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Energy-Efficient Motors

Comparing the Performance of Die-Cast Copper Squirrel Cage Induction Motors with Aluminum Cage Induction Motors

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The problem of the increment of the equivalent efficiency of the huge electric motors family is very far from losing its increasing social importance [1]. We first refer to the natural ambition people have to increase the world's life quality. This is deeply dependent on the amount of the electrical energy at disposal per inhabitant, which is also strictly connected to the utilization of electric motors [2] (see Figure 1). In fact, such a parameter can be considered as a sort of "well-being" index, where more disposal of electric energy may allow for more richness and life quality. In Figure 1, the energy consumed per inhabitant per year is reported as a function of an index depending on the personal income; the results are sorted by nations and by continents. The diagrams clearly suggest that the gross domestic product (GDP) increment of a country is in correlation with the increase of the electric energy consumption (2006).

On the other hand, for an industrial country like Italy, the existence of two phenomena is pointed out below:

1) the constant increment of the portion of the electrical energy with respect to the total consumed amount (the easier management of the electrical energy at the utilization level is evident and convenient)
2) the increment of the motor population, also outside the industrial applications.

With respect to the first point, in order to understand the importance of electric energy because of its intrinsic easiness of handling, we can consider its penetration,

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defined as the ratio between the electric energy and the total energy consumed. Figure 2 points out the increased trend in Italy of such a penetration in the last 40 years.

With reference to the second point, always regarding the Italian scenery, some sectors heavily increased their energetic consumption from 2005 to 2006; among them we emphasize the agricultural (+2.6%) and the tertiary (+5.4%) sectors [2]. In both cases, the increased consumption is strongly correlated with the increased number of electric motors adopted in such working areas. The increased number of small machines in the motors population that are used in working areas is due in part to the use of air conditioning, office machines, and domestic appliances.

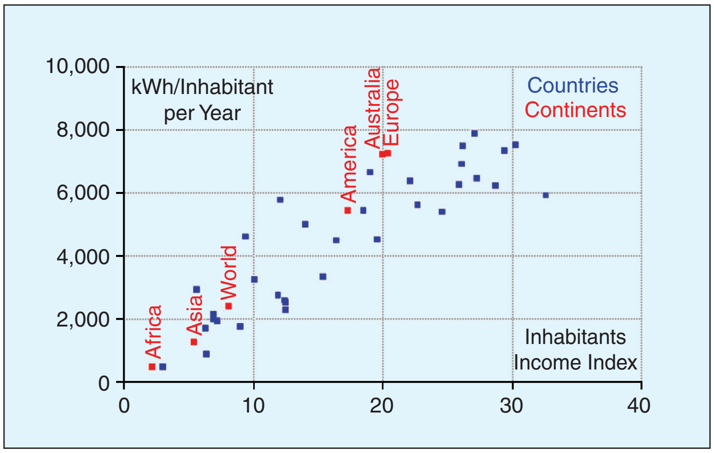

FIGURE 1 – Energy consumption/inhabitant/year for different countries and continents.

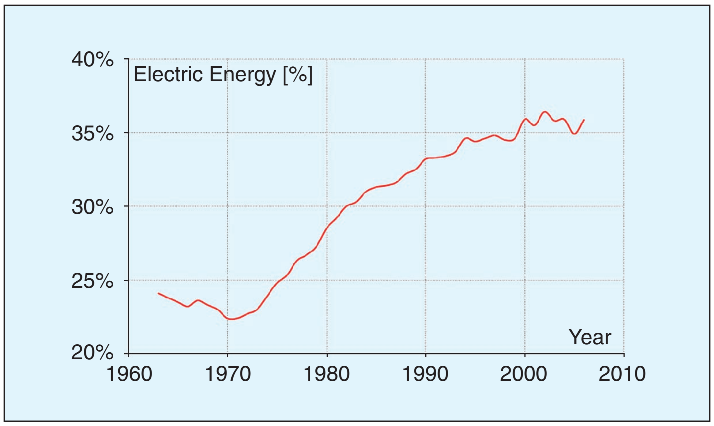

FIGURE 2 – Electric energy penetration in the situation in Italy.

To better understand the connection between economical development and energy consumption due to electric motors, let us analyze the example of the Italian situation from 2005 to 2006: the GDP increased by 1.9%, while the electric energy required by the manufacturing industry increased by 1.8% [2].

