

Medium and Low Voltage Distribution Grid Network Composition Analysis and Review for the North American and European Networks

Master Thesis

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Abstract

The Distribution Network (DN) in Europe and North America today is witnessing a paradigm shift in operation from a conventional passive system where a top to bottom active and reactive power flow is maintained with a low level of monitoring to an active system where the power flow has become bi-directional with the influx of Distributed Generators (rooftop solar photovoltaic units, wind generating units, etc) in the low voltage (LV) and medium voltage (MV) networks. This implementation of DGs poses power quality problems as it causes stress on the existing voltage regulating strategy in the DN. To tackle this issue, utilities in both regions are integrating smart devices for controlling and monitoring the DN to guarantee power quality for their customers.

The initial part of this paper focuses on individually and collectively studying the factors that determine how a network responds to voltage control. After which the impact and response of various load types and composition to voltage control were analysed. The difference between the MV and LV grid topology of the two regions was also highlighted. The second part of the project concentrates on the conventional and improved control devices implemented by utilities for achieving voltage stability. A case study of a representative network from both regions highlighting the advantages and challenges faced by adopting automated voltage regulation (AVR) was also carried out in this paper. In addition, the historical failure of the grids of both regions was examined to identify how the grid will react when a voltage control tool fails intending to suggest possible solutions.

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List of Acronyms

A

alternating current

(AC) · 6

Automatic Voltage Regulation

(AVR) · 36

C

combined heat and power

(CHP) · 1

Conservation voltage reduction

(CVR) · 42

D

degree Celsius

(oC) · 15

distribution network

(DN) · 4

E

extra high voltage

(EHV) · 6

F

Fixed Capacitor – Thyristor Controlled Reactor

(FC-TCR) · 39

H

high voltage

(HV) · 1

L

line voltage regulators

(LVR) · 38

low voltage

(LV) · 1

M

medium voltage

(MV) · 1

N

No load Tap changer
(NLTC) · 37
nominal voltage
(Vn) · 25

O

On-Load Tap Changer
(OLTC) · 36

R

renewable energies
(RE) · 1

S

Series Voltage Regulators
(SVR) · 38
Static Synchronous Compensator
(STATCOM) · 39
System Average Interruption Duration Index
SAIDI · 45

T

Thyristor Switched Capacitor – Thyristor Controlled Reactor
TSC - TCR · 39

U

ultra-high voltage
(UHV) · 6
United States
(U.S.) · 1

V

volt/VAR optimization
(VVO) · 40

1 Introduction

1.1 Background

Global electricity demand has been on a constant rise in the last four decades and there is no predicted decrease in the foreseeable future. Electricity demand continues to increase in developed and developing countries due to the continual increase in the electric form of transportation, heating, air conditioning, digital devices, income, to name a few (IEA, 2019). Electricity is a vital factor in the development of a country as it is the heart of the modern economy. It is used globally across various sectors such as Industrial, Residential, transport, commercial and public services, agriculture and forestry, fishing, and others (IEA, 2021). According to the (IEA, 2021), between 1974 and 2019, the global yearly electricity consumption increased from 5.268TWh to 22.847TWh. This increase continued until 2020 when a 1% drop in global demand was recorded due to the Covid-19 pandemic (Guo *et al.*, 2020). However, 2021 saw a 5% rise in electricity (IEA, 2022). (EuPD Research, 2022) analyses for the DACH region show a significant increase in electricity demand in 2021 with 506TWh from the year 2020 demand of 486TWh. The analysis also predicted an expected electricity gap for 2022 with 512TWh. Studies carried out by the scientific community investigating the impact of Covid-19 on electricity consumption for different countries, indicate almost every developed or developing country was affected. In Italy, at the peak of the pandemic, a significant change was noticed in the power consumption profile because of the closure of schools, businesses, and offices. A 37% reduction was recorded as a result of the pandemic in comparison to the previous year (Ghiani *et al.*, 2020). (Agdas and Barooah, 2020) carried out a similar analysis for the United States (U.S.) and concluded that contrary to earlier studies that reported a decrease in demand in the U.S, the commercial sector consumption may have declined, but the decrease was offset by the corresponding rise in residential sector from individuals working from home. The highest share of electricity consumption (39,4%) in the U.S. is allocated to the residential sector (eia.gov, 2020).

1.2 Problem Statement

The large power plant has predominantly been the producer of electric power until the energy transition. The passive mode operates by transferring bulk electric power to the high voltage (HV) grid which in turn flows into the MV and LV grid before reaching the consumers at their required voltage level.

Due to the continual increase in demand for power and the energy transition, renewable energies (RE) (solar, wind, hydropower), combined heat and power (CHP), electric vehicles, and heat pumps are being introduced LV and medium voltage MV electric

grid. In Germany alone, photovoltaic installations in LV grids in 2015 was estimated to be over 1,5 million (Dietmannsberger and Schulz, op. 2016). RE technology generations are a more sustainable way to generate electricity in comparison to burning fossil fuels (coal, oil, and natural gas) which have been identified by various studies as the main cause of climate change. Nevertheless, the penetration of RE into the electric grid poses uncertainties on both the demand side and supply side. To ensure flexibility (supply-demand balance) from RE generation (Yang *et al.*, 2012; Alizadeh *et al.*, 2016; C. Hsu *et al.*, 2010) recommended the use of *intelligent devices* to regulate reactive power and active power. This counterworks the idea of the grid network as the voltage level and distance increase substantially (Impram *et al.*, 2020). Hence, the production of power from RE into the power mix has requirements to attain *grid stability*. For this to happen, the power grid needs to tackle the inconsistency in frequency and voltage disturbance.

1.3 Thesis Objectives

Power utilities companies' investments in smart devices to enable grid stability are growing every day as network operators continue to combat reaching operating requirement. This paper studies how the North American and European Network responds to voltage and reactive power control in their respective grids. As both grids respond differently to voltage control due to their characteristics (load type and composition, grid topology, consumer type, and weather), this paper will address the following:

- I. Studying the above-listed factors separately and collectively to understand their connections.
- II. Underline the dissimilarities between the MV grid topology of North America and Europe.
- III. Identify the effect of load types and composition on voltage regulation.
- IV. Make known the control devices that can be utilized to control voltage and accomplish grid stability. Also, identifying the appropriate point on the grid for installing the said device.
- V. Comparing grid impedance in connection to the active and reactive power consumption for both regions.
- VI. Carrying out a case study for a representative network from both regions of which the pros and cons in embracing AVR will be highlighted.
- VII. Showing how the grid will react to an equipment failure of voltage control. Examining the failure modes and suggesting conceivable solutions.

1.4 Report Structure

The organisation of this thesis is as articulated below:

Chapter 1: gives an overview of the global electricity demand situation, presents the problem, and outlines the major objectives of the master's research work.

Chapter 2: Presents an overview of the electric power grid, describes the parts of the grid with a focus on the distribution grid. The chapter also defines the major components of the distribution grid.

Chapter 3: provides substantial information on the grid characteristics (topology, weather, load type and composition, consumer type) that results in grid network responding to differently to voltage control. Two regions (Europe and North America) are the focus in this chapter and the entire thesis. The differences between this two regions grid topology are also discussed in this chapter.

Chapter 4: introduces power system stability with a focus of voltage stability. The further classification of voltage stability, and control devices utilize to achieve voltage stability are defined in this chapter. The result of the analysis of a radial distribution as regarding voltage stability is discussed.

Chapter 5: focuses on a representative distribution grid the two regions (German and the United State of America). Examples of real case Automated Voltage Regulation application in both countries are discussed. Emphasis is also given to advantages and challenges of adopting smart control devices. The chapter is rounded off with typical examples of voltage control tool failure and suggestions to prevent the reoccurrence of the events.

Chapter 6: concludes this master's thesis, where the major point through the paper is stated.

2 Basic Structure of the Power Grid

A discussion of the electric power grid is ideal, to understand how different networks responds to voltage control. This chapter starts with an overview of the electric power grid, followed by a brief discussion of the components that makes up the distribution grid.

(Morello *et al.*, 2017) defined a power grid as *an interconnected system that is complex*. It was also described by (Ross, 2018) as *a collection of components that depends on one another to an extend that they form a group and network which can be considered as units*. It was define by energy educations (Bethel *et al.*, 2021) as *a complicated system that is specially designed to supply electric power from the generation to the end users daily needs*. Power plant, substations, and transformer, DN and the load make up the power grid. The generation plant is usually located far away from the end user with the power grid linking them together. Figure 2.1 shows a simple electric power grid setup identifying the generation plants, transmission, distribution lines and the consumer. There are more systems connected to the grid, nevertheless the figure illustrates how a simple grid is interconnected.

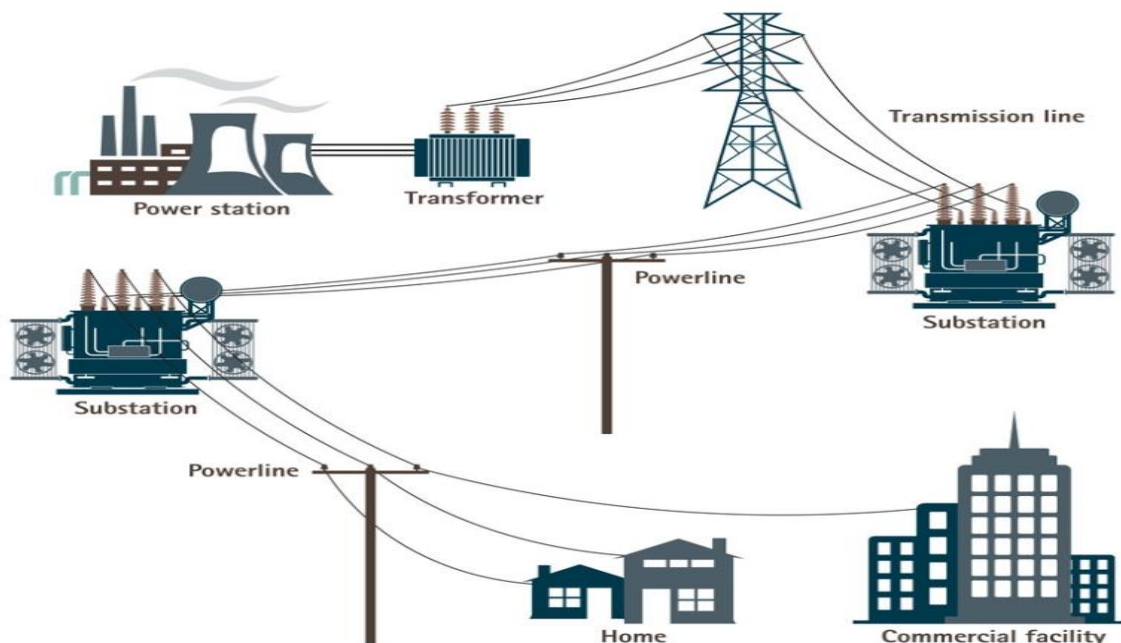


Figure 2. 1: Electric power grid (Copper Development Association Inc, 2022)

2.1 Components of the Electric Grid

Developed and developing regions of the world today are heavily dependent on a steady power supply. Thus, making the electric power grid a very planned infrastructure as can be seen in Figure 2.2.

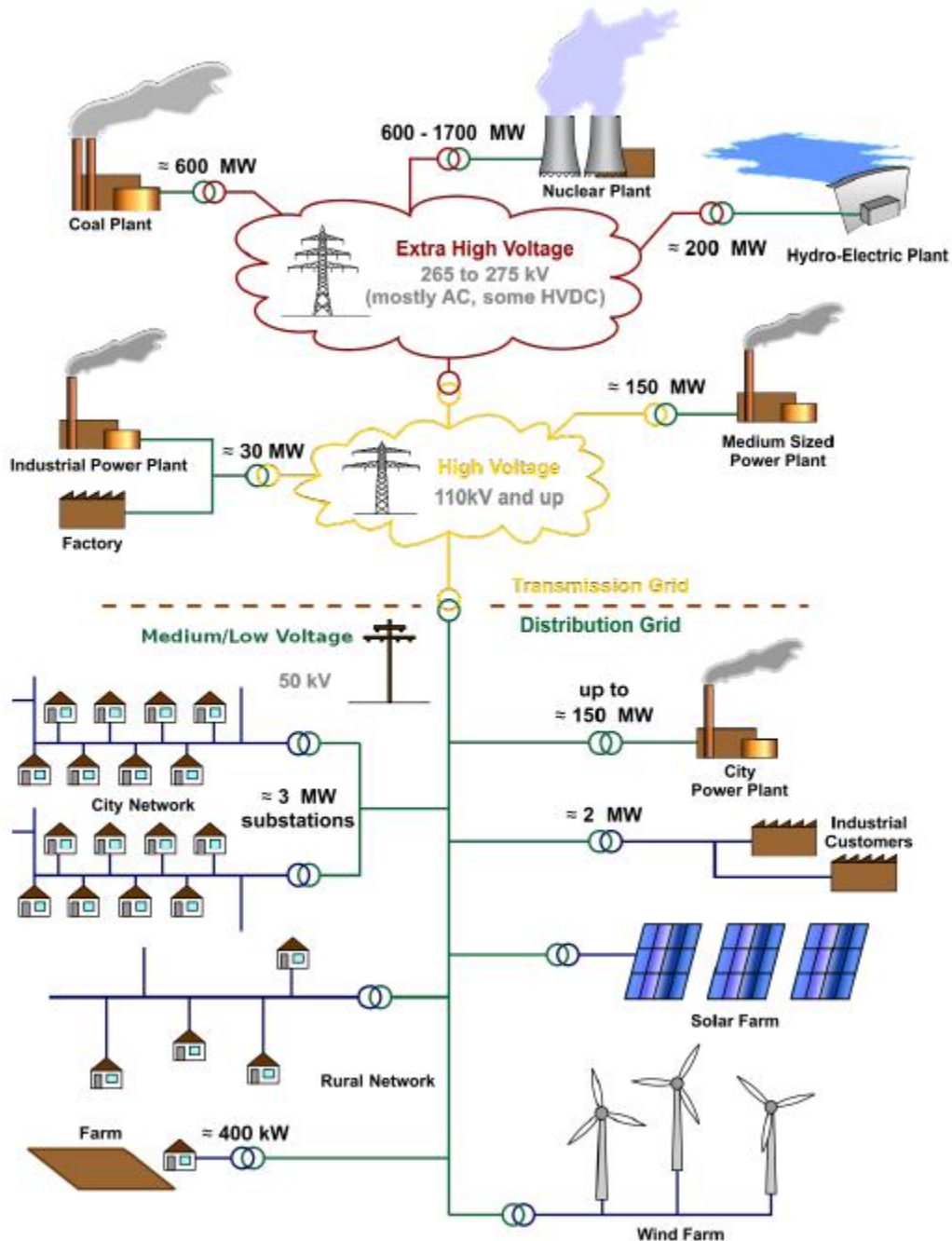


Figure 2. 2: The physical organization of the power grid (Pagani and Aiello, 2016).

This chapter discusses the (3) major components of the electric power grid

2.1.1 Generation

Electricity can either be generated centrally or decentral. The former implies the bulk generation of electricity at centralized facilities. Some typical example of these facilities includes nuclear power plants, fossil fuel fire power plants, hydroelectricity dams, wind farms, etc, (US EPA, 2019). The latter on the other hand involves the generation that occurs outside the main grid and closer to the end-user. A typical example is rooftop solar (Doczekal, 2019).

2.1.2 Transmission

The power network that transmits the electricity from the point of generation to where it is used, the substations, and the transformers all make up the transmission network. A high percentage of power plants generate alternating current (AC), which is the type majorly used for power distribution. AC power lines transmit this AC generated at a power plant over long or short distances to the receiving end through. In this mode, a step-up and step-down transformer are utilized to step up the voltage at the point of generation so it can be transmitted and to step down the voltage for consumption by the end-user. The common method of transmission is through either overhead or underground powerlines (Chudnovsky, 2017; Milczarek and Malinowski, 2020).

2.1.3 Distribution

The low voltage system that comprises the lines, poles switching and protecting circuits, MV and LV transformers, and other electrical equipment makes up the DN. It is practically the final stage as it distributes the electric power to the industrial, residential, and commercial customers by connecting them to several different nodes, with a huge spacing between each other (Chudnovsky, 2017; Milczarek and Malinowski, 2020).

From the consumer's position, the distribution system is the most vital component of the electric power grid. The high-power loads from the industrial customers are connected to the MV grid while other industrial and residential loads with lower power than the MV grid loads are connected to the LV grid. The transformers permit the interconnection of the two (2) different grids as it provides galvanic isolation and demanded voltage ratio between the LV and MV grids (Milczarek and Malinowski, 2020). Table 2.1 shows the typical operating voltages of the different power components in a range. The table classifies the voltage level into LV, MV, HV, extra-high voltage (EHV), and ultra-high voltage (UHV).

Table 2. 1: Voltage level classification (Electrical Engineering XYZ, 2018).

Voltage Classification	Voltage level
LV	50 – 1000 V
MV	1 kV – 100 kV
HV	100 kV – 345 kV
EHV	345 kV – 765 kV
UHV	>765 kV

Each class of consumers requires electricity for various purposes ranging from household appliances, lighting, transportation, industrial machines, and more.

It is important to note that the discussion in chapter 2 on the electric power grid only relates to the conventional electric power grid, without the integration of smart devices to control the voltage. In chapter 3, the discussion will shift focus toward Identifying the effect of load types and composition on voltage regulation. It is also important to keep in mind that even though the basics of an electrical power grid are universally applicable, the topology, operation, and control may differ across regions. The differences between North American and European MV and LV grid topologies will be elaborated on in section 3.1.2. The following section will discuss the components related to the distribution grid which will aid understanding of the report.

2.2 Distribution System Components

Section 2.1 introduced the major components that enable the distribution of electric power to the consumer. The various elements of the DN are presented in this section.

2.2.1 Transformers

The conversion of electric power to a different voltage level in an AC circuit is made possible by transformers. The main function of the transformer is to allow electric power generation at a LV level, then transmit the generated power at HV to reduce transmission losses after which the voltage is reduced to a low-safe level for end-users consumption. (EEP, 2019b) suggested that MV/LV transformers are divided according to their construction and the three types of MV/LV transformers are: oil, air-insulated, and resin-insulated dry-type transformers. A typical MV/LV transformer can be configured as either a star, a delta, or a zigzag configuration. Figure 2.3 shows a graphical representation of a LV/MV transformer (Short, 2018).



Table 2.2 below shows the characteristics of MV/LV transformers.

