |
| 9.  | Technical Report for Guideline of <i>HVDC</i> System Operation Procedure  |
| 10. | External insulation correction for <i>HVDC</i> transmission systems in high altitude area                         |

Considering a multi-terminal *HVDC* network and the most suitable for it at the moment *VSC* technology, the special attention and efforts, by all means, should be devoted to standardization and regulations in *VSC – HVDC* area. The work on some most crucial directions is already in progress, see Table 2.6.

TABLE 2.6: *VSC – HVDC* Transmission Standards to be Established.

| No. | Title   |
|-----|---|
| 1.  | IEC/TR 62543 High-voltage direct current using voltage sourced converters   |
| 2.  | IEC 62751 Determination of power losses in voltage sourced converters for <i>HVDC</i> systems                                     |
| 3.  | IEC 62747 Terminology for voltage sourced converters ( <i>VSC</i> ) for <i>HVDC</i> systems                                       |
| 4.  | IEC 62501 Voltage sourced converters valves for high-voltage direct current power transmission - Electrical testing               |
| 5.  | Guideline for the system design of voltage sourced converters based <i>HVDC</i> transmission                                      |
| 6.  | Performance of voltage sourced converters based high-voltage direct current transmission systems – Part1: Steady-state conditions |
| 7.  | Performance of voltage sourced converters based high-voltage direct current transmission systems – Part2: Faults and Switching    |
| 8.  | Performance of voltage sourced converters based high-voltage direct current transmission systems – Part3: Dynamic conditions      |
| 9.  | Voltage sourced converters based high-voltage direct current installations - System testing                                       |
| 10. | Valve cooling system adopted in <i>HVDC</i> converter station   |
| 11. | Testing for control and protection system of voltage source converters based high-voltage direct current transmission             |
| 12. | Insulation co-ordination procedures for voltage sourced converters based high-voltage direct current converter station            |

## 2.7 Summary.

The *HVDC* transmission technology will face some serious challenges over the next two decades. At the same time, these issues resolving gives an impulse and presents valuable opportunities for further development of new technologies in *HVDC* meeting these challenges smartly.

Various configurations have been considered. For *HVDC* networks a bi-polar configuration with the separately-provided metallic return path appears the most suitable solution for further development and realisation.

Today's electric grid has a lot of shortcomings. Much of power is lost due to inefficient transmission and distribution over long distances mainly because of the remote generation that we have in place right now.

However, the *HVDC* technology also cannot avoid losses in power energy transmission completely. Although, the direct current transmission does not generate large amounts of reactive power and, consequently, this part of transmission losses can be avoided, there are drawbacks of *HVDC* transmission need to be mentioned.

The *AC – DC* conversion process with voltage source converter (*VSC*) is corresponded by dominant portion of the overall losses in stand-by regime. Any possible overloading and related to it rise of inner temperature, the ageing of semiconductor units seem to only worsen the total situation with unavoidable losses.

In case of long transmission lines and especially cables the effectiveness of *HVDC* in comparison with *HVAC* increases due to lower transmission losses, see Subsections 1.4.2 and 1.5.2 for details.

In projects, where long transmission distance is not the case, *VSC – HVDC* converter stations will result in the most of overall system losses (app. 2 – 4% of power being transmitted). Therefore, any possible minimization of losses at converter station is a task of prime importance.

Future developments in semiconductor industry e.g. new materials with shifting manageable conductivity, lower needs for cooling, novel semiconductor devices suitable for these tasks, improved switching techniques and etc. may give a birth to new or fundamentally upgraded converters with significantly better parameters and much lower losses.

Developments of the transmission network must be designed to meet not only first needs on the network, but also shall, to the highest possible extend, be resilient to the needs of the network looking into the future.

On the coming introduction of new generation energy sources with energy densities, amounts and rates, which are hard to imagine now, the *HVDC* grid should serve as a reliable infrastructure to deliver bulk amounts of power over any distances to the end customer.

Predicting the future power energy demands with any level of certainty is a challenge for all system planners worldwide. The best practical approach is to envisage a number of future scenarios, which cover the widest plausible range of development changes of the network.

If a development project addresses the needs for all scenarios then it is considered robust, i.e. able to meet the widest envisaged range of needs on the network. Some possible scenarios for Europe and other parts of the world have been discussed.

Possibly the highest risk to the efficient development of any transmission network is the risk, that the current project will not be ideally suited to act as part of the network in future. So, any steps shall be made only after careful consideration.

## Chapter 3

# Vision of the Future HVDC Grid

This chapter shall be considered as an attempt to describe the future development of existing mainly point-to-point *HVDC* links into the potentially meshed multi-terminal network based on the present trends, technical advances and initial intuition on how this technology could shape the energy industry in the future.

Dealing with the future in the process of the establishment into the real world from the stage of an idea to the final structured object is always a consideration along similar alternatives with multiple-choice, where this or another option may gain concurrence and be realized.

Thus, visions on the future meshed multi-terminal *HVDC* network in various regions of the world are discussed below, what is entirely different from the authorized grid development plans and is assumed to have more flexible stochastic nature.

The vision of *HVDC* network development may be based on the intended large-scale infrastructure projects, plans on establishing of new generation or on the massive upgrade of transmission equipment or just on feeling on how could future *HVDC* network response to the needs of one or another region. The latter shall be taken into account as a first step of materialization of an idea into the real world and as an invitation to further discussion and verification of these ideas.



### 3.1 Vision of the Future Meshed HVDC Grid.

In many places of the world the existing power grids undergo at present significant changes to address a challenge of transporting ever growing amounts of energy generated by decentralized and very floating power generation from renewable sources. The solutions tend to become more important and even more complex, when we look forward at concepts for future *HVDC* networks.

Transmission *HVDC* networks in the foreseen future will step forward from simple back-to-back and point-to-point configurations to relatively complex multi-terminal system with volatile renewable energy sources distributed at a long distance from load centres. Sooner or later, the *HVDC* transmission system will need to incorporate various converter technologies like conventional *LCC*, *VSC* half- and state-of-art full-bridge converters from different manufacturers and be able to operate at several different voltage levels.

Questions of compatibility and standardization will arise immediately embracing at once many factors such as efficient coordination of design and operation, reliable full functionality of control and regulation methods for hybrid AC and DC system etc.

This is particularly the case, when one day point-to-point connections with relatively simple control for power flow and fault clearance procedures will be replaced by more sophisticated multi-terminal operation, where feeding ends may dynamically become receiving ones and vice versa, if only the actual power balance requires so. And again, some special appeal in that instability is brought by high volatility of renewable sources.

In many parts of the world it will not be a pure *HVDC* network, just the opposite, it will have many connections and points of intersection with the already existing transmission infrastructure. To some degree, it may facilitate intermediate power take-off, strengthen the grid and add cost effective solutions where *HVAC* and *HVDC* may effectively complement each other.

In the section below a draw of an approximate picture for future *HVDC* networks on all continents departing from current and planned power demand in the various regions along with the expected industrial, business and residential development in coming years will be given.

The fact, that electrical power becomes a universal substitute for any other forms of energy, should also be taken into account. Thus, the number of electric means of transportation, automation and robotic industrial applications will only rise in the next decades.

## 3.2 Vision of the European HVDC Grid.

In Europe the grid has been developed into a very meshed configuration stretching for several hundred kilometres connecting the European continental grid with the British network and energy pool of Scandinavian countries in the North and just recent "energy islands" like Baltic countries or the Iberian Peninsula on the South. Connections with Russian/CIS synchronized power zone and further expansion to the Mediterranean and North African regions is expected with high probability.

Having reached its limits on-shore, big potential for the European grid expansion is seen in developing undersea links between the European continent and British islands, tapping Scandinavian hydro resources, etc.

Due to existing infrastructure and serious resistance to new lines construction, the concept for *HVDC* grid would most likely have several high-power-rated links from west to east and, when necessary, from north to south, like in Germany.

The projects on retrofitting from *AC* to *DC* with, if it is possible, voltage level upgrade still along with a very rare opportunity of long overlaying point-to-point *HVDC* links construction, would become the main contributors to this future hybrid network.

The typical distance for European *HVDC* links starts from ca. 300-500 kilometres [28] up to more than a thousand kilometers and the typical voltage level is about 400-600 kV carrying 2-3 GW of power.[29]

For ultra-long *HVDC* transmission links over 1000 km the voltage level may rise to 800kV. A reasonable alternative to this, that becomes very applicable in such circumstances, is high voltage overhead AC line with the application of *FACTS* technology. [30]

### 3.2.1 North European HVDC Ring.

Besides the observed mushroom growth in on-shore *HVDC* grid development, an especial attention should be paid as well to *HVDC* off-shore projects. The rising number of *HVDC* off-shore transmission links in North and Baltic seas shapes, step by step, the first real *HVDC* network, forming at first very simple point-to-point, and further radial and circle configurations, but potentially aiming to reach meshed reliable HVDC transmission network.

This *HVDC* network, that is only acquiring its form and features in the reality, will most closely present the "term multi-terminal multi-supplier *HVDC* network", meaning that

in this planned system *VSC* converters, cables, control and protection units etc. will be produced and delivered by different manufacturers for various customers with different needs and inevitably will have to be combined for efficient operation. Evidently, that offshore *HVDC* network will consist of links separated by converter stations and operate on different voltage levels.

A possibility for further expansion of *HVDC* links in the system and additional inter-connection should be also foreseen. No need to say, that altogether, it presents a serious challenge for network planners and operators. The 623 km longest European *HVDC* connection the Nord-Link, which is expected to be in operation by year 2020, will carry the power at the ultimate for the *VSC* technology voltage level of  $\pm 525$  kV and capacity of 1,400 MW. [31] It shall become the backbone connection between Germany and Norway.

Many *HVDC* cable lines like, for example, 580 km,  $\pm 450$  kV and 700 MW the NorNed link between Norway and Eemshaven in the Netherlands [32], the BritNed 260 km 450 kV bi-pole link between the Isle of Grain in the United Kingdom and Rotterdam, the Netherlands [33] or 450km, 700MW link SwedLit (also known as NordBalt) at  $\pm 300$  kV connecting the main European power grid with the "energy island" of three Baltic countries - Estonia, Latvia and Lithuania [34] give already a clue how future on further development could look like.

This development will most probably result at first stages in triangle and circle configuration and then may acquire rarely meshed multi-terminal profile (see Fig.3.1).



FIGURE 3.1: Vision on the future North European HVDC Ring.

Taking into account rapid evolution of wind generation and, thus, need for construction of new *HVDC* cable lines and terminals it is already very likely to see first *HVDC*

multi-terminal network off-shore in the region of North and Baltic seas and adjacent areas within coming years.

### 3.2.2 Interconnection of East and West Power Systems.

The possibility of East and West power systems interconnection has been discussed for a long time. Basically, two principles of association - synchronous and non-synchronous with use of *HVDC* are considered.

Even though, the synchronised AC network is regarded as the most desirable solution, it shall be acknowledged too, that *HVDC* links facilitate many tasks in integrated operation of asynchronous power systems and make this alternative viable.

For example, it becomes possible to control power flow more precisely and start to connect two big power systems with deliberately any small first step. In this case, *HVDC* links would also limit any vulnerabilities that may occur during network congestion or an accident.

Besides, the construction of the first *HVDC* back-to-back connection may be completed just within 1.5-2 years, whereas the preparation time of the synchronous interconnection is estimated by the expert community to take at least ten years.

To interconnect these two giant energy systems is a real challenge, because the *IPS/UPS* and *ENTSO – E* vary greatly in average transmission length, network structure, operation principles and management philosophy.

*ENTSO – E* system is characterized by relatively short transmission line lengths with higher mesh density and significantly influenced by wind power generation. And finally, in the *ENTSO – E* system there are common technical standards are applied, which is not the case in *IPS/UPS* system.

In turn, the *IPS/UPS* power system uses a larger set of nominal voltages, the backbone network covers a considerably larger area, what makes it necessary to use very long transmission lines at ultra high voltage rates.

In recent years several significant research studies have been performed in this regard. According to their results, it was concluded, that from a technical point of view, the heavy workload conditions of the main transmission corridors within *ENTSO – E* network may remarkably restrict the import of electricity from the *IPS/UPS* and back.

Study results analysis also showed the necessity to consider the technical solutions on electricity transmission over long distances, special aspects of dynamic behaviour on

synchronous association, as well as legal and organizational principles of work on both sides in more details.

In principle, the two power systems *IPS/UPS* and *ENTSO – E* are technologically ready to be united. An important step has been done, when *IPS/UPS* has switched to European standards for the power system regulation.

In the case of successful interconnection of *IPS/UPS* and *ENTSO – E* it will be the world's largest energy network with the total installed capacity of over 860 GW, including 12 time zones, 37 countries providing energy to nearly 900 million people on the Eurasian continent.

### 3.3 Vision of the Eurasian HVDC Grid.

Ever increasing need for power exchange and reliable control over it along with energy network development in Europe and Asia necessitate a comparable and sometimes catching-up development in Russian Eurasia to be able to connect this already big energy network into one power transmission chain in the foreseeable future.

Even though the first *HVDC* links were introduced in the Soviet Union long ago and since then have been in constant operation facilitating uninterpreted power exchange between Russia and its neighbours, for any or no reason this technology is out of favour in project development organizations and authorities presently. Significant part of power energy expert society is very sceptical or even does not recognize advantages of *HVDC* technology being applied to transmit high amount of power over ultra-long distances, what is a matter-of-course for size parameters of such a country like Russia.

However, this situation may change very fast and the successful international experience on operation of *HVDC* transmission links makes this direction a high-priority target for further power energy transmission network development in the Eurasian region.

Besides several *HVDC* connections realized in the last 20th century decades, there are some new *HVDC* projects are being discussed and planned at the moment. One of them is an *HVDC* link between nuclear station *LAES 2* and substation *Vyborgskaya* on the northern shore of the Finnish Gulf. This connection is planned to transmit 1000 MW at  $\pm 300kV$ , part of it a little more than 40 kilometres will be realized as an undersea cable line and the rest 65 kilometres as an over-head line. [35]

New *HVDC* link will secure new paths to deliver power capacity from *LAES* nuclear station to Saint-Petersburg metropolitan area and Karelia, and unload transmission networks already in operation.

In full accordance with discernible trends of shifting towards possibly large units of clean renewable generation, several tide-mill power plants have been planned. The most significant projects among them are the Mesenskaya tide-mill power station in Arkhangelsk region and the Tugurskaya tide-mill power station in the Khabarovsk Territory [36]

First step realization is expected to give its electricity already in the time period until 2020. Preliminary calculations in places where tidal lift reaches 10,3 meters show that under favourable conditions up to 11,4 GW power could be extracted. [37]

This enormous amount of clean energy could be economically efficient transmitted only by appliance *HVDC* technology.

Similar situation with the bulk generation coming into operation soon or planned, and thus, the acute need, due to the inability of the existing infrastructure to transmit it over long distance with minimal losses is seen in the Asian part of Russia. The Evenkiyskaya hydro power station just alone is projected to generate from 8 up to 12 GW power with possible extension up to 20 GW. Power energy is intended to carry to the European part of Russia over two *HVDC* bipolar lines at  $\pm 750kV$  with the length of 3500 kilometres. [38]

These and other *HVDC* lines would allow connecting energy abundant, but still isolated regions with the Integrated Energy System.

Thanks to a large amount of collected water in the hydroelectric dam of the Evenkiyskaya hydro station, any steep spikes of energy consumption due to e.g. sharp temperature decrease could be compensated. The station may work in close coordination with the mentioned above powerful Mesenskaya tidal power station to smooth the intermittent effect in generation of the latter.

Apart from the above-mentioned projects, a construction of several *HVDC* transmission lines has been discussed and approved by the Government. Up to now, there are three at  $\pm 500kV$  and five *HVDC* overhead lines at  $\pm 750kV$  have been considered to connect remote areas of Ural and Siberia along with six back-to-back stations of app. 500 MW each, whose task is to facilitate power inter-exchange and power energy trading. [39]

Several converter stations with the use of fully controlled *IGBT* and *IGCT* units are considered to introduce into the grid transmission system of Siberia to improve reliability of power supply for large mining oil and processing plants and companies. [40]

Close more intensive co-operation should stimulate a long-lasting activity in energy transmission field between Russia, China, Japan and Korea. Many promising *HVDC* transmission projects are in contemplation and broadly discussed on various forums and conferences presently. [41]

From *HVDC* multi-terminal grid development point of view this might be very unique region, where construction of interconnected and even meshed transmission network configuration is expected in the nearest future. The front end engineering design works are being done for back-to-back connections between Russia and northern China at voltage level  $\pm 600kV$  and for *HVDC* cable connection of  $\pm 400kV$  between Russia and Japan. More *HVDC* projects, by all means, are to come in the foreseeable future.

Taking into account the forced and rapid development of *HVDC* transmission technology in China, a rather huge energy generation potential in Russia and ever increasing massive demand on energy in Japan, Korea and China again, it is very likely, that under favourable circumstances the corresponding countries come to an agreement to build *HVDC* transmission interconnection, shaping at least multi-terminal *HVDC* ring network configuration with focus on more closely meshed *HVDC* network, (see Fig.3.2).

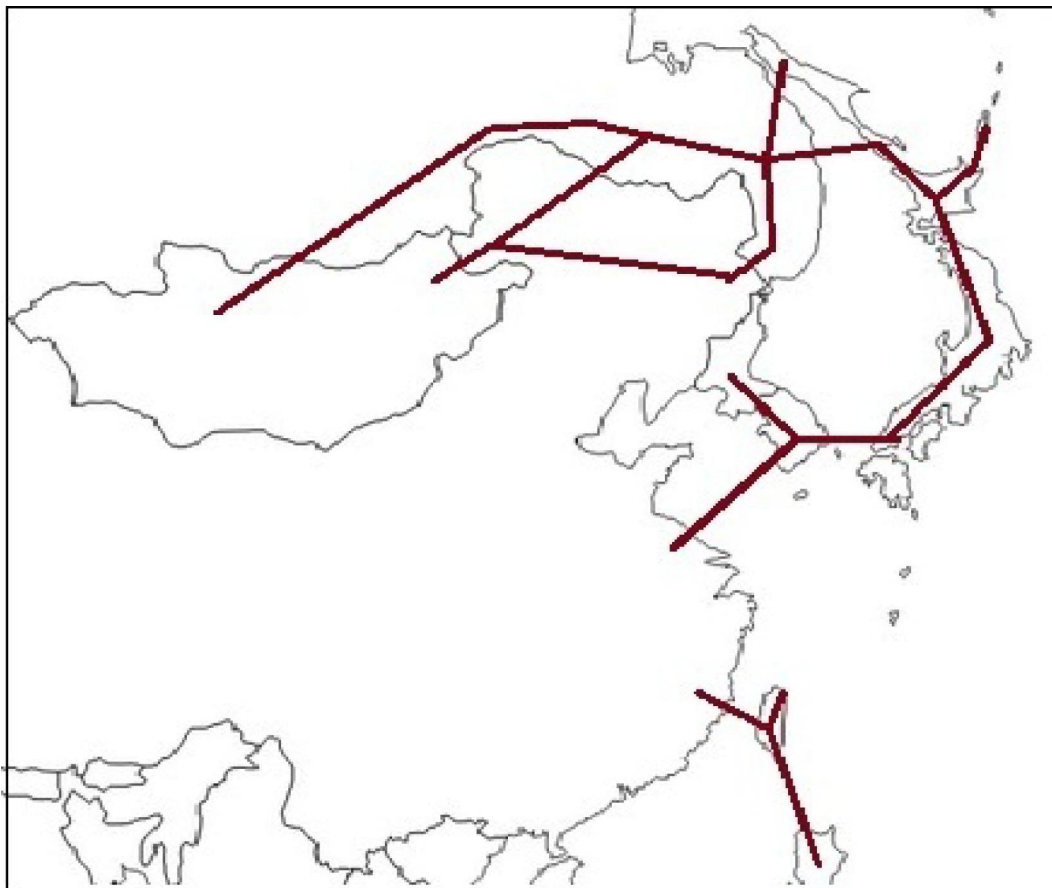


FIGURE 3.2: Vision on the future East-Asian HVDC Ring.

Alternatively to the North and Baltic seas ring *HVDC* network, the operating voltages here may be a step or two higher, as well as, due to the fact, that all these countries have their own competence in *HVDC* technology and production capacities. The main manufacturers of the relevant *HVDC* equipment will be local, what will surely have a considerable impact on standardization and operation guidelines procedures.

### 3.4 Vision on the East and South Asian HVDC Grids.

The most promising area for *HVDC* grid growth is seen in the South-East Asia and China. The tremendous growth in industrialization and consumption rates will face an acute need in scaling their transmission capability up. At the moment this is already a part of reality mainly due to timely construction of new *HVDC* links. A good part of these reference projects are far from being modest and made great progress in terms of voltage and transmitted capacity reaching unimaginable levels of  $\pm 1100$  kV and 11 GW power.[42]

In this region the situation with licensing processes and public opposition seems to be the most favourable for the realization of new ambitious projects. In the nearest future this part of the world will attract experts' attentions by many more challenging *HVDC* projects pushing the boundaries further.

However, these ultra capable power lines still remain point-to-point connections and the real challenge would be not in reaching another milestone in voltage level, but rather in organizing a manageable and reliable multi-terminal *HVDC* grid operation. Here, as anywhere else, an *HVDC* grid will develop gradually in sequential steps from a small number of point-to-point connections and interconnected converter stations to, perhaps, a meshed multi-terminal grid configuration with the optional possibility for future expansion and higher number of interconnections.

#### 3.4.1 China - an HVDC Grid for Tomorrow.

*HVDC* grid development in China undergoes a tremendous increase in investments and attention paid to it. Compared with Europe one typical *HVDC* project in China mainly due to favourable regulation climate could be realized five times faster. According to the new power energy network upgrade plan more than twenty *HVDC* corridors are being planned for commissioning by 2020 in spite of all concerns that present state of regional power grids may be too weak for such an ambitious power amount incorporation.

As most of energy sources in China are located in remote areas, an *HVDC* technology, as no one else, helps the country to solve a sharp problem with the imbalance of energy generation and consumption. It is interesting to note that *HVDC* transmission development is highly dependent on energy generation mixture. The recent governmental focus on renewable generation will favour further *HVDC* lines construction. On the other hand, the recently announced shift from thermal power generation to nuclear, what promises the rise from just a few up to 10% of the total generation in the nearest decade, will slow down the development of *HVDC* industry in the country.



In addition to it, in this particular region of explosive growth, expert and engineers have to face and carefully deal with many new challenging tasks and issues for the first time ever, just like *HVDC* transmission systems construction and operation at high altitudes – several thousand meters, or in others troublesome environmental conditions. [43]

Further development of these projects will inevitably influence many aspects in *HVDC* standards, regulations and operation requirements areas.

### **3.4.2 Indian HVDC - in the Pursuit of Leadership.**

The key focus on the future transmission growth in South Asia is captured the eye of *HVDC* community by India, where, driven by the rapid economic development, significant power transmission system extension is required.

However, the situation in India can be characterized not only by fast emerging economy and rapid population growth, but also by relatively weak transmission connections between various Indian states and very non-uniform distribution of the country's energy resources against primary consumption load centres.

In addition to it, the main overall shift to clean renewable generation will pose supplementary tension at power system.

However, shaping of the future *HVDC* grid has been started here also by constructing several high capacity *HVDC* links. First of all, the *HVDC* East-South interconnection is worth mentioning, which has been already in operation since 2003 with one upgrade from 2 up to 2,5 GW in 2006 and connects asynchronous AC areas. This *HVDC* link performs an important stabilizing function for the Indian transmission system of managing with overload capacity by use of Relative Aging Indication (*RAI*) and Load Factor Limitation (*LFL*) solutions to avoid additional thyristors installation. [44]

Another important step to Indian multi-terminal *HVDC* transmission system is  $\pm 800$ kV line carrying ca. 6 GW of power from North Eastern region to Agra. More than 1700 km long this *HVDC* link will have two rectifier stations in Biswanath Chariala (North-East) and Alipurduar (East) and one inverter station at Agra (North).

Being successfully realized this project could be the first  $\pm 800$  KV multi-terminal *HVDC* system in the world with continuous 33% overload capability by implementing 12 pulse converter layout.

The new *HVDC* transmission system gains its perspective in the light of fast-growing power demand in this densely populated region of New Delhi. Several long-distance *HVDC* transmission lines are planned and few are already in operation.

Having taken these aspects and what was mentioned above in Chapter 2 into account, an *HVDC* technology in this world region shall be a certain part of the final power system solution, offering good performance of accumulating intermittent wind or solar generation to the grid, but first, shaping this national grid by enforcing and tying up separately or semi-autonomous operating local grids by high capacity long distance transmission lines.

### 3.5 Vision on the North American HVDC Grid.

A roughly similar situation is observed in North America, where the lack of planning on the initial stage has led to a great variety of semi-independent regional networks and hardly connected energy islands. Though, a lot of space and the urgent need for reliable interconnection of all grids into one or at least few bigger grids, rise chances for overlying multi-terminal *HVDC* network, see Fig. 3.3.

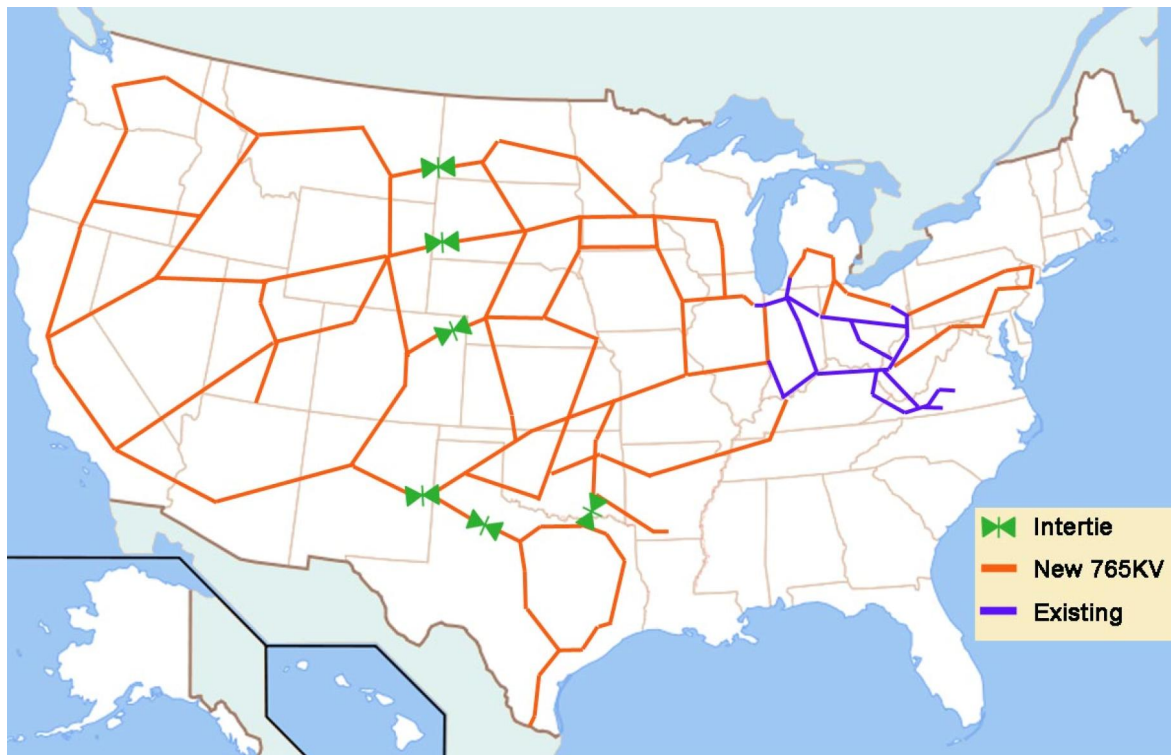


FIGURE 3.3: Concept of the US Grid Development with HVDC Interconnections.

Source: [www.awea.org](http://www.awea.org)

On the picture it is shown the suggested underlying *HVDC* grid configuration as a concept for the main continental part of the US. Three clearly distinguished zones East, West and Texas are supposed to tie via *HVDC* links and high capacity lines to facilitate smooth power delivery from new power plants and projected off-shore wind generation to the certain places with high demand over large distance.

As the distances between generation and load centres are estimated to be rather long than short, it gives us a reason to propose voltage and power ratings starting from  $\pm 800$  kV and few GW of carrying capacity. However, with the further development of *HVDC* technology even this estimation could appear to be very moderate.

At the moment *HVDC* technology attracts a lot of attention and is actively discussed as a possible solution of national grid upgrade. About twenty *HVDC* transmission arrangements are in operation within the national US energy grid. Another 35 installations operate across the North American continent. This number in coming years may at least double. [45]

Main power flow patterns are discerned at the moment as a East-West connection of independent energy zones and North-South direction mostly between vast hydro resources in Canada and big load centres on the east Atlantic coast.

Even though there is enough space for new green-field projects on one the hand and an acute need for a new transmission infrastructure on the North American continent on another hand, the ineffective regulatory environment with time-consuming bureaucracy brings all the efforts to nought. [46]

This, however, may change as soon as related energy security threats, due to obsolescence of not sufficient existing transmission infrastructure, will be realized to the full extent. If it is going to happen, the new high capacity *HVDC* transmission corridors are more presumable.

In this case *HVDC* grid development may start from few *HVDC* link already in operation. In the west part it is the Pacific Intertie connecting load centres in southern California and vast hydro-power generation in the North. And the Mountain Intertie, that is carrying coal-fired power in Utah and possibly wind power in Wyoming in the future. These links could be extended to connect some other generation and load nodes in this part of the continent.

It should be noted, that due to economic reasons high voltage overhead lines projects prevail at the moment over *HVDC* cable links. However, there are some positive signs too. San Francisco Bay project was realized with voltage source converter technology.

A 400 MW 500 kV *HVDC* underwater cable line is stretched over 85 kilometres and is able to transmit up to 40 percent of the peak power needs for the San Francisco area. [47]

In the eastern part the Champlain Hudson Power Express project is worth to mention. It is expected that after commissioning stage in autumn 2017 an *HVDC* cable link will be capable of transporting up to 1 GW of power from Canadian hydro stations to the New York metropolitan area. To minimize the impact on environment and avoid local communities concerns it was decided to lay cables along railways and under the water.

Several *HVDC* projects, that will potentially shape the future *HVDC* network on this continent, are also under consideration and approval in Midwest, Mid-South and Texas.

The characteristic feature of these *HVDC* projects may become a long mileage, something about 600-800 km and longer and potentially high capacity of 6-8 GW power.

Location of big load centres in a close proximity to the coast is able to ease the situation from another point of view. In accordance with the National Renewable Energy Lab report the offshore wind generation resources available off-shore for depths not exceeding 30 meters have been accounted as of 1,071 gigawatts of power. [48]

Along the coastal line according to the US Grand Plan on the development of wind generation many wind parks will be built. This will require significant investments into transmission infrastructure. Among other options a multi-terminal *HVDC* offshore grid is also considered as a viable solution.[49]

Through modelling and research it has also been shown that the DC Grid realized on *VSC* technology base with operational voltage of  $\pm 320$  kV consisting of nine offshore converter stations with 20 cable lines and covering a distance more than 1000 kilometres may perform more cost efficiently in comparison with a number of separated point-to-point connections.

Some *HVDC* transmission connections are on the stage of approval, many others are being considered for feasibility and economic effect. A very sensitive area in power supply on the North American continent is a cross-the-boarder power exchange between Canada and USA, where a lot of energy is being transmitted. At least several *HVDC* connections with capacity from 1 GW have been planned there.[50]

### 3.6 Future HVDC Grid in Australia and New Zealand.

At the moment one of the most important *HVDC* project realized in Australia is the Basslink - a mono-polar scheme with metallic return designed for the rated current of 1250 A, rated DC voltage of 400 kV and rated power of 500 MW, that allows the power flow inter-exchange between Australian mainland and Tasmania Island. [51]

Although, the long distance electricity transmission on the continent at this point is presented by mainly conventional High Voltage Alternating Current transmission, with just a few *HVDC* links to support the national grid, the growing need for reliable integration of distributed generation such as renewable - solar and geothermal sources or to tie eastern and western part of the national grid up, may play in favour of further *HVDC* transmission development in this region.

The typical distances between load and generation centres on this continent, as well as requirements on losses reduction also imply the broad application of *HVDC* transmission technology in the future, when there are sufficient needs and operational experience collected.

In the neighbouring New Zealand there is a need to connect vast hydro-power generation with the more populated North Island and South Island. Moreover, the New Zealand power grid has a long tradition of *HVDC* operation, as it was one of the first in the world to install *HVDC* transmission application in the middle of the XX century. [52]

Even though distances are rather moderate in comparison with other world regions, where an *HVDC* technology could be applied, a real challenge presents the seismic uncertainty and high potential of earthquakes. Thus, the backbone *HVDC* transmission designed for this particular area should be safe enough to operate under though seismic conditions to avoid possibilities of break down and system blackout. [53]

According to the *HVDC* Grid development plan [54] and along with existing and planned *HVDC* links between Tasmania and Australia a very unique and robust transmission grid configuration can be formed in this part of the world gaining access to power market with great opportunities for mutually beneficial collaboration.

### 3.7 Vision on the Future HVDC Grid in Africa.

The situation with power energy grid development and *HVDC* transmission in particular can be characterized as a very favourable. Vast energy resources, growing population and industry mainly presented by the mining sector need to be connected via a smart and reliable transmission links of high capacity.

In some particular cases, exploitation and development of alternative local energy resources may be less economically advantageous, than transmitting the electrical power from remote old-established generation.

A choice for common *AC* transmission is less viable due to long distances and high losses along with transmission process.

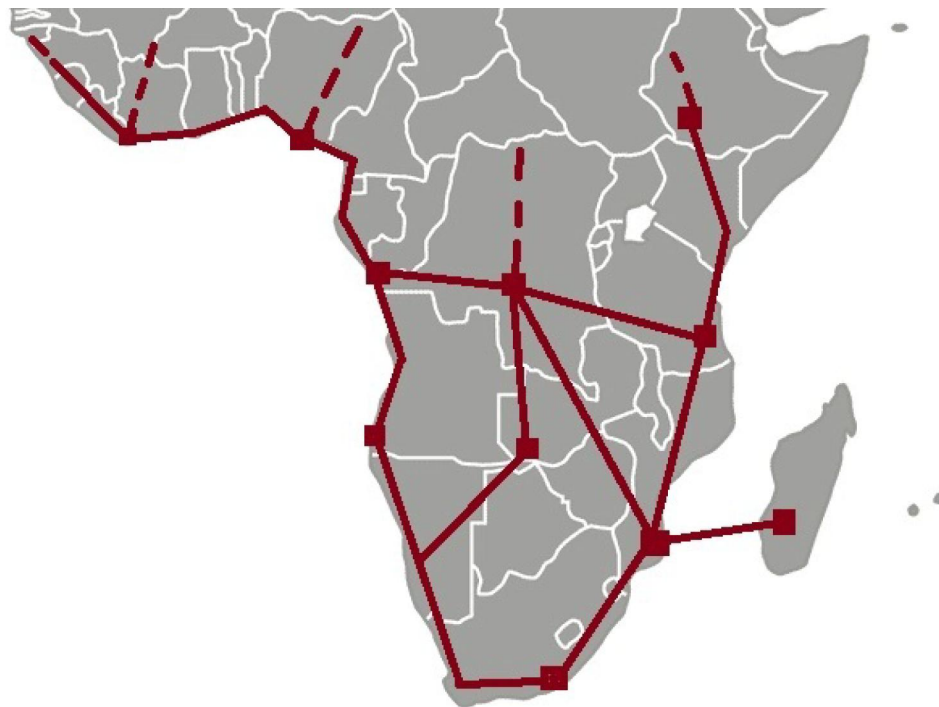


FIGURE 3.4: Vision on the future HVDC grid in Africa.

Moreover, extremely weak local transmission power grids need to be reinforced and on that score an *HVDC* technology is a good solution for several reasons. Among them ability to weak *AC* grids interlinking, after outage “black-start” operation capability, more precise frequency control of islanded *AC* grids or increased “N-1” criteria with the improved reliability of bi-polar *HVDC* lines.

Even though there are some big significant *HVDC* projects realized in Africa, like 580 MW, 1700 km Inga-Kolwezi or 1920 MW, 1420 km Cahora Bassa *LCC HVDC* links that have been in operation since late 1970s – early 1980s or relatively recent 300 MW, 950 km Caprivi Link *VSC HVDC* project, this area of development still can be considered as a green field, what is an absolute advantage over other world regions for the planning and construction of the future *HVDC* multi-terminal network.

*HVDC* development in Sub-Sahara Africa is seen at the moment mainly through a construction of bulk transmission from hydro station to places of industrial and commercial consumption.

Thus, Ethiopia hydro-power could export its energy surplus to neighbouring Kenya, the estimated 39 GW of power from Grand Inga Dams in the Democratic Republic of Congo could be partly transported to the South African load centres etc.

Some feasibility studies for the *HVDC* link between Zambia and Namibia have been considered too. Additionally, the *HVDC* interlinking would help to control the power flow between the East-African and the Southern-African power pools and serve as a “backbone” to secure local power transmission grids.

### **3.7.1 Northern Africa - a Field for HVDC Experiments.**

In the Northern Africa some ambitious projects like, for example, *DESERTEC* and *MedGrid* are discussed as a possibility to shape the future European super grid interlinking the various European countries and the neighbouring regions around Europe’s borders, see Fig 3.5.

Having vast renewable energy sources yet untapped, which potential far exceeds the local power demand at present, mainly with building of new concentrating solar power (*CSP*) stations the North African region may become a potential energy exporter to the European continent. [55]

Even partial realization of this plan would imply essential challenges for the existing transmission grid infrastructure and necessitate its further expansion as it would require up to 5-7 times higher transfer capacity of its present state.

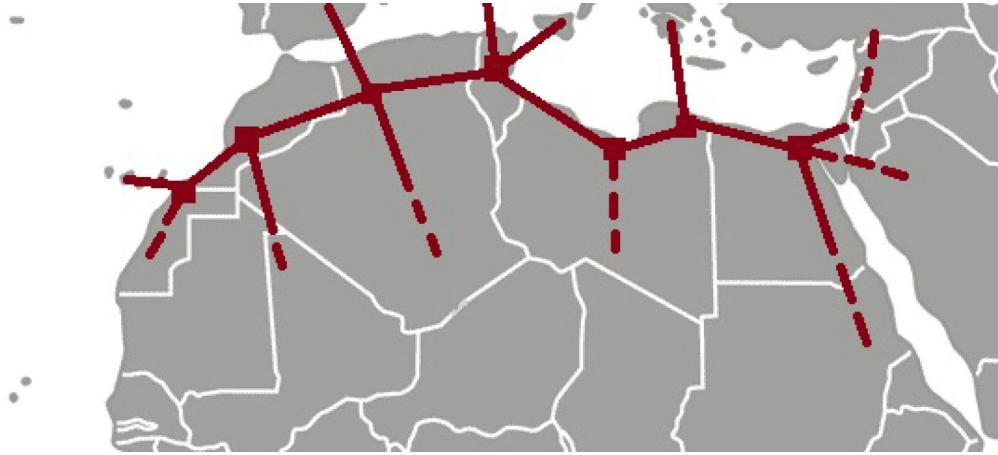


FIGURE 3.5: Vision of North African HVDC.

The AC transmission expansion is reasonable between nearby regions with relatively small power transfer capability or for short line distances, whereas an overlaying *HVDC* transmission shall take on the key part in bulk intercontinental electricity exchange.

However, some independent research studies on the impact of wind and solar broad deployment [56] that have been carried out on the matter, show this vision as only a transient and partial solution for the secure supply of Europe from intermittent renewable generation.

Thus assuming, the *HVDC* Super grid would become even more feasible and efficient, when it is planned big - to cover much larger areas and incorporate greater number of versatile and distributed generation for more pronounced smoothing effect e.g. to exclude unfavourable weather patterns over Europe at one and the same time.



### 3.8 Summary.

In this chapter a possible development of existing point-to-point *HVDC* links, both overhead and undersea, links into the potentially multi-terminal meshed *HVDC* network has been considered and described as a vision for one or another region of the world.

These visions are mainly based on the present trends in power energy, technical advances that play significant role for fast emerging *HVDC* technology and initial intuition on how could the future *HVDC* network response to the needs of one or another region.

Growing-points for such large-scale infrastructure projects in *HVDC* transmission are, first of all, the approved by authorities plans on establishing of new generation or on the massive upgrade of transmission equipment.

The anticipated growth in energy consumption shall be also taken into account when considering *HVDC* projects on feasibility stage or already planning for the possible configuration of the potential *HVDC* network. Political risks due to high volatility have not been considered.

*HVDC* transmission system will likely incorporate various converter technologies like conventional *LCC*, *VSC* half- and full-bridge converters from different manufacturers operating at different voltage levels.

This poses additional pressure on network planning experts and requires a broadly collaborative approach to establishing a common base for secure and reliable *HVDC* network operation including *HVDC* standards, guidelines and regulations.

In many parts of the world it will not be a pure *HVDC* network, just the opposite, it will have many connections and points of intersection with the already existing transmission infrastructure, European or North-American power energy network can be a good example.

The typical distance for *HVDC* links starts from ca. 300-500 kilometres and sometimes up to more than a thousand kilometres. The typical voltage level is about  $\pm 400$ -600 kV carrying app. 2-3 GW of power.

However, in some regions like South-East and South Asia these numbers can be far exceeded in voltage level and transmitted power. For *HVDC* transmission links over 1000 km the voltage level may rise up to 800 kV and higher.

Though, under certain circumstances, high voltage overhead AC lines with the employed *FACTS* technology are seen to be a reasonable alternative to *HVDC* links.

Off- and on-shore wind generation and related to it grid development in the North and the Baltic Seas have a great potential to shape the first meshed *HVDC* - the North European *HVDC* Ring.

Similar situation can be potentially expected in the Far-East, the Sea of Japan and the East China Sea shaping the North-Eastern Asian *HVDC* Ring.

Constructing of *HVDC* transmission links facilitates a shift towards a common energy market, strengthens regional power grids, intensifies bi-directional power transfer and solves issues with energy islands, optimizing grid configuration.

Electrical power becomes a universal substitute for any other forms of energy, that is easy to generate, transmit and transform to any other kinds of energy. The new automated industry will be highly dependent on reliable connections for bulk power energy and informational exchange.

The number of electric means for transportation, automation and robotic industrial applications i.e. overall need for secure and reliable electrical energy supply will continue to rise in the foreseeable next decades of the XXI century.

## Chapter 4

# Problem Statement and Methodology.

In this Chapter the problem statement is defined and focus of the Thesis is specified. Models that are relevant for transient-studies in multi-terminal *HVDC* grids are discussed and compared with each other in order to find best suitable solution. The relevant Methodology is suggested, as a matter of fact there is no other approachable way to experiment with such complex, gigantic and not-yet existing systems, as in the form of graphical numerical representations and transient analysis simulations.

### 4.1 Problem Statement.

*HVDC* power network is a multiple-factor system implying a possibility of complex mutual complementary dependency of all involved elements. With the continuous increase of the elements number in the whole system, the complexity of control and management increases exponentially.

In addition to it, at the current moment there is no any multi-terminal *VSC – HVDC* network with various possible power flow patterns brought into operation, so, only all the expertise and experience collected in *HVDC* point-to-point arrangements or in conventional *HVAC* networks can be applied with particular restrictions, when it comes to *VSC – HVDC* multi-terminal arrangements.

Thus, designing and constructing a multi-terminal grid is still a stiff challenge to many experts and engineers all over the world. Even higher responsibility and risk will be carried during construction and following commissioning tests, where any even slight negligible mistake will be paid with a vengeance during operation and maintenance.

These considerations necessitate thorough approach with a large attention to details already on the planning stage. Electromagnetic transient simulations enable experts and engineers with a powerful tool to predict and take measures to ensure secure and sustainable operation of the future *HVDC* networks.

Various electromagnetic transient (*EMT*) programs are abundantly applied as simulation tools in power systems analysis. Key tasks, that can be solved by *EMT* programs are, for example, transient stability and faults studies, impulse propagation and lightning protection, control and relay protection simulations, power flow studies etc. with results presented either as a static or dynamic picture of processes going on in the system studied.

Usage of *EMT* software is a comprehensively time- and cost-effective way to go through all possible solutions while optimizing the configuration and structure of the designed power network.

Depending on their complexity and requirements, simulations of power networks in various *EMT* programs are relatively prompt and precise procedures. However, every model, even if thoroughly detailed, is ought to be a shallow copy of reality.

Any kind of modelling and simulations are always a compromise between deep, inconceivable and open-ended reality, fairly restricted capabilities of any software solutions and particularly end-user abilities to master the *EMT*-software in modelling and eventual analysis of simulation results.

Fast simulation time implies a simplified model and a relatively big actual time step, what gives a less exact picture in the end. This type of simulation problem treatment is very suitable for large-scale networks, where certain assumptions can be made and accepted.

More detailed models with less assumptions and simplifications, on the other hand, may require more time for design, refining and calculations with reduced speed, but give better and more accurate picture of transient processes under investigation. Usually, this approach is applied to a certain relatively small part of the transmission network.

These two different approaches to some extent can be combined to include the advantages of both principles in simulation philosophy. In a number of *EMT* programs this hybrid approach is realised and making good headway.[57]

## 4.2 Method Description.

Transient simulation software like *ATP – EMPT*, *PSS®NETOMAC*, *TRNSYS*, *PSCAD*, *SimPowerSystems*<sup>TM</sup> etc. are commonly used for transient studies in power networks.