By U.S. considerations, statistics coming from the U.S. Department of Energy give us a complete and clear scenario of the energetic situation in industrial applications. In the 1990s, the Energy Policy Act of 1992 (EPAct) was an important piece of legislation for efficiency because it established minimum efficiency levels for electric motors manufactured or imported after October 1997. EPAct, which was based on National Electrical Manufacturers Association (NEMA) standards, defined a number of terms, including what constitutes an energy-efficient motor [3]–[5].

The industrial sector is the largest of the end-use sectors, consuming 50% of delivered energy worldwide (2003 statistics); industrial energy use is projected to grow very rapidly, with an increase by an average of 2.4% per year from now until 2030 [1]. Other statistics provide that about 60% of the electricity produced in the United States is consumed by motors, particularly with power ratings from 1 to 90 kW.

How Electric Machines Contribute to Limit Energy Consumption

More than 150 TWh of electricity consumed annually could be saved in a cost-effective manner if drive systems were designed from an energy efficiency point of view. Electric motors are one of the components involved that can contribute to energy savings. The situation in the past decade was still divided into different approaches. This is illustrated by an overview of the efficiencies of induction motors manufactured in Europe [6]. On one side, the buyers were trying to purchase motors as cheaply as possible; on the other, the end users were trying to run them as cheaply as possible. The benefits of energy saving can pay back the higher cost of the machine in the first one or two years [7].

The European Commission and the European Committee of Manufacturers of Electrical Machines and Power Electronics (CEMEP) have drafted a classification scheme with a voluntary undertaking by European motor manufacturers [8].

The scheme divides the plane efficiency/power into three areas, from Eff3 to Eff1, as shown in Figure 3.

In [9], the market penetration of Eff3 motors (four pole and two pole) has been dramatically reduced after the introduction of the classification and the efforts of the European motor manufacturers.

Many changes in terms of materials and project criteria have been introduced in the past, with important results under the efficiency point of view, which is the focus of this article.

Once more, this makes more evident the age-old problem of power losses in the electric motors. How can their efficiency be increased?

The problem was addressed in the 1980s; good results came from the adoption of new magnetic materials on one side, and of speed regulators (without dissipation) on the other.

Now the problem must be faced again. Possibilities can be reduced to:

- the adoption of new materials
- new project machine criteria [10], making clear that the increased cost must be spread over the entire life of the machine (evaluating the energy savings it will permit).

In past decades, some of the authors of this article took part in discussions concerning the very low efficiency of the motors adopted for domestic appliances [11]. Their contributions, with technical and demonstrative actions, have been important but at that time, the technological level was so low that the task was quite easy. In this article, the interest is focused on small power rating machines; in fact, their distribution is very significant under the point of view of the total losses and of the costs of production with new technologies. Using [11], it is possible to estimate that today about 30% of the electrical power is absorbed by machines with rated power lower than 5 kW. If we assume an average equivalent efficiency of 80% (very optimistic), this means that 20% is dissipated. As a consequence, more than 6% of the total electric power produced is dissipated in small electric motors.

It is also evident that the possibility to further reduce the internal losses of the motors should permit an increment of efficiency, even if it is limited to 1–2%.

One solution is the adoption of cast copper rotor cages in substitution of the commonly adopted aluminum cages [12]. Copper presents a better value of conductivity that should heavily reduce the rotor I^2R losses. The reduction of rotor losses directly reduces the internal temperatures; lower temperatures means that the stator I^2R losses diminish, with a further decrease of the temperatures. In this way, smaller fans can be adopted to cool the machine with a consequent reduction of windage losses.

Copper rotors represent one of the largest possible loss reductions, avoiding the adoption of a redesigned laminations. It is evident that the adoption of copper in place of aluminum will influence some aspects of the motor behavior that should require project criteria modifications.

The starting point is the copper conductivity, which is about 60% better than that of aluminum. On the other hand, die-cast aluminum rotors are a consolidated and cheap way of production.

The difficulty of producing die-cast copper rotors lies in the high melting temperatures: 1,083 °C in place of 660 °C for aluminum; the consequent thermal shock drastically reduces the life of die materials, with an increase of production costs.

This problem's solution may be the development of new die materials, constituted by nickel-base alloys, which permit the development of die systems customized for copper [13], [14].

