Comparison of Different Arrangement of magnets for the Purpose of Reducing Magnet Usage in Designing an IPM Motor for Electric Vehicles

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Abstract- **Because of the excellent performance of IPM motor, it is widely used in Electric Vehicles. Meanwhile, due to the fluctuating price of rare earth raw material in recent years, the manufacturing cost of IPM motor is difficult to control. So, it is important to research on reducing magnet usage. The purpose of this paper is to compare three kinds of IPM motor with different rotor structures at the same time to improve the magnetic circuit by increasing the reluctance torque. As a result, the amount of expensive NdFeB magnet is substantially reduced by adopting a improved V-shape arrangement.**

I. INTRODUCTION

For the automotive industry, the development of electric vehicles that has virtually no environmental impact during operation represents the optimum long-term approach to protect the environment and generate product demand [1]-[2]. And, a conventional engine with transmission is replaced by EV motor without transmission. In pursuit of high torque density and high efficiency, IPM motor is widely used as the main power of electric vehicles. However, because of the magnet price floating, the cost of IPM motor is difficult to control. So, reducing the magnet usage is one way to solve the cost problem.

In order to find which type of motors is more adapted to the use of electric vehicles, many literatures compare among IM motors, IPM motors, reluctance motors. IPM motor has a high torque density and power density, and good noise and vibration performance [3]. For the IPM research, many studies focus on the comparison of the performance of IPM motor with different pole-slot number [4]. Meanwhile, it also has a lot of people study on different arrangement of magnets, analysis the design parameters affect the performance of IPM motor and research on the solution to improve the performance [5]. This paper focuses on compared performance of three different arrangement of magnets with the same stator and winding design. As a result, the amount of expensive NdFeB magnet is substantially reduced by adopting a improved V-shape arrangement.

In this study, an IPM motor using 48 slots and 8 poles with distributed winding is chosen to investigate a peak 280Nm, 10500rpm motor whose specifications are given in Table I. By comparing the electric-magnetic performance of the I-shape, V-shape, Improved V-shape magnet type of rotors, we examine the performance of different types of IPM motor with no-load and load condition. The structure risk of Improved V-shape is also concerned. Finally, the improved V-shape motor achieves the requirements of electric vehicles and has a minimum usage of magnets by maximizing the reluctance torque.

TABLE I
TARGET SPECIFICATIONS OF THE ELECTRIC VEHICLES MOTOR

Specifications		
Maximum Size	mm	Φ220*135
Peak Power	kW	80
Peak Torque	Nm	280
Rated Power	kW	40
Maximum Speed (under load)	rpm	8000
Maximum Speed (under no-load)	rpm	12000
Rated Voltage	V	280
Maximum Current	Arms	360
Peak Line to line Voltage (no-load)	V	500
Cooling type	-	Water

II. ELECTRIC-MAGNETIC PERFORMANCE

Before we start the motor detailed design, we should confirm the direction of motor design. As we known, the distributed winding design has a better performance on noise and vibration and a bigger winding factor. Considering the size of the stator and the motor cooling, we select a 48 slots and 8 poles IPM motor with a distributed winding design.

In order to compare the three different arrangement of magnets, we choose the same stator and winding design. Parameters of motor are shown in Table II, the 2D-FEM structure of stator assembly is shown in Figure 1. And, all the results show that the simulation models based on 2-D FEM.

TABLE II
PARAMETERS OF MOTOR'S STATOR、AIR-GAP AND WINDING

Parameters		
Inner diameter of stator	mm	Φ143
Air-gap length	mm	1
Tooth width	mm	4.75

Yoke width	mm	3.3
Open slot width	mm	2.5
Winding layers	-	2
Coil pitch	-	5
Number of Turns in a slot	N	24