Results obtained in a relatively fast and inexpensive way, let estimate many important parameters of large complex power systems and avoid the uncertainty already on the planning stage and necessity to build prototypes what in some cases with *HVDC* systems and components is also expensive or hard to perform.

With electromagnetic transients programs it is also possible to simulate various fault scenarios, dynamic process and different system configurations. The power system, if necessary, can be modelled in more details. The more dynamic process is to be modelled the more complex pre-programming procedure, that may require a high level of user programming expertise along with power energy systems understanding, should be foreseen. As a result, very complex power systems with the detailed design under certain dynamic condition present a real non-trivial challenge and when it is possible need to be simplified based on reasonable assumptions.

To ensure that the end model would perform in expected manner it should be well proved against realistic power system conditions, the results of simulations should be clearly understood and well explained. [58]

At first, the whole model and its separate units need to include reliable pieces of technical data and be suitable for steady-state or transient processes simulation in *ATP – EMTP*. There is no such a thing as a universal model suitable for all kinds of studies.

Therefore, each model and method, which may vary to great extend in every electromagnetic transient simulation programs, should at first be well studied and then applied to satisfy the requirements of the software routine in order to get the expected clear results.

Simulation results obtained in *ATP – EMTP* through running routine can then be plotted to allow the user to analyse graphical data of power systems transients and various fault parameters.

Depending on the desirable functionality of a power system model in *ATP – EMTP* it may be supported by a number of external compatible calculation routines and software, as well as by internal adjustable elements like *TACS* and *MODEL*.

However, it should be clearly understood the difference between real time processes and predefined *ATP – EMTP* simulation routine. That is, for example in case of a fault, in

simulation a circuit breaker does not respond to clear the problem part and activation of the relays does not happen until it has not been programmed. The same applies to power electronic or any other elements which in simulation software are capable if withstanding any voltage applied, what is under no circumstances going to happen in the real world. Many elements like circuit breaker or power line model are considered by default as ideal ones etc.

Every case, that is run with help of *ATP – EMTP* is a completely preprogrammed study and has to be adjusted in the case setup before every simulation round according to the needs of the user. So, the user knows well ahead, when a fault happens and what parameters it will have. This important assumption must be well recognized and understood dealing with transient software and especially explaining the results achieved by these simulations.

In the majority of cases considered here *ATP – EMTP* simulations are prepared with one scenario that consists of two parts following one after another, namely, a pre-fault period allowing energizing and normal state operation up to few seconds and an actual fault event testing switching-off capability and study of transients propagation through the power network.

#### 4.2.1 ATP-EMTP Software

*APT – EMTP* software is a practical helpful tool specially developed for computer-based electromagnetic and electro-mechanical transients simulations. In addition to computation of transients, complex networks of various structure, protection and control systems, power electronic devices and new experimental equipment can be modelled and tested through ample modelling capabilities along with supplemental features, namely:

- MODEL is a special element that can be created and introduced to the system. Parameters of MODEL elements can be explicitly described using a simulation language to ensure non-linear characteristics such as arcs or corona of components.
- TACS (Transient Analysis of Control Systems) is another advantageous feature of *ATP* that enables smooth interfacing capability and control of components available in the program library. [59]

The interface between *TACS* and simulated electrical network is realised through continuous exchange of various designated signals as node voltage, switch current or switch status, some other certain internal variables etc.

- Simulation of both symmetric and asymmetric disturbances such as various faults, lightning stroke, quasi-stationary and switching over-voltage impulse propagation is possible.
- Setting of non-zero initial conditions. This can be done automatically by a steady-state or added to library components manually.
- FREQUENCY SCAN feature is designated for frequency response calculation of phasor networks
- HARMONIC FREQUENCY SCAN is useful to perform frequency-domain harmonic analysis

Simulation elements that have been used in simulations of the present research work are presented in the ATP-EMTP library and include various pieces, such as:

- Lumped R, L and C elements with linear characteristics. They may be coupled and uncoupled.
- LCC elements applicable for overhead transmission lines and cables simulations. Parameters can be distributed and frequency-dependent based on several mathematical representations.
- Simple ideal switches with chopping current capability as well as time-dependent and voltage-dependent switches. Additionally, for Monte-Carlo studies statistical switching feature is available. Switches in the conductive state are modelled as a short circuit and as an infinite resistance, when they are open.
- Diode, thyristor or triac valves can be found in the default library. TACS/MODELS controlled switches may be composed too.
- Pre-programmed TACS/MODELS elements suitable for system's dynamic response simulations. Units with non-linear or time-varying parameters can be arranged.
- Ideal voltage or current sources, three-phase synchronous machines, universal machine models.

### 4.2.2 Graphical pre-processor ATPDraw

To facilitate the modelling process in ATP-EMTP a graphical, mouse-driven pre-processor ATPDraw user-friendly interface was introduced. With help of ATPDraw it is possible to combine ATP file in the acceptable format for the ATP-EMTP calculation routine. The program validates the model and assigns names to every node by default. However, naming node with certain names is also possible by hand.

Main standard library accounts for more than 70 types of components both three-phase and single-phase. For certain purposes, for example in Line Cable Component (LCC), a multi-phase system can be configured. TACS and MODELS are supported to create new objects whenever necessary. [60]

Simulation routine and plotting programs are integrated into ATPDraw. PlotXY is a Windows compatible plotting program specially created for usage in ATP-EMTP. It is able to work with input ASCII data files. Having done the simulation a .pl4 output file is simultaneously created and loaded by PlotXY automatically.

Some post-processing operations like calculations of the Fourier series coefficients or algebraic operation on the plotted waveforms are also allowed.

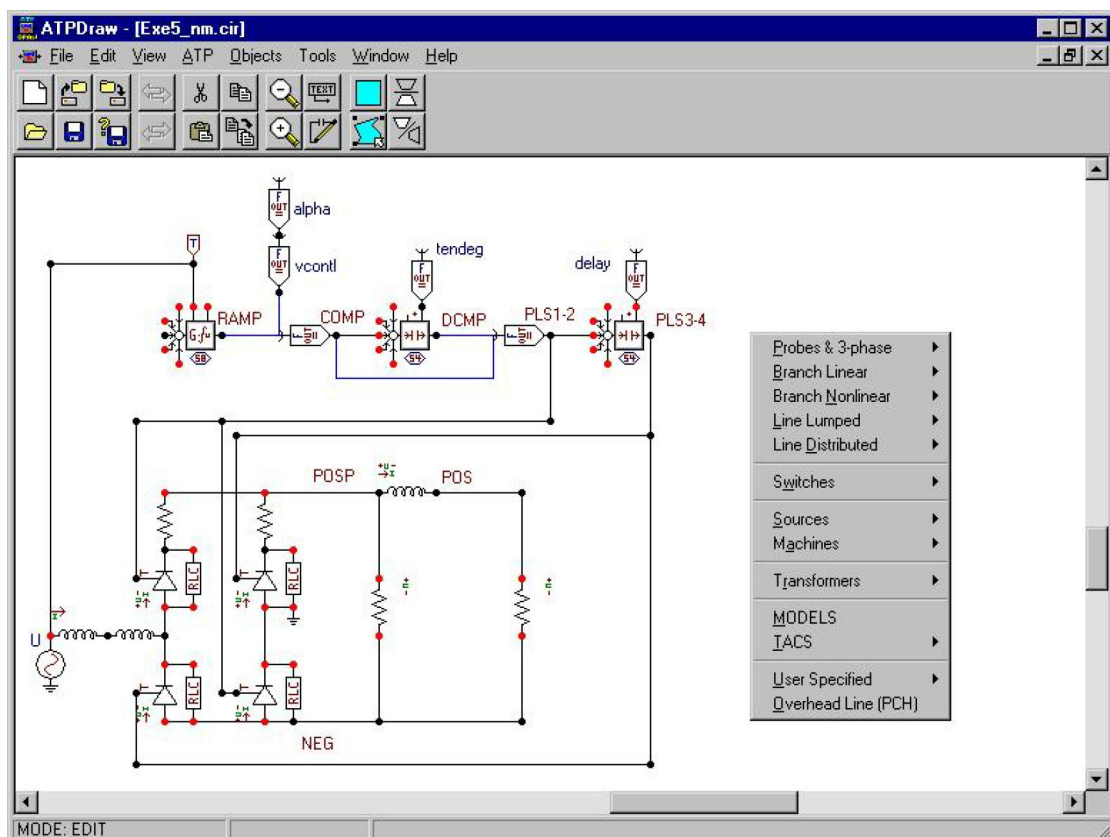


FIGURE 4.1: Graphical pre-processor ATPDraw.



Main PlotXY features:

- Maximal number of curves per plot is 8
- Up to 3 different files can be plotted on the same worksheet
- Plots versus time axe or X-Y axes plots are possible
- Plotting results with two independent vertical axes.
- Automatic axis scaling up and down
- Precise determination of values in numerical format with cursor
- Plot may be exported as Windows Metafile for further processing and analysis

### 4.2.3 Power Transmission Line Models Overview

In present simulations transmission lines play a crucial part in the generation and damping of transients and therefore are critical in proper modelling. Below some consideration are given discussing a few possible options for various transmission line models and their applicability in different power network studies.

A real overhead transmission line or cable parameters are evenly distributed resistivity, inductive, capacitive and conductive elements along the full line or cable length. However, in electrical calculations or model it may be represented by either distributed resistance, inductance, capacitance and conductivity elements along the full line or cable length or treated as simple T or Pi representation with the lumped elements mentioned above.

In transient studies, therewith, some of those parameters are frequency dependent and all the more would have an impact on transient simulation results. In various electromagnetic transients programs different auxiliary subroutines are responsible for the proper transmission line parameters computation as they cannot simply be derived from conventional formulas.

On the other hand frequency dependence can be neglected in steady-state studies, such as load flow cases and thus, transmission overhead or cable line model can be substantially simplified.

Based on the main tasks to be simulated in any electromagnetic transients program one should keep in mind these two conceptually different approaches for the adequate power system simulation.

- Constant parameter models

In a group of transmission line models with constant parameters that are available in electromagnetic transients programs the following options may be taken into consideration:

- Positive and zero sequence lumped parameter representation
- T- or Pi-section representations
- Bergeron model with distributed parameters representation.  
A line itself may be transposed and un-transposed.

- Frequency-dependent parameter models

- The frequency-dependent models presented electromagnetic transients programs usually may be grouped as following:
- A frequency dependent line model with use of constant modal transformation matrix representation. Line may be transposed and un-transposed.
- A line model with use of a frequency dependent modal transformation matrix. Line may be both transposed and un-transposed.
- Phase domain frequency-dependent line model without modal transformation. Line may be transposed and un-transposed.

Thereinunder, few constant and frequency-dependent models with lumped and distributed parameters will be briefly described and considered in the following chapters devoted to simulation results.

### 4.2.3.1 Models suitable for Steady State Studies.

In simulation cases with steady state profile there is a vast number of applications, where overhead transmission or underground cables may be appropriately modelled for only one particular frequency.

In the ATP-EMTP a model of a transmission line with constant and lumped parameter may be represented by either Pi- or T-sections. On the Figure 4.2 a Pi-line equivalent circuit representation single-phase line is shown.

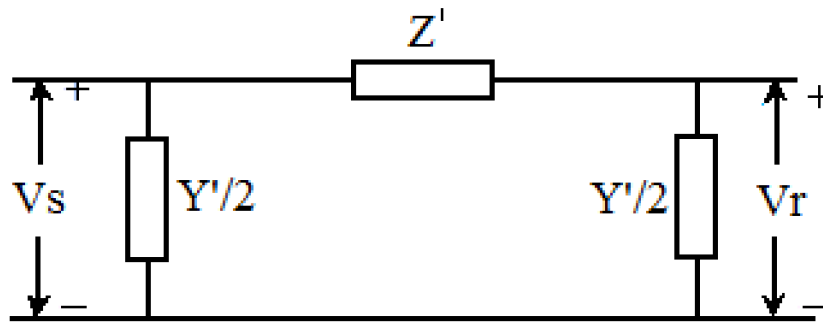


FIGURE 4.2: Pi Equivalent Circuit Transmission Line.

The Pi equivalent circuit representation consists of series impedance and shunt admittance elements. A single-phase transmission line represented by Pi-sections may be described by following equations:

$$\frac{1}{Y_{series}} = (R' + j\omega L') \times l \times \sinh \frac{(\gamma \times l)}{(\gamma \times l)} \quad (4.1)$$

$$Y_{shunt/2} = \frac{(j\omega \times C'/2) \times l \times \tanh(\gamma \times l/2)}{(\gamma \times l/2)} \quad (4.2)$$

In these equations  $R'$ ,  $L'$  and  $C'$  parameters are consequently the resistance, inductance, and capacitance per unit length.  $l$  - is the full length of a transmission line or cable and  $\gamma$  is a propagation constant that may be derived from equations above:

$$\gamma = [(R' + j\omega \times L') \times j\omega \times C']^{1/2} \quad (4.3)$$

Besides the already above-mentioned fact, that such a model with constant and lumped parameter can be accurately applied at only one specific frequency at steady-state conditions, another limitation of its applicability is the length of transmission link to be modelled. [61], [62]

For overhead transmission lines a typical distance of applicability depends on particular frequency of interest and ranges up to 150 km at 50 Hz and rapidly decreases with increase of frequency, e.g. to 15 km at 600 Hz, and only about 5 kilometres at 2000 Hz, etc. To some extent these applicability limits can be boosted by connecting in series a number of cascaded pi-sections, but will inevitably produce travelling waves reflections at every cascading point.

Although, the model includes the hyperbolic corrections with no approximations and accordingly is very precise, as well as it may take into account the skin effect and ground return corrections and be built for any number of circuits as a multi-phase line if only the same right-of-way distance is kept, this model is untransposed by default until a user interposes in a matter by introducing additional transposition schemes. This model cannot be also applied in those cases, where transient processes are involved into creating a picture of the whole system. [63]

#### **4.2.3.2 Models suitable for Transient Studies.**

Models of transmission lines with frequency dependent and distributed parameters are considered the best suitable option for studies of transient processes in a power system. [64] Based on travelling wave propagation approach they are valid for a greater range of frequencies comparing with cascaded Pi- or T-section models.

Frequency-dependent transmission line models with distributed parameters provide a more accurate picture of distributed nature of a transmission line. They also take into account the fact of frequency-dependence of some parameters and their inconstancy in time what also very much improves the accuracy of simulations and related analysis of transients in power systems.

Frequency-dependent transmission line models present themselves as functions of frequency and time and are not constant, i.e.,  $R(\omega)$ ,  $L(\omega)$ ,  $C(\omega)$  and  $G(\omega)$ .

In most frequency-dependent models each multi-phase line equation is splitted through a modal transformation matrix in order to study separately each mode as a single-phase line.

Although, complex and frequency-dependent transformation matrices for un-transposed or unbalanced lines may provide a high accuracy and have been already in-built in many transient programs functionality this alternative shall be used with certain scientific alertness and critical overview as this method may produce sometimes unstable and uncertain results. Model calibration against other transmission models e.g. with simple lumped parameters or thorough comparison with real proven data if available is recommended. [65]

To avoid the problems related to frequency-dependent transformation matrices a transmission line model can be described directly in phase coordinates. [66]

The main issue in phase-domain modelling is the superposition of travelling times in the coupled-phase waves caused by separate wave propagation of two independent constituents - pulse shaping by the real losses and ideal loss-less propagation at the speed of light. [67]

This issue may be resolved by introducing synthesized frequency-dependent impedance matrix  $[Z_{\text{loss}}(\omega)]$  using various approximations of rational functions in the phase-domain. Such a model provides precise and reliable results, especially for strongly asymmetrical line configurations and in other specific cases. [68]

#### 4.2.4 Power Transmission Line Models in ATPDraw

For the high voltage overhead transmission lines, cables and pipes representation in ATPdraw a special element Line/Cable Constants is provided. [69] Several options for mathematical model of transmission line or cable is specified in this element. Below, a short description, functionality and field of application is given.

The ATP-EMTP allows to model transmission lines or cables in several different ways:

- Lumped parameters - T or Pi line representation.
  - Pi LCC Model. The Pi circuit representation is a quantified approximation with unalterable distributed parameters. It is commonly used as a simple and obvious model for steady and transient studies. However, in transient studies Pi circuit gives a big share of phase-frequency distortion in comparison with distributed parameter models.  
  
Pi circuit model cannot adequately describe elements with frequency dependent parameters and gives virtual oscillations due to lumped parameters. Long lines representation can be built by a number of Pi circuits put in series. Main

advantages of Pi line circuit model are very exact results of steady state simulations and in-dependency from time step set in program calculation routine. In the constantly distributed parameter models the time propagation is calculated for components separately in a decoupled mode using a transformation matrix to convert values from mode domain to phase domain. Such an approach is more applicable to simulation of overhead lines rather than cables, where parameters tend to be more frequency dependent.

In addition to it, linear interpolation used for calculation of values may give distortions and different pictures for high peak values at different time step settings, as the parameters are not necessary constant under the frequency variation.

Moreover, time step must be less than the propagation time for short overhead lines and cables modelled with constant distributed parameters. For these reasons several additional model are introduced.

- Bergeron LCC Model. Bergeron representation (KCLee or Clark models) is a travelling waves based model with constant frequency parameters. Bergeron as distinct from Pi circuit lumped parameters model represents reactive elements in distributed manner. Active components is divided as following -  $1/2$  in the middle of the line and  $1/4$  at each end consequently.

The Bergeron model appears to be very useful by simulations at fundamental frequency in steady state in cases where getting the correct impedance or admittance is important. However, being a constant frequency model locked at fundamental frequency the usage of it should be avoided in harmonic behaviour analysis and transient studies.

- Distributed parameters. LCC Models.
  - JMarti LCC Model. JMarti representation uses rational functions to approximate the constant of propagation and the characteristic admittance. With certain limitations JMarti is the most frequently applied model among others with variable parameters.
 

Values are converted to phase domain from mode domain through constant transformation matrix. At very low frequencies the model may show an unstable behaviour. It may require additional data and settings handling to get a more exact outcome. [70], [71] and [72]
  - Taku Noda LCC Model. Taku Noda is one of frequency dependent models with the main distinct from previous ones in calculation routine which is performed in phase domain straightforward. The direct calculation in phase domain helps to avoid the approximation errors caused by dealing with the

transformation matrix and rational functions to adjust the deformation coefficients and the characteristic admittance.

The Taku Noda model's main advantage is the ability to set a time step independent of the propagation time. Thus, a certain time step will be assigned to the current simulation. The model should be recalculated in case if another time step is needed.

The initiation of Taku Noda model could be done in two stages. At first, the proper line data is set in an auxiliary ATP file and then, this data is converted to the form readable and executable by ARMAFIT program which with the help of rational functions sets all input values in order and to generate the final file. [73], [74] and [75]

- Semlyen LCC Model. Semlyen is another frequency dependent model that is presented in line/cable constant element in ATPDraw version 3.9 and higher. The basis for this frequency dependent representation resides in a simple exponential approximation of admittance and the propagation constant.

This conception is sensible to parameters variations depending on frequency. However, due to simplification put into the base of this model in some cases approximation becomes unsatisfactory and may give serious miscalculation. [76] and [77]

### 4.3 Summary.

The ATP-EMTP is among many other transient simulation software a powerful tool proved to be very useful for fast transient studies of high voltage applications and power systems. However, its natural limitations to describe the reality even by multi-factor and detailed model shall be recognized and understood.

Simple and proven in many simulations the Pi-line representation is applicable for steady-state analysis. However, Pi-section model due to inaccuracy in results should be avoided for transient studies and long distance lines.

For analysis of transient processes it is necessary to apply the frequency dependent models for those parts of power system under the main research focus and corresponding models with constant frequency distributed parameter e.g. Bergeron model for secondary supplementary parts.

Certain inaccuracy and numerical instability in simulations may give an employment of the modal transformation matrix as well. Frequency-dependent phase domain models do not use this transformation and related to it the frequency dependence of the transformation matrix. Thus, the higher precision may be ensured even for complex cases of asymmetrical lines.



## Chapter 5

# Modelling and Simulations.

In the present Chapter, numerical simulations results of transient behaviour of the major *HVDC* network components are presented as stand-alone objects, as well as in a systemic interaction approach.

Also, an attempt has been made to adequately describe and analyse transient behaviour of *HVDC* power networks under fault conditions, what are mainly the most suitable field-specific tasks for *ATP – EMTP/ATPDraw* software. Special focus is paid to the transient behaviour and fault response of multi-terminal *HVDC* power systems, which was considered as the primary task of the present research work.

### 5.1 Modelling and Simulations in ATP-EMTP/ATPDraw.

An *HVDC* transmission network, as it has been already mentioned before, is a complex system consisting of several foundational components like converter station of different types based on power electronic devices technology applied, switchgear equipment, measurement, control and protection arrangements, overhead, compact gas-insulated or cable lines connecting generation and load.

Modelling and simulations of such a complex system under various conditions are seen as the most feasible and accessible way, whereas prototyping or real testing might be time-consuming, too risky or too expensive and not necessary as informative as numerical models simulations.

Still, it shall be always kept in mind that there are unavoidable differences between numerical results and reality. Thus, every model and every adjustment need to be carefully verified against the real object test results and measurements.

At the same time, the numerical simulation approach proved its validity through many results presented in scientific papers and broadly used by industry nowadays.

Therefore, within its certain field of application, numerical simulations can be accepted as a reliable way to study transient behaviour of *HVDC* transmission networks.

## 5.2 HVDC Point-to-Point Connection.

An *HVDC* power transmission network as any other complex system consists of a number of relatively simple single elements. More detailed study of them as separate parts in isolation from one another, may bring further and deeper understanding on how these elements could behave during transients either in normal operation or critical working conditions. The calculated picture of transients may then be taken as a basis, which by the use of superposition principle may let us estimate components interaction in the whole system, bearing in mind, where it is only possible, the integrated systemic impact and synergy.

This in its turn may give on a first approximation some new insights into the phenomenon of transients processes in the complex simulated *HVDC* system as the whole. As the first step in this approach, a single *HVDC* point-to-point connection could be simulated and studied. A model of an *HVDC* bi-polar over-head line is presented in Fig. 5.1

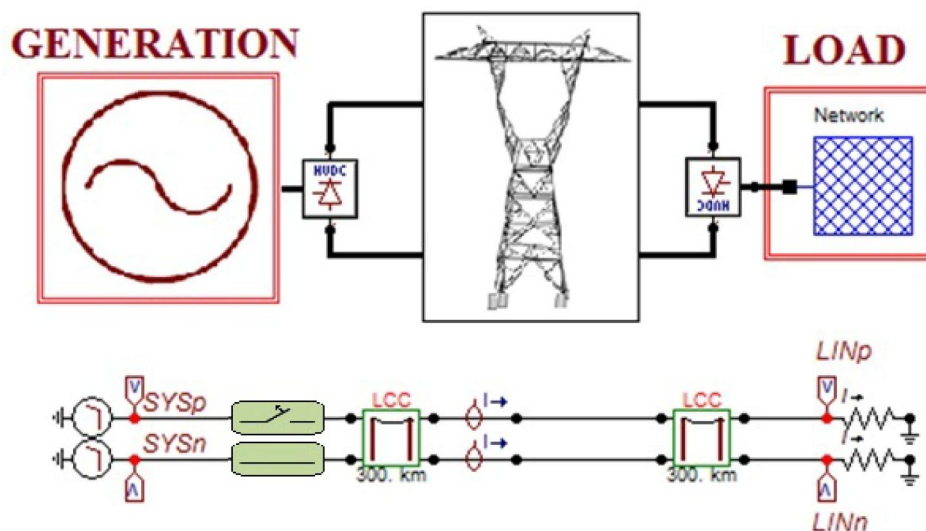


FIGURE 5.1: Model of HVDC bi-polar OHL.

In this model the in-feed from converter substation is presented by *DC* ramp source between zero and constant value (in this simulation case  $400kV$  and  $\approx 2kA$ ) and the high voltage direct current over-head line (*OHL*) by two LCC-elements - line/cable components of 300 km each.

All the parameters of the Model are set in such a way to simulate behaviour during transients processes. Switching-on and -off the *OHL* under load are one of the simplest, but very informative transient processes, that can be done, see Fig.5.2 and Fig.5.3.

### 5.2.1 Switching-off the Bi-Polar Line.

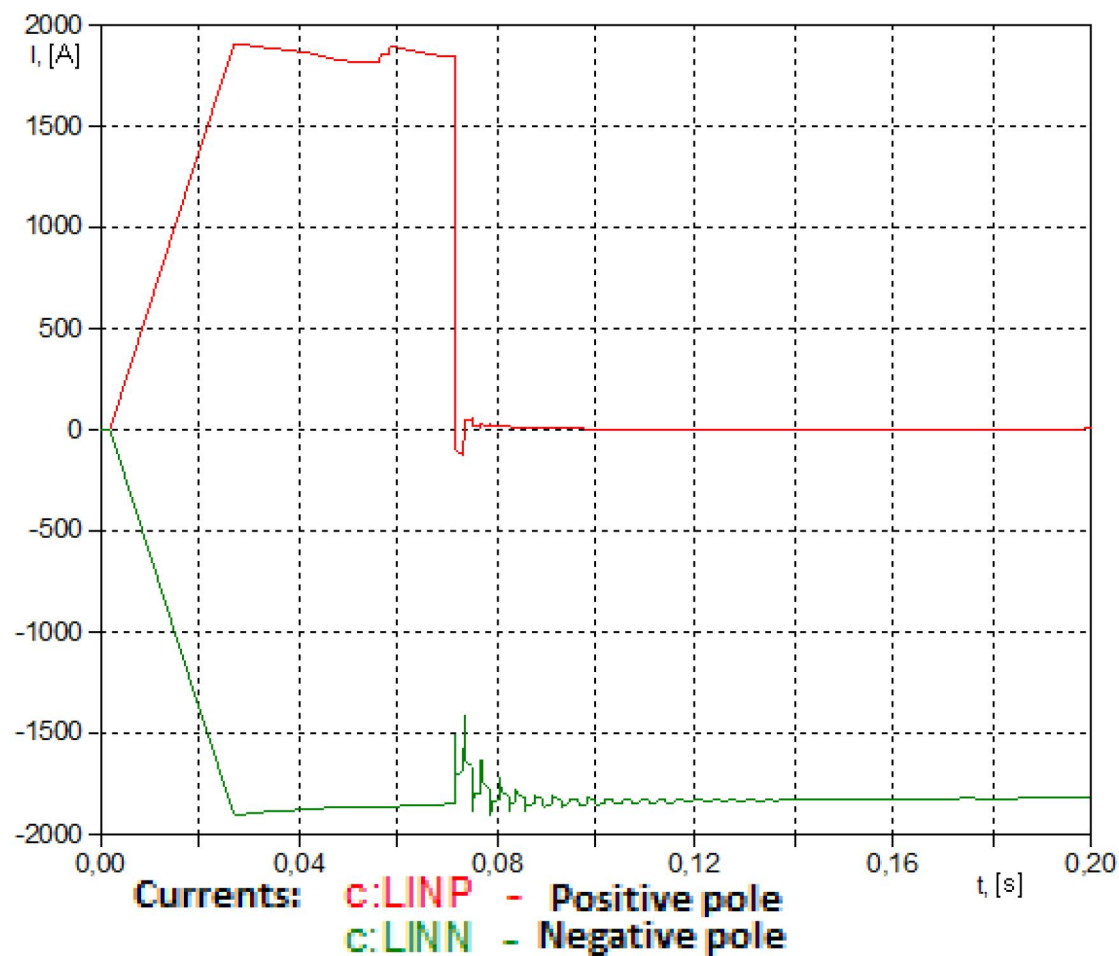


FIGURE 5.2: HVDC Point-to-Point: Switching-off under load (current).

Two current curves here and hereinafter in the text c: LINP (red) and c: LINN (green) are currents in positive and negative poles of bi-polar line consequently.

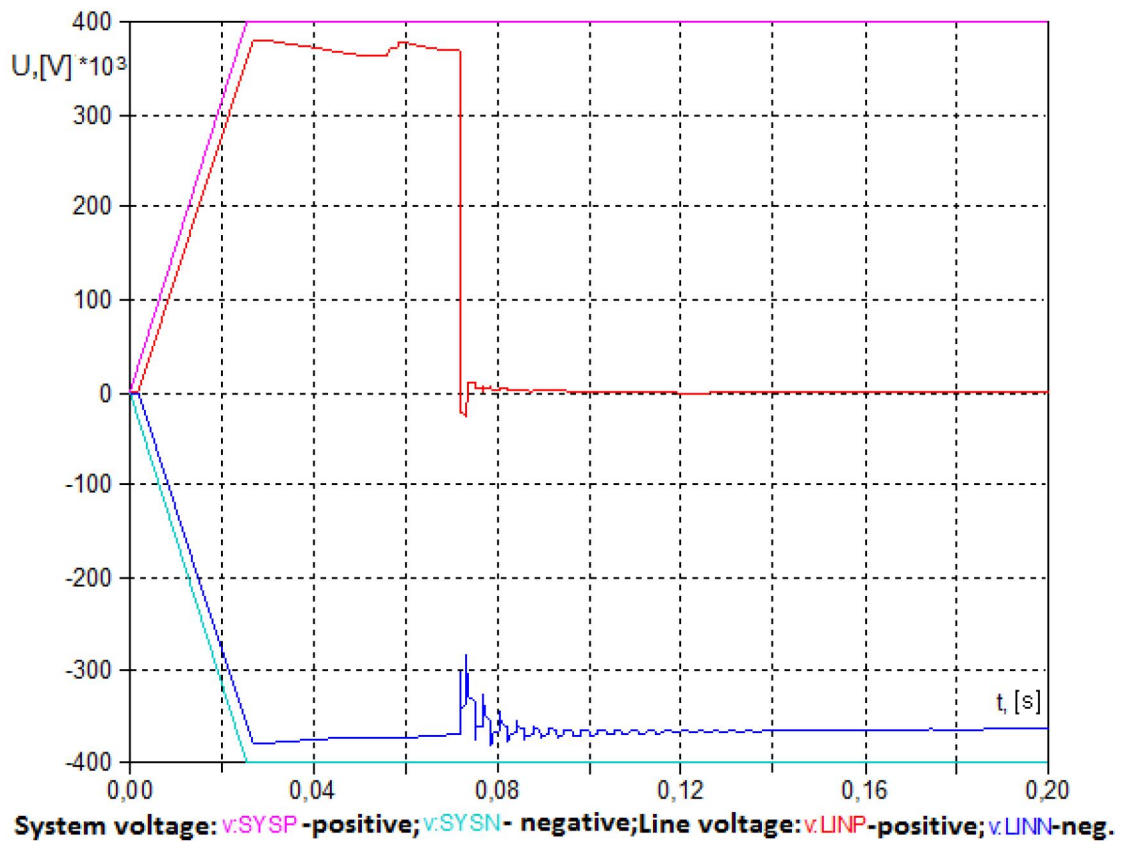


FIGURE 5.3: HVDC Point-to-Point: Switching-off under load (voltage).

On the Fig. 5.3 the behaviour of transient voltage during switching-off the bi-polar line under load is shown. Voltage curves v: SYSP (pink) and v: SYSN (turquoise) are the system voltages applied to positive and negative poles consequently, whereas, v: LINP (red) and v: LINN (blue) are the voltages of positive and negative poles of the bi-polar line.

At the initial moment a converter station in-feed, presented here as a *DC* voltage source, starts to supply bi-polar *OHL* presented by bi-pole *LCC*-element with distributed parameters (JMarty model for distributed line parameters is applied).

Current and voltage reach the peak slightly above their nominal values of app 1800 A and 380 kV, see Fig. 5.2 and Fig. 5.3, within the first ca. 30 milliseconds. Another ca. 15 milliseconds are required for these values to stabilize on the given level (nominal value) set for the presented Model.

The voltage drop on the line in comparison to the system voltage of 400 kV is estimated at about several tens kV (*app.*20 – 30 kV), what is consistent with preliminary expectations.

On disconnecting the positive pole of the *DC* line, Fig. 5.2 and Fig. 5.3, well-pronounced damped current oscillations with duration of about 10 – 20 *milliseconds* and amplitude up to 100 *Amps* (peak value) with a further decrease to zero are observed.

An interesting phenomenon is observed in the negative pole, which according to the experiment remains in operation.

Well-pronounced damped oscillations here can be explained by the inevitable interference with oscillations in the positive pole through the coupling earth path line-generator and electromagnetic field interrelation, identified in dependent parameters of LCC element, and is likely to happen in real conditions, too.

In addition, the simulation shows the successful operation of the *DC* breaker, which is based on the resonant principle with additional oscillating *L – C* circuit.

### 5.2.2 Bipolar Line - One Pole Earth Fault.

The next logically forthcoming step is simulation of transient processes and various faults on the line or at converter stations and primary equipment.

In the considered case, an earth fault in the middle of 600 *km DC* line at 50 *milliseconds* after switching-on is modelled.

The graphic scheme and numerical model are shown on Fig.5.4 below.

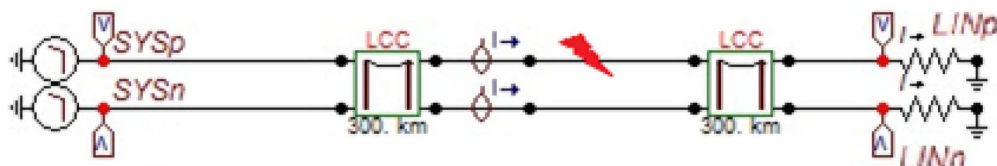


FIGURE 5.4: Pole (middle) to Earth Fault at 50 ms. Bipolar Line 600 km.

In comparison with the previous case 5.2.1, there is no *DC* breaker supposed to interrupt throughout the course of simulations.

Although it is understood, that such an assumption may bring only purely theoretical value and in more refined situations some protecting and interrupting procedures would be doubtlessly required.

Still, the foremost interest here is to observe, first of all, the DC short circuit current development, typical *max.* and *min.* values of time, voltage and current, character of growth etc., and a healthy pole response and involvement.

The earth fault is in the middle of 600km long over-head line, which is resented here by Line and Cable Component available in the ATPDraw library.

Two of the elements, 300 km each, compose a DC line of the required length, while the earth fault itself is modelled by time-controlled switch connecting positive pole and earthed R-element of infinite low resistance.

On the Fig. 5.5 and some others illustrating simulation results, a steep ramping growth of the fault current from nominal value to it's peak is clear to notice. This ramped step-wise growth may be partly explained by the capacitive nature of VSC, and in addition to it, some inner properties of voltage source applied.

Line and converter's numerical models themselves e.g. length of calculation steps, voltage regulation and control routine may also have an impact on the final representation of transients.

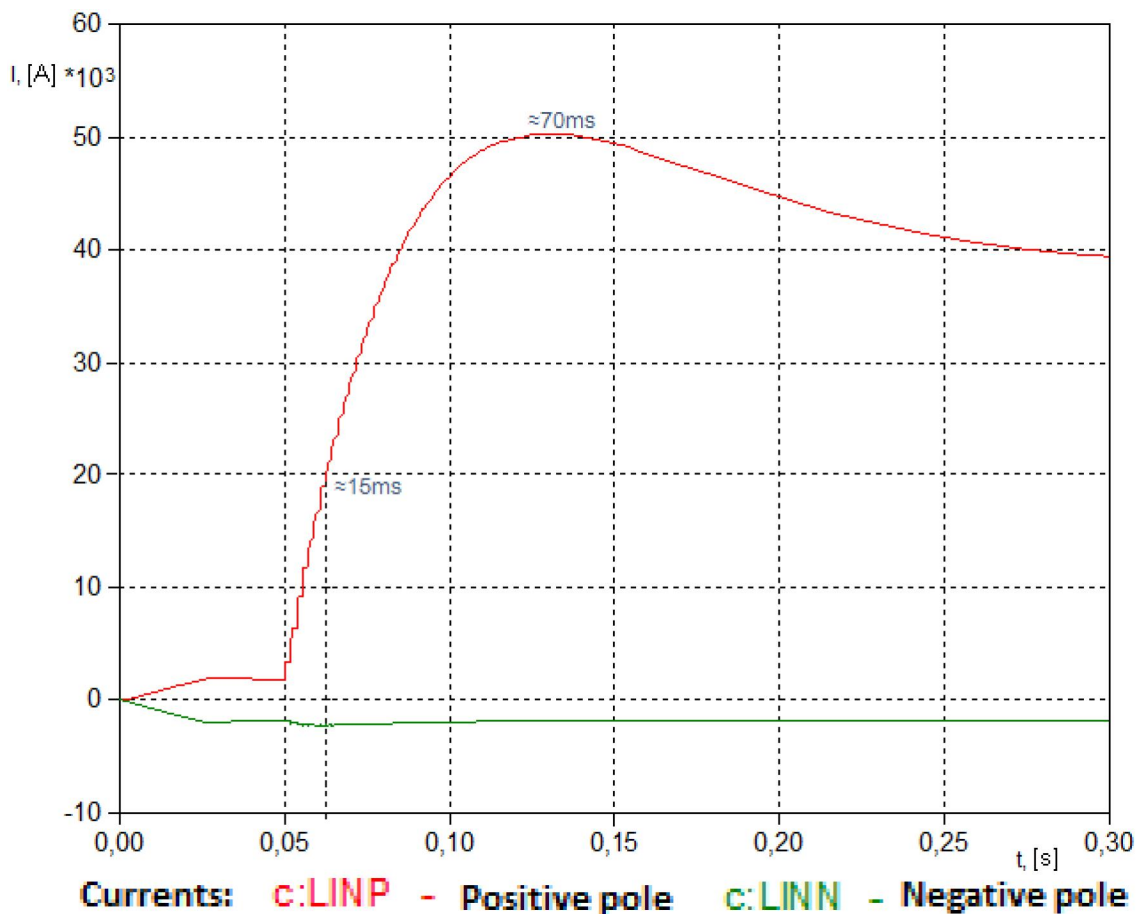


FIGURE 5.5: HVDC Point-to-Point: Earth Fault at 50 ms in Positive Pole. (current)

How it can be observed on the Fig. 5.5 the short current reaches a peak of slightly above  $50kA$  at about  $70\text{ milliseconds}$  after the earth fault event and then within next  $100ms$ . goes down to the level slightly below  $40kA$ .

The earth fault in the positive pole causes current fluctuations, which are, however, not very significant in the negative pole. The negative pole is almost unaffected by the fault and remains in continuous operation.

Stepwise increase of fault current visible on the positive pole current curve can be explained by peculiarities of Line-Cable Component and JMarti mathematical representation in addition to the implied presence of the built-in-the-model capacity with the finite capacitive value.

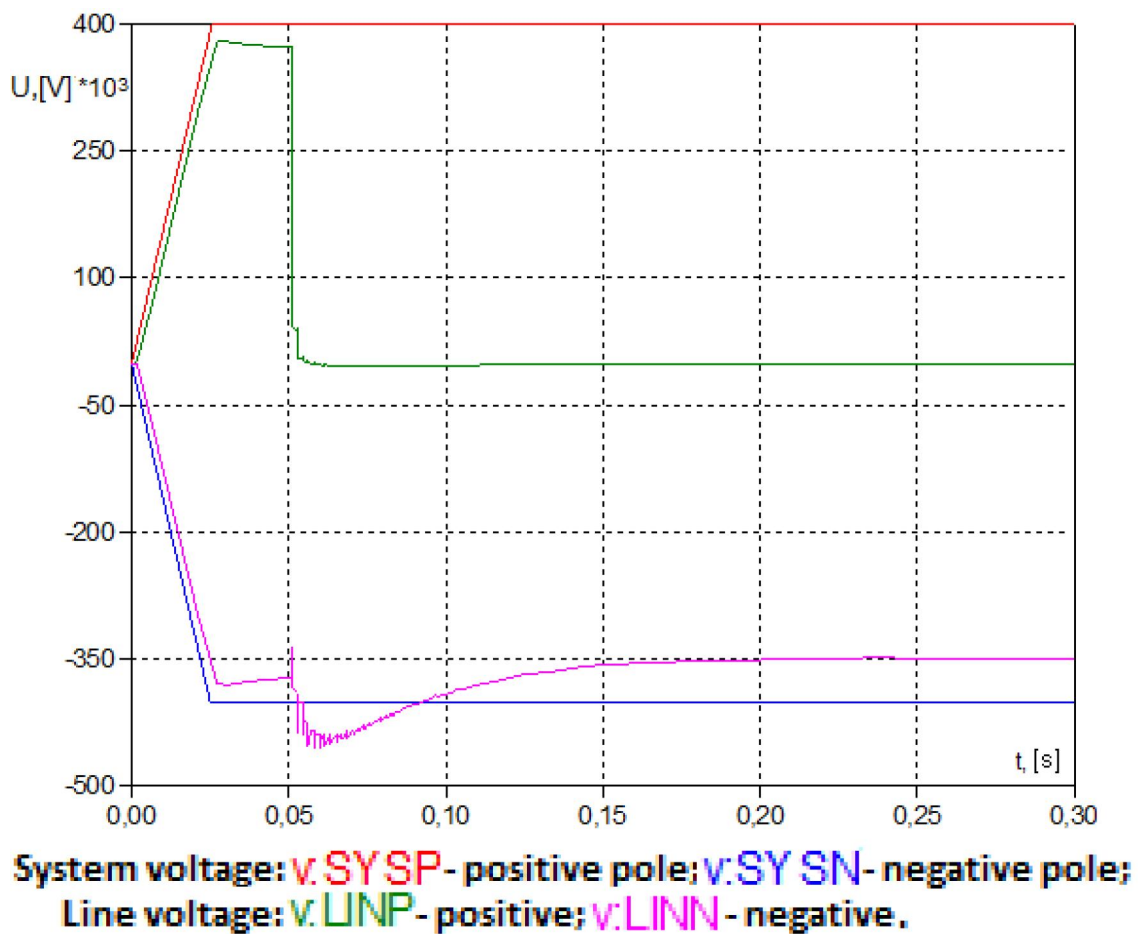


FIGURE 5.6: HVDC Point-to-Point: Earth Fault at 50 ms in Positive Pole. (voltage).

A similar pattern can be observed in the voltage curve, see Fig.5.6. The system voltage of  $\pm 400kV$  is denoted as *SYSP* (red) and *SY SN* (blue) for the positive and the negative poles consequently.

The line voltage  $LINp$  (green) and  $LINn$  (purple) curves are measured at the end of 600km. over-head line. At 50ms, due to the earth fault, the line voltage at positive pole  $LINp$  goes abruptly to zero. Simultaneously discontinuous jump-like voltage swings are observed at the negative pole, see voltage curve  $LINn$  Fig.5.6.

Few *ten* ms. after the earth fault, the line voltage exceeds the nominal system voltage and at about 60 – 65ms. i.e. 10 – 15ms. after the fault, it reaches the peak value of approximately 450 – 460kV, see Fig. 5.6.

The well-pronounced transients take about 40 – 45ms. Right afterwards the line voltage  $LINn$  becomes lower than system voltage and stabilises on the level of about –350kV, what is comparable with the pre-fault state.

These results on the transient behaviour and peak of voltage disturbances in the bipolar line under fault conditions may be worth considering for proper insulation coordination purposes.

From the *HVDC* protection point of view, the reliable registration of the event, when the line voltage becomes jump-like (high  $du/dt$ ) and exceeds the system voltage for a short period of time, could be an additional fault verification coming from a healthy pole, that still remains in operation.



### 5.2.3 Clearing the Fault on the Positive Pole of Bi-polar OHL.

In the previous case an earth fault development at one of the *OHL* pole, without any limiting or interrupting equipment, has been considered. However, such incidents in real practice surely cannot be left unattended and thus, shall be handled by protection system and equipment e.g. cleared by DC circuit breaker.

