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Thomas Weidinger

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Common mode oscillations in electrical drive systems

Thomas Weidinger

University of Erlangen-Nuremberg, Erlangen, Germany

Common mode
oscillations

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Abstract

Purpose – The purpose of this paper is to present an analysis of common mode oscillations of several kilohertz in electrical drive systems. The analysed oscillations occur especially in electrical drive systems with active front end (AFE), common DC link and long motor cables and are independent of the well-known reflection phenomenon. Owing to the resulting overvoltages, the motor isolation lifetime may be significantly reduced.

Design/methodology/approach – For the analysis of the described problem, all parts of the common mode system of an electrical drive system are carefully modelled. This leads to an analysis of the frequency behaviour of the common mode system. The excitation mechanisms are also analysed and simulation in the time domain is performed to show the resulting overvoltages. Finally, measurements confirm the findings.

Findings – The investigations identified the reasons for the oscillations: the common mode system behaviour, including the common mode resonant behaviour of some special kinds of motor. Furthermore, the excitation mechanism is found to be dependent on the modulation schemes of the AFE and the inverters. Accordingly, a special remedy concerning the modulation is derived and compared to other known remedies. The results of the simulations show the good efficiency of the proposed remedy.

Originality/value – The presented results describe important basics for the development of electrical drive systems. By taking these issues into consideration, many unpredictable failures can be avoided.

Keywords Oscillations, Noise control, Torque, Modelling, Electric motors, Overvoltage

Paper type Research paper

1. Introduction

Electrical drive systems such as shown in Figure 1 with an active front end (AFE) and a common DC-link are often used for industrial applications with several axes, owing to the high potential for energy saving. In distributed production lines, the length of the motor supply cables can thereby achieve several hundred metres. To reduce electromagnetic interference (EMI) shielded cables are usually used. They represent parasitic capacitances to ground. Other parasitic capacitances to ground also exist in power semiconductor devices and motor winding. Together, with the sum of these capacitances $C_{par\Sigma}$ the choke used in the AFE builds an inductance for a common mode LC resonant circuit.

The damping of this circuit is almost only represented through the damping appearing in the choke. Excitation is generated through switching in the rectifier of the AFE and the inverter. By reason of resonant frequencies of 10-40 kHz low-damping occurs. As a consequence of these oscillations, high voltages appear on the motor terminals.

At this point, it is important to take a closer look at the high-frequency behaviour of the motor in the common mode region. Owing to parasitic capacitances between winding and grounded core, and the inductances in the winding a common mode resonant behaviour also exists. Most types of AC motor with distributed winding have

Figure 1.
Electrical drive system
with AFE, common DC
link and long, shielded
motor cables

a common mode resonant frequency much higher than the common mode resonant frequency of the drive system. For this reason, the motors can be modelled as capacitances to ground for the frequency range below their resonant frequency. Hence, the voltage at the star point is equal to that on the terminals.

Nowadays especially, permanent magnet synchronous motors are often produced with concentrated stator coils owing to the lower winding losses and easy mounting possibilities (Salminen, 2004). This type of winding is also used in the so-called “direct drives” such as torque or linear motors. These motors typically have low-speed values and high values of torque, respectively, force in the case of linear motors and therefore high numbers of poles. Because of the high-parasitic capacitances in the coils the resonant frequencies may lie in the range of the system’s resonant frequency (Dilling *et al.*, 2000; Heidenhain, 2003; Huber, 2005; Raith and Segger, 2002; Weidinger and Piepenbreier, 2008). As consequence the voltage is strongly elevated from the motor terminals to the star point.

Most analyses of common mode perturbations, such as those by (Cacciato *et al.*, 1999; Muetze, 2004; Costa *et al.*, 2005) describe oscillations from 100 kHz to several MHz. These oscillations are characterised by relatively low amplitudes of the common mode current and relatively high damping compared with the analysed problem.

As regards overvoltages at the motor terminals, reflections are a well-known problem often described, e.g. in Finlayson (1996), Essig (1994) and Kaufhold and Boerner (1993). This phenomenon occurs because of high du/dt at the inverter and the high-frequency characteristics of the shielded motor cables. A maximum voltage of the double of the height at the inverter may therefore appear on the motor terminals. The overvoltages at the motor terminals described in this paper are independent of the reflection phenomenon. The overvoltages owing to reflections may appear additionally and increase the maximum voltages further.

