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Conducted EMI Propagation In Inverter-fed AC Motor

Jarosław ŁUSZCZ, Krzysztof IWAN
Gdańsk University of Technology, POLAND

Summary: **Conducted EMI generated by an inverter-fed induction motor drive systems with the pulse with modulation (PWM) are one of the most difficult current technical problem which limits power electronics drive's evolution. The conducted and radiated emission of PWM drives is essentially related also to the electric behaviour of the frequency converter's load which is AC motor and motor cable. Detailed analysis of the impedance characteristics of the converters load (motor and cable) is fundamental to interpret the common and differential mode of emission spectra of the converter. Presented identification of the impedance parameters of the evaluated drive system is based on the measurement of impedance characteristics, which allows determining the adequate circuit model for different frequency ranges. Obtained results illustrate the different behaviour of the investigated motors for different frequency ranges and explain the influence of the motor power cable on the investigated phenomena in the high frequency ranges. Presented analysis and measurement results leads to the conclusion that the impedance characteristic of the converters load can be very helpful for analysing high frequency phenomena in the converter-motor link. The over-voltage and conducted EMI problems in many of ASD application with high power motor and long cable can be clarified by load impedance analysis. The impedance analysis allow to determine the high frequency range where for modelling transmission line based model is evidently necessary, instead of much more simple circuit model.**

Key words:
AC motor drives, conducted EMI, modelling

1. INTRODUCTION

The contemporary pulse width modulated (PWM) inverters applied in an adjustable speed drives (ASD) results many exceptionable phenomena in the high frequency, which became very important and non negligible in many applications. Increase in the carrier frequency of pulse width modulation and the faster switching rates of the power electronics switches can induce serious problems in many ways. One of the most difficult technical problem to solve, related to this phenomena, is generation of high frequency currents flowing in all parts of the drive system due to the existence of high levels of the $\Delta U/\Delta t$ in the output voltage. In the ASDs we can distinguish two components of these currents: differential mode which flows between power lines and common mode flowing between power lines and ground. Each of these currents sources can cause serious application problems such as: conducted and radiated electromagnetic emission (EMI), over voltages in the motor winding, bearing currents and many others. To find out the method of reduction of this unacceptable effects a number of complex analysis should be carried out. To make this analysis possible adequate and reasonably complex models are needed. Lumped elements circuit models are mostly recommended and useful for analysing power electronics converters feeding AC motor by using Spice type simulators.

The paper presents a relatively simple method which allows to determine the approximate frequency ranges in which the lumped element circuit models are relatively effective. Presented lumped circuit model of the AC motor that allows to analyse the high frequency effects in the motor windings with the good balance between its complexity and adequacy in the frequency range of conducted EMI. Representing electrical behaviour of AC motor in wide frequency range by lumped elements circuit model is very effective as far as the parameters of the model are possible to determine with the reasonable effort. The stray capacitances of the motor windings are most consequential parameters which results its HF behaviour. For the higher frequencies much more complex models are required to describe load's behaviour as a distributed element network.

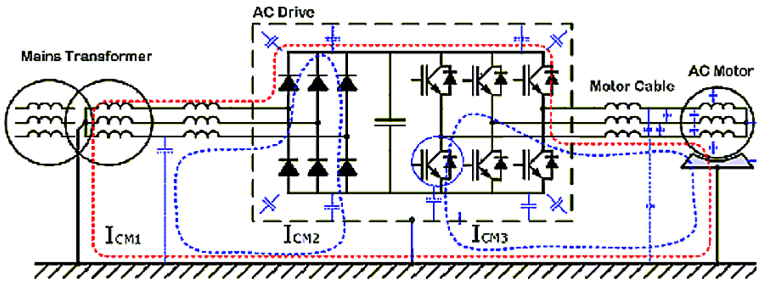

Fig. 1. Common mode current path in adjustable speed AC motor drive application.

