RESEARCH ARTICLE

Available Online at http://www.recentscientificcom

CODEN: IJRSFP (USA)

International Journal of Recent Scientific Research
Vol. 16, Issue, 01, pp.011-016, January, 2025

International Journal of Recent Scientific Research

ISSN: 0976-3031

Subject Area : Electrical Engineering

REVIEW OF DESIGN AND PERFORMANCE ANALYSIS OF PERMANENT MAGNET SYNCHRONOUS MOTOR FOR ELECTRIC VEHICLE

Er. Kiranjit Kaur[1] and Dr. Gurinder Kaur Sodhi[2]

[1]Department of Electrical Engineering, Desh Bhagat University, Mandi Gobindgarh, Punjab
[2]Department of Electronics and Communication, Desh Bhagat University, Mandi Gobindgarh, Punjab

DOI: http://dx.doi.org/10.24327/ijrsr.20251601.003

ARTICLE INFO

Article History:

Received 8th December, 2024
Received in revised form 20th December 2024
Accepted 17th January 2025
Published online 28th January, 2025

Key words:

Permanent Magnet Synchronous Motors (PMSMs), Fuel Cell Electric Vehicles (FCEVs), Battery Electric Vehicles (BEVs), and Hybrid Electric Vehicles (HEVs).

ABSTRACT

Various researchers investigated and analyzed the characteristics of several electric motors utilized in electric vehicles. To develop the study, they used a variety of techniques. Initially, DC motors were employed, but this has the drawback of generating losses because of the usage of commutators and brushes, which lowers efficiency and raises the requirement for motor maintenance. To do away with encounters and commutators, researchers converted from commutator motors to commutator less motors. Among the best commutator less engine types are asynchronous motors. However, one of their primary disadvantages is using controllers, which increases the motor's cost and limits its prolonged constant-power region. A high starting current, a low power factor, and breakdown torque are further disadvantages. Induction motors also have a lower power density and are less efficient than permanent magnet motors. Thus, flux weakening techniques are needed to enhance the constant power region. Other commutator less engines include synchronous reluctance motors, which have severe issues with cogging torque, vibration, and auditory disturbances. The suggested motor is a permanent magnet synchronous motor widely employed in automotive settings because of its rapid dynamic response, small volume and power density and efficiency high. One of its main differences is that rotor cooling is made easier by the synchronous motor's much lower rotor heat production. There are various factors to the design of an electric motor, and given the gaps in knowledge, there may be more than one possible answer. The objective is to design the engine that offers the optimal solution given the available conditions.

INTRODUCTION

The environment and energy are currently major global concerns. Air pollution has significantly increased as urbanization and industrialization have progressed. Many different things cause the poor quality of the air. Utilizing conventional resource-based vehicles that run on gasoline, one of the most contributing factors is diesel. The transportation sector is thought to be responsible for 24% of the world's CO2 emissions as of 2015, which increases the risk of developing diseases including cancer and asthma. The ozone layer is damaged by the discharge of toxic substances, which contributes to unfavorable global warming [1].

Electric Motor: Electromechanical devices, such as electric motors, convert electrical energy into mechanical energy. Essentially, any apparatus generating rotational force qualifies as a motor. The functionality of an electric motor primarily hinges on the interplay between magnetic and electric fields. Motors come in two principal types: AC (Alternating Current) and DC (Direct Current). A Direct Current motor operates on direct current input, while an Alternating Current motor functions with alternating current.

*Corresponding author: **Kiranjit Kaur**

Department of Electrical Engineering, Desh Bhagat University, Mandi Gobindgarh, Punjab

Basic Principle: Electromagnetism is the basis for how motors operate. You were applying electricity to a wire resulting in the creation of a magnetic field. A magnetic field is created all around a rod by electricity flowing through a wire that is looped around it. The same polarity Poles in a rod resist one another while opposite poles are attracted to one another. The rod will revolve due to the attracting and repellent forces when you surround it with other magnets.

Timeline of Electric Motor: Since the advent of technology, innovation has accelerated at an increasing rate. The ease with which innovations and technologies improve our lives is intriguing, but so is the fact that new technology always facilitates the development of even more cutting-edge ideas and discoveries. When you consider that the first electric motor was created in the 1830s, 30 years after the first battery, the history of electric motor technology is fascinating. It's interesting to note that the motor came first, before the dynamo or generator. [1][2]

Types of Electric Motor: According to the needs of the application, both AC and DC motors are employed. Direct motors do have some drawbacks when compared to AC motors.

