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Electrical Machine Topologies: Hottest Topics in the Electrical Machine Research Community

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Abstract:

In this article, the state of the art in electrical machine design is outlined underlining the problems and challenges to be solved by engineers. As highlighted in this article, even if electrical machine design is often considered a mature issue from the technical and technological point of view, every year, new progresses and steps forward are made. New and more sophisticated design tools can be used worldwide, and innovative manufacturing processes, new insulation materials, and higher performance magnetic materials are available on the market. In addition, the evolution of the hardware used in digital control and new powerful power electronic devices represents a constant stimulus to improve the performance of electrical machines and reintroduce electrical machine structures that were not adopted in the past due to technological and technical constraints. As shown in this article, electrical machine design is an evergreen topic, and its importance is rising more each year under the push of more energy-saving requirements and higher-efficiency systems for electromechanical conversion. A green world will not be possible without electrical machines.

Electrical machines are generating and using most of the electrical energy converted worldwide from fossil fuels or renewable sources. An optimized electrical machine means not only less input energy used but also higher electromechanical energy available as output. This is translated into getting more with less and having an impact on the total amount of greenhouse gases released into the atmosphere, thus mitigating global warming. Benefiting from the latest developments in the electrical machine field are various industries such as electric propulsion [new electric vehicles (EVs) and plug-in hybrid EVs (HEVs)], renewable energy harvesting, consumer applications, and military and aerospace products. This article brings together the contributions from several authors working in academia and industrial research and development centers and comprises a collection of short analyses dedicated to the hottest topics in the electrical machine research community. The article focuses on special and difficult problems to be solved in the design process of the most important electrical machine topologies. The topics discussed cover new machine topologies such as fractional slot winding motors and synchronous reluctance motors; electromagnetic, mechanical, and thermal problems in permanent magnet (PM) machines design; operation of high-speed machines and high-power turbo generators; noise and vibration reduction in switched reluctance motors (SRMs) for automotive applications; high-efficiency induction machines (IMs) configurations compatible with the new international standard and a comprehensive analysis of universal motors (UMs).

Illustrated with significant experimental data and images of various machine configurations, this article is bringing into the spotlight the less well-known details related to the design, manufacturing, and operation processes of electric machinery. A fresh view on the systems in which the electrical machines are integrated is the main common factor in this collective and complex work.

Fractional-Slot Concentrated-Winding Machines

Fractional-slot concentrated-winding (FSCW) synchronous PM machines have been gaining a lot of interest over the last few years. This is mainly because of the several advantages that this type of windings provides, which include high-power density, high efficiency, short end turns, and high slot fill factor, especially when coupled with segmented stator structures, low cogging torque, flux-weakening capability, and fault tolerance.

In [1] and [2], a comprehensive review of what has been published in the literature as well as a detailed discussion of the opportunities and challenges of FSCW is presented. Since then, a significant amount of work has been done to address some of the key challenges associated with FSCW and expand the application of FSCW to various types of electrical machines. It has been established in the literature that one of the key challenges of using FSCW configurations is the significant rotor losses (including magnet losses, rotor core losses, and sleeve losses in the case of conductive sleeves), especially at high speeds due to the various sub- and superspace harmonic components inherent to such winding configurations that are not in synchronism with the rotor.

Some recent key articles address the various aspects of rotor losses in PM synchronous machines using FSCW. A few of these articles address the end effects in terms of losses on both the stator and rotor sides. Some articles address the ac losses in the stator windings, and others address ways to reduce the rotor losses, but in most cases, this is at the expense of making the winding configuration relatively more complicated (winding will be somewhere in between true FSCW and distributed windings). Some articles address four-layer windings (as shown in Figure 1), while others address the concept of stator shift for harmonic cancellation [3]. In addition, there are articles addressing introducing low-permeability paths in the stator that reduce the impact of the subharmonic(s) without affecting the synchronous component (see Figure 2) [4]. Although the initial focus has been on FSCW surface PM (SPM) machines, a lot of recent activity has been focused on FSCW interior PM (IPM) machines. Several articles present analysis models and techniques to analyze FSCW IPM machines and how to segregate the various torque components. Other articles provide comparisons of FSCW SPM and IPM machines. Some papers focus on multiphase FSCW PM machines, while others address axial-flux FSCW PM machines as well.

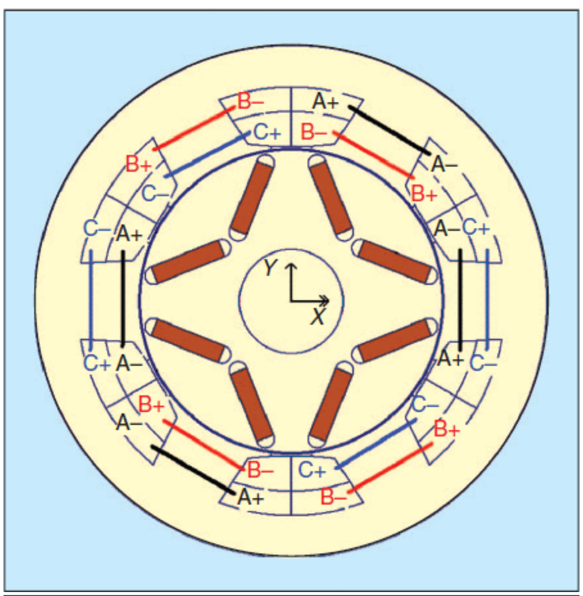

Figure 1 The four-layer winding.