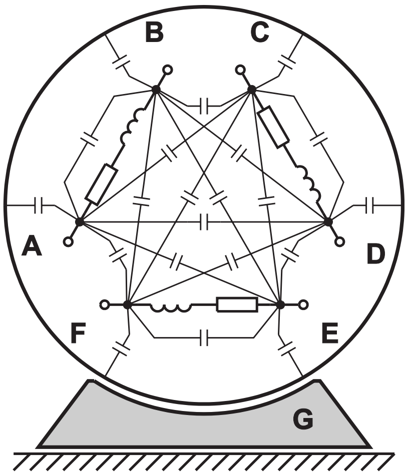

Fig. 2. Lumped representation of the stray capacitances existing in the AC motor

2. AC MOTOR HIGH FREQUENCY CIRCUIT MODEL

Asynchronous motor windings physical construction is usually labyrinthine and detailed determination of it's capacitance is entirely difficult, Finite Element Analysis is commonly required. So some simplification should be considered to make this task work more effortless. One of the possible method to simplify the complex capacitance structure is a lumped elements equivalent circuit model. The approximate representation of the all distributed stray capacitance in the tree phase AC motor by the lumped elements can be done by 21 capacitance related only to the motors terminals and ground. This assumption make possible to evaluate the existing capacitance by measuring motor's inter-terminals impedance The proposed configuration of the circuit model is shown in Figure 2.

The benefit of such a global configuration of the proposed topology is it's adequacy for analysing the common and differential mode EMI components in the both possible motor configurations - star and delta. Determination of all the parameters of this circuit model is quite affordable and requires a number of impedance measurements in a specific winding configuration. The analysis of this impedance characteristics allow to calculate especially the lumped equivalent capacitance of the motor's windings related to it's terminals. To make this identification procedure less complex same simplification can be achieved by analysing the winding structure and related impedance characteristics. To simplify the identification analysis all the lumped capacitance can be divided in some group according to its physical meaning—self capacitance, inter winding capacitance and ground capacitance Figure 3. Analysis of the symmetry of the typical winding configuration (Fig.3) leads to the conclusion that same of the evaluated capacitance are expected to be similar. To prove this assumption series of experimental impedance measurement has been done and the selected impedance characteristics for the investigated induction motor ($U_n = 400$V, $P_n = 7.5$ kW, 1450 r/min) are presented in Figures 4 and 5.

The comparison of the measured impedance characteristics (Figures 4 and 5) confirm that the symmetry between the three windings high frequency parameters is good enough to identify, that the related capacitance are quite similar in each phase of the winding. In real application the configuration of the motor windings configuration (star/delta) is usually fixed and steady. In this case the evaluated circuit model can be simplified more considerably, but in some advanced application the full version of this model is necessary.

3. ANALYSIS OF THE INDUCTANCE MOTOR IMPEDANCE

The induction motor's behavior in the high frequency range is hardly related to the impedance characteristics of its windings. The

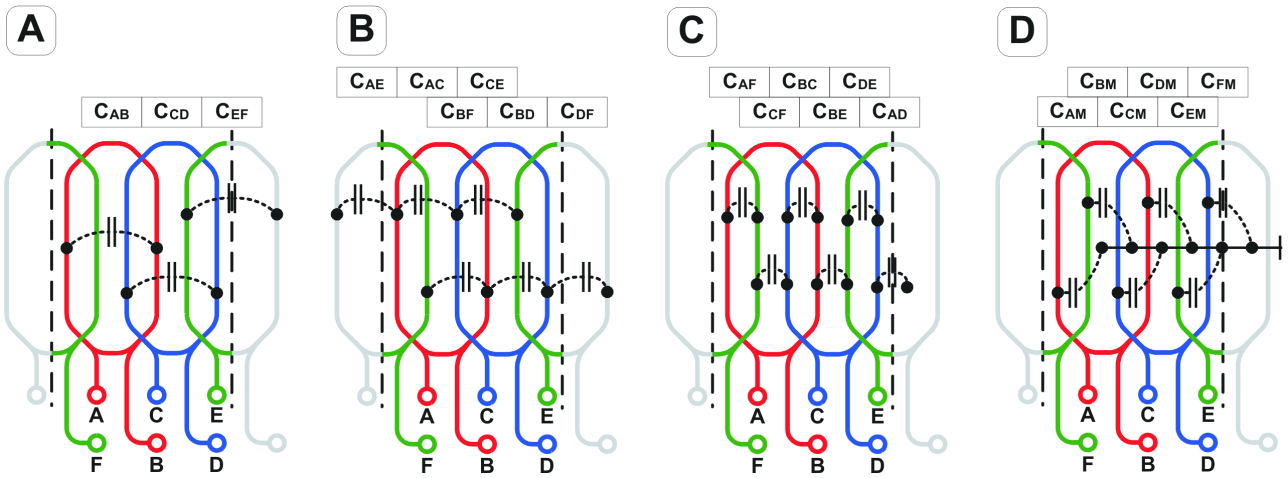

Fig. 3. Physical nature of lumped equivalent parasitic capacitance existing in the AC motor windings:
A – self capacitance of winding, B – inter winding capacitance type 1, C – inter winding capacitance type 2, D – winding to ground capacitance

