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A Novel *Interactive Power Electronics Seminar* (*iPES*) Developed at the Swiss Federal Institute of Technology (ETH) Zurich

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ABSTRACT

This paper introduces the Interactive Power Electronics Seminar - *iPES* – a new software package for teaching of fundamentals of power electronic circuits and systems. *iPES* is constituted by HTML text with Java applets for interactive animation, circuit design and simulation and visualization of electromagnetic fields and thermal issues in power electronics. It does comprise an easy-to-use self-explaining graphical user interface. The software does need just a standard web-browser, i.e. no installations are required. *iPES* can be accessed via the World Wide Web or from a CD-ROM in a stand-alone PC by students and professionals. Due to the underlying software technology *iPES* is very flexible and could be used for on-line learning and could easily be integrated into an e-learning platform.

The aim of this paper is to give an introduction to the *iPES*-project and to show the different areas covered. The e-learning software is available at no costs at www.ipes.ethz.ch in English, German, Japanese, Korean, Chinese and Spanish. The project is still under development and the web page is updated in about 4 weeks intervals.

Keywords: Power electronics, iPES, Web-based teaching

1. Introduction of the *iPES*-Project

Using new media and information technology in the classroom can not only make studying more attractive to the student, but might make also teaching much easier[1][2]. Especially in engineering classes complex technical problems have to be presented in a way which is easy to follow and understand. If, additionally, the system to be described shows dynamic behavior and/or numerous different switching states teaching becomes difficult in case only words and static pictures are at hand.

Based on this experience the authors started the development of *iPES*, a web-based introductory power electronics course employing Java applets, in mid of year 2000. After implementing some basic examples a library of Java classes was established .which does allow to generate an applet for a new circuit topology within a few days. The project is online since July 2001 and a free download of the software is available since January 2002. At the time of this writing (September 2002) there have been about 4,000 downloads and more than 20,000 visits on the *iPES* website[3]. Up to now five papers have been published on *iPES*. There the basic concept has been described[4], a comparison of *iPES* to other e-learning projects and modern teaching activities in power electronics has been given[5], and the teaching of space vector calculus by *iPES* has been described in detail[6].

Furthermore, an overview of the project has been given

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[7], and mathematical concepts behind some *iPES*-applets were described[8].

Besides students also engineers working in the industry have shown interest in *iPES*. Furthermore, there is interest from companies in incorporating *iPES*-based animation into web pages in order to explain the basic concept of innovative products in a direct, and attractive way to potential customers.

At the ETH Zurich in addition to regular courses on power electronics running in the 5th, 7th and 8th semester the authors have started to teach an undergraduate course in the 3rd and 4th semester in electrical engineering on Java programming. The course being very popular among students is on simulation and animation of basic power electronic circuits, and does provide an excellent possibility to introduce power electronics to students in an early stage.

2. Technology for Web-Based Teaching

HTML text and embedded Java applets turned out to be an excellent choice for interactive web-based education, i.e. *iPES*. In order to keep the development time and costs low the authors employ XML for storing all data being used by the Java-applets. Projects using Java applets in different fields of engineering[9][10][11][12] and for simulation in power electronics[13][14][15] can be found in the Internet in a growing number.

Although Java has not been designed to perform extensive numerical computations, it proofed to be sufficient for circuit simulations and even simple calculations of electromagnetic field distributions as long as the programming is done carefully and with minimum computation time in mind[16]. Since Java was designed for the Internet it was possible to make *iPES* available for a large audience within very short time and with minimum effort.

3. Teaching Power Electronics with *iPES*

3.1 Contents of *iPES*

iPES consists of different educational modules. The first module ("*iPES-Circuits*") will face minor changes in the future and is currently available in English, German, Japanese, Korean, Chinese and Spanish. All other modules are only available in English at the moment, but translations and additional applets will be added in the near future.