There have been some attempts to evaluate FSCW in IMs. Earlier studies showed that FSCW squirrel-cage IM is not an appealing option because almost all of the harmonics from the stator side get reflected on the rotor side, causing high losses, torque ripple, and low efficiency. Recent papers have focused on wound-rotor FSCW IM. Although these seem to be more promising, especially in terms of reducing torque ripple and the impact of the stator harmonics on the rotor, there are still several challenges to address when it comes to FSCW IM. In general, the main focus so far has been on radial-flux FSCW PM machines. There is a growing interest in other types of PM machines equipped with FSCW. One key type that has been gaining a lot of interest is flux-switching machines. Different variants with PM, field-winding, and hybrid excitation have been studied. There has been increased activity in the area of sensorless control of FSCW PM machines. Parasitic effects, such as noise, vibration, unbalanced magnetic forces, and torque ripple, continue to be active areas of research in FSCW PM machines. These parasitic effects can potentially be higher in FSCW PM machines because of the additional harmonic contents. In addition to research activities, more commercial applications continue to adopt FSCW PM machines. Two good examples are the Prius 2010 generator (Figure 3) [5] and Chevy Volt's Motor A (Figure 4) [6].

Induction Machines

Currently, the research focused on IMs is expanding very quickly because of two main issues: the high PM cost and the efficiency increase mandated by new regulations imposed in some countries. In particular, the enactment of minimum efficiency performance standards (MEPS) around the globe has renewed interest in high-efficiency design and manufacturing of IMs for industrial applications. Efficiency regulation started in the United States in 1992 with the Energy Policy and Conservation Act (EPACT), which mandated MEPS for certain types of industrial induction motors sold in the United States. Since then, MEPS have been under constant review for stringency, and the scope of coverage has also increased to cover previously excluded motors. Following the U.S. policy, several countries have put into effect or have enacted MEPS for industrial induction motors. For example, in the European Union, the efficiency class named *IE2* has been in effect since June 2011 [7], [8]. Beginning in January 2015, motors rated 7.5–375 kW are expected to meet the IE3 or IE2 level if fitted with a variable–frequency drive (VFD), and in 2017, motors rated 0.75–375 kW are expected to meet the IE3 or IE2 level if fitted with a VFD. For comparison purposes, the IE3 and IE2 efficiency levels are equivalent to the National Electrical Manufacturers Association (NEMA) Premium and EPACT efficiency levels found in NEMA MG-1 Table 12-12 and Table 12-11, respectively [9]. Currently, there are MEPS in at least a dozen countries, including Canada, China, Korea, Brazil, Chile, Australia, and New Zealand.

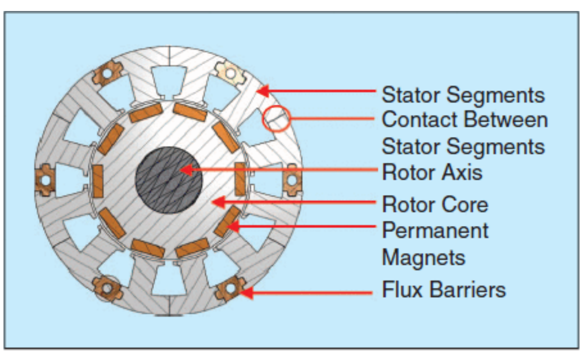

Figure 2 The geometry of the proposed PM design with flux barriers.

At the moment, several other countries are contemplating adopting MEPS. While countries typically start with relatively lower efficiency levels and gradually phase in higher efficiency requirements, the early adopters of MEPS, such as the United States and Canada, have reached the high end of the motor efficiency spectrum and are at the point where a further increase in motor efficiency is not trivial. Industry advocates have called for a look at system efficiency rather than motor efficiency. Other segments of the industry have claimed that higher efficiencies are possible using VFD controls. Consequently, the mandatory efficiency requirements impose on manufacturers the burden of designing high-efficiency machines for business as well as regulatory reasons, with the added concern that the efficiency regulations may be subjected to enforcement with severe consequences to manufacturers. The subject of high-efficiency machine design is therefore currently of extreme importance. Furthermore, the skills and experience required to design IMs are increasingly challenged by the tightening of efficiency standards. For these reasons, the authors presented in [7] a high-level overview of some of the issues and challenges relating to high-efficiency IM design for industrial applications. The discussion started with a brief overview of the classical approach to machine design; the authors are convinced that knowledge of the basic equations and physical behavior of machines (mainly scaling, thermal, and magnetic design considerations) enables designers to correctly approach the design problem and, in many cases, find the right solution. A commentary on contemporary design using finite-element analysis and design optimization techniques followed the classical design. Summarizing the pros and cons of such powerful numerical methods compared to analytical design techniques, it has been suggested that an accurate analytical approach can satisfy the designer's initial needs and the use of the finite-element method (FEM) can be dedicated to design refinements or analyze specific performance problems typically related to saturation phenomena.

> Emerging advanced motor technologies may positively or negatively impact the future direction of the induction motor technology.

The opportunities available to the designer for improving the efficiency of industrial induction motors were introduced. In this case, attention was focused on the segregation and quantification of the different loss contributions and the impact of magnetic lamination grades on the iron losses and efficiency. Alternative production technologies (such as the adoption of die-cast copper cage rotors, as shown in Figure 5) and some results of stack lengthening investigations to achieve incremental efficiency improvements were also discussed.

In the final section of [7], the authors highlighted some challenges the manufacturers face in the design and manufacture of high-efficiency IMs. Some of these challenges are nowadays passionately discussed in industry. The first one is obviously of economic nature because a discussion of efficiency improvement without cost considerations is inevitably skewed. Also, some technical challenges tend to pose limitations on the pursuit of higher efficiency limits (e.g., specifications for locked rotor current and locked rotor torque in industry standards). Finally, emerging advanced motor technologies [such as synchronous reluctance, transverse flux, switched-reluctance (SR), and IPM machines] may positively or negatively impact the future direction of the induction motor technology. This is particularly true when the induction motors are supplied by an inverter and their efficiency is highly dependent on the control techniques employed [10].