Table 2. 2: St Figure 2. 3 LV/MV transformer (Techsci, 2019)

Rated operating power (kVA)		50 – 3150 $P = U_1 I_1 \sqrt{3}$
Frequency (Hz)		50 - 60
Type of operation		Step-down, step-up or reversible
Rated voltages	Primary U1 (kV)	5,5 – 6,6 – 10 – 15 – 20 - 33
	Secondary U2 (V)	237 – 400 – 410 – 525 - 690
Insulation Voltage U_i	Primary (kV)	7,2 – 12 – 17,5 – 24 - 36
	Secondary (kV)	1,1
Short-circuit voltage (%)		Percentage of the rated primary voltage to be applied to achieve the nominal current when the secondary is short – circuited. In general: 4% for $P < 630\text{kVA}$ and 6% for $P > 630\text{kVA}$
Adjustment with power off via tapping		Tapping's that can be adjusted with the power off to alter the highest voltage to adapt the transformer to the actual value of the supply voltage. The standard value is $\pm 2.5\%$
Operating altitude		< 1000m (Standard NF C 15 – 100 & IEC 76)
Operating Temperature	Standard	From – 25 °C to + 40 °C (standard NF C 15 – 100 & IEC 76)
	Hottest months daily average	30 °C (standard NF C 15 – 100 & IEC 76)
	Annual	30 °C (standard NF C 15 – 100 & IEC 76)
Installation Method	Outdoor on post	All powers
	Outdoor/indoor in station	

2.2.2 Power Carrier: Overhead lines/Underground cables

Power cables carry LV and MV in a specified range and are usually deployed with either overhead lines or underground cables (europacable, 2014). Different countries in the world consider various factors in deciding the type of cable for electric power distribution. The decision is usually bounded between the lower cost of overhead cables and higher quality, reliability, and environmental acceptance of underground cables. The difference of underground cables and overhead lines was pointed out by (Listenlights, 2017). The conclusion was the choice of the cable technology is decided based on the circumstance of the region as the overhead lines are the most used technology since they are cheaper and distributed more electric power. Nevertheless, the more convenient and less likely to break technology remains the underground cable (Short, 2018). Figure 2.4 below shows an underground cable trench on the left and overhead lines on a street in Hachioji Japan.



Figure 2. 4: Underground cables and overhead lines

2.2.3 Protection

The protection of the distribution system is very essential to enable the distribution process. There is various equipment used in the protection of DN. However, two key factors (voltage level and protective element) are essential in selecting the type of protection to be installed in a system. The frequently used devices for the protection of the distribution network are reclosers, overcurrent relays, fuses, and sectionalisers (EEP, 2017). Various studies indicate the reclosers have the same task as the circuit breaker. However, it also can reclose after opening when a fault is detected. The open-close loop

of the reclosers is used by the sectionalisers to pinpoint the location of a fault for isolation (Steyn and Rix, 2019). A Chinese recloser is shown in figure 2.5 below.



Figure 2. 5: Polemounted Recloser (Rockwill Electric Group, '2020)

The fuse is the oldest way of protecting the DN. It protects the transformers from overloading and current surges and is mostly used in overhead lines. According to (EEP - Electrical Engineering Portal, 2019) the expulsion and the current limiting type of fuses are widely used for protecting rural DN.

3 Distribution Grid Characteristics

In section 1.3, it was established that different grid networks respond to voltage control differently due to differences in grid characteristics between regions. This chapter presents the study of the typical characteristics of the distribution grids, to understand their relationships. In This paper, only the following factors: load type and composition, grid topology, weather, and consumer type are studied.

3.1 Grid Topology

A networks architecture has a substantial influence on the stability of the grid. To understand how different networks respond to voltage control, it is of utmost importance to understand the network structures. This section briefly describes how the DN is designed and implemented. For this purpose, there are generally three (3) methods (Radial, Loop, and Mesh) of network connection and operation.

3.1.1 Radial Distribution Network

The radial DN structure is shown in figure 3.1. This arrangement is the traditionally used architecture for electric power DN. It is widely used to supply sparsely populated load areas. Overhead lines are utilized for carrying the primary and secondary circuits. In this tree-shaped topology, the power flows in one direction, meaning various feeders branches from a central generating station. The supply system beyond a fault is isolated on failure at a point. Despite the advantages of the simplicity and affordability of the system, various studies indicate that the system is not reliable considering the scenario where a faulty feeder would lead to great difficulty in maintaining supply (electrical easy, 2021; Islam *et al.*, 2017; EEP, 2019a, 2017; Glover *et al.*, 2012; Short, 2018).

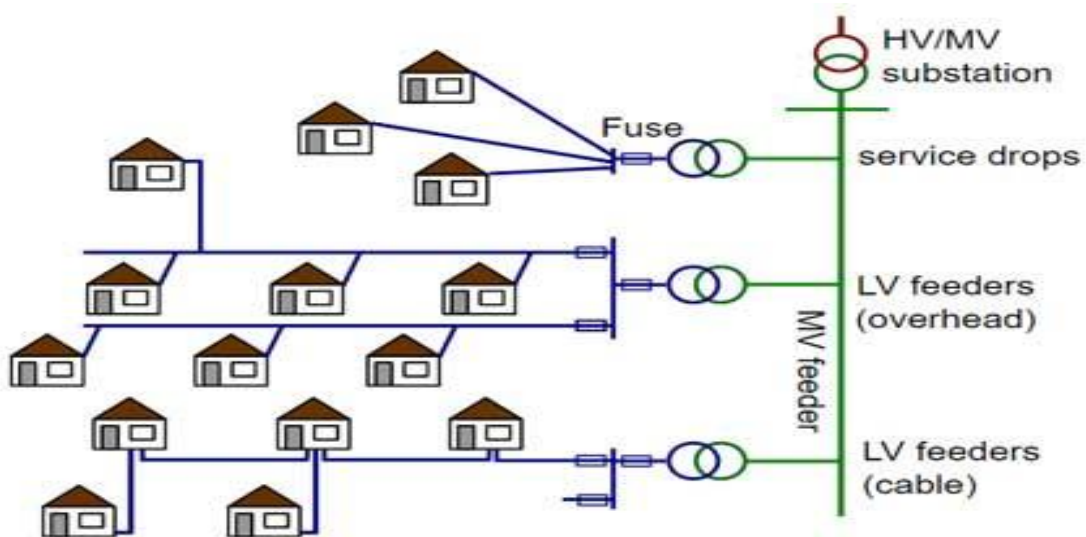


Figure 3. 1: radial distribution network (electrical easy, 2021)

3.1.2 Loop Distribution Network

In the Loop system, all nodes are interconnected to form a closed-loop structure. This system is majorly used in areas where current flow in more than one direction such as the residential areas. It is usually connected over a region distributed to one or more load centers and finally goes back to a similar substation. Ideally, the loop system is considered to deliver a much more improved service in comparison to the radial system. This system is also called a *ring system* as it distributes from a source over various loads and eventually returns to the same source. Studies show that this system is usually allied with another power source. Unlike the Radial system, this system allows the strategic placements of switches in various locations in the loop to allow the supply of power from multiple sources in the case of fault. Thus, the supply of various loads is not disturbed in the isolation of a fault. In contrast to the advantage of the flexibility and improved system reliability, the system is much more expensive than the radial system due to the requirements of conductors and switches. The system also has a drawback of locating a fault which in turn complicates the protection of the system. Figure 3.2 below shows a single-line diagram of a loop Network (Islam *et al.*, 2017; Mehta and Mehta, 2005; Short, 2018).

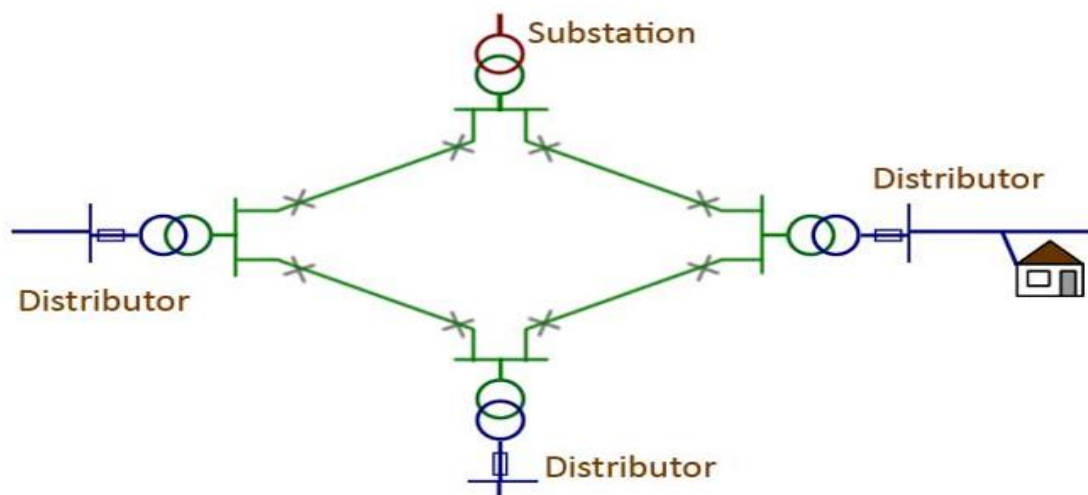


Figure 3. 2: single line diagram of a loop distribution Network (electrical easy, 2021)

3.1.3 Mesh Network

The Mesh Network is depicted in fig 3.3 below. It is widely used in municipal or areas with high load density. It is considered the most complicated DN configuration as it is an interlocking loop system. It is also called an interconnected DN as it consists of various connections between buses which means that a consumer can be supplied by various power suppliers. Even though the system is the most expensive to operate, it has

additional reliability. In the event of failure, the redundant lines included in the system redirect the power in the main line. The fact that power can be supplied from various point challenges the protection of the system as it increases communication delay which can impact the stability of the system (Islam *et al.*, 2017; Electrical Revolution, 2021; Short, 2018).

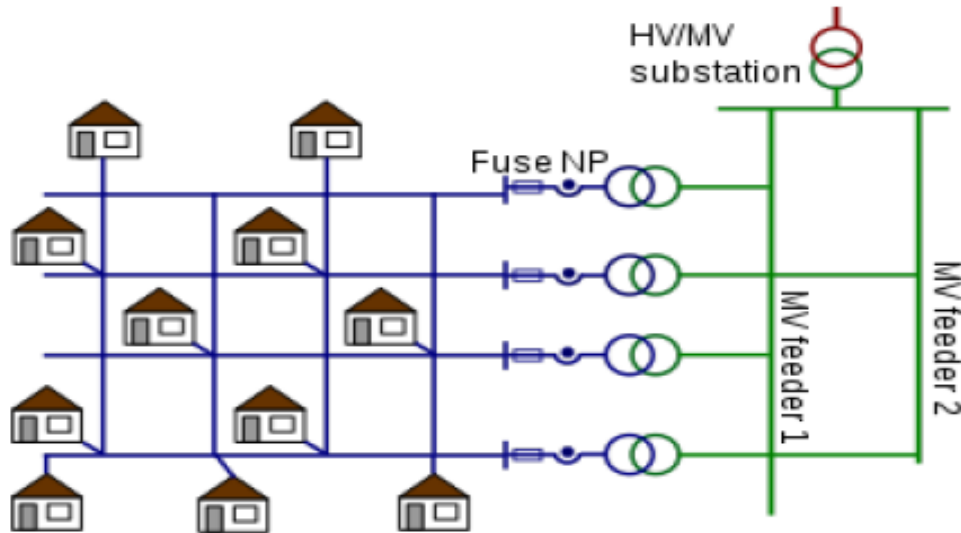


Figure 3. 3: Mesh Distribution Network (Electrical Revolution, 2021; Dong *et al.*, 2018b)

3.1.4 Differences Between European and North American LV and MV grid Topology

The DN of both Europe and North America is essentially the blueprint of DN designs for many of their former colonies. Both networks are similar in components and hardware, voltage and power carrying capacity, and both are radial. However, the major dissimilarities lie between the applications, configurations, and layout (Short, 2018; EEP, 2011). The two major DN topologies used in the U.S. are the radial structure in rural areas and the meshed structure in densely populated areas (Dong *et al.*, 2018b). On the other hand, the DN in Europe generally has a radial topology or in some cases loop structure (L'Abbate *et al.*, 2007). Figure 3.4 below shows the layout of the two distribution systems. One of major differences that can be depicted in figure 3.4 is the difference in the transformers in the two designs. The size and number of transformers in the European network are significantly larger and fewer with more customers per transformer. In North America on the other hand, for every few customers, there are commonly single-phase distribution transformers connected by short service drops. North American Network have the attribute of a three-phase up to MV levels. At this power level, the MV distributes to a location by using a pole-mounted transformer at a building to transform to the LV level. House connection consist of a three-wire single phase system at the LV side of the

transformer (Bohn *et al.*, 2015; Meier, 2006). North America uses 25 or 50 kVA single-phase units, while the European transformers are in the order of 300 to 1000kVA and are mostly three-phase (EEP, 2011). The AC operates at 50 Hz in Europe while the AC in North America operates at 60Hz. Another significant difference is the secondary voltage of which the North Americas is 120/240V while most European countries have 220, 230, or 240V standard nominal voltages making it more feasible to extend LV lines to consumers. The higher voltage level of the European system makes it possible for a four-time feeding of a load by a circuit compared to the North American system. Nevertheless, on rare occasions Utilities in some European countries have been able to transfer electricity with single-phase taps consisting of two phases with single-phase transformers phase to phase connected. Other major differences are centered around the primary level fuses and reclosing of the European system not used as much as the North American system (Short, 2018; EEP, 2011). The European distribution system encompasses the MV/LV transformer substations and the consumer's connection with urban areas, suburban areas, and rural areas with cable lengths of 200m, 400m, and above. The angle between each of the three tri-phase is 120° with a Line-to-Line voltage of 400V.

Some factors that distinguish these two systems are mostly because of the dissimilarities in infrastructure, geography, population, load density, and historical expansion of the two regions' power systems (Meier, 2006). While the North American roads and the grid were designed intermittently, the European electrical system was designed to fit into an already existing infrastructure. Europe generally has a higher population density with smaller individual loads which makes it feasible to extend the LV lines to the consumers. In the rural areas of North America, MV lines are required to reach consumers as consumers tend to be much farther apart. (Short, 2018) also differentiates these systems according to their cost, whereas the European system is more expensive. North American end users are connected directly to the distribution transformer while in Europe, the LV network generally feeds customers in hundreds. Regarding flexibility, the European system is more flexible for the Urban system while the latter is better suited for the rural system. The European system can easily detect high impedance fault while the North American system consists of a multi-grounded neutral which provides protection. In terms of reliability, the frequency of interruption tends to be more in the European system, however, it has a three-wire system that protects against line-to-ground fault making it superior in terms of power quality. The European system can slimly use an underground or blend in for the LV which in turn reduces the location for transformers, but its flexibility makes it easier to be subjected to power theft (EEP, 2011; Meier, 2006; Short, 2018).

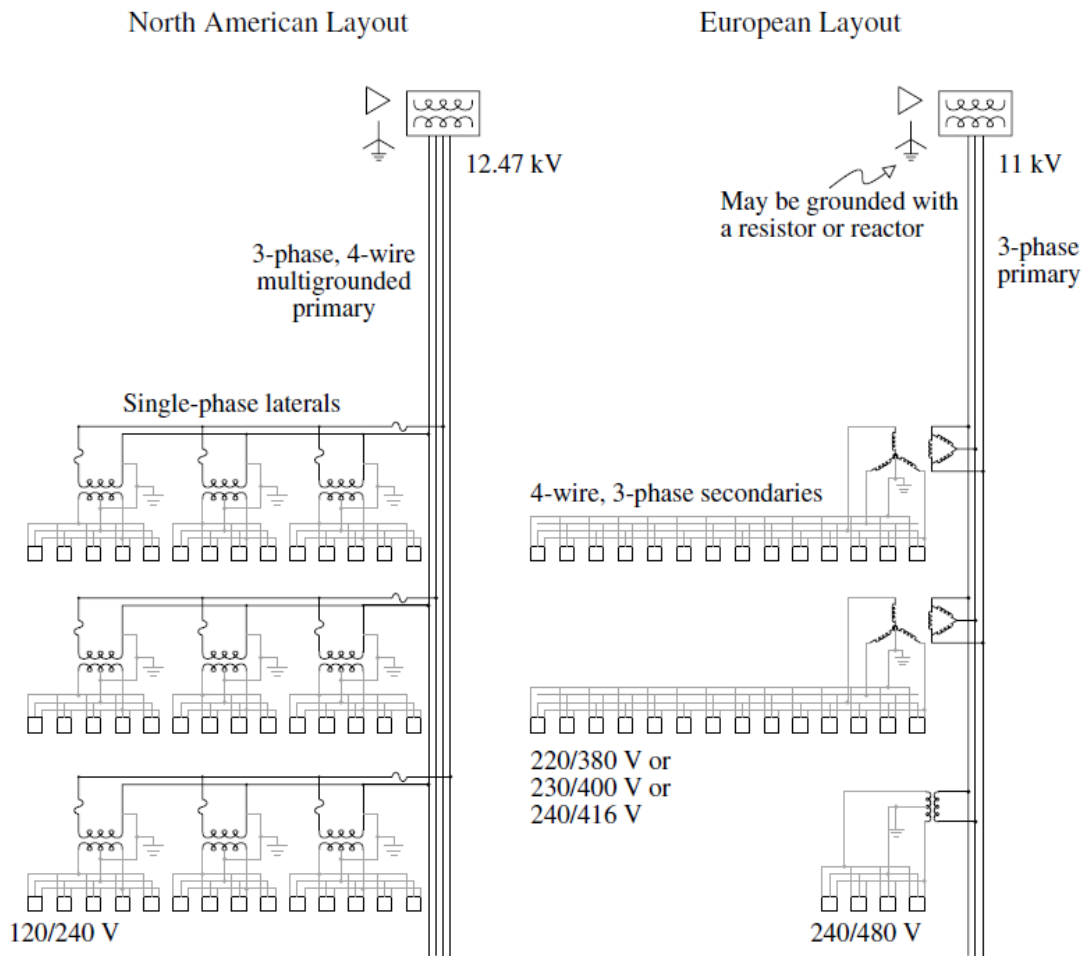


Figure 3. 4: North America versus European distribution layout (Short, 2018)

The structure of various DN across the world is decided based on reliability and cost. Nevertheless, various countries colonized by countries in these two regions have also adopted the system used by their colonizer, meaning the European system are widely used around the world and in rare cases, a mixture of both distribution system have been witnessed (Short, 2018).

3.2 Weather

The effect of climate change has led to the increase of the global average temperature by 1,01 degrees Celsius (°C) between 1880 and 2021 (Nasa, 2021). Extreme weather events caused by these changes have been felt in the electric grid across different geographical regions. Recent examples are the July 2021 deadly flooding in Germany and Belgium which destroyed some part of the grid and left thousands of households in Germany without electricity (The Washington Post, 2021; Reuters, 2021) . The Texas winter storm of 2021 also left millions of households without electricity for days (The Texas Tribune, 2022). The study carried out by (Petrick *et al.*, 2010) to discover the impact of temperature change on residential consumption indicates that energy use drops when temperature rises. Heating is not require and considers cooling as a regional issue not a

global issue. (Zhang *et al.*, 2019) estimates that in rural China, 1°C rise in the temperature in the summer days could inspire 0,021% increase in electricity per capita consumption and a similar temperature decrease could lead to a 0,002% decrease in electricity consumption. This higher demand for electricity that has been felt in the various geographical regions is majorly due to the increase in cooling during hot degree days (HDD). In the U.S, these HDD usually in the summer sees an increase in demand usually for cooling and in the winter days which are the colder degree days (CDD), the requirement of heating is increased. However, with the impact of climate change, warmer winter days are expected soon, where in the heating requirement will be less.