Induction Motors: For applications requiring continuous speed, the AC induction motor is a good option. Brushes are not required in induction motors because electromagnetic induction induces the voltage in the rotor [10], but this induction requires the rotor to rotate more slowly than the magnetic field. Electromagnetic coupling is the only source of interaction between the stator and rotor fields [11].

Synchronous Motors: Synchronous motors synchronize their shaft rotation with the frequency of the AC supply current. These motors consist of a fixed stator winding electrically connected to an AC source while the rotor field windings are linked to an independent excitation source [8]. The stator of synchronous machines comprises a stack of electric sheet laminations, featuring slots for the winding, often designed as a three-phase winding. The rotor's implementation can vary, ranging from a salient pole rotor with distinct magnetic poles, a reluctance rotor, a permanent magnet rotor utilizing permanent magnets to form magnetic poles or a cylindrical non-salient pole rotor. The rotor's construction can either be solid or laminated. In permanent magnet machines, the supply voltage determines the excitation state since the excitation cannot be adjusted due to the presence of permanent magnets. Armature reaction, referring to the machine's magnetization with stator currents, may affect the machine's flux. For salient pole machines, the iron core is wrapped in the field winding [11]. The cross-section image below depicts the structure of a permanent magnet synchronous machine.

Several notable features define synchronous motors [9]:

- Synchronous motors either operate at synchronous speed or not; they consistently run at the same speed. The motor's speed can be adjusted by altering the supply frequency and the number of poles using the formula Ns = 120f/p.
- They do not self-start.
- Synchronous motors possess the capability to operate at various power factors, either leading or trailing, before synchronizing with the supply.
- These motors must operate near synchronous speed through different methods. As a result, they can be employed for power factor correction (PFC) instead of delivering torque to the load.

Permanent Magnet: Permanent Magnet Synchronous Motors (PMSMs) share a stator structure akin to induction motors. However, unlike traditional synchronous motors that use electromagnetic stimulation in their rotors, PMSMs utilize permanent magnets. Meanwhile, the stator comprises a three-phase winding. These permanent magnets contribute to maintaining a stable and unchanging magnetic field in the air gap. Regardless of load variations or applied voltages, PMSMs can sustain rotation at a consistent speed with a fixed power supply frequency. Operating within specific parameters, these motors can maintain a constant speed at different operating torques, making them exceptionally advantageous for high-precision, fixed-speed drives. The precise speed requirements in various sectors make PMSMs an excellent choice. Additionally, their torque/speed characteristics render them ideal for directly powering high-horsepower, low-RPM loads. Synchronous motors, including PMSMs, exhibit high power factors. Consequently, they can help improve a system's overall power factor, reducing utility power factor fines. This enhancement in power factor leads to improved system performance by mitigating voltage drops across the system and at the motor terminals [13].

The Main Characteristics of PMSM: The 3-phase stator of the synchronous motor resembles that of an asynchronous motor and typically employs medium-voltage stators.

1. In a Phase wound rotor, the number of poles equals that of the stator. Rotor current generates the North and South magnetic poles within the rotor pole, allowing it to synchronize with the revolving flux of the stator.
2. Synchronous motors utilize squirrel-cage winding to generate torque for motor starting. The synchronous speed is calculated using the number of stator pole pairs (P) and the stator supply frequency (fs). In the rotor, two pole pairs, which can be activated by various DC sources or are always magnetic in synchronous motors, are present. The 3-phase Permanent Magnet Synchronous Motor (PMSM) stator is excited by a balanced 3-phase supply, inducing a magnetic field rotation. The formula N = 120.fs/P (1.1) is used to determine synchronous speed, also known as rotating field speed, where N represents synchronous speed in RPM, fs denotes AC supply frequency in Hertz, and P signifies the number of poles. In PMSMs, torque is generated through the interaction of two magnetic fields originating from stator coils and permanent magnets, respectively. Maximum torque occurs when the rotor and stator magnetic field vectors are perpendicular (at a 90° angle) to each other. The sine commutation strategy ensures smoother torque production with fewer ripple effects due to the sinusoidal current in each coil, displaced by 120° [14].