The module "*iPES-Circuits*" (cf. section 4.1) includes applets on DC/DC converters, basic diode and thyristor converter systems, inverter systems, space vector modulation and basic signal theory. A second module, denominated "*iPES-Circuits+*" (cf. section 4.2) represents a collection of more complex modern power electronic systems being still under development or being already used in industry with emphasis on three-phase PWM converter systems and three-phase matrix converters. The applets are designed for providing an introduction into the system characteristics and features which should allow to reduce the development time in case of prototyping. Besides the applets other resources like links to relevant papers and brief technical summaries are provided. A third module, "*iPES-Thermal*" (cf. section 4.3), visualizes thermal issues being of importance for the dimensioning and operation of power electronic circuits. Besides basics also applets on the thermal runaway and on the paralleling of power semiconductor devices are provided. Another module, called "*iPES-EMFields*" (cf. section 4.4) is dedicated to teaching the basics and the dimensioning of magnetic components in power electronics with emphasis on the underlying physics and electromagnetic fields. The applets do visualize magnetic fields, effects of magnetic permeability, rotating magnetic fields, and the systematic design of inductors.

3.2 Interactive Animation

Studying or teaching of power electronics subjects sometimes does pose problems to the students as there is a large number of possible reactions of a system to parameter changes and the conduction state of a power electronic circuit typically does go through a sequence of states also for stationary operation. The conventional way of presenting such challenging contents is by a sequence of slides showing a single system state and/or the behavior for a set of parameters.

In *iPES* does provide a time marker which could be moved interactively with the mouse where a Java-applets directly shows the related system state. Additionally, the applets do offer the possibility of a manipulation of system parameters via a graphical user interface and do show directly the resulting time and frequency behavior of the system. The added HTML text provides hints how to interact in order to understand why certain system reactions do occur. As compared to classical approaches of teaching this way of learning does get the student actively involved. A further advantage is that the student could decide on the progress of the presentation of the material and/or could adapt the course individually.

While the professor does employ *iPES* using a laptop and a beamer for supporting conventional lectures, the students are told to repeat the examples on their home computer and to try additional parameter variations.

3.3 Textbook

iPES is comprised by Java applets embedded into HTML pages. The HTML text does describe how to use the various applets but does not give details on the principle of operation of the power electronic circuits shown. This is because most of the applets are self-explaining and students usually dislike reading teaching material on a computer screen. Therefore, the authors have decided to write a textbook which will refer in detail to all *iPES* contents and, furthermore, will provide guidelines how to make most effective use of the Java applets for teaching and/or studying. There, e.g. variations of specific parameters of a circuit will be suggested and an interpretation of the results will be provided. The publication of the textbook is scheduled for 2003.

4. Educational Modules Comprising *iPES*

4.1 *iPES-Circuits* - Teaching Basic Circuits in Power Electronics

This module is dedicated to the principle of operation of basic topologies in power electronics. A representative Java-applet for interactive simulation and conduction state animation is presented in the following.

Example: Single-Phase Line-Commutated Diode Bridge Rectifier with Output Capacitor

The single-phase diode-bridge rectifier with output capacitor is a standard power electronic circuit.

Figure 1(a) shows the time-behavior of input current, output voltage and further characteristic quantities. The vertical time-marker can be dragged by the mouse, the related current flow is visualized in the diagram of the power circuit by moving colored points. In Fig. 1(b) the vertical time-marker is in a position where no input current is present and/or where the resistive load is fed by the output capacitor.

Students often face difficulties in understanding why the output voltage of a system is said to be approximately constant. Here, by simply clicking the capacitor in the power circuit picture with the mouse (and keeping the mouse-button pressed) the capacitance of the capacitor can be increased or decreased. The related voltage and current