Weather events are a significant factor that contributes to instability and loss of power supply in Europe and North America (Ward, 2013). Figure 3.5 shows the percentage of MV and LV weather interruption in Germany between 2006 and 2012.

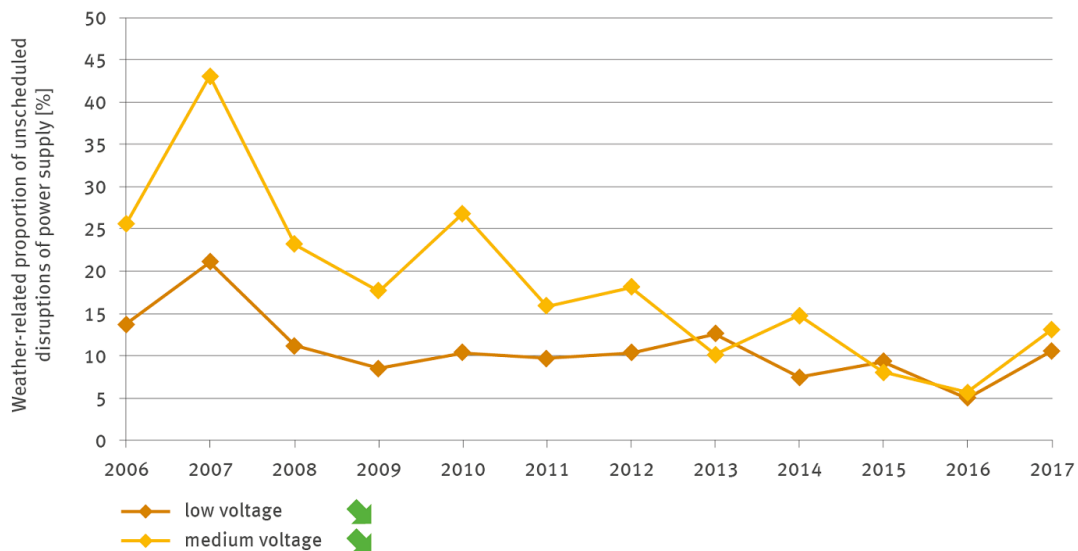


Figure 3. 5: Weather - related disruptions of power supply (Umweltbundesamt, 2021)

Even though the grid network of Germany is categorized as one of the most stable in the world, extreme weather events have been recorded to affect the DN. This was evident in 2007 when the impact of hurricane Cyril left consumers without electricity for an average of 22 minutes in that year (Umweltbundesamt, 2021). Other extreme weather events that have been witnessed in Germany to have disrupted the power supply are hurricane Xynthia of 2010, and Herwart and Xavier of 2017 (Umweltbundesamt, 2021). Figure 3.6 below is a graph depicting the minutes of recorded unavailability of electricity in Germany related to extreme weather.

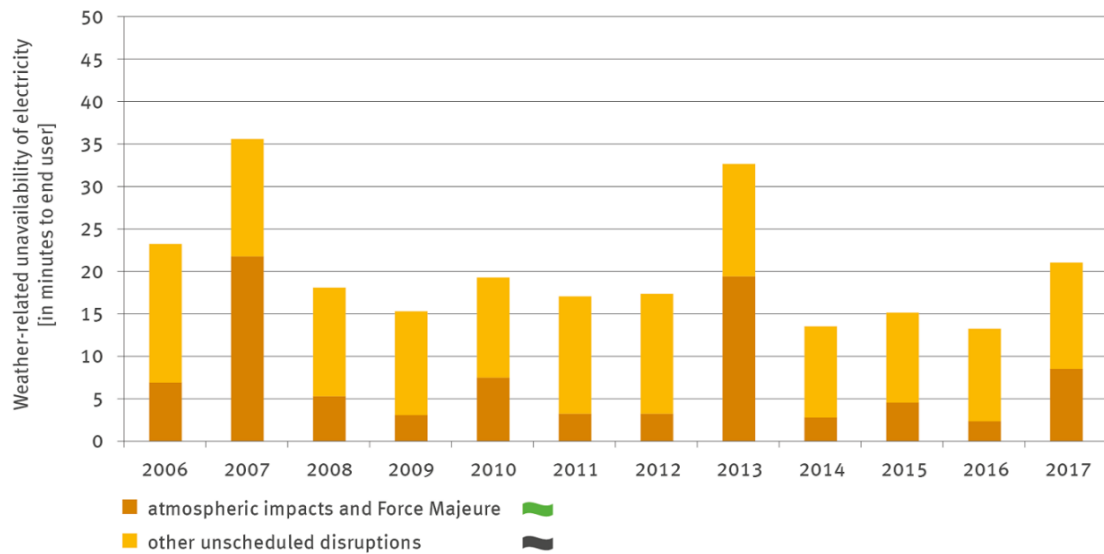


Figure 3. 6: Weather-related unavailability of power supply (Umweltbundesamt, 2021)

Like Germany, Climate change is also negatively impacting the North American DN. In the U.S., large-scale power outages are majorly caused by winter storms, heat waves, and heavy rainfall. According to (Alyson and Urooj Raja, 2014), extreme weather events have been related to 80% of the power outages between 2003 and 2012 where over 147 million consumers lost power supply for above an hour and longer. The research group Climate Central estimated extreme weather events to have caused 67% of major outages in the U.S. since 2000 (Emma, 2021). Some high-profile power outages related to extreme weather events in North America are, the destruction of tens of thousands of wooden poles on the DN by an ice storm in 1998 (Ward, 2013), and the Texas winter storm in 2021 (Emma, 2021). Figure 3.7 shows an analysis of weather and non-weather-related power outages in the U.S. between 1984 and 2012.

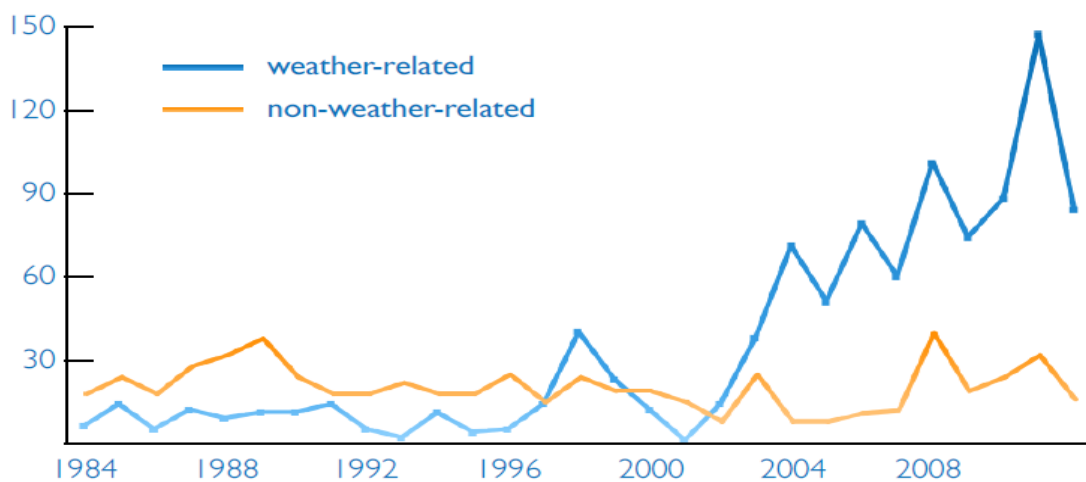


Figure 3. 7: Weather and non-weather related power outages in the U.S. annually between 1984-2012 (Alyson and Urooj Raja, 2014)

An Increase in temperature, high winds, storms, hurricanes, ice, snow, lightning,

drought, rain, floods, and landslides have been identified by (Ward, 2013) as the major effects of weather events in the DN of North America and Europe.

Due to climate change, extreme weather events discussed in this section will continue to be associated with the disruption of power supply. Thus, to tackle this issue, utilities have started introducing smart devices to control voltage and reactive power in the grid. Chapter 4 talk about these devices.

3.3 Load type and Composition

Voltage stability is mostly dependent on the various load type of a region connected to the LV and MV distribution system. Components of load in the DN include induction motors, thermostatic loads, inductive and resistive loads, and lighting loads. The type and number of loads used are dependent on the sectoral activity. This nature of load can also be affected by the change of weather as on colder CDD, the use of an air conditioner would not be needed which in turn spikes the amount of heating required. The lack of voltage control devices in the DN will lead to varying voltages along system feeders making the V-I characteristics of the load very important in the load flow studies (Aziz *et al.*, 2010; Mithulananthan *et al.*, 2000).

3.3.1 Electric load types

This section introduces the different types of loads in LV voltage DN to have a better understanding of the impact of load type on voltage regulation which is discussed in section 3.3.3. The three primary types of electric loads are resistive, inductive, and capacitive loads.

3.3.1.1 Resistive Load

In this type of load, active power is consumed, and the power factor (PF) is in unity (PF = 1). typical examples of resistive loads are heaters, electric iron, incandescent lamps, toasters, electric kettles, etc. Typically, all-electric devices that include a heating element and their working principle is based on resistance working principle are resistive loads (john, 2010)(Meier, 2006). The power formula of resistive loads is given below (Meier, 2006; Daware, 2017; Gaurav, 2020).

$$P = V * I \quad (3.1)$$

P is the power in watt (w), V is the voltage in volt (V), and I is the current in ampere (A).

Figure 3.8 shows the V and I waveform of resistive loads. The diagram confirms that the V and I and in perfect phase with each other.

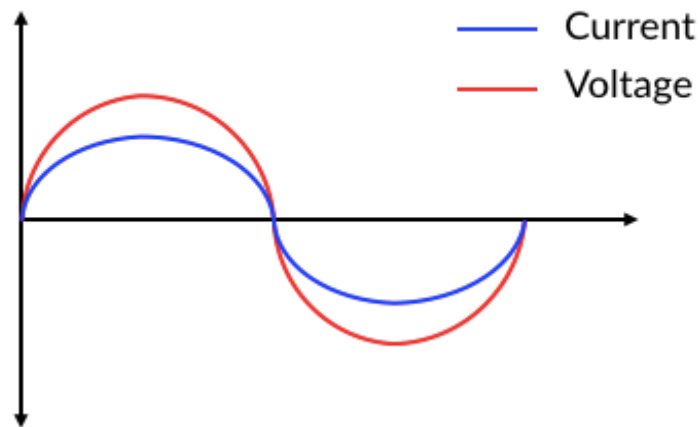


Figure 3. 8: Waveform of Resistive Loads (Gaurav, 2020)

3.3.1.2 Inductive Loads

The inductive loads working principle is based on the Magnetic induction working principle (Electrical4U, 2020a) which absorbs reactive power. The PF of such load is not at unity as it is lagging ($PF < 1$). A typical example is an air conditioner, washing machine, electric motor, transformers, air compressor, etc. Inductive loads can either be single phase or three phase and can be represented by the formulas below (Gaurav, 2020; Meier, 2006; Daware, 2017).

Single phase,

$$P = V * I * \cos(\varphi) \quad (3.2a)$$

P is the power in watt (w), V is the voltage in volt (V), I is the current in ampere (A), $\cos(\varphi)$ is the power factor

for three phase,

$$P = V * I * \cos(\varphi) * \sqrt{3} \quad (3.2b)$$

The V and I waveforms of inductive load are not in phase with each other by 90° , meaning the current is lagging the voltage.

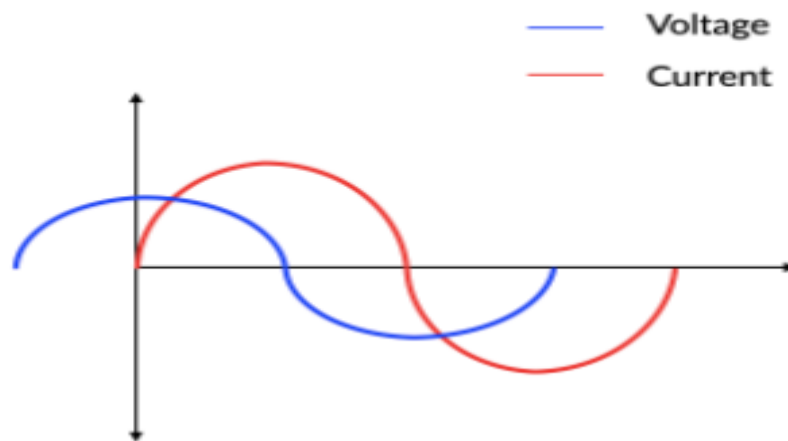


Figure 3. 9: Waveform of Inductive load

3.3.1.3 Capacitive Loads

The capacitive loads are capable of absorbing both active and reactive power. These loads are very much like inductive loads as the I and V are also out of phase. Although, in capacitive loads, current leads the voltage by 90° (PF > 1). They absorb active power and generate reactive power to regularise the power factor. Typical examples are radio circuits, buried cables, capacitor banks, etc. The active and reactive power formulas for capacitive load are as follows (Daware, 2017; Meier, 2006; Gaurav, 2020):

Active power,

$$P = V * I * \cos (\varphi) \quad (3.3a)$$

Reactive power,

$$Q = V * I * \sin (\varphi) \quad (3.3b)$$

Q is the power in watt (w), $\sin (\varphi)$ is the power factor.

The wave form of capacitive load is represented in figure 3.10 below.

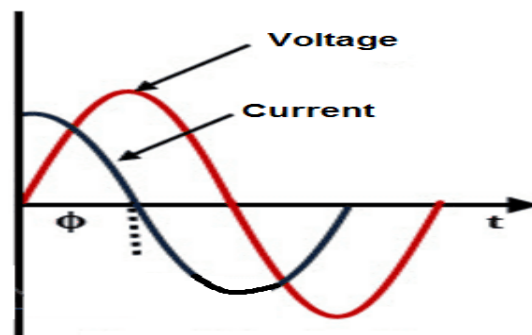


Figure 3. 10: Waveform of capacitive loads (Electrical4U, 2020b)

It is important to note that there are no standalone capacitive loads unlike resistive

loads. Power usages are usually controlled in large power circuit by capacitors. These installed capacitors tend to improve the PF of a load as they supply reactive power.

Modern power circuits use a combination of the three types of loads. An example is a motor which are conventionally controlled using a capacitor during the ignition or operation process.

3.3.2 Load Models

According to (Navarro, 2002) *load modeling was defined as a mathematical representation in terms of the voltage and / or frequency measured on the bus, and the actual and reactive power consumed by the load.* (Qi et al., 2019) further emphasized the importance of load modeling in the stability analysis of power systems. The study also indicated that an unsuited load model could result in inconsistency in the grid. Utilities have taken a keen interest in load modelling to accurately estimate the operating limit of the system (Aziz et al., 2010). This section will elaborate on the two general categories of electric load models.

3.3.2.1 Static Load Models

The static load models can also be classified as the **constant impedance, constant current, and constant power model (ZIP model)**. The model exhibits active and reactive power as a function of bus voltages (Aziz et al., 2010). It is time independent and therefore represents the ratio of active and reactive power at any point in time to voltage and frequency at the same point in time. (Navarro, 2002). The characteristics of the load at any point are expressed as a function of the frequency and voltage magnitude at that instant (Kamel and Nagasaka, 2015). The exponential equations below is a static load model representing the relationship between power and voltage (Kamel and Nagasaka, 2015; Aziz et al., 2010).

$$P = P_0 \left(\frac{V}{V_0}\right)^{np} \quad (3.4a)$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{nq} \quad (3.4b)$$

Where:

P_0 is the active power, V_0 is the reference voltage in volts (V), Q_0 is the reactive power, np and nq are the exponents depending on the load type.

If np and nq equal to zero, the model represents a *constant power static load*. If equal to 1, the model represents a *constant current static load*. Lastly, if equal to 2, the model represents a *constant impedance static load* (Kamel and Nagasaka, 2015).

For polynomial loads where the relationship between power and voltage is expressed as a polynomial of magnitude of voltage. The active power and reactive power characteristics of the ZIP model is represented by the equations below (Kamel and Nagasaka, 2015)

$$P = P_0 [a_p (\frac{V}{V_0})^2 + b_p (\frac{V}{V_0}) + c_p] \quad (3.5a)$$

$$Q = Q_0 [a_q (\frac{V}{V_0})^2 + b_q (\frac{V}{V_0}) + c_q] \quad (3.5b)$$

$a_p + b_p + c_p = a_q + b_q + c_q$ (user defined coefficients which define the ratio of each component).

Multiplying the polynomial model by a factor gives a representation of the frequency dependency of load characteristics as follows (Kamel and Nagasaka, 2015)

$$P = P_0 (\frac{V}{V_0})^{np} (1 + k_{pf}\Delta f) \quad (3.6a)$$

$$Q = Q_0 (\frac{V}{V_0})^{nq} (1 + k_{qf}\Delta f) \quad (3.6b)$$

Or

$$P = P_0 [a_p (\frac{V}{V_0})^2 + b_p (\frac{V}{V_0}) + c_p] (1 + k_{pf}\Delta f) \quad (3.6c)$$

$$Q = Q_0 [a_q (\frac{V}{V_0})^2 + b_q (\frac{V}{V_0}) + c_q] (1 + k_{qf}\Delta f) \quad (3.6d)$$

$\Delta f = f - f_0$ is the frequency deviation

k_{pf} ranges from 0 to 3,0

k_{qf} ranges from -2,0 to 0

Another representation of static model which allows the addition of several load representation is as follows (Kamel and Nagasaka, 2015):-

$$P = P_0 [P_{ZIP} + P_{EX1} + P_{EX2}] \quad (3.7a)$$

$$P_{ZIP} = a_p (\frac{V}{V_0})^2 + b_p (\frac{V}{V_0}) + c_p \quad (3.7b)$$

$$P_{EX1} = d_p (\frac{V}{V_0})^{np1} (1 + k_{pf1}\Delta f) \quad (3.7c)$$

$$P_{EX2} = e_p (\frac{V}{V_0})^{np2} (1 + k_{pf2}\Delta f) \quad (3.7d)$$

For the reactive component of the load, a similar structure of the expression is followed:

$$Q = Q_0 [Q_{ZIP} + Q_{EX1} + Q_{EX2}] \quad (3.8a)$$

$$Q_{ZIP} = a_q (\frac{V}{V_0})^2 + b_q (\frac{V}{V_0}) + c_q \quad (3.8b)$$

$$Q_{EX1} = d_q \left(\frac{V}{V_0}\right)^{nq1} (1 + k_{qf1}\Delta f) \quad (3.8c)$$

$$Q_{EX2} = e_q \left(\frac{V}{V_0}\right)^{nq2} (1 + k_{qf2}\Delta f) \quad (3.8d)$$

Table 3.1 below shows the value of np and nq for several load types.