LITERATURE REVIEW

In a study by Yanbin Li *et al.* (2019) [22], an outer rotor flux switching permanent magnet machine was introduced for a light electric vehicle drive system. Using a sizing equation and finite element-based method (FEM), the design entailed 6 stator slots and 19 rotor poles to achieve specific combinations of 188W power and 120rpm rotation for the intended application. Utilizing FEM analysis, the calculation of magnetic field distribution, machine parameters, and performance was conducted, guided by the current vector strategy. In their work published in 2019 [23], Chan Hao et al. presented a comprehensive parametric sensitivity analysis focusing on the rotor geometry of a V-shaped Interior Permanent Magnet Synchronous Motor (IPMSM). The study delved into an extensive examination of all electromagnetic characteristics, encompassing both low-speed and high-speed operational regions, ultimately yielding enhanced outcomes. Employing optimization techniques, an objective was selected to refine and determine optimal parameters using response surface analysis, leveraging computationally efficient finite element methods (CE-FEM) for performance analysis. It is noted that a motor's performance is contingent on several factors, including geometry, efficiency, and energy loss distribution, among other characteristics.

In their work published in 2019 [24], Zhang Zhenyang et al. proposed the development of a 60kW Interior Permanent Magnet (IPM) V-shaped motor specifically designed for medium-sized electric vehicles, catering to both rated operating conditions and overload scenarios. The study aimed to enhance electromagnetic torque, geometric parameters, permanent magnet dimensions, and air gap density skewing using 2D Maxwell software while conducting thermal analysis under similar operating conditions. The researchers highlighted the potential for further investigation into the impact of motor control systems, such as flux-weakening rate, overload capacity, and peak torque speed range, within the same application context.

In their research published in 2019 [25], Chen Hao et al. introduced the development of a five-phase Fractional-Slot Permanent Magnet (FSPM) motor tailored for in-wheel traction applications across three distinct driving cycles, including a combination of UDDS and HWFET, spanning various operational conditions. To streamline efforts and reduce costs, the study utilized a combination of computationally efficient finite element analysis (CE-FEA), traditional optimization techniques, the k-means clustering algorithm, and response surface methodology. Through this approach, the study achieved diverse outcomes in terms of geometry, losses, and efficiency across low-speed and high-speed operational ranges for different driving cycles. Under the UDDS driving cycle in low-speed conditions, reductions in core losses were observed. Conversely, for the HWFET driving cycle within high-speed conditions, a decrease in core losses was also achieved. Moreover, the combined cycle demonstrated a balanced reduction in losses across low and high-speed operational ranges.

Boztas Gullu *et. al.* (2018)[29] Presented the multiphase BLDC motor for EV. A hub motor having 110Nm and 900 rpm is designed for the proposed EV. Firstly 3-phase motor is designed as a base motor. Then, 5-phase and 7-phase motors are designed with the same dimensions as the stator and rotor. It is observed that a multi-phase motor is a good option rather than a 3-phase motor for the lower torque and lower power inverter structure. Sardana Gunjan, et. al. (2017)[30] Presented the 2D design and performance (BLDC) analyzed using the ANSOFT RMXPRT FEM model. The closely linked flux density and magnetic flux between the stator permanent magnet and motor is analyzed.

Problem Formulation: The following were the problems faced by researchers when motors were used.

1. In DC motors losses due to the usage of brushes and commutators, which reduces efficiency and increases the need for motor maintenance. Researchers switched from commutator motors to commutatorless motors to do away with the need for brushes and commutators.
2. Asynchronous motors are among the best types of commutatorless motors, but one of their main drawbacks is the use of controllers, which raises the cost of the motor and restricts its extended constant power area. Other drawbacks include a high beginning current, a poor power factor, and breakdown torque. Furthermore, compared to permanent magnet motors, induction motors are less efficient and have a lower power density.
3. To improve the constant power region, flux weakening techniques are required. Synchronous reluctance motors fall within the category of other commutatorless motors and have major problems with cogging torque, vibration, and acoustic disturbances.

These problems can be overcome by using synchronous motors which are frequently used in automotive applications such as high efficiency, small volume, high power density, and quick dynamic response. The primary distinction is that the synchronous motor produces significantly less rotor heat, making rotor cooling simple. Permanent magnets are used in motors, which raises the cost of the motor, several studies have suggested using less expensive ferrite materials that contain rare earth elements. However, these materials still have an impact on magnetization strength. Temperature-sensitive permanent magnets experience rapid performance changes with temperature changes, which also have an impact on demagnetization and lower permanent magnet efficiency. To increase the motor's torque working range, not a lot of work has been done thus far in concentrated winding. By maximizing the geometric parameters linked to the stator, rotor, etc. created, several researchers reported using the torque ripple reduction technique in PM synchronous motors to reduce the torque ripples produced due to cogging torque. The synchronous motors can be improved by utilizing design flaws such as demagnetization, minimization of Eddy currents losses, cogging torque minimization, and geometric point of view. Evaluation of the driving cycle-based motor type utilized in electric vehicles is another issue.

