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Design, Implementation and Construction of a Multilevel Inverter for Robot Arm Drive, by Means of a Brushless Motor

Claudio Urrea, Félix Rojas, Juan Dixon, and Julio del Valle

Abstract — *Modern industrial processes depend on the technology for automation, especially in robotics and position control. Electrical Machinery used for these purposes are varied, nevertheless, permanent magnet electric machines have better performance thanks to their high power density and low inertia. On the other hand, the most popular technique used in controlling position is the PWM drive.*

In this work the position control of a permanent magnet machine driven by a multilevel configuration, taking advantage of its benefits is presented. This article presents a first step of the total workforce, showing the state of the art and the overall structure of that work.

Key Words — Multilevel Converters, PMSM, Modulation Multilevel Converters, Robotic Systems.

I. INTRODUCTION

For the automation of a process, e.g. an industrial robot arm, a bottling plant, etc., it is necessary to control motor rotor position. For these kinds of tasks step by step motors and DC or AC servomotors are the most used devices, being the last ones an example of present technology, where a synchronic brushless motor is controlled by means of a two-level inverter with PWM modulation (conventional inverter).

This work intends to control a robotic arm angular position by means of a ***brushless synchronic motor*** (PMM) powered and controlled by a multilevel inverter. Through the analysis and implementation of such configuration, it is proposed to overcome the problems commonly affecting position control of DC servomotors, having lower performance and requiring more maintenance; and the problems of AC servomotors, usually controlled by a converter, thus generating high levels of dv/dt what, in addition to high switching frequencies, can cause motor damages compromising their shelf life. Besides, high switching frequencies increase losses, finally affecting system´s efficiency magnet [1]-[8].

Claudio Urrea is with the Department of Electrical Engineering at the Universidad de Santiago de Chile (USACH), Santiago, Chile. (e-mail: claudio.urrea@usach.cl).

Félix Rojas was with USACH, Chile. He is now Ph.D. student in Germany. (felix.rojas.l@gmail.com).

Juan Dixon is with the Department of Electrical Engineering at the Pontificia Universidad Católica de Chile, Santiago, Chile. (e-mail: jdixon@ing.puc.cl).

Julio del Valle is with the Department of Electrical Engineering at the Universidad de Santiago de Chile, Santiago, Chile. (e-mail: julio.delvalle@usach.cl).

II. WORK PROPOSAL

We want to control the position of a robotic arm by means of a three-phase PMM driven by a 27-level converter; figure 1 shows the general work plan. In order to achieve the desired control, we need to know the rotor position that will be provided by a resolver, and the motor phase currents.

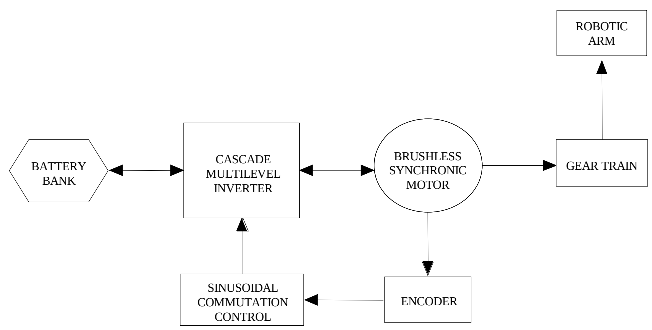

Fig. 1. General scheme for position control of a robotic arm by means of a PMM.

III. PERMANENT MAGNET MACHINE

The PMM is also known as ***brushless*** motor since it does not have brushes and commutator. Its high power density and great efficiency has positioned it as a good choice currently available in markets. This kind of machine is composed by a three-phase stator and a rotor with permanent magnets, making it a synchronic machine. Given the above mentioned conditions, there is no starting torque, so these machines are destined to operate only with power electronics devices that control and optimize their operation. Figure 2 shows the scheme of a permanent magnet [1], [9]-[12].