Permanent Magnet Synchronous Machines

The brushless PM (BPM) machines represent the electrical machinery topology with the highest torque density. In the last three decades, the development and manufacturing of BPMs have seen a significant amount of interest from various industrial fields, including EVs and HEVs, renewable energy generation, aerospace, and home appliances. Being driven by the rare-earth elements extraction and processing, high-energy magnets are used widely in BPM manufacturing. Theoretically seen as an everlasting source of energy within the electrical machine system, the PM materials may be irreversibly demagnetized and, hence, losing energy due to the thermal stress and high faulty electrical loads. There are two main high-energy magnet materials currently employed, NdFeB and SmCo types. The thermal stress on the PMs is created by the losses dissipated in the machine [11]. One can thermally protect the PMs by mitigating local losses, as in the case of induced eddy-current losses in the magnet blocks, or via an efficient cooling system. Depending on the application, cooling systems with natural convection (totally enclosed, not ventilated), forced convection (air or liquid cooling), or radiation cooling (as used in the case of BPMs operating in a vacuum environment) can be employed. The thermal analysis of a BPM motor is a three-dimensional problem with complex heat transfer phenomena such as solving heat transfer through complex composite components like the wound slot, temperature drop across interfaces between components, and complex turbulent air flow within the end caps around the end winding that includes rotational effects.

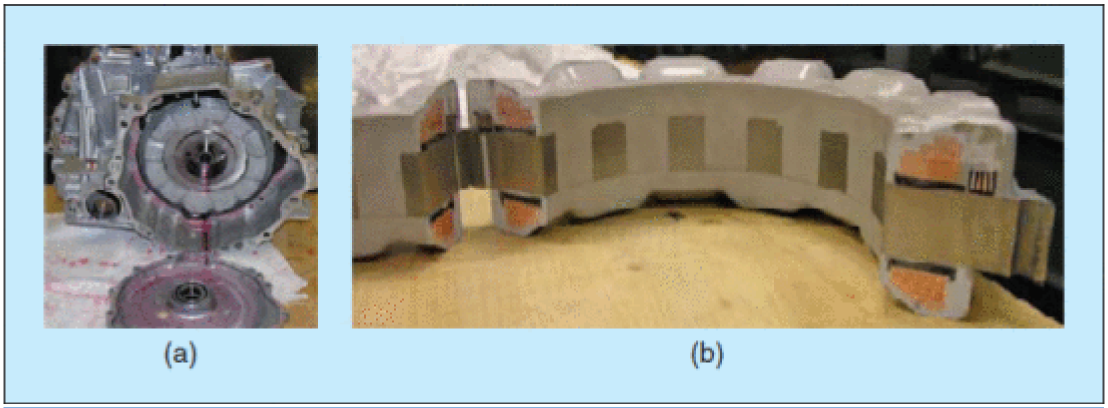

Figure 3 (a) The Prius 2010 FSCW PM generator. (b) A cutout of the Prius 2010 FSCW PM generator stator winding [1].

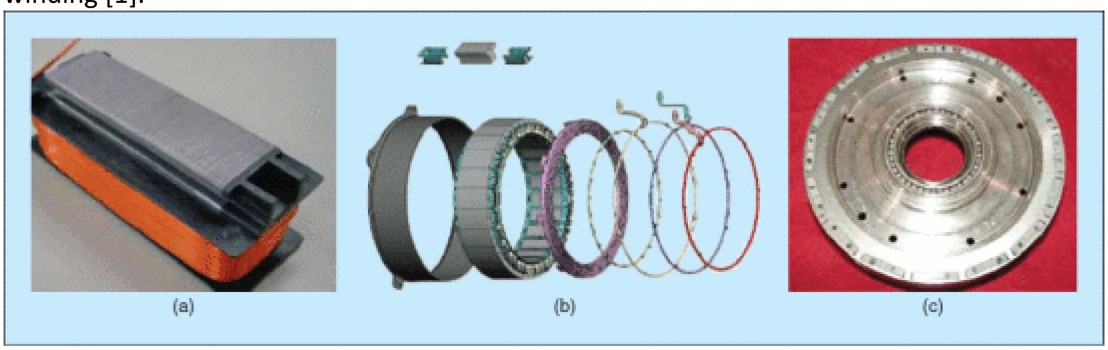

Figure 4 (a) The one-tooth assembly of Chevy Volt's Motor A. (b) Chevy Volt's Motor A assembly diagram. (c) Chevy Volt's Motor A rotor with the end ring removed to show the magnet arrangement [1].

> The mitigation of magnet losses is usually achieved using magnet segmentation along the magnetization lines in the magnet cross-section and/or axially.

Generally, the main loss component in a BPM is the stator winding copper loss. These losses are a function of current and stator winding resistance. In BPMs, the temperature affects both the required current for the motor to deliver an imposed output torque and the electrical resistivity of the material used to build the stator winding. Thus, a 50 °C rise gives a 20% increase in resistance, and a 140 °C rise gives a 55% increase in resistance. A more difficult phenomenon to estimate is the increased stator winding resistance due to the frequency or ac losses, i.e., the skin effect and the proximity effect [12]. BPMs are often wound with coils spanning only one tooth. In high-speed applications, parallel paths may be needed. For a high-current machine, these parallel paths may be within the coil itself and are often referred to as *strands-in-hand* or *multiple bundle strands*. However, parallel paths for coil turns located in the slot top and bottom will experience a proximity effect since there will be some flux linkage between them due to leakage. The strands-in-hand and parallel paths are used in BPMs to mitigate the proximity losses. Alternative solutions for mitigating the proximity losses have been proposed such as twisted wires, a winding arrangement with flat rectangular wire placed along the slot leakage-flux lines, and a reduced slot fill factor with copper wires pushed within the slots further away from the slot opening region. A successful electrical machine design optimization process requires the accurate prediction of iron losses. Power electronic converters, which are nowadays widely used to supply electric motors in variable speed systems, have a nonsinusoidal pulse width modulation (PWM) voltage waveform that causes increased losses in the lamination steel [13]. The material properties are changing with the magnetic load and frequency [14].

