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Editorial

Recent Developments in Electrical Machine Design for the Electrification of Industrial and Transportation Systems

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1. Introduction

The electrification of the industrial and transportation systems has been an important path toward mitigating climate change. However, with the expansion of the electrification of these systems, more demanding specifications have been required for electrical machines. For example, the electrification of the aeronautical transportation system, which has been identified as an important future step [1], has yet to be achieved mainly due to, among others, the still limited specific power/torque of electrical machines.

The research for electrical machines with high specific power/torque and efficiency is a constant challenge for the expansion of the electrification of industrial [2] and transportation systems, such as electric vehicles (EV) [3–6] and future electric aircraft applications, which require high-performance ratios [7–9]. In this context, the proposed Special Issue deals with novel electrical machine topologies, innovative optimization techniques for their design, and the application of new electromagnetic materials for electrical machines. Topics approached in this Special Issue include:

- Techniques for electrical machines design and optimization;
- FEM, BEM, and analytical methods;
- Multiphysics coupled simulation and optimization;
- Electromagnetic, thermal, and mechanical simulations;
- Application of new magnetic materials and soft magnetic materials;
- Novel machine configurations and topologies;
- Electrical machine design for aircraft and automotive applications;
- Alternatives for rare-earth electrical machines.

2. Achieving High Specific Power/Torque in Electrical Machines

The increase in electrical machines' specific power/torque is still a current challenge among the industrial and research communities. They are mainly achieved by increasing:

- Higher mechanical speed, which is typically limited to the application;
- Higher airgap flux density, which is typically limited by the magnetic materials used, and;
- High current loading, which is typically limited by thermal constraints.

This Special Issue focuses on three current approaches to address these challenges, which are mainly focused on electric aircraft and electric vehicles (EV) applications:

1. Using design and optimization techniques to improve the electrical machines further;
2. Using advanced cooling techniques, and;
3. Using novel machines and systems configurations.

The main contributions of this Special Issue's publications are summarized in the next subsections.

2.1. Design Optimization Methods for Electrical Machines

Increasing electrical machines' specific power/torque can be achieved by using optimization techniques to optimize their geometries and topologies further. The increased access to powerful numerical tools has been an important catalyst for an exhaustive analysis of more complex electrical machine designs and reliable topologies.

With the present level of resources, these numerical tools can be applied to computationally intensive optimization methods. Evolutionary algorithms are a popular example of such methods, such as particle swarm optimization (PSO) [10] and the non-dominated sorting genetic algorithm (NSGA) [11,12]. This coupling leads to designs that push the limits of the constraints imposed by the considered topology, current materials, and technologies, thus uncovering new development directions.

However, special attention is required to keep the performance and computational time of the optimization methods at acceptable levels. Particularly when, in electrical machines, several different physics need to be modeled, not only electromagnetic but also mechanical, for vibrations and sturdiness, and thermal, to guarantee a safe operating temperature. A good example of this is research [10], where different machine topologies are investigated for a Synchronous Reluctance Machine (SynRM) that drives a cooling fan in an automotive application. Several combinations of slots/poles for distributed and concentrated windings were considered. Through a multi-objective PSO algorithm based on a 2D electromagnetic finite element model (FEM), insight into the performance limitations of each machine topology is obtained in terms of average torque and torque ripple for a given magnetomotive force and volume, Figure 1. Because of the multiple flux barriers required in the rotor of typical SynRMs, checking the mechanical robustness of proposed designs is critical. The authors opted to make this check after the optimization to avoid impacting the method computation time.