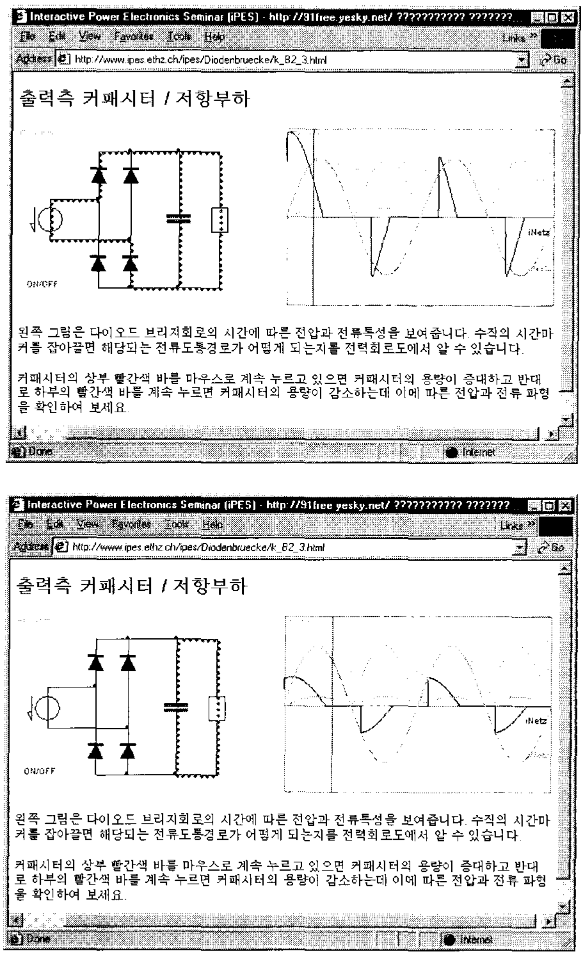

Fig. 1. Diode Bridge with capacitive smoothing; the actual current paths are shown in the power circuit diagram. By clicking on the capacitor the capacitance can be changed where the time-behaviour of input current and of the output voltage is adapted immediately.

shapes shown in the time-behavior diagram are calculated and adjusted immediately. This facilitates to understand why increasing the capacitance results in more and more constant output voltage while the input current is showing an increasing peak value and lower conduction period. The circuit behavior for small output capacitance is shown in Fig. 1(b).

4.2 *iPES-Circuits+* - Teaching Advanced Power Electronic Systems

Besides *iPES* which is serving educational purposes the authors started the development of *iPES-Circuits+* for demonstrating the operating principle of modern three-phase power converters of higher complexity which are employed by industry today or could be of interest for application in future.

Example: Vienna Rectifier 1

The Vienna Rectifier 1[17] is a unidirectional three-phase three-switch three-level PWM rectifier. The applet shown in Fig. 2(a) gives a very detailed insight into the principle of operation of the power circuit (top left), and shows the input voltage space vectors (bottom left), and the time behavior of mains voltages and mains currents (top right). Furthermore, the time behavior of the switching signals and of characteristic system voltages and currents within one switching period are shown (bottom right).

One can drag a vertical time-marker in the applet showing the mains phase voltages (top right) in order to define a point in time to be considered. The according time behavior of the signals, voltages and currents within a switching period is automatically updated in the applet below (bottom right). In the pulse period applet a vertical time-marker can be dragged with the mouse in order to define a point in time within the considered switching period. The corresponding phase current paths are shown in the power circuit applet (top left) while the actual space vectors (applet bottom left) is highlighted in red. Furthermore, the amplitude of the mains phase voltages can be changed by dragging with the mouse.

By changing the key parameters is it simple to investigate the system for different operating conditions and parameter combinations. Since switching patterns for all operating points are given, the applet furthermore is very helpful for debugging a simulation of the system or a hardware prototype.