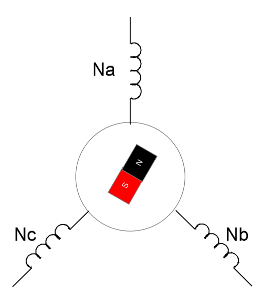

Fig. 2. Scheme of a PMM.

IV. 27 Level Converter

The proposed topology consists in cascaded H bridges, where the independent sources are scaled in power of three, as shown in figure 3.

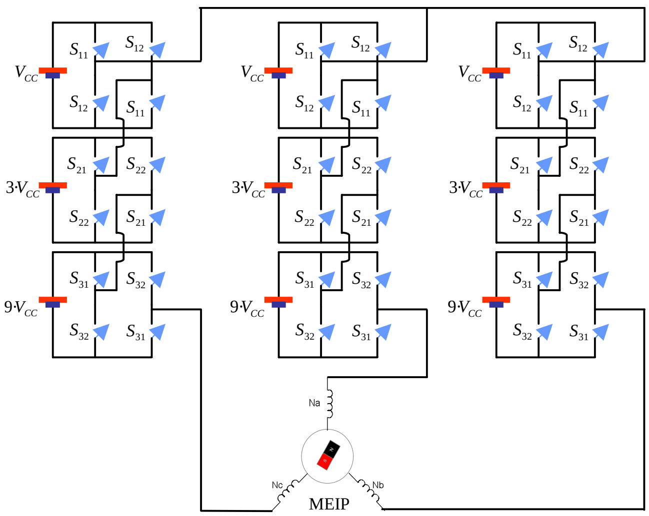

Fig. 3. Scheme of a 27 level converter.

In this work we will employ ladder modulation, a technique consisting in comparing a sinusoidal signal, with a maximal amplitude equal to the maximum value the inverter can give (per each unit); so, the step change carried out by the multilevel inverter will be done with respect to the closest-to-sinusoid value it can reach. This technique is also known as *Nearest Level Control* [13]-[19].

The voltage waveform obtained with this technique is shown in figure 4.

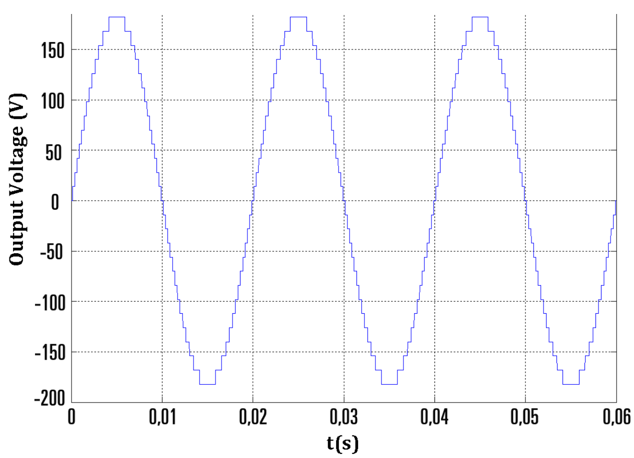

Fig. 4. MatLab simulation of a multilevel inverter, 27 levels with nearest level control modulation.

V. Proposed Control

Figure 5 shows a schematic view of the control philosophy implemented in the robotic arm.

