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***Abstract*- This paper presents a brief overview on recent technological developments related to resolving the issues due to usage of permanent magnets in synchronous machines. This paper sheds some light on the latest technological developments, which have emerged in recent years, such as wound rotor synchronous machines, brushless WRSMs, and many others. Their aim is to address some of the issues with the conventional permanent magnet (PM) machines, such as recent unavailability, high cost, and demagnetization issues. The idea is to develop a brushless and wound-rotor type motors for dual speed applications, such as in washing machines, machines with high starting torque, and few other applications such as hybrid electric vehicles (HEVs). The main idea here is to minimize the use of permanent magnets (PM) by developing alternate methods.**

***Keywords*-Permanent magnets (PM), Synchronous machines, Demagnetization, Permanent magnet synchronous machines (PMSM), Wound-rotor synchronous machines (WRSM), Brushless WRSMs, Dual-speed applications, Hybrid electric vehicles (HEVs).**

I. INTRODUCTION

Permanent Magnet Synchronous Machines (PMSMs) are a type of electric motor that use permanent magnets to generate the magnetic field necessary for operation. The PMSMs offer various advantages, such as high efficiency and power density. Hence, the permanent magnet synchronous machines have been widely used over the years for a wide range of applications such as in pumps, compressors, rolling mills, fans, blowers, washing machines, hybrid electric vehicles (HEVs), to name a few. But in recent times, many challenges have come up, due to increasing use of permanent magnets, such as shortage of rare earth magnetic materials like Neodymium and samarium-cobalt. The cost of these materials can be high, and there are concerns about the environmental and geopolitical implications of relying on scarce resources. Apart from these, the PMs face the issue of demagnetization, and tend to lose their magnetism over time, and under certain operating conditions such as high temperatures, overcurrent and voltage spikes, which affects the motor performance. PMSMs may face limitations in terms of size and weight, especially in applications where space and weight are critical factors. Balancing the trade-off between power density and physical size can be a challenge. This paper therefore presents some of the latest technological developments, which help to overcome some of these problems.

II. DESIGN OF A NOVEL LOW-COST CONSEQUENT-POLE PERMANENT MAGNET SYNCHRONOUS MACHINE

A novel low-cost consequent-pole permanent magnet (CPM) synchronous machine structure, with respect to the reluctance torque utilization. It is presented in this section. In order to maximize the reluctance torque utilization and minimize costs, a novel CPM machine with doubled salient ferromagnetic iron poles (ICP-PMSM) is proposed. It features a N pole iron-S pole iron sequence. In order to preserve the same magnetic rotor pole number as the traditional CPM synchronous machine (CP-PMSM), flux barriers are integrated into the rotor structure. Second, to improve the air-gap flux density distribution and achieve a low torque ripple, a portion of the iron pole in the ICP-PMSM (ISCP-PMSM) is replaced with soft ferrite. In addition, the rotors of the CP-PMSM, ICP-SPMSM, and ISCP-PMSM are tuned for a fair comparison. All of the optimized machines' electromagnetic performances are compared with those of a typical SPMSM (surface permanent magnet synchronous machine). It is shown that, in comparison to the SPMSM, the ISCP-PMSM can achieve nearly equal torque and torque ripple at a lower cost and with less PM (NdFeB) usage. Another important factor influencing motor performance is the material used. When assembling the PM motor, the stator and rotor core are typically made of silicon steel sheets. Soft ferrite is occasionally used in high-speed PM motors due to its high permeability, high resistivity, and low loss in a high-frequency alternating magnetic field; this helps to improve electronic equipment efficiency and eliminate noise. Nonetheless, soft ferrite has a magnetic saturation point of about 0.5 T. The torque density must be low if it is applied to both the stator and the rotor well. However, because of this property, using it in the motor core can aid in the equalization of the magnetic density distribution. In order to maximize the output torque at the zero-phase current angle, this study first proposes the use of PM torque and reluctance torque in CPM machines. The torque performance can be further enhanced by substituting soft ferrite for a portion of the iron pole. The analytical model is based on the following assumptions to analyse the working principles:

1) The rotor and stator iron cores have infinite permeance.

2) The relative recoil permeability of the PMs and the air-gap are the same.

3) The flux leakage and end effect are not considered.