Boundary Element Method: The traditional method for resolving linear partial differential equations (PDEs) with boundary integral form, is then further resolved into a matrix equation for a numerical solution using weighted residual methods. The approach is formulated using steps similar to those in applicable integral equations. Following the discovery of the derivation, it proceeds to step two, which entails discretization to create a matrix equation by using weighting and expansion functions of the matrix elements and obtain the ultimate findings required to solve the matrix. It is a productive technique, and it has applications in the fields of fluid mechanics, acoustics, fracture mechanics, and electromagnetics. This approach is a potent instrument for solving problems in electrostatics, scattering, radiation, biomedicine, mathematical models, etc. However, when the issue is a volume, only the outside surface is taken into account, and not relevant to volumetrically complicated structures. Dielectric materials and materials that demonstrate dispersion. It produces subpar results that are often drawn out and tedious [12,13,15,16].

Finite Difference Method: In CEM tools, the Finite Difference Method (FDM) technique is frequently utilized. It is applied to scattering, photonics, wave propagation, microwave antenna, and high-speed electronics, among other fields. In transient analysis, it works incredibly well. This approach discretizes the issue into governing equations and approximated point-by-point. In essence, it discretizes Maxwell's equation for partial differential equations in differential form. The domain is discretized into units known as nodes, where a differential equation similar to the finite difference method offers a solution for the value at each specific node. This approach converts a differential equation into an algebraic equation employing Taylor's series, where higher-order terms are neglected during the transformation process. It is used to tackle thermal and CFD problems in conjunction with BEM or FVM. With this approach, the original boundary value issue is transformed into a set of geometric equations that can be resolved with ease. It is a straightforward and straightforward method to use. However, it is models with rectangular or block shapes. Complex geometry, materials, assembly, and varied element combinations (1D, 2D, and 3D) all present limitations. The grids' approximations do not have good quality. Possible to employ CAD geometries with curved or irregular shapes is not possible so a different solution is required, one that offers a variety of solutions to address all issues [12,13,14,17].

Finite Element Method: For situations involving partial differential equations (PDE) and integral equations of a higher degree, the finite element method (FEM) is employed to derive an approximate solution. The piecewise/regional approach strategy to overcome the issues. It eliminates any restrictions aforementioned techniques. These days, all challenges are analyzed, visualized, solved, and designed using this methodology. Applications like linear, non-linear, thermal, dynamic, and fatigue analysis use this methodology. Due to its fewer restrictions, the finite element method (FEM) is recommended for low-frequency applications and for computing electromagnetic analyses of different devices. A sizable number of field calculations may be needed to build a motor. Machine field analysis is conducted using finite element analysis (FEA). This is the most prominent method to solve electromagnetic problems. It is well-suited for stress, and strain extraction within 3D objects [12,16,17,18]. In the flow of the finite element method, three basic stages are involved and are described as follows: 4.3.1 Pre-Processing Stage: - The initial stage involves defining the geometric domain, specifying variables, selecting appropriate materials, and simplifications for the computational object. This includes the creation of meshes—such as 1-D, 2-D, or 3-D structures—utilizing finite nodes, and formulating corresponding nodal equations to establish the framework of the problem, as outlined in [16].

Processing Stage: In the second stage, the actual solution or analysis takes place. This phase involves executing the configured analysis, which includes applying essential loading conditions (such as static or dynamic loads) and specifying material details. Analysis methods employed at this stage may encompass modal analysis, static analysis, linear or non-linear analysis, and other relevant procedures, as described in [16].

Post-Processing Stage: In this phase, the software incorporates sophisticated procedures for organizing, printing, generating charts, and comparing the outputs obtained from the processing stage with analytical results. Error analysis is conducted to assess any discrepancies at junction points and ascertain the compliance of the obtained results. The findings can be presented in graphical, tabular, or visual formats, as described in [16].

Validation: From the perspective of engineering analysis, it is a crucial step. Any other method, including FEA, should have its results validated using an experimental or analytical technique. This approach demonstrates adaptability in issues involving inhomogeneous media, media distribution, and complicated geometric structures. Finding computer programs for the FEM formulation is simple and easy. We get a sparse matrix equation in return. There are two types of problems, procedures to solve bounded problems and software to address unbounded problems. The FEM method's approximate solution is inappropriate. Both the time domain and the frequency domain are applicable. The steps in this approach come before the solution of the problem [12,17].

