Systematic Analysis and Optimization of Permanent Magnet Synchronous Motors for New Energy Vehicles

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Abstract. As alternatives to conventional fuel-driven vehicles, new energy vehicles are quickly becoming more and more popular due to their high efficiency and environmental protection features. These issues include resource scarcity and global warming. Permanent Magnet Synchronous Motors are the main power source of new energy vehicles and are widely employed because of their many benefits. This study uses Permanent Magnet Synchronous Motors as its research subject. It examines the bearings, end cover, rotor, and stator structural features, the electromagnetic materials employed in the motor, how vector control is implemented in the motor's operation, and the advantages and disadvantages of the system. At the same time, the key parameters affecting its efficiency are analyzed, including the width of permanent magnets and the number of turns of windings, and the technical methods to improve the efficiency according to its structure and parameters are proposed. It seeks to offer theoretical support and technological direction for the sustainable growth of the electric vehicle industry by examining its development trend and future perspective.

Keywords: Permanent Magnet Synchronous Motor, New energy vehicles, Systematic Analysis, Optimization.

1. Introduction

In recent years, people based on the protection of energy and environment, traditional driving resources such as oil are being replaced by new energy [1]. According to the growth of production and sales volume and market share of new energy vehicles in recent years, the global market share of new energy vehicles will grow from about 0.3% in 2014 to about 12% in 2023, and new energy vehicles have undoubtedly become the core topic of the future automotive industry [1, 2]. As the most powerful core component in new energy vehicles, the motor not only provides efficient and smooth power output, but also improves energy efficiency and environmental performance, and has an indispensable role, while Permanent Magnet Synchronous Motor (PMSM) is the most significant component in the new energy vehicle industry. PMSM is the main choice of drive system for new energy vehicles [3].

This paper firstly introduces the structure and material of the PMSM, then analyses its working principle as well as the advantages and disadvantages, and then proposes two factors affecting the efficiency of the motor, namely the width of the permanent magnet and the number of turns of the stator windings in each phase, and finally discusses the optimization strategy according to the two different structural designs and parameters.

2. Composition and working principle of PMSM

PMSMs, which are classified as AC brushless motors, employ the interaction between the magnetic fields created by the electric current and the permanent magnets on the rotor to achieve energy conversion. This technology is used as the power source for new energy vehicles. PMSMs can offer a more compact mechanical package with reduced dimensions, an optimal torque-to-inertia ratio, good dependability, and improved controllability as compared to conventional motors with equivalent work power [4].

2.1. Structure and Materials of PMSMs

2.1.1 Structure of PMSMs

The structure of a PMSM mainly consists of stator, rotor, end caps and bearings and other auxiliary parts. The stator is the stationary part of the motor as shown in Fig.1 and usually consists of an iron core and windings.

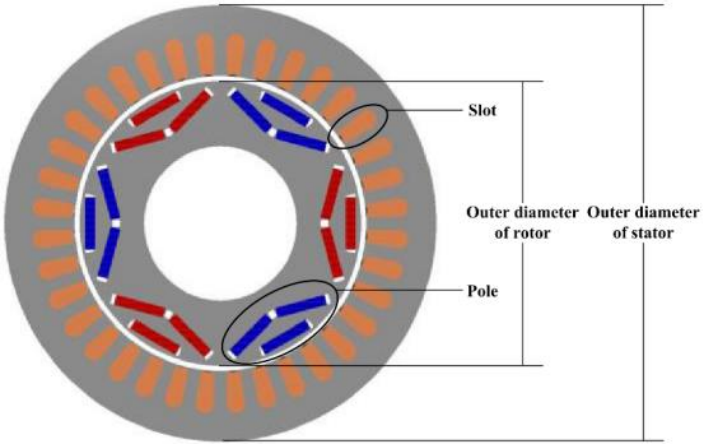


Figure 1. Drawing of the 6-pole 36-slot rotor's structure [5]

The core mainly concentrates and directs the magnetic field and reduces iron loss and eddy current loss, and is made of silicon steel sheet or other materials with high magnetic permeability. The windings are fixed in the slots of the stator and consist of conductive coils. The magnetic field generated when current passes through the windings interacts with the magnetic field of the rotor to generate torque.