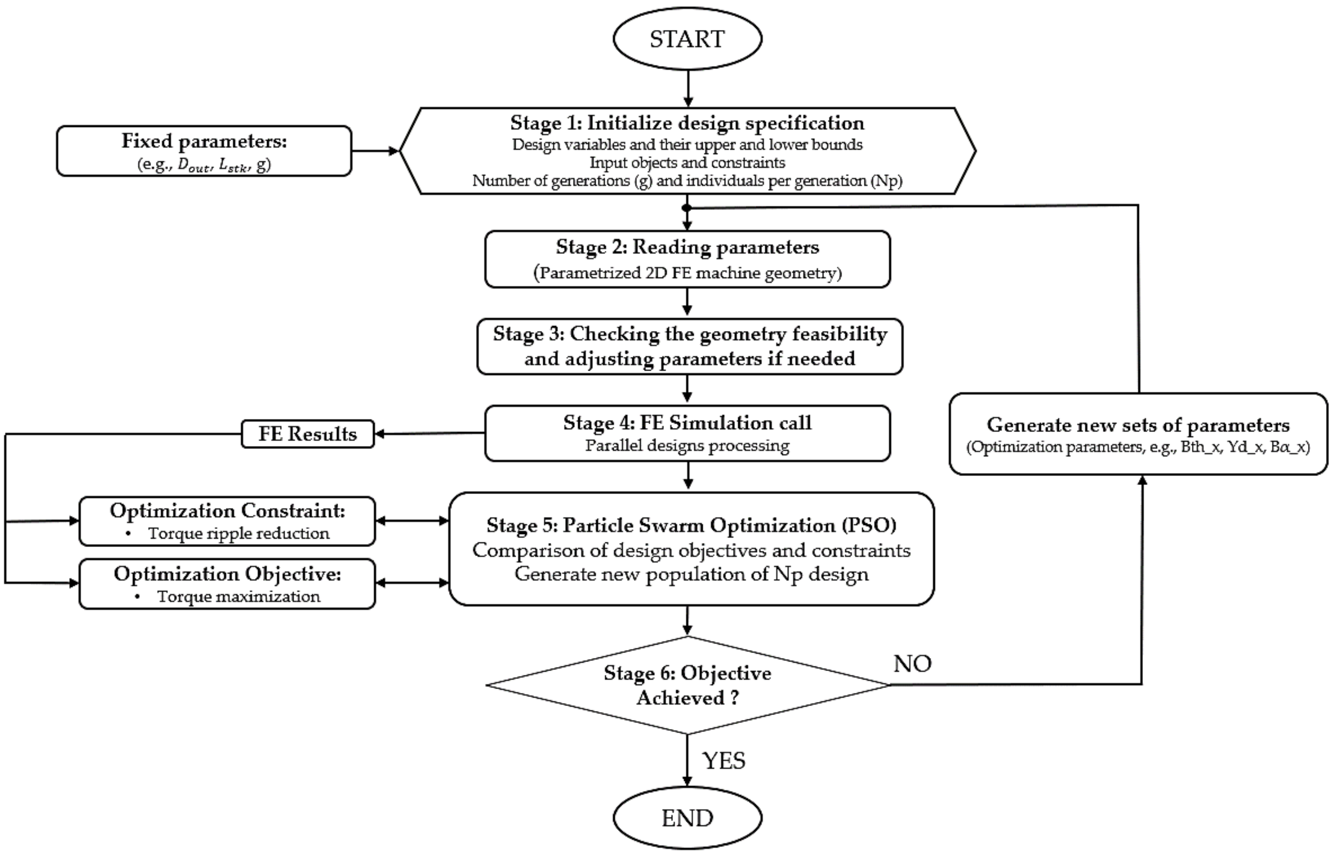
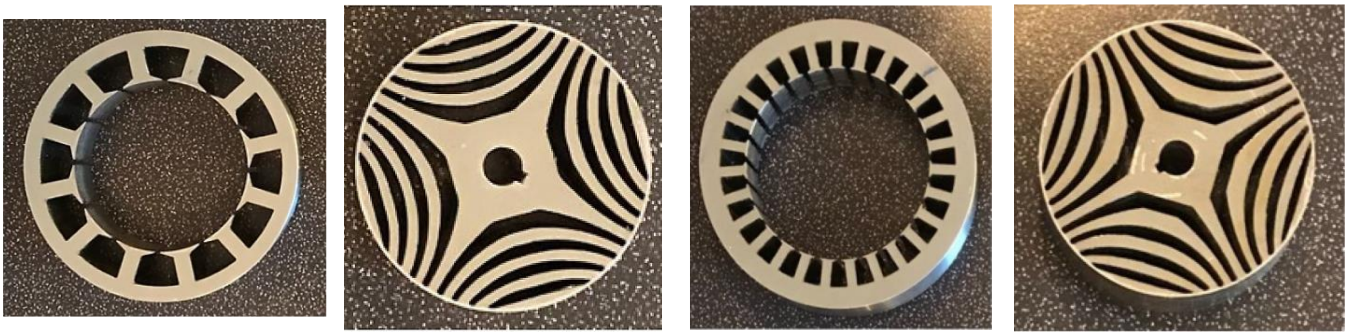


Figure 1. FE-based electromagnetic optimization workflow for the SynRM studied in [6].

As shown in Figure 2, the topologies of each winding configuration that present the best tradeoff between torque, power factor, and torque ripple were shown to be the 12 slots 4 poles concentrated winding machine and the 27 slots 4 poles distributed winding machine. Both were prototyped, and their expected performance was validated experimentally. Compared to the reference permanent magnet synchronous machine, the SynRMs show comparable performance with slightly lower efficiency. Distributed winding topology is also shown to be slightly better than concentrated winding for the application, with measured lower torque ripple and higher average torque (+10%) at the target speed of 2700 rpm.



(**a**) (**b**)

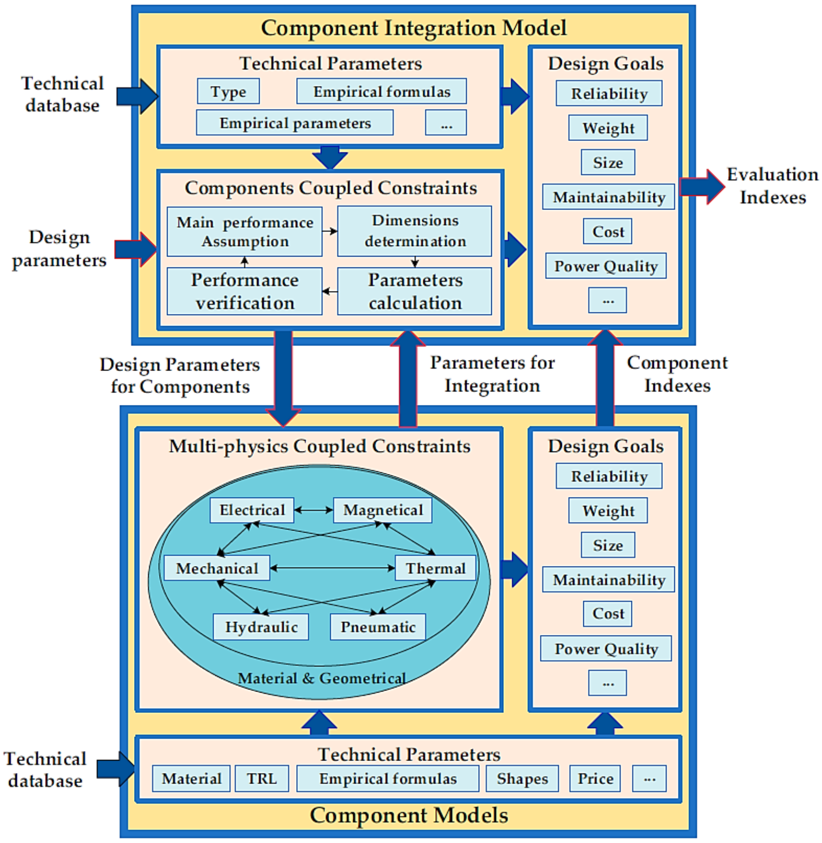
Figure 2. Manufactured optimal stator/rotor topologies from [10]. (**a**) 12/4 concentrated winding and (**b**) the 27/4 distributed winding.

In this sense, to keep computation time acceptable, another option is applying analytical models. Fully analytical models run faster than FEM and have a lower impact when coupled to a numerical optimization method (e.g., multi-objective genetic optimization) that requires several thousands of simulations. Additionally, when whole complex systems are considered, such as an aircraft's power system, a fast model of each component is advantageous to obtaining system-level insights. On the other hand, analytical models often result from simplifications and may decrease the accuracy of the proposed designs. As such, for analytical modeling, care must be taken when modeling the multiphysics phenomena involved in the workings of electrical machines.