Step 1: In the very first step discretization of continuous structure: From the perspective of engineering analysis, A crucial step. Any other method, including FEA, should have its results validated using an experimental or analytical technique. With discretization or meshing (nodes or elements), the finite element approach reduces degrees of freedom from infinite to finite. A small number of locations known as nodes are where all of the calculations are performed. An element is the thing that connects nodes to create a certain geometry, like a quadrilateral or triangle. The entire analytic domain, basic sub-domains known as finite elements (non-overlapping meshes), triangle in two dimensions, and the tetrahedron in three dimensions, and field equations are applied to each of them. Node identification is carried out by assigned node numbers and their corresponding coordinates.

Step 2: Identify the primary unknown quantity.

Step 3: Selection of Interpolation Functions (Shape Functions) and their derivation: FEM uses a variety of elements, including simplex (linear), complex (quadratic), and multiplex (cubic) interpolation functions. The form function in the calculation at other points within the body is another name for interpolation functions.

Step 4: Derivation of Element Equation: The main unknown quantity is connected to the analysis's action through the element equation. For instance, in stress analysis, the force is the action, the primary unknown quantity is the displacement at the node, and the secondary unknown quantity is the stress or strain—either the direct technique or the indirect method to generate element equations. There are two types of indirect approach. Computer equations solve the Rayleigh-Ritz and Galerkin methods [18].

Step 5: Overall stiffness Equation Derivation: The stiffness equation for the entire medium is obtained in this step by combining all of the individual element equations that were determined in step 4.

Step 6: Solve primary unknown quantity: By use of the inverse method or Gaussian Elimination Matrix or its derivative is used to solve nodal quantities from the equation.

Step 7: Solve for secondary unknown quantity.

Step 8: Display of interpolation of results in tabular data, graphic display, or visual display i.e. static contours or animation.

Design of PM synchronous motor for vehicle: When designing a motor, user-specific requirements such as weight, power, torque, speed, voltage levels, and so on must be taken into account in addition to technical specifications like efficiency, power factor, temperature rise limits, noise regulations, and compliance with national and technological requirements. In order to handle intrinsic issues and contradictions and to be in line with real production and processing technology conditions, this approach integrates pertinent motor design theories and calculation methodologies.

Computational Electromagnetic Tools: A vast field that overlaps electromagnetics and scientific computers is computational electromagnetics. A few software programs were available in the market in the past. But from the 1970s, scientists created their projects to address electromagnetic issues. Many numerical methods and computational tools are now accessible for modeling and simulation based on various techniques such as freeware (open access) basis and commercial availability basis. These software programs attract the interest of businesses and academic institutions due to their user-friendly graphic interfaces and ability to create models of actual, real-world problems. The following simulation programs, however, are some of the most popular ones: COMSOL Multi-Physics, Numerical Electromagnetic Codes (NEC), High-Frequency Structure Simulator (HFSS), FEKO, EMAP, MEEP, MaxFem, MagNet Infolytica, Maxwell Ansoft, MEGA Bath University, Emag ANSYS, FEMM, Integrated Engineering Software, FLUX, and CEDRAT Software [13,20]. These general-purpose software programs and specialist software packages are used for designing and working with virtual prototypes. The key methodologies employed in motor design primarily revolve around Finite Element Method (FEM), Boundary Element Method (BEM), and Finite Difference Method (FDM) or Finite Difference Time Domain (FDTD) techniques. These methods encompass pre- and post-processing stages and are instrumental in conducting analyses such as static magneto and electrostatic analysis. Additionally, they enable analysis with nonlinear materials like permanent magnets, assessment of steady-state and transient eddy currents, and evaluations involving stress and thermal analysis. These functionalities are integral components of commercially available software tools [19, 20]. One of the challenging challenges is dealing with multiphysics problems and multi-objective optimization, thus out of all the software programs, we will utilize ANSYS Maxwell Software, which is based on the FEM (Finite Element Method), to develop synchronous motors for Battery Electric Vehicles (BEVs). FEM is a flexible technique, and software has developed tools for generic design, optimization, and performance prediction [21,22]. The electromagnetic analysis of electrical machines, transformers, actuators, and sensors is done using the Ansys Maxwell software. The design of electrical machines involves multiple physics. The performance of an electric motor can be optimized before the first physical model thanks to multi-physics capacity, which also improves design correctness. Both electromagnetic analysis and ANSYS Mechanical for stress, vibration, and heat analysis are available in the ANSYS multi-physics solution [22]. ANSYS offered a combination of four tools for designing and analyzing electric motors i.e. RMxprt (Rotating machine Expert), Maxwell Simplorer, Optimetrics, and ANSYS Mechanical/CFD [21,22].

