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Editorial

Design and Application of Electrical Machines

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Design and Application of Electrical Machines is a Special Issue of *Energies*. In this Special Issue, authors from various research centers present the results of their scientific research on electrical machines. In eighteen papers, they presented simulation studies, design works, and experimental tests on built prototypes.

Electrical machines are the most important components of both the industrial and commercial worlds. They are at the heart of the new industrial revolution brought forth by the development of electromobility and renewable energy systems. Today's electric motors must meet the most stringent requirements of reliability, availability, and high efficiency to match (and exceed) the useful lifetime of power electronics in complex system applications and to compete in a market under ever-increasing pressure to deliver the highest performance criteria.

Today, thanks to the application of highly efficient numerical algorithms running on high-performance computers, it is possible to design electric machines and entire drive systems that are faster and at a lower cost. At the same time, progress in the field of material science and technology enables the development of ever-more complex motor designs and topologies.

The purpose of this Special Issue, "Design and Application of Electrical Machines", is to contribute to the development of electric machines. The aim is to present a variety of problems related to widely understood electrical machines. Unlike other very monothematic issues (available mostly to specialized readers), this allows us to reach a much wider group of scientists and engineers.

Here, scientists report results of their research in the field of design and application of many types of electric machines.

Topics of interest for publication include:

- Simulation tools, modeling, and analysis of electrical machines;
- New design methods of electrical machines;
- Optimization of electrical machines;
- Electrical machines for EVs and HEVs;
- Power electronics used for electrical machines;
- Supply and control of electrical machines;
- New technologies, materials, devices, and systems for electrical machines;
- Linear drives for transportation.

This Special Issue, "Design and Application of Electrical Machines", was established to provide original results of research, simulation, design, and the build of and testing of modern electrical machines. In total, 18 papers related to the main topic were accepted and published in this Special Issue. Most of the papers are concerned with research on cylindrical electrical machines, but there are also papers dealing with axial-flux machines and magnetic clutches.

The first paper, presented by Ullah et al. [1] presents linear flux switching machines (LFSMs) possess the capability of generating adhesive thrust force; thus, problems associated with conventional rotatory electric machines and mechanical conversion assemblies

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can be eliminated. Additionally, the unique features of high force/power density, efficiency, and a robust secondary structure make LFSMs a suitable candidate for linear motion applications. However, deficiencies in controllable air-gap flux, risk of PM demagnetization, and the increasing cost of rare earth PM materials in case of PMLFSMs, as well as the inherent low thrust force capability of field excited LFSMs compel researchers to investigate new hybrid topologies. In this paper, a novel double-sided hybrid excited LFSM (DSHELFSM) with three excitation sources, i.e., PMs, DC, and AC windings confined to short moving primary and segmented secondary providing short flux paths is designed, investigated, and optimized. Second, unequal primary tooth width optimization and additional end-teeth at all four corners of the primary equipment's proposed design with a balanced magnetic circuit and a reduced end-effect and thrust force ripples. Third, the measured experimental results of the proposed manufactured machine prototype were compared with corresponding simulated model results and showed good agreement, thus validating the theoretical study.

The next paper by Kluszczyński and Pilch [2] focuses on magnetorheological clutches (MR clutches) with a disc structure that can be designed as one-disc or multi-disc clutches (number of discs: $n = 1$, $n > 2$). The main goal of the paper was to compare the overall dimensions (lengths and radii), masses, volumes, and characteristic factors—torque per mass ratio and torque per volume ratio for MR clutches that develop the same given clutching torque (Tc) but differ in the number of discs (it was assumed that the number of discs of the primary member varied from one to four). This analysis developed charts and guidelines that allow designers to choose the appropriate number of discs from the view point of various criteria, and with various limitations regarding geometry, geometric proportions, mass, and volume, or restrictions on the amounts of active materials used in the manufacturing process. The limitations on the used active materials are of particular importance in the case of mass production. The methodology used a comparative study, which can also be used when comparing design solutions of other electromechanical converters.

The article by Kocan et al. [3] is applied to high-speed electric machines. Currently, one of the most used motor types for high-speed applications is the permanent magnet synchronous motor. However, this type of machine has high costs and rare earth elements are needed for its production. For these reasons, permanent-magnet-free alternatives are sought. An overview of high-speed electrical machines shows that the switched reluctance motor is a possible alternative. The paper deals with the design and optimization of this motor, which could achieve the same output power as existing high-speed permanent-magnet synchronous motors while maintaining the same motor volume. The paper presents the initial design of the motor and the procedure for analyses performed using analytical and finite element methods. During electromagnetic analysis, the influence of motor geometric parameters on parameters, such as maximum current, average torque, torque ripple, output power, and losses, was analyzed. The analysis of windage losses was performed using analytical calculations. Based on the results, it was necessary to create a cylindrical rotor shape. The rotor modification method was chosen based on mechanical analysis. Using thermal analysis, the design was modified to meet thermal limits. The results of the work were a design that met all requirements and limits.