As regards the problem described, only a few publications, such as Dilling *et al.* (2000), Heidenhain (2003), Huber (2005) and Raith and Segger (2002) have proposed remedies, using basic analysis of the problem. Since, a detailed and fundamental analysis is lacking complex investigations were attempted to achieve exact and detailed information about the system behaviour and important dependences on parameters. The first outcomes of these investigations concerning drive systems

without AC motors with low-frequency resonances were presented in Weidinger and Piepenbreier (2008). In the corresponding conference paper Weidinger (2008) to this paper, further results were published. Thereby motors with low-resonant frequency as well as a special coupling mechanism in the AFE were analysed. Several remedies to the problem were also put forward.

In this paper, the previously released results are condensed and presented as background for the understanding of the system behaviour and for the subsequent accurate analysis of the excitation mechanism in the inverters. As result of these analyses an effective remedy that requires minimum effort is derived and proven through results of simulations. Evident overvoltages, common mode currents and losses are presented and compared to the other remedies on offer.

II. System analysis

A Modelling

To obtain a detailed description of the system behaviour, all components of an electrical drive system were modelled as common mode models in the frequency domain. The derived system model is shown in Figure 2(a). Important aspects of the component models are explained below.

1. *Mains*. Concerning the mains, the common mode impedance Z_m consists mainly of the leakage impedances of the in-feed transformer.

Regarding the electromagnetic compatibility filter in the common mode domain, only the capacitors to ground are important. The common mode choke gets saturated very quickly because of high-common mode currents appearing owing to the oscillations described.

2. *Choke*. The analysis and modelling of the choke used for the AFE operation are important elements of this investigation. Damping of the system is almost only produced in the choke, so the parameters of the choke have an important influence on the system's behaviour. The damping of the choke results largely in iron losses in the core, which cannot be calculated accurately. For this reason, extensive measurements

Notes: (a) Detailed model with separate modelling of every element of the electrical drive system; (b) simplified model for further investigation, arranged as a daisy-chain of two-ports with the input signal v_{ex} and the output v_m

Figure 2.
Common mode system
model

were attempted on different chokes to determine the common mode impedance at the considered frequencies depending on current and temperature. An example of the common mode impedance of an iron powder core choke is shown in Weidinger and Piepenbreier (2008). Two different models were derived. One extensive model including current dependency of the inductance and frequency dependency of the resistance was derived for time domain simulation. One simple common mode model, as shown in Figure 3 was created for the frequency domain, including only the frequency dependency of the resistance.

3. *Active front end.* The model of the AFE consists of a capacitance C_{AFE} to ground that shows the parasitic capacitance to the heat sink in the semiconductor devices. The voltage source V_{exAFE} represents the exciting voltage that is generated through the switching operations. An important point for the excitation is the generation of the switching commands in the control unit. This item is analysed in Section IV.

4. *Inverter.* Owing to its similarity to the AFE, the model of the inverter shows almost the same structure. The exciting voltage is called v_{exinv} and the parasitic capacitance has the value C_{inv} .

5. *Cable.* As regards the motor supply cables, only the parasitic capacitances to the grounded shield are modelled as C_{cb} . High-frequency phenomena like reflections are neglected owing to the comparatively high-frequency range. The damping of the cables is in the concerning frequency range relatively low in comparison to that of the choke and therefore also neglected. The capacitance C_{cb} depends particularly on the structure and the materials used for the cables. The most important factor, however, is the length of the cables.

6. *Motors.* Concerning the motors it is important to have a closer look at the high-frequency behaviour in the common mode region. Owing to parasitic capacitances between winding and grounded core, and the inductances in the winding a common mode resonant behaviour also exists. Most types of AC motor with distributed winding have a resonant frequency much higher than the resonant frequency of the drive system. For this reason these motors are modelled as a simple capacitance to ground C_m that shows the parasitic capacitances to the grounded stator core.

In contrast, “direct drives” such as torque motors or linear motors may show a particular resonant behaviour with resonant frequencies below 40 kHz (Dilling *et al.*, 2000; Heidenhain, 2003; Huber, 2005; Raith and Segger, 2002). This leads to a voltage increase in the ground voltage from the terminals to the star point. The detailed behaviour of these motors is analysed in Weidinger (2008) and a common mode model is derived. This model accords with an investigated torque motor with a voltage increase by $\times 5.3$ at a resonant frequency of 27 kHz.