In [11], the authors propose a multi-disciplinary design optimization (MDO) methodology based on analytical models for the design of electrical machines appropriated for incorporation into a system-level design process. The MDO method allows considering the couplings between the several components of machine design considering structural, magnetic, and thermal features, Figure 3a. Each component (shaft, slots, windings, each section of the magnetic core circuit, etc.) is a sub-model based on corresponding analytical equations. Their relationship with each other and the overall systems was also established.

To further reduce the model complexity, the authors simplify it by performing a thorough sensitivity analysis and reducing the number of relevant inputs for the optimization objectives: to minimize machine weight and power loss. A radial basis function surrogate model then approximates the model. This simplified model can be plugged into a genetic NSGA algorithm to obtain an optimal electrical machine design.

The focus of [11] is on an aircraft application, specifically the auxiliary power unit generator in a Boeing 787, which is made of a variable-speed variable-frequency salient-pole synchronous generator, Figure 3b. Compared to a baseline solution made by a PMSG, replacing the electrical excitation modules (silicon steel pole modules and excitation winding modules) with NdFeB magnet poles, the presented MDO methodology and its simplified surrogate generator model produce agreeable results with a 1.06% deviation on the estimated machine weight and −2.03% on power loss, with lower complexity, requiring only six inputs. In this research, data analysis and techniques are used to reduce the complex multiphysics characteristics of an electrical machine to a simplified model that can be plugged into computationally intensive methods and system-level analysis. In this case, work is invested in creating the model and checking its accuracy to reduce the computational time required for the optimization.



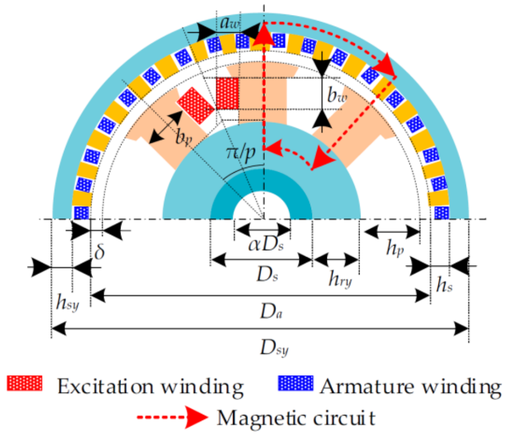
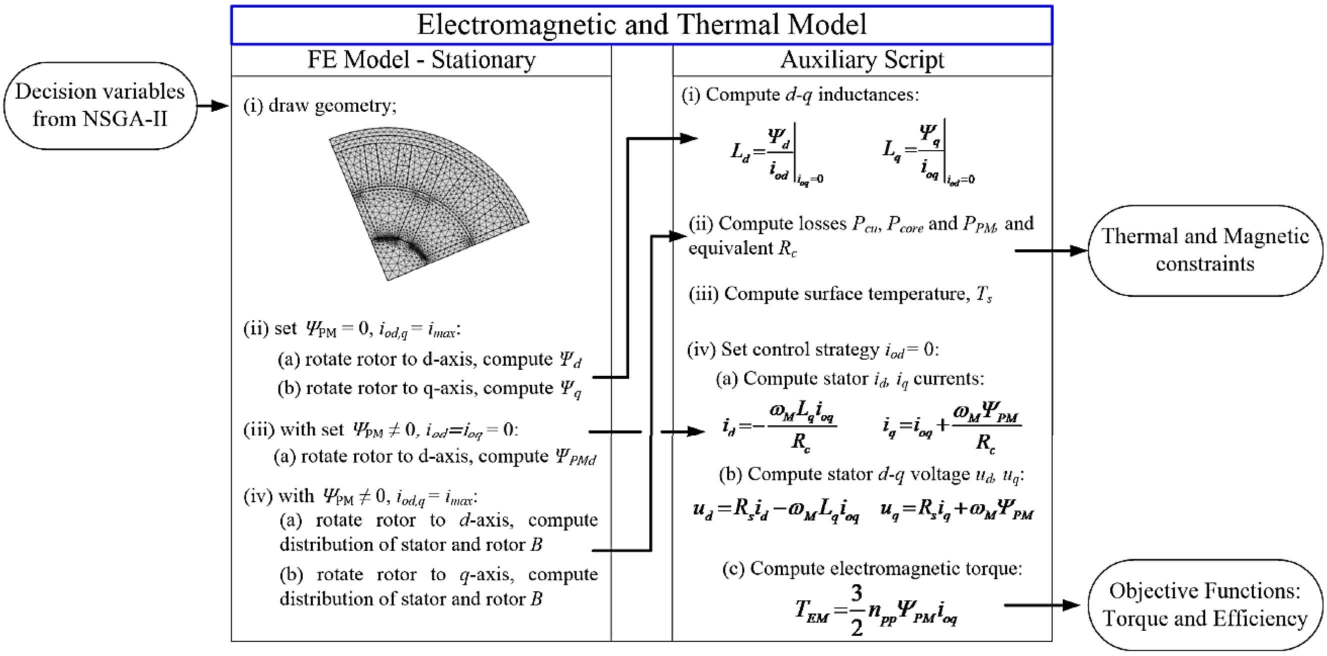


Figure 3. (**a**) The MDO methodology and the relation between its component models in the electrical machine and its integration into a system-level design process. (**b**) Salient pole synchronous generator [11].