Table 3. 1: Sample of Fractional Load Exponents (Taylor *et al.*, 1994; Navarro, 2002)

Load Component	np	nq
Large industrial motors	0,05	0,50
Small industrial motors	0,10	0,60
Incandescent lamp	1,54	0,00
Room air conditioner	0,50	2,50
Fluorescent lighting	1,00	3,00
Resistance space heater	2,00	0,00
Pumps, fans other motors	0,08	1,60
Battery charge	2,59	4,06
Compact fluorescent lamps	0,95 – 1,03	0,31 – 0,46

It is common for utilities to divide load composition into residential, commercial, and industrial loads with a percentage of different loads as it will be difficult to directly divide consumer load further (Aziz *et al.*, 2010). This composition varies according to the country as some regions are more concentrated with residential consumers while some are with residential consumers. Table 3.2 shows the breakdown used by utilities.

Table 3. 2: Typical Load Composition (Morison *et al.*, 2006)

Load Class	Load Composition (%)		
	Residential	Commercial	Industrial
Resistive	25	14	5
Small Motor	75	51	20
Large motor	0	0	56
Discharge Lighting	0	35	19

3.3.2.2 Dynamic Load Models

The study carried out by (Overbye, 1994) indicates that dynamic models have little impact on the stability of a system as it was difficult to verify and develop dynamic models for an aggregate time-varying load, this is why the static models are the most preferred by the industry today. This is not the case anymore as dynamic models are increasingly replacing the static model as load representation censorious result on voltage stability. This modern dynamic model can provide a more precise evaluation of the load behaviour. Therefore, sustaining a highly reliable system operation, and increasing the chances of reducing security margin. At any instant time, a dynamic load model can express the relationship between active and reactive power, as a function of the frequency and voltage. The two major approaches for determining the parameter of the load models are the

measurement-based and component-based approaches (Navarro, 2002).

Equations below signifies an exponential dynamic load model where the active and reactive power are not nonlinearly reliant on the voltage (Karlsson and Hill, 1994).

$$T_p \frac{dPr}{dt} + Pr = P_o \left(\frac{V}{V_o}\right)^{\alpha_s} - P_o \left(\frac{V}{V_o}\right)^{\alpha_t} \quad (3.9)$$

$$Pl = Pr + P_o \left(\frac{V}{V_o}\right)^{\alpha_t} \quad (3.10)$$

T_p is the time constant for active load recovery, P_o is the power consumption before voltage, V_o is the voltage, Pr is the active power recovery, Pl is the total active power response, α_t is the transient active load voltage dependence, and α_s is the steady state active load. Voltage dependence (Karlsson and Hill, 1994).

A similar equation for reactive power is given below (Rouhani and Abur, 2016)

$$T_q \frac{dQr}{dt} + Qr = Q_o \left(\frac{V}{V_o}\right)^{\beta_s} - Q_o \left(\frac{V}{V_o}\right)^{\beta_t} \quad (3.11)$$

$$Ql = Qr + Q_o \left(\frac{V}{V_o}\right)^{\beta_t} \quad (3.12)$$

The reactive power recovery is Qr , the total reactive power response is Ql , T_q is the reactive load recovery time constant, β_t is the transient reactive load voltage dependency factor, and β_s is the steady state reactive load voltage dependency factor (Rouhani and Abur, 2016).

3.3.3 Impact of Load Types and Composition to Voltage Regulation

Section 3.3.2 introduced the two types of load models and their corresponding expressions. The composition of loads is generally connected in the LV and MV. These loads are voltage-dependent and thus this section will elaborate on their impact on voltage regulation. The equations below expresses the consideration of the real and reactive power balance for a node in a power system (Mithulananthan *et al.*, 2000).

$$P_k = P_{gk} - P_{Lk} \quad (3.13a)$$

$$Q_k = Q_{gk} - Q_{Lk} \quad (3.13b)$$

P_{gk} and Q_{gk} are the real and reactive power generated at node k , P_{Lk} and Q_{Lk} are the real and reactive power loads at node k , P_k and Q_k are the real and reactive power injected into the

system.

Figure 3.11 below represents the power balance at a node.

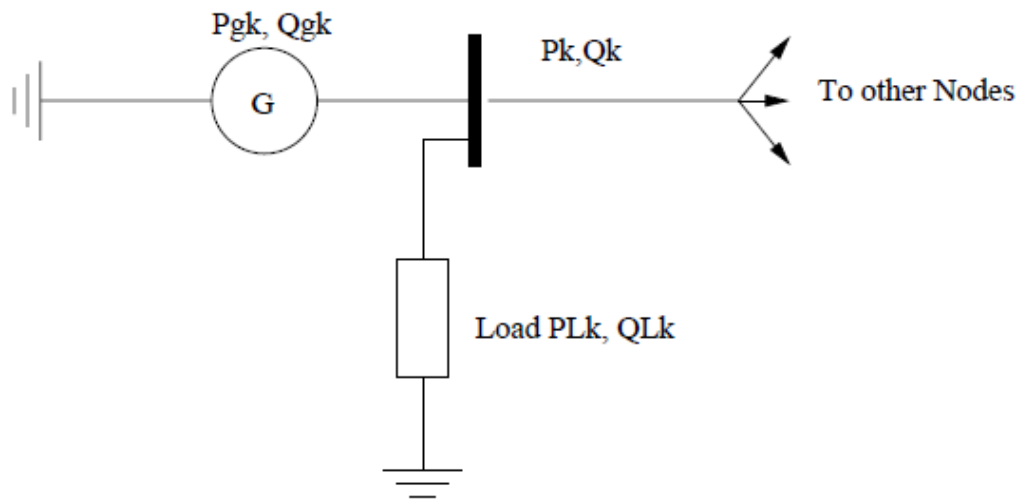


Figure 3. 11:Power balance at node k (Mithulanathan *et al.*, 2000).

Various studies are focusing on the DN as load modelling is not a big concern for the transmission grid.

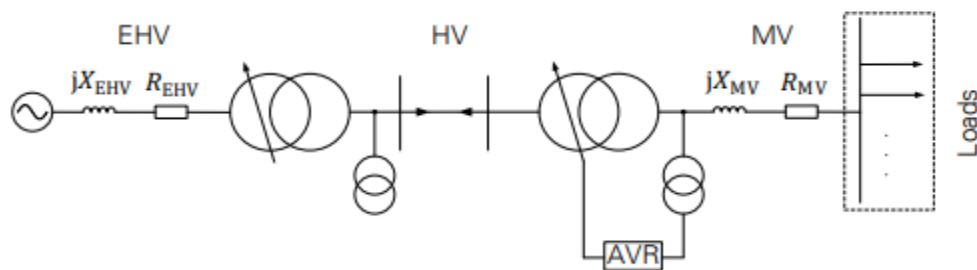


Figure 3. 12: The Location of the Composite Loads in Power Systems (Rengin, 2019).

The load bus represented in figure 3.12 above comprises various types of loads such as heaters, lamps, air conditions, motors, compressors, etc. The composition of these loads changes depending on various factors such as weather, economic development, salary, etc, thus making the exact composition of the load complicated (Rengin, 2019; Roy *et al.*, 2011).

Voltage regulation is usually carried out by utilities at the delivery point by utilizing control devices. What this means is that the voltages at a lot of nodes are not regulated making the voltages across feeders vary. This in turn lays more emphasis on the voltage-current (V-I) characteristics of loads. Various standards such as the American National Standard Institution (ANSI) have assigned predefined voltage levels which utilities follow for their adequate operation. In 2020, the 2016 edition of this standard was revised to the

ANSI C84.1 – 2020 (Stepka, 2020). For the Range A of the ANSI C84.1, the variation of allowable service voltage is between the range of +5% to -5% and +5% to -2,5% for systems operating up to 600V and more than 600V, respectively. Concerning utilization voltage for the same range, the tolerance is +5% to -10%. For Range B, a +5,8% to -8,3% and +5,8% to -5% allowable service voltage for systems operating up to 600V and above 600V, respectively. The Utilization voltage for the same range had a tolerance of +5,8% to -13,3% (Voltage Disturbance, 2020). In Europe, the distribution system operators (DSOs) oversee the system operation and enables home appliances and facilities in Industries to operate safely. The EN 50160 specifies the European DN voltage range from <1kV to 36kV to maintain the stable operation of all connected devices. Nevertheless, various DSOs across Europe still passes the limit as a result of difference in legislation and standard of operation (Rullaud and Gruber, 2020). According to EN50160 the standard nominal voltage (V_n) in LV network is 230V and is usually agreed with the customers in the MV network. 100% of all 10 min mean root mean square values must stay in the range of $V_n +10\%$ / - 15% while 95% must stay in a range of $V_n \pm 10\%$ (Partha Sarathy, 2018; Kulmala, 2014).

For any feeder, the voltage regulation can be calculated with the formula below (Mithulananthan *et al.*, 2000)

$$V_{reg} = \frac{|V_s| - |V_r|}{|V_r|} * 100 \quad (3,14)$$

V_s is the voltage at the sending end, V_r is the voltage at the receiving end.

Transferring loads between feeders is a typical way to improve voltage regulation. (Mithulananthan *et al.*, 2000) used a three-phase radial grid network with 29 segments, 30 nodes, 1 main feeder, and three sub-feeders to find out the effect of various load models in voltage regulation in distributed systems. The report contrasted the load flow solutions of the various static load models described in. 3.3.2 against an already obtained solution of the constant power model. The result was that as the distance increases from the feeding point, the difference between the solution increases. Therefore, different voltages make a difference in the design of the DN. The voltage profile along the mainline in these cases is shown in Figure 3.13 below.

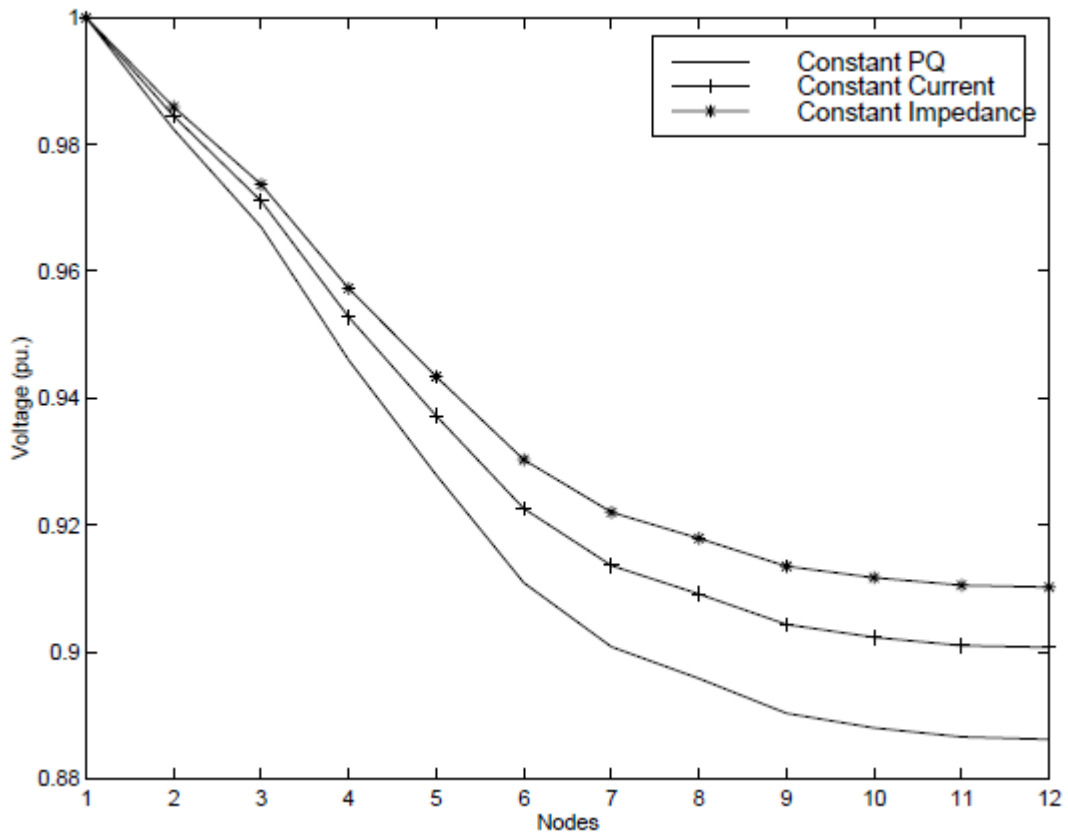


Figure 3. 13: Profiles of the voltage down the main feeder: classical load (cons. P), constant current (Mithulanathan *et al.*, 2000)

The study further indicated the voltage regulation percentage of the different static load models. The P load models were computed to be the highest percentage as power does not change with voltage differences. The percentages of the *I* and *Z* models decreased as the voltage dropped. Table 3.3 below illustrates these differences.

Table 3. 3: Voltage control of the main feeder with different load models (Mithulanathan *et al.*, 2000)

Load model	Voltage regulation (%)
Constant power	12,84
Constant current	11,02
Constant impedance	9,87

A similar investigation was carried out by (Roy *et al.*, 2011) using a static and composite load model, considering a Kumamoto 15 bus distribution system shown in figure 3.14 with bus 1 connected to the main grid while bus 15 is connected to a wind generator. It was recorded that the *P* load models had the highest voltage regulation as they had the highest voltage drop along the feeder followed by the *I* load models before the *Z* load models. For the composite loads, dynamic analysis was carried out, which showed they had the highest voltage drops while the *Z* loads had the lowest dips.

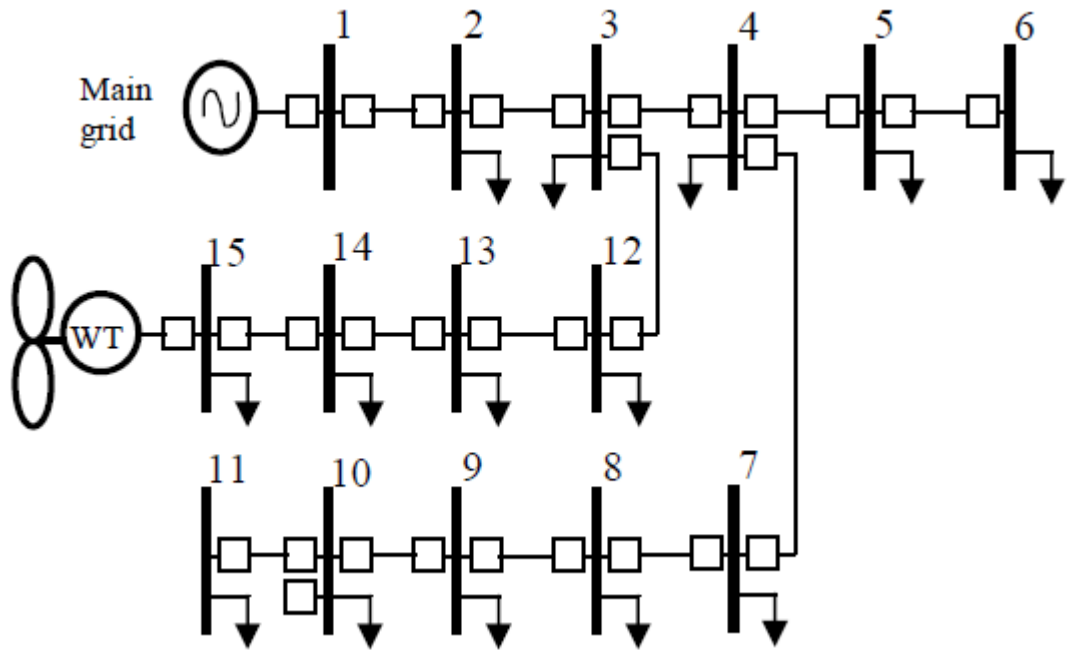


Figure 3. 14: Single line diagram of Kumamoto 15-bus distribution system (Roy *et al.*, 2011)

(Roy *et al.*, 2013) investigated various load components based on the IEEE Task force report with an assumption that point of load delivery comprises 30% static loads (water heater, space heating, cooking, etc), 50% induction motor, and 20% fluorescent lighting. Constant current models are used to represent the active components of static loads. Fluorescent lighting is represented by an exponential model with the exponent's n_p and n_q equal to 1 and 3, residential motor loads are represented by a third-order model. In addition to the above-mentioned static and composite load model, the study added a wind generator to the DN to identify the changes required in the design of the system, operation, and equipment to best allow RE. The study concluded that the voltage stability margin of the system is reduced by the high penetration of distributed wind generation. The system with static load models was simulated according to the time domain and found to return to its pre-fault conditions without violating grid constraints. The composite load characteristics on the other hand responded slower in returning to its initial state after an unexpected disturbance and in turn it violates the grid code. The right load models go a long way in dynamic voltage stability analyses of DN as it is recommended.

Figure 3.15 below shows the example of composite load model representation used by (Roy *et al.*, 2013).

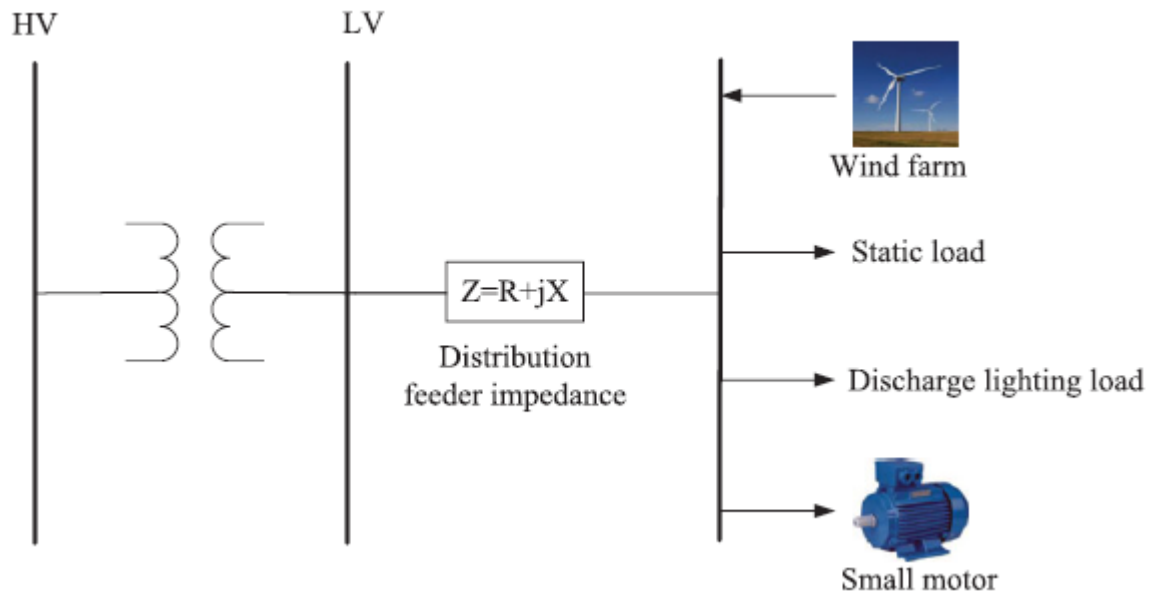


Figure 3. 15: An example of composite load with DG (Roy *et al.*, 2013)

It is of great importance to select an appropriate load model as it could be that the voltage difference can significantly reduce the lifespan or defect loads fed by DN. Thus, the voltage stability of a system is highly dependent on how the load is represented.