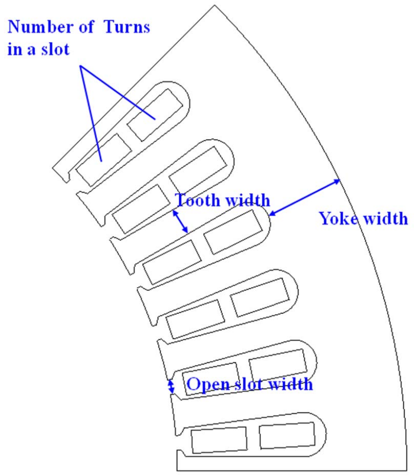
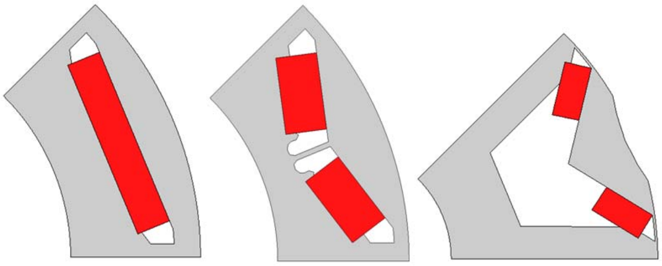


Fig. 1. Stator structures with winding.

Considering the limitation of the target specifications, we design three different arrangement of magnets. Motor structures with different arrangement of magnets are shown in Figure 2. A constant quantity of magnets was used in each case in order to compare accurately the motor characteristics attributable to the differences in the magnet arrangement. From Figure II, it is obviously that the magnet usage of I-shape and V-shape is approximately equal, and the magnet usage of Improved V-shape is about half of the others.



(a) I-shape (b) V-shape (c) improved V-shape

Fig. 2. Rotor structures with arrangement of magnets.

1. Performance under no-load condition

Since the value of back EMF under no-load is limited by the withstanding voltage of capacitor, the value of the peak line to line back EMF is set to be closer to 450V. The quantity of back EMF under no-load is very important to motor's design. The value of back EMF under no-load can response the output power of an motor, and harmonics has an influence on the efficiency, torque ripple, etc.

Fig.3 shows the curves of line back EMF and back EMF which are belong to three different magnet arrangement. From Fig.III, it is obviously that the max value of the three line back EMF is almost the same, but the shapes of the three back EMF are quite different. We can see the curve of improved-V magnet arrangement is more like a rectangular wave. And, the curves of I-shape and V-shape back EMF look like similar.

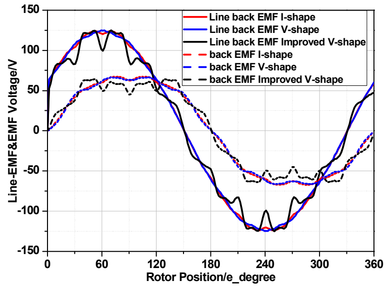


Fig. 3. Back EMF & line back EMF curves of magnet arrangement.

In order to analysis differences among three magnet arrangement better, we do some other calculations. Table III shows performance comparisons under no-load condition among three different arrangement of magnets. The values are calculated at 12000rpm which is the maximum mechanical speed of the IPM motor.

TABLE III

NO-LOAD PERFORMANCE PARAMETERS AT 12000RPM

		I-shape	V-shape	Improved V-shape
Peak line to line voltage	V	497.88	499.72	498.44
Phase voltage	Vrms	203.32	202.56	196.52
THD/Phase voltage	%	8.28	9.57	22.23
Cogging torque (peak-peak)	Nm	1.45	3.10	5.26
Flux linkage	Wb	0.0583	0.0579	0.0577

In order to use the maximum withstanding voltage capacity of capacitance, the values of voltage and flux linkage are almost the same. Because the I-shape arrangement of magnets can provide a strong magnet circuit, the relative position of magnets of I-shape arrangement is farther away from the air-gap. So, the I-shape arrangement of magnets has a better performance on cogging torque and THD of back EMF. And, the waveform of the improved V-shape arrangement of magnets has a bigger distortion. The cogging torque of Improved V-shape is more than 3.6 times as I-shape, and the THD of Improved V-shape is more than 2.6 times as I-shape. Although the maximum value of line to line back EMF and flux linkage of three magnet arrangement is almost the same, the performance under no-load is a bit different.