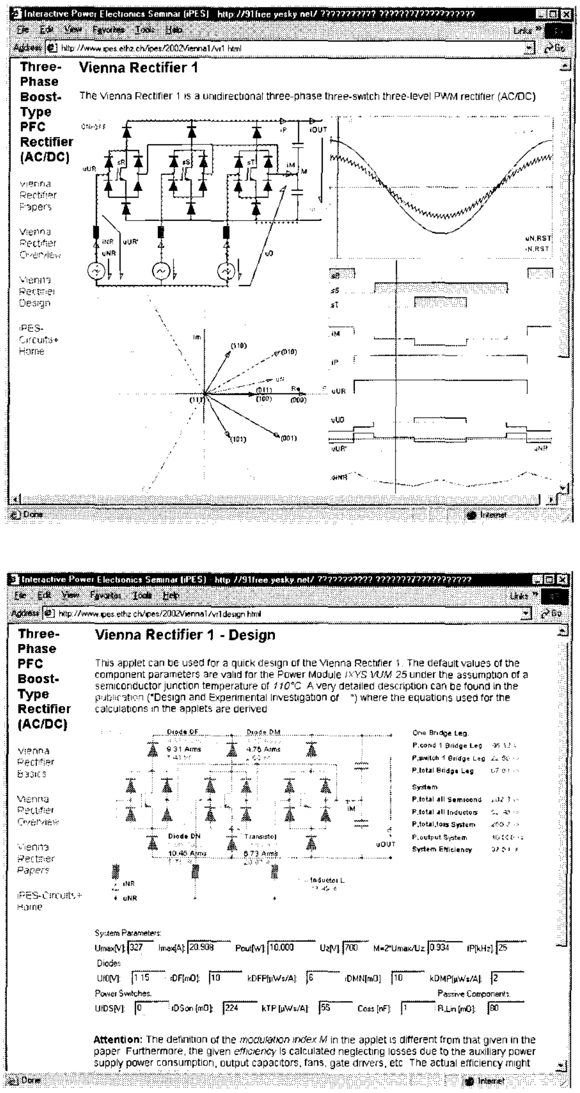

Fig. 2. Principle of operation of the Vienna Rectifier I (left hand side) and (b) Java applet facilitating the dimensioning of the Vienna Rectifier 1 power circuit (right hand side).

The applet shown in Fig. 2(b) can be used as a basis for the dimensioning of the Vienna Rectifier 1 power components. The user specifies the input- and/or output voltage- and current-levels, the output power and the switching frequency. The Java applet calculates all rms- and avg-values of the currents in the power semiconductors. By specifying various semiconductor parameters the applet furthermore calculates switching- and conduction losses of each power semiconductor component and does provide information on the total power loss of a bridge-leg.

Furthermore, a HTML page lists the characteristics and advantages of the Vienna Rectifier 1 as compared to a two-level six-switch boost-type PWM rectifier system and suggests possible fields of applications. Another HTML page provides a collection of key papers which have been published on the Vienna Rectifier 1. The material does give a detailed description of the principle of operation, and of different control concepts, and does show experimental results.

4.3 *iPES-Thermal* - Teaching Thermal Issues in Power Electronics

For designing a working power electronic system an engineer has to have a basic understanding of thermal problems in power electronic systems. Furthermore, for designing a product it is not sufficient to simply put the working prototype into an enclosure. Modified temperature distributions inside the enclosure have to be considered, as there might be a need for enforced cooling. Furthermore, there might in general be a potential for reducing the heat sink size in order to optimize the design. For reliable long-term operation of a power electronic system the temperature of all critical components has to stay below given limits for a wide range of parameters like ambient temperature, humidity and air-pressure. Students in power electronics often lack the understanding of the importance of a proper thermal design as in the lectures the thermal design is sometimes neglected and/or the focus is only on circuit topologies and control concepts.

<u>Example</u>: Transient Thermal Impedance

In datasheets of power semiconductors the value of the transient thermal impedance is often given in form of a diagram as shown in Fig. 3 (scan from a datasheet).

On the right-hand side the time-behavior of the junction temperature (normalized to a power loss of 1 Watt) corresponding to the operating point is shown for two pulse periods. The duty cycle employed could be selected and the operating point could be moved with the mouse. The direct connection between the operating point in the thermal impedance diagram and the temperature time-behavior has proven to be very helpful for understanding the physical meaning of the transient thermal impedance. Such a presentation also could be employed in future smart data sheets.