selected examples of AC motor impedance characteristics for the wide range of rated power are presented in Figure 6.
Based on the impedance characteristics it is possible to determine the resonance frequency of each evaluated motor, which is the results of the winding parasitic capacitance. The maximum impedance value (about 1kΩ –100kΩ), which can be observed in the resonance frequency range between 30kHz and 100kHz for different motors means that in this frequency range there is a minimum load and these spectrum components of motor voltage are only slightly attenuated or even amplified. The level of attenuation or amplification depends on many parameters of the evaluated circuit and is difficult to determine. This phenomenon is known from the experimental experience as a tendency to occurrence of the motor over-voltages in the ASD. Based on the impedance characteristics this hazardous frequency ranges can be determined. The example of measured motor over-voltages in application with the 400kW motor is presented in Figure 7.
For the frequencies higher then the resonance frequency the motor behaves as a capacitive load and its impedance decrease 20dB/dec (Fig.6). This capacitive character clearly appears on the impedance characteristics up to several MHz. For the 400kW motor beyond approximately 1MHz the impedance achieve the level below 10Ω and tends to change regularly. This is the start of frequency range where the motor as a load acts as a transmission line.
Result of the impedance character change (inductance, capacitance and transmission line) can be also observed in the motor terminal voltage waveforms. The measured voltage oscillations for the 400kW motor are shown on Figures 7, 8 and 9. In the Figure 9 are visible two different frequencies of voltage oscillation which starts after each switching process in the converter. In this waveform it is possible to distinguish two dominant frequencies which are about 30 kHz and 1 MHz. This frequencies are closely correlated to the motor impedance characteristic (Figure 6) and decide about the tendency of the evaluated motor as a converter's load to the high frequency over-voltages. The over-voltage problems noticeably increase when the modulation frequency of the inverter became close to this specific resonance frequency of the motor.
The impedance characteristic of the converters load (AC motor) is significantly affected by the motor cable (Figure 10). The parasitic capacitance of the motor cable moves the resonance frequencies towards to the lower ranges. It is a key reason for appearance of serious over-

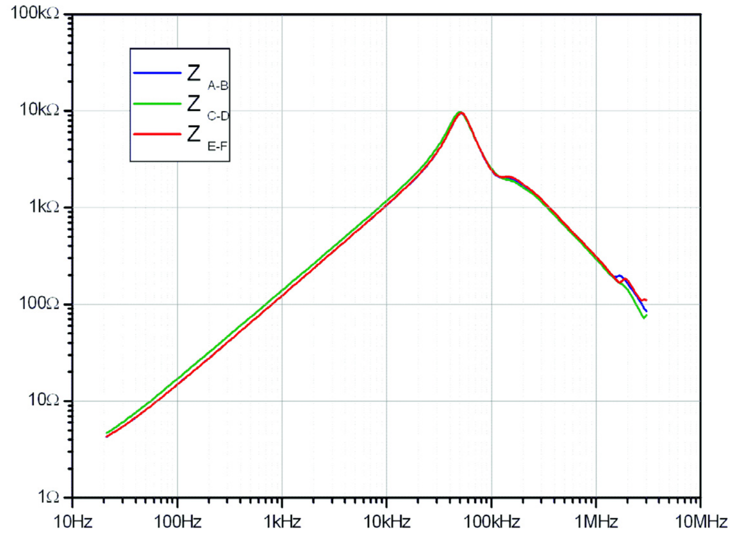

Fig. 4. Winding's impedance characteristics of the evaluated AC motor (7,5 kW)