The resolver gives the absolute rotor position, which is used by two control loops; in first place, we have the loop maintaining the stator MMF in quadrature with the rotor's one, that unites with the second control loop that gives a peak for the value of stator currents. That's how the encoder signal enters the Look Up Table (L.U.T.), that gives, in unit value (maximum value of 1), the currents required for maintaining stator MMF in quadrature with rotor ones, that are further multiplied by the reference voltage, that is, by the maximum real value that we want to obtain for the stator currents. Then, those reference voltages are compared with real voltages, and the error between both voltages is processed by a PI controller that gives the necessary signal for the next block; stage that will activate the required switches for increasing or decreasing the respective tensions and therefore, the voltages. In second place, we have the control loop that is in charge of keeping the desired robot arm position. After entering the value corresponding to the position where we want to place the robot arm, $\theta_{referencia}$, this angle is compared with the rotor real angular value, θ_{real}, and the error is processed by a PI controller, whose output will enter the block controlling machine speed; then, the output of this loop is $I_{referencia}$, that will finally modulate the voltage real value. In this way, the arm will stop when the error becomes zero and the reference voltage value that we will obtain will be the proper as to generate an acting torque, matching the resistant torque generated by the robot arm.

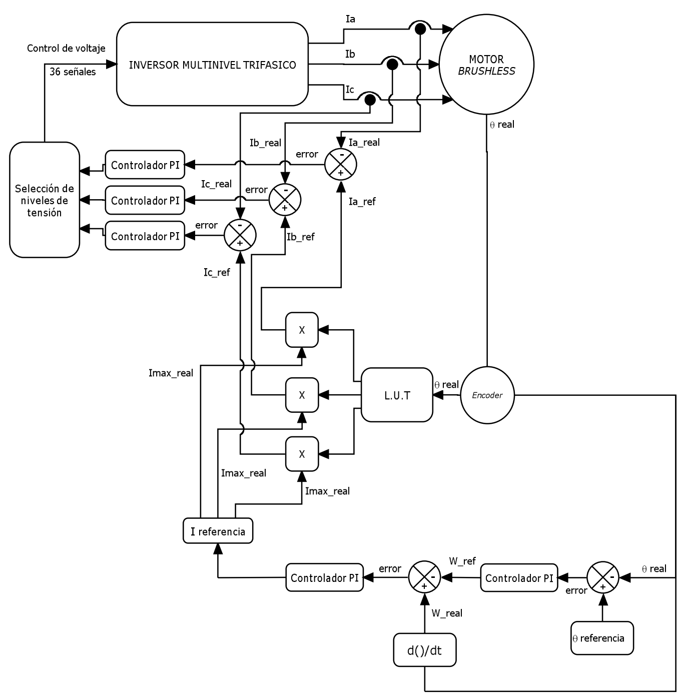

Fig. 5. Position control scheme for a PMM.

VI. Computer Simulations

The simulations were carried out with a real model of a 360[W]/220[V] permanent magnet motor, WEG brand. Motor parameters are: Rs=5.521 [Ω], Ld=20.95 [mH], Lq=20.95 [mH], φ=0.1682 [Wb], J=0.0002189 [kgm^2], D=0.001 [Nms].

The 27-level inverter is composed by 36 MOSFETs with their corresponding antiparallel diodes and 9 power sources (3x14V, 3x42V y 3x126V) as shown in figure 3.

Figure 6 shows position response in terms of time, and here it is seen that we can reach the reference position of 400 [rad] and keep this position without vibrations in the machine spindle.

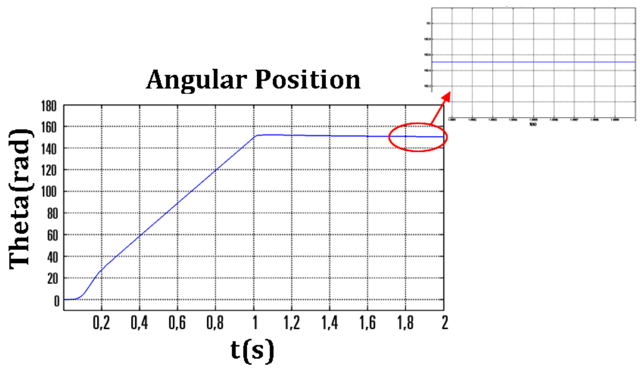

Fig. 6. Motor spindle position angle in terms of time. Simulation run with a reference of 400 [rad] and a final switching frequency of 2 [KHz] (lowest level).