A middle ground approach is to take advantage of the accuracy of FEM and the quickness of analytical models to mitigate the computational impact in optimization methodologies. In [12], as summarized in Figure 4a, the authors took such an approach based on coupling an electromagnetic FEM stationary model and lumped-parameter model of the machine (including its analytical thermal model) with a genetic multi-objective optimization technique (NSGA-II). The method was used to design and construct a 20 kW permanent magnet synchronous machine (PMSM) for a competition electric vehicle that was the optimal lightest and most efficient. The lumped parameter *dq* model of the PMSM is well established. However, its accuracy depends on the estimation of the parameters. To obtain these estimations, stationary FEM simulations of the machine are used. These are less costly computationally than full, time-dependent simulations, but information about time-dependent effects (e.g., torque ripple, induced voltage harmonics, etc.) is lost. A prototype was built, and the model's accuracy was validated experimentally for the considered operating range, Figure 4b. To obtain the prototype, the optimized design had to be adapted to satisfy construction constraints, weighing 5.05 kg in total with a 17.2 kW nominal power. The deviations obtained during the prototyping have shown to have a small impact on the final lap time of the competition vehicle, less than 2%. Using a hybrid FEM/analytical methodology contributed to obtaining an accurate solution for the application while maintaining an acceptable computational time of 22.9 h for a population of 150 elements and 150 generations (i.e., 22,500 different motor geometries tested).

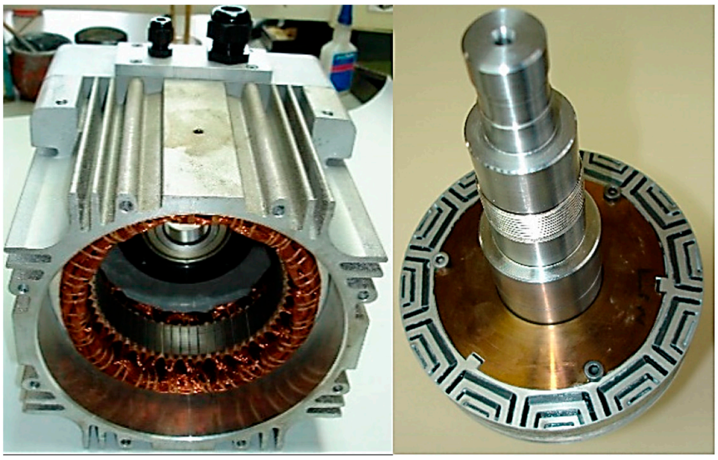


(**a**)

(**b**)

Figure 4. (**a**) Methodology used in [12], coupling an electromagnetic FEM stationary model plus a lumped-parameter magnetic and thermal model of the machine with a genetic multi-objective optimization (NSGA-II). (**b**) The magnetic core of the final PMSM prototype manufactured in [12].

As more high-specific torque/power designs are proposed, some challenges become more evident, including mechanical stability, demagnetization of permanent magnets, or operating temperature. These challenges must be considered during optimization to validate the solutions with realistic designs. In this context, a limiting characteristic of a PMSM is the demagnetization of its permanent magnets. This limitation is further aggravated due to the current trend to move away from rare-earth materials, because of their volatility in supply and price, towards alternatives such as ferrite magnets which are more susceptible to demagnetization. In addition, in ferrite magnets, demagnetization is more difficult to detect, as weaker magnets have a lower impact on the machine performance than rare-earth magnets. In [13], the authors analyze online methods to identify partial demagnetization faults in a five-phase ferrite permanent magnet-assisted synchronous reluctance motor (fPMa-SynRM) shown in Figure 5a. These faults decrease the strength of the magnets and impact the machine's overall performance. Using FEM models, validated experimentally, fault indicators based on the analysis of harmonic content of the electromotive force under no load, the harmonic content of the zero-sequence voltage component, and the analysis of the power factor are found to be the most reliable, Figure 5b. These metrics are sensitive enough to detect low-level demagnetization between 5% and 16.7%. This allows the early online detection of permanent magnet faults in multi-phase fPMa-SynRMs, which are being explored for several applications, including electromobility.



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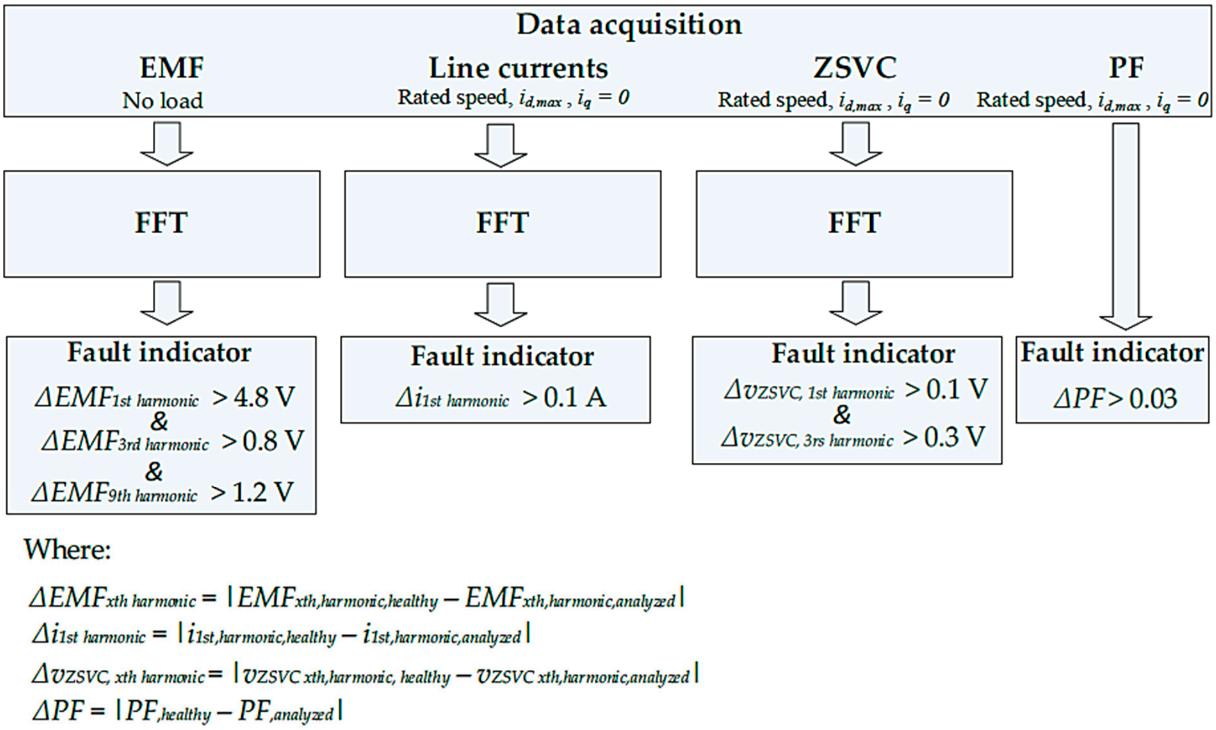