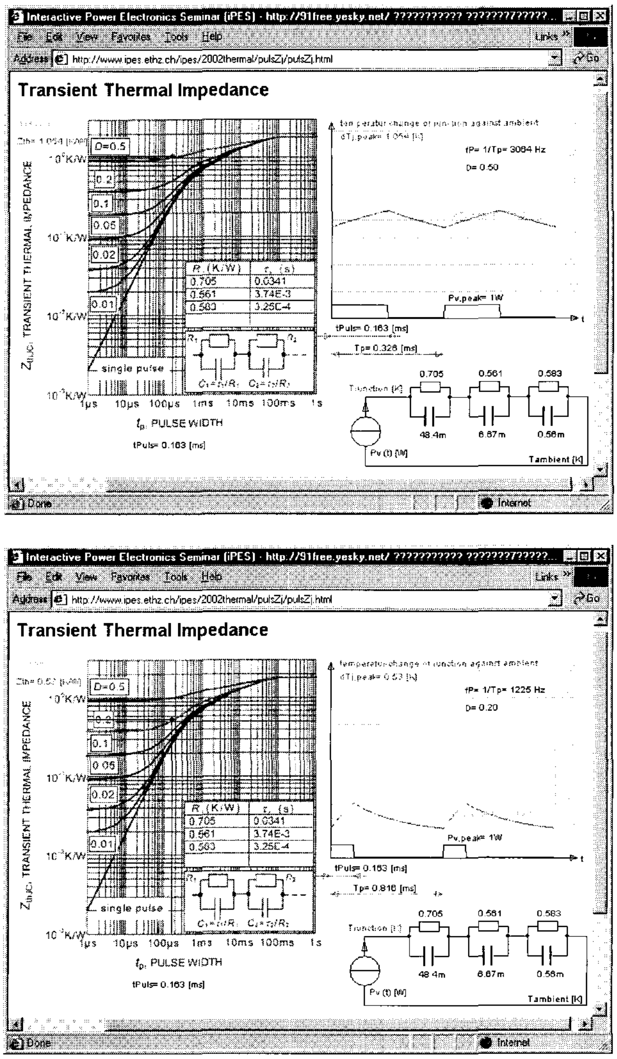

Fig. 3. Applet showing the transient thermal impedance and junction temperature time behavior of a power MOSFET in dependency on the operating parameters; duty cycle D=0.5 (left hand side); D=0.2 (right hand side).

4.4 *iPES-EMFields* - Teaching Theory of Inductors and Transformers

Inductors and transformers are basic elements of power electronic circuits. Understanding the functionality and the dimensioning of theses components is essential, therefore. After attending introductory courses in basic electrical engineering many students still lack a detailed understanding of the physics of magnetic devices. This has given reason for extending *iPES* with Java applets showing the magnetic fields of inductors and transformers.

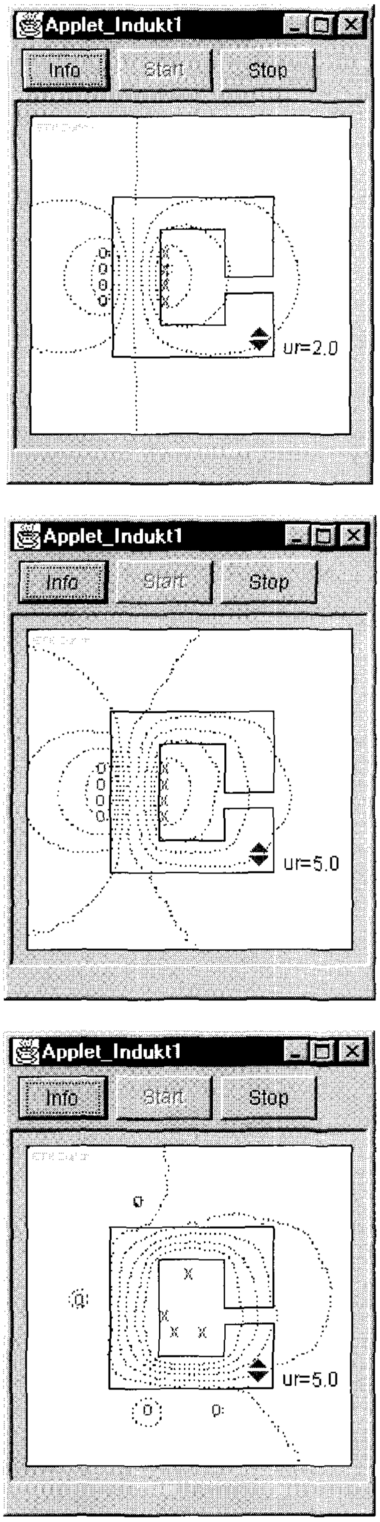

Fig. 4. Magnetic field of an inductor. By changing the permeability (denoted as "ur" in the applet) of the magnetic core one can see how the magnetic flux distribution is influenced by magnetic material.

The main idea of iPES is to provide means for changing parameters of a depicted power system by dragging with the mouse and to immediately show the resulting changes of the time-behavior of characteristic system quantities. This means that the system simulation has to be performed within a few milliseconds in order to give the user the feeling of an immediate response. Performing circuit-oriented simulation within such short time intervals is possible but calculating the distribution of magnetic fields typically is much more time consuming especially if finite element methods are employed. A detailed description of the algorithm employed in *iPES-Fields* is given in [8].