The paper by Ciurys and Fiebig [4] presents an innovative design solution of a balanced vane pump integrated with an electric motor that was developed by the authors. The designed and constructed bench, which enables testing of the system: power supply, converter, integrated motor–pump assembly and hydraulic load at different motor speeds and different pressures in the hydraulic system, is described. The electromagnetic and hydraulic processes in the motor–pump unit were investigated, and new, previously unpublished, results of experimental studies under steady and dynamic states are presented. The results of the study showed good dynamics of the integrated motor–pump assembly and proved its suitability to control the pump flow rate, and thus, the speed of the hydraulic cylinder or the speed of the hydraulic motor.

Wang et al. [5] discuss the subject of prediction of electromagnetic characteristics in stator end parts. In order to study the multiple restricted factors and parameters of the eddy current loss of generator end structures, both multi-layer perceptron (MLP) and support vector regression (SVR) were used to study and predict the mechanisms of the synergistic effect of metal shield conductivity, relative permeability of clamping plates, and structural characteristics of eddy current losses. Based on the eddy current losses of generator end structures under different metal shielding thicknesses and electromagnetic properties, the calculation accuracies of MLP and SVR were compared. The prediction method gave an effective means for the complex design of the end region of the generator, which reduced effort by the designers. It also promoted the design efficiency of the electrical generator.

In the paper by Radwan-Pragłowska et al. [6], an application of the harmonic balance method (HBM) for analysis of an axial flux permanent magnet generator (AFPMG) is presented. Particular attention was paid to the development of mathematical model equations, allowing to estimate machine properties without having to use quantitative solutions. The methodology used allowed for precise determination of the Fourier spectra with respect to the winding currents and electromagnetic torque (both quantitatively and qualitatively) in a steady state operation. Analyses of space harmonic interaction in steady states were presented for the three-phase AFPMG. Satisfactory convergence between the results of calculations and measurements confirmed the initial assumption that the developed circuit models of AFPMG and showed that they were sufficiently accurate and can be useful in diagnostic analyses, tests, and the final stages of the design process.

Ullah et al. [7] propose research on a single-sided variable flux permanent magnet linear machine with a flux bridge in mover core. The flux bridge prevents leakage flux from the mover and converts it into flux linkage, which greatly influences the performance of the machine. First, a lumped parameter model was used to find a suitable coil combination and a no-load flux linkage of the proposed machine, which greatly reduced the computational time and drive storage. Secondly, the proposed machine replaced the expensive rare earth permanent magnets with ferrite magnets and provided improved flux controlling capability under variable excitation currents. Multivariable geometric optimization was utilized to optimize the leading design parameters, such as split ratio, stator pole width, width and height of permanent magnet, flux bridge width, the width of mover's tooth, and stator slot depth at constant electric and magnetic loading. The optimized design increases the flux linkage by 44.11%, average thrust force by 35%, thrust force density by 35.02%, minimizes ripples in thrust force by 23%, and detent force by 87.5%. Furthermore, the results obtained by 2D analysis were verified using 3D analysis. Thermal analysis was done to set the operating limit of the proposed machine.

In the paper by Choi [8], analyses and experimental verification of the demagnetization vulnerability in PM synchronous machine are presented. Safety is a critical feature for all passenger vehicles, ensuring fail-safe operation of the traction drive system is highly important. Increasing demands for traction drives that can operate in challenging environments over wide constant power speed ranges expose permanent magnet (PM) machines to conditions that can cause irreversible demagnetization of the rotor magnets. In this paper, a comprehensive analysis of the demagnetization vulnerability in PM machines for an electric vehicle (EV) application is presented. The first half of the paper presents rotor demagnetization characteristics of several different PM machines to investigate the impact of different design configurations on demagnetization and to identify promising machine geometries that have higher demagnetization resistance. Experimental verification results of rotor demagnetization in an interior PM (IPM) machine are presented in the latter half of the paper. The experimental tests were carried out on a specially designed locked-rotor test setup combined with a closed-loop magnet temperature control. Experimental results confirm that both local and global demagnetization damage can be accurately predicted by time-stepped finite element (FE) analysis.

