EVS24
Stavanger, Norway, May 13-16, 2009

Conversion of a Conventional Vehicle to a Hybrid Electric Vehicle – Step by step Design and Experimental Investigation

Panagiotis Asimakopoulos, Theodoros Boumis, Efstathios Patsias, students
Athanasios Safacas, Professor, Emannuel Tatakis, Associate Professor,
Epaminondas Mitronikas, Lecturer
Department of Electrical and Computer Engineering, Laboratory of Electromechanical Energy Conversion
University of Patras, 26504 Rion – Patras, Greece
Tel.:+302610997351, Fax:+302610997362
asimakopp@upnet.gr, boumisth@upnet.gr, patsiase@upnet.gr, a.n.safacas@ece.upatras.gr

Abstract

This paper presents the study and construction of a hybrid electric vehicle's powertrain. It outlines the conversion of a conventional passenger car to a HEV and its key features which need to be considered. This research project is created at most by undergraduate students in the scope of their diploma thesis and includes the development of an experimental hybrid vehicle in the laboratory. Its propulsion system combines the Internal Combustion Engine with an AC asynchronous motor connected to a lead acid battery pack. All the necessary electric energy converters that carry out this connection are designed and constructed; Boost/Buck bidirectional Converters regulate the voltage to the appropriate level; the three-phase Inverter is responsible for the conversion of the DC to AC voltage and vice versa. A microcontroller undertakes the management of the Inverter and controls the power and system behaviour according to the instructions delivered from the driver through the vehicle's control, while the motor control method is Direct Torque Control (DTC). In order to fit the additional components to the vehicle, some mechanical modifications have also taken place. Furthermore, the function overview of the whole system is illustrated, which is characterized by the two opposite ways of energy flow, one during the use of electric energy in acceleration and one during regenerative braking.

Keywords: HEV (hybrid electric vehicle), powertrain, converter, student project

1 Introduction

Trend or need? Leading car industries "dress" their showrooms with a growing number of modern and shiny HEV car models, but this situation is more than just a trend. HEVs do actually have a major impact on the process of reaching environmental friendly transportation by limiting emissions and saving energy; especially in urban environments where they have the ability to move purely electric (approaching zero emissions) and regenerate energy through deceleration.

This paper deals with the step by step investigation of the technical problems that occurred in the hybridization of a vehicle, the combination of an internal combustion engine (ICE) with an electric motor and the matters concerning energy flow and storage. This investigation arose in the scope of an extensive research in the HEV which takes place in the laboratory and turned out as a challenge to young researchers. Moreover, the project's intention has been to create a prototype HEV for research and educational purposes.

2 Pedagogical Approach

Hybrid electric vehicle technology is rapidly evolving with extensive research being carried out to this direction. Apart from the major car manufacturers which develop new products to be promoted in the global market, there is also a big part of research that is taking place in the universities. Thus, this academic environment will impart knowledge to the students, and the last ones, on their turn, will contribute to the evolution and enrichment of the technology. Hybrid technology interacts with many scientific fields as well as electrical, mechanical, electronic and computer engineering.
To this direction, the project of converting a conventional vehicle to a hybrid electric one has been carried out in the Laboratory of Electromechanical Energy Conversion (LEMEC), in the Department of Electrical and Computer Engineering in University of Patras, Greece. This project was initiated by the interest of the authors in electric and hybrid cars in the educational and research activities of LEMEC, in the last 25 years. Especially, the first three authors deal with HEV technology in the frame of their diploma thesis.
The project's intention was the creation of ideas for the conversion of a conventional car to a hybrid electric one and the resolution of the actual electrical and mechanical problems of this attempt. By this experimental vehicle some inevitable compromises have been made, concerning the financing of the project, the supporting infrastructure and the equipment to be applied.
The actual process of the construction can be considered of great importance in such projects, where extensive research has to be carried out. This process requires the step by step approach of the various subsystems of the experimental hybrid vehicle, including the browse of bibliographical resources, the theoretical analysis, the design and construction and the experimental investigation. During this enterprise, as in the case of every construction, applicable solutions have been given to problems that occur, a factor that strengthens the educational process. Additional positive influence to the educational process can arise from similar or extensional projects. Remarkable is, also, the contribution of such works to the development of ecological conscience.

