New Trends in Electrical Machines Technology—Part I

THE electrical machines technology is in permanent evolution even though their basic principles were invented more than 200 years ago. For any amount of power rate, all moving electromechanical devices need design, manufacturing, testing, condition monitoring, and control techniques. This way, industrial electronics is without any doubt a key partner of electrical machines in their real environments with applications of sensors, power converters, digital control circuits, and more. For these reasons, the Guest Editors have proposed to the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Editor-in-Chief this "Special Section on New Trends in Electrical Machines Technology." This Special Section has drawn large interest within the electrical machines and drives community. Therefore, many authors having something to present in these specific topics have submitted their contributions for the peer-review process. The total number of submitted papers was 156 from which only 37 have been accepted for final publication. If necessary, this is giving proof of a strong selection to have a published contribution in this top-level IEEE journal. The professionalism of the selected reviewers together with a meticulous management of all the review processes guarantee that the accepted papers can be considered the state of the art of the proposed topics, providing readers an updated and broad vision of them.

For editorial reasons, this Special Section is being published in two parts, including 18 and 19 accepted papers, respectively. For each part, the Guest Editors grouped the accepted papers in "*hot*" topics. With respect to this first part, two main topics have been defined, namely, the "advanced applications" topic (including ten papers) and the "thermal and efficiency issues" topic (with eight papers).

In advanced applications, several papers deal with transportation applications, spanning from the most conventional electrical vehicles to the recent usage of electrical machines in aerospace technology. This is not a surprise because the research and development concerning electric machines and drives for the transportation electrification has deeply involved the academic and industrial community over the past few years.

In the selected applications, the focus is not merely on the specification fulfillment; however, in many cases, the proposed developments introduce environmentally friendly and energy-efficient solutions. For this reason, the Guest Editors have decided to include in the first part papers dealing with efficiency and thermal modeling issues. It has been made sure that these aspects are of basic importance in the modern electrical machines technology. Going deeply into detail, papers included within this first part will now be briefly summarized and discussed in order to help readers get an overview of the published contributions.

In [1], the design procedure of direct-driven interior permanent-magnet synchronous motors (IPMSMs) for a full-electric four-wheel-drive sports car is presented. Due to the absence of gearboxes between electrical motors and wheels, the maximum accelerating torque is required at low speed, imposing a dedicated design solution of the stator magnetic core. The cross-coupling effects on the direct-axis and the quadrature-axis synchronous inductances have been considered, such as the loss distribution and the efficiency. By means of the experimental validation of a prototype, authors have proved that the designed motor is able to produce its rated torque with the rated current in a very wide speed range. It is interesting to observe that some experimental data have been recorded during a road-legal electric vehicle race.

In [2], a claw-pole double-rotor synchronous machine is proposed as a viable solution to solve the typical power-split problem in hybrid electric vehicles. In this application, the dual-rotor synchronous machine has to make independent the internal combustion engine speed from the speed of the mechanical load providing the power difference between the two mechanical ports. The speed–torque requirements have been determined by theoretical considerations. The constraints imposed by the automotive application have been considered in the machine design procedure, including permanent-magnet rotor configurations, claw-pole dimensions, and the thickness of two air gaps. In this way, the desired high power density with a reduced torque ripple has been obtained. Tests performed on an ad hoc prototype considering a drive cycle with different working conditions has proved the feasibility of using the proposed dual-rotor synchronous machine as a power-split device for hybrid electric vehicles.

In [3], the electromagnetic sizing procedure for an electrical machine to be used in traction applications is discussed, underlining differences with respect to well-known design methodologies adopted for industrial machines. Then, starting with design targets imposed by the application, the authors have optimized a motor prototype for the available volume. The produced machine is a 110-kW 2.5-p.u. starting torque and a maximum 2.5-p.u. speed IPMSM equipped with a tooth-coil stator winding. Even though some manufacturing defects have been reported by authors as the cause of some differences between measured and computed performances, they are confident that the proposed motor topology can be used properly for traction applications.

Digital Object Identifier 10.1109/TIE.2013.2295770

In [4], the discussion concerns aerospace actuator solutions by comparing both pros and cons of the usage of induction motor and permanent-magnet synchronous motor (PMSM) technologies. The analysis is approached by starting with the optimization of two potential candidates and by considering all the typical constraints imposed by aerospace applications, including well-known safety and reliability aspects. The obtainable electromagnetic performances have been compared under the assumption of common heat dissipation for the two machine topologies. In this comparison, interesting considerations about production costs, such as the impact of the adopted materials, have been reported. Prototypes of the optimized design machine solutions have been produced and tested in order to validate the research activity. The study proves that both induction machine and PMSM are suitable for aerospace actuation. However, they are characterized by complementary advantages in terms of fault tolerance and power density behaviors.