The rotor is the rotating part of the motor as shown in Fig.1 and usually consists of permanent magnets and an iron core. The role of the iron core is similar to that of the stator core, mainly to concentrate and guide the magnetic field, while improving the mechanical strength and stability of the rotor. The permanent magnets are usually made of high-performance permanent magnet materials such as neodymium-iron-boron (NdFeB), which provide high magnetic field strength and stability, thus ensuring that the motor provides stable output during operation.

As motor rotors are made of metal, they generate a lot of heat during operation. Therefore, the dimensions of the motor are influenced by the heat dissipation system during the design process. As a reference, a prototype of 20kW and 4500r/min with axial length less than 200mm and external diameter less than 234mm is used. According to the dimensions of water channel and housing, the maximum external diameter of stator of the prototype is 194mm [6]. The research on the structure of the rotor is also a matter of opinion among the community of baccalaureates. These include the surface-mounted PMSM as shown in Fig. 2, which has the permanent magnet material mounted symmetrically on the rotor surface.

Figure 2. Rotor structure of surface-mounted motor [7]

In order to protect the permanent magnet from damage caused by friction, stress and other factors, the protection device also generates eddy current effect when the motor is running at high speed, resulting in motor heating. Whereas the built-in PMSM as shown in Fig. 3 has a spacer bridge on the rotor punches, which ensures the overall mechanical strength of the rotor.

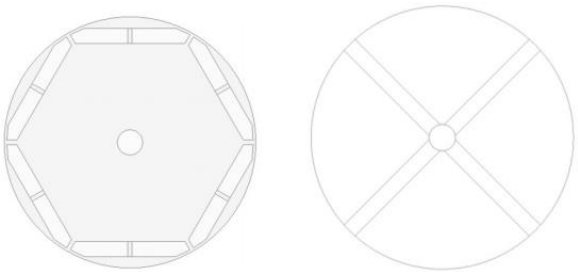


Figure 3. Rotor structure of built-in motor [7]

The mechanical strength of the punches can be improved by increasing the thickness of the spacer bridges, but the thickness of the spacer bridges also increases the no-load leakage coefficient, which affects the electromagnetic performance of the motor [7].

In addition to the stator and rotor, PMSMs include auxiliary parts such as end caps and bearings. The end caps secure the ends of the motor and protect the internal components while holding the stator and rotor in place. The bearings support the rotary motion of the rotor shaft, reducing friction and wear, thus ensuring stable operation of the motor.

2.1.2 Materials for PMSMs

The main electromagnetic materials for permanent magnet motors include permanent magnet materials, silicon steel sheets and enameled wire. Common permanent magnet materials include rare earth permanent magnet materials, alnico permanent magnet alloy, ferrochrome cobalt permanent magnet alloy and permanent magnet ferrite. Alnico and ferrochrome cobalt permanent magnet alloys are gradually being eliminated from the market, while ferrite materials have small remanent magnetism, making it difficult to meet the demand for high torque density. On the contrary, NdFeB is the most common application of rare-earth permanent magnets because they are more adaptable to the environment [8].

2.2. Principle of Operation of PMSMs

A PMSM's stator is a rotor that has three sets of uniformly spaced three-phase windings and semi-permanent magnets. An electromagnetic torque is produced on the rotor by the interaction of the revolving magnetic field created inside the stator windings, which is fed with sinusoidal alternating current, and the rotor's permanent magnet field. PMSMs are hence referred to as "AC synchronous motors" [9]. The rotor operates synchronously because of the stator windings' continuous permanent magnetic field, which is explained by Faraday's Law of Electromagnetic Induction.

Vector control is an advanced form of motor control that is typically used for precise speed and torque control. This control method regulates the current in the stator windings by measuring and calculating the rotor position and speed of the motor. This allows the rotating magnetic field of the stator to precisely follow the rotation of the permanent magnet field of the rotor, resulting in stable operation and efficient output of the motor.