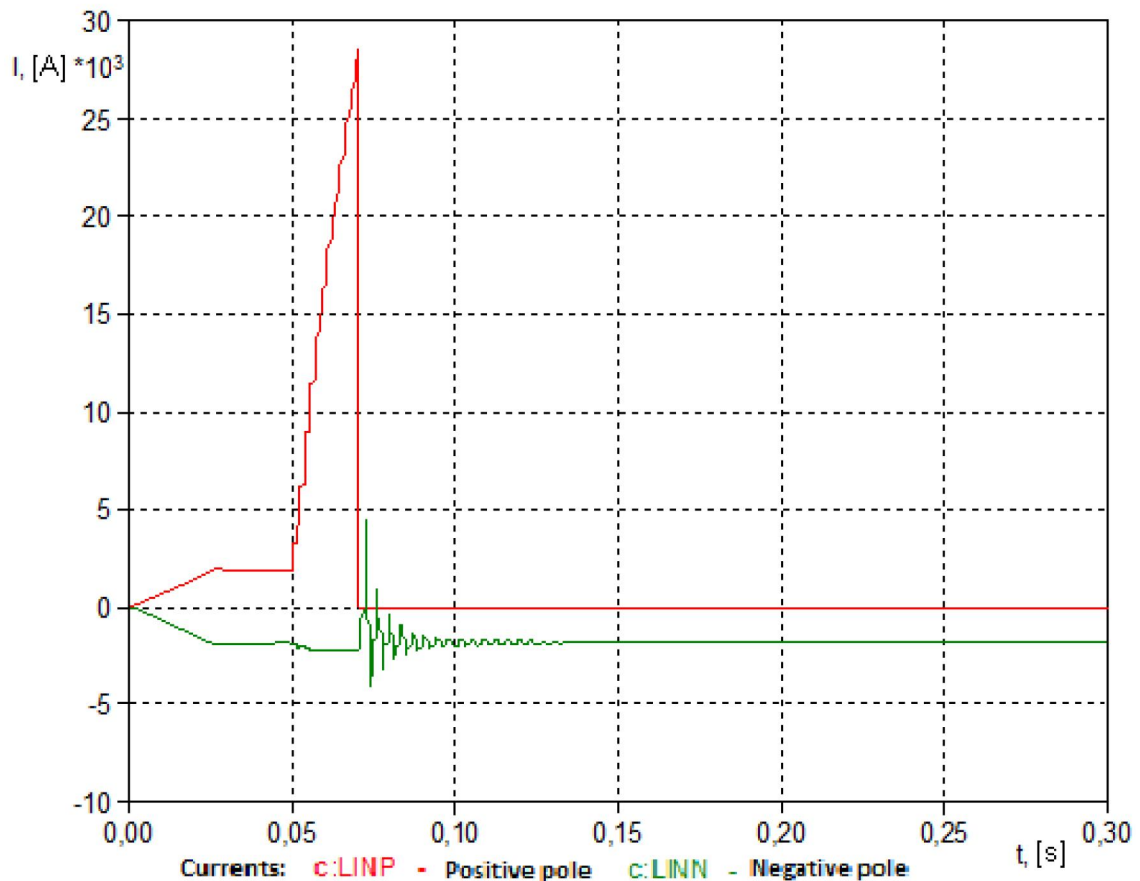


FIGURE 5.7: Clearing-off the faulty positive Pole of Bi-polar OHL. (current).

To clear the earth fault on the line in the present model a conventional DC breaker with auxiliary resonant oscillation loop, see Section 5.2.1, is applied. The first part of earth fault development is just the same as it has been described above in Section 5.2.2. The second part, however, is very different, when 20 ms. after the fault a *DC* circuit breaker initiates and clears the faulty line.

Here, time of 20ms. is considered sufficient for control and protection system to recognise the fault and send a signal to *HVDC* circuit breaker to interrupt. As it is seen from the simulation results, Fig. 5.7, at the very moment of the current disruption performed by *DC* breaker on the positive pole, the second healthy pole experiences some considerable current swings, which are, however, rapidly damped and fade away.

Clearing the faulty Pole of Bi-polar Line (current measured in the end of the OHL)

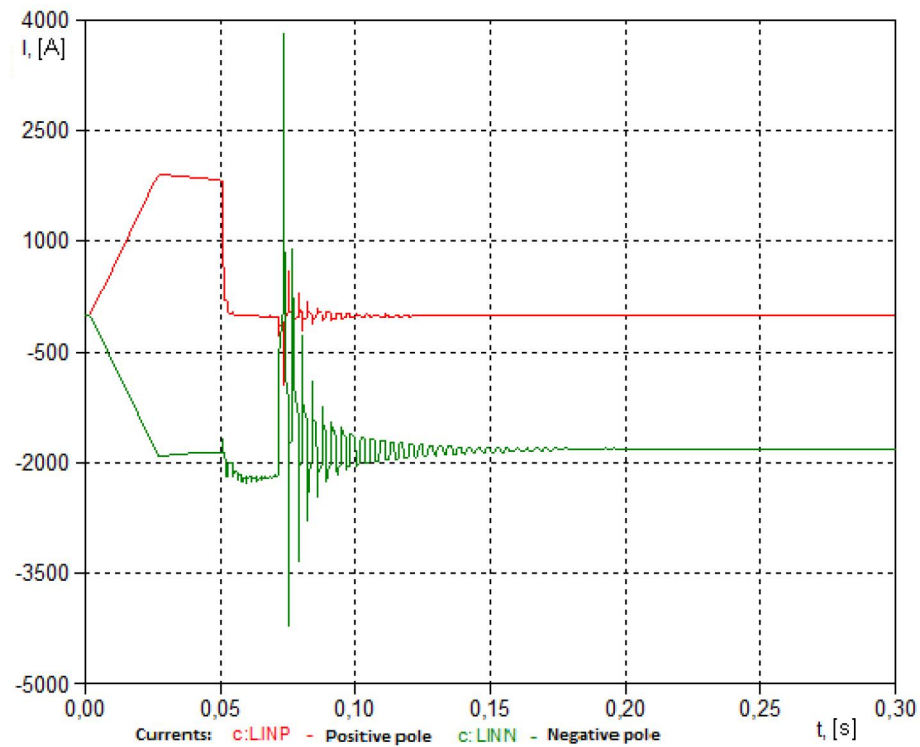


FIGURE 5.8: Clearing the faulty Pole of Bi-polar Line (current measured in the end of the OHL).

Enlarged within time domain 50-100ms.

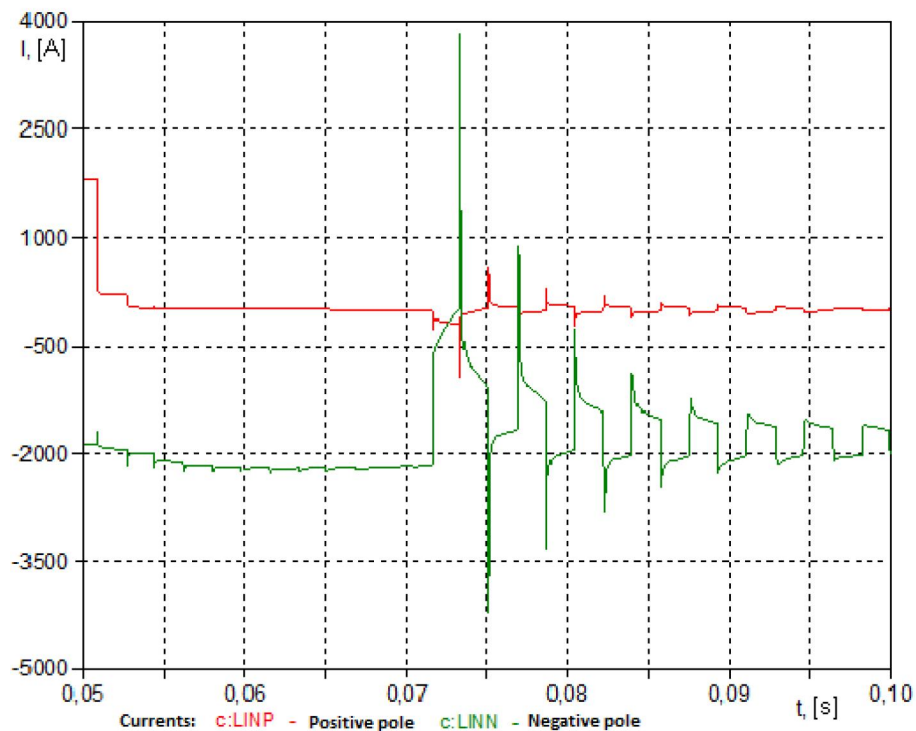


FIGURE 5.9: Clearing the faulty Pole of Bi-polar Line. Enlarged.

## 5.2.3.1 Fault in the End of the bipolar OHL.

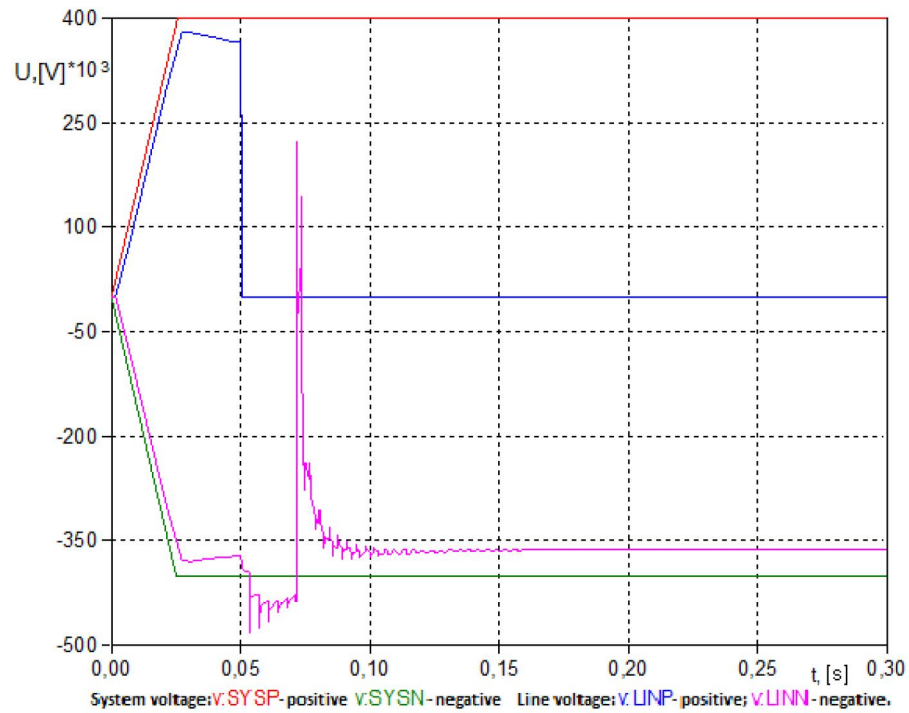


FIGURE 5.10: Earth Fault on Positive Pole at 50 ms. (voltage).

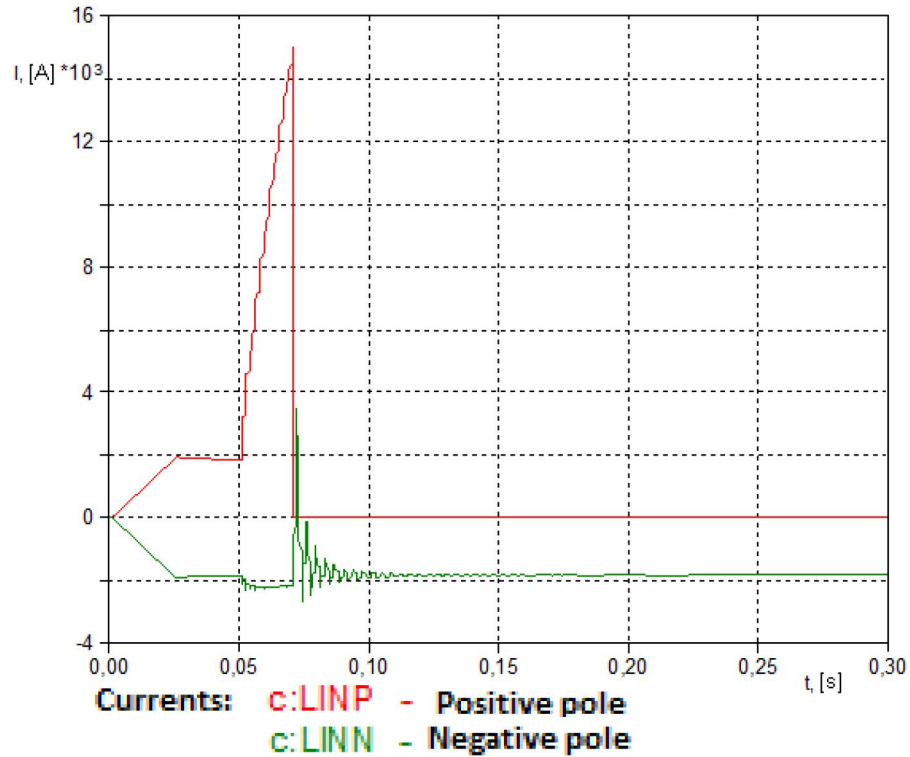


FIGURE 5.11: Clearing the Earth Fault at 50 ms (current) in the end of the line.

In distinction from the previous case with Earth Fault in the middle of bipolar over-head line, see Fig.5.6, in Earth Fault case in the end of the overhead line, see Fig.5.10 voltage and current Fig.5.11 oscillations in the healthy pole after failure due to lower damping last longer and still have quite expressive character.

The voltage peak of fault vulnerabilities according to the simulation results reaches the nominal value of the opposite positive pole and presents itself a somewhat delayed reaction ( $\approx 50ms$ ) on Earth Fault in the positive pole, Fig.5.10.

Oscillation time could be in principle divided into two periods, namely, reaction time straightforward on Earth Fault ( $\approx 50 - 70ms$ ), what is very much comparable with similar simulation picture in case of Earth Fault in the middle of the overhead line, see Fig.5.5 and Fig.5.6. And period of time starting from  $\approx 70ms$ , when the voltage curve crosses *zero* and grows with the opposite sign up to peak values from  $-400kV$  to  $+240kV$ , see Fig.5.10.

This can be explained by a system reaction and overall interrelation poles in the transmission system. Moreover, in that complicated picture of system transients, by all means, an own input from a resonant oscillatory circuit of an *HVDC* circuit breaker shall be mentioned for consideration.

By operational conditions a powerful impulse of opposite polarity is emitted by a resonant oscillatory circuit, what is a necessary requirement for an *HVDC* breaker to be able to break the fault current in a moment, when it crosses zero or at least close to it.

Some unusual separate sharp impulses of high frequency can be partly explained by particular characteristics of the model due to a mathematical approximation function in-built in plot software algorithm and thus, smoothed to a average absolute value curve with only a negligible error. Current on Fig.5.11 after Earth Fault at  $50ms$  grows stair-steps within the fault development period of  $50 - 70ms$ . At  $70ms$  a resonant oscillatory circuit of *HVDC* CB snaps into action and the current is interrupted to zero.

Oscillations in the resonant circuit and very sharp  $\frac{di}{dt}$  induce corresponding disturbance in the healthy pole, where current changes its direction to the opposite and its crest value exceeds the nominal value for the positive pole.

Therefore, current deviation in absolute magnitude is estimated from nominal  $-2kA$  up to more than  $+3kA$  and may present a certain danger for insulation and other equipment parts in terms of thermal capacity. At the same time it presents a definite difficulty for control and protection system, which shall be set accordingly for the most adequate and appropriate response on this kind of transients. The step-like curve appearance has been already explained above.

### 5.3 Line Current Commutated Converter Station.

Thyristor-based Line Current Commutated converter technology has been introduced and put into operation for about a half a century ago and since then has become a classical *HVDC* solution. *LCC – HVDC* converter stations can be found on every continent and for certain countries this technology remains to be dominating and will shape *HVDC* transmission network of the future.

Thus, it should be recognized, that *LCC – HVDC* will eventually be incorporated into multi-terminal *HVDC* grid in combination with more advanced *VSC* technology. Some successful experience could be presented by Skagerrak-4 project, where *VSC* and *LCC* operate simultaneously as a bi-polar/mono-polar configuration. [19]

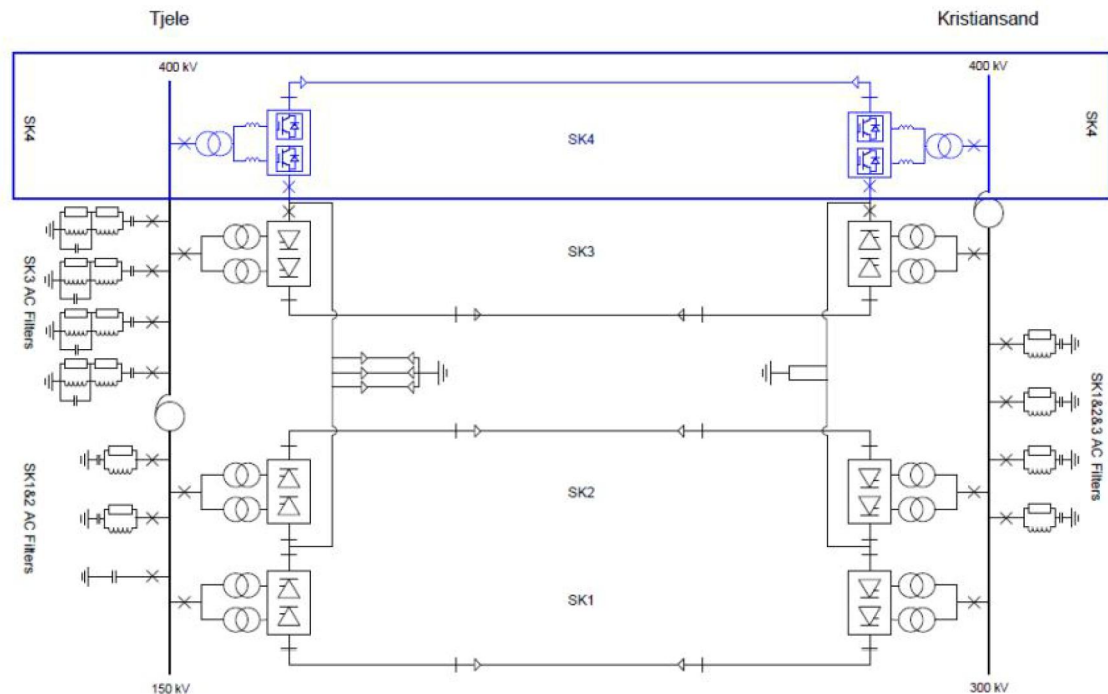


FIGURE 5.12: Skagerrak HVDC Link:(HVDC-VSC pole in blue colour).

The mix of *LCC* and *VCS* technologies will shape the grid of tomorrow. From now it can be already foreseen, that the need to connect *LCC* and *VSC* transmission links and combine them in robust and reliable system, see Fig. 5.12 [19], is an actual question to solve. Even though *VSC* technology is considered as the most appropriate one for multi-terminal operation, it is clear that for every project the special advantages and disadvantages of each converter technology shall be identified, weighted and carefully sorted out according to technical and economical parameters as well as other possible specific project requirements.

Even though line current commutated converter technology has already become classic, it is still emerging and, thus, some additional aspects i.e. various rectifier/inverter bridge configurations, control strategy, fault response and normal operation in hybrid AC-DC networks etc. are worth considering.

### 5.3.1 24 Pulse LCC Converter Station.

Twelve pulse line-commutated converter station can be modelled in ATPDraw relatively easy with predefined in library valve elements, namely, six pulse units in pairs for each pole and three-winding converter transformers, Fig.5.13. The AC system voltage serves here as an essential prerequisite to successfully carry out the commutation.

At the same time, it turns out in practise, that such a system is very dependable on AC voltage and in times of any system faults on the AC side the reliable commutation can not be performed. Therefore, its application in weak AC networks is very much limited.

The weakness of the power system is usually estimated by the ratio called the Short Circuit Ratio (SCR). The SCR is defined by the relation between the short-circuit power at the considered point on AC bus in MVA and the rated DC power:

$$SCR = \left( \frac{S_{sc}}{P_{load}} \right) ;$$

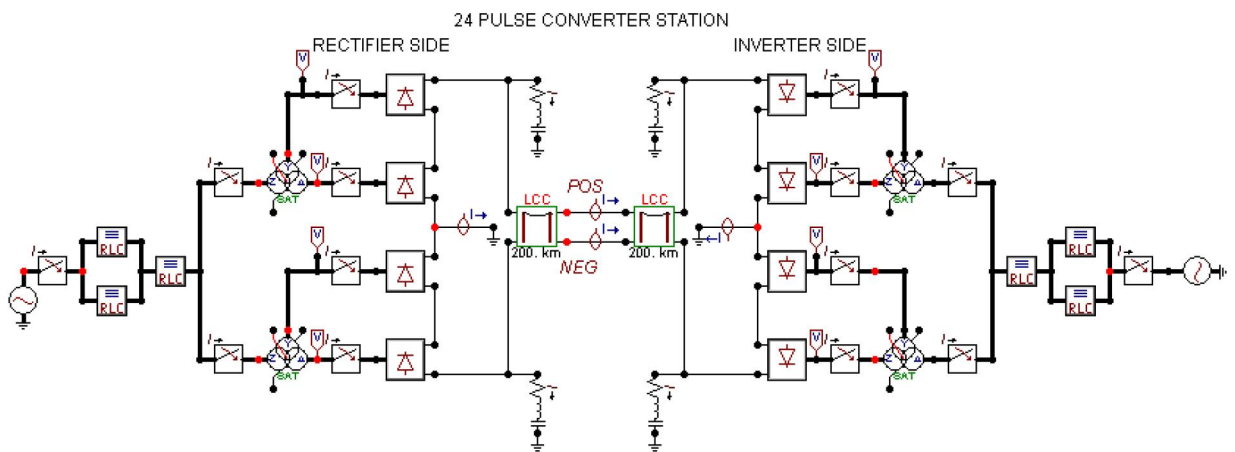


FIGURE 5.13: 24 Pulse LCC Converter Station.

Transmission AC-DC systems with the SCR less than 2.0 are considered to be weak. However, this could be improved, if the impedance changes e.g. due to different circuit parameters or dynamically changing power network topology, as it would also influence the SCR value.

On the Figure 5.13 a model of the 24 pulse *LCC* converter station is presented. One of the key element here is a converter transformer. The two 3-phase transformers have 3-windings configuration - Y0, Z and D11, which are connected to the AC bus and the converter side respectively.

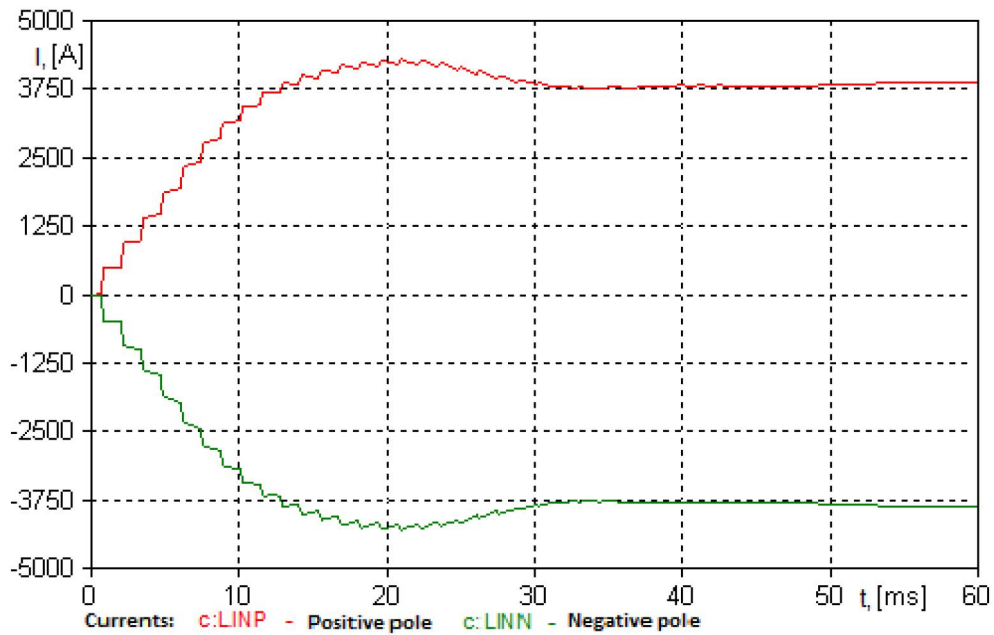


FIGURE 5.14: Current in 24 Pulse LCC Converter Station.

Current in 24 pulse line commutated converter station is presented on Fig.5.14. Converter and over-head line energization related transients take place during the first 30ms. Current in positive and negative poles grows steadily and at about 20ms after switching-on reaches the maximum of  $\approx 4000A$ , then slowly stabilizes at level of 3750A.

Switching-off the current may be performed by any of circuit breakers at AC side, Fig.5.13. In other words, in case of a fault all responsibility on successful interruption lays on control and protection systems in connection with circuit breakers on AC side.

## 5.4 Voltage Source Commutated Converter Station.

Development of insulated-gate bipolar transistors (*IGBTs*) based voltage-source converters enabled their implementation for highest voltage and transmission levels.

One of the main advantage of transistors over their predecessors thyristors is the additional degree of control – *IGBT* units can be deliberately controlled by switching i.e. both turning-on and –off any arbitrary number of times per cycle.

First voltage source converters scaled for power transmission were two-level converters followed by three-level topology, which both enabled switching operation with two or three different voltage levels consequently, Fig.5.17.

### 5.4.1 Cascaded Two-Level (CTL) Converter.

A cascaded two-level (*CTL*) converter is a derivative from this basic topology, which employs same two level converter valves units or blocks of the two switches each connected in series forming a cascade.

The *CTL* converters are claimed to significantly improve voltage output without applying any additional filter banks.

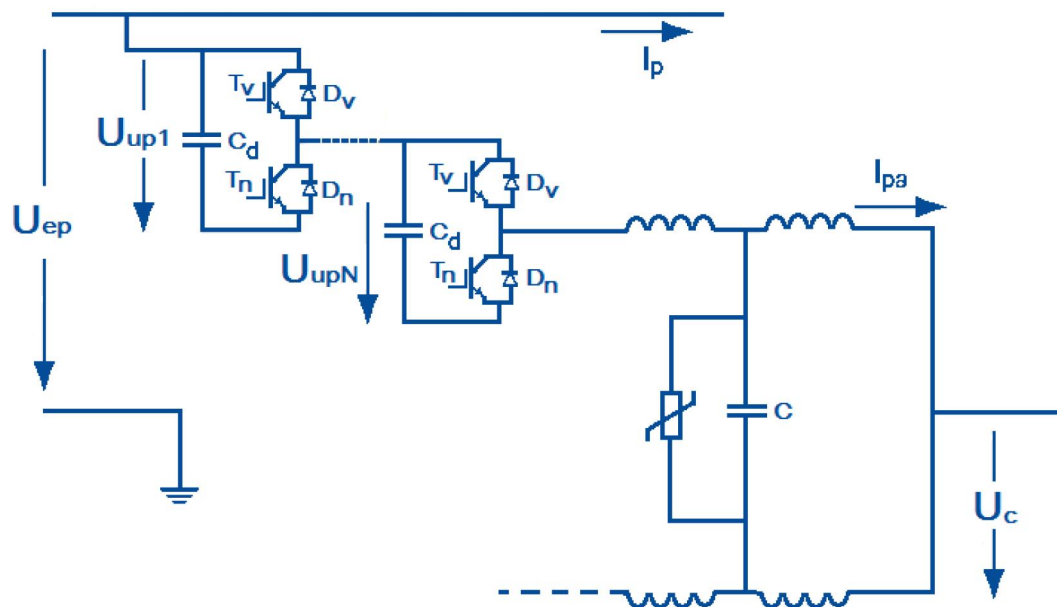


FIGURE 5.15: Cascaded Two-Level (CTL) Converter.



Cascade cell topology and principle of operation can be seen on the Fig.5.15, where each block is represented by a half-bridge two-level scheme with two valves.

Each valve is formed by two *IGBTs* and two diodes, so that three different switching regimes are available:

- 1.  $T_v$  is turned off and  $T_n$  is turned on: standby mode, when the output voltage of the block is equal to the voltage of capacitor  $C_d$ . In this regime the capacitor is charging if the arm current is positive and discharging if it is negative.
- 2.  $T_v$  is turned on and  $T_n$  is turned off: the capacitor  $C_d$  is bypassed by  $T_v$  path, the capacitor's voltage remains at a constant level. In this regime the output voltage of the block is zero.
- 3.  $T_v$  and  $T_n$  both are turned off: block mode of a converter. However, diodes may conduct current in reverse direction to provide a DC discharge path for the remnant energy stored by inductive elements. Capacitor  $C_d$  is charging when the current flowing in the converter arm is positive and ideally shall not discharge.

So, a cascade of prospective number of two-level-converter blocks shapes an arm – a positive or negative one depending on if a positive or negative pole connects it to the AC bus of the converter.

The newest and most advanced *IGBT* and diode chip-sets, which are practically available on the market for *HVDC* transmission applications, up to now have reached the maximum values of 4,5kV voltage and nominal current rating of 4000A.

However, this can be safely exceeded for a repetitive short periods of time  $t_p = 1ms$  - specified pulse duration, what is considered as a peak forward current  $I_{FRM} = 6000$  Amperes in the most recent *IGBT* applications, while the short circuit current  $I_{SC} = 11800$  Amperes.[78]

There is a big potential to move the upper limit further on, as these values are directly related to feasible power dissipation. More advanced housing assembly and cooling may be a convictive answer.

Taking into account, that there are two *IGBTs* placed in parallel, approximately 45 – 50 blocks in each arm would be required to scale the scheme up to  $\pm 400kV$  including already redundancy considerations.

### 5.4.2 Modular Multi-Level Converter (MMC).

A modular multi-level converter (*MMC*) is principally similar to *CTL* converter topology described above. Usage of a number of series connected of *IGBTs* instead of two-level valves through cascade connection basically differentiates it from the *CTL* converter topology. Specifically this technological improvement gives the name “multi-level” to this kind of converters.

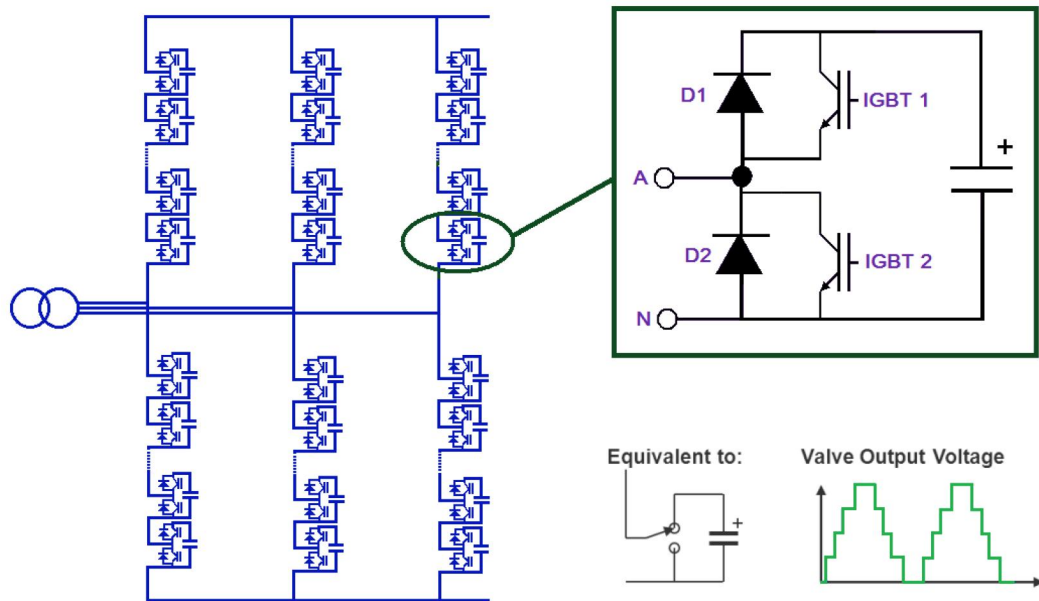


FIGURE 5.16: Multi-Level Converter Concept.

Since the times the multi-level topology of voltage source converters has been introduced, it has become already a standard solution for many different *HVDC* transmission projects all over the world.

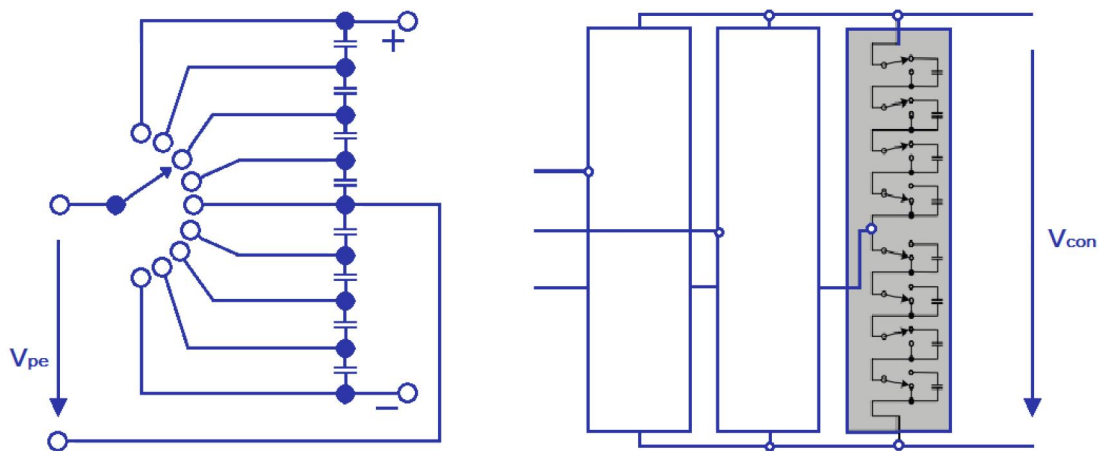


FIGURE 5.17: Switching Principle of VSC-MMC Converter.

This model is based on B.Johnson EMTP model of HV-AC SPWM (Sinusoidal Pulse Width Modulation) for a single half-bridge converter. In this work an original two-level half-bridge model has been upgraded to multi-level configuration.

The initial operating frequency value of  $60Hz$  has been adjusted to the continental European frequency of  $50Hz$  accordingly. Simulation results of converter output current can be seen on the Fig.5.18.

As it can be observed, the output current is built by consistent step-wise impulses and quite close to the sinusoidal form without any additional filtering.

The more step-wise impulses followed one after another could be applied the closer output current to the desired proper sinusoidal shape. In the limit, many impulses of short duration may give a proper sinus output so that none or very few harmonic filters might be required.

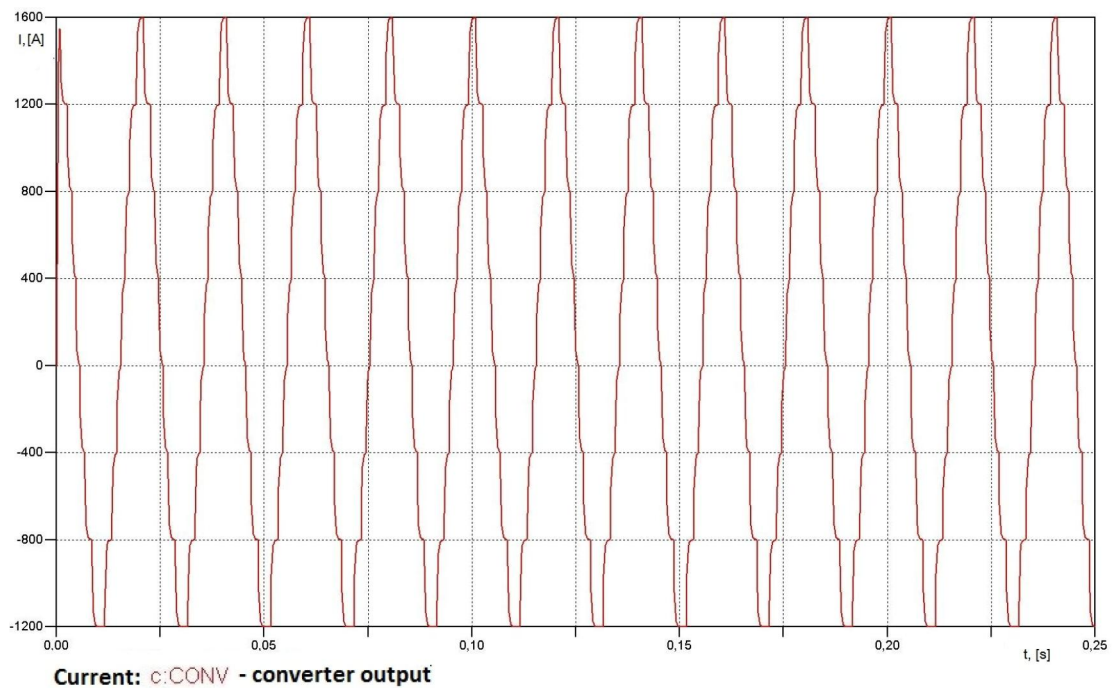


FIGURE 5.18: Output Current of VSC-MMC Converter (50Hz).

As it was mentioned *VSC – MMC* technology offers very good possibility of power flow control and fault current clearance due to very quick reaction of power electronic elements with the only limit by maximal fault current.

Thus, the question of utmost importance is how quick the fault current can be interrupted before it exceeds the maximal withstand current limit of *IGBT*-moduls. To answer this question by EMT-simulations the following realistic scenario has been modelled Fig.5.19.: *VSC – MMC* starts its normal operation at 0sec..

Afterwards, at 0,3s the pole-to-earth fault happens and a rapid growth of fault current can be clearly observed. Immediately the control of converter gets signals of fault and breaks the current bringing it to zero. Then, 100ms later (this duration can be controlled deliberately) the converter gets signal for re-closing starting its normal operation again.

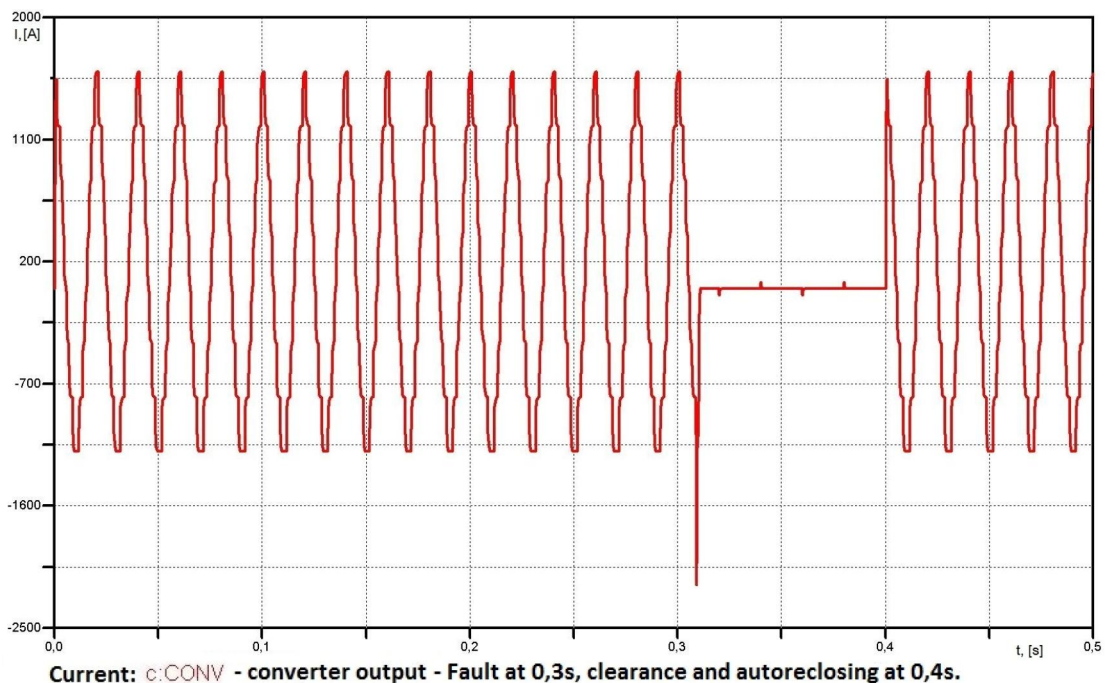


FIGURE 5.19: Current of VSC-MMC on Fault Clearance and Re-Closing.

It is estimated that 10ms from the moment of the failure shall be enough for the converter to receive the proper signal and to trip the short current in the very beginning of its growth ( max. current 2184,8A after 2,5ms ). On the base of the current technological development it is assumed that the maximal current of *IGBT*, which could be securely switched-off, is twice of nominal value i.e.  $\leq 2400A$  or lower.[79]

However, the transient recovery voltage effect right after the fault current interruption shall be considered in more details. As  $TRV$ 's character depends largely on circuit parameters and conditions, transient study in  $HVDC$  network is seen in this light extremely important to formulate certain essential requirements on various switching equipment and especially on  $HVDC$  breakers.

$TRV$  values can be assessed, for example, with help of  $ATP$  simulations, where typical parameters and conditions may be modelled. In the case with multi-modular converter presented here,  $TRV$  value can be measured right after a switching action (fault clearance) performed by converter.

Every transient  $TRV$  is usually known for its high frequency, steepness and amplitude, but the most danger is presented by fault current interruption, which emerge in the system in a very short period of time, but have tremendously negative impact on insulation properties of high voltage equipment.

Thus, the factors, that affect  $TRV$  parameters, shall be carefully considered and thoroughly optimised. Among them, the transmission system inductance and capacitance, fault current level, transmission lines number coming to the point of  $TRV$  observation and their impedance, system grounding arrangements and some other system specific factors. For instance, the number of transmission lines in parallel may significantly damp extreme values in the system.

Ratings and regulations for transient recovery voltages in conventional AC networks are described in *IEEE C37.011*, what basically, could be a solid ground for  $TRV$  studies and investigations in  $HVDC$  networks too.

Assessing  $TRV$  parameters, the most important of them are  $TRV$  peak value, time required to reach the peak value and, consequently, Rate of Rise of Recovery Voltage ( $RRRV$ ).

Here another principal conflict is located, as it is usually desired to reduce time required for interruption and maximal level of the short circuit current, eventually in this situation, circuit breaker  $TRV$  capability needs to be increased, and vice versa. So, the maximal amplitude value of  $TRV$  increases and reaches its peak in a less time, i.e. the  $RRRV$  increases, if short circuit current reduces.

Insulation failures, as it is known, may be caused by  $TRV$  across circuit breaker contacts at short circuits interruption, followed by external insulation flash-over between phases or between phase and ground.

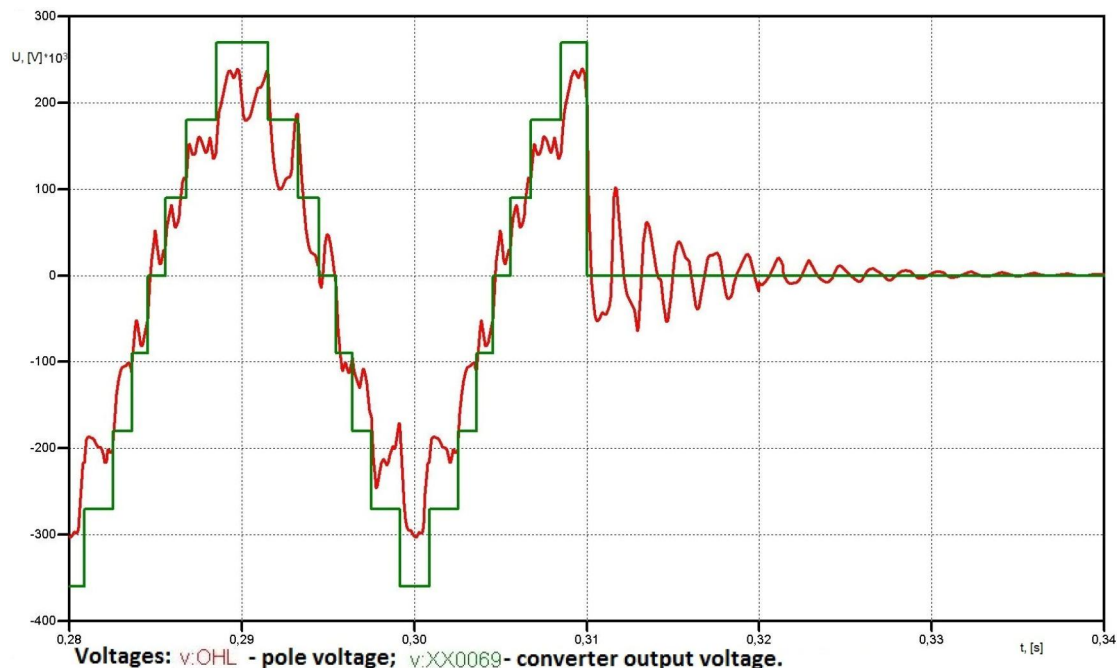


FIGURE 5.20: VSC-MMC Voltage after Fault Clearance.

So, the prerequisite of successful interruption without arc re-ignition and re-strike is the ability of insulation substance to withstand fast emerging recovery voltage and to gain insulation properties competing against the rate of rise of  $TRV$ . Generally, it is considered, that re-ignition occurs immediately after the current zero and re-strike – in a half cycle later after the current interruption, Fig 5.20.

So far it is understood, that capacitance and inductance in calculated circuits play a key role, it becomes clear, that the application of fault current limiters for short circuit current limitation, how it was suggested in Chapter 7 and here [80], may be significantly restricted, if the rate of rise of  $TRV$ , due to their usage, appears to be too high.

However,  $TRV$  can be also influenced by introducing additional surge capacitance into the system, though, by means of additional costs.

## 5.5 Various HVDC Network Topologies Simulation.

In the course of continuing *HVDC* power systems development, it is rationally to assume, that on a certain stage of rapid expansion, various *HVDC* transmission schemes will have to operate in parallel to each other. This parallel operation shall still remain a reliable part of hybrid AC-DC power system.