Bi et al. [9] show research on electromagnetic fields, eddy current losses, and heat transfer in synchronous condensers. Aiming at the problem of end structure heating caused by the excessive eddy current loss of large synchronous condensers used in ultra-high voltage (UHV) power transmission, combined with the actual operation characteristics of the synchronous condenser, a three-dimensional transient electromagnetic field physical model was established, and three schemes for adjusting the end structure of the condenser under rated condition were researched. The original structure had a copper shield and a steel clamping plate. During the research, two modifications were made relative to the original design; in the first, the copper shield was removed, while in the second, a steel clamping plate was additionally replaced with aluminum. By constructing a three-dimensional fluid–solid coupling heat transfer model at the end of the synchronous condenser, and giving the basic assumptions and boundary conditions, the eddy current loss of the structure calculated by the three schemes was applied to the end region of the synchronous condenser as the heat source, and the velocity distribution of the cooling medium and the temperature distribution of each structure under the three different schemes were obtained. In order to verify the rationality of the numerical analysis model and the effectiveness of the calculation method, the temperature of the inner edge of the copper shield in the end of the synchronous condenser was measured, and the temperature calculation results are consistent with the temperature measurement results, which provides a theoretical basis for the electromagnetic design, structural optimization, ventilation, and cooling of the synchronous condenser.

Franck et al. [10] refer to analysis of structural dynamic interactions of electric drivetrains. In electric drivetrains, the traction machines are often coupled to a gear transmission. For the noise and vibration analysis of such systems, linearized system models in the frequency domain are commonly used. In this paper, a system approach in the time domain is introduced, which gives the advantage of analyzing the transient behavior of an electric drivetrain. The focus of this paper is on the dynamic gear model. Finally, the modeling approach is applied to an exemplary drivetrain, and the results are discussed.

In the article by Groschup et al. [11], the influence of a preformed coil design on the thermal behavior of electric machines is discussed. Preformed coils are used in electrical machines to improve the copper slot fill factor. A higher utilization of the machine can be realized. The improvement is a result of both low copper losses due to the increased slot fill factor and an improved heat transition out of the slot. In this study, the influence of these two aspects on the operational improvement of the machine were studied. Detailed simulation models allowed a separation of the two effects. A preformed wound winding in comparison to a round wire winding was studied. Full machine prototypes as well as motorettes of the two designs were built. Thermal finite element models of the stator slot were developed and parameterized with the help of motorette microsections. The resulting thermal lumped parameter model is enlarged to represent the entire electric machine. Electromagnetic finite element models for loss calculation and the thermal lumped parameter models are parameterized using test bench measurements. The developed models show very good agreement in comparison to the test bench evaluation. The study indicates that both the improvements in the heat transition path and the advantages of the reduced losses in the slot contribute to the improved operational range in dependency of the studied operational point.

The paper by Dukalski and Krok [12] discusses the problem of decreasing the mass of a wheel hub motor by improving the design of a motor's electromagnetic circuit. The authors propose increasing the number of magnetic pole pairs. They present possibilities of mass reduction obtained through these means. They also analyzed the impact of design changes on losses and the temperature distribution in motor elements. Lab tests of a constructed prototype, as well as elaborated conjugate thermal-electromagnetic models of the prototype motor and modified motor (i.e., motor with increased number of magnetic poles) were used in the investigations. Simulation models were verified by tests on the prototype. Results of calculations for two motors, differing by the number of pair poles, were compared over a wide operational range specific to the motor application in the electric traction. A detailed analysis of the operational range for these motors was also performed.

Wang et al. [13] deal with nonlinear simulation models of a drive consisting of the four-phase 8/6 doubly salient switched reluctance motor (SRM), the four-phase dissymmetric bridge power converter and the closed-cycle rotor speed control strategy carried out by the pulse width modulation (PWM) with a variable angle and combined control scheme with the PI algorithm. All presented considerations are based on a MATLAB-SIMULINK platform. The nonlinear mathematical model of the analyzed SRM drive was obtained as a combination of the two dimensional (2D) finite element model of the motor and the nonlinear model of the electrical network of the power supply circuit. The main model and its seven sub-modules, the controller module, one phase simulation module, rotor position angle transformation module, power system module, phase current operation module, "subsystem" module, and electromagnetic torque of one phase operation module are described. MATLAB functions store the magnetization curves data of the motor obtained by the 2D FEM electromagnetic field calculations, as well as the data of magnetic co-energy curves of the motor calculated from the magnetization curves. The 2D specimen insert method is adopted in MATLAB functions for operating the flux linkage and the magnetic co-energy at the given phase current and rotor position. The phase current waveforms obtained during simulations match with the tested experimentally phases current waveforms at basically the same rotor speed and under the same load. The simulated rotor speed curves also agree with the experimental rotor speed curves. This means that the method of suggested nonlinear simulation models of the analyzed SRM drive is correct and that the model is accurate.