2.3. Advantages and Disadvantages of PMSMs

Unlike ordinary AC motors, PMSMs provide a stable magnetic field by embedding permanent magnets inside the rotor. Compared to conventional AC asynchronous motors, PMSMs do not require current to flow through the stator before excitation of the rotor, resulting in faster and more controllable starting. Compared to asynchronous motors, PMSMs have higher efficiency values at light loads. In addition, PMSMs have a wide range of high efficiency operation, exceeding 90% within 25% to 120%, which makes them more energy efficient than asynchronous motors, most of which are rated at less than 70% of the rated power and usually operate in the light-load region [6]. Compared to synchronous motors, PMSMs do not need to pass current through the rotor windings to exist stably, making them easier to miniaturize compared to conventional synchronous motors. Overall, PMSMs have relative advantages in terms of efficiency, size, etc. as shown in Table 1.

Table 1. Comparison of Basic Performance of Electric Vehicle Drive Motors [10]

Item	Direct Current Motor	AC Induction Motors	Switched Reluctance Motors	PMSM
Power density	low	medium	relatively high	high
Speed range (r/min)	4000~8000	12000~15000	>15000	4000~10000
Dependability	general	good	good	excellent
Structural robustness	poor	good	excellent	general
Motor external dimensions	giant	medium	small	small
Motor quality	heavy	medium	light	light
Motor cost ($/kW)	10	8~10	8~10	10~15
Controller Costs	low	high	general	high

Most PMSMs use rare earth permanent magnet materials (e.g. NdFeB) due to the high cost of permanent magnet materials and their associated technologies, the production of which is concentrated in a small number of countries, such as China; therefore, instability in the supply and price fluctuations of rare earths can adversely affect the electric vehicle industry and make supply chain management more difficult. As permanent magnet materials are temperature sensitive, especially in high temperature environments, this may lead to a decrease in the magnetic properties of the permanent magnet materials, which may affect the performance and efficiency of the motor. To address this issue, motors require additional cooling systems, which can increase system complexity and cost.

2.4. Analysis of Parameters Affecting the Efficiency of PMSMs

The ratio of output power to input power of an electric vehicle determines the energy efficiency and driving range of an electric vehicle. Therefore, improving the efficiency of EVs is crucial to the development of the new energy vehicle industry. In order to ensure that electric vehicles always run efficiently and reduce energy consumption during operation, rigorous tests must be conducted on electric vehicles to ensure that they comply with relevant national and industry standards [11].

2.4.1 Effect of Permanent Magnet Width on Motor Efficiency

In order to modify the motor's performance and efficiency, the permanent magnets' width must frequently be changed in motor design. The permanent magnet torque of the PMSM will increase with an increase in the width of the permanent magnets because this has a significant effect on the torque performance of the PMSM. However, the reluctance torque of the PMSM will decrease as a result of a decrease in the magnetic permeability of the magnetic circuit of the direct-adjacent axes. Therefore, it is required to ascertain if the rise in permanent magnet torque is higher or less than the decrease in reluctance torque in order to evaluate whether the output torque of a PMSM grows or decreases [7]. In addition, changes in the width of the permanent magnets affect the core reluctance as well as the load induced electromotive force, which can lead to changes in ripple torque and cogging torque. Although too wide or too narrow permanent magnets increase the ripple torque, the magnitude of the ripple torque is not necessarily the same. Electric vehicles using PMSMs do not require excessive torque fluctuations, which can lead to vibration and noise. Therefore, the width of the permanent magnet is chosen to reduce the torque fluctuation while ensuring a larger torque [10]. Effect of permanent magnet width on motor performance is shown in Table 2.

Table 2. Effect of permanent magnet width on motor performance [10]

Width of permanent magnet (mm)	24	30	32	34	36	38	40
Maximum loaded air gap permeability (T)	1.23	1.32	1.36	1.4	1.43	1.44	1.46
Load Air Gap Density Average (T)	0.51	0.53	0.54	0.56	0.58	0.59	0.61
Iron consumption (W)	222	222	228	225	240	248	252
Output torque (Nm)	50	57.5	60	63	64	63.5	62
Output power (kW)	20.4	23.5	24.5	25.7	26.5	26.1	25.3

According to the iron loss curve of the stator-rotor material, the magnetic induction intensity directly affects the loss of the iron core. For the PMSM, the increase in permanent magnet torque is greater than the decrease in reluctance torque before 36mm width, but after 36mm width, the increase in permanent magnet torque is slightly less than the decrease in reluctance torque. Table 3 also shows that too wide a permanent magnet results in increased fluctuations in torque.