In this article, the first investigations consist of the substitution of rotor aluminum with copper. The rotor resistance reduction allows the reduction of the I^2R losses and modification of the torque/speed characteristic: the breakdown torque moves to lower slip values, guaranteeing working points with little speed variations for different requested torques while the starting torque is reduced.

This can present a problem for some applications and require different solutions. The adoption of copper rotors should be associated with an analysis of the project choices in order to maintain the starting performance and to increase the efficiency of the machine. The project should take into account the adoption of different magnetic steels, the variation of some dimensions of the active parts, and the slots profile.

Finally, the relationship between windings temperature and the expected life of the machine is very important. It is a common opinion of motor manufacturers that every 10 °C hotter a motor runs, its life expectancy can be cut in half. A reduction of temperatures, even of a few degrees, contributes to the increased motor life.

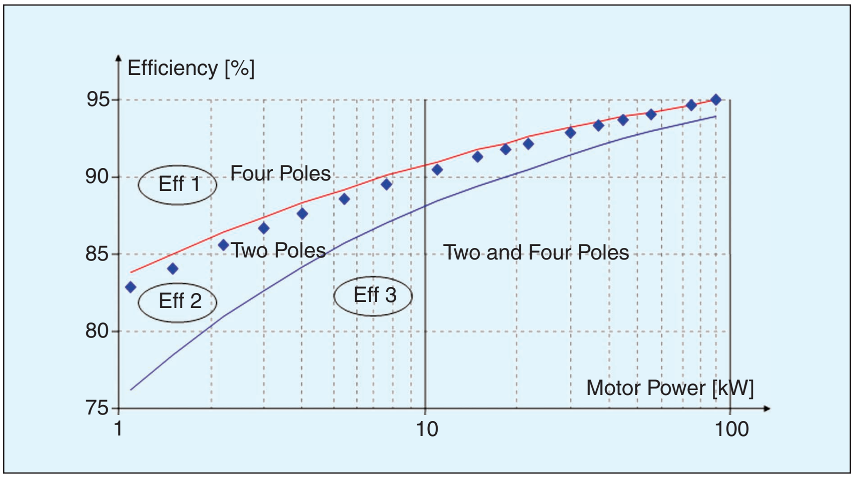

FIGURE 3 – Motor classification scheme depending on the efficiency (the dots represents the Eff 2-Eff1 boundary for two-pole induction motors).

Prototype Realization and Tests

On the basis of the previous discussion, the basic idea was a comparison of several prototypes realized with different rotor materials, in order to investigate their behavior and performance related to significant differences of resistance values. The motor rating has been chosen in order to analyze a significant size of motors, taking into account the problems linked to the adopted technological process for the realization of the copper cage prototype. For this reason, a 1.1 kW, four pole, 380 V, 50 Hz, and name plate prototype has been selected for the investigation. The motor rated torque and speed are respectively 7.8 Nm and 1,340 rev/min, while the rated current is 5.5 A.

In the test campaign, three materials have been addressed to realize the rotor-squirrel cage: aluminum, copper, and silumin.

Aluminum is the most commonly adopted material for rotor cages produced with a die-cast process; the technology is well known and consolidated.

Another adopted material is silumin, an aluminum alloy with silicon content between 4% and 22%; the addition of silicon to aluminum makes it more fluid when liquid, obtaining a very good casting alloy. The alloy resistivity is obviously increased, as well as the starting torque; this makes silumin commonly adopted for frequent start grid connected motor applications. In this article, the silumin cage has been used only for having a third prototype for the comparison, to confirm some trends of the machine behaviors linked to the cage material resistivity.

Better results are expected from the adoption of copper; due to the problems of die casting, a prototype has been realized by means of a process of investment casting.

It is important to note that the three prototypes differ from the rotor cage material only. The prototype design optimization (such as the rotor slot shape as a function of the cage material) is not within the aim of this article.

Cast Copper Cage Prototype Realization

The rotor core, assembled and packed, must undergo a particular treatment in preparation of the investment casting.

Both extremities are covered with wax to close the slot openings; wax tubes are also prepared to connect the extremities in order to improve the metal feeding on both sides (Figure 4).