One of the most important and innovative features of this work is the low MOSFET switching frequency when keeping a fixed rotor position. Since we can have 27 voltage levels for switching, we will logically choose the lowest one, in this case 14 [V], in order to obtain the lowest switching frequency. Considering this remarkable advantage, we can carry on switching at a frequency of 2 [KHz] obtaining a response without vibrations at the moment of keeping the position.

Figure 7 shows a chart of machine angular speed, where we can notice the transient regime and the time lapse required for reaching the permanent regime, obtaining a constant speed; after that, we get the reference position, having zero speed, therefore implying a fixed position.

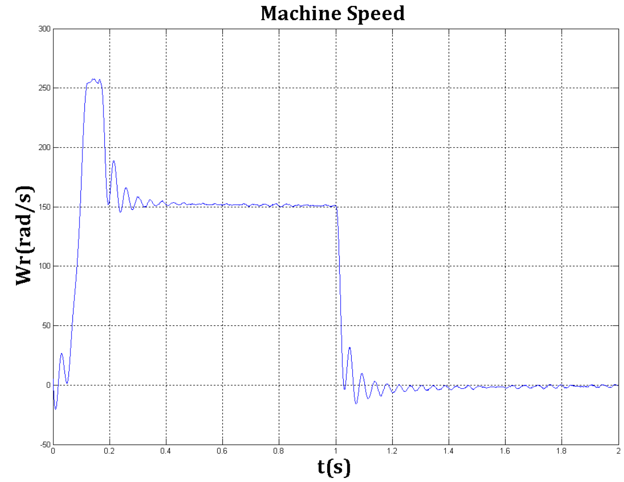

Fig. 7. Brushless motor angular speed. Position control simulation run under multilevel driving.

Figure 8 shows neutral-to-phase voltage, where we can notice this voltage, while the rotor is spinning, approaches the level when we position in a given angle.

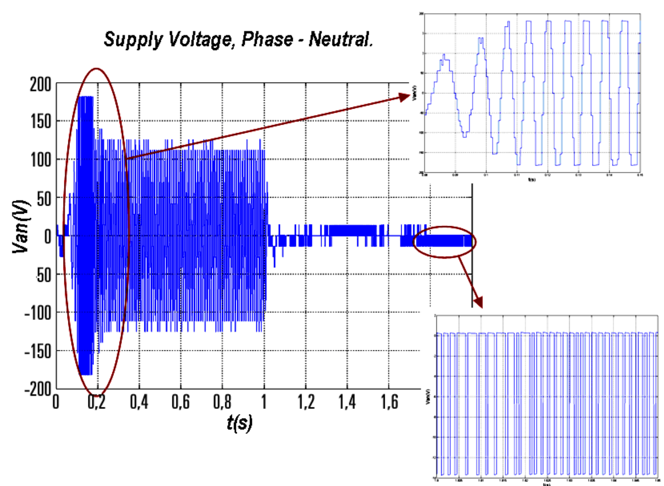

Fig. 8. Phase-to-neutral voltage for motor "a" phase. Position control simulation run under multilevel driving.

Figure 9 shows currents entering the motor. The low distortion is achieved through the 27 level configuration employed in the inverter.