3 Design Procedure

3.1 Concept vehicle conversion

The car that has been available for the conversion is a Chevrolet Blazer with a 2.8lt V6 IC engine producing 110 horsepower (82 kW). It forms a smart solution as it offers the advantages of:

- capaciousness, to adapt the electric motor, the peripheral electronics and the batteries
- tough suspension, to withhold the overall weight.

The aim was to develop a mild hybrid vehicle in parallel arrangement (Figure 1), [6], with approximately 20% hybridization rate.

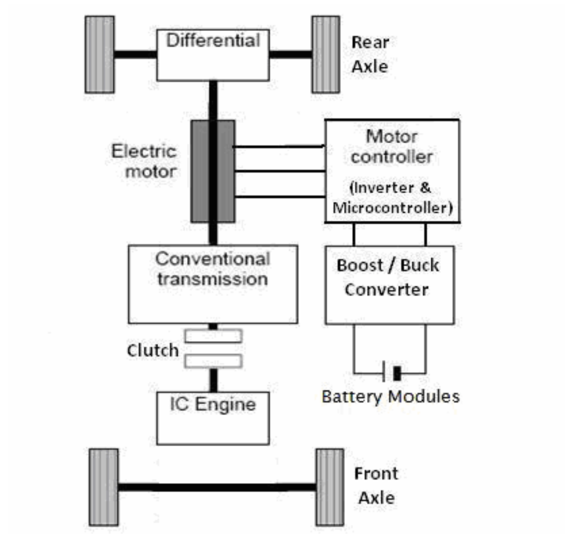

Figure 1: Basic Structure of the Vehicle's Arrangement

In this direction, an AC three phase Asynchronous Motor (1PH04, Siemens) has been chosen, which was commercially available, purposed for automotive applications (robust, water-cooled, lightweight, compact and with high efficiency) with the following characteristics: $P_N = 14$ kW, $V_N = 265$ V, $I_N = 46$ A. In such a construction, the proper, safe and efficient cooling of the motor demands a water-cooling system (Figure 2), [4].

This system composes of:

- a pump, supplied by the batteries or mounted on the motion shaft of the wheelbase, to pump the water into the motor
- a compressor to circulate the coolant into the cooling spiral
- a coolant reservoir for heat exchanging.

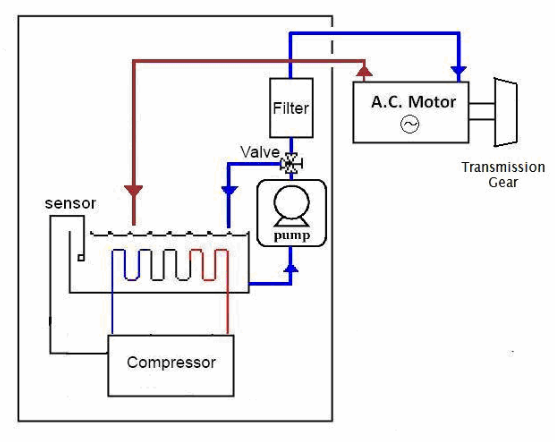

Figure 2: Water Cooling System

Concerning the batteries, lead acid modules of 12 V and 105 Ah each were used. 16 modules set in series achieve the desirable input voltage of 192 V to the power converter. The criteria that were taken into account were their commercial availability, their low cost and also some essential features as the Ampere-hour capacity, the weight, the specific power and the quick recharge time.

3.2 Design of the Boost/Buck Converter

The electric energy between the batteries and the electric motor flows through a DC to DC Boost/Buck bidirectional Converter (Figure 4), which boosts the DC voltage (Figure 3) when the electric motor moves the vehicle and downgrades the voltage when the motor acts as a generator to return energy to the batteries (regenerative braking). The demanded power for the motor (14 kW) is offered by a number of Boost/Buck converters set in parallel. According to the proposed design, the voltage level at the batteries' side is 192 V, at the DC bus side of the inverter 380 V and the nominal AC line to line voltage of the motor 265 V.