At the point of consumption, Voltage regulators and substation transformers ULTCs are tasked to hold constant voltage. However, when the ULTCs get to their tap range, a voltage drop in the DN occurs. The active and reactive loads will drop for residential which will affect the line reactive losses by reducing them. For the industrial loads, a little change will be noticed in the large components of induction motors. Although, less reactive power will be supplied by capacitors in the industrial areas which will in turn cause an increase in the reactive load. In situations where the distribution voltage remains low for a few minutes, devices will operate at any given time to restore the load. Loads that are voltage sensitive will return and the distribution voltage will drop even further. Induction motors are known to draw high reactive current at voltages below 85 to 90% of the nominal voltage which will drop the voltage even more. The load loss will yield a voltage gain after which the motors are restored to service. The service return could continue the circle again if the voltage problem is still present. The representation of load composition should take into account the effect of load voltage regulation devices and in industrial areas, capacitors and motors could be required to be detailed represented (Kundur *et al.*, 1994).

3.4 Consumer Type

Section 2.1.3 introduced the DN as a key component of the electric grid as it delivers the electric power to the final customers by connecting them to several different nodes, with a huge spacing between each other. These diverse types of consumers have different needs for electricity for their various loads. The four major consumer types according to

(IEA, 2020) statistics are Industrial, Residential, Commercial, and public services and transportation. The report indicates all four sectors along with others (agriculture, fishing, and non-specified) consumed 1.919Mtoe of electricity in 2018. Table 3.4 below shows the share of the various customers in the final consumption.

Table 3. 4: Global Electricity final consumption by sector in 2018 (IEA, 2020)

Sector	Final consumption (%)
Industrial	42
Residential	26,9
Commercial and public services	21,5
Transport	1,7
Other	7,9

3.4.1 Residential Customers

This class of customers includes homeowners (Single-family homes, apartments, condominiums, multifamily houses, and mobile homes). The major use of electricity in this sector is for cooling in the summer, heating in the winter for some regions of the world, water heating, appliances, electronics, and lighting. Over one-third of the electricity utilized in the U.S are assigned to residential customers (US EPA, 2015). 37% of overall U.S. electricity consumption is allocated to this sector as can be seen in figure 3.17. The consumption in this sector increased steadily from 1990 to 2007, after which there was minute growth because of improvement in the efficiency of the end-users. 74% is allocated to single-family homes (Schwartz *et al.*, 2017).

According to (Tsemekidi-Tzeiranaki *et al.*, 2018) 29,03% of the final electricity consumption in the EU is allocated to the residential sector as can be seen in figure 3.17. Between 2009 and 2019, the consumption of electricity by the residential sector increased by 0,8% as the household appliances, consumer goods, average number of persons living in a household, and the number of households increased (eurostat, 2021). A typical difference can be seen in a country like France which uses electricity as the main energy source for space heating. Other reasons are due to the difference in the level of energy efficiency and rates of types of equipment between EU countries. It is important to point out that there has been a strong reduction in electricity consumption in some EU countries such as Germany, Belgium, Cyprus, and Ireland (ODYSSEE-MURE, 2021).

3.4.2 Commercial/Service Customers

The Commercial customers are very diverse and are made up of businesses that have storefronts, government facilities, warehouses, public and private organizations, malls, schools, hotels, hospitals, etc. The sector mostly uses electricity for ventilation, heating, lighting, electronics, air-conditioning, etc. Businesses are usually operating

between conventional working hours and tend to be less during the weekends or at night. The sector accounts for one-third of U.S. electricity use (US EPA, 2015). Commercial consumption accounts for 35% of the entire U.S. consumption. However, the commercial end-use intensity in the U.S. is projected to reduce by 8,8% (Schwartz *et al.*, 2017).

The service sector in the EU has been on a slow rise since 2000 with a dip in 2011 after which it continued to rise. In 2016, the section accounted for 30,39% percent of the total electricity consumption as can be seen in figure 3.16.

3.4.3 Industrial Customers

This is the most diverse sector as it is made up of different small, medium, large, and very large facilities (Schwartz *et al.*, 2017). Processes such as construction, manufacturing, and agriculture in the Industrial sector use electricity for their operation. Power motors is the major use of electricity in this sector. Some other typical examples of the use of electricity in the sector are heating, cooling, electrochemical processes, etc. (US EPA, 2015). The sector accounts for 27% of U.S. electricity consumption. However, 11% of the electricity usage in this sector is sourced from CHP. The acquisition of electricity from the grid were similar from 1990 to 2014. Nevertheless, a rapid increase is expected between 2010 and 2025. (Schwartz *et al.*, 2017).

In the EU, most branches of electricity consumption have been on a steady rise since 2014 and studies show chemicals, machinery, paper, and food are the most electricity-intensive branches (ODYSSEE-MURE, 2021). The sector recorded the highest electricity consumption between 200 and 2016 with a maximum of 1.140,7 TWh in 2007. The sector however experiences a huge drop of 13,63% between 2008 and 2009 due to the financial crisis. The increase thus continued in 2010 with a reduced pace between 2011 and 2014. It have been on a rise since then (Tsemekidi-Tzeiranaki *et al.*, 2018).

3.4.4 Transportation

The introduction of electric vehicles (EVs) which uses electricity from the power grid has seen the section included as one of the major electricity consumers. These EVs are usually either battery-powered, or plug-in hybrid and can store electric power. The ratio of electric rails, subways, and buses connected to the grid is on a steady increase across the world today. The future projection of electric transport will see more light-duty vehicles and rails slowly because of the significant changes in technology, infrastructure, and customers' choice required for the growth of electric transport (Schwartz *et al.*, 2017). In the U.S., transportation accounts for 1% of electricity use (US EPA, 2015). The majority of the share of electric transport is a result of passenger rail which accounts for 88% (Schwartz *et al.*, 2017).

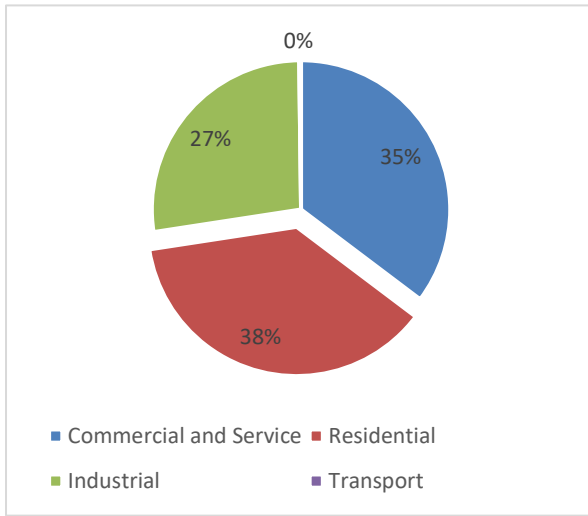


Figure 3. 16: U.S. electricity consumption by sectors in 2013

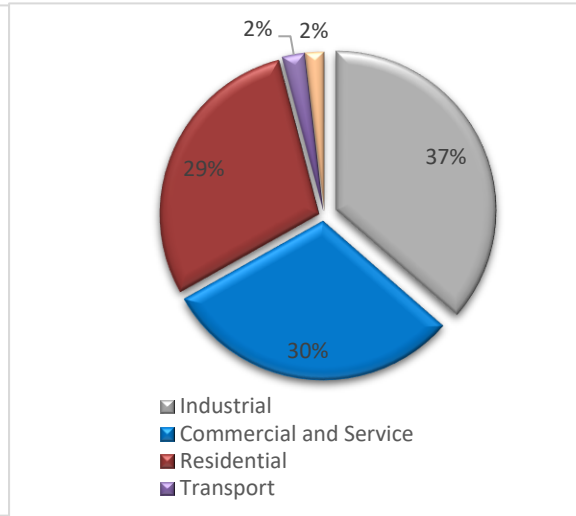


Figure 3. 17 :Germany Electricity Consumption breakdown into sectors in the EU-28 2016

These factors that differentiate DN have led various utilities to carry out investigations on how different load types respond to voltage control. This has led to the introduction of advanced smart devices using an automated feedback process with Supervisory Control and Data Acquisition (SCADA) architecture to control the voltage and reactive power levels in the various grid. These smart devices will be elaborated on in chapter 4.

4 Power System Stability

The electric power grid has operated in a passive mode where customers receive electricity generated to view the DN till before the last decade. Thus, the conventional system maintained a top to bottom active and reactive power flow. The energy transition saw the introduction of distributed generation (DG) at the MV and LV levels, turning the DN into an active system. It is paramount that utility companies guarantee power quality to the final consumer. This introduction of DG into the electric networks has led to various negative impacts on the electric grid (Sanchari *et al.*, 2019). Notwithstanding, the quality of power supplied to the consumer must reach a certain minimum standard considering the constancy of voltage, frequency, and level of reliability (Kundur *et al.*, 1994). (Grigsby, 2007) *Power system stability is defined as the capability of a power system to go back to operational stability after experiencing a physical failure that restricts most system variables to sustain system integrity under certain initial operating circumstances.* According to (Kundur *et al.*, 1994), *it is that characteristic of a power system that allows it to stay in a state of operating stability under regular operational conditions and to reclaim a suitable state of stability after being imperilled to a disturbance.* In other words, a power grid must be able to answer to irregularities in the frequency and voltage disturbance for it to remain stable. It cannot be over-emphasized that the power system must meet the frequent changing of load demand for active and reactive power. To meet this requirement, utilities have developed various smart devices that can assist in returning the system to its normal operating condition. The load, topology, and other key operating parameters change continually and the power system which is a highly nonlinear system must operate with these changes. Instability in each grid could be caused by extreme weather conditions, inadequate topology, personnel error, or malfunction in equipment. If these instabilities are not contained in a section of the system, the end effect could be a major **blackout**. Various components of the power grid are usually operated by a controller which is overseen by a plant controller that interrelates the control of the various components. However, this plant controller is also supervised by system controllers at the control centers of which their decisions are ordered by pool-level master controllers. Needless without saying that there are distributed steps in controlling an entire system. Other systems such as the SCADA are used to provide the status of a system. There is usually a human operator that monitors that is tasked to maintain the minimum performance of the system, manage resources, and system restoration during emergencies.

Studies show power system stability is not considered a single problem as system instability is of different forms which are affected by various factors. In other to find out the

factors that contribute to instability and create measures to tackle and stabilize the operation of a system, one must consider how big the disturbance is, the nature of the disturbance, the best method to calculate and predict the stability, and the devices, approach and time required to determine the stability (Kundur *et al.*, 1994; Grigsby, 2007).

The stability of a power system is classified into various categories as shown in figure 4.1 below to address the complex problems. Utilities must consider all classes of the stability phenomena. However, this study will only focus on Voltage stability which will be elaborated on in the following section.

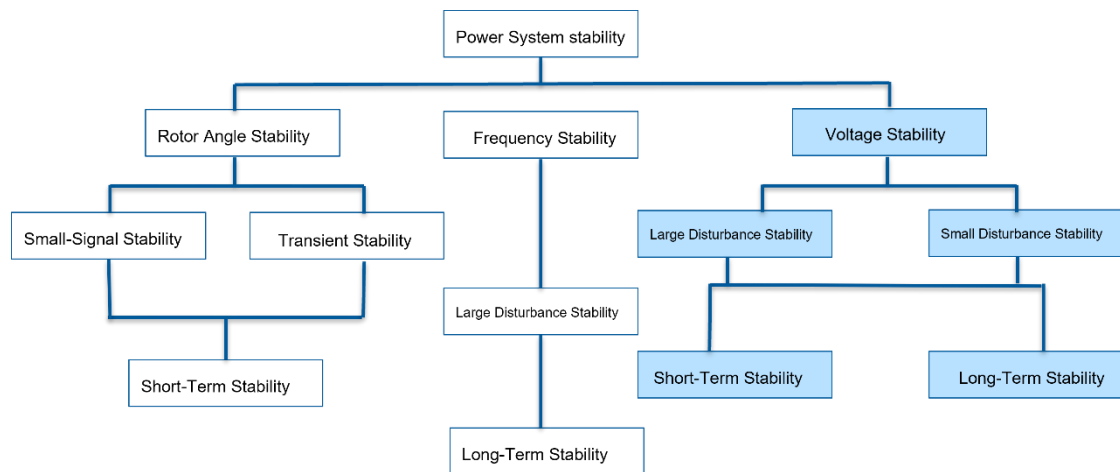


Figure 4. 1: Classification of Power system stability

4.1 Voltage Stability

The continual increase in the load side against the power generation side has contributed immensely to the instability of the grid which has been a challenge for the electricity industry in the last decade. A very common problem is voltage stability which can be seen in figure 4.1. Voltage stability is one of the major classifications of power system instability which has been responsible for various grid network failures in recent years. It is widely considered the major category of power system failure and has attracted the attention of many power system operators and researchers as it is the frequent cause of many power network failures. (Kundur *et al.*, 1994; Grigsby, 2007) defined voltage stability as *the capability of a power system on every bus to maintain an acceptable voltage on the network under normal conditions after being disturbed*. Ensuring voltage stability is very important for the reliability of the grid as when voltage instability is not detected, it can lead to *voltage collapse*. Section 3.1.4 introduced the voltage quality standard of Europe, and the U.S. Table 4.1 show the comparison of various standards laid out by utilities around the world to prevent fault on equipment connected to the grid.

Table 4. 1: Long duration supply voltage variation statutory limits in different countries (Partha Sarathy, 2018)

Standard	Statistical evaluation	Compliance w.r.t U_N
EN 50160 (Europe)	95 % of the time in 1 week	$\pm 10 \%$
ANSI C84.1 (USA)	100 % of the time	-2,5% to + 5%
NVE (Norway)	100 % of the time	$\pm 10 \%$
NRS-048-2 (South Africa)	95 % of the time in 1 week 100 % of the time in 1 week	$\pm 5 \%$ $\pm 10 \%$
GB/T 12325-2003 (China)	100 % of the time	$\pm 10 \%$
CEA (India)	Not specified	-10% to + 6%

Some examples of voltage instability are the U.S. – Canadian grid blackout on 14th August 2003 as a result of reactive power supply challenges (Haes Alhelou *et al.*, 2019). Power outage on September 28, 2003, in Italy. This disconnected the Italian system from the European power grid for 12 seconds. During these 12 seconds, the overloading of the available line caused a voltage instability phenomenon whereby several generating plants tripped (Makarov *et al.*, 2005). Other typical examples of disturbances were experienced in France in 1978 and 1987, Florida in 1982, Sweden in 1983, and New York in 1970 (Kundur *et al.*, 1994). Various studies indicate a rapid decline or increase in voltage occurs when there is a fault, increase in demand, or a deviation in the condition of a system occurs. During this phenomenon, the power system becomes unable to meet the reactive power demand. At this point where the voltage has reduced to an unacceptable value, there will be a loss of load. Another outcome will be the power system losing its integrity. A voltage drop could also occur when a rotor angle goes out of step. Concerning the load, a voltage drop occurs when the load absorbs large reactive power which means a lagging PF (Grigsby, 2007).

In response to interruptions caused by voltage instability, the operation of distribution voltage regulators, tap changers, and thermostats restores the power consumed by the load. (Grigsby, 2007).

4.1.1 Voltage Stability Analysis in Radial Distribution Network

Eqn 4.1 below represents the voltage variation along a line (Sanchari *et al.*, 2019).

$$\Delta V = \left(\frac{PR + QX}{V} \right) \quad (4.1)$$

Where ΔV is the voltage change and P and Q are the outputs of the DG's active and reactive power. X and R are the reactance and resistance of the line connecting the DG, and V is the nominal voltage of the terminal of the DG.

The instability of power systems to meet the demand of reactive power is the main factor causing voltage instability. To determine the ability of a system to maintain voltage stability, P-V and Q-V curves are utilized. The P-V curve represents voltage changes as power transfer between two systems increases, while the Q-V curve represents the

reactive power demanded by buses because of voltage level changes. Our focus in this paper is on the P-V analysis, The simple radial network shown in figure 4.2 can be used to illustrate the power flow relationship between the source and load (Roy *et al.*, 2013).

$$\sim I = \left(\frac{\sim V_s}{\sim Z_{line} + \sim Z_{load}} \right) \quad (4.2)$$

Where, $\sim V_s$ is the constant voltage source, $\sim Z_{load}$ is the load, $\sim Z_{line}$ is the series impedance, $\sim I$ and $\sim V_s$ are phasors, $\sim Z_{line} = Z_{line} \angle \theta$, $\sim Z_{load} = Z_{load} \angle \phi$. The magnitude of current is

$$I = \left(\frac{V_s}{\sqrt{(Z_{line} \cos \theta + Z_{load} \cos \phi)^2 + (Z_{line} \sin \theta + Z_{load} \sin \phi)^2}} \right) \quad (4.3)$$

Which may be expressed as

$$\left(\frac{V_s}{\sqrt{F Z_{line}}} \right) \quad (4.4)$$

$$F = 1 + \left(\frac{Z_{load}}{Z_{line}} \right)^2 + 2 \left(\frac{Z_{load}}{Z_{line}} \right) \cos (\theta - \phi) \quad (4.5)$$

The magnitude of the receiving end voltage

$$V_r = Z_{load} I \quad (4.6)$$

The power supplied to the load is

$$P_r = V_r I \cos \phi \quad (4.7)$$

$$= \left(\frac{Z_{load}}{F} \right)^2 \left(\frac{V_s}{Z_{line}} \right)^2 \cos \phi \quad (4.8)$$

Decreasing the load Z_{load} will simultaneously increase the loading of the network. The loading of the network is increased with V_s , line parameter fixed and load power factor for the P-V analysis. Equation 4.8 shows P_r increases when Z_{load} decreases, this increase in power transmitted. Due to F , the value of P_r decreases when Z_{load} approaches Z_{line} . From equation 4.6. V_r decreases gradually as Z_{load} decreases (Roy *et al.*, 2013).