In BPMs, the iron losses are created by the variation in the magnetic field due to the PM rotation and the pulsations in the stator winding magnetic field. The highest iron loss density in a BPM will occur on the stator-laminated teeth region and the rotor surface. These losses will generate heat that has to be extracted or dissipated. In a BPM, the magnets are located either in the vicinity of the stator heat source, as in surface-mounted BPMs, or they can be better thermally protected by embedding them in the rotor lamination pack. High-energy PMs (NdFeB and SmCo) are also characterized by locally generated losses. These losses are created by the eddy currents induced by dips in the air gap flux density due to slotting and by current time and space harmonics. The latter cause is more significant in BPM with dc commutation, i.e., square wave currents, as compared to the synchronous BPM where the currents have a very low total harmonic distortion (THD). Depending on the number of slots/pole and the winding configuration, the magnet losses may be significant even for low-speed applications. Compared to low-energy magnets such as ferrite, the rare-earth magnets have a much lower electrical resistivity. NdFeB and SmCo magnets have an electrical resistivity approximately 100 times and 40 times, respectively, higher than that of copper. Table 1 summarizes the electrical resistivity values for some relevant materials used to manufacture electrical machines.

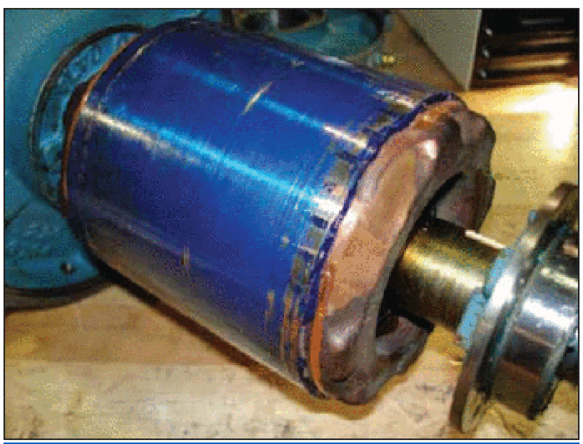

Figure 5 The die-cast copper rotor for an induction motor.

Table 1 – ELECTRICAL RESISTIVITY VALUES (ΩM).

Material	Value
Copper	1.724×10^{-8}
Iron	10×10^{-8}
Aluminum	2.8×10^{-8}
Sm-Co 1-5 alloys	50×10^{-8}
Sm-Co 2/1 alloys	90×10^{-8}
NdFeB-sintered	160×10^{-8}
NdFeB-bonded	$14{,}000 \times 10^{-8}$
Ferrite	10^5

Practically, analyzing various magnets data only in sintered NdFeB and SmCo materials, the locally induced eddy-current loss may be significant, requiring a technical solution to minimize them a better cooling system for heat extraction. The mitigation of magnet losses is usually achieved using magnet segmentation along the magnetization lines in the magnet cross-section and/or axially. Typically, for a 100 °C temperature rise, NdFeB magnets will lose 11% of the magnetic flux, while SmCo magnets will lose 3% and ferrite magnets will lose 20%. Magnets are usually isolated from the main heat sources located on the opposite armature (stator). The thermal behavior of BPMs can be analyzed using thermal lumped circuit models that are similar to electrical networks and numerical methods such as finite-element and computational fluid dynamics methods. Heat can be extracted through conduction, convection (natural and forced), and radiation [15]. Forced convection can be achieved using configurations of channels, ducts, water jackets, spray cooling, and axle cooling. Figure 6 shows several housing configurations for the cooling systems of BPMs.

The main difficulty in setting up an accurate thermal model for BPMs is in circuit components that are influenced by manufacturing uncertainties, such as air in the winding impregnation, how good a fit there is between the stator lamination and housing. Measurements have been made on many machines in the past to set a set of default parameters for an average machine. Calibration using test can be used to give better absolute accuracy. The process of calibration and comparing parameters with default values gives an indication of how well the machine is constructed.

Synchronous Reluctance Machines

The synchronous reluctance (REL) motor with a transversally laminated rotor was proposed several years ago, but it is becoming more and more attractive thanks to the growth of knowledge about it, its low cost in comparison with other solutions, and the improvement of the control systems [16]. A sample of an REL rotor lamination is shown in Figure 7(a). The REL motor is becoming a competitor in applications requiring high dynamic density, high torque density, and fault-tolerant capability. A PM can be inset in each rotor flux barrier, as in Figure 7(b). The resulting configuration is called a *PM-assisted synchronous reluctance machine* [17]. The aim of adopting a PM is manifold: to saturate the rotor iron bridges, increase the motor torque, and increase the power factor. In fact, the REL machine is characterized by a very low power factor, which mainly depends on the saliency ratio, ξ. It reaches about 0.8 with $\xi \approx 10$ 10.

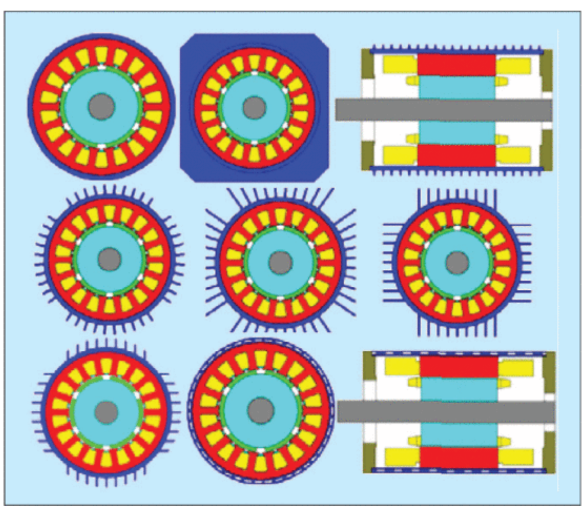

Figure 6 The housing configurations for BPM cooling systems.

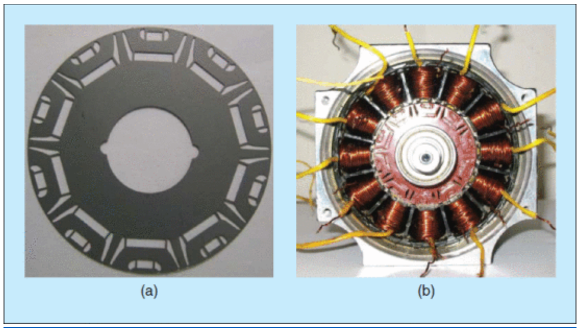

Figure 7 (a) The rotor lamination of a ten-pole synchronous REL machine. (b) The prototype of a fractional 12-slot PM-assisted synchronous REL machine.