2.4.2 Effect of Number of Turns Per Phase of Stator Winding on Motor Efficiency

The number of turns directly affects the resistance and inductance of the motor. Typically, the more turns a motor has, the lower the resistance and the higher the inductance. Low resistance and proper inductance help reduce losses and increase efficiency. In terms of magnetic field control, an increase in the number of turns improves the flux density and power density of the motor, resulting in greater power output in the same volume, which is critical to the power performance and energy efficiency ratio of electric vehicles. At the same time, the number of turns has a direct impact on the current and voltage requirements of the motor. Typically, motors with a high number of turns require a lower voltage to produce the same amount of power, which reduces resistive and thermal losses and improves the overall efficiency of the motor. The number of turns in a PM motor can have a beneficial effect on the efficiency of an EV, particularly in terms of increasing motor power density, reducing motor losses and optimizing motor control, as shown in Figure 4 for reference. However, selecting the correct number of turns is a complex engineering problem that requires consideration of a variety of factors including, but not limited to, the overall performance requirements of the motor, cost effectiveness, and manufacturing technology.

3. Optimization Analysis of Pmsms

3.1. Different Parameters and Structural Design

3.1.1 The Removal of The Stiffener

This concentrate on the PMSM's output shaft end cover optimization. A locally constructed structure called a reinforcing rib can increase a component's strength and rigidity without making its wall thicker. The PMSM's strengthening serves to increase the strength of the output shaft end cover while lowering the modal frequency of the motor and raising the amplitude of each mode in the area surrounding the output shaft end cover. Therefore, it is advised to remove the stiffener to maximize the output shaft end cover of the PMSM. The strengthening rib on the output shaft's end cover is removed to guarantee that installing and operating a PMSM won't be impacted. Fig. 4 depicts the improved PMSM.

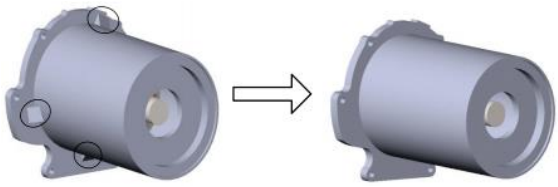


Figure 4. The removal of the output shaft's end cover's strengthening rib [5]

The computational modal study is carried out using the improved PMSM configured to the same material properties as the prototype. Fig. 5 displays the PMSM meshing following optimization.

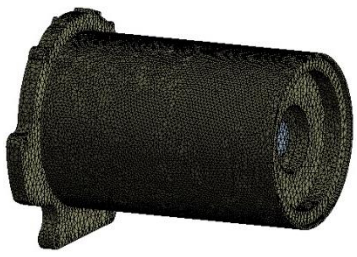


Figure 5. Optimized motor meshing [5]

When we compared the PMSM's natural frequency before and after optimization, we found that each motor step's frequency improved and that the low-order mode's increase was most noticeable [5]. Table 3 displays the optimization PMSM's modal frequency.

Table 3. Modal frequency of motor after optimization [5]

Order	Frequency (f/Hz)	Relative deformation (x/mm)
1	1525.4	0.232
2	2156.7	0.226
3	3153.6	0.265
4	3298.3	0.272
5	3823.4	0.258
6	4356.3	0.321

3.1.2 Taguchi Design Methodology

Several elements are chosen at varying degrees in the Taguchi optimization approach in order to examine how the factors affect performance. Utilizing specifically designed orthogonal arrays (OA), the DoE in the Taguchi technique permits a reduction in both the number of experiments and the amount of time spent executing the tests. A loss function is utilized in the Taguchi technique to compute the deviation between the desired and experimental values. The loss function yields the signal to noise ratio (S/N). The analysis makes use of three different kinds of S/N ratio quality parameters. These three are nominally the best, the higher the better, and the lower the better. The S/N ratio is computed based on response characteristics for every response in the analysis. The goal of the current study is to maximize power factor and motor efficiency. The drawing of PMSM design is shown in Fig.6.