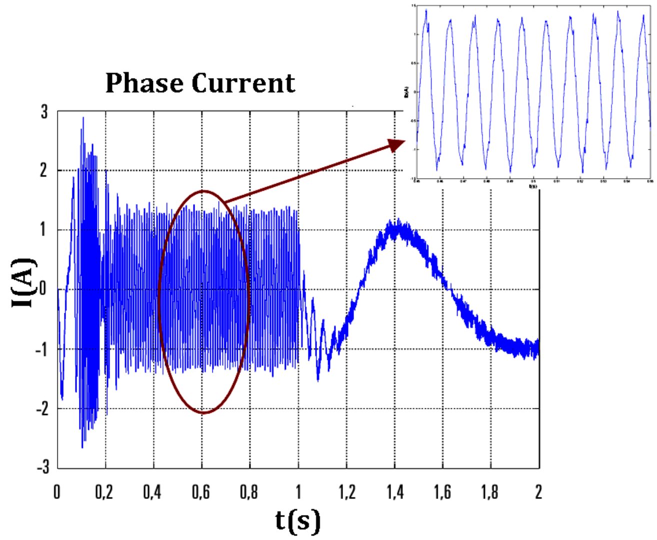

Fig. 9. Motor phase "a" voltage for position control by means of multilevel driving.

In the other hand, we also carried on a simulation to analyze how the machine responds to a load step when already positioned. Figure 10 shows the position response facing a load step; we can see its spin axis returning smoothly to the original position.

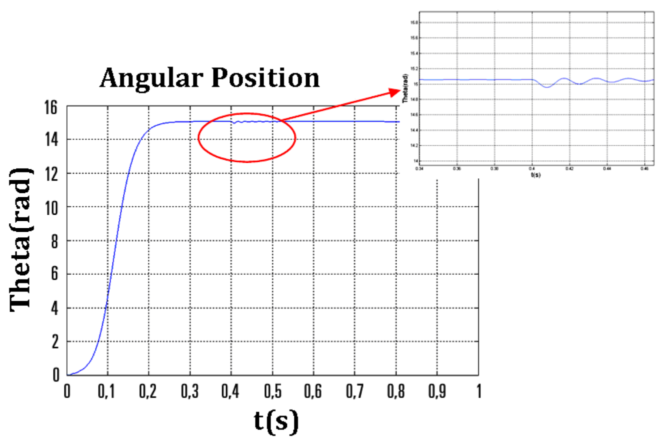

Fig. 10. Machine position angle facing a load step.

VII. Experimental Results

Figure 11 shows the implementation final results, where we have the nine H bridge cards generating the three phases of the inverter. The control card, responsible of controlling the three inverters, is located at the left side of the figure. Besides, we can notice the three transformers, each one having a primary and three floating secondary scaled in power of three, along with the three LEM voltage meters, used for achieving the current closed loop.

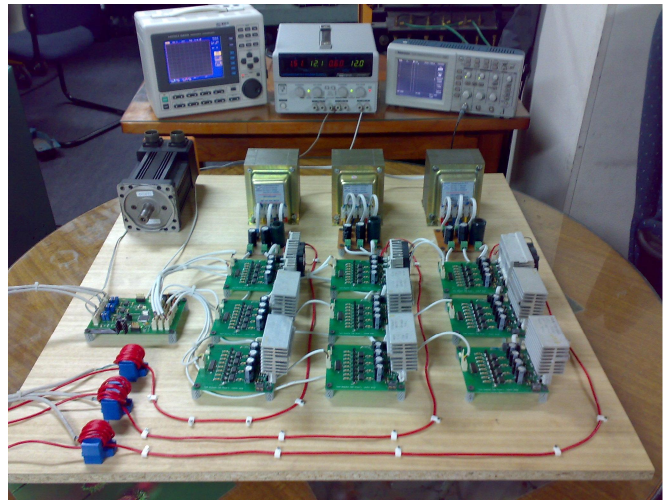

Fig. 11. Implementation of the three-phase multilevel inverter with 27 final levels, along with the control card, the power feedback and the synchronous brushless motor.

Figure 12 shows the voltage signal per motor phase; we observe how the frequency begins to increase gradually, causing a smooth motor starting, therefore arriving in a proper way to the desired speed.