The d- and q-axis flux linkages are expressed as $\lambda_d = L_d i_d$ and $\lambda_q = L_q i_q - L_m$ respectively, where L_d and L_q are the apparent inductances, L_m is the flux linkage due to the PM, and i_d and i_q are the stator currents. The electromagnetic torque depends on the cross product between the flux linkages and the currents, i.e., $(\lambda_d i_q - \lambda_q i_d)$ and the variation of the magnetic coenergy with the rotor position ϑ_{m} with ϑ_{m} $\mathrm{i_d}$, and $\mathrm{i_q}$ as state variables. However, the average value of the variation of the magnetic coenergy during a rotor turn is zero; therefore, this term is generally omitted when referring to the average torque.

Thanks to the rotor anisotropy, the machine is proper to be sensorless controlled by means of the high-frequency signal injection sensorless technique. When the motor is operating in the generic (I_d, I_q) working point, the high-frequency current trajectory is an ellipse. The amplitude and displacement of the major and minor axes of such an ellipse are strictly dependent on the differential inductances of the motor: L_{dh}, L_{qh} and L_{dqh} in that particular operating point (I_d, I_q) The detectable high-frequency saliency can be defined as the ratio between the current oscillation along the major and the minor axes, that is, $\xi_{\mathrm{h}} = \Delta \mathrm{I}_{max}/\Delta \mathrm{I}_{min}$ The same ratio can be expressed as a function of the inductances $L_{\mathrm{avg}} = (L_{dh} + L_{qh})/2$ and $L_{\mathrm{dif}} = (L_{qh} + L_{dh})/2$ that is, the ratio depends on the machine geometry configurations. The cross-saturation inductance, L_{dqh} causes an angular displacement of the ellipse, which has to be compensated in the control.

A common drawback of the REL and IPM machines is their high torque ripple, which is due to the interaction between the spatial harmonics of electrical loading and the rotor anisotropy causing a torque ripple that is intolerable in many applications. There are different techniques to minimize the torque ripple, including rotor skewing (or step-skewing using PMs), which is a suitable choice for the number of flux-barriers, and flux-barriers shifting, where the torque harmonics are compensated by the rotor asymmetry (getting “Romeo and Juliet” motor, or “Machaon” motor as called by the author) [18].

Fractional-slot winding machines, especially with nonoverlapped coils, are used to take advantage of the short coil, which means a reduction of the copper weight and cost, as shown in Figure 7(b) [19]. In fractional-slot winding machines, the reluctance torque component is reduced even though two or three flux barriers per pole are adopted. The dominant torque component is due to the PM flux. When the anisotropic rotor is adopted within a fractional-slot machine, achieving a smooth torque is a challenge. A two-step optimization has been proposed to reduce the torque ripple of REL and IPM motors with fractional-slot winding. At first, the winding is optimized, adopting a multilayer structure so that the harmonic content in the magnetomotive force (MMF) is reduced. However, the winding arrangement has no effect on the slot harmonics, whose order is $\nu_{\mathrm{sh}} = kQ \pm p$ where k is an integer. Then, as the second step of the optimization procedure, an accurate analysis of the rotor geometry is carried out. An analytical model of the fractional-slot IPM machine is adopted to optimize the flux-barrier angles, which mainly affects the torque ripple associated to the slot harmonics. A torque ripple of about 5% has been achieved.

SR Machines

SRMs are finding interesting applications in EVs and HEVs [20], [21]. To ensure good performance of a propulsion system in an EV or an HEV, the electric machine must maintain high efficiency over a wide range of speed and torque, high power density, high torque density, and an acceptable cost. Research has shown that SRMs are capable of delivering these performance requirements. They are magnet free, winding free in the rotor, and very simple to manufacture. These features enable the implementation of SRMs in high-temperature environments such as a packaging inside a vehicle transmission.

The noise, vibration, and harshness (NVH) characteristics of a vehicle are among its major acceptance criteria in terms of overall quality. Compared to an internal combustion engine (ICE), an electric machine emits significantly lower sound pressure levels. Although EVs and HEVs are always considerably quieter than conventional ICE-powered vehicles, their interior noise is characterized by high-frequency noise tones, which can be subjectively perceived as unpleasant and annoying. Indeed, the acoustic noise spectrum of an electric machine contains high-frequency pure tones, higher than 1 kHz, while ICE noise spectra are typically of broadband nature and confined below 1 kHz. As for SRMs, they are widely known to be noisier than other machine technologies. Their poor sound quality constitutes a major drawback for their penetration in the automotive industry. In addition, we have observed over years of research that smaller- and bigger-size SRMs exhibit similar acoustic noise signatures, especially when operating at full load [22].

An SR machine was designed using some key features with the aim of reducing its NVH as a challenge to a BPM machine in an electric brake for automotive applications [see Figure 8(a) and (b)]. Both motors were successfully designed to fit all the required tasks using the same space envelope. The acoustic and performance goals were well achieved, as revealed by the measured sound pressure data at a same operating point [see Figure 8(c) and (d)]. Under the same full load, the SRM and BPM motor emitted total sound pressure levels equal to 47.7 and 47.1 dBA, respectively. According to a selected sample of listeners, the two motors were similar in loudness, which was in agreement with the psychoacoustics theory. However, the SR motor produced more high-frequency pure tones [see Figure 5(d)] that were prominent and perceived as unpleasant by the jury. The spectral content of BPM noise was limited to 8 kHz, whereas that of the SRM was spread out up to 12 kHz. These results were typical and characteristic of SRM drives, compared to other types of machine drives. In our opinion, this issue is the key obstacle of SRM technology for possible large-scale implementation in the automotive industry.