The two magneto-motive force (MMF) sources that make up the magnetic flux paths in a typical SPMSM are the N and S PM poles, which have opposing polarities, and the reluctance of each component. The air-gap flux in each magnetic pole of a conventional SPMSM can be obtained using the simplified MEC modelling method as follows:

$$\Phi_g = \frac{2\,F_m}{2\,R_m + R_{gm} + R_{gip} + R_{sc} + R_{rc}} \approx \frac{2\,F_m}{2\,R_m + R_{gm} + R_{gip}} \qquad (1)$$

where Fm denotes the magnetic reluctance of the PM pole, Rm is the magnetic reluctance of the PM, and Rgm and Rgip are the magnetic reluctances of the air-gap facing the PM and iron pole, respectively. Rsc and Rrc are the stator and rotor core reluctances, which can be ignored in the simplified magnetic model. For the conventional SPMSM, there is no difference in inductance between the d- and q-axes, so no reluctance torque is generated. The torque equation is written as follows:

$$T_m = \frac{3p}{2}[\Lambda_{pm} i_q] \qquad (2)$$

where p denotes the number of pole pairs, Λ_{pm} denotes the maximum fundamental value of the rotor flux connecting the stator windings, and iq denotes the maximum value of the phase current. As a result, id = 0 control is commonly used for conventional SPMSMs as the most cost-effective and efficient method. All of the N- or S-pole PMs in the conventional CP-PMSM are replaced by salient ferromagnetic iron, which provides the magnetic flux path for the remaining PMs. As a result, the number of PMs in the conventional CP-PMSM is half that of the SPMSM; that is, the MEC of a pair of poles consists of only one PM to form an MMF source.

The problem with this type of machine here is that regardless of the PM-arc ratio, the average torque and torque ripple cannot reach that of a conventional SPMSM. And that even though the average torque can be satisfied, the torque ripple is still high.

III. THREE-PHASE DUAL-WINDING MULTITASKED PMSM MACHINE USING DOUBLE LAYER CONCENTRATED WINDING FOR HEV APPLICATION

This section proposes a three-phase dual-winding permanent magnet synchronous machine (PMSM) for accessory drive systems in hybrid electric vehicles (HEV). The proposed machine is to be designed with special slots and pole combinations with specific configuration of two sets of double-layer concentrated group windings. They are separated by the unwound tooth between the phase groups formed on the same stator to achieve both motoring and generator operation simultaneously as well as independent of each other. This is the novelty of this research. These operations are carried out by incorporating separate motor and generator windings on the same stator of a single PMSM machine. This single machine is specifically designed to eliminate mutual coupling between these two sets of windings, so that load variation on the generator has no effect on the motor's mechanical output power. To validate this multitasking, the machine's electromagnetic design and operating modes are presented and analysed. The performance is compared to that of a conventional PMSM machine with a double-layer winding configuration using finite element analysis. This single machine is specifically designed to eliminate mutual coupling between these two sets of windings, so that load variation on the generator has no effect on the motor's mechanical output power. To validate this multitasking, the machine's electromagnetic design and operating modes are presented and analysed. The performance is compared to that of a conventional PMSM machine with a double-layer winding configuration using finite element analysis.

Some essential accessory loads in conventional hybrid electric vehicles, such as the power steering pump, air conditioner compressor, heating system, lighting, and power windows, require continuous power regardless of vehicle motion. This power is supplied either directly from the internal combustion engine via the belt mechanism or via an Electric Accessory Drive (EAD) system's Lundell alternator.

However, in the EAD system, a single PMSM machine (with a double-layer winding) is proposed to perform multitasking while eliminating both the separate alternator and the need for engine operation when the vehicle is not moving. This EAD system demonstrates the advantages of cost and installation space utilization. The dual winding single PMSM machine's motor will power the mechanical loads, while the generator will power the electrical loads and charge the low-voltage battery via a converter. The reference and proposed PMSM machines have the following topologies: the reference machine has 48 slots on the stator and 64 magnet poles on the rotor, while the proposed machine has 60 slots on the stator and 64 magnet poles on the rotor. Both machines incorporate two sets of double-layer concentrated winding (one set as M-winding for the motor and another set as G-winding for the generator) into the stator slots to accommodate 48 coils, but the proposed machine is unique in its design. The winding configuration in the reference machine is typical, with a coil span of one slot, and M1, M2, M3, G1, G2, and G3 are the phases of the motor winding and generator winding respectively. On the other hand, the suggested machine has twelve groups of coils on the stator, each with four coils and a coil span of one slot. These coil groups are further separated into two sets of distinct windings, known as the generator (or G-winding) and the motor (or M-winding). Furthermore, the balanced three-phase winding is maintained while one tooth between the neighbouring groups is left unwound. The spatial distribution of windings in two machines varies as a result. Zero mutual coupling effect between M- and G-winding, ease of winding, and the ability to divide the machine's stator into equal parts from the centre of the unwound tooth for transportation convenience are some of the advantages of the suggested topology.

