IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676, p-ISSN: 2320-3331, Volume 19, Issue 1 Ser. 1 (Jan. – Feb. 2024), PP 08-14
www.iosrjournals.org

Review On Resolution Of Issues Related To Permanent Magnet Usage In Synchronous Machines

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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).*

Date of Submission: 01-01-2024 Date of acceptance: 11-01-2024

I. INTRODUCTION

Electric motors known as permanent magnet synchronous machines (PMSMs) create the magnetic field required for operation using permanent magnets. The PMSMs have a number of benefits, including high power density and efficiency. As a result, permanent magnet synchronous machines have seen extensive use over time in a variety of applications, including pumps, blowers, compressors, rolling mills, fans, and hybrid electric vehicles (HEVs), to mention a few. However, as permanent magnet usage has increased recently, a number of issues have emerged, including a lack of rare earth magnetic materials like neodymium and samarium cobalt. These materials can be expensive, and depending on limited resources raises questions about the geopolitical and environmental effects. In addition to this, the PMs experience demagnetization, which causes them to lose their magnetism over time and in response to specific operating circumstances like high temperatures, overcurrents, and voltage spikes, all of which impair motor performance. Size and weight restrictions may apply to PMSMs, particularly in applications where these parameters are crucial. It can be difficult to strike a balance between power density and physical size. In order to address some of these issues, this paper highlights some of the most recent technological advancements.

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

This section presents a novel low-cost consequent-pole permanent magnet (CPM) synchronous machine structure in terms of the reluctance torque utilization. The proposal is for a novel CPM machine with doubled salient ferromagnetic iron poles (ICP-PMSM) to optimize the reluctance torque utilization while reducing expenses. It has an iron sequence with N poles and S poles. Flux barriers are built into the rotor structure to maintain the same magnetic rotor pole number as the conventional CPM synchronous machine (CP-PMSM). Second, a portion of the iron pole in the ICP-PMSM (ISCP-PMSM) is replaced with soft ferrite in order to improve the air-gap flux density distribution and achieve a low torque ripple. Furthermore, for a fair comparison, the rotors of the CP-PMSM, ICP-SPMSM, and ISCP-PMSM are tuned. The electromagnetic performances of all the

optimized machines are compared with a standard SPMSM (surface permanent magnet synchronous machine). Evidence is presented that the ISCP-PMSM can achieve nearly equal torque and torque ripple at lower cost and with less PM (NdFeB) usage when compared to the SPMSM. The material used has a significant impact on motor performance as well. The stator and rotor core of the PM motor are usually constructed from silicon steel sheets. Because of its high permeability, high resistivity, and low loss in a high-frequency alternating magnetic field, soft ferrite is occasionally used in high-speed PM motors. This helps to reduce noise and increase the efficiency of electronic equipment. However, the magnetic saturation point of soft ferrite is approximately 0.5 T. If the torque density is applied to the rotor as well as the stator, it needs to be low. On the other hand, this characteristic makes its application in the motor core advantageous for promoting magnetic density distribution equalization. This study first suggests using PM torque and reluctance torque in CPM machines to maximize the output torque at the zero-phase current angle. 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 three-phase dual-winding permanent magnet synchronous machine (PMSM) for hybrid electric vehicle (HEV) accessory drive system. The proposed machine will have a unique slot and pole combination as well as a unique configuration of two sets of double layer concentrated group windings. They are separated by unwound teeth between phase groups formed in the same stator to achieve simultaneous motor and generator operation independent from each other. This is the novelty of this research. Separate motor and generator windings are installed on the same stator of a single PMSM machine to accomplish these tasks. The purpose of this single machine is to remove mutual coupling between these two sets of windings, preventing load variation on the generator from affecting the mechanical output power of the motor. The electromagnetic design and operating modes of the machine are presented and analysed in order to validate this multitasking. Finite element analysis is used to compare the performance to that of a traditional PMSM machine with a double-layer winding configuration. The purpose of this single machine is to remove mutual coupling between these two sets of windings, preventing load variation on the generator from affecting the mechanical output power of the motor. The electromagnetic design and operating modes of the machine are presented and analysed in order to validate this multitasking. Finite element analysis is used to compare the performance to that of a traditional PMSM machine with a double-layer winding configuration.