III. System behaviour in the frequency range

As regards the system behaviour of the whole electrical drive system, as shown in Figure 2(a), several simplifications such as the combination of the two excitation

Figure 3.
Simple common mode
model of the choke

sources and the combination of all parasitic capacitances to ground lead to the equivalent circuit shown in Figure 2(b) where $C_{par\Sigma}$ is:

$$C_{par\Sigma} = C_{AFE} + C_{inv} + C_{cb} + C_m. \quad (1)$$

The complete system model is formed as an iterative network. Chain matrix descriptions of the different elements $\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3, \mathbf{A}_{tm}$ lead to a system matrix $\mathbf{A}_{sys}$:

$$\mathbf{A}_{sys} = \mathbf{A}_1 \cdot \mathbf{A}_2 \cdot \mathbf{A}_3 \cdot \mathbf{A}_{tm} \quad (2)$$

whereof the voltage transfer function $\underline{H}(2\pi f)$ can be derived:

$$\underline{H}(2\pi f) = \frac{V_{st}(2\pi f)}{V_{ex}(2\pi f)} = \frac{1}{\mathbf{A}_{sys(1,1)}(2\pi f)}. \quad (3)$$

$|\underline{H}(2\pi f)|$ shows the voltage increase from the excitation to the star point of the motor where $V_{ex}(2\pi f)$ and $V_{st}(2\pi f)$ represent the Fourier transformation of v_{ex} and v_{st} .

Given a system with a certain configuration of choke and inverter, the parasitic capacitances of the motors and the length of the motor cables hence $C_{par\Sigma}$ is the only parameter to be varied. Thereby systems with and without motors with low-resonant frequency have to be distinguished.

In Figure 4, the system behaviour of sample systems with iron powder core chokes are shown as absolute value of the transfer function $|\underline{H}(2\pi f)|$ with parameter $C_{par\Sigma}$. Systems with the analysed torque motor are shown as normal lines and systems with only motors with resonant frequencies high above the concerned frequency range are marked with dashed lines. It can be seen that an increment in the parasitic capacitance leads to both an increment in the maximum voltage increase at the resonant frequency and to a decrease of the resonant frequency. At the same value of the parasitic capacitance $C_{par\Sigma}$, systems with torque motors show a higher voltage increase.

Notes: Dashed lines describe systems without, and normal lines systems with, the analysed torque motor. H_{max} and H_{maxTM} depict the maximum points of the absolute values of the different transfer functions without and with torque motor

Figure 4.
Description of the system
behaviour: absolute value
of the voltage transfer
function $|\underline{H}(2\pi f)|$ of the
system at different sums
of parasitic capacitance
 $C_{par\Sigma}$

The maximum values of the voltage increase vary from two at $C_{par\Sigma} = 10\text{ nF}$ and 20 at $C_{par\Sigma} = 800\text{ nF}$ in systems without a torque motor, and between five and 23 in systems with the torque motor. For parasitic capacitances of between 200 and 800 nF especially, high values of voltage increase are reached.

IV. Excitation mechanism

As regards excitation, switching in the AFE as well as switching in the inverter generates significant excitation. As shown in Weidinger and Piepenbreier (2008) the modulation index has a strong influence on the excitation. The highest excitation is generated with modulation indices near zero, because all three phases often switch at the same time and voltage steps with the height of the full DC voltage may appear. Whereas at high-modulation indices only one phase ever switches at the same time and so excitation steps of one third of the DC voltage appear.

A Active front end

The aim of the control scheme in the AFE is, on the one hand, to generate a DC link voltage that is above the naturally rectified DC voltage and, on the other hand, to reach an approximately sinusoidal line current. Possible control structures are on the one hand a superior control scheme for DC voltage and line current coupled with sine-triangle, space-vector or other modulation generators. On the other hand a superior control scheme for the DC voltage can be coupled with a hysteresis control for the line current. The first structure generates periodic switching commands which create a periodic excitation voltage V_{exAFE} with different harmonics that excite the common mode system. The second structure generates commands that appear non-periodically. Although this seems to be a lower excitation, a special coupling mechanism may generate an enforced excitation. As described in Weidinger (2008) this phenomenon appears especially when a two current measurement is used. As consequence increased overvoltages may appear at the motor terminals.