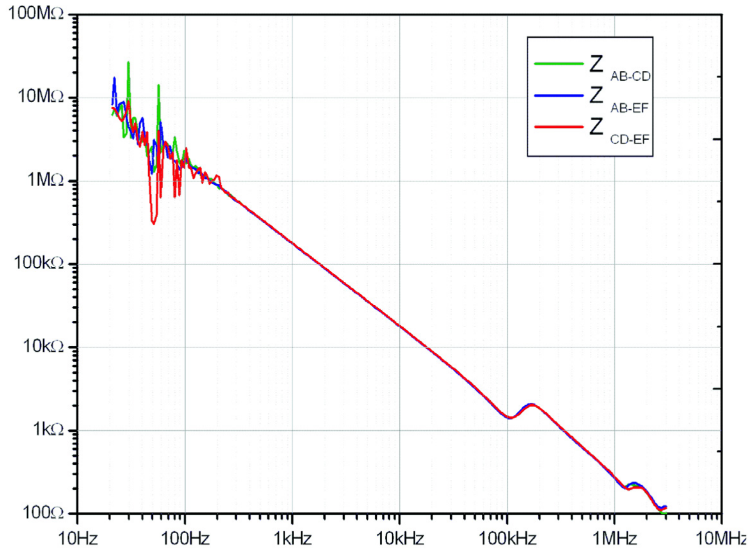

Fig. 5. Inter winding impedance characteristics of the evaluated AC motor (7,5 kW)

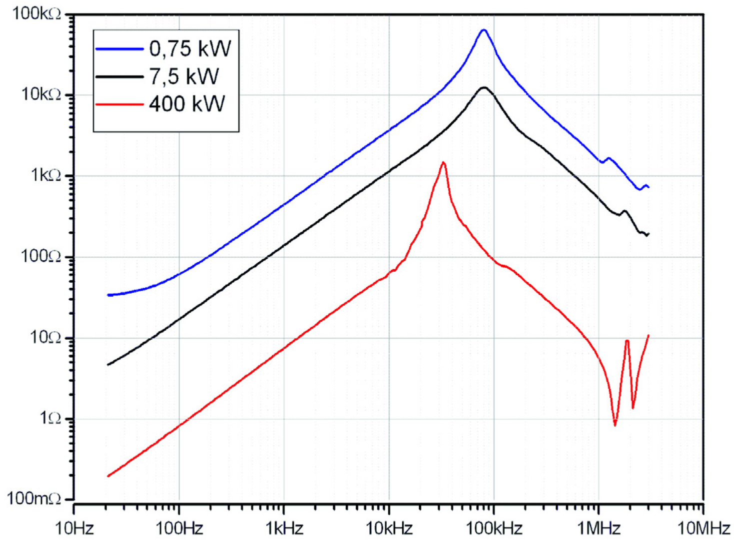

Fig. 6. Comparison of the impedance characteristics of the AC motors for different rated power