In traditional hybrid electric vehicles, certain necessary accessory loads—like the air conditioner compressor, power windows, heating system, power steering pump, and lighting—need to be powered continuously even when the vehicle is not moving. The Lundell alternator of an Electric Accessory Drive (EAD) system or the belt mechanism of the internal combustion engine are the two sources of this power. In the EAD system, on the other hand, a single PMSM machine (with a double-layer winding) is suggested to accomplish multitasking while doing away with the requirement for an independent alternator and running the engine when the car is not in motion. The advantages of cost and installation space utilization are demonstrated by this EAD system. The two-winding PMSM machine when working as a motor will power the mechanical load, while the generator will power the electrical load and charge the low-voltage battery through the inverter. The reference and proposed PMSM machines have the following topologies: the reference machine has 48 slots per stator and 64 magnetic poles per rotor, while the proposed machine has 60 slots per stator and 64 magnetic poles per rotor. Both machines incorporate two sets of two-layer concentrated windings (one set as M-winding for the motor and the other set as G-winding for the generator) into the stator slots to accommodate the 48 coils, but the proposed machine is unique in its construction. The reference machine has a standard winding configuration with a coil span of one slot. The phases of the generator and motor windings are denoted by the letters G1, G2, G3 and M1, M2, M3 respectively. Alternatively, the stator of the suggested machine has twelve coil groups, each with four coils and a coil span of one slot. Two sets of unique windings, referred to as the generator (or G-winding) and the motor (or M-winding), are created by further dividing these coil groups. Additionally, one tooth between the neighbouring groups remains unwound while the balanced three-phase winding is maintained. This leads to variations in the windings' spatial distribution between the two machines. Some benefits of the proposed topology include zero mutual coupling effect between M- and G-winding, simplicity in winding, and the ability to split the machine's stator into equal parts from the centre of the unwound tooth for ease of transportation.

In a reference PMSM machine, the coil sides of M-winding and G-winding overlap in a few slots due to the typical nature of winding. On the other hand, an unwound tooth divides the end coils of the M- and G-winding groups in the suggested machine. The airgap allows the flux from the north magnet pole to enter the stator tooth, and it uses the stator yoke, neighbouring tooth, and airgap to return to the adjacent south magnet pole. Ultimately, flux seals the rotor core loop. Both sets of windings on the stator sense the flux linkage, which causes their induced back-EMF. The polarity of the currents in the coils within this phase group attracts and aligns four rotor magnet poles with the corresponding teeth on the stator. Consequently, the rotor rotates in tandem with the winding excitation when eight rotor poles are in line with the teeth of two groups per winding phase at any given time. As a result, the machine is built so that there is no mutual coupling between the two sets of windings in the suggested PMSM machine. To do this, the machine's windings must be isolated both electrically and magnetically. The main problem here is that the core losses of the proposed machine are higher than the reference machine due to the high current density in the specially designed stator teeth. The respective efficiencies of the reference machine and the proposed machine are 91.9% and 90.8%. Since there are more losses in the proposed machine, its efficiency is less than the reference machine.[2]

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

Researchers are very interested in Consequent-pole Permanent Magnet Synchronous Machines (CP-PMSMs) because they can reduce manufacturing costs by a significant amount by which the volume of permanent magnet needed to meet a given torque specification can be reduced. In this paper, we develop novel rotor topologies for a CP-PMSM in order to realize its full design space potential. High average torque and low torque ripple are the goals of rotor design, and the immune algorithm is used to find the best material distribution for the given problem. The ON/OFF method is introduced to control the laminated steel material distribution over the rotor region. In a 12-hour period, this methodology generates and assesses more than 9000 distinct rotor topologies. In this paper, we examine the optimal topologies under various design strategies and analyze their performance. The analysis's findings demonstrate that, by suppressing torque ripple to a low degree without sacrificing average torque, the suggested methodology can produce novel rotor topologies for the CP-PMSM with surprisingly high torque quality.

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.

The primary goal of this section is to use a topology optimization-based approach to investigate optimal rotor topologies in a CP-PMSM. The machine is modeled using the Delaunay triangulation, ON/OFF method and the finite element (FE) method in order to control the distribution of laminated steel material over the rotor region. The immune algorithm (IA) finds the optimal material distribution for the given problem, with the optimization objects being high average torque and low torque ripple. The CP-PMSM's untapped design potential is found using the topology optimization technique. Rectangle cells are used to form the optimization model in topology optimization studies that have been published previously. 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

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

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.[3]

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.

Additionally, the suggested 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 because the Delaunay triangular FE elements are used as the cells in the ON/OFF method to constitute the optimization model.