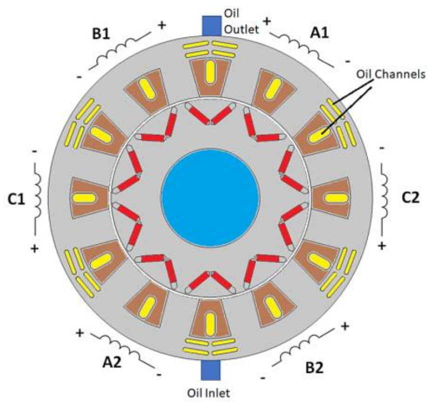
(**b**)

Figure 5. (**a**) The five-phase ferrite permanent magnet-assisted synchronous reluctance motor analyzed in [13]. (**b**) Proposed fault indicators and partial demagnetization diagnosis strategy.

2.2. Cooling Techniques

In addition to the design optimization of electric motors, new cooling techniques were incorporated to expand further the current limits of electrical machines in aircraft and automobile applications [14–16]. Using advanced cooling techniques increases the current loading and, thus, specific power and torque.

Direct cooling in the stator yoke or winding slot is a possible cooling technique to improve electrical machines' specific power/torque. In [14], the authors propose using a direct-oil cooling on the stator yoke of a 50 kW, 11.000 rpm, tooth-coil concentrated winding machine (TCWM) designed for a small passenger electric vehicle. The electromagnetic design and optimization of the machine are presented and validated using a FEM tool and an experimental setup. Using a hybrid model, with analytical sizing and FEM mapping, the influence of the placement of the stator yoke oil cooling channels on the electromagnetic performance is evaluated, Figure 6a. The best position for the oil cooling channels is found between the phase groups, with a 2.0 mm channel height that produces a negligible impact on the degradation of the electromagnetic performance and still offers a sufficient high cross-section area for low viscosity of the oil without significant pressure drop. Experimental tests were conducted following the setup in Figure 6b to validate performance improvement using the stator yoke oil cooling technique. Compared with standard water jacket cooling, the direct-oil cooling increased the current density from 10 A/mm^2 to 25 A/mm^2, increasing the continuous power by over 75%. The measured efficiency was between 90.0% to 94.7% for motor speeds between 1000 to 3000 rpm.



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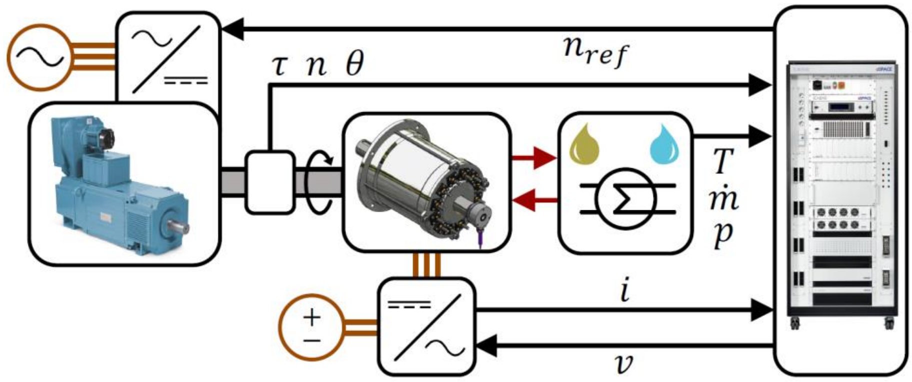
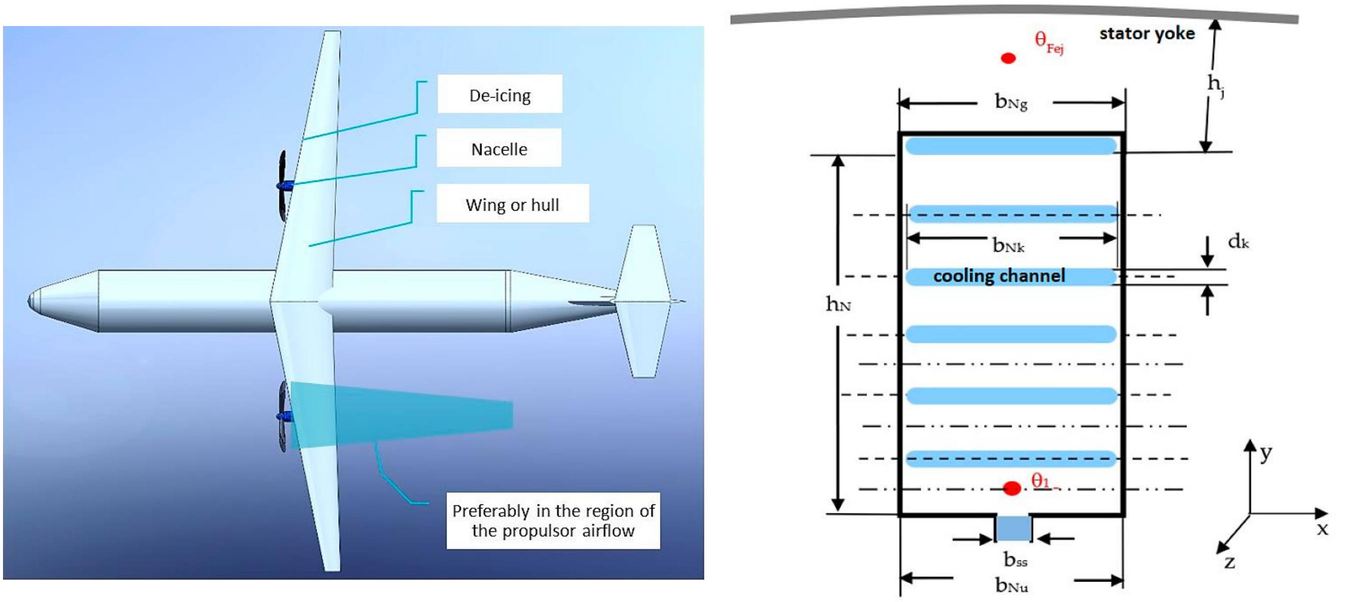


(**b**)

Figure 6. (**a**) Electrical machine design established and manufactured in [14] for direct oil cooling in the stator yoke and winding slot. (**b**) Calorimetric measurement system setup.