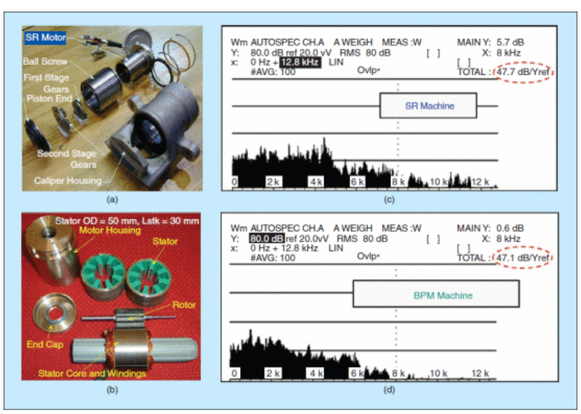

Figure 8 An electric brake for automotive applications: (a) the brake caliper assembly, (b) the four-phase 8/6 SRM implemented, and (c) and (d) the measured acoustic noise spectra of SRM and BPM brake systems at the same operating point.

The main challenge of SRM implementation in EVs and HEVs was found in the spectral content of their emitted acoustic noise. Most NVH spectra of SRMs contain high-frequency pure tones up to 12 kHz. There are possible solutions to this issue, such as encapsulation of the SR machine and/or the use of appropriate acoustical absorption material in the machine compartment to reduce the peaks of annoying tones to imperceptible levels. However, these solutions are still expensive today. Recent supply disruptions of high-energy NdFeB magnets have given new life to SR machines by making PM machines much more expensive.

Turbogenerators

Large synchronous generators are the fundamental machines in nuclear, fossil fuel, and alternative energy generation [23]. Large four-pole turbogenerators reach 2,191 MVA with torques of 12.6 MNm, and low-speed hydrogenerators reach even up to 96 MNm. Nevertheless, the backbone of the energy market is given by gas-turbine- and wind-turbine-driven generators. Generators with large numbers of machines per year as well as extremely large generators are based on highly sophisticated design and calculation methods. It is inevitable to combine the basic principles of electrical engineering with fluid dynamics, heat transfer, and mechanical engineering.

In principle, two families of machine design can be identified. One family of generators consists of machines, which are first developed for a unique plant. These generators are optimized to the individual site conditions of, for instance, a hydroplant with an individual water turbine. Once the machines have been built, their design is reused on power plants with the same requirements. The main target of these machines is to get what has been guaranteed without having the chance to do any corrections in a second design step. The guaranteed efficiency and the apparent and active power are predefined during the sales process.

The second family of generators represents a series of machines affiliated by a strong basis of identical components. These components are characterized by the same drawings and parts lists. This second class or family of generators has to be developed at an optimum level regarding market sector requirements, reliability, and production methods. Less adjustment to the individual site condition has to be compensated with more efforts to streamline the material utilization for the rated operation point of the machine. Constraints such as shaft vibration levels, noise levels, or insulation test voltages have to be fulfilled by both families of machines due to international standards and local requirements, which are often merged in plant requirement specifications. Last but not least, the individual grid connection underlies the regional grid codes.

For this size of machines, the design process is a great challenge. A first milestone is given already by a clear definition of the main product requirements and boundary conditions. Few experts are able to combine the technically feasible with the application requests. Within the next step, electrical, fluid dynamic, thermal, and mechanical constraints have to be challenged to create an initial machine layout [24]. Special attention is given during this development to rotor-dynamic and transient-torsional calculation [25], [26]. Based on the first layout, more detailed investigations shall be done, particularly on the rotor with its centrifugal forces. These will be based on design drafts, which can be used as the basis for mechanical stress and/or stiffness calculations. Tentative mechanical limits may require electrical design adjustments. Afterward, the detailed design of the machine will be elaborated on. Engineering ingenuity is especially necessary to ask the right questions, which will be investigated in detail by the numerical solution of the following equations:

- Euler air- or gas-flow equation

$$\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = \frac{\vec{F}}{m} - \frac{1}{\rho}\,\mathrm{grad}\, p. \quad (1)$$

- Transient eddy-current equation

$$\Delta\vec{A} = \mu\gamma \cdot \frac{\partial \vec{A}}{\partial t} + \mu\gamma \cdot \text{grad}\ \varphi. \quad (2)$$

- Laplace temperature equation

$$\lambda \cdot \Delta\vartheta = p_{\text{el}} - \rho \cdot c \cdot \frac{\partial \vartheta}{\partial t}. \quad (3)$$

- Beltraminische mechanic equation system

$$\begin{aligned}
&\Delta\tau_{\text{xy}} + \frac{1}{1+\nu}\frac{\partial^2 \sigma}{\partial x\,\partial y} + \frac{\partial \frac{\partial F_x}{V}}{\partial y} + \frac{\partial \frac{\partial F_y}{V}}{\partial x} = 0, \\
&\Delta\sigma_{\text{x}} + \frac{1}{1+\nu}\frac{\partial^2 \sigma}{\partial x^2} + 2\frac{\frac{\partial F_{\text{x}}}{V}}{\partial x} + \frac{\nu}{1-\nu}\left(\text{div}\frac{\vec{F}}{V}\right) = 0. \\
&\Delta\tau_{\text{zx}} + \frac{1}{1+\nu}\frac{\partial^2 \sigma}{\partial z\,\partial x} + \frac{\frac{\partial F_{\text{x}}}{V}}{\partial z} + \frac{\frac{\partial F_{\text{z}}}{V}}{\partial x} = 0, \\
&\Delta\sigma_{\text{y}} + \frac{1}{1+\nu}\frac{\partial^2 \sigma}{\partial y^2} + 2\frac{\frac{\partial F_{\text{y}}}{V}}{\partial y} + \frac{\nu}{1+\nu}\left(\text{div}\frac{\vec{F}}{V}\right) = 0, \\
&\Delta\tau_{\text{yz}} + \frac{1}{1+\nu}\frac{\partial^2 \sigma}{\partial z\,\partial y} + \frac{\frac{\partial F_{\text{x}}}{V}}{\partial z} + \frac{\frac{\partial F_{\text{z}}}{V}}{\partial x} = 0, \\
&\Delta\sigma_{\text{z}} + \frac{1}{1+\nu}\frac{\partial^2 \sigma}{\partial z^2} + 2\frac{\frac{\partial F_{\text{z}}}{V}}{\partial z} + \frac{\nu}{1-\nu}\left(\text{div}\frac{\vec{F}}{V}\right) = 0.
\end{aligned} \quad (4)$$

The combination of years of experience with the available numerical tools enabled strong development steps in the direction of machine utilization, reliability, and machine efficiency. These improvements show more and more success in the development of large-series machines for the energy market, with all the flexibility of load scheduling in energy systems, as shown in Figure 9.