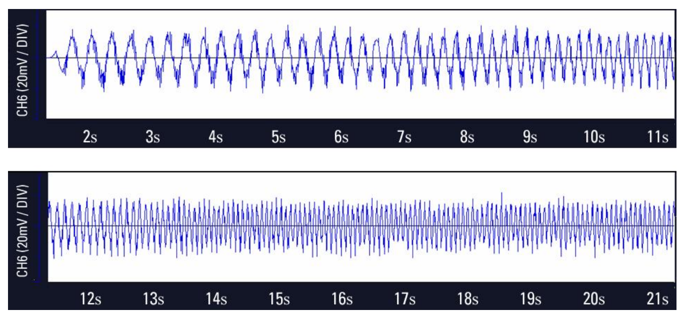

Fig. 12. Synchronous brushless motor per phase voltage at machine start.

Figure 13 shows machine per phase voltages when it has already reached permanent regime. It is important to remark that switching frequency is 2 [KHz] (this is valid only for the lowest bridge), and that we employ only the lowest levels of the multilevel inverter, that's why the voltages shown in figure 13 are not completely sinusoidal.

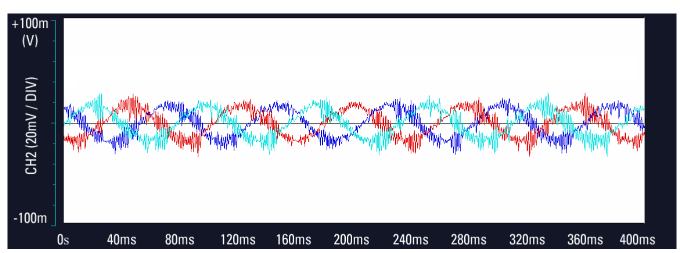

Fig. 13. Motor voltages in permanent regime.

Figures 14, 15 and 16 show switching patterns of the MOSFETs shots, for 14 [V], 42 [V] and 126 [V] bridges, respectively (see figure 3).

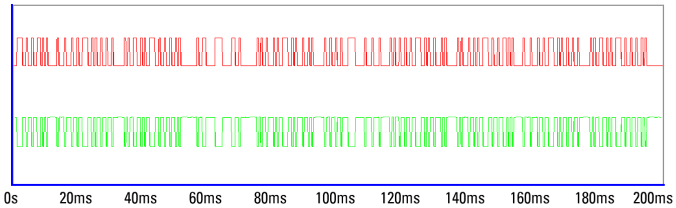

Fig. 14. Gate-Source Voltage (0-15 [V]) for MOSFETs of the auxiliary 14 [V] H bridge. Scale from 0 to 200 [ms].

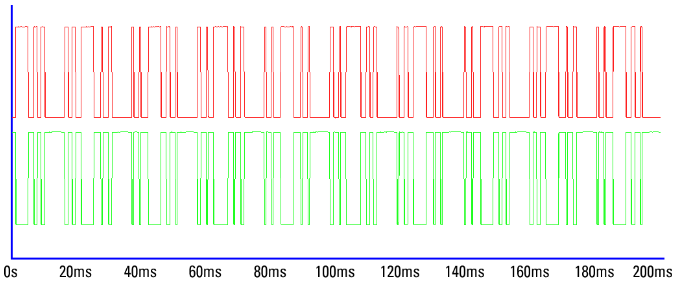

Fig. 15. Gate-Source Voltage (0-15 [V]) for MOSFETs of the auxiliary 42 [V] H bridge. Scale from 0 to 200 [ms].

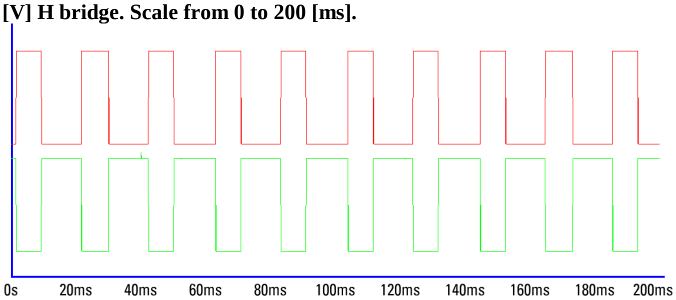

Fig. 16. Gate-Source Voltage (0-15 [V]) for MOSFETs of the auxiliary 126 [V] H bridge. Scale from 0 to 200 [ms].