Another option is including cooling channels in the winding slots, directly in contact with the copper windings. In [15], the authors evaluate the impact of current density and winding slot cooling on the weight of the electric drive system (electrical machine, power electronics, and cooling system) for a small-range aircraft with a conventional fan or propeller with 2 MW PMSM, Figure 7a. The required weight is evaluated considering the aircraft's start, climb and cruise conditions, defined by the SE2A consortium, where the ambient temperature ranges from 40 °C (start conditions) to −24 °C (cruise conditions). This evaluation uses hybrid numerical models for the electrical machine design, temperature calculation, and cooling system design. From the point of view of the electrical machine, the highest specific torque is achieved with higher loading capabilities (higher current density). However, these will originate in higher losses that must be dissipated by the cooling system, leading to an increase in the cooling flow and system weight. By changing the number of cooling channels and current density, the resultant decrease in the electrical machine weight and increase in weight of the power electronics, cooler, pump, and piping are analyzed, Figure 7b. The authors verified a minimum weight for a current density between 30 to 35 A/mm^2. This minimum is achieved with a specific system power of 6.6–6.7 kW/kg.

In alternative to liquid cooling techniques, the authors in [16] propose using forced convection to cool the electric motors due to the aircraft speed. This solution reduces the complexity and weight of the system when compared with liquid cooling methods and promotes higher reliability. In this research, a design methodology is proposed to investigate the use of forced convection, due to the aircraft airflow, for electric motors in the propulsion system of an unmanned hybrid/full electric aircraft. The electric motor is positioned behind the propeller. As the propeller rotates, it increases the airflow speed, improving the cooling capabilities of the motor. The motor is cooled by forced convection on its external surface. Starting from an existing surface-mounted PMSM, self-ventilated, a hybrid design methodology was applied to optimize the motor under forced convection due to the aircraft speed. Considering its electromagnetic and thermal models, a differential evolutionary algorithm is used for the optimization. Two optimization scenarios were used: (a) minimization of the motor weight to achieve a rated power of around 60 kW, and (b) maximization of the motor-specific power and rated power. Considering (a), a 4% mass reduction was obtained relative to the initial motor design, achieving a 1.2 kW/kg power density. However, with the less restrictive design in (b), a power density up to 1.7 kW/kg is achieved with rated power between 87 to 107 kW. Therefore, the forced convection due to the aircraft speed allowed an increase of around 50% of the power density for the analyzed PMSM.



(**a**) (**b**)

Figure 7. (**a**) Small-range aircraft topology considered in [15] to study the optimization of the winding slot cooling on aircraft 2 MW PMSM for decreasing the weight of the electric drive system. (**b**) The layout of designed cooling channels in the electrical machine slot.

2.3. Novel Electrical Machines Configurations and Topologies

Novel electrical machine configurations and system topologies may also contribute to the increase of specific power/torque of electrical machines and expand the electrification of industrial and transportation systems. In [17], the authors proposed the development of a novel axial-flux permanent magnet dual-rotor generator (see Figure 8a) for counter-rotating wind turbines. Counter-rotating dual rotors have been identified as a potential alternative to using gearboxes in wind turbine applications. Compared to single-rotor topologies, these allow an increase of about 13% of the power. To fully use the potential of dual-rotor wind turbines, the authors propose a novel axial-flux topology with the field and armature parts made by two independent rotors and a coreless armature with a dual permanent magnet disc-shaped field. The design process consisted of a three-step methodology, through analytical and FEM calculation and experimental tests to a prototype. Special attention must be given to the mechanical coupling and supply of the rotating armature in these types of dual-rotor machines, where the double rotor and armature rotate in opposite directions. In this machine, concentric slip rings are used to supply the armature windings. After FEM verification, an experimental prototype of the electrical machine was developed. Preliminary laboratory results using the setup shown in Figure 8b show an efficiency of about 80% with an output power of around 1000 W at 1000 rpm for the 200 mm diameter electrical machine prototype. The authors seek to perform further experimental tests with the axial-flux machine connected to a double-rotor wind turbine in a wind tunnel.