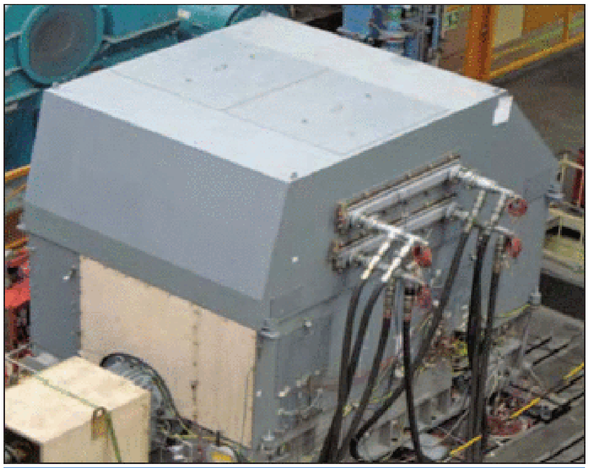

Figure 9 An example of a 40-MVA salient pole-synchronous generator.

Universal Motors

The UM is a series-excited collector machine, as shown in Figure 1(a), extensively used for more than one century, mainly for small-rating household appliances such as portable drills, vacuum cleaners, cloth washers, coffee grinders, blenders, flour mills, pumps, and bench tools [27]. The UM applications rating ranges are from a few hundred to a few thousand watts, with speeds from a few thousand r/min to 40,000–50,000 r/min. Despite a simple operation principle, this motor exhibits specific features, which until today have been objects of research and development:

- a rather complex internal behavior, mainly concerning commutation, whose good quality strongly impacts brush wear
- a great effort by researchers and manufacturers to ensure effective performance improvements.

Various modeling and design aspects of UMs have been developed in the literature over the last few decades including magnetic core structure and geometry; models for the evaluation of global instantaneous quantities; steady-state operation modeling and related parameter identification; efficiency figures of merit; and commutation waveforms and estimation of brush wear, electronic converter feeding topologies, and design methods [28]–[29][30]. Regarding core configuration, in the case of invariable rotation direction, a peculiar stator lamination geometry has been proposed, with asymmetrical yoke and pole shoe widths to reduce saturation [see Figure 10(b)]: since the trailing pole shoe operates also as an auxiliary pole, the local saturation mitigation improves commutation. Other proposals rose from the soft magnetic composite materials availability, with the adoption of prewound poles, a claw-pole stator, and concentrated rotor windings, with the advantages of a unit iron stacking factor, a three-dimensional core shaping, and easier motor manufacturing and assembly. For the analysis of the UM global operation concerning waveforms at the terminals, rms values, torque, and efficiency, different approaches have been adopted such as phasor diagrams, equivalent circuits, and FEM transient analysis. Among the developed overall motor models, some equivalent circuits enable description of the instantaneous evolution of the global operation quantities, taking into account the core saturation, losses, and actual winding data. In this way, the corresponding air gap MMF distribution can be accurately decomposed in demagnetizing and torque components. An important aspect concerns the linkage factors involved in the analytical expression of the the motional and transformer e.m.f.s, which are dependent on the coil pitch and the brush shifting angle. Other analytical approaches adopted for the motor parameters estimation are based on approximated field models and conformal transformations. As concerns the analysis of commutation, some authors have adopted a field-circuit approach, based on the use of FEM two-dimensional transient tools, including the description of the brush–commutator contacts, while the typical purely circuit approach is based on the solution of selected reduced equivalent circuits including the brush-commutator contact model, the sections e.m.f.s, the self and mutual section inductances, and the arc model. As regards these section inductances, it has been experimentally verified that, during commutation, some minor hysteresis loops are covered with rotor core lamination permeability much lower than the normal one: this affects the commutation transients. To perform accurate commutation analyses, a great deal of effort has been devoted to model the brush–commutator contact voltage. Some authors distinguished static and dynamic voltage–current density curves, while others studied special brush–commutator equivalent circuits based on the conduction field at the contact interface and inside the brush. From the commutation analysis, brush wear estimation has been obtained, by adapting classical brush wear models developed for the dc commutator machines. In particular, some useful winding design indications followed, aimed to increase brush life by suitably rearranging the turn number of the coil sections disposed in the same couple of slots. As concerns the used feeding electronic converters, the simplest one is the triode for alternating current, but dc and ac choppers have also been considered; to limit line current distortion, Cuk topology converters have also been proposed.

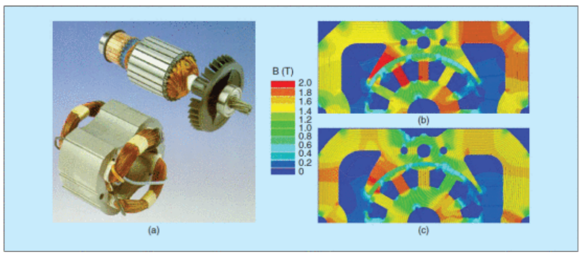

Figure 10 (a) A typical layout of a UM. (b) and (c) FEM analysis of the magnetic core: (b) a standard symmetrical core and (c) the lamination geometry with an asymmetrical yoke and pole shoe widths to reduce local saturation.

As for the UM motor design methods, both FEM-assisted optimization procedures and algorithms based on design modeling equations have been proposed. Analytical approaches based on sizing equations have led to expressions of average torque, armature and field Joule losses, line current THD, and optimal brush shift as a function of the field over armature turns ratio. Some redesign criteria have been developed that are suited to improving motor performance and reducing losses and line current harmonic distortion.