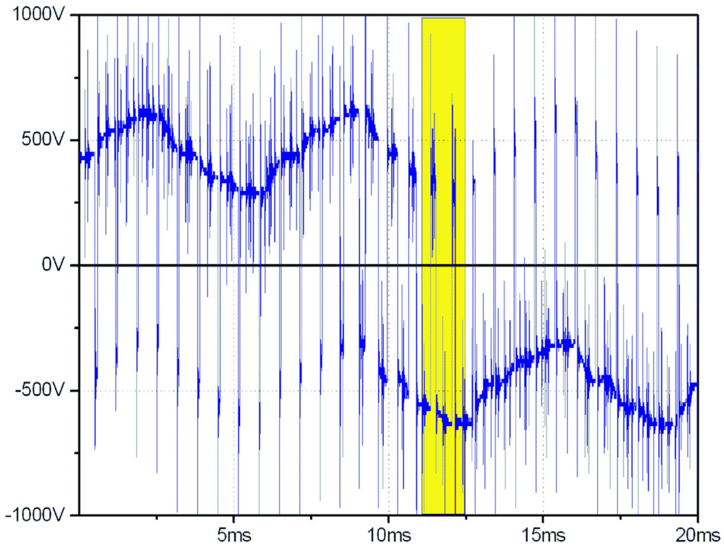

Fig. 7. PWM modulated voltage on the motor terminals

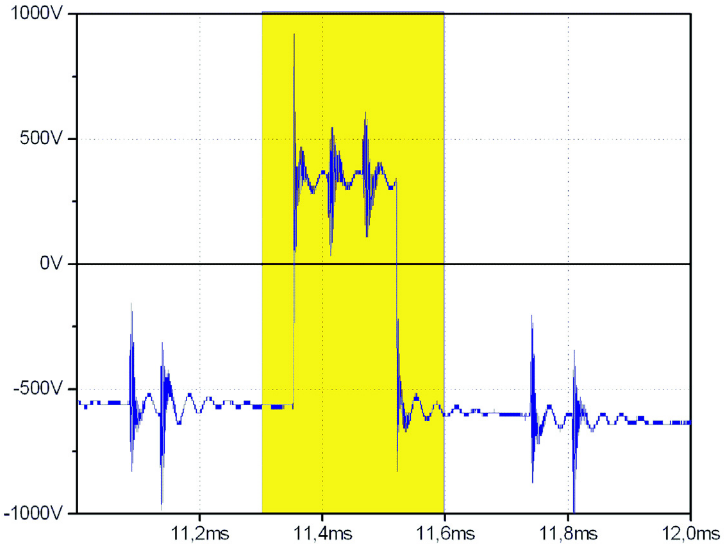

Fig. 8. PWM modulated voltage waveform on the motor terminals - low frequency ringing

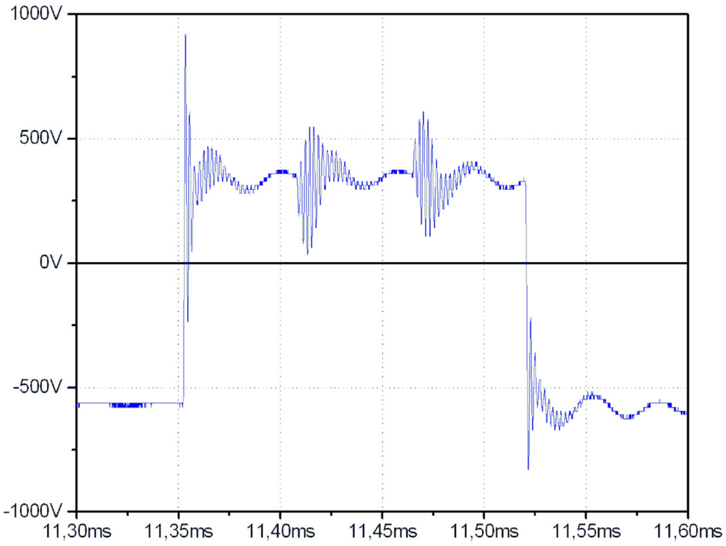

Fig. 9. PWM modulated voltage waveform on the motor terminals - high frequency ringing

voltage problems in ASD application with long motor cable (e.g. over 100m), where over-voltage and EMC problems arises very often. For the evaluated motor the effect of the distributed behaviour can be observed (on the impedance characteristic Figure 10) in the frequency range below 1MHz.

4. CONCLUTION

The evaluated impedance characteristic of the converters load, motor with the cable, can be very helpful for analysing high frequency phenomena in the converter-motor link. The characteristic frequency ranges where over-voltage problems appear can be relatively easily determined based on the impedance characteristics. The over-voltage and conducted EMI problems in many of ASD application with high power motor and long cable can be clarified by load impedance analysis. The impedance characteristics analysis allow to determine the high frequency range where distributed element modelling approach is evidently necessary, instead of much more simple circuit model.

REFERENCES

1. Kempski A.: *EMI Noise Splitting Into Common and Differential Modes in PWM Inverter Drive System*. Proc. 4th International Workshop Compatibility in Power Electronics CPE 2005, 1–3 June 2005, Gdynia 2005.
2. Arnedo L., Venkatesan K.: *High frequency modeling of induction motor drives for EMI and over-voltage mitigation studies.* Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International, Volume 1, 1–4 June 2003.
3. Grandi G., Montanari U., Reggiani U.: *Effects of power converter parasitic components on conducted EMI.* International Zurich Symposium on EMC, Zurich, 18–20 February 1997.
4. Gubia E., Sanchis P., Ursua A., Lopez J., Marroyo L.: *Frequency domain model of conducted EMI in electrical drives*. IEEE Power Electronics Letters, Vol. 3, Issue 2, June 2005.
5. Huibin Zhu, Jih-Sheng Lai, Hefner A.R., Jr. Yuqing Tang, Chingchi Chen: *Modeling-based examination of conducted EMI emissions from hard and soft-switching PWM inverters.* Industry Applications, IEEE Transactions on Volume 37, Issue 5, Sept.–Oct. 2001.
6. Kempski A., Smoleński R., Strzelecki R.: *Common mode current path and their modelling In PWM inverter-fed drives*. Proc. 33rd IEEE Power Electronics Specialists Conference PESC 2002, Cairns, Austria, 2002, Vol. 3, pp. 1551–1556.
7. Kempski A., Strzelecki R., Smolenski R., Fedyczak Z.: *Bearing current path and pulse rate in PWM-inverter-fed induction*. PESC. 2001 IEEE 32nd Annual , Volume: 4 , 17–21 June 2001 Pages:2025– 2030 vol. 4.
8. Łuszcz J., Iwan K., Nieznański J.: *Propagation of conducted electromagnetic interference in power electronic converters with transformers.* 9th European Conference on Power Electronics and Applications EPE'2001.