In [5], an ultrahigh-speed electrical machine drive has been presented. The reported design considerations are certainly of interest because many new emerging applications require very-high-speed electrical machines. Just to cite some examples, it is possible to think of the milling spindles, ultracentrifuges, and turbo compressor systems. An important problem to be solved in ultrahigh-speed motors is related to mechanical aspects linked to the bearing system. To overcome the limitations of previously presented high-speed magnetic bearings when the speed is above 100 000 r/min, a slotless self-bearing PMSM prototype has been presented. Specific behaviors of the proposed motor design are the ironless structure for the rotor and the slotless for the stator side allowing ultrahigh-speed operations and very high frequency bandwidth of bearing actuators. The drive has been assembled and tested verifying its functionality up to speeds of 505 000 r/min. To reach these speed values, the adopted switching frequency was 1 MHz. It is interesting to observe that due to the magnetic bearing system employed, the proposed motor drive should be operated in very clean environments only.

In [6], the focus is on a hybrid reluctance motor drive by investigating its potentialities in terms of fault tolerance, efficiency, and specific power density with respect to other more conventional and well-established switched reluctance motor (SRM) topologies. The proposed hybrid reluctance machine is characterized by a quite conventional rotor structure having five salient poles but without windings, permanent magnets, or a squirrel cage while the stator is assembled using three separated concentrated equivalent windings. Each electromagnet is a motor phase, and it uses a permanent magnet placed between the two stator pole tips. The machine is initially designed by means of an analytical approach. Then, the design is validated by using numerical simulations and measurements performed on a prototype. In addition, measured machine performances have been compared with the performances of SRM drives having a similar size. On the basis of the reported comparison, the authors conclude that the proposed solution is able to provide higher power and efficiency than a conventional SRM, including the advantage of having a very low cogging torque.

In [7], a linear PMSM with a cylindrical structure and a transverse flux-type behavior is proposed, designed, and built. An interesting aspect of the proposed solution is that the stator core is produced by using magnetic laminations with conventional shapes for rotating electrical machines and overcoming the difficulties in the production of complex 3-D magnetic structures typically required for the transverse flux-type topology. The authors introduced the proposed magnetic core solution and the related structural advantages. Then, they investigated, by using both analytical and numerical approaches, the obtainable thrust density and the cogging force requirement. Since a transverse flux-type linear motor is studied, the numerical simulation required a 3-D finite-element method in order to consider the side effects. By means of an initial test campaign performed on a prototype, the authors have collected enough data to validate the proposed solutions in particular from the structural point of view. In the last part of the paper, a comparison among performances measured for the prototype and four other commercial motors is reported in terms of different thrust density indexes, proving that the designed prototype is able to provide performances very close to the latest linear motor technology.

In [8], an axial magnetic coupling comprised by two-faced magnetic discs equipped with rare-earth permanent magnets is proposed to transmit the torque from a prime mover to a mechanical load without any contact. This type of coupling is particularly interesting for applications requiring electrical insulation between the motor and the load. The authors have developed a simplified analytical model to compute both steady-state and transient operations of the proposed coupling device. By using the reported equations, it is possible to evaluate the pull-out torque and the torsional stiffness when the geometrical dimensions are known. In the analysis, both radial and angular displacement effects on the coupling performances have been also taken into account. The 2-D analytical models have been calibrated by means of 3-D finite-element simulations and by introducing a suitable corrective coefficient. Finally, the proposed model is validated through experiments conducted on a laboratory prototype. During tests, the predicted overload self-protection of the magnetic coupling was also verified. The transient analysis tests have put in evidence that during the start-up, the low torsional stiffness of the magnetic coupling introduces oscillations between the two discs. This behavior is of basic importance in high dynamic applications, and it should be carefully taken into account.