B Inverter

As regards the inverter the control scheme generates the switching commands. Here, different control schemes are typically used (Kazmierkowski *et al.*, 2002). Most of them consist of a superior control that calculates a voltage phasor and passes it to a pulse width modulator with a definite switching frequency. Different types of modulator produce switching commands. In a stationary case the exciting voltage v_{exinv} depends additionally on the modulation index, the switching frequency and the value of the DC voltage. Out of the waveform the different harmonics can be derived with the aid of Fourier analysis. In Figures 5 and 6, the harmonics appearing at the most frequently used modulator schemes space vector modulation and sine triangle modulation are shown. Thereby a switching frequency of 4 kHz is supposed, the modulation index M is varied and the 12 highest amplitudes of the harmonics are shown.

From these diagrams, it can be clearly seen that the worst case appears with a modulation index close to zero. In this case, the exciting voltage v_{exinv} has a rectangular waveform with the switching frequency and an amplitude of the full DC link voltage from peak to peak.

With respect to the system behaviour shown in Figure 4 it can be found out that the third and the fifth harmonic of the switching frequency are lying in the frequency

Figure 5. Harmonics of the common mode exciting voltage v_{exinv} of the inverter with sine triangle modulator (12 highest values)

Figure 6. Harmonics of the common mode exciting voltage v_{exinv} of the inverter with space vector modulator (12 highest values)

range of a very high-voltage increase of the systems. Hence, they might produce overvoltages at the motor if the resonant frequency lies close to one of these harmonics. In addition, if a higher switching frequency is used, for example 8 kHz, even the fundamental frequency might lie near the resonant frequency of the system, with the consequence of yet higher overvoltages at the motor.

As shown above, in electrical drive systems several axes are usually used. Thereby the control schemes and the switching commands are normally synchronised. As described in Weidinger and Piepenbreier (2008) the resulting excitation of a single switching operation in the inverter equals:

$$\Delta v_{ex} = -V_{DC} \cdot \frac{C_1}{C_{par\Sigma}} \quad (4)$$

whereas C_1 is the sum of all capacitances to ground of the switched phase and $C_{par\Sigma}$ is the sum of all parasitic capacitances to ground. Accordingly, the maximum possible exciting voltage step appears if all capacitances are switched at the same time. Therefore, the worst case in an electrical drive system appears if all axes are

synchronised and the modulation index in every axis is very close to zero. This phenomenon occurs, for example, in the case of the controlled standstill of an industrial production line. Therefore, in many applications, this is a state that is often used.

V. Remedy

As shown above, oscillations in the common mode system of electrical drive systems are originated on the one hand by the low-damped resonant behaviour of the system and the motor, and on the other hand by the excitation through the AFE and the inverters. Remedies can therefore either improve the system behaviour or reduce the excitation. In Weidinger (2008) two different kind of remedies are presented. One kind concerns the excitation of the AFE that reduces the enforced excitation in the hysteresis control and the other increases the damping of the system.

In this paper, a remedy is proposed that reduces the excitation through the inverters. As described in Section IV.B the highest excitation appears if the modulation index is very close to zero. To reduce the excitation in the common mode system the modulation scheme is often modified (Cacciato *et al.*, 1999; Gonzalez *et al.*, 2003). Thereby drawbacks such as distortion in the differential mode currents and a very strong reduction of the maximum modulation index have to be accepted.

In our case, the so-called “flat top” modulation scheme is used. This modulation scheme was introduced in Depenbrock (1977) and, with variations, presented in Hava (1998). The primary purpose of the scheme was the reduction of the switching losses. However, this modulation scheme can in addition also be used to significantly reduce the common mode excitation, especially at very low-modulation indices, without the drawback of a limitation of the maximum modulation index.

“Flat top” modulation adds an additional zero-sequence to the set point values. Thereby the differential mode voltages stay the same, only the common mode fraction is modified in such a way that over the range of 60 degrees of the fundamental frequency one phase is clamped to the plus or minus rail of the DC link. Hence, at very low values of the modulation index or even zero, switching operations of all phases at the same time appear very rarely or even never. The switching-frequency excitation and its harmonics in the common mode voltage is then very low. This can be shown in Figure 7 where the

Figure 7.
Harmonics of the common
mode exciting voltage
 v_{exinv} of the inverter with
“flat top” modulator

amplitudes of the common mode exciting voltage v_{exinv} with switching frequency and their harmonics are depicted at different modulation indices M .