Due to the typical nature of winding, the coil sides of M-winding and G-winding overlap in a few slots in a reference PMSM machine. In the proposed machine, however, the end coils of groups of M-winding and G-winding are separated by an unwound tooth. The flux from the north magnet pole enters the stator tooth via the airgap and returns to the adjacent south magnet pole via the stator yoke, adjacent tooth, and airgap. Finally, flux closes the loop through the rotor core. The flux linkage is felt by both sets of windings of the stator, resulting in their induced back-EMF. Four rotor magnet poles are attracted and aligned with the corresponding teeth on the stator based on the polarity of currents in the coils with this phase group. As a result, at any given time, eight rotor poles are aligned with the teeth of two groups per winding phase, and the rotor continues to rotate with the winding excitation. Hence, the machine is designed in such a way that zero mutual coupling exists between two sets of windings in the proposed PMSM machine, for which the machine's winding needs to be isolated magnetically and electrically in order to remove the coupling. The main problem here is that the core losses in the proposed machine are higher compared to the reference machine, because of the higher flux densities in the teeth of the particularly designed stator. The resulting efficiencies of the reference machine and the proposed machine are 91.9 % and 90.8%, respectively. The efficiency is significantly lower in the proposed machine than that of the reference machine due to increased losses.

IV. DERIVATION OF OPTIMAL ROTOR TOPOLOGIES FOR CONSEQUENT-POLE PMSM BY ON/OFF METHOD

Consequent-pole permanent magnet synchronous machines (CP-PMSMs) have sparked considerable interest among researchers as a means of lowering manufacturing costs by significantly reducing the volume of permanent magnet required to meet a given torque specification. Novel rotor topologies for a CP-PMSM are developed in this paper to realize the full design space potential. The ON/OFF method is introduced to manage the laminated steel material distribution over the rotor region, the objects of rotor design are high average torque and low torque ripple, and the immune algorithm is used to search for the optimal material distribution for the formulated problem. This methodology generates and evaluates over 9000 different rotor topologies in 12 hours. The optimal topologies under different design strategies are looked upon in this paper, and performance of these topologies are analysed. The analysis results show that the proposed methodology can deliver novel rotor topologies for the CP-PMSM with surprisingly good torque quality since the torque ripple is suppressed to a low level with no sacrifice in average torque.

Electrical machines, particularly permanent magnet (PM) machines, have been used in a variety of industrial applications to meet the ongoing demand for energy savings and emission reductions across several related sectors because they can combine competitive torque density with high efficiency. However, because the processing of rare earth PMs emits a significant amount of greenhouse gases and the supply of rare earth in some countries is limited, the conventional topologies, such as surface mounted PM (SPM) machines and interior PM (IPM) machines, which rely on relatively large quantities of

PM material, are becoming an issue. As a result, many less or no PM machines have been developed in recent years. Despite the fact that developed PM-saving machines such as hybrid excitation PM machines, switched reluctance machines, and synchronous reluctance machines can reduce PM consumption, they still have low torque density or efficiency. The consequent-pole (CP) structure is an appealing option for PM machines. The CP structure is proposed first to improve the flux adjusted capability of hybrid-excited machines, and then to improve the suspension force of the bearing less PM machine.

In this section the main aim is to investigate optimal rotor topologies in a CP-PMSM using a topology optimization-based approach. To manage the distribution of laminated steel material over the rotor region, the machine is modelled using the finite element (FE) method and Delaunay triangulation, ON/OFF method. The optimization objects are high average torque and low torque ripple, and the immune algorithm (IA) is used to find the best material distribution for the formulated problem. The topology optimization approach is used to discover the undeveloped design potential of the CP-PMSM. However, previously published topology optimization studies make use of rectangle cells to form the optimization model. Whereas, the Delaunay algorithm-based FE meshes are directly used as the cells in this study to present the optimization model, making the proposed methodology a general technique for optimal material distribution design that can be directly integrated into commercial FE analysis software.