High-Speed Machines

A useful definition of high-speed electrical machines would be one that in many ways encompasses the multifaceted approach required when attempting their design [31]. The term *high speed* in itself already invites the prospective designer to think in terms of high fundamental frequencies and, therefore, reduced overall dimensions resulting in high power densities and intensive cooling systems [see Figure 11(a)]. Furthermore, the mechanical stresses involved due to the centrifugal forces experienced [32] need to be considered to ensure a reliable and safe design. Thus, assigning the high-speed definition as a function of peripheral speed provides for a more holistic definition of this motor class and encompasses a vast spectrum of machines with peripheral/tip speeds up to 367 m/s being reported [33].

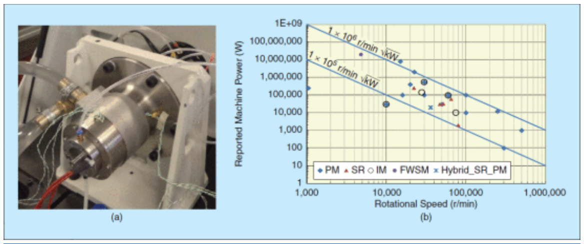

Figure 11 (a) A PM machine with 120,000 r/min and 5 kW under test. (b) The speed-power distribution of reported high-speed generator designs to date.

In an effort to account for a number of rotor dynamic issues in such machine types, a convenient way to quantify the difficulty in reaching the high-speed, high-power requirements is the r/min√kW index. Currently, electrical machines reach limits of 1×10^6 r/min√kW for solid rotor machines, with the bulk of the high-speed applications encountered reaching between the latter limit and 1×10^5 rpm√kW [see Figure 11(b)]. Such high-power speed operating points are only possible through the use of novel materials. Developments in this field brought about a number of significant changes from traditional materials, with such salient changes being reported in the following. In terms of soft magnetic alloys, losses as low as 5.7 W/kg (at 400 Hz 1T) for materials exhibiting high tensile strengths at 605 MPa have been reached, while higher strengths and induction values (up to 800 MPa at 2.2 T) have also been reported at the expense of higher losses. Hard magnetic materials exhibiting very high energy products and being able to operate at high temperatures have been used (such as RecomaHT520, which operates safely at up to 550 °C with a BH_{max} of 230 kJ/m^3). In terms of winding materials, lightweight aluminum-based Litz wire has been developed, while for high-speed rotor-cage applications, high-strength, high-conduction copper alloys having 0.3% by weight of Al_2O_3 and reaching 92% international annealed copper standard at 440 MPa have reportedly been used [34]. To meet the intensive cooling requirements set out by such machines, high thermal conduction insulation systems for encapsulation at 3.49 W/m×K are now commercially available for silicon-based resins, along with high-temperature conductor insulation systems capable of reaching 220 °C (Nomax 410) while retaining most of their dielectric strength. Magnets and other elements making up multielement high-speed rotors are retained against detachment from the rotor shaft (due to the experienced centrifugal forces) using high yield strength, materials such as Inconel 718 (1.1GPA $R_{p0.2}$), and carbon fiber composites, the latter reaching 3.4 GPA at a mass density, which is approximately ten times less than that of Inconel. High-bandgap materials allow for the development of power converters with high switching frequencies and high power density (20 kW/dm^3 having been reached for SiC JFETS switching at 50 kHz). Silicon nitride-based rolling elements make high-speed contact-type bearings possible while providing a lightweight solution. The intelligent control of active magnetic bearings might present a solution for low-maintenance, high-speed applications and for harsher environments. Air foil bearings have also been successfully employed [31].

In terms of high-speed applications, the more electric aircraft, encompassing the more electric engine, presents a major application area within aerospace, with PM and SR machines being the topologies of choice and reaching 250 kVA at 22,000 r/min [35]. The automotive sector is also moving toward a more electric engine concept, integrating heat-recovery turbocycles with the Otto-based engine. PM, reluctance, and IM types have been considered for this application with power-speed nodes up to 60 kW at 100,000 r/min being reported [36]. High-power (2–5 MW) PM machines are being built for the directly coupled generator sets for use in the marine sector [37]. A similar application is to be found in land-based microgeneration systems employing lower-power yet higher-speed machines for microturbine generation with nodes at 200 kW at 53,000 r/min being reported. Fly-wheel-based grid-frequency regulation systems have also created a need for high-speed electrical generation with 300-kW peak 36,000 r/min machines being commercially available.

Machine design for such high-speed operation always (for every topology considered: IM, PM, and SR) presents a tradeoff between better magnetic utilization (high pole number) and lower iron losses. In terms of the IM and PM machines, two further considerations need to be catered to, namely, eddy-current-induced losses due to spatial harmonics and rotor element retention at high speeds [38]. For such distributed-field machines (IM and PM), the typical converter topologies considered present a tradeoff between switching losses and excitation frequency harmonics; to this end, PWM rectifiers with a three-level neutral point clamped topology are most commonly reported. The SR machine design in its pure state has no particular high-speed retention issues; however, careful electromagnetic design is required to minimize its torque ripple, kVA/kW ratio, and weight [36], [39].

The design of the high-speed generator system requires a multidisciplinary approach involving not only the electromagnetic and power electronic designer but thermal and mechanical designers as well.

Conclusions

In this article, the state of the art in electrical machine design is outlined underlining the problems and challenges to be solved by engineers. As highlighted in this article, even if electrical machine design is often considered a mature issue from the technical and technological point of view, every year, new progresses and steps forward are made. New and more sophisticated design tools can be used worldwide, and innovative manufacturing processes, new insulation materials, and higher performance magnetic materials are available on the market. In addition, the evolution of the hardware used in digital control and new powerful power electronic devices represents a constant stimulus to improve the performance of electrical machines and reintroduce electrical machine structures that were not adopted in the past due to technological and technical constraints. As shown in this article, electrical machine design is an evergreen topic, and its importance is rising more each year under the push of more energy-saving requirements and higher-efficiency systems for electromechanical conversion. A green world will not be possible without electrical machines.

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