Palomo and Gwozdziewicz [14] present the design and analysis of a permanent magnet synchronous generator. The interior permanent magnet rotor was designed asymmetrically and with the consequent pole approach. The basis for the design was a series-produced three-phase induction motor and neodymium iron boron (Nd-Fe-B) cuboid magnets that were used for the design. For the partial demagnetization analysis, some of the magnets were extracted and the results are compared with the finite element analysis.

Gozdowiak [15] presents simulation results of hydro generator faulty synchronization during connection to the grid for various voltage phase shift changes in a full range ($-180°$; $180°$). A field-circuit model of salient pole synchronous hydro generator was used to perform the calculation results and was verified using the measured no-load and three-phase short-circuit characteristics. This model allowed observing the physical phenomena existing in the investigated machine, especially in the rotor which was hardly accessible for measurement. The presented analysis shows the influence of faulty synchronization on the power system stability and the construction components that are the most vulnerable to damage. From a mechanical point of view, the most dangerous case was for the voltage phase shift equal to $-120°$, and this case was analyzed in detail. Great emphasis was placed on the following physical quantities: electromagnetic torque, stator current, stator voltage, rotor current, current in rotor bars, and active and reactive power. The physical quantities existing during faulty synchronization were compared with a three-phase sudden short-circuit state. From this comparison, the values of physical quantities that should be taken into account during design of new hydro generators to withstand the greatest possible threats during long-term work were taken into account.

In the paper by Korkosz et al. [16] tests on a brushless permanent magnet DC motor with different winding configurations were carried out. Three configurations were compared: star, delta, and combined star–delta. A mathematical model was constructed for the motor considering the different winding configurations. An analysis of the operation of the motor in the different configurations was performed, based on numerical calculations. The use of different winding configurations affects the properties of the motor. This is significant in the case of the occurrence of various fault states. Based on numerical calculations, an analysis of an open-circuit fault in one of the phases of the motor was performed. Fast Fourier transform (FFT) analysis of the artificial neutral-point voltage was used for the detection of fault states. The results were verified by tests carried out under laboratory conditions. It was shown that the winding configuration had an impact on the behavior of the motor in the case of an open circuit in one of the phases. The classical star configuration is the worst of the possible arrangements. The most favorable in this respect is the delta configuration. In the case of the combined star–delta configuration, the consequences of the fault depend on the location of the open circuit.

The paper by Wardach et al. [17] deals with the overview of different designs of hybrid excited electrical machines, i.e., those with conventional permanent magnets excitation and additional DC-powered electromagnetic systems in the excitation circuit. The paper presents the most common topologies for this type of machine found in the literature—they were divided according to their electrical, mechanical, and thermal properties. Against this background, the designs of hybrid excited machines, that were the subject of scientific research of the authors, are presented.

The final paper [18] by Baek et al. develops a simulation model of a 120-kW class electric all-wheel-drive (AWD) tractor and verify the model by comparing the measurement and simulation results. The platform was developed based on the power transmission system, including batteries, electric motors, reducers, wheels, and a charging system, composed of a generator, an AC/DC converter, and chargers on each axle. The data measurement system was installed on the platform, and consisted of an analog (current) and a digital part (rotational speed of electric motors and voltage and SOC (state of charge) level of batteries) by a CAN (controller area network) bus. The axle torque was calculated using the current and torque curves of the electric motor. The simulation model was developed using 1D simulation software and used axle torque and vehicle velocity data to create the simulation conditions. To compare the results of the simulation, a driving test using the platform was performed at a ground speed of 10 km/h in off- and on-road conditions. The similarities between the results were analyzed using statistical software and we found no significant difference in axle torque data. The simulation model was considered to be highly reliable given the change rate and average value of the SOC level. Using the simulation model, the workable time of driving operation was estimated to be about six hours and the workable time of plow tillage was estimated to be about 2.4 h. The results showed that the capacity of the battery was slightly low for plow tillage. However, in future studies, electric AWD tractor performance could be improved through battery optimization through simulations under various conditions.

The subject of the "Design and Application of Electrical Machines" Special Issue turned out to be very topical, as evidenced by 18 scientific papers included in it. Currently, more and more scientists are taking up the topic of electric vehicle drives. A huge role in this respect is played by the significant development in the field of modern electrotechnical materials (such as permanent magnets, electrical steel sheets, insulation materials, etc.). In addition, faster and more efficient computational software that supports the process of designing electrical machines prove that the results obtained using them are more and more similar to the results obtained during experimental research. All these problems were also discussed in this Special Issue of *Energies*. Similar research about design, simulation and electrical machine optimization are also discussed in some previous publications [19–22] not included in this Special Issue.

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