9. Łuszcz J.: *Conducted EMI Propagation Modelling in the Wound Components*. Seventeenth International Wroclaw Symposium and Exhibition on Electromagnetic Compatibility EMC'2004, 29 June-1 July 2004, Wroclaw 2004.
10. Łuszcz J.: *Iron Core Inductor High Frequency Circuit Model for EMC Application*. Coil Winding International & Electrical Insulation Magazine. Volume 28, Issue 1, 2004.
11. Musznicki P., Schanen J-L., Chrzan P.J.: *Design of high voltage busbar: trade off between electrical field and stray inductance*. Proc. 3th International Workshop Compatibility in Power Electronics CPE 2003, Gdańsk 2003.
12. Ogasawara S., Akagi H.: *Modelling and damping of high-frequency leakage currents in PWM inverter-fed AC motor drive systems*. Thirtieth IAS Annual Meeting, IAS '95., Conference Record of the 1995 IEEE , Volume: 1 , 8–12 Oct. 1995.
13. Skibinski G., Kerkman R., Leggate D., Pankau J., Schlegel D.: *Reflected wave modelling techniques for PWM AC motor drives*. APEC '98. Conference Proceedings 1998., Thirteenth Annual, Volume: 2, 15–19 Feb. 1998.

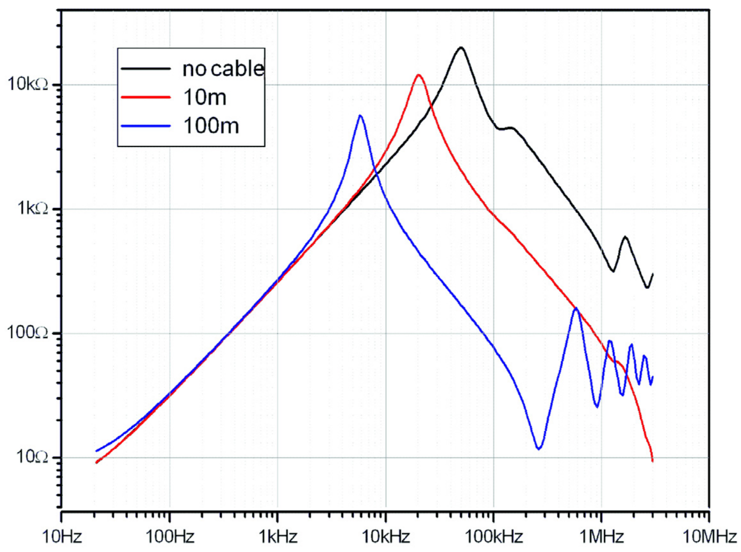

Fig. 10. The influence of the converter-motor cable on the impedance characteristics

Jarosław ŁUSZCZ
received the M.Sc. and PhD degrees in electrical engineering from the Gdansk University of Technology (GUT), Poland, in 1988 and 1998 respectively. Since 1999 he is an Associate Professor with the Electrical and Control Engineering Faculty at GUT. His main research interests are focused on electromagnetic compatibility applied to power electronics converters feeding AC motors drives and electromagnetic interference measurement and modelling of power electronics systems.
Address:
Gdansk University of Technology
80-216 Gdańsk, Sobieskiego 7
email: jlusz@ely.pg.gda.pl

Krzysztof Iwan
received the M.Sc. and PhD degrees in electrical engineering from the Gdansk University of Technology (GUT), Poland, in 1988 and 1999 respectively. Since 1999 he is an Associate Professor with the Electrical and Control Engineering Faculty at GUT. His main research interests are modeling and simulation of power electronics and drives systems at normal and fault conditions.
Address:
Gdansk University of Technology
80-216 Gdańsk, Sobieskiego 7
email: kiwan@ pg.gda.pl