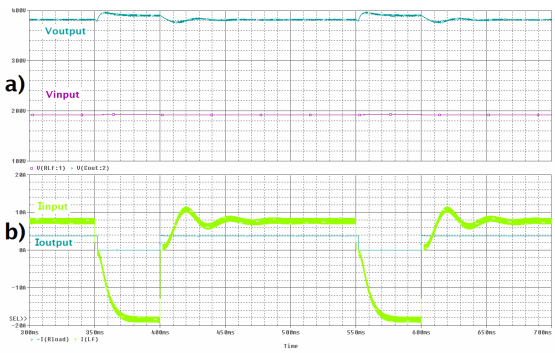

Figure 3: Simulation results of the Boost Converter using PSpice software
a) Input and Output Voltage
b) Input and Output Current

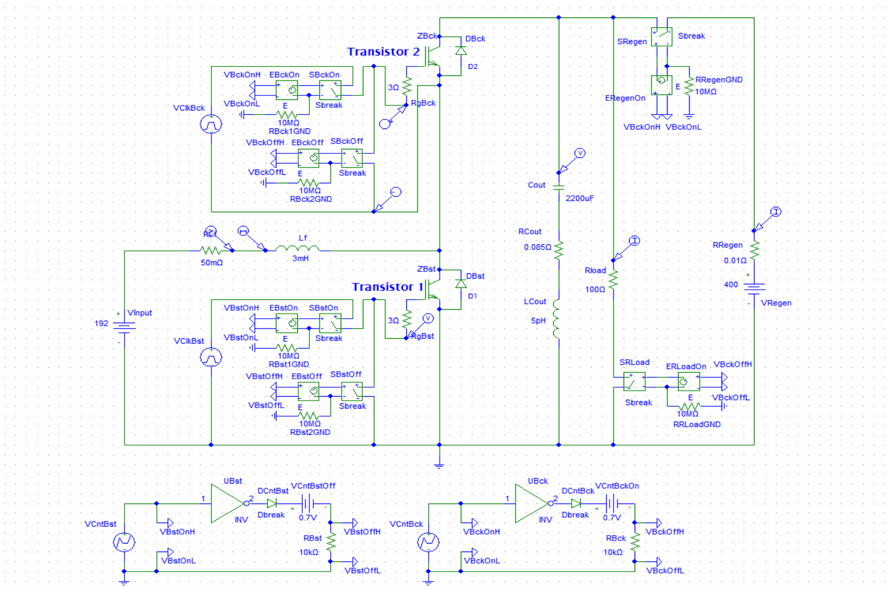

Figure 4: PSpice schematic of the Boost/Buck Converter

The DC to DC Boost/Buck bidirectional Converter consists of two MOSFET elements with maximum absolute ratings of V_{DS} = 600 V and I_{DS} = 23 A. The required inductor with the value L = 3 mH was designed and constructed in the laboratory. The most appropriate material for the inductor's core has been chosen to be Ferrite N27 because of its high performance at the desirable switching frequency f_{SW} = 20 kHz. The simulation of the converter was considered to be necessary in order to have an overview of the system operation and, specifically, of the inductor's response by the operation change of the boost and the buck phase. For this reason, an accurate model of the converter was designed and tested via the simulation software Orcad PSpice. The motor's equivalent circuit was based on its real characteristics, which were calculated through experimental processes. The control of the Converter has been assigned to the digital signal controller DSPIC30F4011. The whole circuit of the microcontroller was developed in the laboratory.

The DC to DC Boost/Buck bidirectional converter operating as a Boost converter has to provide a set output voltage at the level of 380V, so as to supply the motor. A voltage transducer connected in parallel with the output capacitor (C_{out}) "informs" the digital signal controller about the voltage level. If the voltage is lower than 380 V, the microcontroller increases the duty cycle of the transistor 1, in order to rise up the output voltage. If the converter is, still, in the Boost operation and there is energy returning from the motor-generator side charging the capacitor, the duty cycle of the transistor 1 is decreased till a minimum value in order to hold the voltage at the level of 380 V. The voltage value, though, continues to increase and a maximum level of 450 V has been set as a limit to the Boost phase to turn to the Buck operation. Specifically, when the voltage reaches 450 V, the microcontroller stops the pulses at the gate of the transistor 1 finishing the Boost operation phase and after 2 ms turns on the transistor 2 starting the Buck operation phase. This period of time has been specified by the PSpice simulation and is considered to be long enough for the inductor demagnetization. The output voltage is, now, regulated at 192 V to charge the batteries. In the Buck phase, when the voltage starts diminishing under 400 V, the signal controller increases the duty cycle of the transistor 2, in order to hold the output voltage constant. When the voltage reaches the level of 380V, the transistor 2 is turned off. After a pause of 2 ms between the two phases the DSPIC30F4011 allows the system to operate again as a Boost converter.