Example: Inductor Magnetic Flux Distribution

The applet shown in Fig. 4 should help the student to understand the field distribution in case of the presence of a magnetic core with a high relative permeability. The current carrying conductors can be dragged with the mouse in order to change their positions. The relative permeability of the magnetic core can be increased starting from *1.0* (free space) to higher values by simply clicking on the triangular symbols with the mouse. The student experiences that magnetic material does increase the magnetic field and, on the other hand, does concentrate the magnetic flux.

5. Future Developments

iPES as a basic course on power electronics will be finished in 2003. A textbook being coordinated with *iPES* will be published in near future. This book will cover the theory of operation of all systems shown and will give recommendations how to make most efficient use of *iPES* in studying and teaching.

While *iPES-Circuits* will face only minor changes and additions, *iPES-Circuits+* will be extended continuously with system or circuit topology becoming relevant to the industry. Furthermore, *iPES-Thermal* and *iPES-EMFields* will be completed by adding further subjects. Educational modules on the internal behavior of power semiconductors, control concepts and EMC are currently under development.

Several colleagues have expressed the desire to have the *iPES* material available in their native language. Therefore with the help of power electronics specialists all over the world further translations will be added. German, English, Korean, Japanese, Chinese and Spanish and are already available at the time of this writing (September 2002) for *iPES-Circuits*. Translations for the other educational modules (and more languages, e.g. French, Portuguese and Norwegian) will be added in near future.

6. Conclusions

In this paper a novel operating-system-independent e-learning software - *iPES* – supporting education in the field of power electronics has been introduced. *iPES* could be used via the Internet or on CD-ROM due to the combination of HTML text, Java applets and XML. The Java applets are inserted into the HTML text and are written to provide interactive animations, dimensioning and circuit simulation and the calculation of electromagnetic fields, all with an easy-to-use and self-explaining graphical user interface.

The material does constitute a one semester interactive course on fundamentals of power electronic circuits. Due to the underlying software technology *iPES* is very flexible in use and could advantageously be employed in addition to conventional teaching. Interactive animation also is very efficient for self-studying because the student is actively involved. *iPES* is available for free download at www.ipes.ethz.ch. The whole project is still under development and the web page is updated on a continuous basis.

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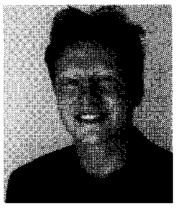

Uwe Drofenik was born in Moedling, Austria in 1970. He received the M.Sc. degree and also the Ph.D. degree in electrical engineering from the Vienna University of Technology, Austria, in 1995 and 1999, respectively. He is currently performing scientific research and teaching at the Swiss Federal Institute of Technology Zurich where he is developing web-based interactive educational software. In 1996 he was a researcher at the University of Tokyo, Japan. His research interests include power factor correction, single- and three-phase converters, numerical simulation and Java programming. He published 25 conference papers, 3 journal papers and 4 patents.

Johann W. Kolar has been Professor at the Swiss Federal Institute of Technology (ETH) Zurich since February 1, 2001. He is the Head of the Power Electronics and Electrometrology Laboratory.

Johann W. Kolar was born in Austria on July 15, 1959. He studied industrial electronics at the University of Technology Vienna, Austria, and received his Ph.D. degree (summa cum laude) in 1998.

Since 1984 he has been with the University of Technology in Vienna, and has been teaching and working in research in close collaboration with the industry in the fields of high performance drives, high frequency inverter systems for process technology and uninterruptible power supplies. He has proposed numerous novel converter topologies, e.g., the VIENNA Rectifier concept. Johann W. Kolar has published over 120 scientific papers in international journals and conference proceedings and has filed 48 patents.

The focus of his current research is on novel converter topologies with low effects on the mains, e.g. for power supply of telecommunication systems and distributed power systems in connection with fuel cells. A further main area of research is the realization of ultra-compact intelligent converter modules employing latest power semiconductor technology (SiC) and novel concepts for cooling and EMC filtering. Here, apart from a detailed theoretical analysis, also the practical realization in accordance with industrial requirements is the main goal.

Johann W. Kolar has been a member of the IEEE and the IEEJ and of Technical Program Committees of numerous international conferences in the field (e.g. Director of the Power Quality branch of the International Conference on Power Conversion and Intelligent Motion). Since 1997 he serves as an Associate Editor of the IEEE Transactions on Industrial Electronics.