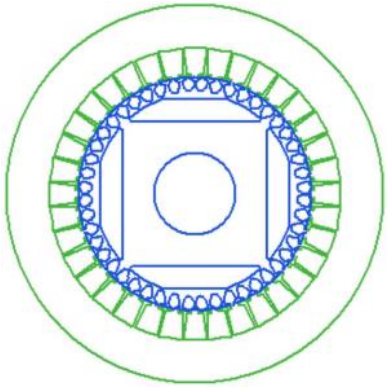


Figure 6. The drawing of PMSM design [12]

Equations (1) and (2) describes the quality characteristics [12].

(1) Higher-the better:

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{1}$$

(2) Lower-the better:

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right] \tag{2}$$

n is the number of observations, and yi is the ith experimental data. The amount of control parameters and intended levels determine which arrays are used. Many design criteria affect how well a PMSM performs in terms of efficiency, power factor, etc. [12].

3.2. Control Strategy

Modern control theory-based control techniques. contemporary control theory-based control techniques, such as predictive control, robust control, variable structure control, adaptive control, and so forth. Modern control systems can maintain system performance even in the face of model or parameter variance by taking into account the target's structural variance, changes in parameters, the nonlinearity impact, changes in operating conditions, environmental disturbances, and other unknown elements. Adaptive control keeps pulling out pertinent model data and pinpointing pertinent system parameters, which can gradually complete the model. As a result, it is now one practical way to get around the parametric variation. Model reference adaptive control, parameter identification self-tuning control, and other novel nonlinear adaptive controls are examples of the adaptive control techniques used in PMSM control. Adaptive control is currently widely used in PMSM control system parameter identification, effectively mitigating the impact of parametric variation [13].

Variable structure control can be thought of as a particular type of discontinuous nonlinear control technique that has the ability to change its structure discontinuously. The motor's dynamic qualities can be less affected by variations in load and parameter variation due to its insensitivity to external disturbances. Recent years have seen an increasing use of sliding mode variable structure control in AC speed control systems due to its good control performance and ease of implementation. Nevertheless, its uses are limited by the chattering issue that arises during the sliding mode switching [13].

Targeting the uncertainty issues in the PMSM model, robust control can ensure system stability and maintain some performance indices even when the control system is subject to external disturbances or internal parameter changes. The two major techniques for resilient control are the algebraic method and the frequency domain method. Using the frequency domain method, a controller is designed using the transfer function matrix of the system. The core of the relatively advanced H∞ control is using the bound norm of the transfer function H∞ as the regulator's ideal design index. In order to prevent destabilization and obtain robust stability, feedback controllers are made to stabilize a closed-loop system while requiring that its bound norm H∞ be smaller than a certain value. H∞ control is an effective way to control instability issues that arise in PMSM [13].

The future of the new energy automobile sector should focus on researching and developing new and more efficient electric vehicles, with the ultimate goal being to optimize the efficiency of the PMSM drive system. The efficiency of the PMSM drive system can be increased from many parameter viewpoints and control tactics to support the advancement and use of electric vehicles [14].

4. Conclusion

This paper further analyses the structural characteristics of PMSMs, detailing the stator and rotor operation principles and structural configurations, as well as describing the advantages of PMSMs, such as their small size, low noise, fast torque response, and high efficiency, which have led to their wide application in the field of electric vehicles. However, this paper also objectively points out several significant drawbacks of PMSM, including high material costs (especially rare earth permanent magnet materials), temperature sensitivity, manufacturing complexity, and challenges to environmental sustainability. These shortcomings not only raise the cost of producing electric cars, but they also reduce the ability of motors to operate in harsh environments. Two optimization and control methodologies for parameter and structural design, as well as future research objectives and difficulties, are described following an analysis of the elements affecting the efficiency of PMSMs. It also calls for further optimization of PMSM performance through research and development of new high-efficiency drive systems to cope with the technological and market competition in the electric vehicle industry. Overall, this paper delves into the importance and complexity of PMSMs as the core technology of new energy vehicles, providing a deep understanding and guidance for research and practice in this field.

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