### 5.5.1 Monopole and Bipole Operating in Parallel.

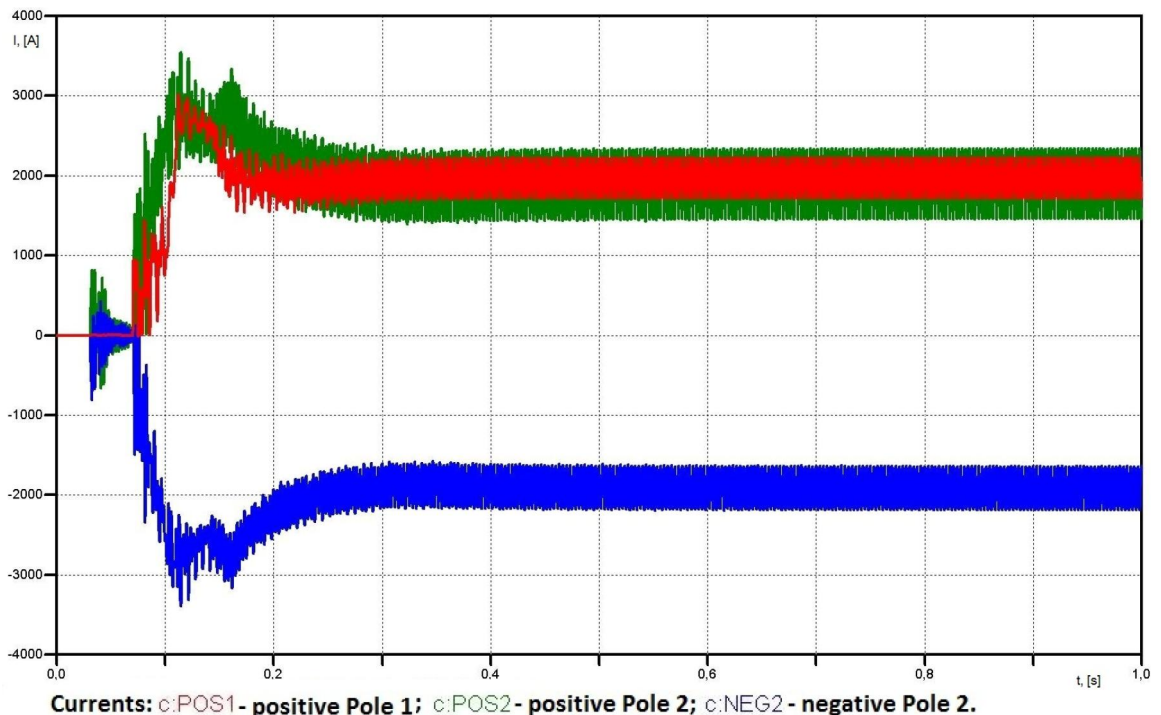


FIGURE 5.21: Monopole and Bipole in Parallel.

Considering various options, one of the those schemes most likely to be used in parallel operation is mono-polar and bi-polar on- or off-shore coupling assembly connected to AC power grid.

In the present case (see Fig.5.21) a mono-polar *HVDC* over-head line (red curve: POS1 current) with metallic return together with bi-polar over-head line (green curve: POS2 current in positive pole; blue curve: NEG2 current in negative pole;) are considered.

The current flowing in mono-pole (red) overlaps positive current (green) in bi-polar DC line. It draws attention the fact that fluctuations during transient process of putting rectifiers in operation and charging the lines in case of monopole are less pronounced and the whole transients take less time in comparison with bi-pole.



Partly, this can be explained by the fact, that filters on the *DC* side, namely inductance  $L$  connected in series with the line and capacitor  $C$  connected in parallel i.e. pole-to-earth, are better tuned in this model in order to observe the influence of  $L$  and  $C$  elements of various ranges of values.

In this case  $L = 75mH$  and  $C = 1.5mF$  that proved to be a good balance for this topology. It is important to note, that even small changes in this interrelationship may cause significant consequences in current output.

For instance, simultaneous increasing inductance up to  $L = 100mH$  and capacitor banks value up to  $C = 2.5mkF$  gives a rather different simulation results of transient currents flowing on starting converter (rectifier) of both mono- and bi-poles, see Fig.5.22.

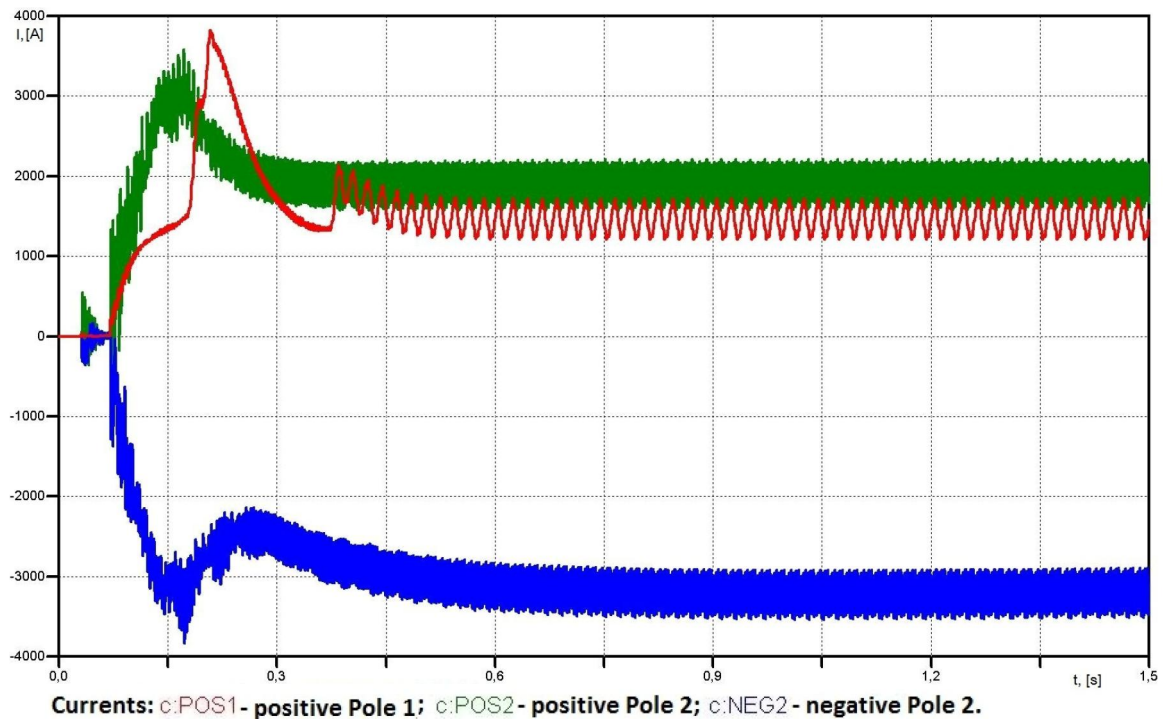


FIGURE 5.22: Monopole and Bipole in Parallel. Adjusting Filters.



### 5.5.2 Multi-terminal HVDC Network. Ring.

Geographical location, among other important factors, determines the topology of power transmission network, which could be formed by either under-sea cables off-shore or by DC overhead lines on-shore in rural areas, or by a combination of both.

At the moment a rapid development of high voltage gas insulated DC lines has made it possible to implement this yet expensive, but very compact solution in urban densely populated areas, where space available for new installations is very limited.

Although, *DC GIL* applications are not explicitly presented in this work, nevertheless, they are suggested for the future studies considerations, as a possible factor of influence on shaping the future *HVDC* power transmission network.

Various network configurations are also determined by transmission grid development and on the planning stage by requirements on reliability of electric power supply. A certain network configuration plays a decisive role in forming of control and protection principles, see Chapter 6.

Ring configuration of *HVDC* network geographically is most likely expected off-shore, as it was mentioned in Chapter 3, please see Fig.3.1 and Fig.3.2

From the system development and reliability point of view, the ring configuration is more robust, elaborated and reliable, than point-to-point or star topologies. It may be considered as a forerunner of namely meshed transmission network topology.

The question on the most optimal arrangement is absolutely essential on long-term network planning and might be answered integrally by considering future network development, associated investments together with inherent system stability properties.

Although economical part is not broadly discussed in the present work, the system stability issues can still be trustworthy covered by means of EMTP-simulations, examining the ring system topology advantages and disadvantages under fault conditions.

The purpose of these simulations is to study *HVDC* network transient behaviour under fault conditions (namely, pole to earth fault) in the full absence of any protective mechanisms i.e. DC circuit breakers or control and protection system interference.

Putting an *HVDC* system in such a rough conditions lets considering the system stability in the worst possible situation, and thus, helping to formulate the tight requirements on *HVDC* breakers performance.

Nevertheless, I fully accept the point, that in the real power transmission systems certainly there are control and protection systems and protective mechanisms to be implemented, so that, the overall disturbance influence and fault propagation in reality should have somewhat less impact than in the present simulations, as if there were no DC breakers and protection system at all.

On the Fig.5.23 the model of five terminals *HVDC* system with ring topology is presented. Power flow in this system is controlled by pre-set voltage. Initially, Stations 1, 3 and 5 are adjusted to feed into a system and Stations 2 and 4 act as a load.

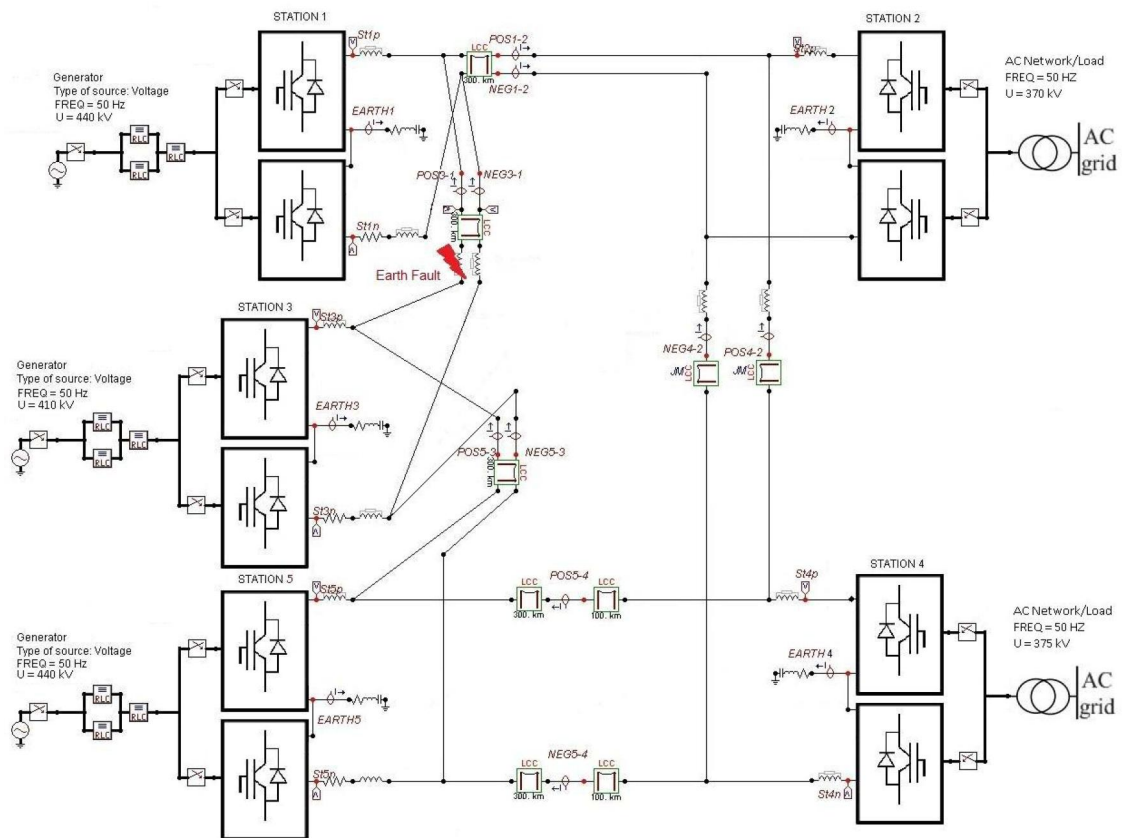


FIGURE 5.23: Multi-terminal HVDC Network. Ring Configuration.

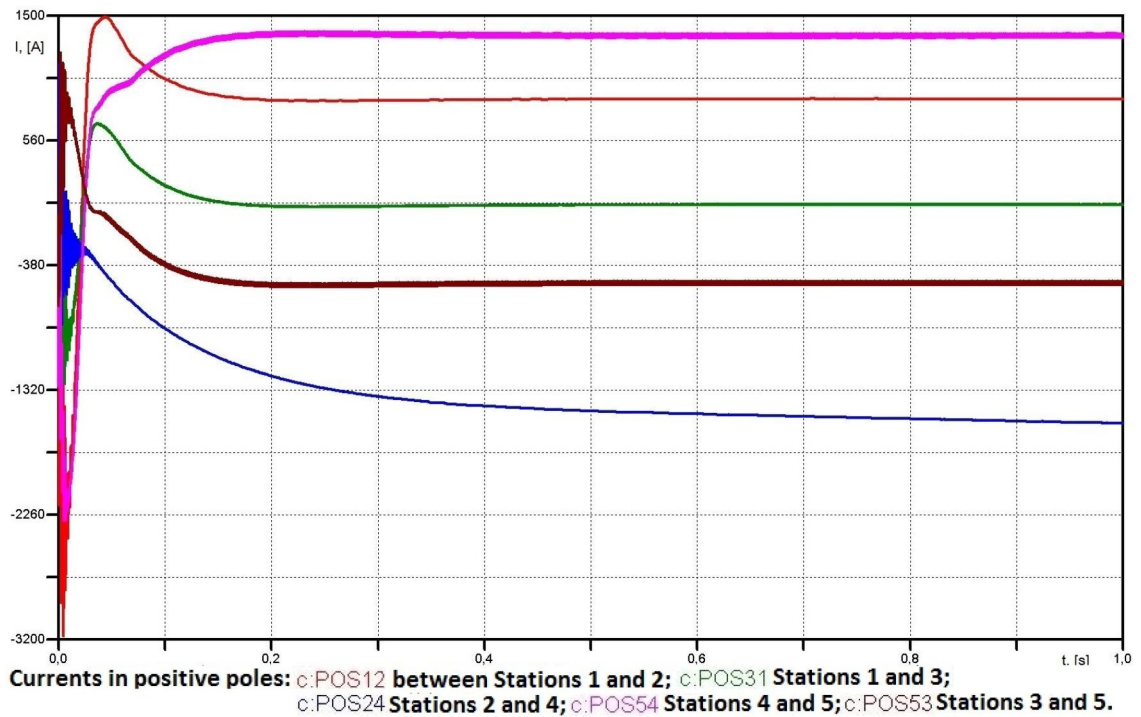


FIGURE 5.24: Ring: Currents in Positive Poles. Normal Conditions.

Pole-to-earth fault in the line between Station 1 and 3 is modelled how it is shown on Fig.5.23, the simulation results are presented on Fig.5.25.

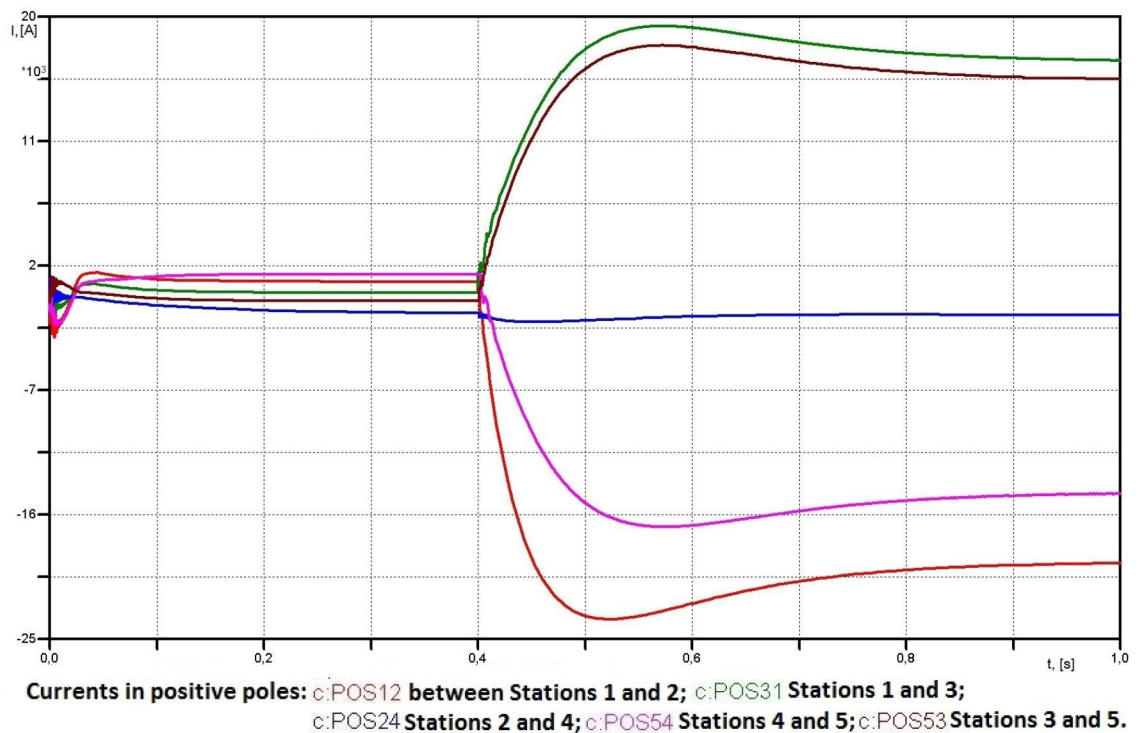


FIGURE 5.25: Ring: EF between Station 1 and 3. Positive Pole Currents.

If we look closely at the faulty line between stations 1 and 3, we will notice that although the short circuit current rises immediately after the fault in the positive pole, the observed current and voltage disturbances in the negative pole are relatively insignificant and can be kept within acceptable operating limits.

Already after 40 ms, see Fig.5.26, the pole returns to normal operation. These results support the idea that in accordance with N-1 principle for bi-pole, in case of a fault a healthy pole may still remain in operation ensuring additional stability of power grid and uninterrupted power supply.

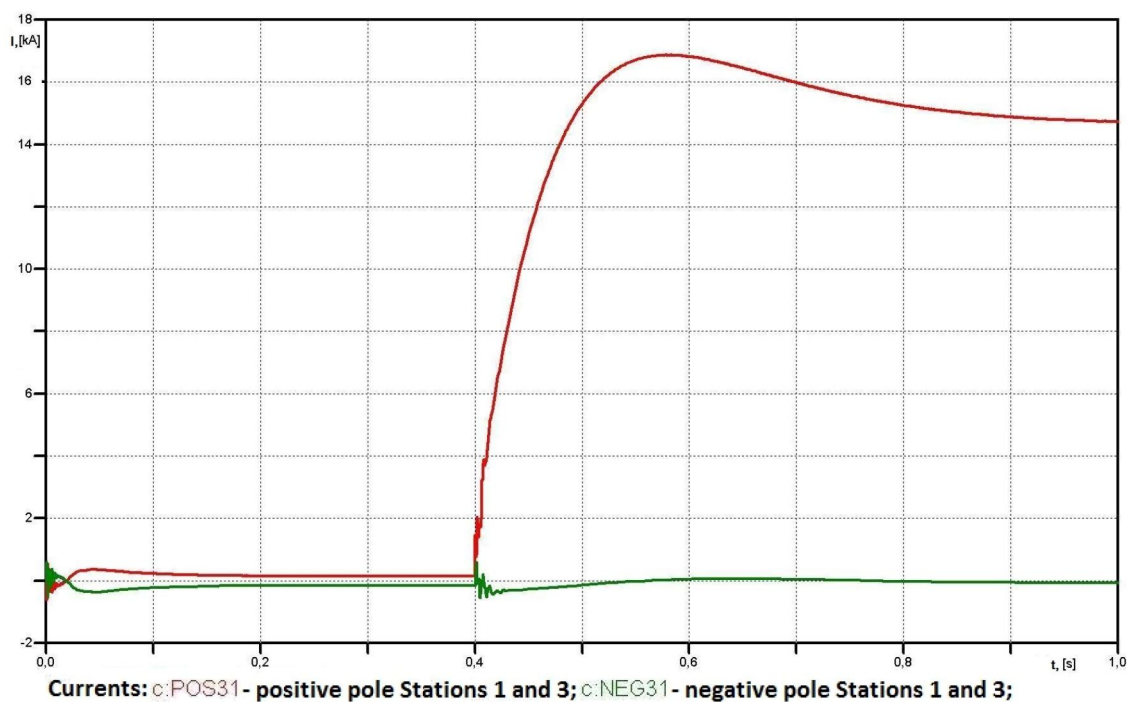


FIGURE 5.26: Ring: EF between Station 1 and 3. Currents in Line 1-3.

On the Fig.5.27 a voltage drop due to the pole-to-earth fault (EF) in positive pole and its influence on negative pole can be examined in details.

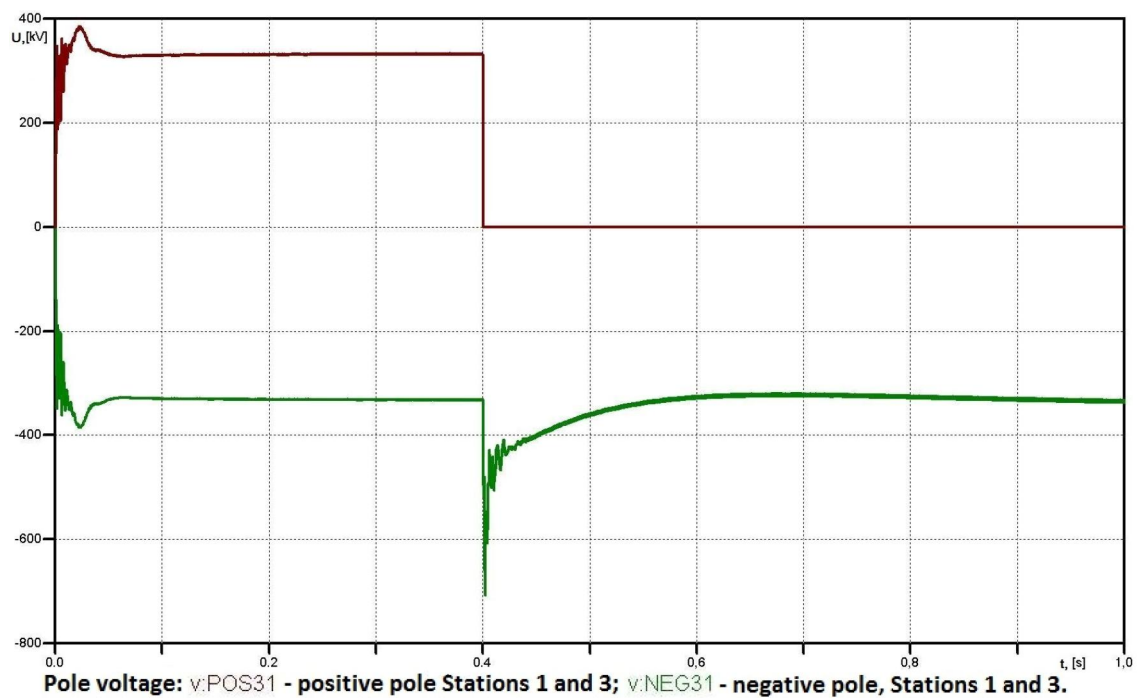


FIGURE 5.27: Ring: EF between Station 1 and 3. Voltages.

As it can be seen, at the very moment of EF, the voltage peaks almost  $700kV$  i.e. possibly twice as much as of nominal rating, what shall be properly taken into account already on the insulation coordination stage. However, quite fast - at  $0,5ms$  the voltage sets back to its pre-fault value.

### 5.5.3 Multi-terminal HVDC Network. Meshed.

If just a few connections between stations in the previous model of ring topology, see Fig.5.28, will be added, it will result in a 5 terminal meshed topology of *HVDC* transmission network.

In transmission networks typically the reliability is evaluated by  $N - 1$  parameter. Under  $N - 1$  concept it is commonly understood, that a sudden failure of any one single component in the whole transmission network will not irrecoverably influence the continuous supply of electric power.

As it is discussed in Chapter 2 in case of bipolar line the loss of one pole should be exactly recognized as  $N - 1$  condition.

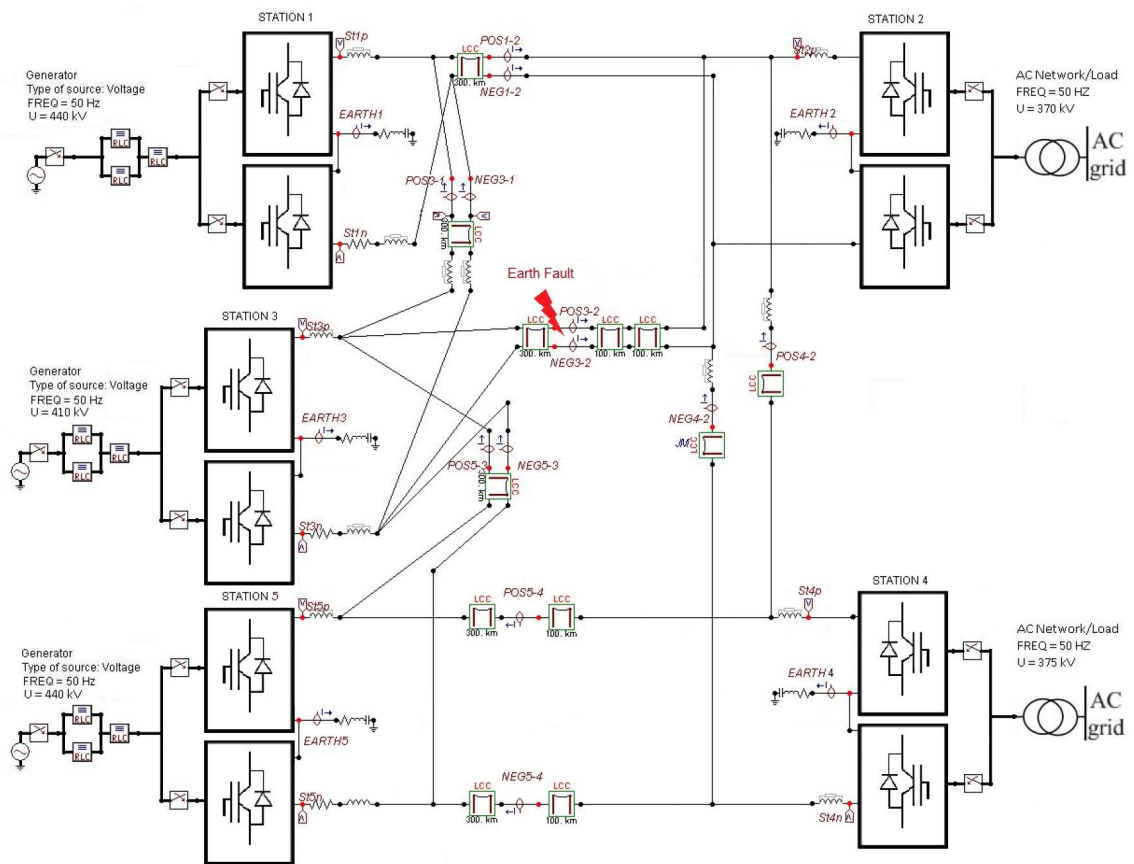


FIGURE 5.28: Multi-terminal HVDC Network. Meshed Configuration.

This model is intended as an attempt to investigate the transient behaviour and development of fault currents in meshed five terminal power transmission network. Based on the results of the present and previous models of various topologies some certain regularities influenced by the network layout may become evident.

In comparison with radial or ring topologies, see Fig.5.23, the meshed grid possess inherited qualities, as for example, higher redundancy in systems stability, increased flexibility in power flow management, what in turn benefits again to systems stability, higher ratings of transmitted power and fluent power exchange i.e. for power trading, and in the end to savings in operational costs.

Particularly in this model, Fig.5.28, only pole-to-ground faults are examined, even recognising the fact, that pole-to-pole faults may have more severe consequences for HVDC power grid, still the latter are considerably less frequent to happen in comparison with pole-to-ground faults.[81]

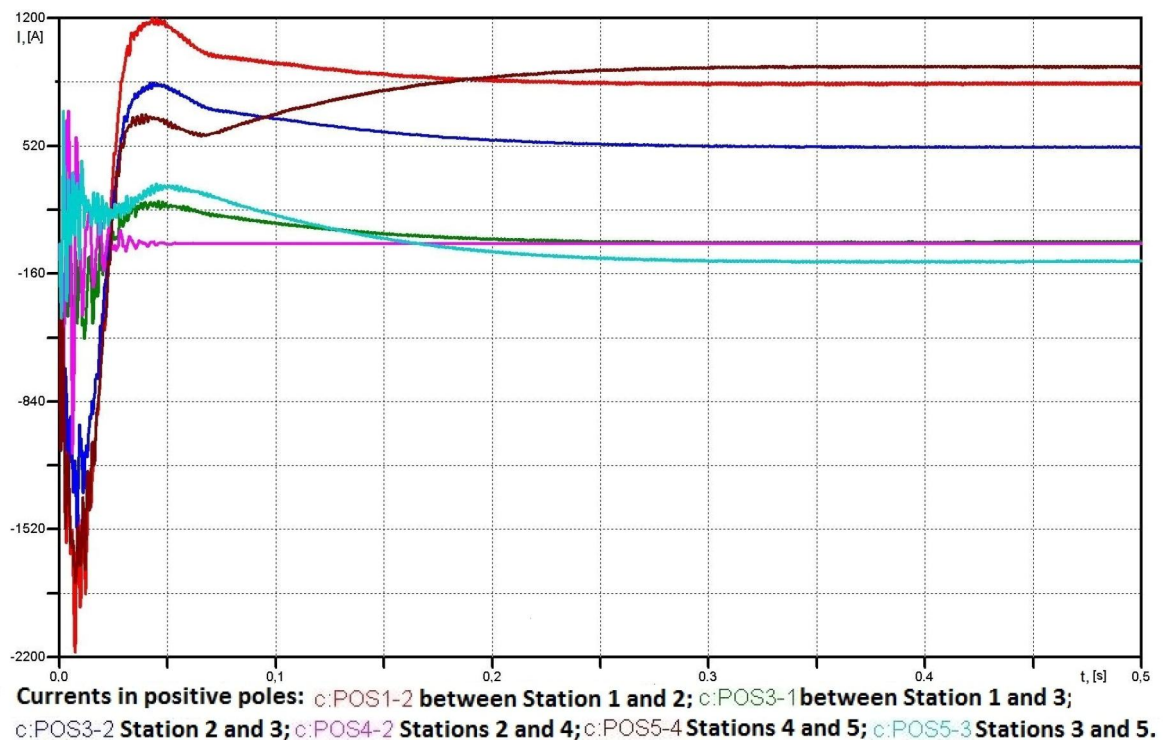


FIGURE 5.29: Meshed: Currents in All Positive Poles. Normal Conditions.

On the Fig.5.29 the current distribution on positive poles of *HVDC* over-head lines between all five terminals can be seen. The actual currents distribution on negative poles is similar, but reversed in sign (opposite direction). Stations 1, 3 and 5 as power sources and Stations 2 and 4 consequently represent passive load centres. Thus, Line 2-4 (purple on Fig.5.29) between them is considered as a reserve one and runs first into operation only if it becomes necessary i.e. in case of a fault with a need for an alternative power flow path to ensure system stability.



Under normal conditions Fig.5.30 after short ( $\approx 60ms$ ) transient period due to energizing process in Line 1-2 with peak about  $1,9 - 2,1kA$  currents stabilize at level of  $930A$ .

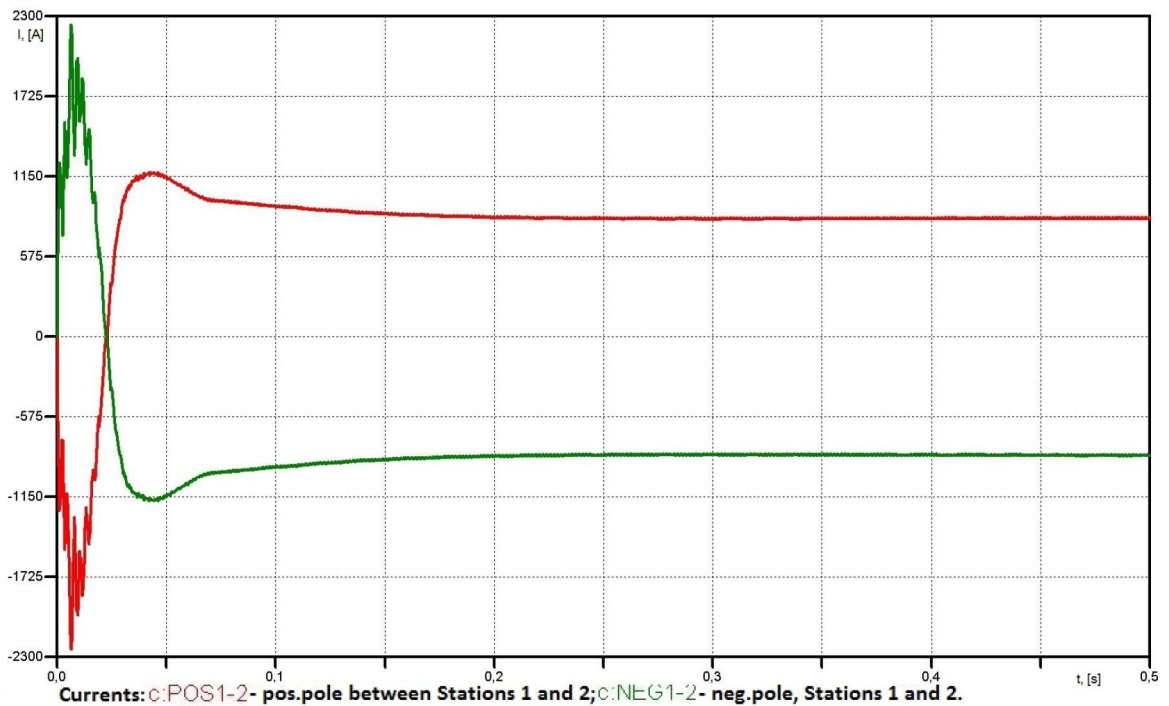


FIGURE 5.30: Meshed: Currents in Line 1-2. Normal Conditions.

At the moment, when the pole-to-earth fault in Line 3-2 happens, Fig.5.31, the Line 1-2 notes approximately similar disturbances few next milliseconds in both poles, but then the fault current in positive pole changes its direction and starts to increase rapidly reaching its peak of about  $7,4kA$  within next  $20ms$ , while the current in negative pole slowly goes back to almost pre-fault level of  $1110A$ .

In the faulty Line 3-2 itself, Fig.5.32, the emergency conditions appear to be far more extreme – here the faulty current in the positive pole reaches the maximal value of  $56,1kA$ , while the negative pole sees only minor disturbances and remains in operational limits.

On Fig.5.33 all fault currents flowing in positive poles of the whole five terminal *HVDC* system are presented.

Current distribution in all lines under fault conditions are shown on Fig.5.34 allowing to evaluate fault propagation in bi-pole lines and over all fault development in the *HVDC* multi-terminal system.



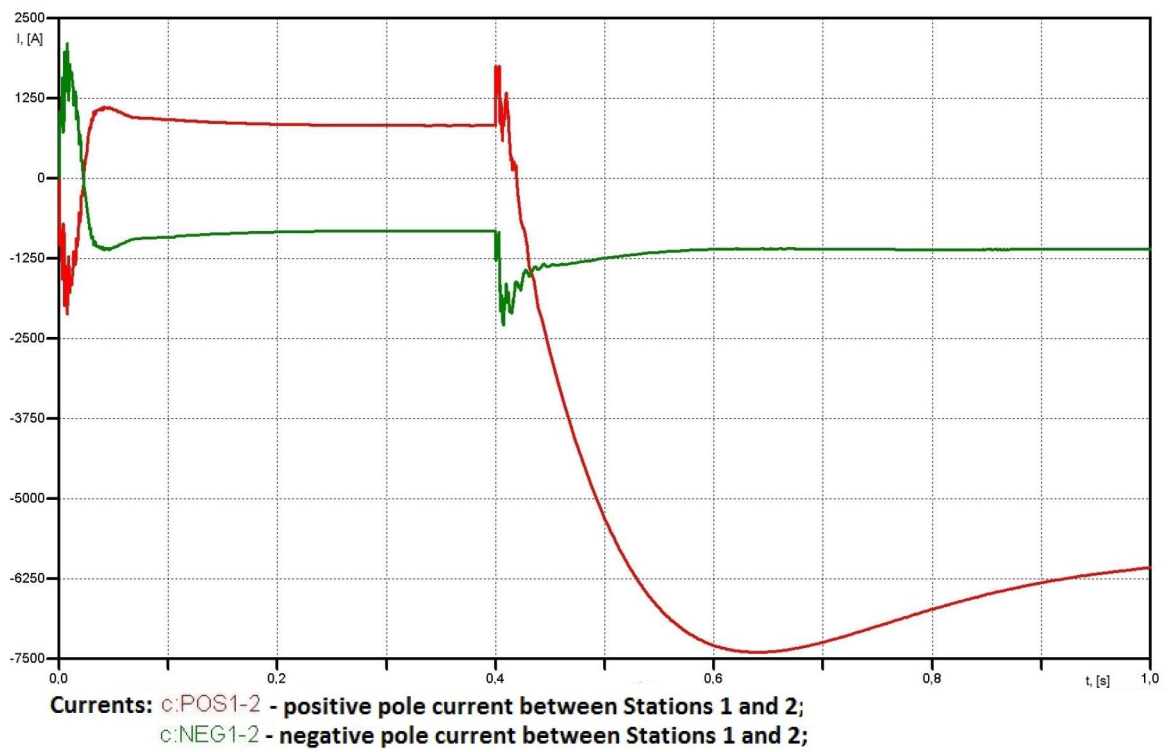


FIGURE 5.31: Meshed: Currents in Line 1-2. Earth Fault on Line 3-2.

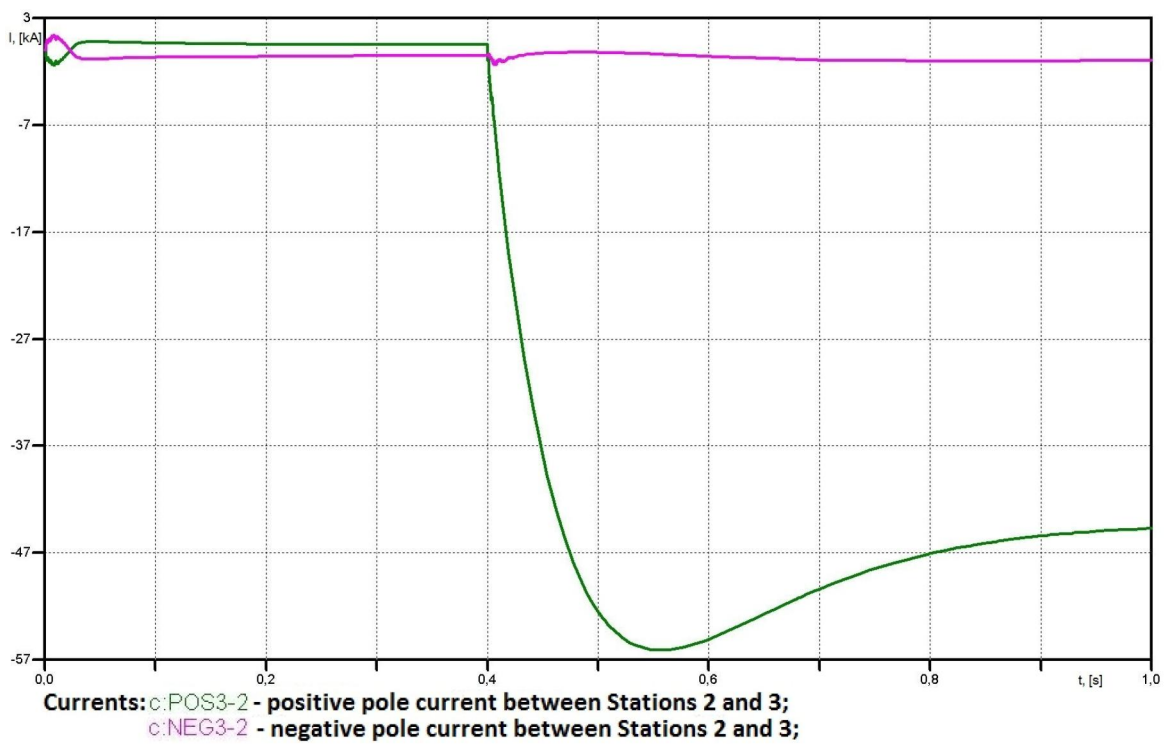


FIGURE 5.32: Meshed: Currents in Line 3-2. Earth Fault on Line 3-2.

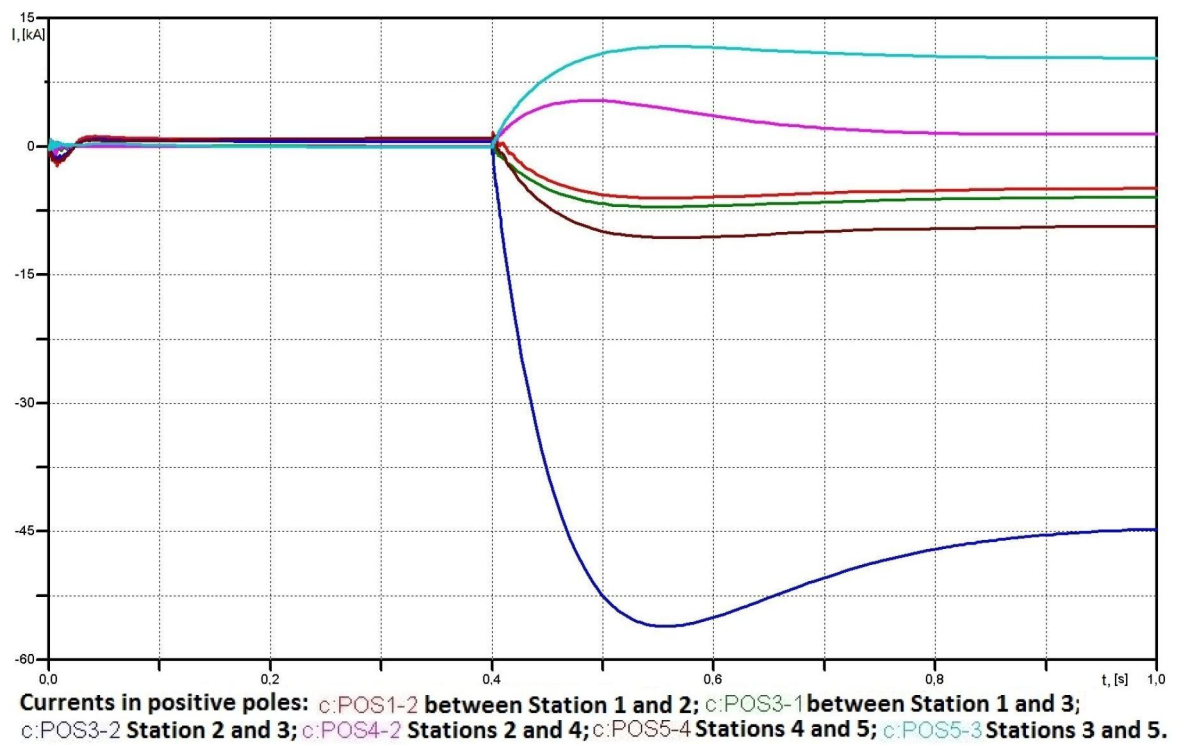


FIGURE 5.33: Meshed: Positive Pole Currents in the System. EF Line 3-2.

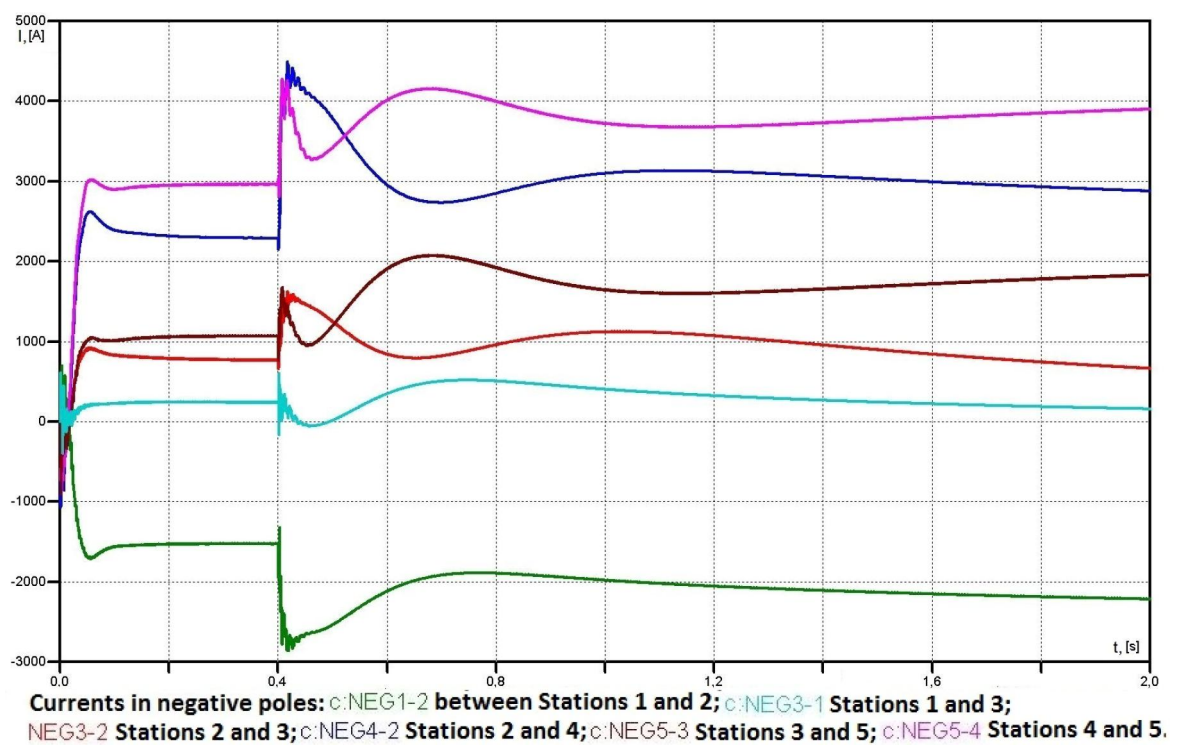


FIGURE 5.34: Meshed: Negative Pole Currents in the System. EF on Line 3-2.