3.3 Three Phase DC-AC Inverter

To control the electric motor, a three phase DC to AC Inverter has been designed and constructed in the laboratory. The Inverter consists of:

- three IGBT modules
- the cooling system
- the microcontroller
- the protection system

The three IGBT modules having the technical characteristics I_{CE} = 160 A, V_{CE} = 1200 V and V_{CEsat} = 2.2 V compose a six-pulse bridge. An aluminium coolant and two fans mounted on it are used for the heat exchange of the switching devices and ensure their safe operation (Figure 5).

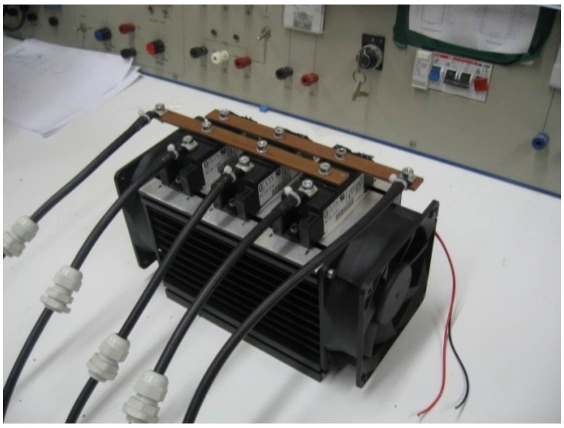

Figure 5: Power part of the three phase DC-AC Inverter

The inverter's power electronic elements are driven by a microcontroller circuit whose main part is the high performance digital signal Microchip controller DSPIC30F4011.

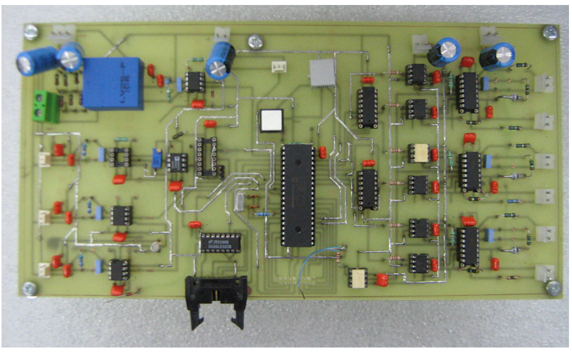

Figure 6: Microcontroller Circuit

In order to reduce the electromagnetic interference (EMI) to the microcontroller, due to high currents of the inverter, a copper shield has been installed between them. Furthermore, the safe operation of DSPIC30F4011 is achieved by using separate power supplies and optocouplers between this and the IGBTs drivers.

The power supply of the integrated circuits of the microcontroller is provided by a separate 24V battery module and step-down voltage regulators, which set the desirable voltage levels of 5 V, 15 V and ±15 V, with low ripple and better accuracy.

The protection arrangement of the whole system composes of a switch connecting the batteries with the inverter, a fuse installed at the DC bus line of the inverter against high currents, and a snap switch at the three-phase output to avoid any possible overload of the electric motor.

In addition, voltage and current transducers have been used in order to monitor and ensure safe operation of the electric motor. Specifically, two current transducers are mounted on two lines of the electric motor's input. Moreover, a voltage and a current transducer have been applied to the output of the battery modules. In this way, the digital signal controller can calculate the currents at the three lines of the electric motor and, additionally, the power supplied during the vehicle's acceleration or the power that returns to the batteries during regenerative braking. Finally, the microcontroller protects the system if the transducers detect high current.

The pulses at the gates of the IGBT modules are generated according to Direct Torque Control (DTC) method [7]. This method is an optimized AC drives control principle which enables the motor's torque and stator flux to be used as primary control variables. The measured input values to the DTC are the motor current and voltage. These signals are inputs to an accurate motor model which produces an exact actual value of stator flux and torque. Hereupon, comparing the actual values to the reference values, which are produced by torque and flux reference controllers, it is indicated whether the torque or flux has to be varied. The outputs from these controllers are updated periodically and determine the switching of the inverter's power electronic elements. Consequently, the desirable torque and flux are set by regulating the motor's voltage and current. Comparing to other control methods, such as Pulse Width Modulation (PWM), DTC offers the advantage of accurate and quick response, torque control at low levels of frequency and torque linearity.