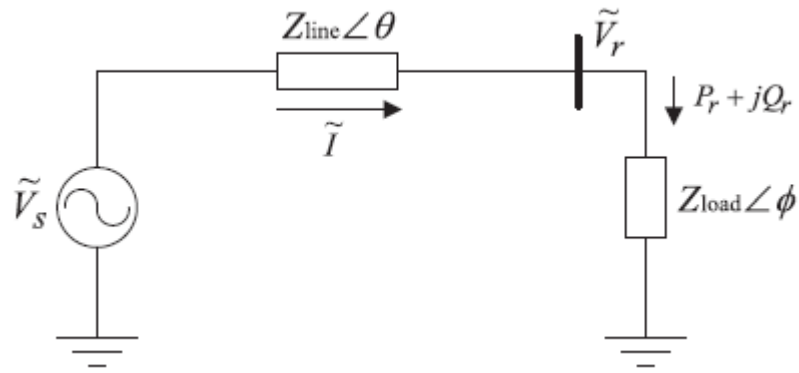


Figure 4. 2: A simple radial distribution system (Roy *et al.*, 2013)

4.1.2 Classification of Voltage Stability

Figure 4.1 showed that voltage stability is further sub-categorized into large and small disturbance voltage stability. The subcategories distinguish phenomena to be analysed by using nonlinear dynamic analysis from the ones analysed with steady state.

4.1.2.1 Large Disturbance Voltage Stability

This type of voltage stability deals with the capacity of a system to control voltages when disturbances such as loss of generation, circuit contingencies, and system faults occur. The communication of the discrete and continuous control, as well as the system load characteristics. An examination of the nonlinear dynamics of the system over some time is required to estimate the large disturbance stability (Grigsby, 2007).

4.1.2.2 Small Disturbance Voltage Stability

Small disturbance has to do with small disturbances such as a change in the system load and the system's ability to control the voltages in this phenomenon. Continuous and discrete control and attributes of the load define stability at a certain point. Studies show the concept is very important as it can determine at any time how the system voltage responds to small changes in the system (Grigsby, 2007).

It is common that voltage instability is either a short- or long-term phenomenon and rarely occurs on its own. It is usually accompanied by rotor angle instability as various studies indicate. Notwithstanding, utilities must make it a priority to distinguish problems caused by voltage stability from the other types of stability to develop adequate procedures for operation and design.

Various devices are used to improve nodal voltage profiles in DN with the aim of increasing the reliability and performance of the distribution grid. The common regulating devices will be established in section 4.1.2.4 while other more improved devices in section 4.1.2.4

4.1.2.3 Conventional Control Devices

4.1.2.3.1 On-Load Tap Changer (OLTC) Transformer

The most common control device to maintain stability at the MV level is the centralized control known as OLTC. The OLTC is capable of operating while the load is still connected to the transformer feeds. *The primary substation transformers are typically equipped with OLTC* that manoeuvre the voltage down the line through the command of sensors and relays. The transformer's ratio can be changed by changing the amount of turns a side of the transformer. Normally between 10-15% in steps of 0,6 – 2,1% (Romero, 2010). Based on the tap position, the voltage could be decreased or increased. It resets the voltage magnitude and shifts the phase angle to control the voltage. It can also set the nominal value of the voltage using a dead band on a specific point on the line and can also use an integral controller to control it (Romero, 2010). This type of transformer is comprised of a Line Drop Compensation (LDC) which serves as a compensator for a further drop in voltage between the end load and the OLTC. Meaning it performs correction of the voltage at a specific point considered as the load center. The line voltage drop based on the line current, resistance, and reactance is estimated by the LDC. The high-speed resistor and reactor are the two main types of OLTC (Viawan, 2008). The reactor type is used in smaller transformers while the Resistor type is installed in bigger transformers. (Dong *et al.*, 2018a). The LDC uses the knowledge of the resistance and reactance of the line to calculate the voltage drop after which it sets the voltage values on this basis with the tap changers of the transformer (Romero, 2010). The AVR within the transformer monitors the output of the voltage and sends instructions to the tap changer for voltages over the pre-set limit. It makes a comparison between the measured side and regulated side voltages with the target voltage (Gutierrez-Lagos, 2018). The controller also has a time delay to prevent the occurrence of high frequency on the tap changer. Step voltage regulators (SVR) is an equipment that improves the voltage by a transformer with LTC and can be connected at the center of a feeder. The control circuit of the SVR setting requires a desired voltage level at the load center to be held between 114V to 126V, a voltage bandwidth, and a typical 30 to 90 seconds time delay (Dong *et al.*, 2018b). In this voltage bandwidth, the OLTC is instructed not to make changes to prevent hunting effects which are the oscillating of taps between two positions. For voltages outside the set bandwidth, the OLTC is instructed by the AVR to change the tap position. However the AVR only instructs the OLTC to change tap position when the voltage recorded has stayed outside the set bandwidth for a time range to avoid excessive tap changing (Gutierrez-Lagos, 2018). The medium voltage is usually supplied with a No load Tap changer (NLTC) which simply allows the change in ratio when the transformer is in its de-energized state

(Sanchari *et al.*, 2019; Danielsen, 2019). The reverse current flow still restricts the reliability of the OLTC. Figure 4.3 shows the schematic of the transformer with a tap changer. Unfortunately, the reliability of the OLTC is restricted by reverse current flow.

Another common type of Tap changer is the off-load tap changer. This type is distinguished from the OLTC with the fact that the load must be disconnected to change the tap position. It is the major type of tap changer used in European secondary substation where a tap position is chosen through a life cycle and is permitted to take care of the maximum voltage drop that occurs in the LV network (Gutierrez-Lagos, 2018).

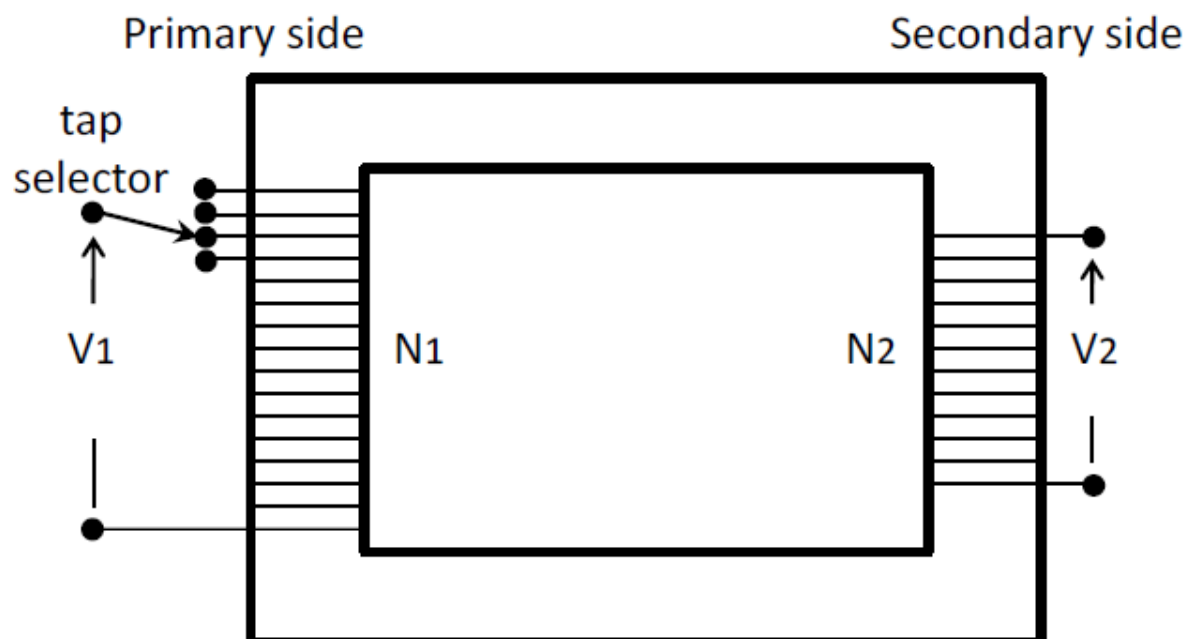


Figure 4. 3: Schematic of transformer with tap changer (Gutierrez-Lagos, 2018)

4.1.2.3.2 Capacitor Banks and Reactors

The use of a capacitor can either be in series with the line or shunt connection. Connection in series with the line is preferred in the transmission network as it can reduce reactive losses which will in turn reduce voltage drop. However, in the DN, the capacitors are connected in a shunt as a series connection is not adequate to lessen the flow of reactive power into the line (Gutierrez-Lagos, 2018). *These shunt capacitors are usually installed close to the load (at the receiving end substations)* for reactive power compensation which will consequently reduce voltage drop. The capacitor bank can be sub-categorised into switchable capacitor bank (SCB) and fixed capacitor bank (FCB). The SCB and FCB provide power factor correction at a different voltage level in the DN. They are usually installed at appropriate locations along the length of the heavily loaded MV feeder to verify voltages at every point remain in the permitted condition as the load changes (Kundur *et al.*, 1994). Power electronics and mechanical switches can be used

to switch the SCB. A typical example is a Thyristor switched capacitor (TSC), Thyristor switched reactor (TSR), and Thyristor controlled reactor (TCR) which are all basic types of Static Var compensators (SVC) (Kundur, Balu and Lauby, 1994). SVC is a step-less and fast control is obtained thyristor switched devices capable of controlling both capacitors and reactors. The SVC is usually injected near high reactive power consumption loads (Danielsen, 2019). The reactive power supplied or absorbed by the SVC and synchronous condensers are automatically adjusted to maintain the voltages of the bus they are connected to (Dong *et al.*, 2018b). In other words, reactive compensation is connected to reduce voltage while capacitive compensators are connected to increase it and in turn correct power factor and feeder voltage control. The ratio of R/X is a key factor for these devices as the underground cables use an R/X ratio between 0,5-1 with a higher resistance making the reactive compensation less efficient in distribution lines (Romero, 2010).

4.1.2.3.3 Series Voltage Regulators (SVR)

SVR are usually installed along the feeder of voltage violations to provide voltage regulation over the feeder. They can regulate the voltage in a specific feeder without influencing further feeders connected to a specific bus. The equipment uses a transformer that has a tap-changing mechanism to stabilize the voltage (Partha Sarathy, 2018). The bottleneck of this system is to decouple the MV line and reboot the bandwidth of the voltage on the line. The SVR can also be referred to as line voltage regulators (LVR). It can modify the voltage and disconnect the voltage operating in a MV line from HV/MV transformer voltage. A good choice of positioning is 1/3 to 2/3 down the line (Carlen *et al.*, 2015).

The approach of the conventional voltage regulation in an hierarchal structure as indicated in figure 4.4 below.

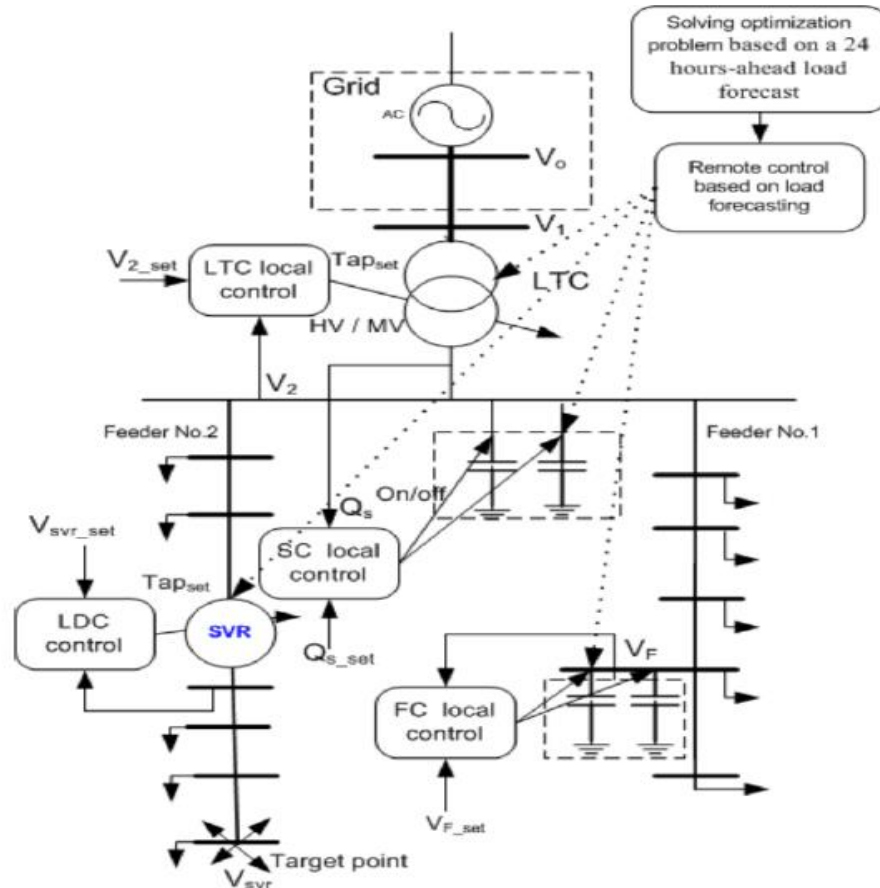


Figure 4. 4. Conventional voltage and reactive power regulation in DN (Dong *et al.*, 2018a)

Challenges in the DN have led to DSOs investments in various smart devices that are capable of sustaining customers' voltages within operating limits. technologies utilities have been looked upon to achieve voltage stability is discussed in section 4.1.2.4 below.

4.1.2.4 Improved control devices

4.1.2.4.1 FACTS Based Shunt Compensator Technologies

These technologies are popularly used to subdue voltage violations in the DN. The main shunt compensation technologies are the Static Synchronous Compensator (STATCOM) and the Static Var Compensators (SVCs) (Partha Sarathy, 2018). A unified power flow controller (UPFC) is a FACTS device used for regulating line voltage. The equipment may overcompensate for slow voltage variation. However, it can adequately be utilized to protect against fast voltage fluctuation within the operating voltage range as it has a fast response (Xu and Taylor, 2008). STATCOM compensates for reactive power by converting the DC input voltage to the AC output voltage. As a result of a few bulky reactive elements, STATCOM has a faster response to disturbance than SVC. Nevertheless, SVC can also react fast (within 2-3 cycles) to voltage violations. The two types of SVC are the Thyristor Switched Capacitor – Thyristor Controlled Reactor (TSC –

TCR) and the Fixed Capacitor – Thyristor Controlled Reactor (FC – TCR) (Partha Sarathy, 2018). figure 4.5 shows a combination of TSC-TCR layout. These FACTS method is much faster in response to a change in the system in comparison to conventional voltage devices. To sustain the required AC voltage at the bus that is STATCOM connected, the reactive output is usually regulated. STATCOM is differentiated from reactive power control of generation as it can deliver a solution that does not require a generator. Aside from the usage in DN, it can also be used in the transmission network. STATCOM can be employed as both the sink and source of reactive power. STATCOM still faces a rapid deployment as a result of its high cost (Xu and Taylor, 2008). *They are installed close to a specific load or in the substation along the feeder* (Dong et al., 2018b). Studies show the use of self-commutated semiconductor switching devices at the distribution level to create distribution STATCOM and Unified power quality conditioner (UPQC) is currently being promoted to perform voltage control and other issues in the transmission network (Dong et al., 2018a).

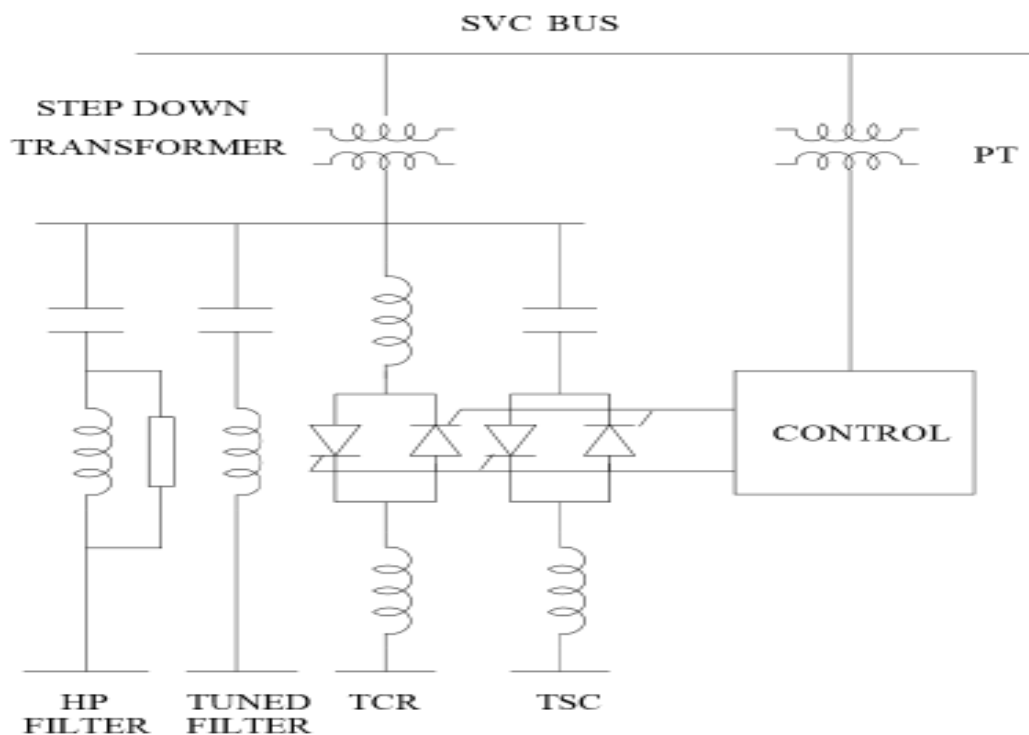


Figure 4. 5: A Typical layout diagram of a SVC (TCR-TSC) (Partha Sarathy, 2018)

4.1.2.5 Voltage/VAR Optimization

The process where utilities can optimize voltage and reactive power at the same time is known as volt/VAR optimization (VVO) (Lawlor, 2017). Today, smart devices in DN have experience verse technology advancements and have shifted the focal point of

reducing energy consumption to the controlling of volt-ampere-reactive (VAR) and voltage power levels. This phenomenon is indicated in various studies as VVO (Dong *et al.*, 2018a). VVO prioritizes the circuit level operations, where it reduces reactive power flow along the DN, thereby reducing energy losses (Lawlor, 2017). VVO control can either be centralized or decentralized structured. An LTC transformer and SCB/FCB voltage regulators are used in the centralized VVO method to control voltage and reactive power. This centralised VVO method can be further divided into distribution management system model-driven, SCADA rule-base, and hybrid VVO. Figure 4.6 represents the DMS model-driven IVVC scheme (Dong *et al.*, 2018a).