In [9], an interesting rotating piezoelectric actuator able to produce up to 2.5 Nm at the maximum speed of 85 r/min is presented. In the proposed solution, a ring is maintained in rotation by using both the third and fourth bending vibration modes of the actuator main body containing the bolt-clamped transducer. In fact, due to frictional forces and a suitable preload in the axial direction, the elliptical rotation of two lateral “horns” are converted in the rotation of the output shaft connected to the ring. The third vibration mode is mainly used to produce the rotation, whereas the fourth one is used to overcome the preload force. In the paper, the authors have proposed a particular shape of “horns” in order to obtain very close values for the resonance frequency of the two vibration modes of interest. Finite-element method simulations based on the modal analysis have been performed to define the optimal shape of actuator parts. An actuator prototype has been produced and tested allowing the authors to prove the feasibility of the concept and the validation of the vibration analysis.

The last paper of "advanced applications" is related to a study on the magnetic lamination material quality effects on the noise emission in transformer cores [10]. The emitted noise is discussed and analyzed in terms of Maxwell's forces between laminations, particularly in joints, and general magnetostriction effects in the magnetic material. In order to segregate these two phenomena, the authors have proposed two annular sample structures suitable for the analysis of the different vibration sources. In addition, different material anisotropies have been considered in order to correlate their magnetic behavior to vibration components. The impact of the supply voltage harmonics has been also taken into account together with the local saturation of the magnetic circuit. On the basis of the reported experimental results, the authors have deeply analyzed vibration mechanisms of transformer magnetic cores, thus concluding that from the point of view of vibrations, both Maxwell's forces and magnetostriction effects play a similar role in terms of magnitude. In addition, local saturations, such as nonsinusoidal supply waveforms, lead to both significant vibrations and noise emissions.

The second topic of Part I of this Special Section is the thermal modeling and efficiency aspects of electrical machines. It starts with [11], in which one electrical machine cooling system design is approached by considering both numerical computational fluid dynamic simulations and lumped-parameter models. The main target is to obtain an accurate estimation of the cooling system performances by using reduced computational resources. From this point of view, the authors report several methods to design and to simulate the cooling system used in electrical machines by means of the computational fluid dynamic methodology, considering, for example, both fan characteristics and computation of local heat transfer coefficients along the cooling system. Then, these data can be used in lumped-parameter models to reduce the computational time. In order to prove the efficiency of the proposed methodology and of the different design tools, a real case has been studied, and the results have been validated using a 10-kW motor prototype. The reference application is a motor for an elevator. For the considered case study, the authors stated that the adopted high-efficiency air-forced cooling system is able to appreciably reduce average temperatures in windings and magnets.

In [12], the cooling system of a double-rotor axial flux motor with a sandwiched stator is analyzed again by using computational fluid dynamic simulations. In particular, the authors considered three cooling possibilities for a 25-kW 100-r/min axial flux prototype, in terms of different configurations for axial and radial air inlet ducts. The effects of these configurations on the convective heat transfer coefficients on both stator and rotor surfaces facing the air gap have been investigated. The reported results should help designers improve the ventilation system of such type of machine. The loss distributions have been carefully discussed and determined by means of a detailed electromagnetic analysis, and they have been considered as input for the fluid dynamic model. Conjugate heat transfer analyses have been performed to consider both heat transfer phenomena on the surfaces and the presence of the air flow. Due to numerical simulations, the authors also validated typical heat transfer correlations used for fluid dynamic analyses of axial flux machines.

In [13], the focus is on transient thermal analysis of a PMSM for aerospace actuators to be used with high ambient temperatures. As additional constraints related to the selected application such as heavy overload operations, an insufficient convective heat transfer has been considered. Due to a high integration level of actuator components, the unsymmetrical geometry of the motor housing can be only studied by using a 3-D finite-element method. The authors assumed that for the PMSM, convective heat transfer phenomena were negligible. This way, the time-consuming computational fluid dynamic analysis is not necessary. The loss components for the transient thermal analysis have been computed by using conventional multislice bidimensional finite-element electromagnetic simulations. Due to a particular technique implemented in the proposed thermal study, the impact of the unsymmetrical housing geometry on the cooling system is discussed. Even though the implementation of this technique requires parallel computing resources, a reasonable simulation time for the complete thermal transient analysis has been achieved.

In [14], the authors propose the accurate determination of winding Joule losses under *ac* current supply by taking into account the different scale effects of the temperature on both *ac* and *dc* components of the winding losses. In other words, for thermal modeling purposes, temperature-dependent values for the ratio of the *ac* and *dc* resistance are proposed together with a methodology to scale the *ac* winding loss component as a function of the temperature. The problem has been approached by using both 3-D finite-element thermal analyses, and an interesting experimental test activity performed on a complete wound stator and on a simple winding "motorette." Some winding-type arrangements have been considered and discussed reporting challenges to obtain accurate results both with a numerical model and experiments. The authors observed that the usage of the "motorette," instead of the complete stator assembly, might lead to nonrepresentative results even if the real accuracy depends on the winding structure. For example, *ac* winding losses can be reasonably estimated with the "motorette" system for single-layer concentrated windings only.