2. Performance under load condition

Then, we compare the performance under load condition of three magnet arrangement. For the IPM motor, the output torque can be expressed as [6]

$$T_{em} = p(\psi_f i_q - (L_d - L_q) i_d i_q) \tag{1}$$

where p is the rotor pole pair, Ψ_f is the PM flux linkage, Ld and Lq are the stator d- and q-axes inductance, id and iq

are the stator d- and q-axes current. It can be seen that the output torque consists of two components, the PM torque Tm and the reluctance torque Tr. With the different angles of supply current, the id and iq are also changed. Since Lq is greater than Ld, the reluctance torque of the IPM motor is positive if the id is negative. Figure IV. shows the output torque, the PM torque and the reluctance torque versus the current angle at the maximum current (400Arms).

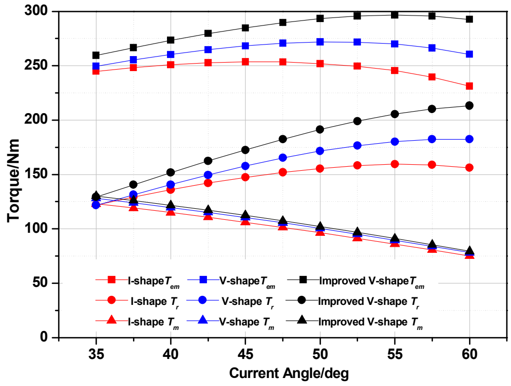


Figure 4. Torque curves of the arrangement of magnets

From Figure 4 can be seen that due to approximately equal flux linkage, the PM torque of three magnet arrangement is nearly the same. But the reluctance torque of three magnet arrangement is different . With the maximum current at 60 current degree, the reluctance torque of Improved V-shape is 30.8Nm bigger than V-shape, and the reluctance torque of V-shape is 26.3Nm bigger than I-shape. Because of the biggest reluctance torque, the Improved V-shape arrangement can provide 297Nm output torque. It is about 17.4% bigger than I-shape, and 9.2% than V-shape. At the same time, the Improved V-shape's usage of magnets is only half of the others. Meanwhile, the bigger reluctance torque has an influence on the current angle, the current angle in MTPA method is 57.5 degree. It's bigger than the other two arrangement. So, control strategy of IPM motor should consider the current angle changing.

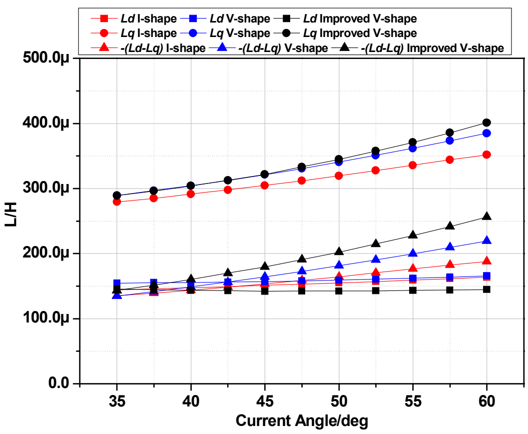


Figure 5. Inductance curves of the arrangement of magnets

From the Formula(1), we could find that the PM torque is decided by the PM flux linkage, and the reluctance torque is decided by the difference between Ld and Lq. In order to illustrate effects of three magnet arrangement, Figure 5 shows the curves of Ld , Lq and -(Ld-Lq). It can be seen from Figure.5 that because of the smallest Ld and the biggest Lq, the Improved V-shape has a best performance on the-(Ld-Lq). So, the Improved V-shape can provide a large torque which contains a great reluctance torque.

As we know, inductance depends on the motor's flux, and the shape of motor structure will influence the flux circuit. So, due to the special design of rotor, different magnet arrangement can have different performance.