3.4 Mechanical Design and Construction

The motion is transferred from the IC engine to the rear wheels through a central axle (Figure 1). The electric motor is mounted on the rear differential using a special base and four electrically welded joints and connected to the axle with a special steel reinforced polymer belt. Modifications have also been done at the chassis of the vehicle. The rear seats have been substituted by a special metallic construction holding the batteries, and both the microcontroller and the inverter have been positioned in a suitable polymer air cooled box. A second case contains the Boost/Buck converters.

4 Operation Overview

The main goal is to reduce the IC engine's energy losses and emissions. The reduction of kinetic energy does not end up as heat at the brake disks, but it is converted to electric energy and stored in the batteries. When the driver releases the throttle the motor starts operating as a generator. The current flows back through the inverter antiparallel diodes and the Boost/Buck converter (Buck operation, Figure 7), which regulates the charging voltage of the batteries at 192 V.

When the driver pushes the acceleration pedal, a potentiometer adapted on it sends a digital signal to the microcontroller setting the reference torque to be produced by the motor. This reference torque is compared with the actual one at the motor shaft which is calculated by measuring the motor current and voltage. Then the microprocessor using the DTC method specifies the current to be driven to the motor (and as a result the torque) and applies the appropriate pulses to the gates of the IGBTs. In this case the current flows through the Boost/Buck converter (Boost operation, Figure 7) controlling the DC voltage at 380 V and so the inverter offers the demanded voltage to the motor. The energy previously stored in the batteries is now re-used and reduces the need for fuel of the IC engine, as well as its polluting emissions.

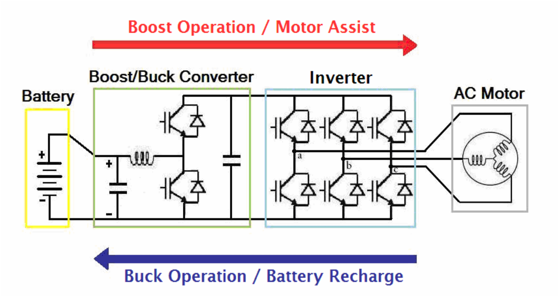

Figure 7: Basic Structure of the Powertrain System - Power Flow

5 Conclusion

The development of the propulsion system of an HEV is outlined in this paper which has been achieved through the conversion of a conventional passenger vehicle. A complete power electronic conversion system has been designed and constructed. Moreover, some specific mechanical modifications have been applied in order to achieve an optimal placement of the drive system on the vehicle. The key feature of this project is the transition of hybrid electric vehicle technology from theory to implementation. In general, such attempts have pedagogical value, as in the educational process the theoretical consideration should be accompanied by practical application. This project can, also, work as a guideline for investigation in the educational and research activities in a university laboratory. Further improvement can be carried out to this experimental vehicle and can lead to a more advanced construction. In addition, other technologies, such as photovoltaic cells in order to use solar energy for battery charging or fuel cells for hydrogen motion, etc. can also be adapted in the converted vehicle. These acts, surely, require society's as well as private support. After all, hybrid technology gets great importance, being the mediate step to fully electric vehicles and zero emissions.

References

[1] N. Mohan, T. Undeland, W. Robbins, *Power Electronics: Converters, Applications and Design*, ISBN 0471226939, J.Wiley & Sons, Inc., 1995.

[2] Ali Emadi, *Handbook of Automotive Power Electronics and Motor Drives*, ISBN 0-8247-2361-9, Taylor & Francis Group, LLC, 2005.

[3] Antoni Szumanowski, *Fundamental of Hybrid Vehicle Drives*, ISBN 83-7204-114-8, Warsaw Radom, 2000.

[4] C. Kral, A. Haumer, T. Bauml, *Thermal Model and Behavior of a Totally-Enclosed-Water-Cooled Squirrel-Cage Induction Machine for Traction Applications*, IEEE Transactions on Industrial Electronics, ISSN 0278-0046, vol.55, no.10, 2008, 3555-3565.

[5] Ion Boldea, *Control Issues in Adjustable-Speed Drives*, IEEE Industrial Electronics magazine, ISSN 1932-4529, 2008, 32-50.

[6] James Larminie, John Lowry, *Electric Vehicle Technology Explained*, ISBN 0-470-85163-5, J.Wiley & Sons, Ltd, 2003.

[7] ABB, *Technical Guide No.1 – Direct Torque Control*, http://library.abb.com/global/scot/scot201.nsf/veritydisplay/299c5d307cb78a34c1256d28003fed0c/$File/ABB_Technical_Guide_1_%20EN26042002.pdf, accessed on 2009-04-12.