The rotor is then placed inside a cylinder and completely covered with refractory material added with an excess of water in order to make it in a pseudo-liquid state. After this material has hardened, the cylinder is placed into a furnace for dewaxing, usually under vapor steam, obtaining a hollow die structure having the desired shape. A process of burn out (generally at temperatures greater than 700 °C) is then required to harden the refractory material.

Pure copper material is placed in a chamber for induction heating, in vacuum conditions to maintain the purity of the metal. The cylinder containing the flask is positioned in the chamber below, with a vacuum grade bigger than that of the melting pot. Finally, the material in the molten state is cast below, with the additional contribution of the whirlpool phenomenon due to the difference in vacuum grades between the two chambers.

The aluminum and copper cage rotors are shown in Figure 4. The aluminum and silumin cages have been realized by the manufacturer with a standard die-cast technology.

Experimental Tests

A wide test campaign has been conducted on the three prototypes to characterize them and to deeply evaluate their behavior under different working conditions.

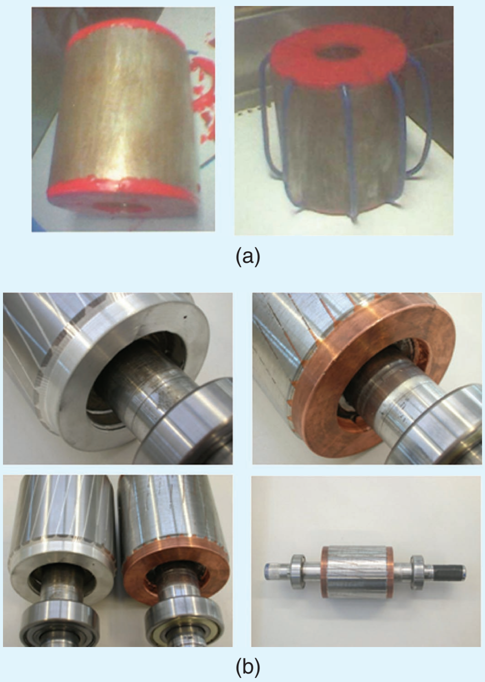

FIGURE 4 – (a) Copper cage prototype preparation and (b) aluminum and copper rotors.

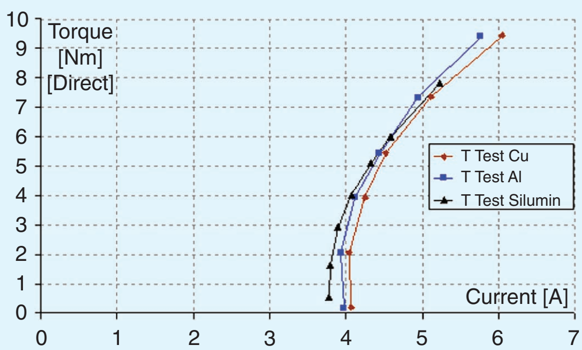

FIGURE 5 – Torque values of the three motors directly measured during the tests.

First of all, the prototypes have been tested with sinusoidal supply. No-load and locked rotor tests (to obtain their equivalent circuit and an evaluation of mechanical and core losses) have been done.

To perform a significant analysis on the different solutions adopted for the three rotors, a condition of uniformity has to be defined for the stator. Even if the three stators appear to be identical, possible differences in their realization can compromise the comparative analysis on the rotors.

Hence, on the basis of the results coming from the no-load and locked-rotor tests, one stator has been selected to become "the" stator for the three rotors.

In this way, the tests have been conducted inserting any time a different rotor inside the same stator.

The motors have been tested in the authors' laboratory. In particular, for each machine the following standard tests have been performed:

- no-load test
- locked rotor test
- rated load temperature test
- variable load test.

In the load tests, the motors are connected to a synchronous reluctance machine (constant torque controlled) with regenerative inverter and the braking torque is measured with a torque/speed transducer mounted on the motor shaft. The electrical quantities have been measured using a power-meter, with 800-kHz bandwidth.

Variable load tests and no-load tests have been conducted under sinusoidal supply, according to the methodology prescribed by the IEEE Standard 112-B [15].

The sinusoidal supply is provided by a static sinusoidal power converter with a voltage total harmonic distortion lower than 0.1%.

Experimental Results

The characterization tests results for sinusoidal supply are reported next.

Equivalent Circuit Parameters

By the no-load test and locked rotor tests the motor parameters have been measured.