In the next pole-to-earth fault case we will consider the situation with similar parameters, but different fault location, see Fig.5.35 anticipating a certain dissimilarity in system response to disturbance and fault propagation in comparison to the previous case.

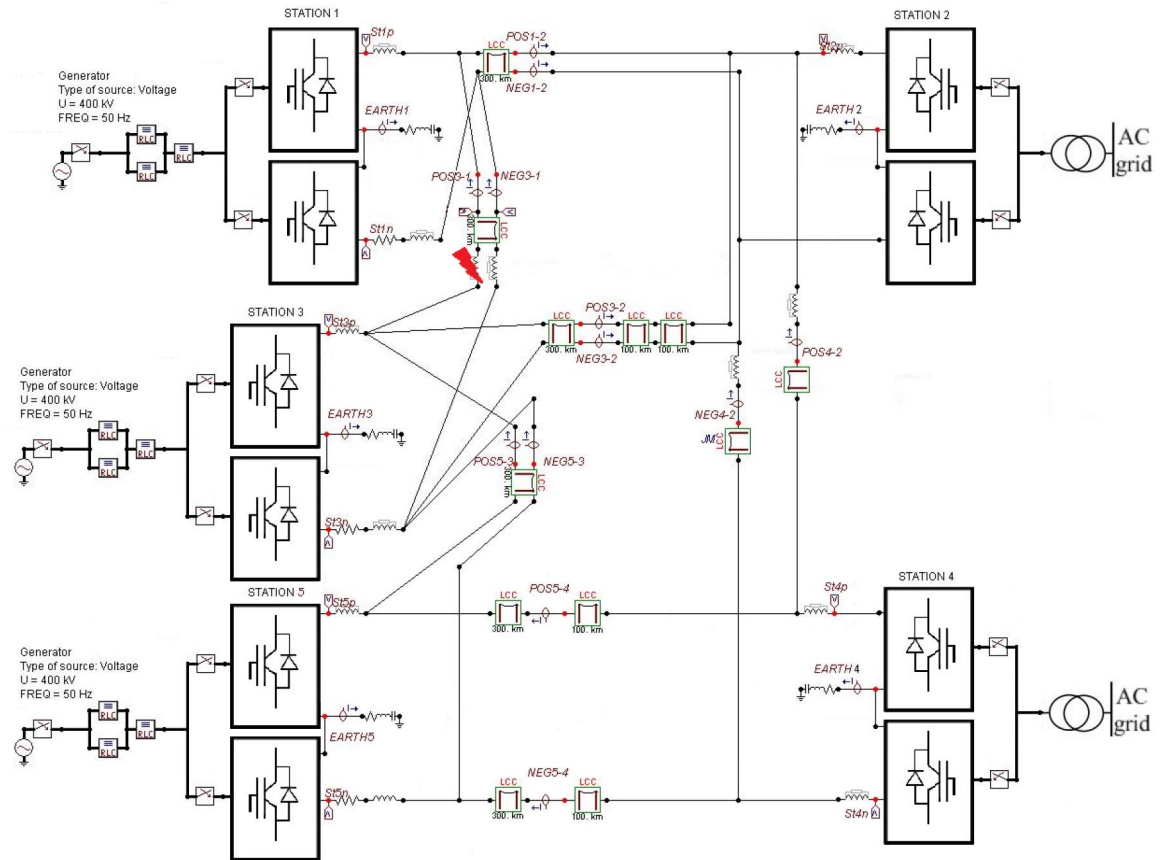


FIGURE 5.35: Multi-terminal HVDC Network. Meshed Configuration. Case3

Pole-to-earth fault in Line 3-1 causes remarkable destabilization in the whole *HVDC* system, what can be observed for example on Fig.5.36 where currents in the Line 1-2 neighbouring to the faulty Line 3-1 are demonstrated.

In comparison with the pre-fault situation, see Fig.5.30, the current in positive pole changes direction and grows from nominal 855A up to 28,7kA within next 150ms – the duration of fault current peak development.

Some disturbances in the range from 190,24A to 2229,1A are also observed in the negative pole of Line 1-2, but those could be safely handled by protection devices without interruption in operation.

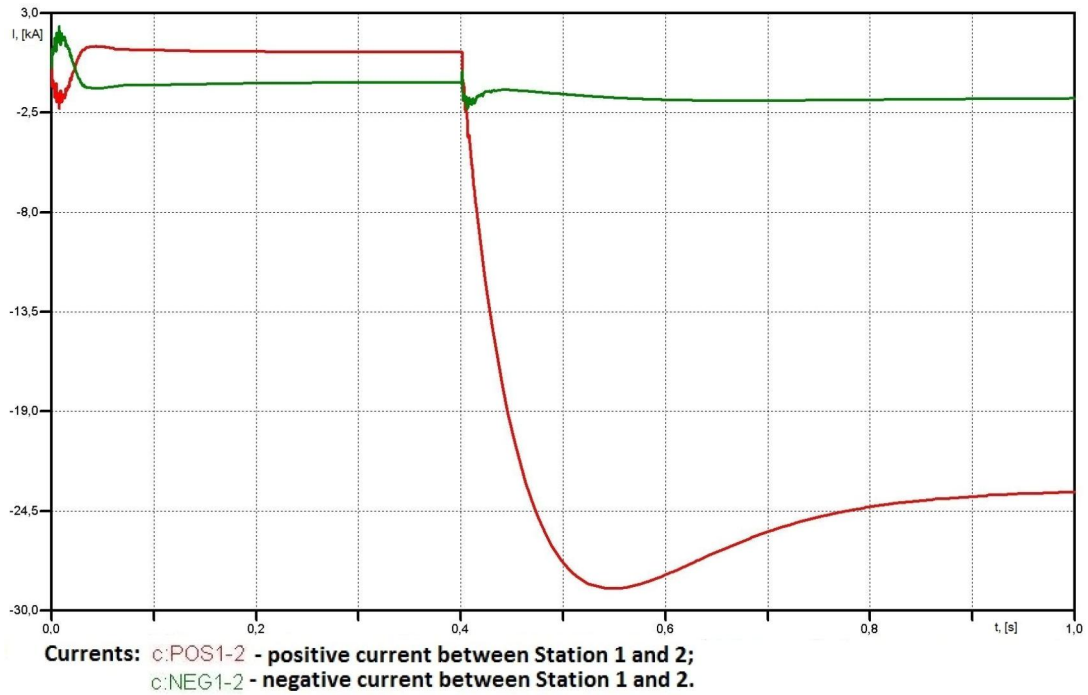


FIGURE 5.36: Meshed: Currents in Line 1-2. EF Line 3-1.

The other adjacent Line 3-2 also experiences well pronounced breakdown after-effects. Accident aftermath is expressed by positive pole current reaching a peak of  $11,3kA$   $140ms$  after the fault. After the fault the negative pole of Line 3-2 becomes almost as twice as much loaded in comparison with its pre-fault operational conditions i.e.  $520A$  before versus  $1040A$  after.

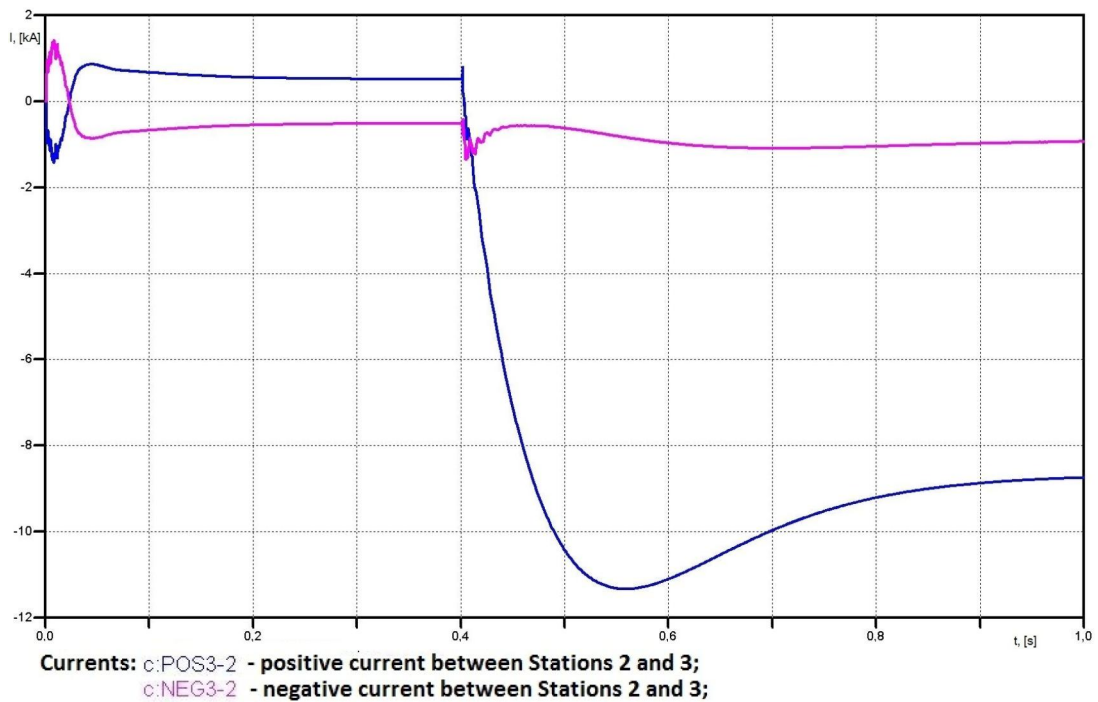


FIGURE 5.37: Meshed: Currents in Line 3-2. EF Line 3-1.

## 5.6 Summary

In this Chapter several different *HVDC* network topologies are considered starting from the most simple point-to-point connection gradually increasing in complexity to five terminal ring and meshed power grid configuration.

For all topologies the simulation results are presented as a plot of few states, namely, switching-on transients, pre-fault steady-state, pole-to-earth fault transients and new after-fault steady-state.

For all simulated cases the distributed parameter models of HV over-head lines are taken, in spite of the fact, that at least for the ring configuration an *HV* cable-based multi-terminal grid may be realised in the nearest future in the North Sea and, therefore, are of practical interest.

These results are claimed to be valid for cable-based grids too, with the only remark, that due to much larger capacitance of cables the fault current peak would be more pronounced.

In all models the *HVDC* grid operating voltage level is set on the level of 400 kV, what corresponds well to the analysis of present technologies, level of current grid development – at the moment this is the highest voltage level in the European transmission networks, and common sense expectations on the future *HVDC* power inter-exchange rates.

Pole-to-earth fault is taken as a basic scenario in all simulated cases, as statistically most frequent emergency situation, even though, recognising the fact, that pole-to-pole faults may cause more severe consequences. Ground resistance is assumed the same for all models and all locations and is not varied. This, however, may be a good point for further investigations.

Normal operation, fault current clearance and re-closing is modelled for *VSC* multilevel converter. As it follows from simulations, the converter is capable to break the short current safely within few next milliseconds after the fault.

Otherwise, due to the very steep  $di/dt$  short current quickly exceeds the level, when *IGBT* elements are not any more able to switch it off.

For the multi-terminal configurations it can be concluded, that pole-to-earth fault in one line propagates to the whole network without exception and within next 100 ms reaches its peak up to 50 kA.

Thus, special protective measures such as *DC* circuit breakers, fault-current limiters, control and protection system etc. are absolutely necessary.

It is also worth mentioning that, in case of bi-polar lines, the second pole of a faulty line, as a rule, experiences only minor disturbances and, thus, may still safely remain in full operation.

Overload level after the fault depends on pre-fault operational parameters and is a subject to optimal power flow regulation. As a result, bi-pole based *HVDC* networks are thought to have the greater rate of reliability, robustness and fault tolerance.

Ring topology, where all stations have two connections with other ones, is seen to be quite simple in construction and exploitation (i.e. power flow, control and protection etc.) and, obviously, requires less initial investments in comparison with meshed network configurations.

Nevertheless, due to lower reliability and flexibility to optimise power flow in the event of an accident, ring topology may become the less favourable option in the long run. The reliability and flexibility parameters could be fixed by adding one or few interconnections inside the ring getting more densely meshed network configuration.

For these reasons three various fault cases in the meshed configuration consisting of five *HVDC* terminals have been simulated. In comparison with radial or ring power network topologies, the meshed configuration offers such qualities as increased redundancy and overall system stability, higher flexibility in power flow control, and thus, lower operational costs. Higher ratings of transmitted power and opportunities for fluent power inter-exchange are also seen as positive and strong points of this topology.

## Chapter 6

# HVDC Network Protection.

In this Chapter some thoughts and general requirements that outline control and protection systems for future *HVDC* networks will be given. No operation of multi-terminal grid consisting of many complex units like sets of power electronic devices, switching equipment etc. is realistic without comprehensive and reliable control and protection system. The system that secures transmission network from fatal failures, unsafe operational environment and hazardous break-downs.

Having operated for already many decades in conventional AC grids protection and control with the common approach, it becomes still more and more clear, that in *HVDC* multi-terminal operation some fundamentally new principles should be considered, developed and applied in order to facilitate accident-free operation of an *HVDC* transmission network.

The present study does, certainly, not claim to be exhaustive, just the opposite, it is doomed to be incomplete, but still, talking about *HVDC* multi-terminal grids it is rather impossible to avoid such an important subject. At the moment there are several known prevailing principles that tend to give a solid basement for *HVDC* control and protection development.

However, some other promising techniques are under consideration too, and thus, are expected to be employed in future *HVDC* grid operation if they only show their full consistency of performance under various service conditions. Therefore, one of the very important points is to explicitly formulate requirements on *HVDC* network control and protection abilities as well as to make a thorough description of the completely new operational environment and tasks for newly developed principles and expected outcome of their operation at the initial stage.

## 6.1 HVDC Network Protection Requirements.

Drawing a concept for control and protection system of *HVDC* multi-terminal network several important aspects should be noted as a starting point for further development. General requirements on *HVDC* protection system to the great extent correlate with the well-proved AC protection system requirements.

First of all to be mentioned is the ability to fast enough and reliably detect vulnerabilities in the system that may bring some elements or the whole network to unexpected shut-down. Vulnerabilities detection shall go along with precise fault location, so that a prime cause of fault could be neutralized and equipment separated from stressing factors in a controlled way.

Control and protection system complex arrangements should constantly monitor the situation and be able to differentiate various conditions on the base of information collected. Still, protection system topology needs to be designed with a certain redundancy. Main protection zones may in some points overlap each other, what shall certainly not result into overlapping of activities and double response time required to detect and isolate the fault in a power system.

Thus, an arrangement depending on fault case may foresee several protection layers i.e. fast, but limited protection zone or expanded zone with the relatively slow response, or a complementary compromise between both options, when and where it is accepted in full accordance with actual operating conditions and requirements.

The main protective layer can be additionally supported by less sensitive protection algorithms serving in a system as a backup function. To make an important input to the improved adequacy all or part of backup functions should be desirably built on fundamentally different measuring principles. Protection functions should serve as a backup for as much part of main protection zone as possible covering at least all crucial nodes of transmission system.

However, this arrangement with main and backup function is not universal and for those cases, where it cannot be so easily applied, the most important and substantial elements and functions of protection system should be obviously redundant.

Protection selectivity should be taken into account to reduce false activation of protection system in one pole or in one converter when the fault happens and action is required only in another pole or another converter station. Thus, in the case of multi-terminal operation all necessary steps need to be taken to ensure minimal effect on the system by forced outage and to keep maximal possible power transmission ratio through unaffected parts of transmission system.



In the process of continuous monitoring, all the parameters essential for protection system should be recorded and stored for further analysis, which is very useful in case of emergency situation. In complex *HVDC* multi-terminal transmission networks it may be advisable to set protection tripping with different priority and time.

Under normal conditions in the *HVDC* network a protection system is active on routine monitoring and data recording. All possible false activation causes at fault-free operation should be reduced to the minimum.

Communication channels responsible for emergency signal delivery on tripping activation of circuit breakers and protection at converter stations should be excessive. It is rational to arrange protection system in a way it allows running testing or maintenance procedures without risk for its stability and operational functionality.

Quite logically bipolar lines are considered for the future *HVDC* grid as a dominant solution especially for bulk and reliable transmission systems. Altogether, the above-written considerations are valid for bipolar configuration with some additional specificity.

The main point here is the need to separate related functions of protection for every pole. Any fault in one of two poles and consequent activation of control and protection system shall not disrupt the normal operation of the healthy pole.

### **6.1.1 N-1 HVDC Network Redundancy Philosophy.**

The amount of electric power carried by a bipolar line is rather huge. From the reliability point of view a bipolar line has certain advantages. Resilience is ensured by N-1 redundancy equation that means in the emergency event a failed element  $N$  has at least one additional element as a back-up ( $+1$ ). Back to a bi-polar line under failure conditions, a sudden loss of one pole can be in large part smoothly counter-balanced by taking some additional load by the remained in operation second pole.

Therefore, the N-1 protection philosophy is applied to only one pole not to the whole bi-polar line, as it would be by analogy with AC power transmission systems, where control system interferes for all three phases affected.

However, some aspects of proper protection system adaptation shall be considered with due diligence. Amongst others issues involve relevant control and protection system adjustments for common disturbances in AC system, that cause disturbances in both poles of a bi-polar line.

On the DC side such common disturbances could be connected with a common neutral bus or station ground, earth return via ground electrode, metallic return via low voltage

conductor and transfer breaker. Converter fault at one station of a multi-terminal system may activate protection procedures at other connected converter stations, what, from uninterrupted power supply requirements of transmission systems, is not always desired.

Thus, an adequate protection system for *HVDC* grid shall have several layers, when protection functions could be applied with high-definition and selectiveness. That necessitates the measuring and signal acquisition system on one pole to proceed separately and not be shared with another one. In addition to it, a protective algorithm should take into account more than one single parameter before tripping procedure is activated.

### 6.1.2 Converter Station Protection System.

*HVDC* converter station, as the key element of the *HVDC* system, requires a special focus on control and protection functions. Even though *HVDC* multi-terminal networks in a general way will be based on Voltage Source Modular Multilevel Converters, some aspects can be applied to the classic *HVDC* thyristor-based converter technology. The opposite is also true, innovative development of protection for *VSC – MMC* may apparently benefit from the valuable experience drawn upon many years operation of classic *HVDC*.

Main considerations are based on inherent characteristics of *MMC – HVDC* systems, related research results as well as on the preparatory system planning including such essential measures like surge arresters installation at the most vital locations. The primary task and the ultimate goal of control and protection system is to monitor in real-time the situation with key parameters (performance analysis), precisely detect potential hazards and vulnerabilities in the system and timely restrict them to the acceptable level. Only such faultless performance of operation sequences may guarantee a strong security for key equipment units.

Recently research on new protection schemes has become even more intensive. Though, a lot of efforts are invested mostly in mathematical models and analysis. As it is seen from now, it is just a question of time, when these newly developed schemes are applied in real projects. With help of numerical simulations, many critical issues can be examined from different perspectives and probably be solved. Not the least, numerical simulations in research and development help to save a considerable amount of money and time on very iterative and repetitive operations, especially in comparison with building real prototypes and testing them.

TABLE 6.1: Requirements on Converter Station Protection.

| Type of protection function  | Requirements. Description.   |
|--|--|
| <ul style="list-style-type: none"> <li>• Short circuit protection.</li> <li>• Short circuit protection back-up</li> </ul>                      | <p>On this protection level short current in valves and converter transformer DC side is aimed to be detected and cleared. As a reference for protection algorithm current measurements on AC side, pole of DC line and currents flowing in the neutral conductor may be used.</p> <p>Short circuit protection is considered to be a crucial one. Thus, it is suggested to backing-up this function for the secured system robustness.</p>   |
| <ul style="list-style-type: none"> <li>• Protection from voltage disturbance</li> <li>• Protection from voltage disturbance back-up</li> </ul> | <p>Voltage disturbances may be harmful because of dielectric stresses on the related converter equipment. This level of protection should be designed to hedge voltage disturbances in <i>HVDC</i> system by mutual interrelation with converter transformer. Tap changers interlocking restricts ideally no-load direct voltage.</p> <p>Protection algorithm is based on the correspondence between the measured <i>AC</i> bus voltage, <i>DC</i> voltage, frequency and tap changer position. Protection from voltage disturbance also requires a solid back-up.</p>                                     |
| <ul style="list-style-type: none"> <li>• Protection from commutation failure</li> <li>• Protection from commutation failure back-up</li> </ul> | <p>The aim of this protection level is to discern failures arising from improper commutation procedure. This possibly could be done by instant comparison of measured currents on AC and DC sides. In case of abnormal rise of DC current this will be immediately detected and all necessary protection functions activated.</p> <p>Commutation failures are considered as one of the maximum credible accident that may happen in HVDC system. Thus, function of protection from commutation failures is important for fault-free performance and evidently needs an advance back-up.</p>                |
| <ul style="list-style-type: none"> <li>• Over-current protection on DC side.</li> <li>• Over-current protection on DC side back-up.</li> </ul> | <p>Valves on converter station and other power electronic equipment might be very sensitive to over-current peaks, which present two threats simultaneously: over-current itself and related to it overheating. Therefore, protective algorithms should control currents in AC conductor and the neutral bus and to constantly monitor temperature cooling agent (air, water etc.).</p> <p>Due to high over-current vulnerability of power electronic devices and over-temperature conditions the related protection function plays an important role and needs to have parallel reservation on board.</p> |

### 6.1.3 Requirements on Over-Head Line Protection.

High Voltage Direct Current transmission links are characterised by considerable length, large amount of power transmitted, what is attended with high voltage and large capacity. It is especially true for *HVDC* cable connections. Therefore, *HVDC* protection system operating environment presents, to some extent, similarities with long lines *AC* protection and, at the same time, certain specifics, which are typical only for the multi-terminal *HVDC* technical solutions.

A special attention is to be paid on the fine precision faults differentiation based on various protection algorithms and high degree selectivity, what becomes important on developing point-to-point DC links into the meshed network. These points at the moment present a real challenge on the way to well-functioning protection in a *DC* system.

Fast fault detection, localization, classification and clearance are required for secure operation in multi-terminal *HVDC* network. Flexibility and high adaptability of protection should allow its smooth functioning whatever concept or complementary configuration of them would be applied.

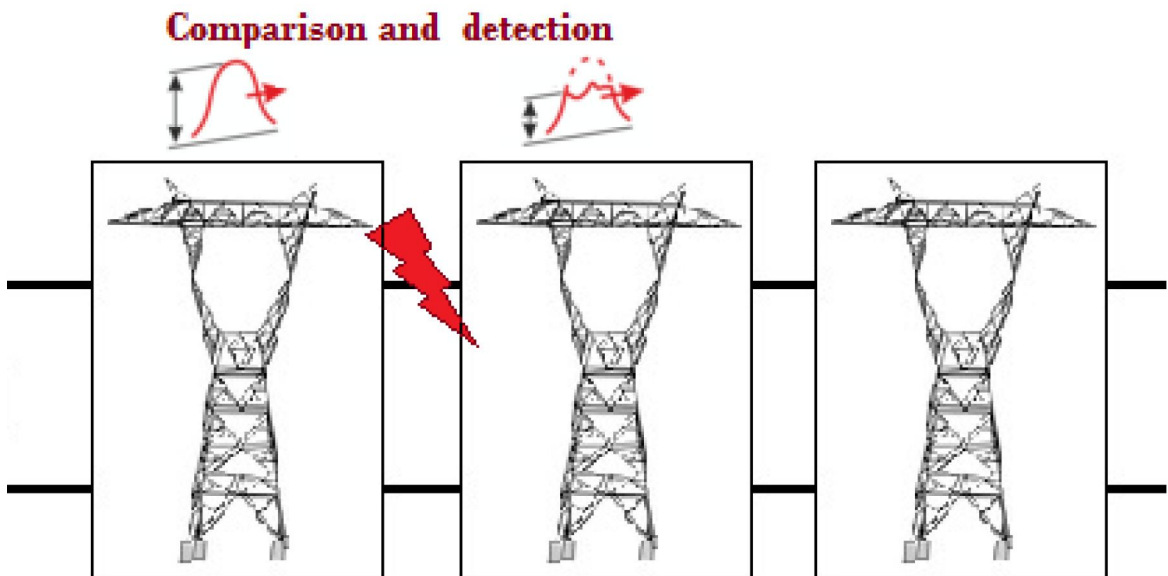


FIGURE 6.1: Comparison and Detection of Fault in OHL.

TABLE 6.2: Requirements on Over-Head Line Protection.

| Type of protection function  | Requirements. Description.   |
|--|--|
| <ul style="list-style-type: none"> <li>• Protection from DC voltage deviation.</li> <li>• DC voltage deviation protection back up.</li> </ul>    | <p>The main function of this protection is to define any voltage deviations from reference voltage in both directions: over- and under-voltages on DC line poles. The key control parameters like DC pole voltage and DC pole current have to be constantly measured and processed.</p> <p>The zone of responsibility is spread on converter station valves and all primary equipment that are subjected to voltage deviations. As it is, critical for normal HVDC system functioning this type of protection needs a solid back up.</p>   |
| <ul style="list-style-type: none"> <li>• Protection from harmonics with line DC filters.</li> <li>• Protection from harmonics back up</li> </ul> | <p>In case of network disturbances or valve units malfunction a converter station may produce undesirable harmonics, that will spread along the lines over great distances and may become especially troublesome for proper function of control equipment and power electronic devices at any point of multi-terminal network.</p> <p>This type of protection is designed for abnormal DC harmonic detection. Filter elements should be selected in a way to match DC filtering for the fundamental frequency and harmonic effect reduction.</p>   |
| <ul style="list-style-type: none"> <li>• DC line protection from earth fault.</li> <li>• Line earth fault protection back up</li> </ul>          | <p>A major concern of such protection algorithm is to timely detect earth fault and take whatever measures are necessary to eliminate potential harm. The operational sequence, though depends on conditions, is seen as timely revelation of a fault at the first stage, followed by protection measures activation to quench the faulty current, isolate affected area and then, when it is applicable, to restore the power transmission operation.</p> <p>Linear DC circuit, DC voltage on the pole and their interrelation will serve as main indicators to evaluate operational status and should be constantly measured and controlled. Duplication of this protection function is advisable.</p> |
| <ul style="list-style-type: none"> <li>• Neutral electrode equipment protection.</li> </ul>  | <p>Dielectric stresses to which neutral electrode equipment are periodically exposed during the long-lasting period of time, when the neutral electrode circuit is open, may considerably reduce equipment service life and cause increased insulation deprecation. This harmful influence of dielectric stresses on neutral electrode equipment protection shall be minimized. To cope with this task a separate protection algorithm monitoring current and voltage in a neutral electrode should be introduced.</p>   |

Table 6.2: Requirements on Over-Head Line Protection. Continued.

| Type of protection function  | Requirements. Description.  |
|--|---|
| <ul style="list-style-type: none"> <li>• Blocking procedure from DC filter overload.</li> <br/> <li>• Blocking procedure from DC filter overload buck up.</li> </ul> | <p>This protection procedure is aimed at timely detection of extra load stressing of DC filter components to prevent a potential failure. An exhaustive estimation of present state at any moment can be performed with reference to current flowing in RL-filter element and resulting current in the whole <i>RLC</i> oscillative circuit in filter unit.</p> <p>In case of substantial overload in these two branches an additional extra current will be automatically detected. In addition to it, any extra current will be inevitably accompanied by subsequent rise of temperature in inductive and resistive components, what can also be sensed to support secure decision making process and trigger measures activating protection system. Depending on converter technology applied <i>DC</i> filter may play a core role providing required power quality and stability. Thus, it is desirable in certain cases to duplicate this protective routine.</p> |

Some additional measures on *DC* equipment protection may include line impedance control, transfer breaker protection and protection of station ground from over-current. The latter is applied mainly to limit the current that may flow in a path between line, neutral bus and converter transformer. Line impedance control is accomplished through sending a high-frequency signal into the line between reflecting ends (filters). The line impedance is calculated based on reflected waves response.

Wide acceptance of fast and sensitive electronic devices open the way for rather new approaches to protection in *HVDC* transmission grid. Some key solutions may lie in the area of transients processes analysis when applied to large *DC* systems.

Respective magnitudes of voltage and current, the specific character of waveforms - rate of  $\frac{di}{dt}$  current or  $\frac{du}{dt}$  voltage growth, frequency etc. are significantly related to the network configuration.

Through numerical simulations it seems reasonable to get a clear understanding what typical characteristics would have this or another type of disturbance or fault in transmission network, what in turn shall considerably help in developing protection principles and algorithms. Therefore, properly adjusted sensitive electronic devices, that are responsible for monitoring and collecting network data, may be able to timely detect and adequately deal with many emergent situations.

### 6.1.4 Requirements on Protection of HVDC Switchyard Equipment.

TABLE 6.3: Requirements on Protection of HVDC Switchyard Equipment.

| Type of protection function   | Requirements. Description.   |
|---|--|
| <ul style="list-style-type: none"> <li>• Earth fault protection for metallic return conductor.</li> </ul> | <p>This type of protection performs the function of monitoring a current that flows through the earth at the grounded switch-yard. The protection algorithm is immediately called into action promptly upon earth current detection, what is understood as an earth fault on the metallic return conductor. If for protective grounding measures a grounding switch is foreseen, then the grounding switch current is a parameter of monitoring. If protective grounding is realized as grounded electrode conductors, then corresponding currents should be of interest.</p>  |
| <ul style="list-style-type: none"> <li>• Differential protection in neutral of bipole.</li> </ul>         | <p>This protection is enabled when switch-yard metallic return is not operating and is aimed at detecting a differential current. Within a switch-yard protection zone some preset values for normal operation and earth fault conditions are determined. When differential current rises, this is understood by protective logic as a faulty conditions and all necessary actions shall be instantaneously taken to fence off the drastic consequences. Important signal values to be monitored are currents on metallic return, the station grounding point and two poles, and, consequently, the reproduced correlation between these measured currents.</p>                              |
| <ul style="list-style-type: none"> <li>• Lengthwise differential protection.</li> </ul>                   | <p>Lengthwise differential protection may consist of two sensing elements that measure currents at both ends of cable or line conductor. On the base of these measurements a built-in logic element differentiates normal and fault operation conditions. This arrangement necessitates a constantly secure communication pathway to receive and process values and send commands on protection activation. For very long lines sampling time difference shall be taken into considerations. Under all other things known and constant for overhead line or cable, a certain peak value, character of fault current rise and its shape may be informative and helpful in fault location.</p> |
| <ul style="list-style-type: none"> <li>• Line unbalance control</li> </ul>                                | <p>A predefined level of current complying with normal operational mode is chosen as a reference point. Currents on two poles of a bipolar line are measured to be compared with a reference current. If any of them reaches a maximum and becomes higher fault conditions are assumed.</p>  |

## 6.2 Some Aspects of HVDC Protection Implementation

Protection and control usage in future *HVDC* grids will depend to a high extent on grid topology, as well as interruption capability and presence of fast and reliable *HVDC* circuit breakers. The latter will ensure clearance of a DC fault within acceptable time scale. However, the role of *HVDC* circuit breakers may vary depending on control and protection concept to be applied in the particular *HVDC* network topology.

As it is described above in Subsections 6.1.2, 6.1.3 and 6.1.4 and in consequent Tables 6.1, 6.2 and 6.3, protection and control algorithms may rely on measurements of main indicators – current and voltage, applying direct sequence procedure. The direct sequence includes particularly a constant data processing, fault detection, sending a tripping signal, fault clearance operations. This direct sequence with the same consistent operations is an iterative cycle through several states: “normal operation - fault conditions evaluation and clearance - successful re-closing back to normal operation”, but with the successful re-closing in the end brings the operational mode to the logical end point.

These schemes, philosophy and principles have been widely used in conventional *AC* systems. To some extent, they can relatively easily be reassigned and then applied in *DC* systems too. However, with all remarkable advantages of many years experience, well-known operation activity and experience transferable to the new *DC* area, many bottlenecks will appear there as well and due to some specific *HVDC* network conditions even in amplified form. So, what aspects of *HVDC* protection implementation should be considered anew?

First of all, dealing with very short tripping times may not always be as easy in *HVDC* as it used to be in conventional *AC* grids. This can be explained by a few simple considerations. In the *AC* system a transient overload, that is inherent to synchronous machines, sets a certain time gap for protection to manage the situation with minimal possible losses.

In contrast to it, in *HVDC* systems power electronic devices are considered as the weakest unit exposed to risk in the whole DC system. Thus, supplying converter stations have very limited capability to stand against overloads and normally block any potentially dangerous deviations by internally inbuilt protection very rapidly. The converter fault blocking function is a very crude tool from the selectivity point of view and results in a temporary loss of all *HVDC* lines attached. Therefore, in case of a multi-terminal network configuration, it would lead to the loss of significant part of the whole network, what is hardly acceptable.



In such case, selectivity has a very low resolution and significant part of network loss becomes unavoidable until a fault is isolated or cleared. This makes the time window for the proper reaction of protection system notably short, as it has to compete with fast by default internal converter protection and be at least one step ahead or have priority.

The second issue, which is very specific to *DC* systems only, is the absence of natural current zero. In many applications a natural current zero is used as an optimum on energy costs to trip fault current.

As the DC current never crosses zero, the fault current rises right from a certain non-zero level and, consequently, accumulates greater energy within its development phase. The accumulated energy of a *DC* fault can roughly be estimated as an integral function of voltage and current (power) and time (duration of fault) values.

The accumulated energy evidently would have to be dissipated in the system, presumably by means of *HVDC* circuit breakers or other additional and specially arranged equipment. This addition would demand, in its turn, the more complicated *DC* network configuration making it, therefore, more costly and less reliable.

As the current in a *DC* system is non-zero and constant by default, it is of optimization interest to limit the time (duration) of *DC* fault development. Thus, it is very desirable that protection algorithms would intervene into a process of *DC* system fault development as early as possible. In this way, a protection system would be able to hedge the amount of burst of energy associated with a *DC* fault and possibly minimize energy dissipation demand.

Another aspect that is worth mentioning, is an immanent to *DC* networks faster system response, which in comparison with *AC* grids does not substantially limit a fault impulse and lets it spread rather rapidly across the whole *HVDC* grid. Then, these considerations above push the requirements on protection system speed towards rather a short reaction time within just a few first milliseconds.

As speed, selectivity and sensitivity along with security concerns remain to be main priorities for protection and control system, there are at least two different approaches, which can be considered as a separate and still viable solutions for future *HVDC* grids.

### 6.2.1 “Open-End” Protection Concept.

The first approach is tending to have very much in common with classical AC protection and can be named as “open-end protection”. As it follows, protection algorithms here are based on the data gathered at one point in the system, exactly where this protection has been applied. See Fig. 6.2.

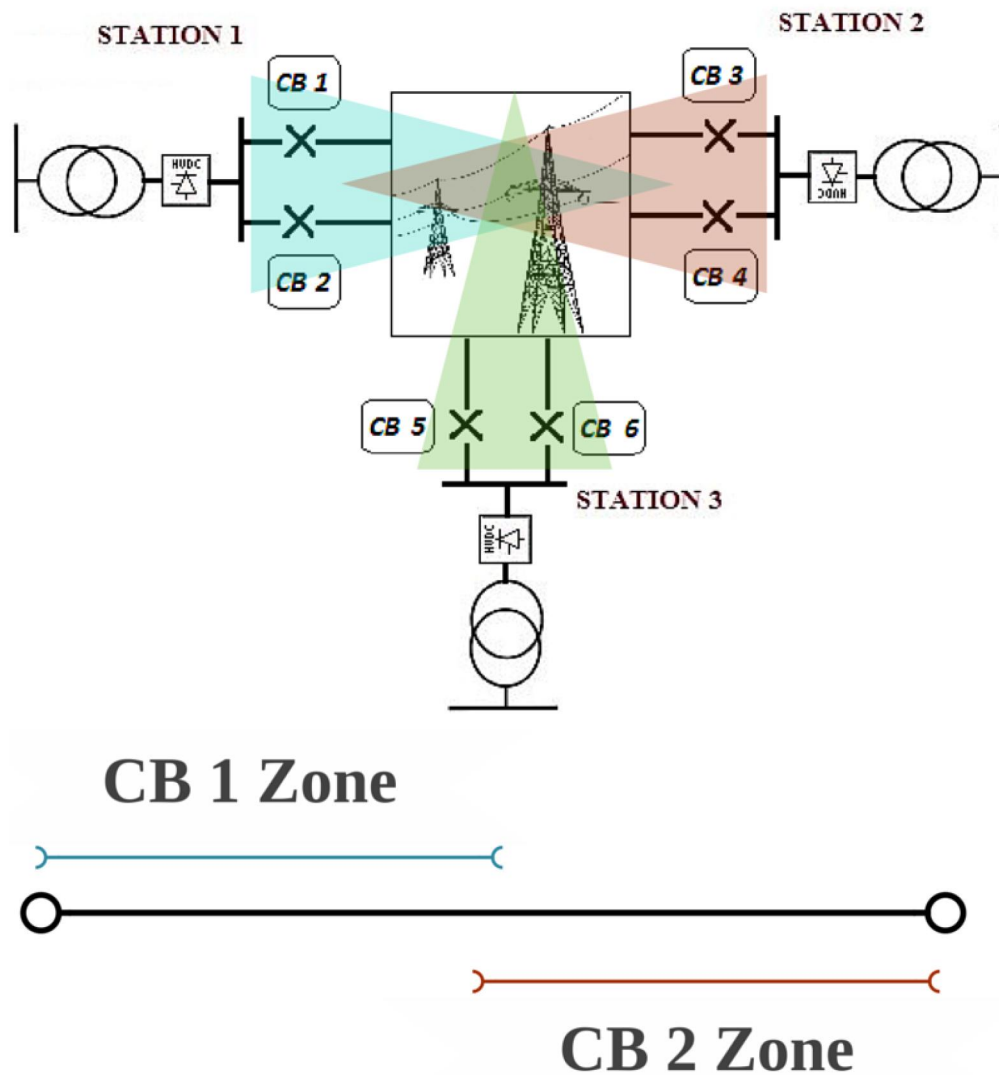


FIGURE 6.2: “Open-End” Protection Concept.

In Tables 6.1, 6.2 and 6.3 some of the aspects on protection system requirements have been discussed. From there it can be concluded that various protection algorithms such as distance protection and over-current blocking protection basically rely on “open-end” protection approach.

For the “open end” protection concept no additional communication devices and dedicated communication bus to transmit signals are required. This concept is secure and

reliable due to its apparent simplicity, what has certainly a positive distinction to minimise installation and maintenance costs.

Moreover, in *HVDC* systems, where transmission link lengths are supposedly much longer than in AC systems, an issue with time delay, that influences speed of signal transfer and, consequently, protection reaction quickness, becomes very acute. In "open-end" concept this issue is resolved by applying measuring, processing and tripping functions altogether at one local point. With all that said, the "open end" protection concept will likely dominate in ultra-long *HVDC* transmission links, where otherwise time delay may exceed reasonable limits within the first ten milliseconds.

Reliability of protection is not exposed to any risks due to possible communication malfunction or failure. However, the "open end" protection concept lacks certain explication and in particular cases is not able to provide the desired selectivity.

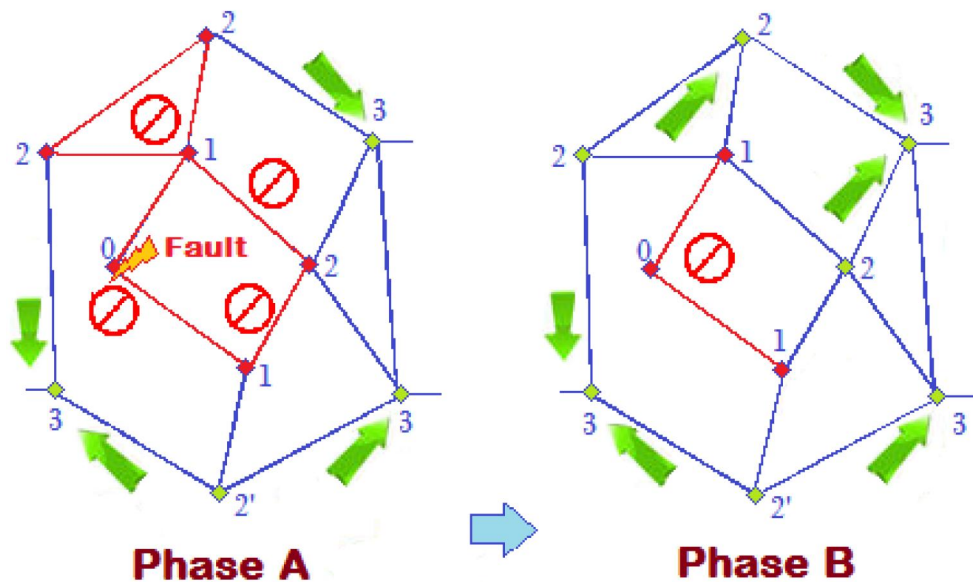


FIGURE 6.3: "Open-End" Protection Operation.

On the Fig.6.3 the basic principle of the Open-End protection concept is shown. Phase A begins immediately on detection of a fault at one of the terminals. For the reference the faulty terminal is marked as terminal "0".

Those terminals that are connected directly to terminal "0" by over-head lines, cables or bus-bars experience big stresses under fault conditions. On detection the potentially hazardous conditions by protection algorithms an emergent disconnection procedure is consequently activated in the system. These affected terminals are marked as terminals "1".

Depending on the protection system pre-settings any vulnerability in second tier terminals "2" could also lead to disconnection from the network. In order to provide uninterrupted operation some terminals marked as 2' and located in crucial for transmission network points could have less sensitive pre-settings to remain in operation nevertheless.

Phase A with the open-end protection concept should take just a few milliseconds to detect a fault and securely block its development preventing black-out of the whole transmission system. The power flow under fault conditions in Phase A is shown in green arrows leading to load terminals "3".

Phase B is the "intellectual" phase for protection system logic. During Phase B it is supposed that the protection system would precisely sense and locate the fault. Based on measurements a decision-making algorithm should send a command for the re-closing of terminals that are out of danger. This will lead to system reconfiguration. The power flow shown in green arrows regains its pre-fault level in the newly reconfigured system.

### 6.2.2 “Closed-End” Protection Concept.

“Closed-end” protection concept is the second one to be considered. To apply the “closed-end” protection concept current and voltage parameters need to be measured at both ends of the safeguarded zone, see Fig. 6.4. Current differential, phase fault protection and other algorithms based on directional comparison may well illustrate the “closed end” protection concept in practice.

“Closed-end” protection concept has been applied and very common in most power systems, both in conventional AC grids and point-to-point *DC* transmission.

Since measurements are being done at two ends at once, a robust coordination between measuring devices and their interconnection via reliable communication channel are needed.

This condition makes application of the concept more complicated in *DC* systems as compared with *AC*, where the fault current is normally limited by highly reactive system impedance. In *AC* networks it gives enough time (some tens milliseconds) for detection, making a decision and sending a tripping signal, if appropriate, to current breakers.

In *DC* grids, just the opposite, system impedance is low and has rather active resistance component. Thus, the conditions for the protection operation and fault clearance are significantly worse. Overall time for protection reaction accounts in best case not more than few tens milliseconds only.

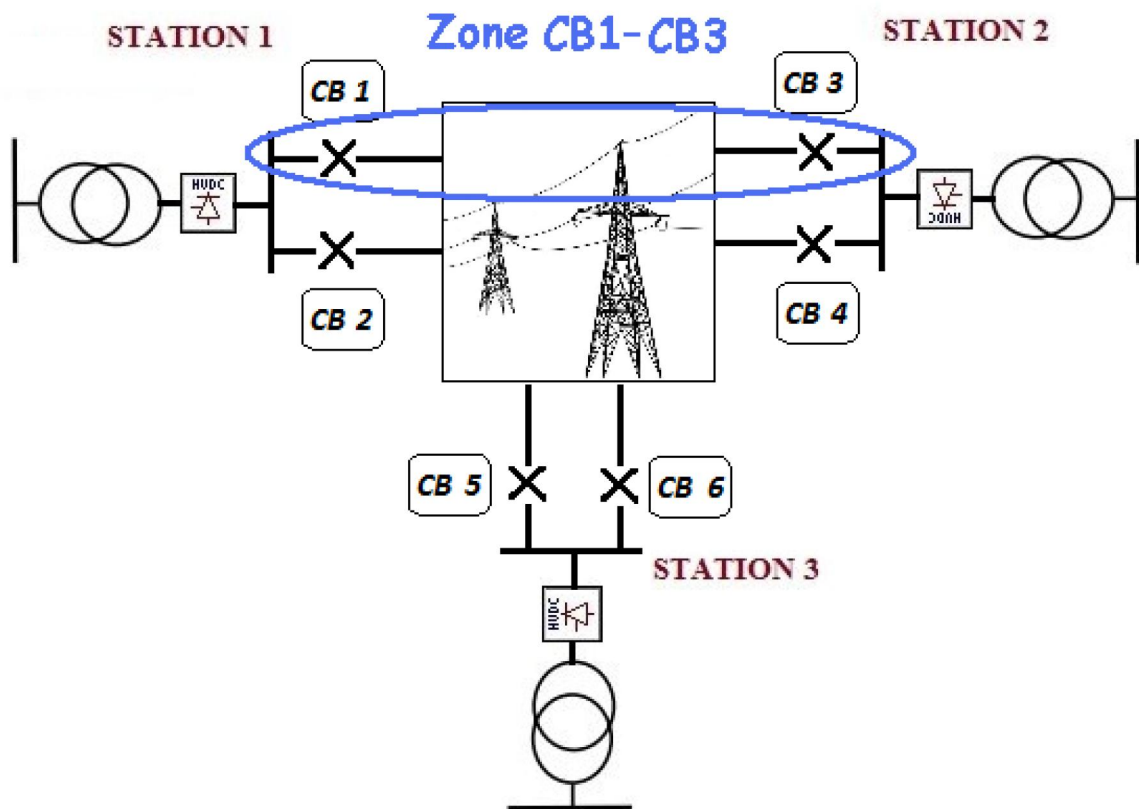


FIGURE 6.4: “Closed-End” Protection Concept.