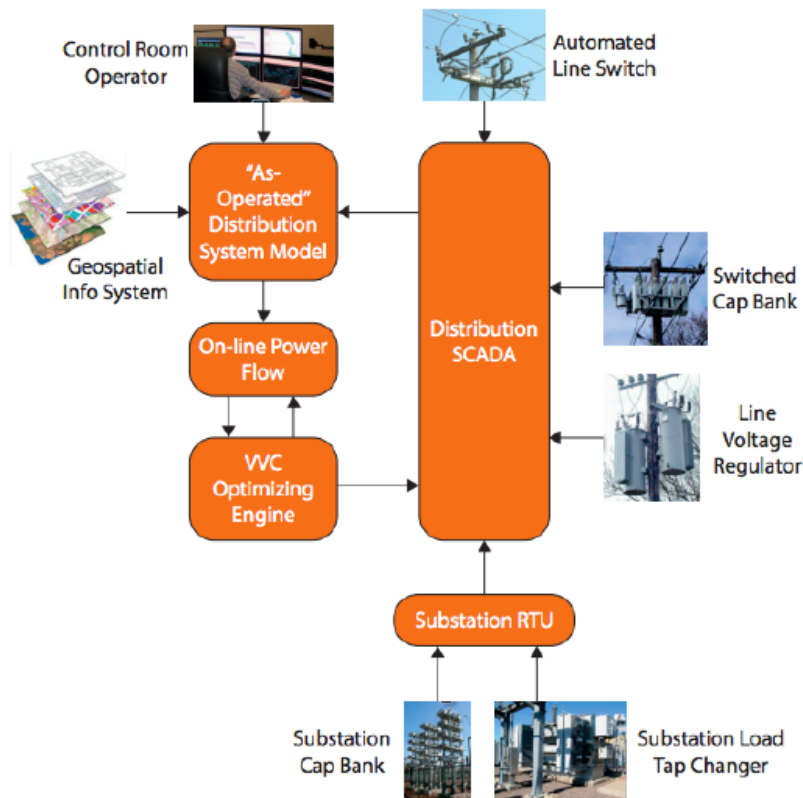


Figure 4. 6: DMS model-driven IVVC scheme (Dong *et al.*, 2018a)

The model driven VVO uses a lot of the equipment and information present in the DMS. These include a geographic information system, outage management system, advanced metering infrastructure, and real-time network configuration, to configure and carry out an optimal switching schedule to achieve an aspiring result for the controllable devices.

In figure 4.7 the rule based VVO is represented, and it incorporates a remote terminal unit and a VVO processor together. The VVO processor communicates with the line devices via SCADA or cell phone. To attain lower energy consumption, power demand, feeder losses, or a combination of each one of these, the architecture is capable of adding the feeder end voltage, and switching the tap position ON/OFF based on some

rules and programmed thresholds for voltage and VAR (Dong *et al.*, 2018a).

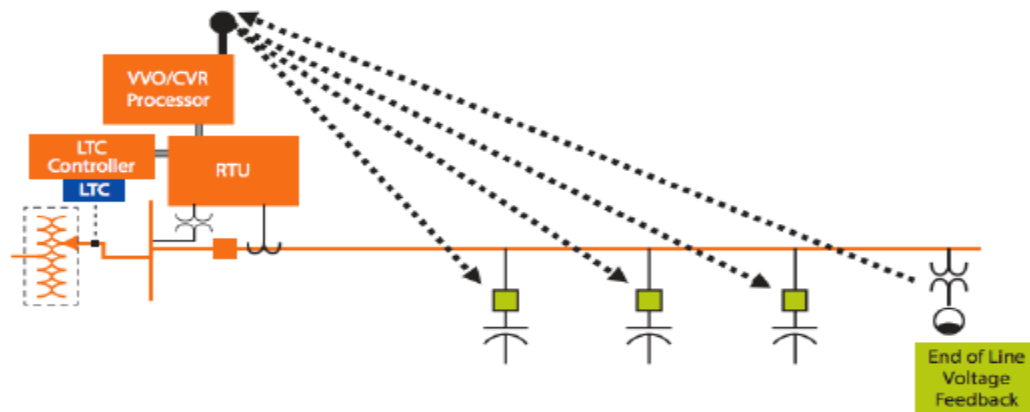


Figure 4. 7: SCADA rule based VVO approach

The most recent advancement is the hybrid VVO approach. This approach uses auto-adaptive controllers at the system level or in the field devices to tackle the changing conditions. The auto-adaptive controllers are based on historical behavioural patterns or closed-loop control with real-time voltage measurements to improve the power flow based on pre-set conditions by the utility (Dong *et al.*, 2018a).

VVO Coordinated devices assist utilities in adequately controlling reactive power and voltage levels at any time or location. The DSOs can easily be alerted in situations of voltage instability when a customer load behaviour changes and thus a quick response can be carried out by the VVO operators to adjust the voltage close to optimum levels (U.S DOE, 2012, p.151). The decentralized VVO method has been gearing more attention in response to control scalability.

4.1.2.6 Conservation Voltage Reduction (CVR)

CVR is an approach in the VVO scheme which performs the task of conserving energy and increasing efficiency and reliability in the DN. The CVR is a strategy designed to reduce distribution feeder voltage within the statutory bandwidth to obtain demand and energy reduction for customers. Mostly at the primary substation (Dong *et al.*, 2018b). Today, the CVR is implemented by consenting fixed voltage reduction at points that can be controlled closest to customers. CVR ensures that customer voltages are within the operating limit. Equation 4.9 below shows the proportionality constant called the “CVR factor” (U.S DOE, 2012, p.12).

$$CVRf = \frac{\Delta E (\%)}{\Delta V (\%)} \quad (4.9)$$

A CVRf of 1 means that 1% reduction in voltage is achieved from a 1% reduction in energy

consumption.

Devices such as the OLTC and remote monitoring in the LV network permit managing voltages closer to the customer and it is unlocked to continue to reduce voltage and save energy at the same time using CVR. There are two active CVR control schemes which can be implemented in the growth phase. (Gutierrez-Lagos, 2018).

4.1.2.6.1 Rule Based Active CVR Control

This scheme oversees voltages in OLTC. It allows LV networks in opposition to voltage reduction in primary substations. This control method is ideal for a transitioning period as it is best suitable for a system where there is not much DG. Thus, reduced monitoring and communication equipment are used. The control can also be further developed for cases with various DG (Gutierrez-Lagos, 2018).

4.1.2.6.2 Optimal Power Flow - based CVR

This scheme uses the entire network monitoring for the end users' voltages, OLTCs, and capacitors through the MV and LV network that is unbalanced. This approach considers the MV and LV limitations as it manages voltages to reduce energy consumption (Gutierrez-Lagos, 2018). It selects one of the different actions compared and subjected to specific operating constraints.

CVR has been around for a long time, however, it is limited by the inability to observe the level of voltages along the distribution feeder length. CVR was developed primarily in North America. The fact that the few customers are fed by a small transformer limits the application of voltage regulation in the North American LV grid as a lot of devices would be needed for voltage regulation. In the European LV network, on the other hand, hundreds of customers are fed. Nevertheless, the application of voltage regulation from primary substations would still be restricted by some LV customers with consequential voltage drop, MV customers complying with the standard of voltage and on the OLTC itself (Gutierrez-Lagos, 2018). Another common reason CVR is not used is that it is hard for utilities to earn a rate on return on lost revenues as customers would have lower bills from consuming less electricity. CVR could benefit in voltage control at the secondary substation, allowing sizeable reduction.

4.1.2.6.3 Solar PV inverters

In recent years rooftop photovoltaic (PV), large- and small-scale solar farms have been developing all around the world. PV inverter have thus been developed to perform ancillary services. These smart inverters can perform communication, measuring, and computing tasks which in turn makes them capable of performing control functions asides from the conventional power conversion responsibility. The PV inverter can provide

compensation for reactive power concerning their local voltages based on piece-wise linear functions. As these inverters are versatile in reactive power management, it gives them the advantage of mitigating over voltages. Grid codes such as the IEEE standard 1547 and CA Rule 21 have advocated for the inclusion of smart inverters in voltage regulation. These smart inverters can act fast in solving real-time network violation in voltage caused by load variation of the generation of the PV (Nguyen *et al.*, op. 2018).

A very common technique of mitigating voltage violations is power curtailment whereby DSOs trip DGs from the network to prevent issues of voltage (Danielsen, 2019). This is because of the inflexibility of voltage control strategies. For networks where DGs are connected to the grid, this method wastes a lot of RE potentials and the profit of the DGs is largely reduced (Lawlor, 2017). Other methods include adding extra feeders, energy storage technologies, increasing conductor sizes, balancing load between different phases, etc (Staff, 2015).

4.2 Grid Impedance

Grid impedance is a vital parameter in present-day power systems, which includes a significant number of power electronic converters. The connection between current and voltage is referred to as the grid impedance. The grid impedance consists of the cable impedance and MV/LV transformer impedances and can be either asymmetrical or symmetrical. Figure 4.8 below represents the grid impedance and the relationship between current and voltage unbalances (Al-Jaafreh and Mokryani, 2019). According to (Al-Jaafreh and Mokryani, 2019), the major reasons for current and voltage unbalanced are uneven distribution of single-phase loads, Variations in load demands, propagation from the MV network, asymmetrical network impedances, and high penetration of LCTs in the LV network.

A Grid impedance estimate can help contribute to power system stability as its value can be used in collaboration with active filter control, and a line impedance information value can be used to detect fault and depict the location of the fault. The value can also serve as a threshold for disconnecting plants of power generation in situations of islanding. The common methods for estimating impedance are the passive method and filtering techniques of grid current and voltage.

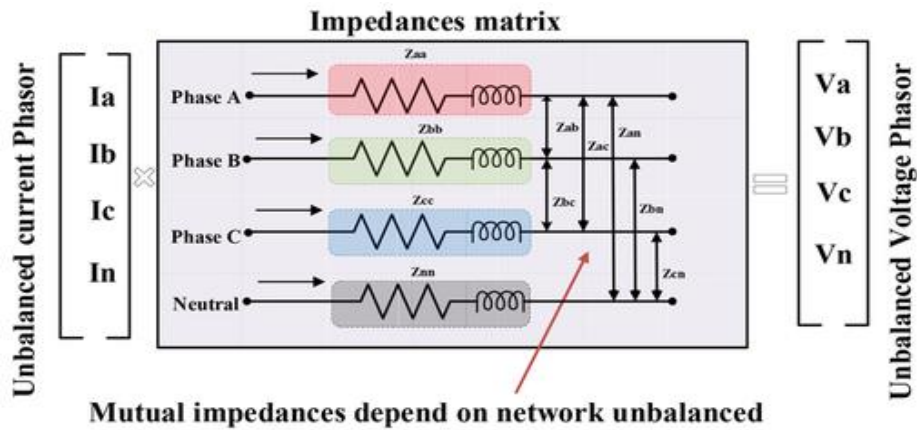


Figure 4. 8: Relationship between current and voltage unbalances (Al-Jaafreh and Mokryani, 2019)

Germany is one of the frontrunners in RE integration in the electric grid with a growing focus on PV and wind technologies. According to (BMWK, 2022), the integration of RE poses risk to the grid where an acute risk may result in a large-scale disturbance to the European synchronous grid. These tools are normally coupled to the LV and MV network. The DSOs in Germany tackle voltage constraints brought about by the integration of RE by using ring grids in closed-loop operations. In this practical implemented method, a radial structure that is of open ring grids is changed to a closed ring. In this method, various separate powerlines are connected at a switching station in a closed-loop structure. This method minimizes the construction of new power lines. The DSOs have also realized dynamic voltage control at MV substations, applied the N minus zero rule, and used the RE system to produce reactive power for the control of voltage. In addition, the DSOs have also started the grid expansion process, installed voltage-regulated distribution transformers (VRDT), voltage regulators, express feeders connecting substations with centers of generation, and substations primarily for RE systems (Bayer and Marian, 2020).

In the U.S., DERs connected to the distribution grid are also causing similar issues such as bidirectional power flow, variation in voltage, stability and protection problems, quality of power issues, etc, for the DSOs. However, the regulation of ac voltage aids the control of active power while the change of voltage amplitude controls the reactive power. To tackle this, grid operators require all converters integrating DER to the distribution grid must have fault ride-through possibilities. Operators also use advance distribution management systems (ADMS) to monitor and respond to events in the grid.

5 Case Study

The Electric power Grid has come a long way from the conventional power generation to see more and more DG being introduced into the distribution grid. The challenges this active generation poses have already been over-emphasized in chapter 4. Utilities meet these challenges by utilizing control devices discussed in section 4.1.2. The advantages and challenges of adopting these control devices in the European and North American grid taking Germany and the U.S. as the representative network will be further discussed in this chapter.

5.1 Part 1: Germany Grid Network

The German power Grid is widely considered one of the most vital power grids in Europe and a frontrunner for the energy transition. System Average Interruption Duration Index (SAIDI) measured Germany to have a downtime per customer of 12 minutes in 2019 compared to 128 minutes in the U.S. (Kerstine Appunn and Ruby Russell, 2021). This power Grid is witnessing more DGs being introduced into the distribution grid with voltage levels less than 110kV. Figure 5.1 below shows the schematic representation of the voltage levels in the German Power Grid which indicates the power grid is divided into four (4) voltage levels.

Germany's electricity distribution grid (more than 1.7 million kilometres long)



Figure 5. 1: Diagram of the German Power Grid

5.1.1 Germany Distribution Grid

Germany's MV DN covers 520.000km and it is fed by an HV grid via a substation that aids

the transformation to a range between 6kV and 60kV (BMWK, 2022). In this grid stations in the same urban or rural districts distributes electricity between themselves. If faults occur, the MV network can be disconnected from the power grid without affecting the other parts of the grid as they are coupled to the power grid via isolating points. On rare occasions, consumers are connected to the MV grid (Energie-experten, 2022). Electricity is distributed by the MV grid either directly to factories or hospital customers on rare occasions or transformer stations (BMWK, 2022).

The German LV distribution network covers 1.120.000km. It is the part of the grid that distributes to the consumers. The substation connects the MV to the LV network and has a voltage not exceeding 0.4kV (BMWK, 2022). Smaller industries, private households, small farms, administrations, and trade are connected to the LV grid. In Germany, DG systems are connected to this voltage level. The LV grid has a radial structure in the rural areas, supplied by a single local distribution transformer. Densely populated rural may have a ring grid setup or a power line can be supplied with two local distribution transformers. In urban areas, the grids are commonly interconnected. The proportion of overhead lines in the LV grid is 40% while the underground cable is 60% (Bayer *et al.*, 2018).

In Germany, there are more than 1300 electricity suppliers than ensure the distribution grid DN supplies the consumer. They usually buy electricity through organized trading venues or direct trading between partners and resell it to their specific customers. In an area, the supplier with the most customer is usually considered the default supplier. The DSO on the other hand guarantees the transport of electricity. They oversee the entire operation and maintenance of the German power grid. The DSOs in Germany are over 800 and some belong to bigger companies such as E. ON, EnBW, RWE, Vattenfall and Innogy. The others are regional utilities. End consumer in Germany can change their energy provider but not the DSO. The end consumers of the German electricity Grid consist of households, commercial enterprises, and large industrial customers. Even though the household customers are most end users, the latter is recorded to consume more. Electricity in Germany is mostly distributed via overhead or underground cables with underground cables gaining more demand in most areas (Energie-experten, 2022).

In November 2006, Germany among other regions in Europe experience its latest blackout because of grid instability. The fault originated in North Germany under E. ON Netz control area. Lines were overloaded when a high voltage line was switched off to accommodate the safe passage of a ship. The grid reacted by splitting the EU into three zones. The failure of the voltage control tool which resulted from the lack of power in the Western zone resulted in the switching off customers in various countries including

Germany. The major reasons for the failure were the lack of technical tools to verify the operation of the system within allowable limit, lack of security procedure, lack of communication with other European operators on their action to switch of a line, and lack of investments on smart devices to ensure reliability and safe operation of the grid (European Commission, 2007).

Even though the German grid has been very reliable since the incident, 162.224 supply interruptions in the LV ad MV were reported by operators in 2020. This interruption increased by 2.400 in comparison to 2019 (Bundesnetzagentur, 2021). This goes without saying that urgent actions need to be taken to prevent further grid instability in the future.

This paper suggests the following solutions to prevent a reoccurrence of the 2006 blackout:

- Invest more on grid automation and modernization to ensure real-time monitoring of the grid and reliability. Power generation, the power grid, and the demand must be smartly connected to ensure efficiency. To achieve this all parties will have to act together.
- Set standards and requirements grids operator must follow regarding the security of the grid.
- Transparent and effective communication between system operators to ensure real-time demand for electricity is being met.
- Development of incentive regulation for R&D of new grid innovation tool and pilot projects.

German DN are currently facing increasing challenges. 95% of renewable power generators connected to the DN have called for an urgent need to update the infrastructure to meet the rising bi-directional flow of power (Kerstin Appunn and Ruby Russell, 2021). Currently, DSOs are only responding by expanding their grids which is a high-level investment. Studies show a lot of research and pilot projects have been directed toward AVRs to provide more reliability of the DN. Some of the pilots projected adopted in the German DN are outlined in the following section.

5.1.2 Adoption of AVR in German Distribution Grid

AVRs are devices designed to automatically regulate voltages by achieving normal voltage levels from fluctuating voltage levels. These devices integrate the use of interfaces and communication systems with control of field devices. There are different types of AVR such as LDC, SVR, Electronic voltage regulator, Magnetic induction voltage stabilizer, etc. The following are typical examples of adopting AVR in the German distribution Grid.

- A collaborative project between RWE and ABB revealed a 20kV prototype LVR in

2014. In the 20kV pilot installation of Westnetz, an LVR was realized which could adjust the LV/MV line within a certain range to a desired. The LVR could also distribute electrical power up to 8 MVA by making a new reference point for the voltage. In other words, the LVR notably raised the capacity of generation power. The LVR was significantly cheaper when compared to the cost of expansion of the MV grid. The whole LVR can also seemly be disconnected and transferred to another location. Thus, giving the grid more flexibility for future changes (Carlen *et al.*, 2015). According to (Hitachi Energy, 2022), the LVR developed by Hitachi Energy also has additional benefits of connection to the grid control system for remote control or monitoring of the grid.

- ABB developed an AVR called PCS100 AVR. The AVR is applicable in MV when installed with the supply in series to deliver dynamic and continuous voltage rectification reaching $\pm 10\%$ for loads up to 10MVA and over. In LV, it can be placed near an already placed secondary substation. It can easily be reconfigured to fit with different distribution transformers sizes and provide voltage regulation for all feeders supplied. Its major advantage is that it can solve voltage regulation for a central position (ABB, 2018, p.2). ABB installed this AVR on RWE Germany's grid in 2011 to stabilize the voltage level in a 20kV network also at 20kV/0.4kV transformer stations. It resulted in cost savings and increased grid capacities. ABB has also installed PCS100 AVRs on 10 DSOs networks at 20kV/0.4kV station of transformer (Buchholz, 2015).
- In Bavaria, the RiesLing project saw a collaboration of ABB AG, Deutsche Telekom, EnBW Regional AG and EnBW Ostwuerttemberg Donau-Ries to develop new solutions for voltage regulation. FIONA came into light which can eliminate voltage measurements at the 20kV side of a transformer station and replace them with values from the 400V side. It prevents the installation of an expensive voltage transformer on the 20kV side. A PCS100 AVR was also installed to ensure the low-voltage grid is maintained within the permissible range (Buchholz, 2015).
- ABB developed a distribution transformer called Smart-R Trafo which was designed to regulate voltage automatically on-load. It is made up of OLTC which identifies voltage change in a network and quickly resets the voltage ratio. It has the advantage of increasing the capacity of hosting networks for RE generation and is a cost-effective alternative to grid expansion. Network infrastructure adaptation is not needed by this technology. It can also allow remote control and monitoring (ABB, 2013). According to (Buchholz, 2015, p.5), the Smart-R transformer is on its way to being a standard operating device for DSO in Germany

and other markets.