As expected, on the basis of the material better conductivity, the rotor resistance of the copper cage is lower (4.43 Ω) than the other two (6.167 Ω aluminum—12.3 Ω silumin). The copper rotor leakage reactance is slightly larger (9.29 Ω) than the aluminum (7.12 Ω). This is probably due to the different slot openings in the two motors, introduced by the rotor surface grinding and the technological process of the copper investment casting (see Figure 4).

Torque and Current Performances

In Figure 5, the measured torque-current characteristics for the three motors are shown. The figure illustrates that the rotor material contribution is not consistent for the torque-current performance in the range of the rated current. Obviously, the rotor resistance value strongly influences the torque-speed characteristics in the same range. It is the authors' opinion that the torque-speed curves are not significant for a correct motor comparison because they are strongly influenced by the actual rotor temperature.

Efficiency Comparison

In Figure 6, the measured direct efficiencies evaluated as the ratio between the measured mechanical power at the shaft and the absorbed electrical one are compared for the three prototypes.

The load tests on the three motors have been performed at the same ambient temperature, with the three machines at similar steady-state thermal temperatures, at the rated supply voltage.

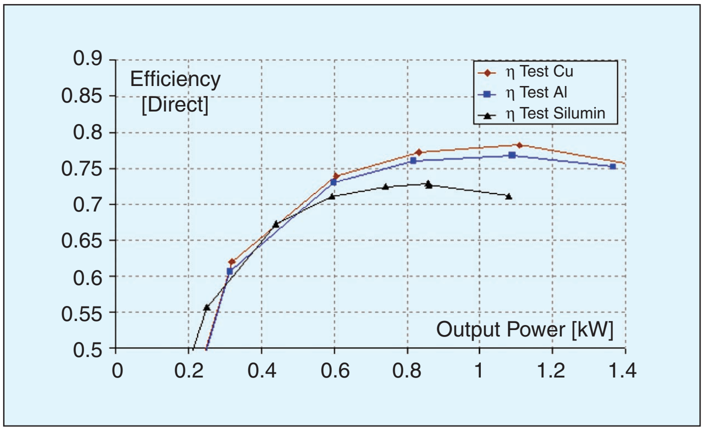

FIGURE 6 – Efficiency of the three motors directly obtained from the test measurements.

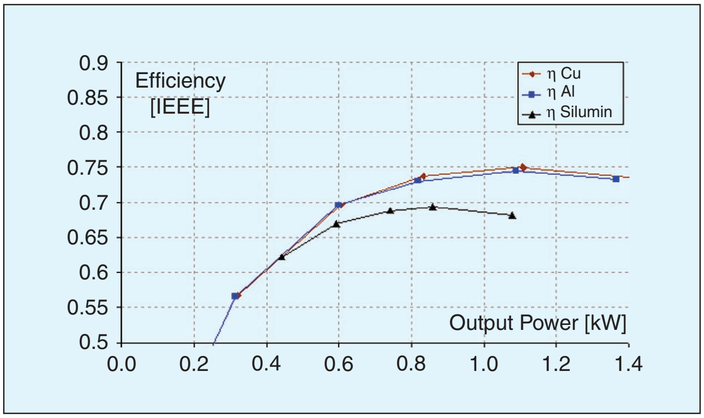

FIGURE 7 – Efficiency of the three motors according to IEEE Standard 112-B.

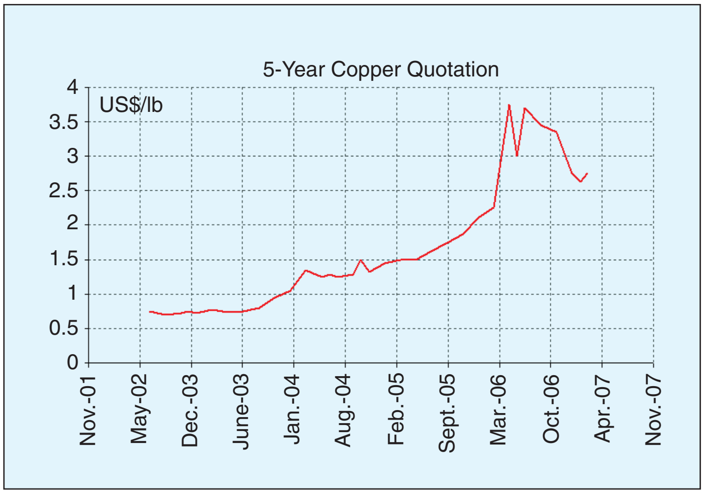

FIGURE 8 – Growth of the copper cost in the last five years.