Therefore, due to relatively high time delay this type of protection is recommended for transmission links of up to few hundred kilometres, what perfectly suits to the vision of future multi-terminal *HVDC* network with the mesh size of approximately 300 – 500 km.

However, immanent properties of this arrangement make the “closed end” protection concept irreplaceable in terms of selectivity in highly meshed multi-terminal networks, what cannot be provided by “open end” protection.

As one may see from AC network performance, “closed end” and “open end” protection concepts may be successfully implemented on different layers in the same transmission system simultaneously.

Logically, the supplementary combination of these two protection types presents a legitimate solution, that may compete with or complement “converter fault-blocking” approach, which foresees absolutely no usage of *HVDC* circuit breaker in the power system.

### 6.2.3 Fault-blocking Converter Concept

Point-to-point transmission links, as it was already mentioned, have control and protection algorithms that very well recommended themselves in terms of reliability. They are already well described and known and have been proved in many-years practice. The basic regulation principle for these algorithms rests upon the ability of converter to control current and voltage. In other words, when one station is assigned for the control of DC voltage, the other one is responsible for the DC current regulation and, therefore, controls the DC power.

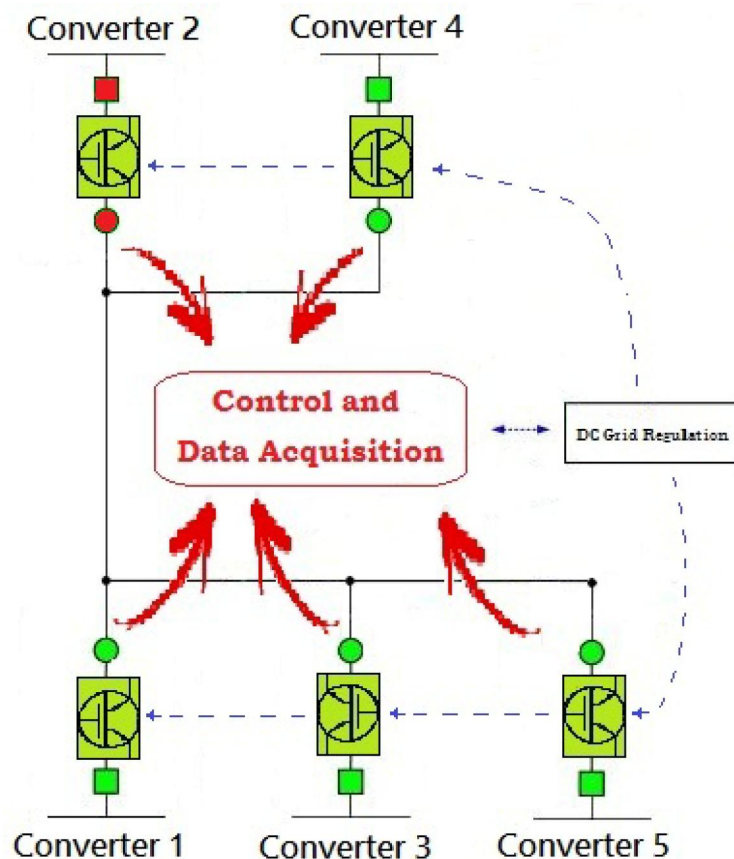


FIGURE 6.5: Fault-blocking Converter Concept.

This regulation principle is very simple and common, as it could be applied regardless of the used semiconductor technology in the respective rectifier and inverter station. Should the network configuration change, all necessary adjustments have to be immediately done at both ends of regulating converters.

In a desirable manner this adjusting procedure takes place automatically through a fast coordination loop between the control units of the respective stations. However, manual intervention into coordination and adjusting procedure has been also envisaged and can be activated in certain emergent cases.

In contrary to point-to-point connections, the multi-terminal *HVDC* network will inevitably pose some fundamentally different demands on the fault-blocking concept. Some of these points can be listed as following:

- *overall control and protection strategy* has to be developed for large number of terminals to be controlled smoothly and reliably. Appropriate control strategy shall be applied to all converter stations involved what includes instant coordination between stations to control DC voltage and current/power.
- *flexible extension* of multi-terminal *HVDC* grid shall be foreseen and be a certain advantage. At any point of time and network a conflict less incorporation or disconnection lets maintain reliable and flexible operation. This, however, shall not necessitate deep changes in control and protection algorithms of any substations that are already in operation.
- *full-featured and comprehensive justification* shall be reached through coordination loop in case of planned or unplanned changes in *HVDC* network configuration. Fast adjustments are destined for complete fitting of the most important control parameters and compensation of power flows after grid reconfiguration.
- *converter technologies* in large multi-terminal *HVDC* networks may significantly differ from one to another. Therefore, overall control strategy should aim to get full conformity in all stations not depending on producers of power electronic units or converter technology applied.

Under normal conditions in an *HVDC* grid every *AC/DC* converter allows to control instantly the power flowing to and from the *HVDC* transmission system. In this way the over-current protection could be easily performed as it is possible to limit the current within nominal operation values or to bring it to zero.

### 6.3 Protection Principles.

Protection principles differ fundamentally by the nature of their operational concept. When protection embraces an ability to operate with characteristics of voltage and current parameters in steady-state regime, this protection is classified as a steady-state based protection.

The another option is when protection algorithms use characteristic difference of current and voltage parameters to perform the tasks under transient conditions. This type of protection is referred as “transient-based protection”.

In contrast to *AC* transmission systems, where it is still possible to implement protection algorithms based either on steady-state or transient processes, due to the nature of alternating current, in *HVDC* transmission, as it has been already mentioned, the steady-state approach is of little value.

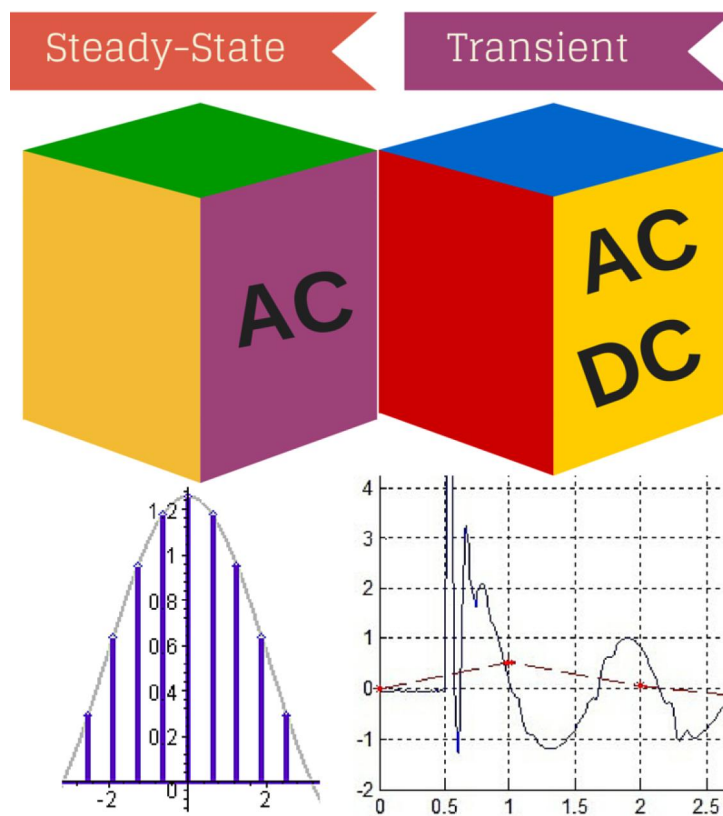


FIGURE 6.6: Steady State and Transient Protection Principles.

Even though the steady-state based protection is the most commonly used in *AC* networks, it cannot be just as easy applied in meshed *HVDC* grids. The main reason for it, is that the Fourier-transformation of the constant steady-state DC current does not allow the internal protection logic to draw a solid distinction based on incoming signals.



Therefore, determine and manage the fault. Since the duration of transient processes in *HVDC* systems is longer than in *AC*, transient-based protection presents the only feasible solution with the conventional approach to this problem.

To detect the presence of a fault in a network during transient processes a fair number of samples should be taken to allow a protection algorithm to distinct clearly between external and internal nature of the fault and based on these measurements decide on the next steps. The larger number of samplings need to be collected the longer time window is required, what eventually has an impact on the protection function speed.

If a sampling rate for *HVDC* transient-based protection function is assumed to be 100 kHz (e.g. 100 samples are collected per 1 millisecond) and the required fault clearance time is no more than 5 milliseconds, then the length of time window for samples collection is roughly equal to 10% of the required fault clearance time i.e. less than 0.5 ms. This time would be enough to collect around 50 samples at 100 kHz.

Build on samples collected a transient-based protection algorithm should be able to distinguish external fault from internal one and make a weighted decision.[82] If not, a sampling rate for *HVDC* transient-based protection should be reasonably increased.

In the remaining time of about 3 ms a signal would cover a distance ca. 450 km maximum in both direction between sensing ends. Thus, from this point, it may be concluded, that the "open-end" protection concept without a need to be connected to the second end might be much faster and reliable, what is more than desirable in future meshed *HVDC* transmission networks.

Even though several protection schemes find a common use in *AC* networks, the different operating conditions in *HVDC* networks make the transient-based open-end protection concept a primary one.

Based on considerations above and perspective protection philosophies, that are already on research and development stage, it can be concluded, that at the moment just a few out of a number of various protection concepts can be potentially considered and applied.

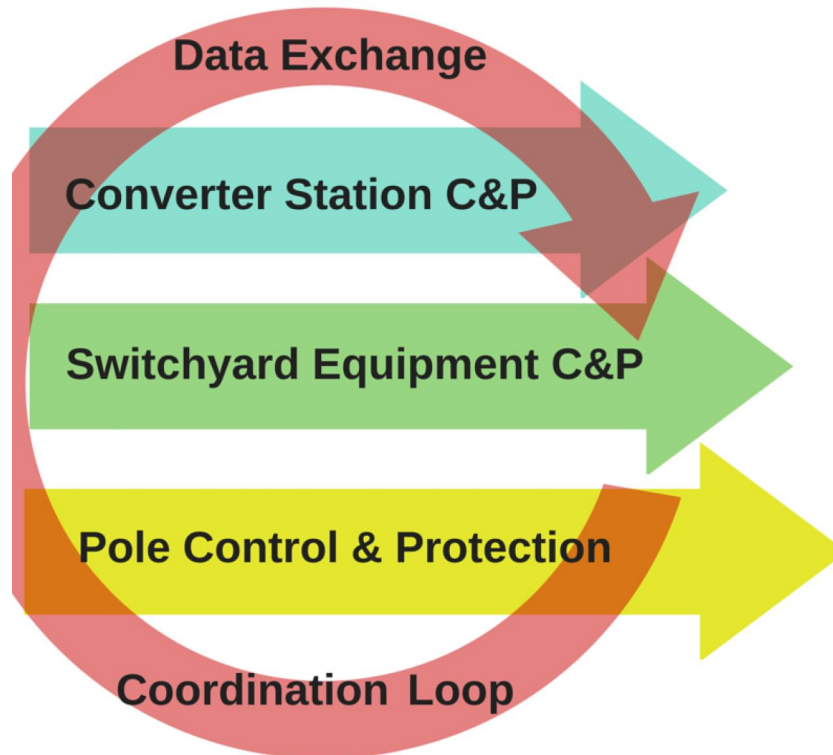


FIGURE 6.7: Three Levels of Protection System.

The primary protection, which is considered to form a backbone for *HVDC* protection system, may consist of several algorithms including, but not limiting to:

- transient-based direction-over-current relay;
- transient-based distance relay in combination with transient-based high-speed remote trip detection, which does not rely on communication between both ends.

The backup protection is an important auxiliary subsystem that could also include some other complementary types of protection algorithms, such as:

- transient current differential relay;
- transient-based directional comparison unit protection;
- transient-based distance unit protection together with a scheme relying on communication between the ends, etc.

All these protection philosophies are presently in the development stage, and there are already several patent applications in this field.

The alternative protection operational policy proposed recently is that a rapid fault location and tripping are possible with locally placed measurement devices at every essential node of a network.

If we consider conventional protection philosophy applied in *AC* networks, tasks execution sequence would be the following:

- **1 step.** A disturbance detection of measuring devices of protection system;
- **2 step.** Based on inbuilt algorithm protection detects whether this emergency event has evidence of an external disturbance or internal *HVDC* system fault;
- **3 step.** Localization of fault, to reduce a number of lines to be switched-off;
- **4 step.** Sending a tripping signal to related *HVDC* breakers;
- **5 step.** Fault clearance; in case of unsuccessful emergency tripping a job sequence should be repeated until a fault is fully cleared.

All in all, this protection operation sequence may last in *AC* systems several tens of milliseconds. In *HVDC* networks this is inexcusably long, as in that case *HVDC* breakers should have an exceptional ability to break rather high fault current far exceeding normal operation value by at least several times.

Again, the amount of energy to be dissipated in the system is rather high and suitable options on how to secure breaking capability, before it comes too far beyond of the level when *HVDC* circuit breaker is still able to interrupt, in this situation are not very clear.

The alternative protection policy suggests cutting the reaction time from few tens milliseconds down to just a few milliseconds by implementing local distributed measurements. Based on the measured data, in case of any vulnerabilities, all corresponding parts of the *HVDC* network will be cut off immediately, thus, allowing the *HVDC* breaker exceptionally favourable conditions to disconnect on early stages, when the current rise is not so pronounced and the associated amount of energy to dissipate is not very large.

So, in contrast to the conventional protection philosophy applied in *AC* networks, the suggested tasks execution sequence could be the following:

- **1 step.** A disturbance is detected by locally installed measuring device of protection system;

- **2 step.** Immediate tripping off / fault clearance without distinction under favourable for *HVDC* breaker conditions;
- **3 step.** Based on in-built algorithm a protection system detects whether this emergency event has evidence of an external disturbance or internal *HVDC* system fault;
- **4 step.** Localization of fault to optimize/minimize a number of lines to remain switched-off;
- **5 step.** Sending a command signal to related *HVDC* breakers for re-closing;
- **6 step.** Returning to normal operation of healthy lines; in case of unsuccessful re-closing a job sequence should be repeated until a normal operation of healthy *HVDC* lines is fully established.

In a meshed network with several breakers a usually fast *DC* fault propagation will be apparently limited within time reaction of the nearest ones. The located on a distance *DC* breakers will not sense any sufficient disturbance and, thus, will remain in the closed position.

Back to the short reaction time of protection algorithm, this strategy has certain advantages. However, it should be still tested in practise, especially, when it comes to organizing a robust meshed *AC/DC* network with *DC* breakers in it. Anyway, these both are not yet an event instance and their practical realization is still a question of time and development.

The simulation results Fig.5.5. show that in the course of approximately 75 milliseconds the fault current reaches approximately 50 kA with a very steep  $\frac{di}{dt}$  curve. This implies a very high current interruption ability, a need to create a counter-impulse with powerful capacitive batteries in an oscillating circuit letting this way the fault current cross the zero. This unavoidable operation evidently necessitates reliable ways to dissipate large amounts of energy.

Therefore, reducing the reaction time by placing detection and distinction operations in other places in tasks execution sequence facilitates operational conditions (lower fault current, reduction of energy requirements on *HVDC* circuit breaker) for the *HVDC* breaker to interrupt.

However, in this sequence the time required for precise fault localization and following re-closing operation should also be reduced to the possible minimum in such a way allowing *HVDC* network to restore its full pre-fault configuration as quickly as possible, so that, the selectiveness would not suffer much.

### 6.3.1 HVDC Protection Review. Differences and Similarities.

As it has been mentioned, *HVDC* grid protection principles may to the certain degree be based on the well-known *AC* protection principles. Let us consider, what are the applicability limits of *AC* protection principles in *DC* grids, their differences, similarities and principles, on which the reliable *HVDC* protection may be built on:

- **Over-current protection.** In the *DC* Grid under normal conditions, the over-current protection is easy, as individual *DC* converters allow the control the power flow through the system. The relay trips after a pre-defined period of time, if the observed current gets over a certain threshold.

An additional directional criterion based on current and voltage direction may be applied to improve basically low selectivity of this type of protection.

- **Distance protection.** This type of protection is based on accurate measurements of the distance to the fault by dividing the measured voltage value by the current. This method is very widely used in *AC* grids and has good references there. However, there are several reasons, why use of distance protection in *HVDC* networks may be difficult. The major challenge is evidently very low short circuit impedance of *DC* grid.

Proper functioning of relay heavily depends on impedance change, and thus, the lower short circuit impedance, the harder to notice negligibly minor changes of it and the finer and more precise shall be adjustments of this type of protection. In addition to it, low resistance of the cable or long line, may give glaring inaccuracy in distance, due to measurement errors.

Vector sum of line/cable resistance and fault resistance are congruent in direction, and therefore, does not give sufficient grounds for reliable distinction.

- **Differential protection.** This type of protection provides an improved selectivity to the system. At first, the difference between the current at the sending and the receiving end of the transmission line is calculated (see Fig. 5.7 and Fig. 5.8). If the difference hits a threshold, a fault event in the system is recognised. Disadvantages of differential protection are evident.

Firstly, it requires a presence of constant communication between two measuring points, what complicates already enough sophisticated control and protection system. Besides that, it negatively impacts the overall reliability – breakdown or distortion on communication would mean a failure of protection as it is.

Secondly, in ultra-long transmission links, the signal delay, due the travelling wave finite speed rate (e.g. 300 km take approx. 1 ms for the current wave in an

overhead line and approx. 2 ms for a cable) and delivery to the comparator may exceed reasonable times. Thus, in large *DC* systems application of differential protection due to large passing on a signal times becomes difficult.

However, differential protection is suitable for short distances and as protection at converter station.

- **Directional protection.** This type of protection seems to have positive perspectives in multi-terminal *HVDC* networks. This protection method directly relies on measurements of the current direction. Should the current change its direction, the measuring device immediately senses this change for the further analysis of the situation. That could mean, for example, a failure on the line or cable.

However, this protection type has a certain lack of depth in event discrimination. It becomes more evident, when it comes to distinction between power flow control errors, minor switching transient vulnerabilities and serious failures. Some additional information e.g.  $dt/dt$  derivative, may be used for this reason to support the protection in fast and reliable analysis and accurate decision making.

Viable concepts of protection in *HVDC* multi-terminal systems are mainly seen to be based on derivatives of voltage and current measurements, together with travelling wave protection, that has been in use for over a decade, to complete the accuracy and reliability. This new type of protection needs to be fast and probably non-communicant protection, i.e. an open end concept, how it was described in the Subsection 6.2.1.

There are some alternative measures and values (mainly current/voltage derivatives, for example second derivative of current) could be analysed for reliable *DC* protection as well. With the use of *FCL*, a huge inductance introduced at the end of each line may make use of the derivative and travelling waves together. Another promising methodology uses wavelets, wavelets transformation and Fourier analysis for the measurement signals processing and comprehensive analysis.

## 6.4 Requirements on Protection

Taking into account all that have been considered above in this Chapter, the following "6S" requirements on *HVDC* grid protection could be formulated:

- **Security:** the protection system shall be secure, in other words, it shall operate only when it is required with the highest reachable probability (up to 100 %) and it shall stay aside when it is not needed to operate.
- **Sensitivity:** the protection system shall sense any disturbance in the *HVDC* system and any potential fault.
- **Selectivity:** the protection system shall leave operational space for the healthy part of the grid untouched by the fault and operate only within its own protective zone.
- **Speed:** the protection system shall be fast enough to detect, decide and send either tripping signal or command to re-closure.
- **Survivability:** the protection system shall have all necessary back-up and be sustainable to shut-downs.
- **Surveillance:** the protection system shall continuously scan the system and be able to detect any type of fault in any operational mode.

These requirements are applicable for all the considered above *HVDC* protection principles, which are shown as a Table in Fig.6.8 below.

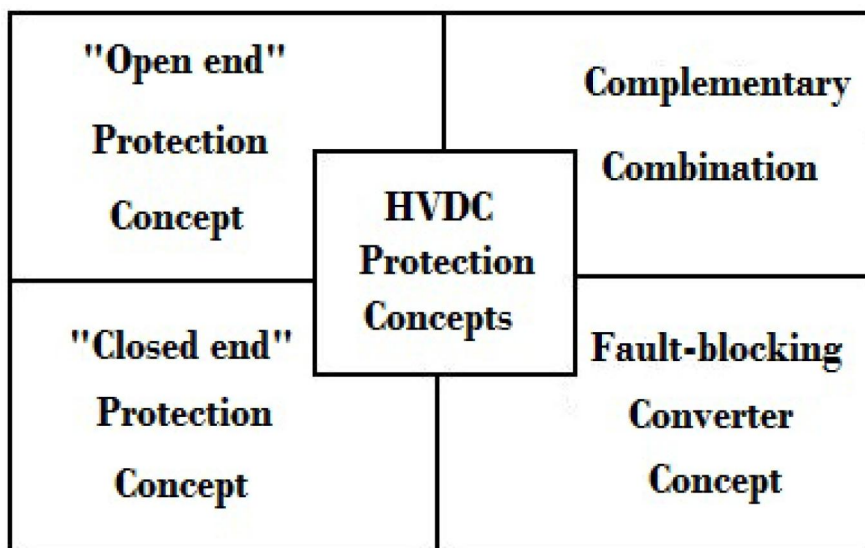


FIGURE 6.8: Table of Converter Concepts.

## 6.5 Summary

In this Chapter the need for a protection system in the *HVDC* meshed grid have been identified. Availability of reliable *HVDC* protection and control system have been defined as a cornerstone towards meshed *HVDC* networks to become a viable solution. *HVDC* protection system operating environment presents similarities with long lines *AC* protection and at the same time certain specifics typical for the multi-terminal *HVDC* solutions only.

The existing *AC* protection system has been evaluated against *DC* grid conditions. It has been found that in *HVDC* multi-terminal operation some fundamentally new principles should be considered and applied in order to facilitate uninterrupted operation of the transmission network. At the moment, there are several known prevailing principles that tend to give a solid basement for *HVDC* control and protection development. At the initial stage, it is important to explicitly formulate requirements for the completely new operational environment and tasks as well as the expected outcome from newly developed protection principles.

Secure vulnerabilities detection shall go along with precise fault location, so that a prime cause of a fault could be neutralized and equipment separated from all stressing factors in a controlled way. Constant monitoring of the situation would support to differentiate various conditions on the base of the information collected.

Protection system topology needs to be designed with a certain redundancy and grid may be covered by several protection zones. Main protection zones may in some points overlap each other. This shall not result into doubling of activities and response time required to detect and isolate a fault in the *HVDC* system.

A network arrangement depending on fault case may foresee several protection layers i.e. combination of fast, but limited protection zone with relatively slow response in the expanded zone. A complementary compromise between both options is also possible. The main protective layer can be additionally supported by less sensitive protection algorithms serving in a system as a backup function.

Protection selectivity should be taken into account to reduce false activation of protection system, when action is required only in one pole. In multi-terminal operation the minimal effect on the system by forced outage and maximal possible power transmission ratio through unaffected parts of transmission system shall be ensured.

N-1 *HVDC* network redundancy philosophy envisages in bi-polar configurations the related protection functions to be separated for every pole. A fault in one pole and consequent activation of control and protection system shall not prevent normal operation



of the healthy pole. A sudden loss of one pole can be in large part counter-balanced by taking some additional load by the second pole remaining in operation.

Requirements on the protection of converter stations, over-head lines and *HVDC* switch-yard equipment have been formulated and described in Tables. Any protective algorithm should take into account more than just one single parameter before tripping procedure is activated.

Protection and control in *HVDC* grids depend on the grid topology, the interruption capability and the presence of fast and reliable *HVDC* circuit breakers. Though numerical simulations is a reliable tool to get a clear understanding on typical characteristics of disturbances and faults. This shall considerably help in developing protection principles and algorithms.

Direct and reverse operation sequences are considered. The former is widely used in conventional AC systems and can be reassigned for DC systems. The latter refers to the "open-end" protection scheme. Operating within very short tripping time frames may become a convincing argument in favour of it. In long *HVDC* links an issue with time delay, that influences speed of signal transfer and reaction of protection, becomes very acute. By applying measuring, processing and tripping functions altogether at one local point this issue may be solved. The "open end" protection concept will likely dominate in ultra-long *HVDC* transmission links.

The "closed-end" protection concept measurements are being done at two ends at once. A robust coordination between measuring devices and their interconnection via reliable communication channel is needed. For transmission links of up to few hundred kilometres, what perfectly suits the future multi-terminal *HVDC* network vision with the size of the mesh of approximately 300 – 500 km, this protection principle is also suitable.

"Closed end" and "open end" protection concepts may be successfully implemented on different layers in the same system simultaneously. The supplementary combination of these two protection types presents a legitimate solution that may compete with or complement "converter fault-blocking" approach, which foresees no usage of a *HVDC* circuit breaker in the system, but lacks selectiveness.

Protection principles differ fundamentally by the nature of their operational concept. When protection embraces an ability to operate with characteristics of voltage and current parameters in steady-state regime, this protection is classified as a steady-state based protection.

When protection algorithms use the characteristic difference of current and voltage to perform the tasks under transient conditions, this type of protection is referred as “transient-based protection”.

In *HVDC* transmission the steady-state approach is of little value. It is possible to tell external fault from internal one and make a weighted decision based on samples collected by transient-based protection algorithms.

Several essential for *HVDC* protection system contradictions were defined: a rapid fault location and tripping are possible with locally placed measurement devices at every essential node of a network.

This facilitates operational conditions (lower fault current amplitude and steepness, reduced need for energy dissipation etc.) for the *HVDC* breaker to interrupt. At the same time quick protection algorithms and short interruption time result in lower resolution and lack of selectiveness. The need for the improved selectiveness implies the increased interruption time and more stressful operation conditions for the *DC* breaker.

Common requirements on protection have been formulated in form of "six-S" requirements, namely - security, sensitivity, selectivity, speed, survivability and surveillance.

It is concluded, that though *HVDC* operation conditions impose rather strict requirements, which are hard to meet with the existing protection system, the *HVDC* protection is, by no means, a dead-end for the potential multi-terminal grid development. However, new *HVDC* protection algorithms may require non-trivial solutions and come at a high cost.

## Chapter 7

# Circuit Breakers in HVDC Networks.

In this Chapter various *HVDC* circuit breakers (*CB*) concepts in the dynamic picture of their development along with related considerations on which concept for the reasons could be applied in *HVDC* multi-terminal networks have been examined. Bottlenecks and problems of existing *HVDC CB* technology are identified to give some possible directions for further research and finding solutions in the most promising areas. In addition, recommendations and requirements on *HVDC CB* that could be adaptable in multi-terminal *HVDC* networks are given.

Quite often multi-terminal high voltage direct current (*MTDC*) systems are considered as the next step in development from segmented point-to-point *HVDC* connections. Various *HVDC* multi-terminal networks have been discussed already for more than 30 years.

However, a certain underdevelopment of key elements of such a network prevents from its full realisation in the nearest future. In spite of the great amount of research work has been done before only two thyristor-based *LCC* systems, namely: the Sardinia-Corsica (SACOI) *HVDC* system with three terminals in Italy and the Quebec-New England *HVDC* transmission system in Canada are in operation. [83] and [84]

Still, this three-terminal operation due to inherit properties of *LCC* technology and corresponding control and protection system presents rather an upper boundary condition for this technology than intermediate step towards meshed configuration.

As it has been discussed in Chapter 5 even a simplified form of *HVDC* system based on *LCC* converters consisting of just a few terminals implies very complicated control and power flow direction cannot be easily changed without interruption in supply and

high transient process vulnerabilities. A possibility of smooth power flow direction, nonetheless, is one of the evident advantages of the meshed multi-terminal network and shall not be restricted to converter technology capability.

However, forming a network with more than two-three terminals may bring some advantages, especially when a fault on one *HVDC* line does not interrupt the power supply of the whole system. Moreover, the meshed *HVDC* grid may avoid using additional converter terminals what will result, in turn, in reduced losses and costs. Each terminal could function at different current and power rate with full control on power exchange on *DC – AC* connection points.

If this view on *HVDC* system topology is accepted and several connections will be linked to one terminal, then more accurate selectiveness is absolutely necessary. This selectiveness can be provided by the combination of converter station, *HVDC* circuit breakers and their interactive control and operation.

Based on research and studies completed in this area recently, it is possible to say, that at the present moment voltage source converter applications are seen as the most promising solution to form *MTDC* systems. Just in rare cases thyristor-based *LCC* or hybrid *VSC + LCC* solutions are considered as a suitable candidate for meshed networks.

To the advantage of *VSC* choice may be added some weighty arguments as fast and reliable control of power flow in any direction, connection to “weak” *AC* systems and reactive power supply, no need in converter transformers, size of filters can be also significantly reduced as fully controlled semiconductor units supply smooth almost pure sinusoidal wave and etc.

Still, the *VSC-HVDC* converter technology is under development and has several critical areas, especially highly vulnerable valves, which require very fast operation of the *DC* breaker. Until then they may be perfectly applicable in the systems, where the short-circuit level is very low and, thus, can be managed by converter itself.

Short circuit fault on the *DC* side is the main obstacle towards multi-terminal *HVDC* grids. The parameters – fault current magnitude, time, speed of rise and etc. are so, that can be coped at the moment neither by converter nor by present prototypes of *DC* circuit breakers. So, it could be concluded that in comparison with alternating fault current interruption of direct current in system fault condition is the more complex issue to solve.

## 7.1 Current State.

To start with the current state of DC breakers solutions, that are available on the market or are already in operation, it is necessary to distinguish circuit breakers for *LCC* and *VSC* niches. The line commutated converter technology is already a mature one and has reached quite significant level of 800–1100 kV that may not surprise specialist in *HVDC* area. Circuit breakers, that are used there, have been proved by years of operation and are capable of interrupting 4 – 6 kA in bipolar configuration. [85]

The losses at nominal current are relatively moderate and account only 0,7 – 1,0 % half of which are losses in the converter transformer. [86]

The need for space-consuming and costly filters may become a challenging, but promising opportunity. Some of research and development activity can be intensified in coming years in this direction.[87]

Any other improvements for this technology are seen in further increasing of nominal current and voltage ratings as well as in solution of possibly lower consumption of reactive power. [88] and [89]

The current state of the *VSC* technology opens a great variety of options and space for experiments and advances. To the main merits belong possibilities to cut costs on filters and use smaller ones, as only harmonics of high-frequency constitute a danger. Another advantage of *VSC* is the ability to transfer only active power while reactive power can be compensated sufficiently at both receiving and sending ends. On the opposite side, *VSC* terminal losses are pretty high in comparison with conventional *LCC* technology and amount up to 1,6–2,0 %, where the lion's part of losses caused by the converter valves. [90]

Until recent time *VSC* technology was limited by relatively low voltage level and moderate amount of power to be transmitted. The latest advances in cable manufacturing and power electronics make it possible to raise the voltage ratings up to +/- 500 kV and reach up to 1.8 GW transmitted power, what is already considered to be sufficient for future *HVDC* networks. [91]

From DC breaker point of view, the essential difference *LCC*– based from *VSC*– based networks is the presence of inductances and capacitances of different sizes that eventually impacts on transient behaviour under normal and fault conditions limiting the rate of the fault current rise. So, *L* and *C* elements in the case of a fault will slow down the rate of short current rise and therefore, facilitate the work of *HVDC* breaker.

However, introducing an additional inductance to *VSC*-based network may lead to lag in control system operation, what play a crucial role for very vulnerable *VSC* valves in the case of a *DC* fault.

At this point, it must be concluded that consequent choice of proper converter technology to build an *HVDC* network would completely define as well the requirements on *HVDC* breakers to be installed in this network. Still, these requirements could considerably differ from each other depending on interruption capability and interruption time to be provided.

Therefore, the basic contradiction is presented here by opposition and mutual exclusion of interruption time (how fast an *HVDC* breaker can operate) and interruption capability (how high fault current values and how steep  $di/dt$  curve an *HVDC* breaker can deal with), where *LCC* tends to have advantages in terms of higher voltage withstand capability, while *VSC* is uppermost in short interruption times.

## 7.2 HVDC Breaker Concepts.

Though the purpose of this Chapter is to give a look at an issue from the *HVDC* network of view, a short description for better understanding of existing *HVDC* breakers concepts to identify the needs and requirements might be of good help.

First of all, we can start from the equipment that is already in use in *HVDC* applications. For various switching duties the *DC* interrupters are applied. Among them are neutral bus (*NBS*) and neutral bus ground switches (*NBGS*) to secure the system at the neutral point, where a bus-bar is connected to ground. In this sense, neutral bus and neutral bus ground switches are closely related. A metal return transfer breaker (*MRTB*) is used to forward the return current flowing through the earth back to the non-exploitable pole in a bipolar *HVDC* transmission system configuration when it is used temporarily as a monopole. [92]

Ground return transfer switch (*GRTS*) accompanies *MRTB* at *HVDC* switch-yard to support pole restart by switching to the earth return from the metallic return. Some other types of switches like high-speed bypass switch (*HSBS*) have also found their application in *HVDC*. [93]

In spite of these *DC* switches listed above and many other *HVDC* breaker concepts that have been presented recently in many papers and on conferences, at the moment there is not yet a viable solution of a *HVDC* breaker on the market.

However, the development of the concepts focuses on few main directions which differ by physical principles.

- *Mechanical HVDC breakers* could be with active and passive resonance circuit. Mechanical passive resonance circuit breakers have been in use for many years and developed for circuit source converter *HVDC* systems.[94] This is a mature technology, where conventional air blast interrupter units are applied. Several interrupter units connected in series serve the purpose of raising the operational voltage rating of such a circuit breaker to a sufficient level.

The interruption process and current flowing can be described by the differential equation as following:

$$L_C \times \frac{d^2 i_C}{dt^2} + \left( R_C + \frac{\partial u_{arc}}{\partial i_C} \right) \times \frac{di_C}{dt} + \frac{1}{C_C} i_C = \frac{I_0}{C_C}$$

The operating principle is simple. Under normal conditions the current flows through the main path of a circuit breaker. In the case of a fault, the current is forwarded to the auxiliary commutation branch, see Fig.7.1

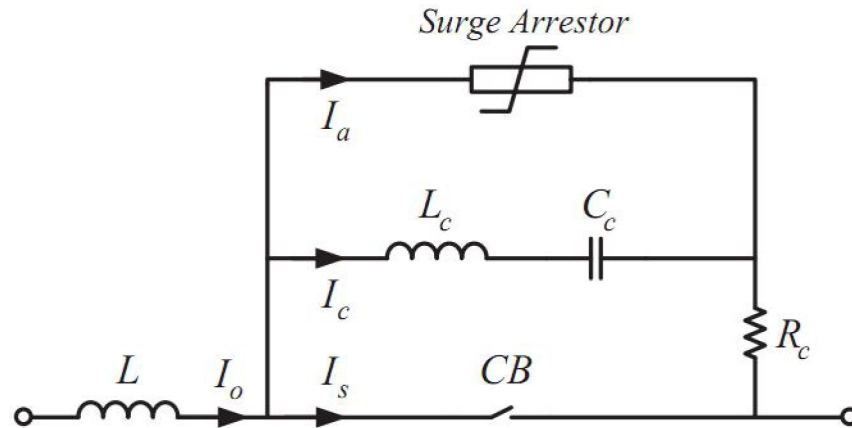


FIGURE 7.1: Mechanical HVDC Breaker Concept.

Mechanical active resonance circuit breaker is equipped with a pre-charged capacitor. Under normal conditions the current flows, as in the previous concept, through the main path of a circuit breaker. When a fault is detected the oscillation circuit is activated and the pre-charged capacitor is connected to the circuit to give an impulse of the opposite polarity. So that, the counter current will compensate the fault peak and bring it to zero crossing, as a result of currents superposition.

Parameters of a pre-charged capacitor in mechanical *HVDC* breakers with active resonance circuit should be fitted towards higher  $C/L$  ratio. Higher ratio between capacitance and inductance is propitious as it gives larger in amplitude impulse of counter current while the amount of energy collected in capacitive element is the same. Several optional schemes for a mechanical active resonance circuit breaker are known.

- *Pure Solid HVDC breakers* have no moving mechanical parts and consist only of power electronic devices. The key advantage of pure solid *HVDC* breakers is their fast reaction and very short interruption time. In comparison with mechanical breakers, whose switching time is sometimes more than few tens milliseconds, the interruption time of pure solid *HVDC* breakers is just about a few milliseconds.

On the other side of the main contradiction are very limited interruption capability, high costs and vulnerability of power electronics. High costs are basically related to large power losses in conducting mode under normal operation. These losses are considerably higher than in mechanical breaker under the same conditions. [90]

Still, the ability of semiconductor devices to interrupt *DC* current very fast highlights pure solid-state circuit breakers among all other concepts. Various configurations are possible through different types of semiconductor devices combinations like *IGBTs*, *IGCTs* or other.



Similar to mechanical breakers method is applied to solid-state circuit breakers too by putting elements in series and parallel to reach the desirable current and voltage ratings under normal and emergent conditions. However, this may be a good solution up to the certain limit as semiconductors have a common applicability bottleneck.

At the moment pure solid *HVDC* breakers find a wide use in medium voltage niche. Nevertheless, it is expected that advances in power electronics will remarkably broaden the applicability area to higher voltage ratings as well. [95]

- *Hybrid HVDC breaker concept* is logically a combination of pure solid and mechanical breakers in an attempt to benefit from advantages of both concepts and to balance their drawbacks.

Hybrid *HVDC* breaker includes both solid-state semiconductors excelling at very short interruption time and superior controllability and mechanical switch characterized by low losses and higher interruption capability.

Thus, in a combined hybrid *HVDC* breaker concept in the normal state the current flows through the mechanical part enabling lower losses, while the auxiliary path with semiconductors is activated immediately on the interruption procedure.

One of the realisable alternative with short switching time and adequate reliability is suggested on the Fig.7.2.

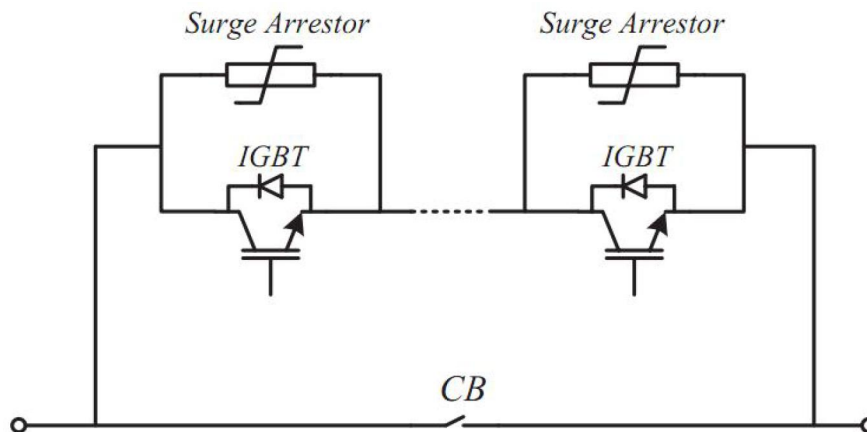


FIGURE 7.2: Hybrid HVDC Breaker Concept.

So, how it follows from the concepts description above, at the moment, there are two principal concepts – mechanical and solid state *HVDC* breaker concepts are available. They are completely different by physical nature and principles; nevertheless, they do not only compete, but also, to a large extent, complement each other. Though they have unavoidable drawbacks, in the hybrid *HVDC* breaker concept they can be balanced by the combination of advantages of each concept and proper compensating of disadvantages.

- *Hybrid HVDC breakers with the fast mechanical switch.* Recent advances in semiconductors have significantly improved their characteristics allowing assign them the functions of the main interrupter. By improving the maximal allowable breakdown voltage for a semiconductor unit and decreasing conducting losses, it becomes possible to rely on the hybrid interrupter in the main path.

The key element, that sets this concept in the advantageous zone between solid-state and mechanical concepts, is so called, the fast mechanical switch in the same branch together with small *IGBT* breaker, what brings low conducting losses in normal operation.

In parallel to it, semiconductor switches are connected in series and responsible for fast response in the case of a fault. They form the main path. Such a configuration may successfully operate without artificial zero crossing.[96]

The task of small *IGBT* breaker unit under fault conditions is to raise voltage to a sufficient level and thus, forward the current to the main path with series connected *IGBT* switches of the main breaker. As the fault current is guided to the main path, low voltage stress conditions let the fast mechanical breaker manage the situation and provide an apparent break in a circuit. Right after it, when the mechanical switch is already in open position, the full *IGBT* breaker cuts the fault current off in the main path.

Against all the advantages of this configuration a necessary evil here is the presence of a small *IGBT* breaker in series together with the mechanical switch, which in normal current conducting mode causes additional losses.

Another aspect that is worth mentioning, is the maximal voltage withstand capability of series connected *IGBT* units. On approaching this edge, the whole configuration becomes very vulnerable and, therefore, less reliable.

Though interruption is performed by fast solid-state devices, the speed of the interruption process is determined not by semiconductors, but by the fast mechanical switch. As the fault current is being cleared, when the fast mechanical switch is already in open position, it is inevitably exposed to the full recovery voltage.

A simplified scheme of this *DC* breaker concept is shown in Fig.7.3.

According to the performed tests and experiments the proved voltage rating of a hybrid *DC* breaker reached the level of  $320kV$  at the maximum fault current rise of  $3.5\text{ kA/ms}$ . [97]

There are some other *DC* hybrid breakers concepts with vacuum or *SF6* insulation are suggested. These breakers may be especially beneficial for compact *SF6* systems for *HVDC* applications mainly aimed at transmission installations off-shore. [98] Some viable solutions of *HVDC* hybrid-breakers are also considered here.[80]

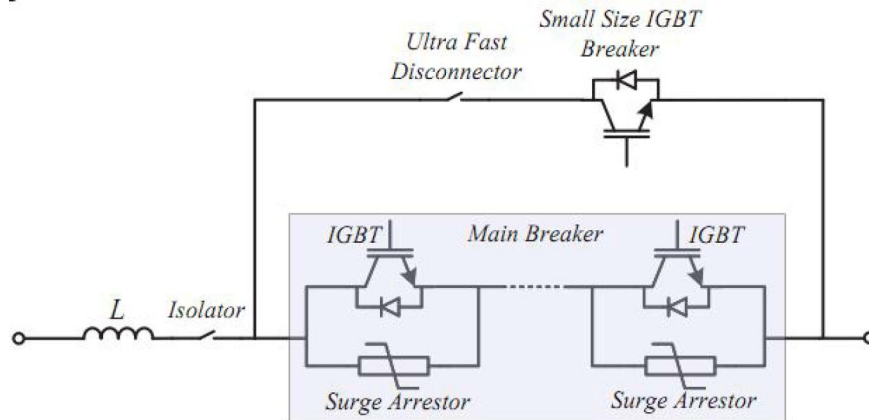


FIGURE 7.3: Hybrid HVDC Breaker with Fast Switch. Source: [95]

Combining an excellent interrelation between high-frequency and high-current interruption capability, that are inherent to vacuum breakers together with  $SF_6$  breakers ability to withstand high-voltage levels it becomes possible to build another reasonable and robust  $DC$  breaker configuration, where interruption speed is of second priority and rather compensated by other undeniable advantages of  $SF_6$  and vacuum properties. The key contradiction here is just the same as the key benefit – mutual interaction of  $SF_6$  and vacuum switches with different properties is complex and hard to realise, however not impossible. Further research on interrelated working principles of various  $SF_6$  and vacuum configurations will be done to broaden a detailed technological insight and understanding as well.

- *HVDC breaker + Converter Station.* As the hybrid  $DC$  breaker presents a compact combination of the fast mechanical and solid state devices within one arrangement, evidently, it is reasonable to separate these parts, assigning them their best-performed tasks each after each. Thus, the other possible approach to this issue is the regulated operation of  $HVDC$  breaker together with the converter station. In this approach converter stations with the use of control system should perform an important task of facilitating the interruption process for  $DC$  breakers and when necessary to de-energize the related faulted part. At the extreme, this could be done with minimal  $DC$  breaker participation, and thus, with minimal requirements to its performance characteristics. However, as it was discussed earlier, such approach is fraught with danger to be inadequate to the weak selectiveness in meshed  $HVDC$  networks. Within one single structure the mutual operation of valves and  $DC$  breakers is also considered as realistic. Inside a converter station the voltage can be divided between valves and at these reduced levels it may be already possible for  $DC$  breakers to interrupt, as they could have more light-duty conditions for operation. Nevertheless, the design of the converter valves yet needs to be reconsidered to be able to incorporate  $DC$  breakers into its structure.