Concerning higher values of the modulation index, the amplitudes do increase a little, but always stay below the values shown in Figures 5 and 6. It has to be assumed also that in this case usually the different axes have different modulation indices, and then that the axes are switching at different times hence the excitation of single switching operations is reduced significantly (Weidinger and Piepenbreier, 2008).

VI. Simulation and measurements

As a consequence of the oscillations, high voltage appears at the motor terminals: in the case of the investigated torque motor it also occurs at the star point and stresses the winding isolation. Other consequences of the oscillations are common mode losses in the choke that decrease the efficiency of the inverter system and raise the temperature of the choke. Furthermore, common mode currents elevate the current loading of the semiconductor switches. To determine the resulting voltage stressing, losses and common mode currents simulations were investigated.

The main parameters concerning the system behaviour are the sum of the parasitic capacitances $C_{par\Sigma}$, the inductance and the damping behaviour of the choke. So for a given choke numerous simulations were processed over the full range of possible $C_{par\Sigma}$. The simulated system was modelled in the time domain and simulated for a sufficient amount of time. To get the results of the worst case operating point the modulation index of all inverters was set to zero. In Figure 8(a), an example of a simulated waveform is shown.

As a result the absolute maximum value of the voltage $V_{m\max}$ at the motor terminals in the case of systems with the torque motor at the star point $V_{st\max}$, the average value of the common mode losses P_{cm} and the root mean square value I_{cmrms} of the common mode current were saved. The simulation parameters are generated from measurements on parts of a given drive system, that was also used for measurement of the system behaviour. In Table I, the data of the simulated and measured systems are given.

A Simulation results

Concerning the maximum values of the voltage on the motor isolation, it is compared with the recommended maximum voltage $V_{\max IEC} = 1.56 \text{ kV}$ for designing winding isolation in AC motors described in the international standard IEC/TS60034-25:2004. If exceeded, partial discharges may appear degrading the winding isolation and abbreviating the lifetime (Kaufhold and Boerner, 1993). The higher the voltage, the worse the damage. In the simulations and measurements overvoltages owing to reflections on motor cables are not regarded. So, if they do appear, they would additionally elevate the overvoltages, but only on the terminals of the motors. The overvoltages at the star point of the torque motor are not elevated owing to the fact that the overvoltages of reflections only reach the first winding turns.

In Figure 9(a) and (b), the overvoltages of systems with and without the investigated torque motor are shown. As regards systems without torque motor, in the case of systems without remedy in a wide range the proposed maximum value $V_{\max IEC}$ is exceeded, especially where harmonics of the inverter excitation lie near the resonant frequency of the system. The proposed remedy of “flat top” modulation ameliorates the system for the full range of possible $C_{par\Sigma}$.

Figure 8.
Waveforms of common
mode currents and
voltages

Notes: (a) Simulation of a system without torque motor ($C_{par\Sigma} = 100$ nF); (b) measurement of a system with torque motor ($C_{par\Sigma} = 269$ nF)

Table I.
Data of simulated and
measured electrical drive
systems

<i>Active front end</i>	
Nominal power	34 kW
Current control	Hysteresis control
<i>Choke</i>	
Type	Iron powder core
Nominal current	62 A
<i>Inverter</i>	
DC-voltage	600 V
Modulation	Sine triangle
Modulation index	0
Switching frequency	4 kHz
<i>Axes</i>	
Number of axes	1, ..., 21
Sum of cable lengths	20 m, ..., 1,300 m
Sum of parasitic capacitances	10 nF, ..., 800 nF

Notes: (a) Maximum voltage appearing at the motor terminals $V_{m \max}$ in systems without torque motor; (b) maximum voltage appearing at the star point of the torque motor $V_{st \max}$ in systems with torque motor; (c) common mode losses P_{cm} ; (d) rms-value of common mode current I_{cmrms} in systems without torque motor