In Figure 7, the efficiencies evaluated in accordance to the IEEE Standard 112-B [15] are compared.

From the energetic point of view, the copper cage adoption brings an efficiency increase of no more than 1.5% at rated load conditions. This improvement is in line with the results reported in literature for the same motor size [16].

As reported in [16] and [17], a better improvement for copper rotor machines could be obtained with the use of better magnetic materials and introducing a complete redesign of the motor lamination.

As expected, the silumin rotor is the worst one; its efficiency is much lower than the other two, and this is obviously due to its high rotor resistance. Due to the applications of this type of motor, the results are justified.

Final Remarks

As a first attempt, the choice has been adopting the same rotor stack (with the simple substitution of copper in place of aluminum), without taking into account the opportunity of rotor slots redesign. Since only one copper cage rotor had been built, the very expensive copper die-cast process was not feasible. As a consequence, the copper cage prototype has been realized with a process of investment casting. The obtained results proved that the increase of the efficiency is quite small. The starting current values (18.9 A) are similar to those of the aluminum rotor (19.8 A), while the starting torque (9.5 Nm) is significantly lower with respect to the aluminum rotor (14.8 Nm).

Taking into account the copper cost growth in the last five years (Figure 8), the opportunity of its adoption can be discussed, also in relation to the increase of the break-even time due the bigger costs of die systems customized for copper.

The great diffusion of domestic devices and home appliances adopting speed regulators with pulse-width modulation (PWM) inverter supply has also been taken into account. Further analysis is required, particularly for low-power applications [18]–[21]. The comparison of performance and efficiency between sinusoidal and nonsinusoidal supply will be of particular interest.

Conclusions

The use of a copper-squirrel cage in induction motors has been analyzed testing a prototype rated 1.1 kW and comparing the performances with a twin machine with an aluminum cage.

The comparison has been made using torque, efficiency, starting torque, and starting current.

For the considered machine size, the obtained results show that the simple substitution of the aluminum with copper can improve the efficiency of no more than 1.5% at rated load.

Taking into account the copper market cost trend, the use of copper cage increases the break-even time due to the higher cost of copper rotor respect to the aluminum one. For this reason, the discussion about the use of copper cage can be still considered open.

Biographies

Aldo Boglietti received the Laurea degree in electrical engineering from Politecnico di Torino, Italy, in 1981. In 1984, he joined the Department of Electrical Engineering, Politecnico di Torino, as a researcher in electrical machines. He joined the Department of Electrical Engineering in 1984 and has been a full professor since November 2000. His research interests include energetic problems in electrical machines and drives, high-efficiency industrial motors, magnetic materials, and their applications in electrical machines, electrical machine and drive models, and thermal problems in electrical machines. He is the author of approximately 100 papers. He is a Senior Member of the IEEE.

Andrea Cavagnino received the M.Sc. and Ph.D. degrees in electrical engineering from Politecnico di Torino, Italy, in 1995 and 1999, respectively. He is an assistant professor with the Department of Electrical Engineering, Politecnico di Torino. His research interests include electromagnetic design, thermal design, and energetic behaviors of electric machines. He is the author of more than 60 papers published in technical journals and conference proceedings. He is a registered professional engineer in Italy and a Member of the IEEE.

Luca Ferraris received the Laurea degree in electrical engineering from the Politecnico di Torino, Italy in 1992. He joined the Department of Electrical Engineering of the Politecnico di Torino in 1995, and he is now an associate professor of Electrical Machines and Drives. His research interests are the energetic behavior of machines, electrical traction, electromagnetic compatibility, and renewable energies. He has published more than 40 technical papers in conference proceedings and technical journals.

Mario Lazzari received the Laurea degree in electrical engineering from the Politecnico di Torino Italy, in 1969. In 1970, he joined the Department of Electrical Engineering, Politecnico di Torino where he is currently a full professor of electrical machines and electrical drivers. His research interests include the dynamics of electrical machines and electromechanical design, particularly in regard to energetic problems. He is the author of several technical papers on these topics.

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