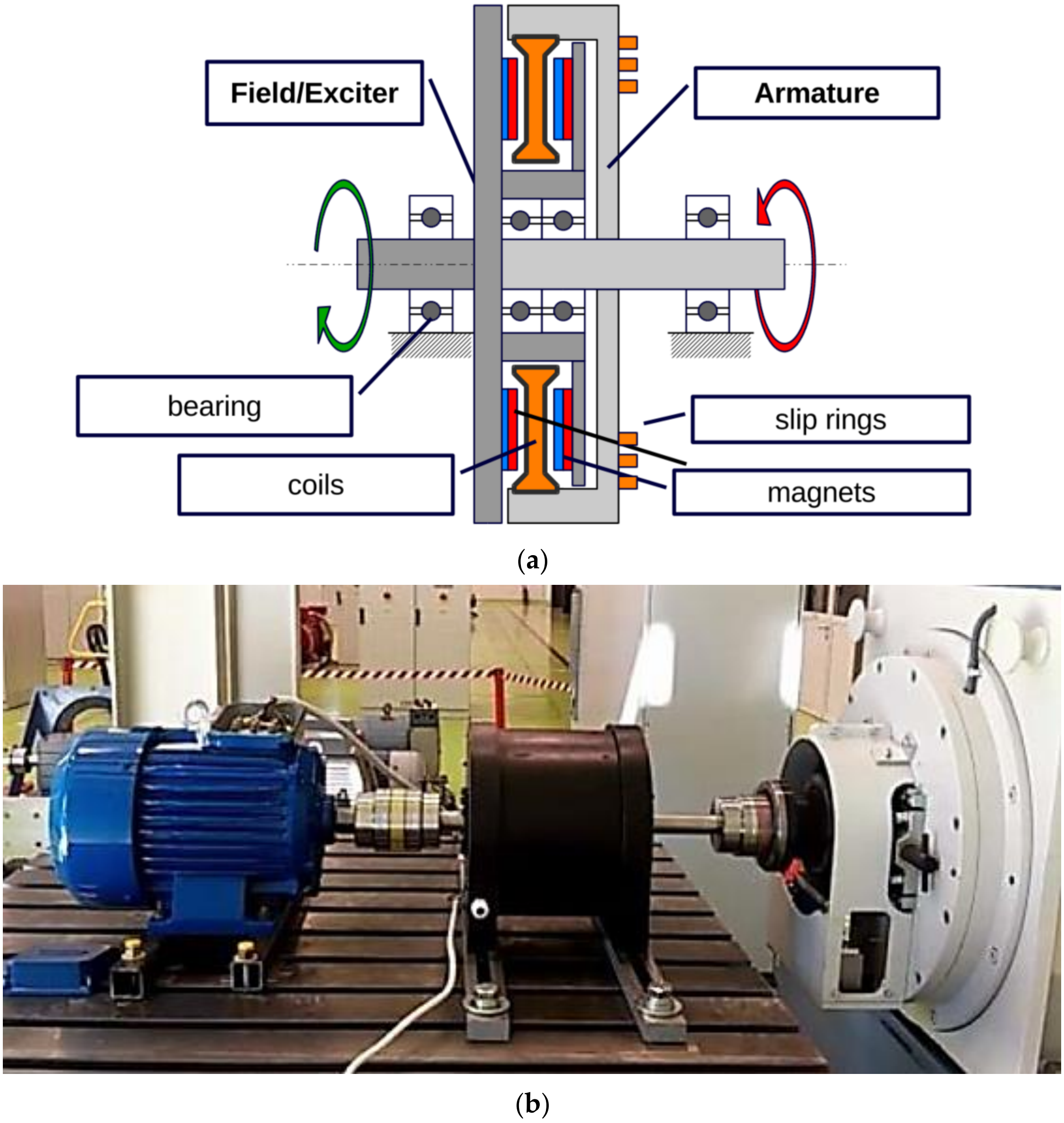


Figure 8. (**a**) Axial-flux permanent magnet dual-rotor generator. (**b**) Laboratorial setup [17].

The development of multi-degrees of freedom (DOF) electric actuators is another important research field for the electrification of advanced industrial applications. In [18], the authors propose the analysis and improvement of a novel layered permanent magnet motor with a 3-DOF deflection and zenith rotation. The stator is made of three layers, where the first and third are responsible for the motor deflection, and the second promotes the rotor zenith spinning rotation. The rotor is made of butterfly permanent magnets to reduce the amount of PMs used and to increase the magnitude of the magnetic field. The main advantages of this motor are its small volume, high slot utilization, high magnetic density, specific torque, and stability. Using analytical and FEM models, the stator and rotor of the motor are optimized and compared with their initial design. Results show an increase of 22.7% in air gap flux, 25% in rotation torque, 50% in tilting torque, and a reduction of 54.7% in permanent magnet material.

Finally, in [19], the authors address the challenge of charging EVs using wireless power transfer (WPT) systems. Generally, the WPT systems in passenger cars have a high gap distance between the transmitter and receiver coils. To solve this problem, the authors propose designing and analyzing a novel magnetic coupler installed on the EV wheel. The WPT is based on an inductive type with a station and the EV side. The station side comprises an AC/DC converter, a DC/high-frequency inverter, a transmitter coil, and a compensation network. The EV side consists of a receiver coil coupled to an AC/DC converter to rectify the energy received and store it in the battery packs. The optimization of the WPT system is based on the coil geometry and shape, its outer and inner diameters, and coupling coefficients. In addition, five ferromagnetic core geometries are analyzed: circular, slotted, bar, circular bar, and divided circular cores. Simulation results have shown that the circular bar type presents the best characteristics in terms of coupling efficiency and power transfer efficiency while consuming less ferromagnetic core material and presenting excellent tolerance against misalignments. Through optimization, a magnetic coupler with similar coupling coefficients was designed using 55% less ferromagnetic material than the circular core. This study indicates that the in-wheel WPT system with the proposed magnetic coupler could efficiently replace the existing wireless charging systems. However, further developments are required regarding integrating the receiver coil into the tire rubber and experimental validation.

3. Trends and Future Development

In addition to the previous research works, the authors would like to identify other trends and future developments important for the design of electrical machines. Here, we list some other works that we recommend in the field of electrical machine design.

Applying new or advanced magnetic materials in electrical machines is also a key to further expanding their current limits. Some examples are:

(a) High-temperature superconductors that can be used as tapes for conducting high electric currents, or as bulks, for storing or shielding high magnetic fluxes [20,21];
(b) Cobalt-iron alloys, which allow a higher magnetic flux density [22];
(c) Soft magnetic composites, which allow 3D magnetic flux paths useful for multi-DOF machines [23], and;
(d) Nanofluids for cooling, such as aluminum oxides and nitride, further expand electrical machines' cooling capabilities [24].

Regarding the use of high-temperature superconductors (HTS), in [20], the authors explore the use of magnetized HTS bulks in a 500 kW radial flux double armature electric generator for a contra-rotating wind turbine. By replacing permanent magnets with HTS bulks, the magnetic flux density in the armature windings was increased to 2.5 T when a peak of 6 T is trapped on the HTS bulks. Alternately to HTS bulks, the excitation circuit of synchronous machines can be made using HTS tapes as field coils. In [21], the authors describe future aircraft propulsion systems development based on HTS electrical machines cooled by liquid hydrogen. The studied project comprises a hybrid electric aircraft with one HTS generator and multiple HTS motors. The motors and generator are fully superconducting machines, with field and armature HTS windings. HTS technologies are seen today as a potential technology to achieve the high specification requirements for the electrification of the aeronautical transportation system.