Still, it is seen rational when in the *DC* breaker – converter station coupling, the latter limits the fault current providing more favourable conditions for a *DC* breaker to trip. This can be done also by activating of circuit breakers on *AC* side and by applying current limiting equipment. Thus, the synergy of enhanced coupling and close coordination between converter valves and the *DC* breaker should hopefully lead to beneficial and meaningful results.

- *HVDC breaker concept. Missing chain.* This concept is based on results got from fault transient simulations in this Thesis. The worst case scenario for bi-polar line with no load and absence of any protection devices limiting fault current growth was modelled. Right after the fault in the next 15 ms the current reaches  $20kA$  level and after following  $70ms$  gets the maximal point slightly above  $50kA$ . Relying on these simulation results, it is assumed, that in a presence of fault limiting devices and under load, there are some  $15 - 25ms$  to break the faulty current at the level of  $15 - 20kA$  until it reaches dangerous levels, see Fig. 5.5.

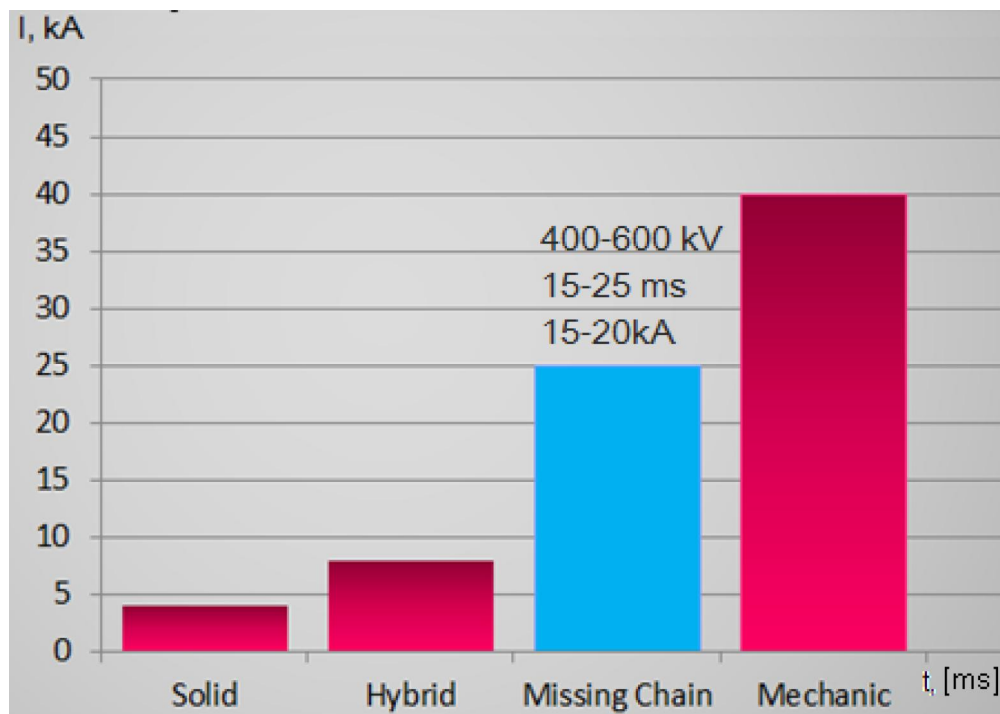


FIGURE 7.4: "Missing Chain". HVDC Breaker Concepts.

The "missing chain" *HVDC* breaker concept should be able to clear the relatively steep faulty current, but does not need to be fast as pure solid devices, see Fig.7.4. In other words, it is a combination of solid electronic devices and fast mechanical switch with improved withstanding and breaking capabilities. However, some further research in this direction is required.

### 7.3 System Topology and DC Breakers Optimisation.

A systematic approach to optimization of *HVDC* breaker concepts implies a careful consideration of this point together with protection and control system optimisation and optimisation of system topology in close relation with each other.

Development of *DC* breakers is hard to complete in full without proper understanding what role plays in this multi-factorial process the optimization of grid topology and fitting and setting of protective system to current needs.

Very often research efforts are focused on certain aspects of either *HVDC* breakers or multi-terminal schemes of *HVDC* grids separately.

However, a systematic approach gives an opportunity to solve many problems and consider these interrelations in a single set, as it clear that optimal operation of *DC* breakers to the high extent related to control and protection algorithms applied, which in turn have to be adjusted to current network requirements.

*HVDC* breakers are at least a part of the solution on the way to real multi-terminal *VSC – HVDC* transmission systems. In these terms realised concepts lack performance characteristics and their present ratings are limited to be applied only to certain niches.

Even with limited ratings, the *DC* breakers, that are in use at the moment, suffer from inconveniently massive sizes and high costs of components. To cope with these challenges an interaction of a *DC* breaker with converter control can be explored in deep to facilitate interruption process. [99]

This interruption operation, highly depending on the technology applied, could take from 100 ms. [100] and [101]

System topology and complexity is one of the major factors. Up to the certain level, when an *HVDC* network has few terminals, but is not yet very much meshed, so to say, in small-size *HVDC* systems, it is possible to go with the converter control only and de-energize some parts of an *HVDC* network.[102]

Though, it is clear that this strategy is also limited to rather small and not intensively meshed *HVDC* systems with three or four terminals, see Fig.7.5.

Again, with the development of *HVDC* network, the more complex and meshed it becomes, the more acute need for a fast and reliable *DC* breaker arises.

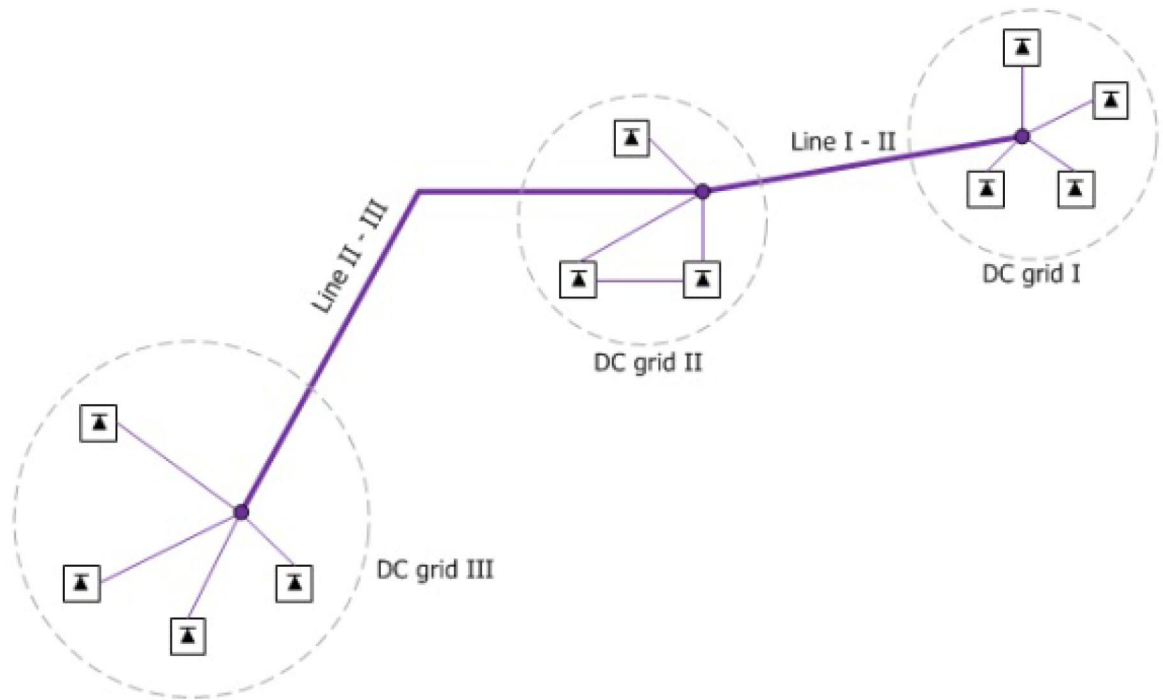


FIGURE 7.5: Not-Intensively Meshed HVDC System. Source: [103]

Thus, having met all the requirements on reliable, efficient and economic operation of a *DC* breaker, as a key technical solution, it becomes possible to enable further development of the multi-terminal *HVDC* network.

A broad-based view is needed to deal with the "topology & control & *DC* breaker" equilibrium supposing that there are no strictly and permanently determined components.

Just the opposite, it should be assumed, that all of them shall be reasonably modified and adjusted to each other in order to get the best running position.

Few attempts are done on the way of broad-based optimisation of modular multilevel converters based on *VSC* schemes. [104]

## 7.4 Problems and Solutions

In *HVDC* networks based on voltage source converter technology the faults occurring on DC side present severe danger. Even when the *IGBT* units are blocked, they still act as an uncontrolled rectifier conducting through diodes connected in parallel to them. [105]

Due to these circumstances, to de-energize the uncontrolled converter a breaker is required. Basically, a conventional *AC* breaker may perform this task, but having several bus-bars connected to one converter station, the selectiveness and possibility of the uninterrupted power supply will suffer in this case. This issue, however, could be solved by applying new modular multi-level converter *VSC – MMC* concepts.

The sustainable solution is needed to reduce conducting losses in the normal operational state. Reducing the losses down to few tenths of a percent would enable several alternative concepts of *DC* breakers from the technical and economical point of view. This issue remains sharp also by applying full-bridge topology, which potentially helps to reduce undesirable harmonics produced by converter valves. [106] and [107]

Another shortcoming of available at the moment breakers is that, they are not yet able to interrupt high enough current for the provided interruption time. To be applied in meshed *HVDC* networks *DC* breaker should reliably clear currents higher than 10 kA in the operational time range of a hybrid *DC* breaker.

To interrupt *DC* current with mechanical switches a zero crossing is needed, which is created by counter current impulse. The amplitude should be at least similar or better larger than system voltage. However, the facilitated operation conditions in form of zero crossing with not steep  $\frac{di}{dt}$  result in a very large amount of energy stored in this circuit that needs to be compensated and harmlessly dissipated.

So far, counter impulse technique has been used in low and medium voltage applications, where the amount of the dissipated energy is moderate, whereas in high voltage applications this could be a challenge. Some concepts are being developed, but they are not yet proved efficient against real operating conditions in practice.

Vacuum breakers may find their application in the *HVDC* transmission network, as they demonstrate good performance characteristics, namely, short interruption time of just a few milliseconds and excellent interruption performance - large  $\frac{di}{dt}$  with large  $\frac{du}{dt}$ , with the reference to papers [108] and [109].

At the present moment vacuum switches are broadly used in medium voltage applications (36 kV – 72,5 kV), their progress into high voltage ratings is very much expected. This is very challenging from a mechanical point of view and needs to be improved further.

Solid state *DC* breakers may provide the shortest possible interruption time among all *DC* breaker concepts available. This ability is of high value in *VSC* based *HVDC* networks vulnerable to fast rising short-current and thus, solid state breakers have great potential to find a use there. To enable solid-state devices with the higher ability to withstand the full current and voltage ratings they are connected in parallel and series arrangements of several interrupters. [110]

However, with the development of semiconductors and their performance capabilities it would be possible to design more compact and less complicated arrangements, what in turn, would directly reflect on higher reliability of operation.

New wide band-gap materials such as *SiC*, *GaN*, and diamond are considered to have a big potential. [111] [112] Devices produced out of these materials might be much thinner, have lower losses and higher breakdown field strengths. [113]

More intensive research activities in this area aims to answer many questions and find solutions to current obstacles and concerns. In the best case, any significant technical breakthrough in this direction will have a tremendous impact on *HVDC* transmission, including, of course, ways of design and application of semiconductors *DC* breakers.



## 7.5 Fault Current Limiters

Fault currents limiting applications may accompany *HVDC* breakers in order to support interrupting capabilities of a breaker. Several options of fault current limiters that have been in use in AC systems could be basically applied in *HVDC* transmission system as well.

Fault currents limiters owing to inherent characteristics aim at smoothing a very steep rise of fault current  $\frac{di}{dt}$  restricting and slowing down the development of a fault in the DC system because of reactive elements added. Due to original lack of over-current limiting ability in *HVDC* networks, this is one of the important tasks to be coped with help of *FCL* units.

According to the type of triggering, fault currents limiters can be either externally activated or self-activated. The latter is preferred because of fast reaction time, what is absolutely necessary considering how fast the fault current may reach the peak in *DC* power systems.

During operation of a fault currents limiter a great amount of energy needs to be harmlessly released and dissipated. [114]

However, introducing reactive elements in order to increase the overall impedance of the system may have a reverse side, not to the benefit of broad application of fault current limiters with high inductance. All the pros and cons of the possible application of additional reactive elements in *HVDC* grid have to be thoroughly weighted.

As a matter of fact, an additional large inductance on a *DC* side may result in much slower control during normal operation in spite of undeniable advantages in case of a fault.

It is clear, that operation under normal conditions shall account the major part of operation time. Therefore, these aspects shall be carefully considered before the issue is solved in one or another solution's favour.

Attention shall be paid also to the way, in which the *HVDC* system is grounded, as well as to resistive properties of the earth contact. In the case of a line-to-ground fault, the fault current flow will be restricted by earth contact of high impedance.

Fuses may be also qualified as self-triggered fault limiters under reservations that a fuse may act only once and after the successful operation it must be replaced.

Therefore, manual intervention is required, what may be considered very convenient. At the moment such fuses are used in medium voltage applications up to 36 kV.

With the development of superconductors, that are able to reliably operate under normal ambient temperatures, wide application of superconducting fault current limiters (*SCFCLs*) has a great potential. [115] [116]

Owing to inherent properties of superconductors, their zero resistance may rapidly start to grow on reaching a critical current density. It is also known, that short current causes a rise of temperature in conducting parts.

Thus, any change in current density and temperature in *SCFCL* would lead to the considerable decrease of resistance of fault current limiter, thus, sufficiently limiting the fault current.

Superconducting fault current limiters are instantiated by low losses in nominal operation. To particular qualities belong their fast operation and frequently repeated usage ability.

Still, very intensive cooling is required to maintain superconducting state, making the application quite cost demanding. To raise voltage withstand capability to a sufficient level *SCFCL* units can be connected in series.

## 7.6 Grid Protection Philosophy

*HVDC* breaker is eventually a core element in any grid protection philosophy. However, conditions of practical application may slightly differ depending on what approach of several possible ones is applied.

- *Conventional Protection Philosophy.* The protection philosophy implies just the same operation principles for *HVDC* networks that are employed in high voltage AC transmission. Only some small adaptations are necessary. The apparent simplicity of this approach turns into a severe challenge to provide a very short interruption time. This capability cannot be inherited as easy as protection principles and schemes successfully applied in *AC* systems.
- *“Open End” Protection Philosophy.* The another approach is the “open end” protection philosophy that utilizes *DC* breakers within *HVDC* transmission networks as completely autonomous units.

External control from the system control area dispatcher can be avoided and may be needed only in urgent cases, when the manual interruption or re-closing decision is indispensable.

It is supposed that any fault is immediately tripped based only on measurements at local points in a grid, where they are directly applied. Re-closing procedure is performed right after to improve overall selectiveness and bring into the operation those lines and networks parts that are not affected by the fault.

Allowing *HVDC* circuit breakers in “open end” philosophy to trip immediately on fault detection is only then meaningful, when each *HVDC* circuit breaker is able to interrupt and re-close again within just a few milliseconds. Longer interruption times or any delays in switching procedures make this approach disadvantageous in comparison with others.

These considerations place, therefore, certain restraints on *HVDC* breaker operational characteristics and would probably necessitate revision with the following update of communication modes and methods along with discrimination logic for faults and disturbances in transmission grid.

- *“Fault-Blocking” Protection Philosophy.* Application of “fault-blocking” or “fault-limiting” converter principle is another possible option in grid protection philosophy. Use of *HVDC* circuit breakers could be minimised or at least operating requirements on *DC* breakers can be significantly reduced. The latter is preferable in terms of selectiveness.

When protection algorithms are set to safely locate a fault, *DC* breakers in cooperation with converters may rapidly isolate the associated with fault grid parts and redirect power transfer in the healthy part of the grid.

This cannot be performed relying on converters only, as power flow management and post-failure grid reconfiguration require more delicate and precise tools.

Interruption time is a clear advantage of this grid protection philosophy, as it allows *DC* breakers to break much lower fault current at the initial phase of fault.

The requirements on energy dissipation can also be significantly reduced for *DC* breakers applied.

In addition, equipment reliability can be maintained on a very high level as *DC* breakers interruption capability will be always supported by proper operation of converters.

Faults in the *HVDC* network could be effectively located if only mutual interoperation and data exchange as required between converter stations, *DC* breakers and protection system is appropriately adjusted.

## 7.7 Requirements on HVDC Circuit Breakers.

Having considered various types of circuit breakers, their main directions of development at present and future research, questions related to coordination with a *HVDC* network of various configurations, it may be possible at this point to derive some specific requirements on *HVDC* breakers, that shall be installed in future *HVDC* transmission networks.

- *Design of VSC-HVDC converters.* The central importance has stable and reliable operation of *VSC*-based converters in meshed *HVDC* networks under vulnerable fault conditions. When *IGBT* units are designed with integrated diodes connected in an anti-parallel way, there is a risk of flash-over, so that, *VSC* loses control and starts to act in uncontrolled rectifying mode after *IGBT* units get a signal to turn off.

Thus, the design of *VSC* converters should take into account all possible risks and drawbacks of technology. Measures shall be taken towards reasonable improvement of existing converter technology, design and durability of elements. Modes of operation and way of control and fast and precise reaction to various kinds of system disturbances shall be recognised and properly processed.

- *Compatibility with the HVDC control system.* Close and reliable interrelation between DC breakers and converters is expected to be decisive in *HVDC* control system implementation. Thus, compatibility and flexibility in precise and accurate adjustments between DC breakers and control system algorithms should be realised on the highest level.

It is understood that in *HVDC* networks fault current rises very fast and logically a quick interruption measures are desirable with highest achievable selectiveness – only the faulty lines from should be isolated from the system allowing power transmission through the rest of transmission links, even though in overload mode probably.

This, in turn, demands a very strong interaction between the *DC* breaker and the transmission system. Further elaboration and answers can be partly obtained from numerical simulations.

- *Interruption time.* The capability of proper functioning is very important for *HVDC* breakers as they are intended to clear quickly rising fault current as fast as possible. Therefore, short interruption time is considered as one of the main requirement for the successful *DC* breaker operation. Among all concepts that are

available the mechanical breaker is the slowest one with switching response time up to 50-60 ms.

On the opposite side is a solid-state breaker, interruption time of which is just a few milliseconds. Somewhere in between various hybrid *DC* breaker configurations are placed with switching response between ca. 5 milliseconds and up to 20 – 30 milliseconds depending on the concept and technology applied.

- *Power losses.* Evaluating power losses for various types of *DC* breakers it is necessary to note that for solid state and, to a lesser extent, for hybrid concepts with semiconductors in a conducting path under normal operation this issue appears to be especially sharp. The mechanical *DC* breakers without any solid-state elements have very low voltage drop on the main metallic switching contacts. This results in very low losses negligible in comparison with solid-state breakers.

High power losses are a soft spot for *IGBTs* or other semiconductor devices in use. Though power electronic elements may provide very fast response, their application in the main conducting path, where it is possible, shall be avoided. The total drop of voltage in pure solid-state and hybrid breakers is rather high and overall losses could be about one-third of power losses in the whole *VSC* station. These topologies of *HVDC* breakers need to be further developed and tested.

So, the design of a *DC* breaker should aim at lowest possible losses as one of the main operational requirement.

- *Voltage ratings.* For future meshed *HVDC* networks the voltage level is expected to be about 400 – 500 kV with an option to raise this voltage at least one step upwards. Only mechanical *HVDC* breakers operating at 500 kV are commercially available and may be applied.

For hybrid and solid-state *DC* breakers the maximal voltage level at the present day is about 300 – 320 kV and is limited mainly by semiconductor technology.

- *Current rating.* The same is true for current rating requirements. For the moment mechanical *HVDC* breakers with passive resonance circuit are capable of carrying and interrupting currents up to 4 – 6 kA. The performance of mechanical *HVDC* breakers with active resonance circuit is even higher - up to 8 – 10 kA. In ultra-high voltage applications, the mechanical *HVDC* breakers have the strongest position among the other concepts.

In hybrid *DC* breaker topologies it appears to be achievable to interrupt fault currents comparable to those in mechanical *HVDC* breakers with active resonance circuit. Yet, as it has to be noted, that the nominal voltage rating is much lower.

Significantly higher currents are considered in principle for the hybrid breaker technology.

Experimentally, the current interruption capability of 9 kA has been proved and this theoretically this level can be improved even more. For solid-state DC breakers, the fault current of 5-6 kA is estimated as a feasible current rating. [117]

This requirement could be formulated as the highest achievable interruption current level within lowest possible time period. From simulations it could be derived, that the interruption current of ca. 10 kA within 20 ms seem to be reasonable and achievable.

Some other requirements are also essential in the *DC* breakers development and could be specified as follows:

- *Ability to produce one or multiple zero current crossing* in order to facilitate fault current interruption process. In some breaker configurations the voltage impulse generated by the auxiliary circuit should not exceed the particular level and be adjusted in full compliance with the insulation coordination of the *HVDC* transmission network. This requirement is mainly for mechanical *DC* and some hybrid breakers.
- *Reliability and sufficient protection* measures against different types of faults such as pole to ground and pole to pole faults.
- *Re-closing operation.* The *DC* breaker shall be able not only to interrupt the current, but also to re-close and, if necessary, to repeat the switching operation again after a short period of time.
- *Dissipation of energy.* The *DC* breaker design should allow a large amount of energy to be stored in the system inductance and to be harmlessly dissipated.
- *Over-voltage withstand capability.* The ability to withstand switching over-voltages and to prevent over-voltage impulses from penetrating into a *DC* transmission system. This also refers to power network response right after fault current has been cleared. Switching under load, where the *HVDC* system operates at nominal voltage, may also lead to significant over-voltages imposing a stress on breaker parts and particularly on power electronic elements.
- *Arcing reduction measures.* In the case of *DC* breakers with mechanical switches, all measures shall be taken to reduce the arcing after the separation of the contacts.

Non-specific for *HVDC* breakers requirements can be listed, as follows:

- *Sufficient isolation capability* corresponding to nominal ratings of the transmission system.
- *Reduced or maintenance-free operation* with affecting reliability and other working parameters to the worse. If manual intervention is unavoidable, it should be possible to bypass the power through additional paths and thus secure un-interruptible system operation.
- *Durability and sufficiently long lifetime* that may prove considerable initial investments into *HVDC* equipment.
- *Modularity and operational interchangeability* to reduce the time required for installations, commissioning and start-up of *HVDC* equipment; to simplify maintenance and repair activities enabling, when and where it is possible, a hot tapping i.e. service execution without interruption in the power supply. Operational interchangeability of key components from main *HVDC* producers will play significant role on reliability and quality assurance of *HVDC* power systems operation.



## 7.8 Summary

*HVDC* breakers are considered an integral part of the multi-terminal *HVDC* transmission network. Absence of reliable DC breaker for high voltage application is seen the main obstacle on the way to *MTDC* networks. This technological step is absolutely required in order to provide reasonable performance and reliable operation under different operational conditions. Reconfiguration of *DC* power systems, questions of selectivity and fault clearance, power flow regulation require the presence of sustainable and reliable *DC* breakers in the grid.

At the moment, there is no *HVDC* breaker available and applied in any real project. However, a number of various concepts are suggested and intensively discussed. All of them can be classified into few groups: *DC* mechanical breakers based on conventional AC interruption technology, pure solid-state DC switches, various hybrid *DC* breakers without or with ultra-fast mechanical switch, some other concepts, where *DC* converter station together with proper regulation methods, protection and control system may well complement and facilitate *DC* breaker performance.

All of them, certainly, have their own advantages and disadvantages. However, the combination of most promising concepts may result in successful *DC* breaker configuration. The instant search for a successful configuration is still going on. All present *DC* breaker schemes are limited either by interruption time, or interruption current and high voltage withstand capability. This is defined as the main contradiction in the modern *HVDC* breaker design.

Therefore, the optimisation of the *DC* breaker interruption performance shall be closely tied with the system topology and protection concepts optimisation. Several of possible ways are considered in this chapter.

In the case of mechanical breakers, the main focus of development shall be paid to resonance circuit size minimisation and preventing counter-impulses, generated in this circuit, from penetrating into the power system. Large amount of energy to be harmlessly dissipated is another challenge.

Main breakthrough solutions in pure-solid state breakers are expected in wide-band-gap semiconductor applications with the use of experimental materials. Their limits to applicability and performance related characteristics shall be carefully and diversely investigated.

Combining advantages of both main concepts – mechanical and pure-solid state, a hybrid *DC* breaker concept has all the potential to become an efficient and viable solution with desirable performance parameters. Development of fast mechanical switches could

bring the hybrid breakers technology to the new edge, securing low on-state losses, few milliseconds of interruption time and acceptable level to withstand over-voltage impulses.

For the “converter fault blocking” concept the existing modular multilevel converters could be applied, see Fig. 5.19, as the conventional *VSC* converters under fault conditions remain in conducting state, and thus, are “non-fault blocking”.

Core requirements have been formulated for *HVDC* breakers. They are: request on efficient design of *VSC-HVDC* converters and sufficient compatibility with *HVDC* control system; quick interruption time and low power losses; acceptable for transmission networks voltage and current ratings.

The ability of *DC* breaker not only to interrupt the fault current, but also to re-close fast and efficiently is in a great demand. Close interrelation with protection algorithms shall enable *DC* breakers to recognise risk level and hazard category to successfully cope with different types of faults such as pole to ground and pole to pole faults.

Due to a large amount of energy allocated in inductive circuit, it is necessary, that *DC* breakers would be able to dissipate this energy without risk and harm for elements in the inner circuit and network units located nearby. It is also true for appropriate measures to prevent over-voltage impulses from penetrating into *DC* transmission system. Ability of *HVDC* breakers to withstand switching and surge over-voltages is of high importance as well.

The higher the speed the easier fault network conditions for the *DC* breaker to interrupt. However, the interruption speed is limited to physical properties of breaker elements. In some not highly meshed multi-terminal topologies the application of *HVDC* converters in the role of regulating and clearing-the-fault units is possible. In this case low degree of selectiveness shall be accepted.

Simulations of electromagnetic transient processes are considered as a reliable tool to study internal processes and dynamic models in *DC* breakers, as well as, the interaction between *DC* breakers and the transmission network, as a whole. Calibration and validity of such models shall be proved by practical tests and experiments. Results of simulations could be, by all means, beneficial for the successful design of various *DC* breaker concepts.

*DC* fault current limiters may also find their application in *HVDC* networks. In practice, the use of conventional and superconducting *FCLs* at some point reduces requirements on interruption capabilities for *DC* breakers, facilitate distinguishing of hazardous currents under the fault condition and in transient events in transmission grid.

## Chapter 8

# Power Flow in HVDC Network.

In this Chapter several power flow control methods relevant to multi-terminal *HVDC* grids are described. Power flow profile depends strongly, above all, on general configuration of the considered system and abilities of technologies e.g. converter technology applied to manage power flow. The task of power flow, as a matter of fact, is far from being trivial. In general, the more interconnections there are in *HVDC* network, the more sophisticated methods for power flow control should be elaborated.

However, especially on the initial planning stage, this question is unavoidable, so that the coming multi-terminal *HVDC* network could be smoothly incorporated into the already existing *AC* network infrastructure. Simulations of *MTDC* systems with different configurations may give useful insights and be used for the optimisation and planning purposes of transmission systems.

Thus, it is important to distinct two perspective direction – optimisation of power flow in a pure *DC* network and power flow exchange between *AC* and *DC* parts of the grid. This necessitates a clear definition of an *HVDC* network which is considered in this work under various perspectives.

In this work, therefore, an *HVDC* network can be defined as a network, with elements, converter stations, lines, equipment units etc. distributed over a large area to organize reliable paths for *DC* current flow in the most effective way through the constant monitoring of crucial network performance parameters, data exchange, optimisation, measurements etc. to deliver necessary amounts of power and to effectively balance generation-load correlation at every moment of operation.

## 8.1 Technological Prerequisites.

In previous Chapters the difference between two prevailing on the market and available at the moment converter technologies was described – namely, line-commutated converters (*LCC*), a current sourced converter based on thyristor technology, and voltage sourced converters (*VSC*), a self-commutated converter based on transistor (*IGBT*, *GTO* etc.) technology, which are able to pass the current flowing in either direction. They both have own inherit advantages and disadvantages.

### 8.1.1 Power Flow Control in LCC-HVDC Network.

In *DC* networks based on *LCC – HVDC* converter technologies the power flow control presents a non-trivial task. Due to the inherent properties of *LCC*-converters the power flows in one direction, while the reverse of current is only possible by changing the polarity. [118]

Another drawback of *LCC* technology is the fact that thyristors are only turn-on devices and their principal dependence on the external circuit in commutation and switching off. Active power is controlled by firing angle, that turns thyristors on and by overlapping time (e.g. extinction time instant) before the commutation to another valve.

So, any disturbance or fault on the *AC* side will cause commutation failures and, consequently, influence the *DC* line voltage too. [119]

Therefore, it may be concluded that *LCC – HVDC* is highly vulnerable in case of faults on associated *AC* side.

At every terminal in *LCC – HVDC* network some certain amount of reactive power will be inevitably consumed. Additional measures like installation of filters and additional capacitors would be necessary on the *AC* side to compensate reactive power and run thyristor-based converters connected to *AC* grid.

Even though the more developed and mature *LCC* technology may achieve significantly higher voltage and power levels with lower losses in comparison with its counterpart, still, it is pretty awkward and complicated in control and power flow management.

Thus, it takes time and actions to gradually decrease voltage down to zero, change the voltage polarity at a given converter station and finally switch on the line again. The whole set of operations is unacceptably slow, vulnerable, complicated and costs additional losses.

Moreover, with the increase of numbers in *HVDC* terminals, the complexities of the implementation unproportionally increase.

In the case of the common *DC* voltage line or bus-bar, the change of the voltage polarity at one station will inevitably affect the power flow direction at all interconnected terminals. This makes multi-terminal *HVDC* grid based on the *LCC* technology hardly feasible. Just few *LCC – MTDC* projects were realised, moreover, no one of them operates at present in more than three-terminals configuration.

### **8.1.2 Power Flow Control in VSC-HVDC Network.**

On the other side high voltage direct current transmission systems equipped with voltage source converters (*VSC – HVDC*) are not yet facts of reality, but according to claimed performance characteristics and projects realised as point-point connections provide with relatively smooth control and flexibility in terms of power flow.

Additional benefits are seen in the ability of the black-start and the reactive power compensation. And, what is the most important point, in terms of power flow control in various multi-terminal configurations and, as opposed to *LCC – HVDC*, *VSC – HVDC* based systems are able to reverse the current direction seamlessly without changing the voltage polarity.

This ability of *VSC – HVDC* envisages a scenario, when the transmission system may operate in a flexible way and be quickly optimised according to the present situation with intermittent generation, available transmission corridors and load.

The effect of the *DC* power flow on the connected *AC* grid is, to great extent, predictable and controllable, and thus, is scalable from point-to-point connections to various multi-terminal configurations covering considerable larger areas.

In addition to it, *VSC – HVDC* technology is able to handle the big variety of generation sources with high intermittent, that is naturally inherent to renewable generation like on- and off-shore wind farms and solar panels. Their significant volatility in energy generation may cause some considerable fluctuations into the whole power system and jeopardise its stability.

With all that has been said above, it is possible to come to the conclusion that the future multi-terminal operation will most likely be based on the *VSC – HVDC* converter technology, and thus, hereinafter only this type of converters to be considered in this Chapter.

## 8.2 Power Flow Modelling.

Power flow simulation of *HVDC* network may lift the curtain over some questions. Modelling should be followed by careful model evaluation against the consistency of data, rationality and fairness of the model representations and comparative study on the real network behaviour.

However, at some initial stage, it is already quite clear that model suitable for transient processes studies does not satisfy the needs on power flow steady state simulations.

Depending on purpose and objectives of research the power flow model may be to some degree simplified or just the opposite may require additional refinement.

In power flow model, for example, voltage source converters may be represented as ideal current sources on the *DC* side. This will enable connection of several *DC* converter stations in parallel avoiding difficulties with converter control blocks.

As it was already mentioned, in the *VSC – HVDC* network the current direction can be easily changed in such a way reversing the power flow, while the voltage polarity will remain unchanged. This advantage of the *VSC – HVDC* gives a certain degree of freedom in *HVDC* power flow control and management in multi-terminal systems. [120].

### 8.2.1 Configuration of Multi-terminal HVDC Network.

Another important factor, that needs to be discussed along with converter technology, is the type of network configuration and connection.

Two possible types of connection and a mix of them may be adopted in future *HVDC* systems.

In the all realised by now multi-terminal *LCC – HVDC* networks all stations were connected in series. In such network one converter is responsible for keeping the current at rated level and the rest ones manage the power output.

On modelling, an *LCC* terminal can be represented as a voltage source in series without a need for special switching arrangements. Nevertheless, this configuration has several significant disadvantages, such as raised requirements on insulation, higher losses and, what is the most important, lower reliability ratio.

So to say, in case of a failure on one *DC* line the whole power system will fall out of service. Due to this reason, it is strongly recommended that future *HVDC* network configuration will be shaped as parallel or mixed connections.

However, for *VSC* it is more reasonable to connect terminals in parallel, see Fig.8.1, as such parallel connection adds to reliability and uninterrupted operation of the whole transmission system and thus has a great potential to be applied.

The considered here meshed *HVDC* network anticipates reliable strong links between large *AC* systems and embedded renewable energy sources with the high degree of volatility.

To implement such a network in full force and effect some comprehensive studies and research on steady state and dynamic behaviour of the system should be carried out.

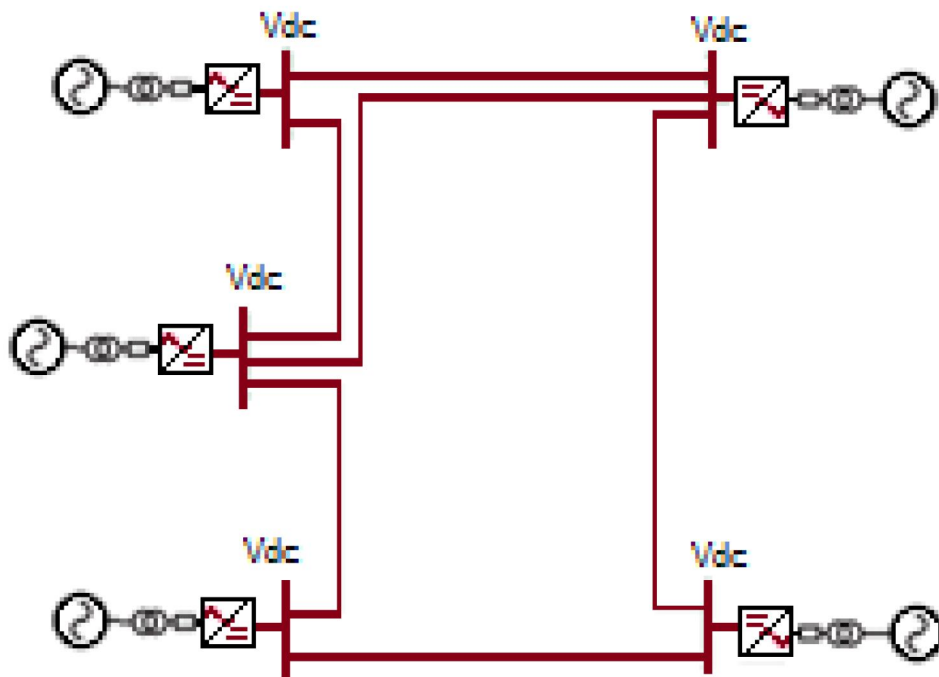


FIGURE 8.1: HVDC Network with Parallel Connection.

In parallel connection, *DC* converter stations operate on the common base of rated *DC* voltage.

Still, *LCC – HVDC* systems, because, in the first instance, of their voltage source nature on the *DC*-side, will require very complicated and sophisticated methods of control and switching to balance voltage precisely between terminals.

The closed-end control approach will necessitate a fast and reliable channel for information exchange, what is not an easy task between remote stations.

Due to these reasons, it has been concluded that practical realisation of more than 5 terminal based on *LCC – HVDC* converter technology is hardly possible. To the opposite, voltage source converters allow parallel functioning without any supplementary complications. As a model, the voltage source converter can be represented by ideal current source. [120] [121]

In multi-terminal *HVDC* networks with parallel configuration, the current direction can be reversed independently from the voltage polarity opening opportunities for *VSC – MTDC* transmission systems in the future including a *DC* 'SuperGrid' that connects several *HVDC* networks into a unified one.

Employing *VSC – HVDC* technology foresees several advances in terms of *MTDC* systems:

- relatively easy control of power flow in *MTDC* systems;
- ability to incorporate a large number of converters into one grid;
- network voltage profile update;
- improvement in transmission capacity;
- successful coping with intermittency of various renewable resources like wind and solar;

### 8.2.2 Model Description of Multi-terminal HVDC Network.

With a reference to the previous work, which has been already done in this area, a generic model of *VSC* station may include converters with *IGBT* elements represented by a set of ideal switches, resistors and capacitors, phase shift reactors and filters. [122]

Such a model presents an actual converter station configuration and takes into account the possible influence from equipment, for example, filters. Knowing the structure of a *VSC* station, it is possible to model it with all elements, that are relevant only for steady state studies, as transients present a secondary interest in these studies.

Multi-terminal *HVDC* transmission system consists of a number of *VSC* stations, that for the sake of simplicity are considered similar in design and parameters.



It is also important to note, that models developed for steady-state, are not the same to the models intended for dynamic and transient processes studies.

In the present study case, the *VSC – MTDC* meshed transmission system with five terminals is considered. As it has been mentioned above, all *VSC* stations are supposed to be identical in design and parameters.

Even though in real life losses are the inescapable part of converter station performance, in state-of-art *VSC* station losses may be significantly reduced down to 0.9% or even to 0.5% in the modular multi-level design. It would not be an oversimplified assumption if losses at the considered *VSC* stations would be neglected. [123]

No need for additional *AC* filters can be justified by application of modular multi-level converter design with cascade connection as a modulation method, that implies fully controllable shape and amplitude of a curve.

### 8.3 Power Flow Control Modes in HVDC Networks.

Embedded capabilities of *VSC* station allow control of reactive power or voltage level on the *AC* side at the common *DC – AC* connection point.

In a multi-terminal configuration, knowing the reference power, from the system point of view it is possible to determine every single converter as either voltage regulating bus or power regulating bus.

The exact role separation depends on certain control mode of every converter, which can be set as constant voltage or constant power mode.

In constant *DC* voltage mode one voltage source converter is assigned to control the level of voltage and to keep it strict within a certain range of values. The constant voltage mode can be characterised by the voltage-power relation, how it is shown on Fig. 8.2

The bus associated with the converter in constant voltage mode of control is called a *DC* slack bus. The slack bus is responsible for overall power balance in the system.

In other words, the slack converter in constant voltage mode controls that the total amount of active power feeding into the system is dynamically kept equal to the total demand e.g. amount of active power supplied to load with the deduction of losses on conversion and transmission losses.

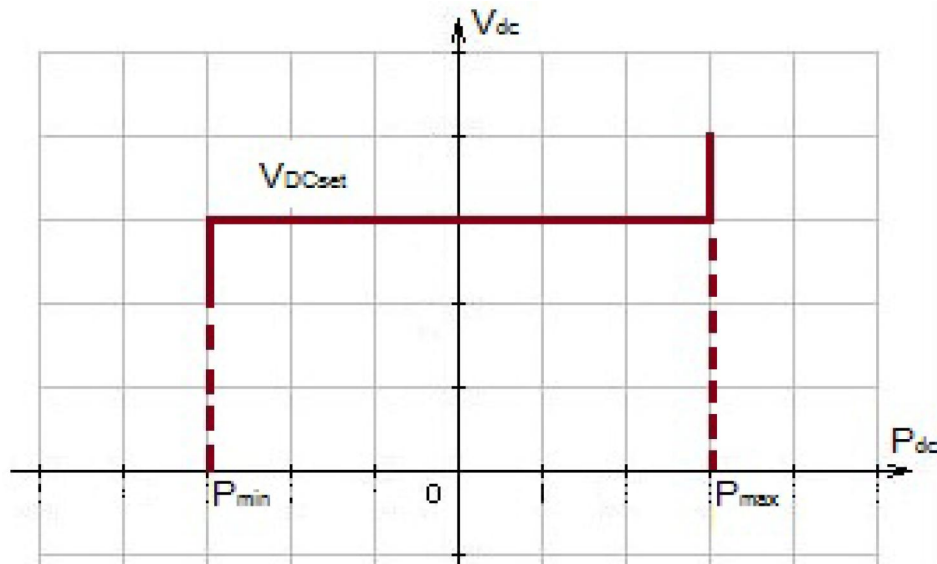


FIGURE 8.2: Constant DC Voltage Mode in HVDC Network.

This balance can be written as following:

$$P_{DC1} \pm P_{DC2} \pm \dots \pm P_{DCn} - P_{losses} = 0$$

Where  $P_{DC1} \dots P_{DCn}$  is the power at each terminal, positive sign corresponds to power in-feed, negative to power drain;  $P_{losses}$  – overall losses in the system.

This approach with constant voltage mode in a moment's consideration shows a certain similarity with conventional frequency control in high-voltage *AC* transmission systems. As there is no frequency in *DC* network, the level of voltage is used as a control parameter instead.

In multi-terminal configuration one terminal operates in constant voltage mode as a slack terminal, the others simultaneously operate at constant power control mode. The constant power control mode can also be characterised by certain voltage-power relation, how it is represented on Fig.8.3:

In reality, the combination of these two modes gives a required flexibility and accuracy in *HVDC* power system control. The complimentary method of power flow control is called a voltage droop-control mode. The method operational principle involves *VSC* stations activity to keep voltage level within the acceptable range around a fixed value and to balance power in *HVDC* system simultaneously.

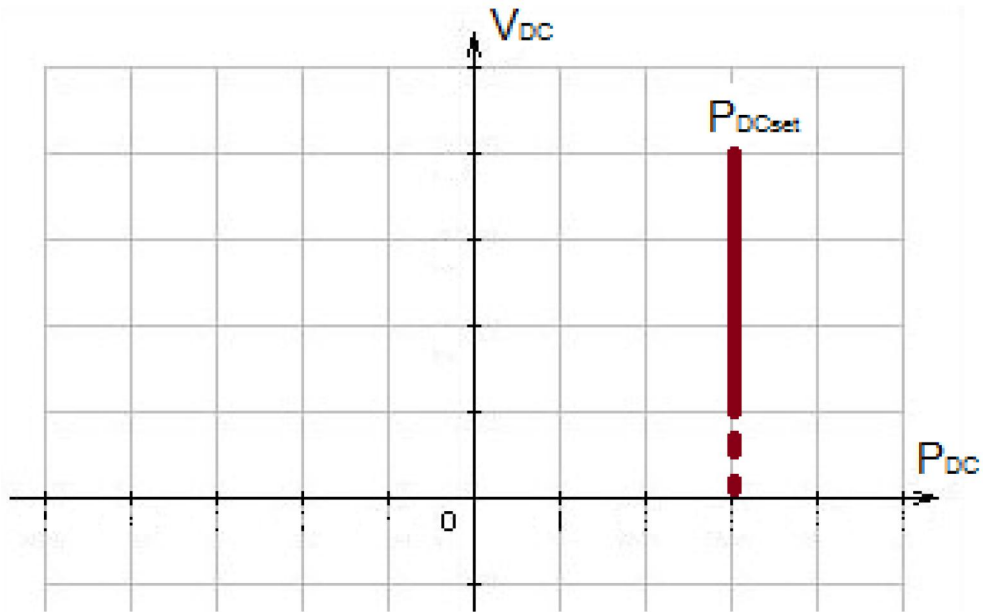


FIGURE 8.3: Constant DC Power Mode in HVDC Network.

The voltage-power characteristic diagram of the voltage droop control mode is shown on Fig.8.4

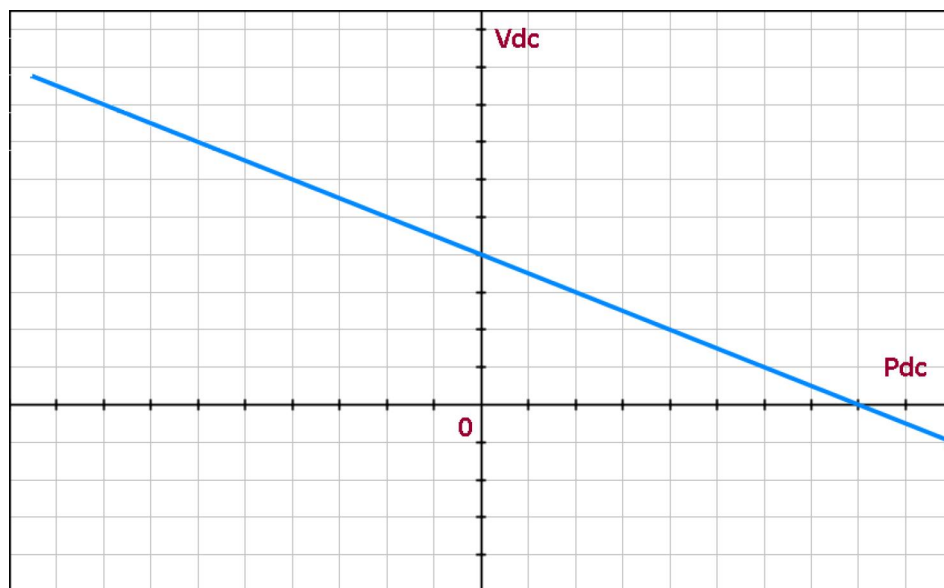


FIGURE 8.4: Voltage Droop Control Mode in HVDC Network.