[8] Takaji Kikuchi, Osamu Shinmura, *Development of Power Control Unit for SUVs*, EVS 21 Proceedings, Monaco, Apr.2-6, 2005.

[9] Junhong Zhang, Lai Jih-Sheng, Kim Rae-Young, Wensong Yu, *High-Power Density Design of a Soft-Switching High-Power Bidirectional DC-DC Converter*, IEEE Transactions on Power Electronics, ISSN 0885-8993, vol. 22, no.4, 2007, 1145-1153.

[10] J. Faiz, M.B.B Sharifian, A. Keyhani, A.B. Proca, *Sensorless Direct Torque Control of Induction Motors used in Electric Vehicle*, IEEE Transactions on Energy Conversion, ISSN 0885-8969, vol. 18, no.1, 2003, 1-10.

[11] Alen E. Fuhs, *Hybrid Vehicles and the Future of Personal Transportation*, ISBN-13 978-1-4200-7534-2, CRC Press, Taylor & Francis Group, LLC, 2009.

[12] H. Plesko, J. Biela, J. Luomi, J.W. Kolar, *Novel Concepts for Integrating the Electric Drive and Auxiliary DC–DC Converter for Hybrid Vehicles*, IEEE Transactions on Power Electronics, ISSN 0885-8993, vol. 23, issue 6, 2008, 3025-3034.

Authors

Panagiotis D. Asimakopoulos was born in Athens, Greece, in 1985. He is an undergraduate student in the Department of Electrical and Computer Engineering at the University of Patras, and currently is working on his Diploma thesis in the area of HEV technology.

Theodoros A. Boumis was born in Athens, Greece, in 1985. He is an undergraduate student in the Department of Electrical and Computer Engineering at the University of Patras, and currently is working on his Diploma thesis in the area of HEV technology.

Efstathios A. Patsias was born in Athens, Greece, in 1985. He is an undergraduate student in the Department of Electrical and Computer Engineering at the University of Patras, and currently is working on his Diploma thesis in the area of HEV technology.

Athanasios N. Safacas was born in Amphilohia, Greece, in January 1943. He received the Dipl.-Ing. and Dr.-Ing. degrees in electrical engineering from Karlsruhe University, Karlsruhe, Germany, in 1967 and 1970, respectively. During 1971, he was with Siemens, Karlsruhe. Since 1975, he has been a Professor with the Department of Electrical and Computer Engineering, University of Patras, Rio-Patras, Greece, where he is the Director of the Electromechanical Energy Conversion Laboratory. His current research interests include electrical machines, power electronics, and electric motor drive systems. Prof. Safacas is a member of the Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE), the Conseil International des Grands Reseaux Electriques (CIGRE), European Power Electronics and Drives Association (EPE), the European Association for Battery, Hybrid and Fuel Cell Electric Vehicles (AVERE), the International Association of Science and Technology for Development (IASTED), and the Technical Chamber of Greece.

Emmanuel C. Tatakis was born in Alexandria (Egypt), on October 1957. He received the Dipl. degree in electrical engineering from the University of Patras, Rion-Patras, Greece, in 1981, and the Ph.D. degree in Applied Sciences from the University of Brussels, Brussels Belgium, in 1989. He is currently an Associate Professor in the Department of Electrical and Computer Engineering, University of Patras, Rion-Patras, Greece. His teaching activities include Power Electronics and Electrical Machines. His research interests include Switch Mode Power Supplies, Resonant Converters, High Frequency Transformers, Power Factor Correction, Electric Drive Systems and Electric Vehicles, Converters for Photovoltaic and Wind Energy Systems, Educational Methods in Electrical Machines and Power Electronics. Dr.-Ing. E.C. Tatakis is a member of the European Power Electronics Association, the Sociéte Royale Belge des Electriciens and the Technical Chamber of Greece.

Epaminondas D. Mitronikas was born in Agrinio, Greece, in March 1973. He received the Dipl.-Eng. degree in electrical and computer engineering from the Department of Electrical and Computer Engineering, University of Patras, Rio-Patras, Greece, in 1995. He received the Ph.D. degree in Electrical Engineering in 2002. From December 2003 he is a Lecturer at the Department of Electrical and Computer Engineering, University of Patras. His research interests include power electronics, electrical machines, simulation and digital control of electric motor drive systems, control of low power electromechanical systems. Mr. Mitronikas is member of the Technical Chamber of Greece.