The two optimal design targets, the average torque and torque ripple, are normalized tom from the objective function

$$F=(1\text{-}w)\,\frac{T_{ave}}{T_{ave}^{conv}} - w\,\frac{T_{rip}}{T_{rip}^{conv}}$$

where T_{ave} and T_{ave}^{conv} are the average torque and torque ripple (peak-peak value) of the conventional CP-PMSM. T_{ave}, T_{rip} , and w are average torque, torque ripple and weighting factor, respectively. A penalty function for average torque is not used in the objective function since we consider that a little torque sacrifice is acceptable if the ripple can be suppressed to a low level.

The Topology Optimization (TO), is carried out with two optimization strategies (OS) in mind, with the weighting factors w set to 0.5 and 0.8, respectively. It is worth noting that in both cases, the algorithm prioritizes improving average torque and suppressing torque ripple. The TO is performed as the stop condition over 200 generations. In this case, the program evaluates over 9000 topologies in about 12 hours.

Furthermore, because the Delaunay triangular FE elements are directly used as the cells in the ON/OFF method to constitute the optimization model, the proposed optimal topology derivation methodology is general for the optimal material distribution design in other electric machines and can be directly integrated into commercial FE analysis software.

Future research could focus on topology optimization in terms of processability, efficiency, and machine drive. The main drawback though here is that the optimized solutions might be difficult to interpret physically. The resulting rotor topology may be a mathematical solution that is challenging to implement practically or may not have clear physical insights. Understanding and incorporating practical considerations into the optimization process are essential. Also, deriving these optimal topologies involves complex mathematical and computational processes. Depending on the method used, these optimization techniques may be computationally sensitive and may require sophisticated algorithms, and could lead to longer design times and higher computational costs.

V. DUAL-MODE WOUND ROTOR SYNCHRONOUS MACHINE FOR VARIABLE SPEED APPLICATIONS

A new dual-mode wound rotor synchronous machine (DWRSM) for variable speed applications is presented here. The suggested device incorporates the salient features of both the conventional wound rotor synchronous machine (CWRSM) and the brushless wound rotor synchronous machine (BWRSM). Unlike the current BWRSM, the suggested machine's dual-mode operation allows for the achievement of constant torque in the constant torque region by running it in mode-I, or as a CWRSM, and constant power in the field weakening region by running it in mode-II, or as a BWRSM. An extra thyristor drive circuit is used to carry out the mode change. An analytical method is used to derive the airgap magnetomotive force (MMF) in both modes. This principle was verified using Finite Element Analysis (FEA) technique, an experiment was performed on a 1 horsepower (HP) prototype machine, and the key influential factors were verified. The transients in the stator currents and torque during the change of mode were analysed. The correctness of the theory and the FEA results were validated by the test results.

The proposed DWRSM is validated by designing an eight-pole, twelve-slot machine with three-phase double layer distributed windings on the stator. To make the proposed DWRSM work, the stator winding is distributed in such a way that there are two sets of windings called as winding ABC and winding XYZ. They are placed on opposite sides of the machine and are connected in series. The machine's rotor has two distinct windings: the harmonic winding and the field winding. To achieve the proposed topology's operating principle, the pole pitch of the rotor harmonic winding is kept double that of the rotor field winding. As a result, the harmonic winding is composed of four poles. The eight-pole field winding is used to generate output torque by synchronizing with the eight-pole stator MMF.