It is worth to mention, that could be applied as an open-end concept and thus, every single converter station could participate in power flow balance with no information exchange required between converter stations. Moreover, this approach is expected to lighten the work of the master converter with slack bus.

## 8.4 Power Flow Control Simulations.

The initial state of power-voltage distribution in a meshed *HVDC* Network shown in Fig. 8.5 can be described by relatively simple results of power flow simulation of this network configuration.

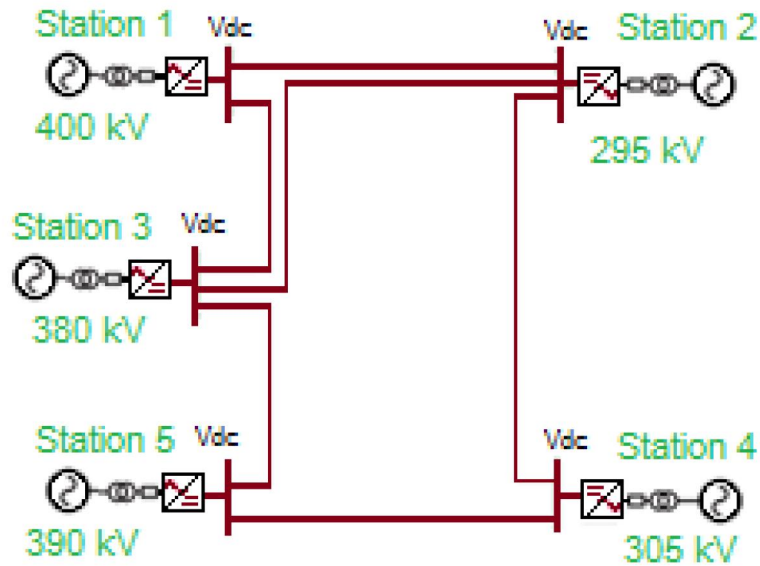


FIGURE 8.5: HVDC Network with Parallel Connection.

Power flow is controlled by voltage. Stations 1, 3 and 5 have higher voltage to assure power flowing from these stations to Stations 2 and 4 with lower voltage maintained.

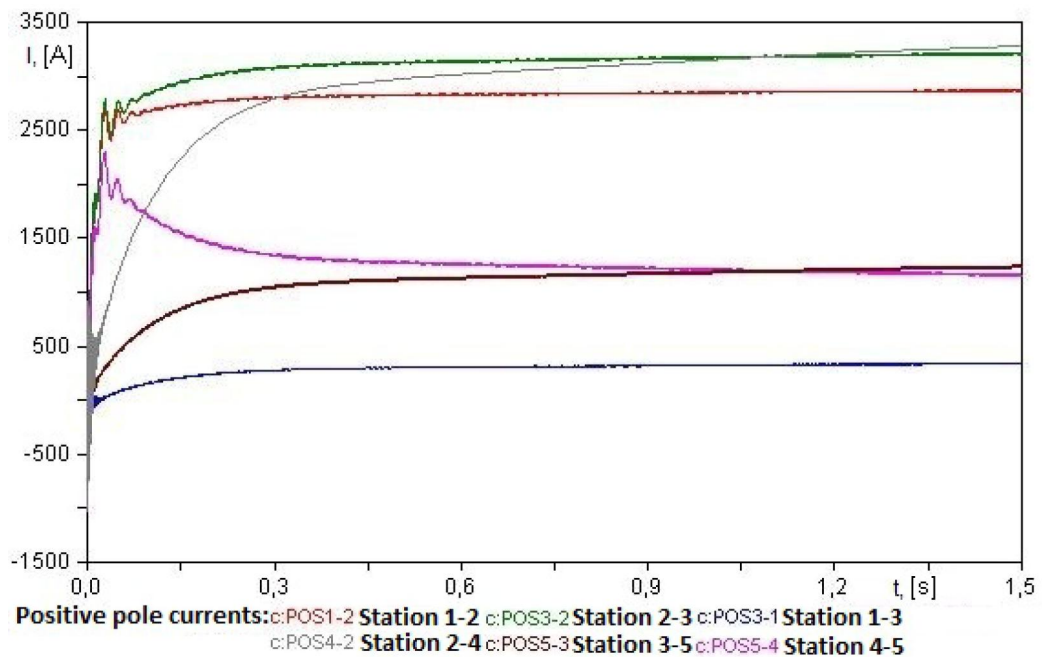


FIGURE 8.6: Initial State of HVDC Network.

At the certain moment the voltage at Station 2 rises, what may happen due to load decrease, and becomes slightly higher than at Station 4, but still significantly lower than at feeding Stations 1,3, and 5 Fig. 8.7. Nevertheless, such a minor variation leads to a completely different power distribution picture in a meshed HVDC network Fig. 8.8.

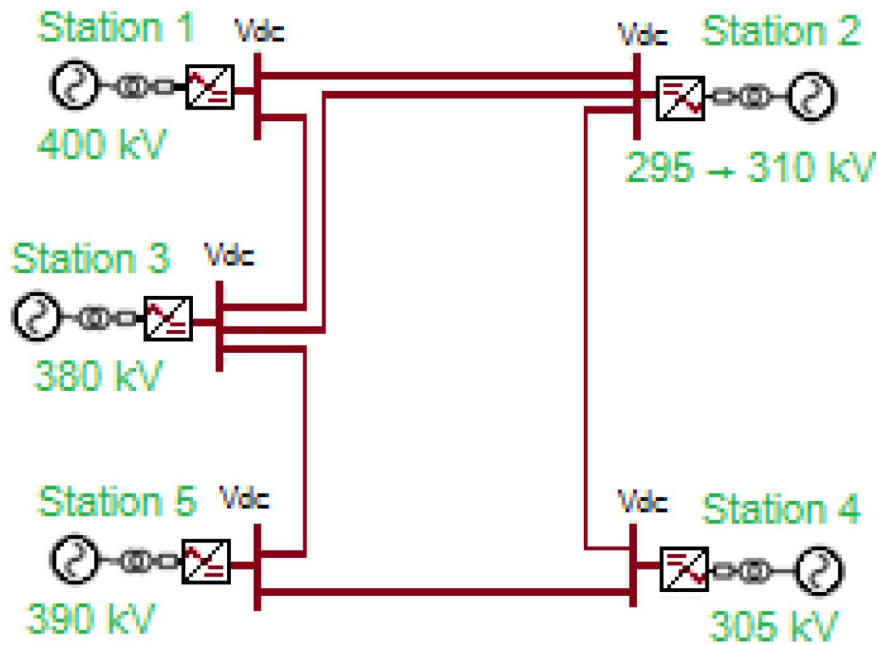


FIGURE 8.7: Model of for Power Flow Control.

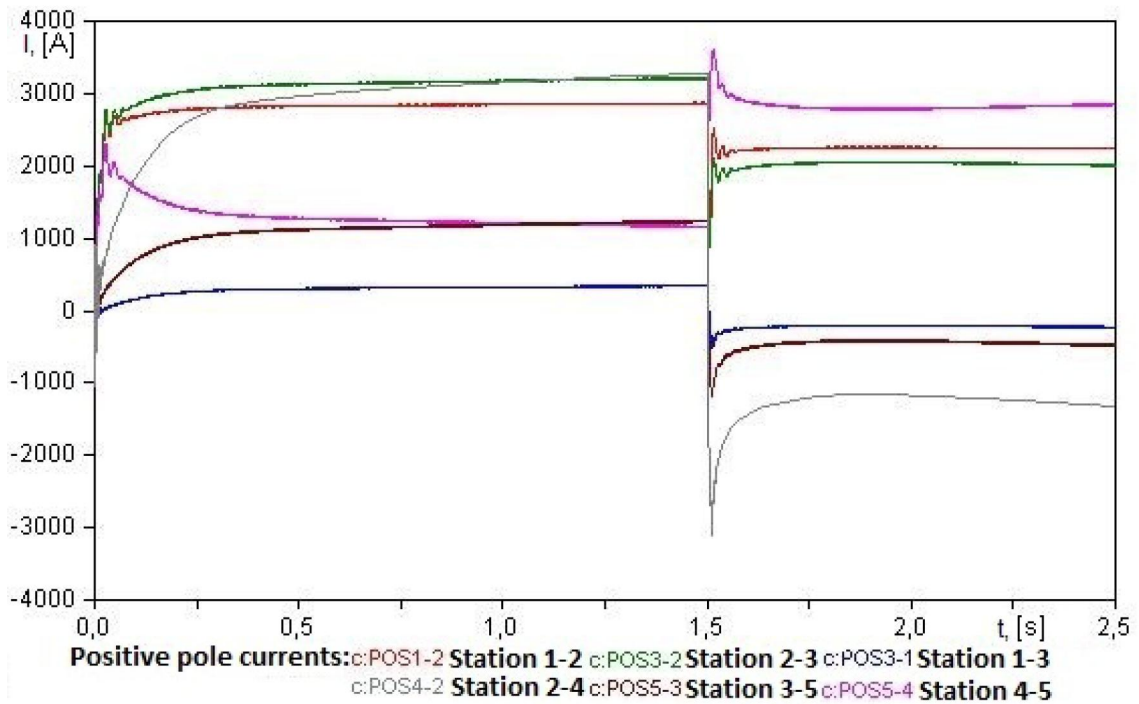


FIGURE 8.8: Transient and New Steady State Regime.

In the considered system, the power balance between in-feed and output is kept equal. To be more precise, the power balance in the presented simulation model is described as an equation between total power input on one side and total power output with associated transmission losses on the other side.

If we take a *DC*-voltage parameter as a power-balance indicator for the whole *HVDC* transmission system, then the power flow can be controlled between in-feeds with higher voltages and loads with lower voltages directly at corresponding converter stations.

However, as it can be clearly seen from the simulation results, applying the voltage mode for the power flow control, though an effective instrument, but not an efficiently sensitive one - a small change at one station may lead to a complete power flow redistribution in the whole system whenever it is desired or not. During power flow redistribution some of the transmission lines may become overloaded and thus, require a manual override control.

Consequently, the constant *DC*-voltage control mode shall be possibly supported by other effective power flow control methods and tools. This condition could be met by using the constant power mode in combination, when a *DC*-voltage indicator is not only a governing parameter, but can be influenced too.

It is possible, when following conditions are complied power regulation strategy. In a case of power surplus voltage will inevitably raise, whereas some extra load may, in turn, cause a power deficits and, consequently, an immediate decrease in voltage.

These parameters can be played around to reach the necessary power equilibrium in the meshed *HVDC* system seamlessly loading and un-loading transmission connections within their operational limits.

Mechanical reconfiguration of the *HVDC* transmission system, when only it is appropriate, could be used as well in gradual shaping of a certain power flow pattern.

## 8.5 Conditions for AC-DC Power Exchange.

Power exchange between *AC* and *DC* grids is another practical question. In this case, a voltage source station is considered as a point, that separates the grid into *AC* and *DC* parts with power consumption or injection.

As it was said above, power losses at converter station are just about a few percent and in the general case can be neglected. If these conditions apply, then power flow equation is quite simple – same amount of power flowing in and out e.g. energy balance equation.

Constraints are set on power amount, that can be transferred at every *VSC* station. These limitations will play a sizeable role in consideration of various regimes of multi-terminal *HVDC* network operation, for example, fault or maintenance cases e.g.  $N - 1$  reliability conditions.

Besides that, there are maximum bus voltage and maximum valve current limits to consider, especially when it comes to regulation with help of slack converter, constant voltage and constant power regulation strategy.

In *AC - DC* power flow every *VSC* station fulfils not only the coupling for the active power exchange, but also the reactive power compensation function. Thus, it becomes important to keep reactive power compensation ability ready at the certain point of the network, when and where it could be potentially needed.

A special attention shall be paid to the application of the half-bridge voltage source converter technology. In this configuration a close interdependence between *DC* and *AC* voltages is unavoidable. So to say, every change in the network configuration would necessitate voltage adjustments to a new level within the converter nominal range.

The full-bridge converter configuration gives an important ability to decouple *DC* and *AC* voltage with more degree of freedom. This technical solution might be uniquely positioned in a continuously changing context of the future *HVDC* network development.

## 8.6 Summary

In this Chapter some methods for power flow control, that are specific for the *HVDC* multi-terminal system, were considered. On the analogy of frequency in conventional *AC* systems, DC-voltage is a restrictedly efficient reference parameter for the power flow control in *HVDC* systems.

Although, the *DC*-voltage as the only control parameter is sufficient enough for the total power flow control in point-to-point or other relatively simple configurations of *HVDC* systems, the need for a more sophisticated strategy on power flow control becomes evident, when it comes to ability to directly manipulate the currents in all lines in a meshed *HVDC* system. Constant voltage and constant power modes in combination with each other may give a reliable control in more complex *HVDC* transmission systems.

For power flow calculations a five terminal *HVDC* system model was composed and simulated with help of *ATPDraw* software. In these simulations, the details on transient processes receded into the background and power flow re-distribution picture in the first instance depending on the control parameters applied is of the utmost interest.

Condition for power exchange between *AC* and *DC* grids were also discussed. Any converter station in the power exchange is considered as a point, that separates grid into *AC* and *DC* parts with power consumption or power injection.

However, depending on the converter technology applied, the separation can be real or fictitious. Application of full-bridge converter technology provides with real decoupling of *AC* and *DC* sides. Moreover, the ability of reactive power compensation, besides their primary converting function, may call these technology into operation at the certain point of the network, when and where it could be potentially needed.



## Chapter 9

# Future Research

Even though *HVDC* Networks have not yet become a part of reality, it has been already evident, that by the development of power energy infrastructure and implementation, a lot of practical questions and need for future research will only arise. Some of these points are discussed below.

- Further Advance in Power Electronics and Converter Technology

Fast-developing power electronic industry gives fertile ground to expect some advances in *VSC – HVDC* converter technology and key parameters increment such as rated voltage, rated current and power along with decreased losses and requirements on cooling, maximal *TRV* and short-circuit current withstand.

Negative factors that arise under short circuit conditions shall be minimized for *IGBTs*. In principle, the *IGBT* short circuit withstand parameters and overall performance can be improved by improving high impact parameters such as thermal impedance of *IGBT* housing , cooling intensity or wire bond contacts number.

The drawbacks of these measures are seen in increased costs, larger sizes and energy losses together with the basic contradiction of the *IGBT's* forward transconductance  $G_{FE}$ , which has a negative thermal coefficient. In other words, applying more powerful cooling system the *IGBT's* forward transconductance  $G_{FE}$  increases, and hence, increasing the short circuit current as well. [124]

Thus, experimental results of normal operating conditions in relation with various short circuit profiles should be considered to find an ideal rate and improve *IGBTs* performance with the highest possible efficiency for the whole system.

- Results Assessment

Repeatability and reproducibility of results as a rigorous scientific method of enquiry play an important role in research work. Reproducibility of simulation results is the test result characteristic that determines the proximity of the numerical models re-testing or re-simulation results.

It is one of the most important criteria to prove the data authenticity and to evaluate the significance of conclusions made on that behalf.

Thus, it is highly welcomed to repeat and possibly broaden the scope of simulations made for this work in future research by implementing various numerical simulation software described in Chapter 4 or any others suitable to this purpose.

- Counter-trends in Networks Development

The undergoing development and retrofitting of middle voltage distribution networks toward smart grids is another interesting perspective, that also should not be left out of account. Smart grid is seen at the moment as a key part in forming alternative hi-end energy supply infrastructure.

Instead of few large centralized power substations with only one pre-determined power flow direction to no other way than to passive consumers, *SmartGrid* concept suggests the flexible continuous interaction between end-customers and network, where both parts may play a role of energy producers or consumers changing off each other.

Successful realisation of based on smart grid paradigm obviously would influence *HVDC* network planning too. Simultaneously many questions on compatibility and interoperability of *SmartGrids* with *HVDC* transmission technology should be addressed in future research works.

- Classification and Standardisation in *HVDC*

To be able to study *HVDC* network disturbances more deeply and systematic the latter ones shall be carefully classified just as it has been done for some transmission system operators and *AC* networks in guidelines for the classification of grid disturbances. Type of faults and grid disturbances, duration of grid outages and other issues could be more precisely defined there and based on that then modelled with higher accuracy.

By means of simulations and real time tests it might be set to which stresses *HVDC* converter station equipment, for example, might be exposed to. As one of the following steps, the standardization for *HVDC* applications performance based on the related data may be done too.

- Equipment Compatibility Issues

Evidently, equipment compatibility from different manufacturers shall be taken into account too, not only in case of disturbances, but also in sense of common operational alignment. If AC equipment standards and norms were developed for various regional markets separately, now it is the greater opportunity at a well-chosen moment to work out the globally accepted standards, preferably one for all at once.

This should be done through cooperative research and opinions exchange, open platform discussions with participation of all experts and parties interested, and through activity of well-reputed international technical professional organizations, councils and institutions like *IEEE*, *CIGRE* etc.

Clearer regulation and strategic vision will, by all means, influence positively *HVDC* network planning in the middle and especially long-term. However, emerging of *HVDC* network will, in its turn, inevitably influence energy policies overhaul in many countries as well. Unavoidable uncertainties shall be possibly kept within short-term planning time-frame and cleared-off in a timely manner.

- Real-time Grid-Control

As the balance in *HVDC* network should being found dynamically at every point, the system parameters like voltage and power at converter stations and current in lines etc. have to be dynamically kept within the allowed operational limits.

To cope with dynamic balancing state of a network with many time-variant and inter-dependent parameters in running condition a real-time grid control model may be of help. Thus, there is a need to develop a real-time running model of all *HVDC* interconnections forming *HVDC* networks. With the help of the model real-time calculations with available from distributive computing facilities shall provide with several optional operational regimes alternatively acceptable at a time and possibly with short-term pre-calculated prediction.

Real-time grid control model, that is to be run by computational capacities of the electrical power system dispatch centre, could be also possibly supported by some separate modules located remotely at certain control points and responsible for various crucial system parameters.

This might be exceptionally helpful for finding an optimum in power flow regulation as *HVDC* grids can be dynamically adjusted. Another evident advance is to improve stability and security concerns, as the data could be provided by different independent channels based on the open-end and closed-end philosophy excluding mal-synchronisation of different parts of the *HVDC* network. For example, in the case of a fault or even a chain of critical events following one after another.

- Control Strategy for Converter Stations

As it has been discussed in Chapter 8 the further studies on enhanced control strategy and optimisation of power flow management is needed.

The focus should be paid towards such strategies that would allow converter stations in meshed multi-terminal network act independently or at least with the highest reachable grade of freedom on input/output between AC and DC networks. Full-bridge *MMC* topology is seen the most appropriate candidate to fulfil these requirements.

Questions on power injection and interaction between *HVDC* and conventional *AC* grids with ever growing penetration of highly intermittent wind power generation are worth significant research efforts too.

- Arc Behaviour Study

The further optimisation of interruption capability of *DC* breakers may not only proceed in the direction of hardware elements improvements. It is known that arc characteristics under certain conditions may significantly refined the overall operation of *DC* circuit breaker.

So, it is advisable to concentrate not only on elements of *DC* breaker itself, but also on study of arc that may potentially lead to fast-growing oscillations and smooth current interruption.

Further optimisation of *DC* breaker performance is rational to consider together with arc behaviour.

The well-managed and predictable process of optimal oscillations excitation is a core-point for understanding arc burning process and thus, for successful *HVDC* design and reliable operation in multi-terminal *HVDC* networks with large amount of *DC* breakers applied.

This can be partially done by mean of *EMTP* simulations. The proper model of arc needs to be thoroughly developed and proved against the reality. [125] and [126]

- Interaction between DC Breaker and *HVDC* Power Systems

With help of electromagnetic transient simulation program, a number of deep and specific questions on the interaction between complex *HVDC* power systems and *DC* breakers can be potentially answered. In many studies the arc is modelled as a black box model.

This approach is reasonable, when the focus is mostly on transmission network behaviour, but when the research focus shifts closer to a *DC* breaker, the more precise

and detailed arc model is necessary. Verification and calibration of arc parameters and simulation results must be accompanied by experiments and practical results.

- Solid-State Devices Development for DC Breakers

Current interruption process depends also on solid-state switching devices. Thus development and related research in this direction should lead to new materials application with better performance characteristics.

Especially known semiconductors drawbacks such as high on-state losses shall be covered by further research and possibly improved to acceptable values. This may be particularly beneficial in hybrid DC breaker configurations.

- "Fast-Switches" in Hybrid DC Breakers

Another core point what also may have a particular application in hybrid *DC* breaker configurations is a so-called fast switch.

If it becomes realistic for high voltage breakers to interrupt the fault current with the value of 10 – 15 kA within few milliseconds then probability of hybrid *DC* breakers to be applied in multi-terminal *HVDC* networks becomes very high.

The technical solution relying upon the fast mechanical switches on board, remains viable even if it would be necessary to arrange them in series to get the desirable voltage level.

- Fault Current Limiters for HVDC Grid Application

Scaling up may be necessary for fault current limiters to be applied in *HVDC* networks. At the moment most of them are designed for medium voltage distribution networks. Higher voltage levels are served by limiting reactors and resonant-circuits with in-line capacitors.

Tapping into the field of fault current limiters, intended for transmission high-voltage levels, opens up many new opportunities for *HVDC* breakers as well.

[116]

# Conclusions

In the present work it an attempt has been made to describe, as fully as possible, the main conceptual aspects of high voltage direct current (HVDC) transmission networks, as well as, their possible development in the coming future, their optional structure, advantages and obstacles, that are still quite many on the way of the realisation of first HVDC multi-terminal network projects worldwide.

Building reasonable plans for the future becomes solid, when at first the present state of HVDC transmission technology is accessed and taken into consideration. The general survey of the current situation with some important historical insight has been made to get deeper into the subject.

Although in many sources the HVDC transmission technology is considered as an innovative one, especially in terms of its application in fast-developing on- and off-shore renewable generation with implementation of state-of-the-art power electronic devices, materials, tools, processes, skills, know-hows, etc., in fact, it has own quite long history of development.

Technological breakthroughs in solid semiconductors technology naturally became a turning point in the HVDC development. Many new power electronic devices have been introduced to make AC-DC conversion more cost effective, smooth and reliable.

Intensification of research and development efforts to further improve crucial technical parameters such as limited power capacity and voltage capability, acute needs for intensive cooling etc. of current devices will bring their performance to the next operational level.

Before all, the new technical parameters of solid semiconductors should add to the most recent VCS-MMC converters technology performance and unlock their potential in full and broaden their area of application. At the moment, the most powerful ultra-long transmission links still operate with thyristors-based line-commutated converters - LCC.

Several potential benefits of HVDC power transmission have been described. An HVDC transmission represents a more flexible and smart solution for of renewable energy integration, what makes it preferable over conventional high voltage AC transmission.

A number of crucial disadvantages and temporarily existing shortcomings have been also discussed together with clear advantages, specific niches and potential benefits of HVDC power networks as a viable option for high voltage power transmission in the nearest future.

It shall be understood, that many of the mentioned bottlenecks of HVDC transmission are permanent and could be solved through-out further research and practical operation.

Thus, it has been concluded, that HVDC transmission has a certain potential and own exclusive applicability, where only the HVDC-based solutions may be beneficially applied.

Many case-specific factors come into force on estimation of power losses and on technical and economical comparison between HVDC and conventional high voltage AC transmission. It turns out that the analysis becomes quite a complex and non-trivial task and shall be considered more carefully on the case-by-case basis.

Some general typical features of HVDC projects have been determined. In most cases, realisation of huge HVDC projects implies enormous initial investments significantly exceeding the known initial investments in conventional AC transmission projects.

This should be evaluated as unavoidable costs mainly due to high costs of converter stations. Nevertheless, the total operational costs, including improved power delivery capabilities, reduced transmission losses, environmental excellence, relatively small footprint area and etc., in long-life systems and especially for long-distance transmission links, may be more favourable to HVDC solutions.

Constant and ever growing interest in HVDC technology will gather headway, with its aim at solving existing puzzles and getting a number of technology breakthroughs in several crucial for HVDC directions, what will facilitate implementation of innovative HVDC projects shaping the future transmission network in the years ahead.

Serious challenges over the next few decades are anticipated. Solving these issues, at the same moment, would give a strong impulse and unseen opportunities for further development, if these challenges to be resolved smartly, effectively and on time.

Various configurations of network and converters have been also discussed. Obviously, all of them have own advantages and disadvantages. Though, for future long-distance high power HVDC transmission networks a bipolar configuration with separately provided metallic return path appears to be the most profitable and suitable solution.

In today's electric grid with the remote generation, a significant amount of power is lost on transmission and distribution stage. This situation, we have in place right now, could be significantly improved by letting high and medium voltage HVDC applications more penetrate into existing electric grid. The synergy effect in this case might be even more pronounced in comparison with pure usage of only AC or only DC solutions in transmission grid.

The importance of long-lasting effect on the planning and development of the transmission network should be recognised. The power energy infrastructure that is being built these days will serve our needs in next 30-50 years. So, the current projects shall not only meet our current needs, but also to a certain degree be resilient to the needs of the future network expansion.

Predicting the future needs of transmission grid is a big challenge connected with the highest degree of uncertainty for all power system planners worldwide.

The best approach, that has been found very practical so far, is to envisage a number of future scenarios covering the most plausible development changes in transmission networks.

Some of these scenarios for the German transmission network have been mentioned in this work as well. The significant role in the grid development in these scenarios has been deliberately given to point-to-point HVDC links connecting northern regions and located there well-developed on- and off-shore wind generation with southern industrial load centres.

The most plausible solutions are required to address the needs of network development in all or most scenarios. If it happens, the suggested developments are considered robust, viable and able to meet the widest envisaged range of needs on the network.

Some possible scenarios for Europe and other parts of the world have been additionally discussed in fewer details.

Possibly the highest risk to the efficient development of any transmission network is the one, that any of present projects will not be ideally suited to act as part of the network in future.

Dealing with these risks many decisive factors shall be taken into account. Namely, those certain factors, which will shape the future grid configuration on all continents.



The factors such as anticipated industrial growth and rising at a rapid rate live standards in developing countries, road maps on existing, approved or planned bulk generation of power, possible cooperation and trade unions, delayed consequences from political decisions, technical bottlenecks and advances, and etc.

As it is seen from today, HVDC transmission systems will incorporate various converter technologies like conventional LCC, VSC - half- and full-bridge converters and probably some other converter types, that are being considered as experimental at the moment, from different manufacturers and operating at various voltage levels.

This poses additional pressure on network planning experts. A broadly collaborative approach is required to establish a common base for secure and reliable HVDC network of the future.

Important issues on HVDC transmission network operation also include cooperative development of HVDC worldwide standards, guidelines, codes and regulations.

It is clear, that in many developed regions of the world it will not be a pure HVDC network. Just the opposite, the HVDC grid will have many connections and points of intersection with the already existing AC transmission infrastructure. The continental European or North-American power grid can be a good example to illustrate this hypothesis.

In developed regions we will likely see the typical distance for HVDC links ranging between ca. 250-500 kilometres and the typical voltage level will be about  $\pm$  300-600 kV carrying app. 2-3 GW of power.

However, in North America, Russia and, perhaps, Australia due to longer distances and higher demand to transmit more power over few transmission links may rise the voltage level and carried capacity accordingly.

In some developing regions like Africa, South America, South-East and South Asia these values might be far exceeded in voltage level and transmitted power. For HVDC transmission links over 1000 km the voltage level may rise up to 1000 kV and even higher. Some experimental HVDC links are being tested at the moment.

Under certain circumstances, high voltage overhead AC lines with FACTS technology are seen to be a reasonable alternative to HVDC transmission links and shall be project-based evaluated in terms of investments and performance effectiveness.

Recent and very rapid development of on- and off-shore wind parks in the North and Baltic Seas implies several big construction projects with cables laying under the sea establishing HVDC interconnections between regions.

Soon and successful realisation of these projects will have a great potential to shape the first meshed North European HVDC Ring.

A similar situation can be potentially expected in the Far-East, where realisation of HVDC connections in the Sea of Japan and the East China Sea may compose in such a way the North-Eastern Asian HVDC Ring with similar parameters.

Constructing of HVDC transmission interconnections would facilitate a shift towards a common energy market, strengthen regional power grids, intensify power transfer between countries and unified grids solving problems with isolated energy islands, optimizing the whole network configuration.

Transient behaviour of HVDC transmission network and power flow studies are the core part of the present thesis. For these studies and simulations of various HVDC applications and power grid configuration the ATP-EMTP software has been applied.

The ATP-EMTP software is among a number of other transient simulation programs is considered as a powerful tool proved to be very useful for transient studies of high voltage applications and power systems.

Some inherent limitations of this method to describe the reality even by multi-factor and detailed models have been examined.

Additionally, proper application of various representations and models has been considered. It has been concluded, that the Pi-line representation is best applicable for steady-state analysis, whereas for long distance lines and analysis of transient processes, due to higher accuracy and numerical stability in simulations, the frequency dependent models should be applied.

The employment of the modal transformation matrix may cause certain distortion and numerical instability in simulation results.

Frequency-dependent phase domain models do not use this transformation and, consequently, related to it frequency dependence of the transformation matrix. Thus, the higher precision in the obtained results can be obtained even for complex simulation cases.

Several different HVDC network topologies have been considered starting from the most simple point-to-point connection gradually increasing in complexity to five terminal ring configuration and meshed power grid configuration.

For the all mentioned topologies, the simulation results have been presented as a plot of few sequential states. Namely, switching-on transients, pre-fault steady-state, transients related to pole-to-earth fault, and finally, new after-fault steady-state regime.

In all simulated cases, the distributed parameter frequency-dependent phase domain models of over-headlines have been applied. These results are claimed to be valid for cable-based grids too, with the proviso, that due to much larger capacitance, naturally inherent to cable lines, the fault current peaks would be more pronounced and energisation and de-energisation of a cable line will take longer.

In all models the operating voltage has been set on the level of 400 kV, what corresponds to the highest voltage in the European transmission network at the moment and to common sense expectations on the future continental power inter-exchange rates.

The pole-to-earth fault, as statistically most frequent emergency situation, has been taken as a basic scenario in all simulated cases. Even though, it has been recognised the fact, that pole-to-pole fault may cause more severe consequences, statistically pole-to-pole faults in properly designed bi-polar HVDC lines are considered as an event of very low probability.

Ground resistance has been assumed the same for all simulated cases and all locations, and thus, has been not varied at various points. Thus, it may be suggested, that ground resistance in different locations to be considered as a variable value in future investigations.

Normal operation, fault current clearance and re-closing have been modelled for VSC multilevel converter topology. The converter is capable of breaking the short current safely within few next milliseconds after the fault, so the most vulnerable in these conditions IGBT elements remain within their operational limits.

For the considered multi-terminal network configurations it can be concluded, that pole-to-earth fault in one DC line quickly propagates to the whole network without exception and within next 100 milliseconds reaches its peak about 50 kA.

Thus, a fast and reliable control and protection system along with special protective measures such as DC circuit breakers, fault-current limiters etc. are absolutely required to operate multi-terminal HVDC grid safely.

In bi-polar lines, the second pole of a faulty line, as it has been shown in simulations, experiences only minor disturbances and, thus, may still safely remain in full operation. So that, in power network contingency studies the rule N-1 and related to it considerations shall be applied to only one pole and not to the whole bi-pole line.

As a result, bi-pole based HVDC networks are thought to have the greater rate of reliability, robustness and fault tolerance.

Ring topology, as a meshed power network configuration, has been modelled for fault transient studies. This configuration, where all stations have only two connections with other ones, is seen to be quite simple in planning, construction and exploitation (i.e. power flow management, control and protection etc.) and has lower initial costs in comparison with more densely meshed network configurations.

Nevertheless, due to the lower reliability and flexibility, for example by power flow optimisation in the event of an accident, the ring topology may become the less favourable option versus more meshed topology in the long run. This could be fixed by adding another one or few interconnections inside the ring.

Three fault cases for meshed configuration of multi-terminal HVDC network have been simulated. In comparison with radial or ring power network topologies, the meshed configuration offers stronger qualities such as increased redundancy and overall system stability, higher flexibility in power flow control, and thus, lower operational costs.

Availability of reliable HVDC protection and control system, besides the assumed availability of DC breaker, have been defined as a cornerstone towards meshed HVDC networks.

The operational environment of HVDC protection system presents many similarities with protection of long lines AC and, at the same time, possesses certain specifics, which typical for the multi-terminal HVDC solutions only.

Based on simulations performed, the existing AC protection principles have been evaluated against DC grid conditions. It has been found, that in HVDC multi-terminal operation some fundamentally new principles should be considered and applied in order to facilitate uninterrupted operation of the transmission network.

Initial requirements on HVDC control and protection system for completely new operational environment and tasks and for various parts of HVDC network have been mentioned. At the moment there are several known prevailing principles that tend to give a solid basement for HVDC control and protection system development.

Precise fault location together with secure detection of vulnerabilities would allow more accurate neutralisation of fault prime cause and timely separation of equipment and healthy lines from a fault in a controlled way. Constant monitoring of the network parameters would support to differentiate various conditions on the base of information collected and processed.

Protection system needs to be designed with a certain redundancy. Main protection zones may in some points overlap each other, but this shall not result in the doubling of activities with the delay response time required to detect and isolate a fault in an HVDC system. A protective algorithm should take into account more than one single parameter before tripping procedure is activated.

A network arrangement with several protection layers has been suggested. An optimum could be found in the combination of very fast protection, limited to its zone of responsibility and relatively slow protection with significantly improved selectiveness.

A complementary compromise between both options is believed to be a viable and reasonable solution. The main protective layer can be additionally supported by less sensitive protection algorithms serving in a system as backup functions.

Selectivity of protection should be taken into account to reduce the number of false activation of emergency tripping. In multi-terminal operation the minimal effect on the system from the forced outage and the maximal possible power transmission ratio through unaffected parts of transmission system shall be ensured in every possible way.

Protection and control in HVDC grids to a greater extent depends on the grid topology and on the presence and interruption capabilities of sufficiently fast and reliable HVDC circuit breakers to ensure certain selectiveness at the scene of the accident.

The "closed-end" and "open-end" protection principles have been considered. Ability to operate within very short tripping time may favour "open-end" protection scheme, for example, in long HVDC transmission links, where an issue with slow reaction of "closed-end" protection, due to signal transfer time delay, may become insuperable. Moreover, in the long distance transmission links a robust coordination between remote measuring devices and their interconnection via the reliable communication channel is needed. The "open-end" based protection may operate without ancillary equipment making these complications optional.

However, the "closed-end" protection concept can be well implemented in meshed HVDC networks, where the assumed distances between terminals hardly exceed 300-500 km. "Closed end" and "open end" concepts may be successfully implemented on different protection layers in the same system simultaneously.

The supplementary combination of these protection types also presents a legitimate solution that may compete with both on equal ground or complement the “converter fault-blocking” approach, which foresees no usage of HVDC circuit breaker in radial or ring systems, but lacks certain selectiveness in more meshed topologies.

The principal difference between “steady-state based” and “transient-based” protection have been explained and illustrated. In direct current transmission, the steady-state approach is of little value. Thus, a weighted decision can be made based on samples collected by transient-based protection algorithms.

Several essential contradictions for HVDC protection system principals have been identified: a rapid fault location and tripping are possible with locally placed measurement devices at every essential node of a network ("open-end" concept).

Obviously, it results in better operational conditions for HVDC breaker: lower fault current amplitude and steepness, reduced need for energy dissipation, etc. At the same time, quick protection algorithms and short interruption time imply lower resolution and lack of selectiveness.

On the other side, the improved selectiveness implies the increased interruption time and more stressful operation conditions for HVDC breaker.

Common requirements on protection have been formulated in form of "six-S" requirements, namely - security, sensitivity, selectivity, speed, survivability and surveillance.

Also, it has been concluded, that even though the expected HVDC operation conditions may impose rather strict requirements, which are hard to meet with the existing protection system, the HVDC protection is by no means an insurmountable obstacle towards the potential multi-terminal grid. However, new protection algorithms may require new non-trivial solutions and come at a cost.

HVDC breakers are considered an integral part of multi-terminal HVDC transmission network. The current absence of reliable DC breaker for high voltage application has been seen as one of the main milestones on the way to MT-HVDC networks, where breaker's responsibilities are reconfiguration of grid, increased selectivity and fault clearance, power flow regulation and etc.

Although there is no HVDC breaker available on the market with a reference in implemented projects at the moment, a number of various concepts have been recently suggested and intensively discussed in the scientific and engineering experts' community.

All of them can be classified into few groups: DC mechanical breakers based on conventional AC interruption technology, pure solid-state DC switches, various hybrid DC breakers without or with ultra-fast mechanical switch, some other concepts, where DC converter station together with proper regulation methods together with protection and control system may complement and facilitate DC breaker performance, and etc.

All current DC breaker concepts are limited either by interruption time, or interruption current capability and high voltage withstand capability, what is naturally identified as the main contradiction in current breakers design. The higher the interruption speed the easier fault conditions for DC breaker to interrupt, however, interruption speed is limited to physical properties of breaker elements.

On consideration of their advantages and disadvantages, the combination of most promising concepts may result in successful DC breaker configuration. Search for such a successful configuration is still going on.

Optimisation of high voltage DC breaker design and interruption performance shall be directly tied with system topology and protection concepts optimisation, what is demonstrated by power system simulations in the present work.

The main focus of mechanical breakers development shall be paid on resonance circuit size minimisation and prevention counter impulses generated in this circuit from penetration into the power system. Another challenge in this concept is the harmless dissipation of a large amount of energy stored in the resonance circuit.

Main breakthrough solutions in pure solid state breakers are expected in wide-band-gap semiconductor applications with use of experimental materials. Their limits to applicability and performance related characteristics shall be carefully and diversely investigated by materials and components science experts.

Combining advantages of both concepts – mechanical and pure solid state, a hybrid DC breaker concept comes into being. This concept has all the potential to become efficient and viable solution with desirable performance parameters.

Development of so-called fast mechanical switches could bring the hybrid breakers technology to the new technological edge securing low on-state losses, few milliseconds of interruption time and acceptable level to withstand high over-voltage impulses.

Multilevel VSC converters could be applied in ring or radial networks realising “converter-fault-blocking” concept without circuit breakers implementation at all. This interruption approach is fast, but has too low selectiveness for densely meshed network topologies.

Basic requirements on HVDC breakers have been formulated. Among other issues they are: request on efficient design of VSC-HVDC converters and sufficient compatibility with HVDC control system; quick interruption time and low power losses; also they should be acceptable for transmission networks voltage and current ratings.

The ability of DC breaker not only to interrupt the fault current, but also to re-close fast and efficiently, is of utmost importance. Close interrelation with protection algorithms shall enable DC breakers to recognise risk level and hazard category in detailed elaboration to successfully cope with different types of faults such as pole-to-ground and pole-to-pole faults. Switching and surge over-voltages withstand of a DC breaker is of high importance as well.

DC fault current limiters may also find their broad application in HVDC networks. Use of conventional and superconducting FCLs significantly reduces requirements on interruption capabilities of a DC breaker, facilitates distinguishing of hazardous current under fault condition or potentially dangerous peaks smoothing in transient events.

Still, reducing the interruption time and the short circuit current level, the converter and circuit breaker TRV capability needs to be appropriately increased too. As in this situation, the maximal amplitude value of TRV increases and reaches its peak in a less time, i.e. the RRRV increases, if short circuit current reduces. Here another principal contradiction is found with the recognition of the fact, that the balanced approach reinforced by transient simulations is required.

Methods for power flow control, that are specific to HVDC multi-terminal system, have been described and simulated. On the analogy of frequency in conventional AC systems, DC-voltage is a restrictedly efficient reference parameter for power flow control in HVDC systems.

Although, the DC-voltage as the only control parameter is sufficient enough for the total power flow control in point-to-point or other relatively simple configurations.

A more sophisticated strategy on power flow control becomes evident, when it comes to the need to directly manipulate the currents in all lines in a densely meshed HVDC power system.



To illustrate that by power flow simulations a model with five terminal HVDC system has been composed with help of ATPDraw software. In these simulations, transient processes receded into the background, whereas power flow re-distribution picture, depending on the applied control parameters, was of the utmost interest.

From these simulations, it can be concluded, that the DC-voltage, as the only control parameter, gives a certain possibility to re-distribute power flows within the relatively simple network.

However, with the increase of terminals number usability of DC-voltage as the only control parameter decreases rapidly, as the voltage margin between terminals becomes too small to rely on.

Constant voltage and constant power modes in combination with each other may give more reliable control in complex HVDC transmission systems.

The condition for power exchange between AC and DC grids have been also discussed. Any converter station in the power exchange is considered as a point that separates grid into AC and DC parts with power consumption or injection i.e. either load or generation.

However, depending on the converter technology applied, the separation can be real or fictitious; as, for example, in half-bridge voltage source converter technology a bidirectional current flow between DC and AC voltages is unavoidable. Whereas in contrast to it, the full-bridge converter technology offers a valuable advancement and the AC-DC separation becomes real.

The application of the full-bridge converter technology gives more degree of flexibility in decoupling AC and DC sides, when and where it is necessary.

Moreover, the ability of reactive power compensation may call these converter stations into operation at the certain point of the network, if it could be potentially needed besides their primary converting function.

# Appendix A

## ATPDraw Program Code.

### A.1 MODEL VSCRECT

```
INPUT UA, UB, UC
VAR V1, V2, V3, SIGN1, SIGN2, SIGN3
OUTPUT SIGN1, SIGN2, SIGN3

INIT
SIGN1:=0, SIGN2:=0, SIGN3:=0
ENDINIT

EXEC
IF dV1/dt>=dV3/dt AND V1>=V2 AND V1>0 THEN SIGN1:=1, SIGN2:=0, SIGN3:=0
ELSE SIGN1:=0
ENDIF

IF dV2/dt>=dV1/dt AND V2>=V3 AND V2>0 THEN SIGN1:=0, SIGN2:=1, SIGN3:=0
ELSE SIGN2:=0
ENDIF

IF dV3/dt>=dV2/dt AND V3>=V1 AND V3>0 THEN SIGN1:=0, SIGN2:=0, SIGN3:=1
ELSE SIGN3:=0
ENDIF
ENDEXEC
ENDMODEL
```

## A.2 MODEL MMCSWITCH

```
MODEL MMCSWITCH
```

```
INPUT x, y, z, % operands% "AND", "OR", "NOT"
```

```
VAR y(0...1), g(0...1), c(0...1), SIGN1, SIGN2, SIGN3
```

```
OUTPUT SIGN1, SIGN2, SIGN3
```

```
DATA b=const. B=50Hz, t - "TIME"
```

```
x>0
```

```
x=0.8 - const. "AMP"
```

```
INIT
```

```
X>0, y=(0...1)
```

```
x*y=z, z=(0...1)
```

```
SIGN1:=0, SIGN2:=0, SIGN3:=0
```

```
ENDINIT
```

```
EXEC
```

```
X>0, y=(0...1), c=(0...1), g=(0...1)
```

```
b*x*y=z
```

```
IF t<=0.3 %0.0 till 0.3 THEN g=1, c=0, OR=1=y % THEN g:=1, c:=0
```

```
IF 0.3<t<0.5 %t=0.3 till 0.50 % THEN g=0, c=0, OR y=0
```

```
IF t>0.5 %t=0.5 till 1.50 % THEN g=0, c=1, OR y=1,
```

```
ELSE SIGN1:=1, SIGN2:=1, SIGN3:=1 %deliberate mismatch%
```

```
ENDIF
```

```
IF g=0 AND c=0 THEN y=0
```

```
IF g=1 OR c=1 THEN y=1
```

```
IF g=1 AND c=1 THEN y=1
```

```
ENDIF
```

```
ENDIF
```

```
ENDEXEC
```

```
ENDMODEL
```

### A.3 MODEL TACSWITCH-ON / -OFF

```
MODEL TACSWITCH-ON / -OFF
```

```
OUTPUT SIGNAL
```

```
DATA Tinit
```

```
VAR SIGNAL
```

```
INIT
```

```
SIGNAL:=1
```

```
ENDINIT
```

```
EXEC
```

```
IF t>=Tinit THEN SIGNAL:=0
```

```
ENDIF
```

```
ENDEXEC
```

```
ENDMODEL
```

```
-----  
OUTPUT SIGNAL
```

```
DATA Tinit
```

```
VAR SIGNAL
```

```
INIT
```

```
SIGNAL:=0
```

```
ENDINIT
```

```
EXEC
```

```
IF t>=Tinit THEN SIGNAL:=1
```

```
ENDIF
```

```
ENDEXEC
```

```
ENDMODEL
```

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