Using higher magnetic saturation alloys is another approach that can contribute to increasing the electrical machines' specific power. In [22], the application of cobalt-iron (CoFe) alloys is explored for a PMSM. The authors perform two optimizations of the PMSM, with FeSi and CoFe, for the same machine volume. Optimization results show that CoFe allows an increase of up to 64% in torque for the same efficiency level or up to 5% in efficiency for the same torque, Figure 9.

Developing multi-DOF machines typically requires soft magnetic composites that present good isotropic characteristics. For example, using laminated iron cores limits magnetic flux density paths into one geometric plane. However, a 3D path of the magnetic field is typically required for multi-DOF machines. In [23], a multi-DOF spherical actuator using a soft-magnetic iron core is analyzed. Its rotor is composed of a soft magnetic core covering a matrix of permanent magnets, and its stator by a multi-pole system with coils to control the rotor movement. The spherical actuator can perform a 40° of the angle of rotation around the x- and y-axis and 360° around the z-axis.

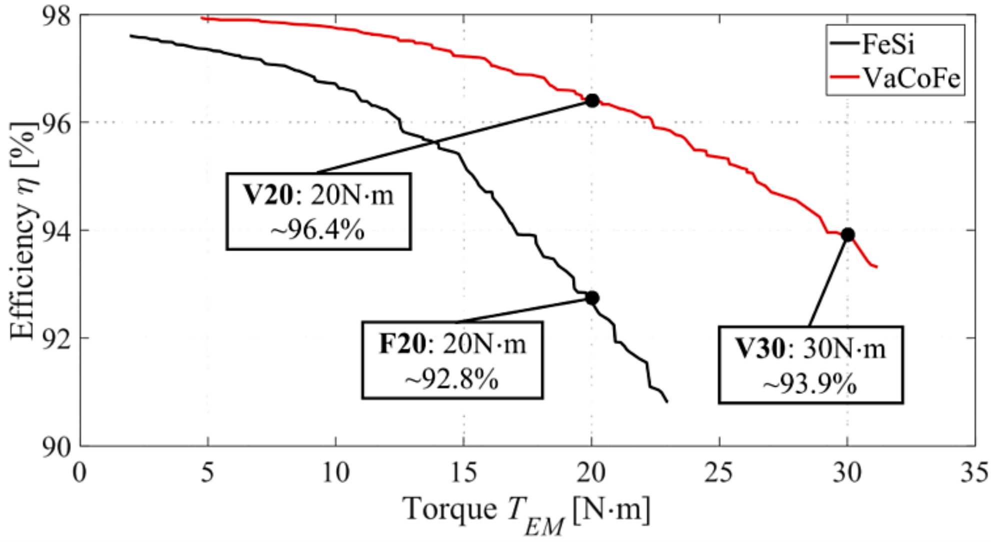


Figure 9. Optimization results present the efficiency as a function of the torque for the FeSi and CoFe PMSMs [22].

In addition to new materials for developing the electrical machines' main active components, the use of nanofluids for their cooling may also allow a further expansion of their loading capabilities. For example, in [24], the authors study the impact of adding nanoparticles of aluminum-oxide in the water-cooling system of electric motors, Figure 10. Using a cooling jacked around the stator, the authors analyze the cooling capacity when adding the nanoparticles to the water fluid. By adding only 4% of nanoparticles, the heat transfer capacity of the cooling system increases by 40%.

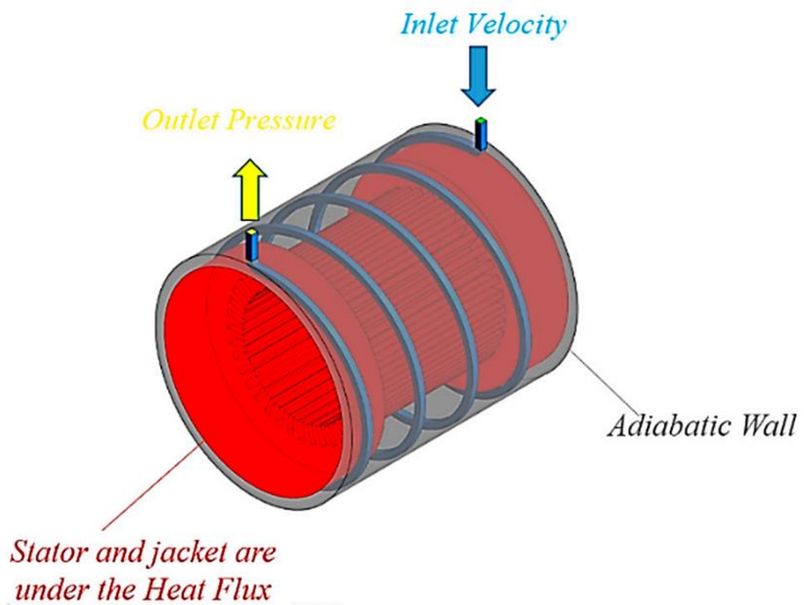


Figure 10. Schematic of the cooling system [24].

Another important research topic is the development of cryogenic machines with conventional or superconducting materials [25,26]. These have also been identified as potential solutions to achieve the high specific power/torque requirements for future electric aircraft [27]. In [25], the performance of two induction machines is investigated and compared when operating at room temperature, at cryogenic conditions, and with superconductors in the rotor. Even with conventional materials, the induction machines present almost double the torque when immersed in liquid nitrogen. With superconductors in the rotor, an additional increase of up to 30% is achieved.

4. Conclusions

This Special Issue is composed of ten papers focusing on designing and optimizing electrical machines to further optimize their specific power and torque for the continuous electrification of industrial and transportation systems. Researchers have presented different optimizations, cooling techniques, and novel electrical machine topologies capable of achieving higher levels of specific power/torque. The authors of this editorial paper have summarized each work's main contributions and highlighted future trends and developments. The guest editor would like to thank the contributions of all colleagues and reviewers.

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