In [15], an experimental setup to directly measure total losses of a PMSM under full-load operations is reported. The proposed method requires back-to-back connection of shafts of two twin electrical machines. The two machines are supplied by a single power converter, and they are operated as a motor and a generator, respectively. The mechanical joint employed between the two machines allows changing the relative angular position between the two rotors. In this way, by changing the coupling angle, it is possible to regulate the load torque of the two machines. The common shaft speed is controlled by the converter in order to have the same absorbed current value in the two machines. In this condition, even if there is a power exchange between their electrical and mechanical terminals, the converter has to provide the total losses to the whole system. In other words, the two machines can be thought of as an *equivalent* one operated at no-load conditions even if each one is really loaded with the desired torque and speed. The measurement procedure has been initially simulated and validated by experiments performed on two PMSMs. Finally, the authors discuss the possibility of extending the methodology for salient-pole machines with the same modes of operation.

In addition, [16] deals with a direct loss measurement technique based on the calorimetric method. The target is the accurate power loss measurement of high-efficiency electric drives. In fact, for such kinds of apparatus, it could be difficult to measure the total losses by the conventional input–output method. The authors describe the experimental calorimetric test-rig and the required data processing methodology for loss measurements up to 2 kW. For modern solutions, this maximum measurable total loss value means a maximum rated power around 110 kVA for the electronic power converter. The proposed calorimetric system is mechanically quite simple, and it can be assembled at the measurement site. With respect to the balance type calorimeter data processing, the authors considered mass flow corrections, the determination of stable thermal conditions, and a methodology to increase the repeatability and the accuracy of obtained results. Due to the proposed methodologies, the described calorimetric concept reached a measurement uncertainty of 0.4%, which has been verified by laboratory tests on commercial electrical drives.

In [17], line-start PMSMs are discussed and analyzed as a viable and interesting solution to respect the highest efficiency class prescribed by the present-day international standards. This motor type is now a commercial product at least for a rated power of up to 7.5 kW. The main aim of this study is the determination of efficiency of a 4-kW three-phase line-start PMSM, taking into account effects of the operative temperature on both machine performances and loss components. The thermal problem has been solved by using lumped-parameter thermal-network modeling, while the efficiency has been preliminary computed by using a finite-element analysis and then directly measured on the motor. It is important to remark that the indirect method for the efficiency determination, prescribed by the IEC60034-2-1 standard and requiring the segregation of loss contributions, cannot be adopted for such type of motors. For this reason, the authors used numerical simulations to separate losses. From the thermal modeling point of view, the authors stated that it can be easily derived by the induction motor thermal model by making few marginal changes.

The last paper deals with stray losses inside structural parts of large power transformers such as flange–bolt elements, and possible solutions to mitigate this problem have been proposed [18]. These stray load losses usually lead to hot spots that can be visualized through a thermal mapping test. The authors studied an overheating effect noted in bolts used to lock the cover of the tank of a 420-MVA three-phase transformer. As a viable solution to reduce stray losses in the flange–bolt regions, the authors suggest the use of copper links for each bolt in order to electrically connect the tank frame to the cover. The practicability of the proposed solution has been verified both by numerical finite-element simulations of the geometry of interest and through experiments.

Acknowledgment

The Guest Editors take this opportunity to thank all the authors that submitted their valuable contributions to the journal and to express their gratitude to all of the anonymous reviewers for spending their time and expertise in the review process. In addition, the Guest Editors dedicate a special acknowledgement to the past and present Editors-in-Chief of the IEEE Transactions on Industrial Electronics, Prof. M.-Y. Chow and Prof. C. Cecati, respectively, and to the Journal Administrator, Mrs. S. McLain, for their indispensable support during this Special Section management.

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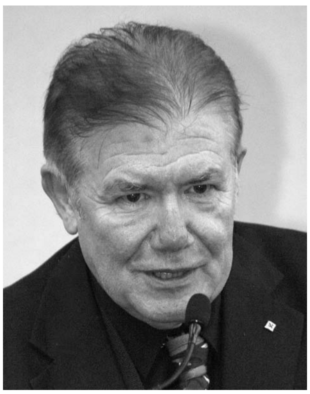

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