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.[3]

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

We present a new dual-mode wound rotor synchronous machine (DWRSM) designed for variable speed applications. The proposed apparatus integrates the key components of the brushless wound rotor synchronous machine (BWRSM) and the conventional wound rotor synchronous machine (CWRSM). The proposed machine, in contrast to the existing BWRSM, has two modes of operation: mode-I, which operates as a CWRSM, can achieve constant torque in the constant torque region, and mode-II, which operates as a BWRSM, can achieve constant power in the field weakening region. The mode change is implemented via an additional thyristor drive circuit. The airgap magnetomotive force (MMF) in both modes is obtained analytically. Using the Finite Element Analysis (FEA) method, this principle was confirmed through experimentation on a prototype machine with one horsepower (HP), and the main influencing factors were confirmed. Analysis was done on the stator current and torque transients during the mode shift. The test results confirmed that the theory and the FEA results were correct.

An eight-pole, twelve-slot machine with three-phase double layer distributed windings on the stator is designed in order to validate the proposed DWRSM. The stator winding is distributed so that there are two sets of windings, known as winding ABC and winding XYZ, in order for the proposed DWRSM to function. They are connected in series and positioned on opposing sides of the device. The harmonic winding and the field winding are the two separate windings on the machine's rotor. The pole pitch of the rotor harmonic winding is maintained twice that of the rotor field winding in order to realize the operating principle of the proposed topology. Four poles make up the harmonic winding as a result. By synchronizing with the eight-pole stator MMF, the eight-pole field winding generates output torque.

The proposed DWRSM topology has two modes of operation, mode-1 and mode-2. In mode 1, the machine operates as a Dual Wound Rotor Synchronous machine (DWRSM) in the constant-torque region. An inverter supplies three phase sinusoidal currents to the stator winding. Brushes and a slip-ring assembly connect the field winding to the external DC supply. The theoretical explanation for the generation of the air-gap MMF in mode-1 is an eight-pole machine with concentrated full-pitch winding on the stator. The three phase alternating currents excite the stator windings and generate the rotating MMF in this mode of operation of the DWRSM. 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.[4]

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, electrical stress and electrical losses on the brushes and sliprings are eliminated in the constant power region. In addition, the proposed DWRSM was tested for wide speed range operation, resulting in a four-times-rated speed range. A prototype was also built to test the dual mode operation of the proposed machine. A thyristor drive circuit was used to switch modes in two steps. The increase in phase current during the transient was approximately two times the rated current for one cycle. The experimental results validated the proposed machine's suitability for variable speed applications. The proposed machine has a problem in 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. When compared to brushless machines, the use of slip rings and brushes can result in additional electrical losses and decreased efficiency. This is especially true in applications where energy efficiency is crucial. Regular maintenance is required to ensure proper operation, which can be difficult in some applications. Furthermore, dual-mode machine construction and control systems 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

This section proposes a dual-mode brushless wound rotor synchronous machine (DBL-WRSM) with a high starting torque. There are two operating modes for the proposed DBL-WRSM: brushless (BL) synchronous and induction. Initially, the induction mode functions as a wound rotor induction machine (WRIM) in order to produce a high starting torque. Second, by employing the stator magnetomotive force (MMF) subharmonic, the BL-synchronous mode functions as a brushless wound rotor synchronous machine (BL-WRSM) in a steady state. The stator of the suggested machine is composed of two divided armature windings and two subharmonic-producing inverters in order to achieve its dual-mode topology. Five switches on the rotor allow it to alternate between the two modes of rotor winding configuration. Using finite element analysis (FEA), the suggested DBL-WRSM topology was verified. It was verified by the FEA results of the transient electromagnetic torque for the voltage source that the suggested DBL-WRSM has a high enough starting torque even when operating at full load. It also functions as a BL-WRSM in a steady state.

In order to obtain a high starting torque, this section suggests a dual-mode BL-WRSM (DBL-WRSM) that considers the benefits of a wound rotor induction machine (WRIM) over traditional BL-WRSM. 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 a WRIM-like induction mode and a BL-WRSM-like BL-synchronous mode. To achieve a high starting torque in induction mode, the machine acts as a WRIM. The machine operates on the BL-WRSM principle in the BL-synchronous mode, utilizing the stator MMF subharmonics. Two inverters generate the subharmonics required for BL-WRSM operation. To generate subharmonics with two inverters, the input current of one inverter must be half that of the other. However, in order to cut the current in half, the magnitude of the voltage must be reduced. As a result of the electrical time constant of the stator winding, the induction mode is divided into 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. [5]

In the BL-synchronous mode, the machine operates as a BL-WRSM with subharmonics. In this mode, the stator topology and input voltages in the ABC and XYZ armature windings are the same as in step-2 of the induction mode. The rotor's switches S1 and S3 are turned off, while S4 and S5 are turned on. As a result, the winding structure of the rotor is altered from three-phase winding connected in parallel to field winding connected in series. Furthermore, the rectifier connects the rotor's field winding to the excitation winding.[5]

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.

VII. 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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