Features of COMSOL Multiphysics: In the realm of static or low-frequency products and components, meeting specific requirements is crucial for real-world functionality. To thoroughly analyze the impact of various physics on design, COMSOL Multiphysics software, particularly the AC/DC Module, is employed. Many electromagnetic components and devices are intricately linked to other fields of physics, such as structural mechanics and heat transfer. The software allows simultaneous exploration of these effects, enabling a highly precise analysis by coupling multiple physical effects within the COMSOL Multiphysics platform. The AC/DC Module utilizes Finite Element Method (FEM), Boundary Element Method (BEM), or a combination of both to formulate and solve Maxwell's equations. A diverse array of mesh elements, including linear and high-order nodal-based and edge elements (such as tetrahedral, prismatic, pyramidal, hexahedral, triangular, and quadrilateral elements), are employed in the FEM and BEM meshing approaches. To address various issues, linear and nonlinear solvers are employed with these numerical techniques.The AC/DC Module covers different research types, including static, frequency domain, and time domain analyses, as well as automated terminal sweeps for circuit parameter extraction [27].

Features of Ansys Maxwell: It is essential to simulate electric motors early on in the design process, regardless of whether the electric motor is being designed for industrial use or needs to be tiny, effective, and silent. From design sizing options through in-depth electromagnetic, thermal, and mechanical evaluations of the motor, Ansys provides a comprehensive process. Using Ansys tools, a motor's coupled electromagnetic, thermal, stress, and vibroacoustics simulation produces a high-fidelity, accurate, and resilient design that is optimized for performance, cost, and efficiency. AC/DC Maxwell's equations are created and solved by the module. Ansys Maxwell simulates all stages of the motor design process including:

Template-based design, quick motor sizing Multiphysics analysis across the entire operational spectrum.

D and 3D finite elements analysis of Electromagnetics
Thermal control with enhanced system cooling
Robust design that reduces noise and vibration
High-fidelity electro-thermal motor modeling is used in system-level simulation (HiL/SiL/MiL).[26]

Features of MATLAB Simulink: Motor modeling and simulation play pivotal roles in intricate electric motor drive design and system-level performance analysis. These tools enable motor drive designers to achieve optimized design parameters while minimizing losses, often by importing Finite Element Analysis (FEA) data. When evaluating the system-level performance of a motor drive, designers often use abstract motor models that harmonize mechanical and electrical power considerations. Motor modeling and simulation encompass various fidelity levels, catering to different design aspects such as system design, control design, and motor drive design. These diverse fidelity levels allow designers to analyze and optimize motor-driven systems comprehensively [28].

Scope and Possible Outcomes: According to a literature review, the characteristics of several electric motors utilized in electric vehicles are investigated. They used a variety of tactics when designing the study. DC motors were initially employed, however, this has the drawback of generating losses because of brushes and commutators, which diminishes efficiency and also increases the need for motor maintenance. To do away with the requirement for brushes and commutators, researchers shifted from commutator motors to commutatorless motors. The need for controllers, which increases the cost of the motor and limits its extended constant-power area, is one of the main limitations of asynchronous motors, which are among the best commutatorless motor types. Other drawbacks include a high beginning current, a poor power factor, and breakdown torque. Furthermore, compared to permanent magnet motors, induction motors are less efficient and have a lower power density. To improve the constant power region, flux weakening techniques are required. Synchronous reluctance motors fall within the category of other commutatorless motors and have major problems with cogging torque, vibration, and acoustic disturbances. The proposed one is a synchronous motor, which is frequently used in automotive applications, with high efficiency, small volume, high power density, and quick dynamic response. The primary distinction is that the synchronous motor produces significantly less rotor heat, making rotor cooling simple. By maximizing the geometric parameters linked to the stator, rotor, etc. created, several researchers reported using the torque ripple reduction technique in permanent magnet synchronous motors to reduce the torque ripples produced due to cogging torque. The performance of synchronous motors can be improved by utilizing design flaws such as demagnetization, eddy current loss minimization, cogging torque minimization, and geometric point of view.

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