There are two modes of operation of the proposed DWRSM topology, namely mode-1 and mode-2. In mode-1, the machine works under constant-torque region, operating as a Dual Wound Rotor Synchronous machine (DWRSM). The three phase sinusoidal currents are supplied to the stator winding through an inverter. The field winding is connected to the external DC supply through brushes and slip-ring assembly. The generation of the air-gap MMF in mode-1 is theoretically explained by considering an eight-pole machine with concentrated full-pitch winding on the stator. For this mode of operation of the DWRSM, the three phase alternating currents excite the stator windings and generate the rotating MMF. The rotating MMF can be expressed as

$$F(\Phi, i) = \sum_{i=1}^{m} N_i(\Phi)\, i_i(t)$$

where Φ denotes the angular measure around the air-gap of the machine, N_i is the winding function describing the position and the polarity of the coil sides, and $i_i(t)$ is the current in the respective winding. In the mode-2 of operation the proposed topology works as a Brushless WRSM (BWRSM). The stator is connected in such a way that the number windings in the XYZ winding becomes half of that of ABC winding. Meanwhile, the external DC supply is disconnected from the field winding. The benefits of creating a difference in the number of turns in both windings, winding ABC and winding XYZ, are twofold: first, the difference in winding ABC and XYZ turns is responsible for the generation of a sub-harmonic MMF alongside fundamental MMF; second, it reduces the stator total number of turns per phase by a factor of four, which will help to increase the constant power speed region.

Hence, a novel DWRSM for variable speed applications was looked upon in this section. The proposed machine overcomes the problem of achieving the desired torque in the constant torque region, making this machine topology suitable for variable speed applications.

Although brushes and sliprings are still used in the proposed DWRSM's constant torque region, the electrical stress on the brushes and sliprings, as well as the electrical losses of the brushes and sliprings, are eliminated in the constant power region. Furthermore, the proposed DWRSM was analysed for wide speed range operation, yielding a four-times-rated speed range. A prototype was also built to test the proposed machine's dual mode operation. The mode change was performed in two steps using a thyristor drive circuit. The increase in the phase current in the transient was around two times the rated current for a duration of one cycle. The experimental results proved the feasibility of the proposed machine for variable speed applications. The problem in this proposed machine is that at certain operating points, dual-mode wound rotor synchronous machines may exhibit torque ripple, which can affect the smoothness of operation and overall performance in variable speed applications. The use of slip rings and brushes can lead to additional electrical losses and reduced efficiency compared to brushless machines. This is especially important in applications where energy efficiency is a critical factor. Regular maintenance is required to ensure the proper functioning, which can be challenging in certain applications. Moreover, the construction and control systems of dual-mode machines can be more expensive than other variable speed drive options. This cost factor may have an impact on these machines' overall competitiveness in certain markets. When compared to other variable speed drive technologies, the design of dual-mode machines may result in larger and heavier machines. This can be a major issue in applications where space and weight are critical.

VI. DUAL-MODE BRUSHLESS WOUND ROTOR SYNCHRONOUS MACHINE FOR HIGH STARTING TORQUE

A dual-mode brushless wound rotor synchronous machine (DBL-WRSM) for high starting torque is proposed here, The proposed DBL-WRSM has two operating modes: induction and brushless (BL) synchronous. First, to achieve a high starting torque, the induction mode operates as a wound rotor induction machine (WRIM). Second, in steady state, the BL-synchronous mode operates as a brushless wound rotor synchronous machine (BL-WRSM) by utilizing the subharmonic of the stator magnetomotive force (MMF). To realize the proposed machine's dual-mode topology, the stator is made up of two divided armature windings and two inverters capable of producing subharmonics. The rotor is equipped with five switches that switch the rotor winding configuration between the two modes. Finite element analysis (FEA) was used to validate the proposed DBL-WRSM topology. Through the FEA results of the transient electromagnetic torque for the voltage source, it was confirmed that the proposed DBL-WRSM not only operates as a BL-WRSM in a steady state but also has a sufficiently high starting torque even under a full load condition.

This section proposes a dual-mode BL-WRSM (DBL-WRSM) that takes into account the advantages of a wound rotor induction machine (WRIM) over conventional BL-WRSM to achieve a high starting torque.

The proposed DBL-WRSM topology is designed in such manner that the stator has two sets of armature windings with the same number of turns, viz. ABC and XYZ.

To generate subharmonics, different magnitude currents are injected into the two parts of the stator windings via two inverter operations using the brushless topology. The DBL-WRSM rotor has three windings and an excitation winding. To improve starting torque and achieve dual-mode operation, three resistors and five switches are used. Based on the proposed DBL-WRSM, a 2-D model of the machine with 48 stator slots and 8 poles was created. The stator has armature windings that are distributed in two layers. The armature winding is divided into two sections for the two inverter operations: ABC and XYZ. An excitation winding and three rotor windings make up the rotor.