Figure 9. Results of simulations and measurements with and without remedies

Concerning systems with the investigated torque motor in Figure 9(b), in general the voltages appearing at the star point of the torque motor are much higher than in systems without torque motors. Without remedy the proposed maximum value $V_{\max IEC}$ is exceeded across the full range of possible $C_{par\Sigma}$. In a wide range, the overvoltages lie between 2,400 and 4,700 V which is a multiple of the voltage $V_{\max IEC}$. The proposed remedy greatly reduces the overvoltages at the star point of the motor. For some values of $C_{par\Sigma}$ however the maximum value $V_{\max IEC}$ is exceeded. The reduction of the maximum voltage is comparable to the reduction of the choke with transformational damping (Weidinger, 2008); however this is achieved with much less effort and has a much higher efficiency in comparison to the reduction of the increased excitation (Weidinger, 2008).

As regards common mode losses as shown in Figure 9(c), they are compared with the nominal power $P_n = 34 \text{ kW}$ of the active front, owing to the fact that they are extracted from the DC capacitor and therefore from the mains. Here, systems without torque motor are shown, because both cases show similar results. Concerning systems

without remedy, high values appear. The losses reach a maximum of about 12 per cent of the nominal value P_n and a strong dependency on the parasitic capacitance $C_{par\Sigma}$ can be observed. They are additionally elevated near the harmonics in particular. This means a huge reduction of the overall efficiency of the electrical drive system. The proposed remedy reduces the losses by a great amount over the full range of possible $C_{par\Sigma}$, also with respect to the remedies proposed in Weidinger (2008).

Concerning the common mode currents, the results of the simulations show similar dependences to the losses.

B Measurement results

To prove the simulation results, measurements on an electrical drive system were made. The modelled system corresponds to the measured one except for the exact values of $C_{par\Sigma}$. Several configurations with different $C_{par\Sigma}$ were investigated. As a result of the measurements the values of the maximum voltages appearing at the terminals $V_{m\max}$ and at the star point of the torque motor $V_{st\max}$ were determined and compared with the simulation results in Figure 9(a) and (b). As regards systems without remedies, the measurements do match the simulations. Even very high values of 2,300 V without torque motor and 2,700 V at the starpoint of the torque motor were measured. At the maximum point of the simulation results no measurement was done in the test owing to the possibility of destroying the torque motor.

Concerning the proposed remedy no measurements could be investigated because of the very high effort entailed by modification of the used electrical drive system with up to 21 axes.

Nevertheless, the results of the measurements on systems without remedies and systems with the remedies proposed in Weidinger (2008) show a good accordance with the simulations which demonstrates the high quality of the simulation model. Hence, a high quality of the simulation results for the proposed remedy is also expected.

VII. Conclusion

By means of system analysis reasons for the appearance of relatively low-frequency common mode oscillations in electrical drive systems were derived.

The switching operations in the AFE and the inverters excite the common mode system and lead to overvoltages on the motor terminals and, in case of the use of a torque motor, also at the star point. This may lead to a significant reduction of the isolation lifetime. The parameters of the excitation through the inverters in particular were investigated in depth. From these results a remedy was derived: the use of “flat top” modulation in the inverters greatly reduces the excitation in return for a comparatively low effort. Simulations and measurements are presented that compare the voltage stressings at the motor winding of systems with and without remedy.

Additionally, as shown, the common mode losses and currents are not negligible and mark strong disturbances to the electrical drive system. Furthermore, as well as proving the effectiveness of the analysed remedy concerning overvoltages the simulations also demonstrate a reduction of common mode losses and common mode currents by a large amount, and therefore an increase in the efficiency and reliability of the whole electrical drive system.

VIII. Outlook

Further results of the investigation, including detailed analysis of different chokes and other system variations are published in Weidinger (2009).

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About the author

Thomas Weidinger was born in Neumarkt i. d. Opf, Germany in 1977. He received the degree Dipl.-Ing. in Electrical Engineering from University Erlangen-Nuremberg in 2003. Until 2008, he was working on the Chair of Electrical Drives of the University Erlangen-Nuremberg, where he received the PhD degree in December 2008. He works as Development Engineer for power electronics and high voltage technology with Siemens Healthcare. His present interests are power electronics, EMI and silicon carbide transistors. Thomas Weidinger can be contacted at: weidinger@eam.eei.uni-erlangen.de