VIII. Conclusion

The designed and implemented 27-level inverter, apart from providing good quality waveform, allows an efficient PMM speed and position regulation with excellent response. Particularly, the inverter scaled in powers of three, as shown in figure 3, allows switching of the greatest power H bridge with a low frequency; as well as switching the smaller power bridge with a higher frequency, as can be seen in figures 14, 15 and 16, therefore protecting the machine against the dv/dt and improving its performance. This configuration (inverter scaled in powers of three) and switching pattern implies a significant advantage compared with conventional inverters.

One remarkable objective of this work is to show that torque behavior is practically flat (without ripple) for any load range, allowing to position machine rotor in a precise way, without vibrations. This feature is especially important when we employ low inertia machines like the PMM.

One of the problems in controlling the synchronous brushless motor arises when it is stopped. Under this condition there is no induced EMF in the machine stator, and at the same time, voltages per phase are continuous; this implies that phase resistance is the only factor limiting the current. In a two-level VSI inverter we can operate only between +Vcc, 0, or -Vcc, what means switching at a very high frequency (around 20 [KHz]) in order to avoid exceeding the motor current limit values and keeping the spindle without vibrations. Using the inverter configuration scaled in powers of three, we achieve the same goals but with a switching frequency of 2 [KHz] for the lowest power bridge, since we operate with the inverter lowest voltage levels (14 [V]), allowing voltage gradients be smaller than the ones in conventional VSIs.

The obtained experimental values validate simulation results; however, the machine stator currents have a greater distortion due to interactions and synchronicity between MOSFET switching of the different inverter bridges.

Depending on power and tension levels, other types of inverter scaling can be employed.

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BIOGRAPHIES

Claudio Urrea was born in Santiago, Chile. He received the M.Sc. Eng. and the Dr. degrees from Universidad de Santiago de Chile, Santiago, Chile in 1999, and 2003, respectively; and the Ph.D. degree from Institut National Polytechnique de Grenoble, France in 2003. Ph.D. Urrea is currently Professor at the Department of Electrical Engineering, Universidad de Santiago de Chile, from 1998. He has developed and implemented a Robotics Laboratory, where intelligent robotic systems are development and investigated.

Juan Dixon (SM) was born in Santiago, Chile. He received the Ms. Eng. and the Ph.D. degrees from McGill University, Montreal, PQ, Canada in 1986, and 1988 respectively. Since 1979, he has been with the Electrical Engineering Department, Pontificia Universidad Católica de Chile, where he is presently Professor. He has presented more than 70 works in International Conferences and has published more than 40 papers related with Power Electronics in IEEE Transactions and IEE Proceedings. His main areas of interest are in Electric Traction, PWM Rectifiers, Active Filters, Power Factor Compensators and Multilevel converters. He has created an Electric Vehicle Laboratory, where state-of-the-art vehicles are investigated.

Felix Rojas L. was born in Santiago, Chile. He received the B.E.E. and M.S. degrees in electrical engineering in 2009, from Universidad de Santiago de Chile, Chile. He has worked in some research projects related to Active filter for Train Applications, Matrix Converters and in Multilevel converters as well. Currently he is working in a Chilean company as a consultant engineer.

Julio Del Valle J. was born in Santiago, Chile. He received his Bachelor degree in Electrical Engineering in 1974 from University of Antofagasta, Chile; his Master degree in Statistics in 1982, Industrial Engineering diploma in 1984 and Doctorate degree in Electrical Engineering in 1987 from Polytechnic University of Madrid, Spain. Dr. Del Valle is currently Professor of the Department of Electrical Engineering at University of Santiago de Chile. His main areas of research are power electronics, electric-machine drives and power quality.