The proposed DBL-WRSM has an induction mode that acts as a WRIM and a BL-synchronous mode that acts as a BL-WRSM. In induction mode, the machine acts as a WRIM to achieve a high starting torque. In the BL-synchronous mode, the machine operates on the BL-WRSM principle, utilizing the stator MMF subharmonics. The subharmonics required for the BL-WRSM operation are generated by two inverters. To generate subharmonics with two inverters, one inverter's input current must be half that of the other inverter. To halve the current, however, the magnitude of the voltage must be reduced. Therefore, considering the electrical time-constant of the stator winding, the induction mode has two steps, step-1 and step-2.

In the induction mode, the machine acts as a WRIM to increase starting torque. This mode is divided into two steps: step-1 and step-2.

Step 1 involves running the proposed machine as a WRIM to generate a high starting torque. The armature windings XYZ and ABC are connected to two independent inverters in the stator and the same voltage and current are applied to the ABC and XYZ armature windings, respectively. Furthermore, the applied current is the same for both the ABC and XYZ armature windings. Switches S1 and S3 of the rotor are ON, and switches S4 and S5 are OFF; thus, the rotor consists only of three-phase windings and resistors. This topology is similar to the WRIM, with a structure that connects the windings and resistors. To improve the starting torque, the amplitude of the machine proposed in STEP-I operates as a WRIM and has a high starting torque. The step-2 of the induction mode involves adjusting the input voltages of the two inverters to implement the subharmonic of the stator MMF. The topology of the stator and the switching state connected to the rotor windings in step-2 are the same as in step-1. Only the input voltage and current values of the inverter on XYZ differ. The magnitude of the input current at the inverter in the XYZ armature winding should be half that in the ABC armature winding to generate the subharmonics. The voltage must be reduced to reduce the current. Even if the stator XYZ's armature winding voltage is reduced, the current does not decrease immediately due to the electrical time constant of the stator winding, and it remains unstable. Unstable current conditions cannot generate the desired subharmonics, which can cause mode changes to fail.

The machine operates as a BL-WRSM using subharmonics in the BL-synchronous mode. The stator topology and input voltages in the ABC and XYZ armature windings in this mode are the same as in step-2 in the induction mode. Switches S1 and S3 of the rotor are turned off, while S4 and S5 are turned on. As a result, the rotor's winding structure is changed from three-phase winding connected in parallel to, the field winding connected in series. Furthermore, the rectifier connects the field winding in the rotor to the excitation winding.

Hence, a DBL-WRSM with a high starting torque is proposed in this section. The proposed machine has a compact structure and can generate a high starting torque by utilizing the WRIM, as opposed to the DWRSM, which has a complicated overall system structure by utilizing brushes and an external

DC power supply. To validate the proposed DBL-WRSM, a 2-D FEA was performed. The dynamic performance demonstrated the system's actual performance. The proposed machine operated as a WRIM in induction mode, and transient simulation results confirmed a high starting torque. The proposed DBL-WRSM's brushless operation was verified in BL-synchronous mode. The simulation results and theoretical discussion demonstrate the feasibility of the proposed DBL-WRSM. But, the main drawbacks of the machine presented in this paper are that the transition between asynchronous and synchronous modes can result in energy losses, which may occur during the switching process and the use of additional components, reducing overall system efficiency. The transition between asynchronous and synchronous modes can have an impact on power quality, causing voltage fluctuations and harmonics. To address these power quality concerns, additional filtering or compensation devices may be required. Dual-mode wound rotor machines, particularly in asynchronous mode, may have a limited speed range. This limitation may limit the machines' applicability in certain applications requiring a wide speed range.

CONCLUSION

In conclusion, this review paper offers a thorough examination of the difficulties and developments in the field of resolving problems with permanent magnet use in synchronous machines. A comprehensive analysis of the state of permanent magnet uses in synchronous machines today, stressing on both the achievements and the obstacles still present, is presented here. In order to overcome these obstacles and realize permanent magnet technology's full potential in the realm of electrical machines, it emphasizes the significance of continued research and technological innovation. Hence, this review paper outlines the potential future directions for research and development in the field. This entails investigating novel materials, cutting-edge production processes, and clever control schemes to further enhance the effectiveness and performance of permanent magnet synchronous machines.

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