- Netze BW and Siemens are developing a grid automation solution that will serve as a benchmark for a future project. The emphasis of the system is on monitoring the network and managing faults with intelligent technology and long-range control of active voltage stability. There will be a distributed grid area controller in the Niederstetten substation that will be based on a Siemens SICAM automation system for the control of voltage and fault management. The major advantage is the cost and energy efficiency of the distribution grid as no need for costly grid extension is needed. A significant reduction in SAIDI value can also come about from the improved fault detection and rapid troubleshooting result (Siemens, 2022).
- In 2017, ABB also was contracted to install its STATCOM at the Borken substation in Hessen. The grid will be strengthened by the FACTS technology which will provide reactive power compensation and dynamic voltage assistance to reduce voltage variations from RE (NS Energy Staff Writer, 2017) .
- ABB collaborated with RWE and TU Dortmund to demonstrate a pilot Grid4EU project in Reken, Germany where the autonomous device is capable of monitoring conditions of the load in the grid and adapts quickly to changes in demand. The technology also permits the switching of open ring lines and uses advanced control functions to detect voltage irregularities (Knack, 2013; Robin, 2014).

5.2 Part 2: United States of America Grid Network

The U.S. electric grid is also made up of power plants, transmission lines, and the DN. The U.S grid comprises 7.700 power plants, 3.300 utilities, and around 2,7 million miles of power line (McBride and Siripurapu, 2022). However, this is a total of all three separate U.S grids (Eastern, Western, and Texas interconnections) split into three regions. These three grids are standalone irrespective of each other and share a small amount of energy between themselves. Over the years, the vulnerability of the grid has also increased as a result of extreme weather even of which the latest example is the Texas winter storm that occurred in 2021 (The Texas Tribune, 2022). Figure 5.2 illustrates the U.S. Power Grid. The US grid is monitored by the North American Electric Reliability Corporation (NERC). The electric grid of regions is operated by the ISOs (Independent system operators). They also provide the reliability planning of the grid. The RTOs (regional transmission organizations) perform a similar responsibility but have more responsibility for the transmission network. They also control and monitor the functioning of the entire system within their specific territory. In areas, without ISOs/RTOs the utilities perform these functions. In the U.S., there are 7 ISOs (California ISO, New York ISO,

Electric Reliability Council of Texas, Midcontinent Independent System Operator, ISO New England, Alberta Electric System Operator, Independent Electricity System Operator) of which three are for the U.S. There are four RTOs in the United States: PJM Interconnection (PJM), Mid-Continent Independent Systems Operator, RTO (MISO), Southwest Power Pool, Regional Reliability Council (SPP), and ISO New England (ISO-NE). The U.S has over 3.200 electric utility companies known as balancing authorities that perform the generation, transmission, and distribution of power for over 145 million customers. However not all perform the three stages. The regulation that sets the standard of reliability of the operation of the grid comes from the Federal Energy Regulatory Commission (FERC) (Gilstrap *et al.*, 2015, pp.6 - 30)

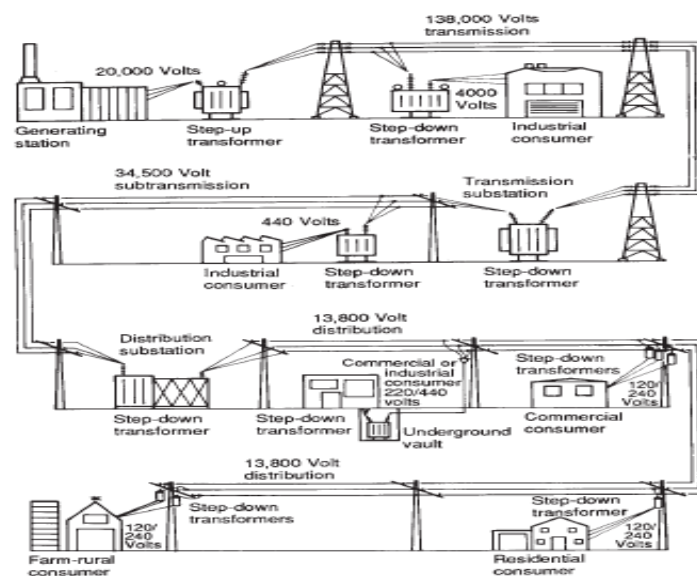


Figure 5. 2: Diagram of the U.S. Transmission and Distribution Networks

5.2.1 U.S Distribution Grid

The MV also known as the primary distribution system in the U.S makes up most of the DN. The distribution lines cover more than 96.560.640km and have over 200.000 distribution circuits. In this network, the distribution substation aids the connection of transmission or sub-transmission lines to the MV network. The voltage is lowered at the substation to MV 13,8kV. At load centers, power is stepped down by a distribution substation to limit the voltage to medium ranges. It is important to note that heavy loads such as Industrial customers and Railways are directly connected to either the transmission or sub-transmission network through distribution transformers (Gilstrap *et al.*, 2015).

The LV network (also known as secondary network) in the U.S. is practically non-existent as 3-phase supplies to end users in residential areas are very rare. The distribution transformer located very close to the load's steps down the voltage to LV which

is <1kV (415V, 480V, 208V). These smaller transformers are mostly mounted on concrete pads of local distribution lines in an area. There are also common underground transformers. This low voltage is distributed to residential or small commercial and industrial customers. The low voltage lines usually cover short distances (Gilstrap *et al.*, 2015).

The distribution is mostly carried out at the MV which is different from Germany's practices. In the MV network in the U.S, a single-phase DN distributes to the various single-phase transformers, which supplies one or several consumers straight from the transformer (Schneider Electric, 2022).

In the U.S, customers experienced over 8 hours of power interruption in 2020 which is a record-breaking year according to SAIDI. The U.S grid is interrupted frequently by factors such as extreme weather events, maloperation of protection systems, old power infrastructure, utility practices, and vegetation patterns (Anodyne and Sara, 2021). One of the latest major events was in February 2021 Texas winter storm blackout, where generation failure resulted in a loss of power for 4,5 million homes (Ning *et al.*, 2021).

In August 2003, about 50 million people were affected by a major power outage in eight states in the United States. This was a result of a reactive power problem in the states of Ohio and Indiana. As a result of software dysfunctionality and failure, the First Energy (FE) real-time situation was unknown in the control center. The Northern Ohio service area was generating increasing reactive power where the grid reacted where the high content caused the Eastlake unit 5 voltage regulator trip because of over-excitation. To restore the automatic voltage control, the generator reacted by tripping again. Other lines such as the Chamberlin-Harding, the Hanna – Juniper, and the Star-Canton also tripped because of tree contact. No proper action could be taken at the FE and MISO control center as they were unaware of the situation. This led to a wider range of cascading tripping in the Sammis-Star line and some other lines in Ohio and Michigan. This cascading loss caused power to flow in the opposite direction from Pennsylvania, through New York into Michigan and Ohio. This caused the voltage regulation tool to fail and the voltage to collapse from the heavy loading which resulted in a regional blackout. The entire North-East and Ontario turned into separate electrical. This island was further divided into different smaller islands where some islands could reach equilibrium without experiencing a total loss of power. The indicated cause of the blackout according to the U.S. – Canada Power System Outage Task Force was a result of lack of situation awareness, lack of understanding of the system, lack of FE alarm failure detection system, lack of tree trimming, and lack of support from reliability coordinator (Andersson *et al.*, 2005; Haes Alhelou *et al.*, 2019; Makarov *et al.*, 2005).

This paper suggests the following solutions to prevent a reoccurrence of the 2003 blackout:

- Deployment of automatic devices that is capable of load shedding which could have prevented the blackout in North-east Ohio
- Investments in more efficient real-time tools to be aware of what's transcending in the grid and coordinate actions responsibly
- Old standards must be evaluated, compulsory standards of reliability must be adopted and there should be repercussions for noncompliance.
- Investments in automated voltage control and reactive power practices must be adopted.

5.3 Adoption of AVR in U.S. Distribution Grid

Recent technological advancements have made it feasible to monitor voltages in the DN and send information obtained to the voltage regulating devices and capacitor bank. The U.S. utilities are already focusing more on these smart devices to solve the rising outages and unreliability of the U.S grids. Witnessing a transition to the smart grid as the investments from both private and public sectors in the Smart Grid Investment Grant Program (SGIG) geared up to 7,9 billion dollars (\$3,4B in federal funding, \$4,5B in industry funding) of funding to help increase the development of smart grid was provided by the American Recovery and Reinvestment Act of 2009. 2,19 billion dollars was allocated for the electric DN, and 82.000 intelligent and automated devices were installed out of which 10.665 were AVRs (U.S DOE, 2016; SMARTGRID.GOV, 2016). The SGIG which enabled cost-shared grants in billions to assist the production, buying, and implementation of smart grid technologies ran from 2010 – 2015 (SMARTGRID.GOV, 2016; Arnold, 2011). The U.S. Department of Energy (DOE) implemented the SGIG program which involved 99 projects deploying smart technologies in the U.S. Power grid. 26 of these projects covered advanced VVO technologies to upgrade the DN (U.S DOE, 2012) while 62 projects implemented distribution automation (DA) technologies (U.S DOE, 2012). The SGIG project aimed at Reducing voltage levels by reducing them for a period to obtain conservation of electricity (CVR for Energy), Reducing voltage levels at peak stages to obtain the lowering of peak demand (CVR for Peak), and Dropping energy losses over feeders.

- Northern Virginia Electric Cooperative (NOVEC) deployed 14 automated feeder switches, 164 automated capacitors, and 340 Automated regulators among other distribution automation devices. NOVEC reduced voltage variation by using monitors on transformers and meters. The daily report received was used to

confirm the number of operations per regulator device, feeder voltage levels, and tap position of the regulator. By remote controlling or precise repair to VR, the voltage levels to customers stayed at the acceptable level (U.S DOE, 2016, p.35).

- Duke Energy installed 914 AVRs, and 2,098 automated capacitors among other distribution automation devices. Devices are installed to measure and relate digital information concerning distribution line loading, and voltage levels to a system that can remotely pinpoint and isolate the faulted lines. Duke Energy also used CVR to manage peak demand by reducing service voltage levels. 2% voltage drop was achieved for over 200 circuits in Ohio utilizing an integrated volt / VAR controller (U.S DOE, 2016 pp. 40 - 43).
- Consolidated Edison (Con Edison) installed 111 AVR among other automated devices. Con Edison was able to increase PF and reduce the reactive power consumption which in turn improved voltage management capabilities by using an overhead MV distribution circuit (U.S DOE, 2016, pp. 44-45).
- Southern Company has used CVR to reduce voltage levels by 5% during extreme weather and reduce peak load to achieve a peak reduction of 300 MW (U.S DOE, 2016, pp. 61 - 62).
- Central Lincoln People's utility district integrated the CVR control system with SCADA and AMI systems. The system analysis the AMI data every 15 minutes to see if the AMI voltage is outside the target range where an alert is sent by the smart meter to the control system which notifies the SCADA command to regulate the voltage at the substation. The utility saved 360MWh as a result of CVR in 2013 compared to 2012 (U.S DOE, 2016, p.69).

Other notable applications of AVR in the U.S. DN were carried out by Florida Power & Light Company (FPL), Burbank Water and Power (BWP).

5.4 Advantages of AVR in the U.S and German distribution Grid

The SGIG project in the U.S outlined the benefits of implementing DA technologies on the grid. The benefits are as follows (U.S DOE, 2016),

- Automating the grid resulted in the improvement of grid connection of some DER such as thermal storage for buildings. In California, Burbank Water and power could control ice storage systems with DER management systems that helped reduce the cooling requirement by 5%.
- The installations of these smart devices at the key location also assisted in providing real-time alerts when issues arise whereby utilities can properly plan to

fix issues be it repair, maintenance, or replacement. This was evident when Florida Power and Light stopped an outage that could have affected a lot of customers and prevented a huge sum in restoration costs.

- The resilience of the DN to extreme weather events was recorded to be improved as automation aided the constraining of the level of blackouts and the ability of grid operators to identify and repair faulty equipment is enhanced.
- Fewer and shorter duration outages were experienced as the location and isolation of a fault are highly improved. This has resulted in reduced outage costs and fewer equipment failures which in turn have led to a better experience for the consumers. SGIS utilities prevented \$1,46 million switching costs in over 3 years.
- Equipment has been monitored more efficiently which has reduced the need for maintenance. The reduced maintenance means the operation cost is also reduced. This reduction in operating cost enables a faster restoration as repair crews are used more efficiently which will in turn reduce emissions in the environment (U.S DOE, 2016). The SGIG utilities prevented distribution operation costs of about \$6.2 million in a year. Duke Energy also benefited from O&M savings while Southern company deferred t \$3,4 million from distribution capacity investment.
- AVR assisted utilities in reducing peak demand more efficiently which resulted in a deflection of capital investments and power quality improvement. Reactive power could also be managed better which led to an upgrade in the power quality. CVR implementation by some utilities serves the function of feeder voltage level reduction in which the energy consumption is reduced at peak demand time and efficiency of the entire distribution system is increased. ConEdison is a typical example where CVR was used to increase substation capacity by 2,8% and saved \$15,7 million.

The advantages of utilizing AVR in the German grid is as follows:

- The implementation of AVR and grid intelligence for network monitoring and fault management leads to a cost and energy efficient DN as it prevents the need for a costly expansion. This is evident in the grid automation being implemented by Netze BW and Siemen in Niederstetten. This project enables more integration of RE sources into the grid without causing system instability (Siemens, 2022).
- Fault detection can also be improved and quick troubleshooting results which can contribute to a further reduction in the SAIDI value, and in turn cost savings.
- Supporting and stabilizing the grid whereby enabling RE sources to be transported

to the heavy load center. In Hessen, a Hybrid SVC light STATCOM was installed in the broken substation to serve this purpose (Hitachi Energy, 2020).

- Voltage regulation of voltage rise caused by the increase in photovoltaic and wind generation. The use of ABBs PCS100 AVR can perform this function. It has proven to be cheaper than building new cables and substations. This easy implementation AVR is currently undergoing trials in key German utilities both in the MV and LV installation as addressed in section 5.1.2 (ABB, 2018).

5.5 Challenges of AVR in the German and U.S distribution Grid

This advanced device is not without some challenges. This section depicts the challenges of AVR in the U.S. and German grids. The SGIG project in the U.S. experienced the following (U.S DOE, 2016),

- The automation of the grid resulted in changes in the operation of the grid that demanded experts in various fields. This expert will also be tasked with carrying out training of new individuals as an increased workforce is needed.
- Installing many smart devices resulted in the production of many data to be analysed and processed. This new data must also be collected, error-checked, and transformed into actionable data.
- It was discovered that lab conditions for testing devices were not as precise as actual field tests. These automated devices needed more upgrades and testing.
- It was quite a challenge for utilities (especially first-timers) to integrate automated devices into the already existing system. This integration needed newly made software for various functions that were non existing. This software must be able to simulate as fast as possible to operate the grid.
- The cost-effectiveness depended on the scale of the project, the purpose of the devices, the need for software and retrofitting, and the know-how of the utility. The large-scale project saw a better return on investments.
- Unavailability of data standards for many technologies and systems.
- The need for improvement of cybersecurity and interoperability tools, protocol, and standards for the safe implementation of automated devices:

Germany on the other hand has had a stable power grid over the years despite the high integration of RE sources into the grid. The country has an average interruption time of 10.73 minutes in 2021 according to SAIDI (Bundesnetzagentur, 2021). However,

experts are warning about the need for smart devices to keep the grid stable with the further transition from reliable sources. Northern Germany is currently experiencing overloading of networks from the rapid integration of RE and in the south where PV plants already exceed the Bavarian demand (BDEW, 2012, p.4). Germany's conservative attitude towards and the following are the challenges facing the AVR in the grid.

- Network operators unable to guarantee investment security for smart devices projects. The rate of return to be obtained from capital expenditure determined by the regulatory authority falls under the equity interest rate (BDEW, 2012, p.15).
- Even though AVR pilots have proven to be successful in grid integration, the rapid deployment of these smart devices is limited by the utility focus on the conventional grid expansion measure which the existing incentive schemes that regulate the revenues of German DSOs depict grid expansion as more cost-effective as these smart devices have higher operating cost (Bayer and Marian, 2020, p.6).
- Current regulation provision only focuses on brief-term cost slashing and does not compensate for a state-of-the-art solution that smart devices are based on. Demonstration projects by operators and research and development activities require the provision of incentives by the regulation (BDEW, 2012, p.15).
- Data security concerns, delay in technology development, and lack of certification standard procedures which is evident in the slow implementation of smart meters roll-out in Germany.

6 Conclusion

This Thesis looked at the different factors that contribute to the variation in grid response to voltage regulation. The work compares European and North American distribution grids to learn more about their differences. The study showed that the European system have the advantage of flexibility in the LV design and disadvantaged by the high cost and subject to theft. On the other hand, the North American system is more flexible in the MV design but requires small transformer for every few customers. The benefits and limitations of adopting automated control in the DN of both regions were outlined where the U.S could increase the grid resilience to extreme weather, Germany could regulate voltage rise from the increase in DER. To address the adoption of automated control, a case study was conducted for Germany and the U.S. investigating recent schemes was carried out. The study showed that U.S.is ahead of Germany in the implementation of automated devices in the distribution grid. An in-depth study of new and old voltage control devices was also undertaken to gain insight into the appropriate point of installation of the various devices. Finally, a brief overview of *voltage stability* as a focused category of power system stability gave insight into the two types of disturbances. It was discovered that voltage instability is either a short- or long-term phenomenon and rarely occurs on its own. It is usually accompanied by rotor angle instability

The objective of this thesis is to examine how the grid will react to voltage control tool failure and suggest on the best way to address the failure. Investment in grid automation and modernization in both regions surfaces as a key solution in both regions as it ensures real-time monitoring and control of the grid. This solution will have both economical and distribution efficiency benefits whereby the reliability of the respective grids is improved considerably.

Lastly, Automation of the grid also aids the limitation of grid expansion, however, the deployment of these technologies still faces challenges such as uncertainty of return of investments, lack of incentives and workforce, data security concerns, and problems in integration to existing systems, etc.

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