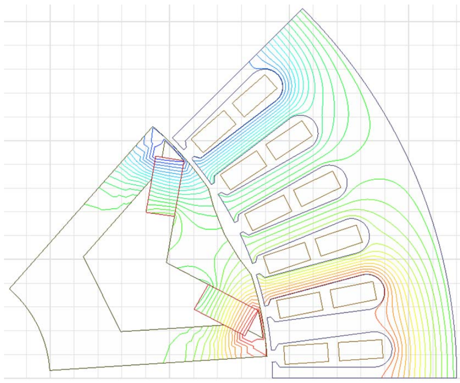


Figure 6(a). Flux distribution under no-load

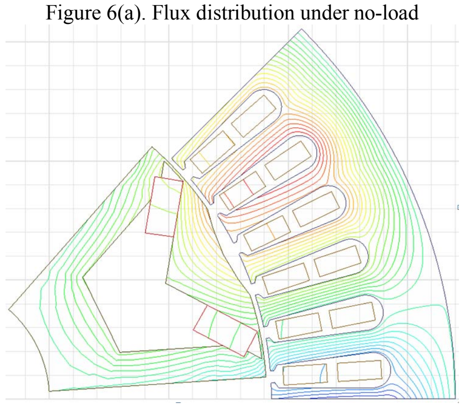


Figure 6(b). Flux distribution under load with no-magnetic magnet

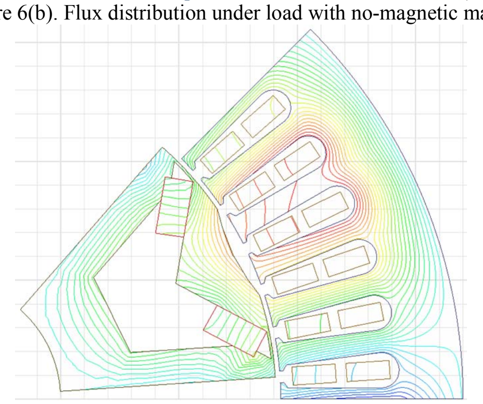


Figure 6(c). Flux distribution under load

Figue 6 shows the flux distribution of Improved V-shape under different conditions. From Figure 6 can be seen that the flux distribution under no-load is different from under load.

The flux distribution under no-load is a reaction of the PM torque. So, we can get the conclusion that the PM torque is a small part of the output torque. The distribution of flux generated by coil itself and flux under load is more similar, but the flux under load is under the influence of the magnet flux. It can be regulate the flux distribution of motor by optimizing the shape of the rotor. As a result, the output performance of motor can be increased and the usage of magnets can be reduced.

The Improved V-shape has a bigger reluctance torque. Meanwhile, the torque ripple is also a problem. Figure 7. shows the torque ripple of three magnet arrangement versus the current angle at the maximum current (400Arms). Due to the worse harmonic performance, the torque ripple of Improved V-shape is about 12% which is about double I-shape. Considering the position and function of the motor in the EV, we think that the torque ripple of Improved V-shape can be accepted.

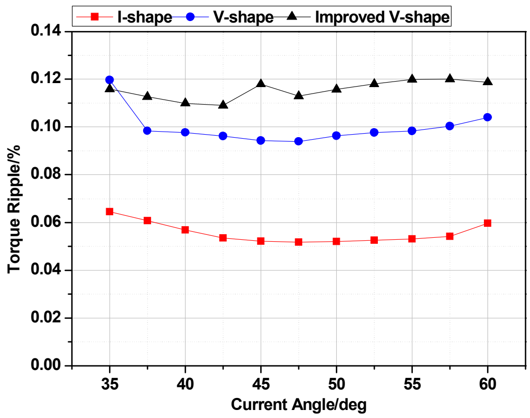


Figure 7. Torque ripple curves of the arrangement of magnets

In addition to peak load performance, we are also concerned about the performance in all conditions. Motor is the main power source of electric vehicles, so the N-T/N-P characteristics of motor is very important. Figure 8 is shown the N-T/N-P curves of the three arrangement of magnets.

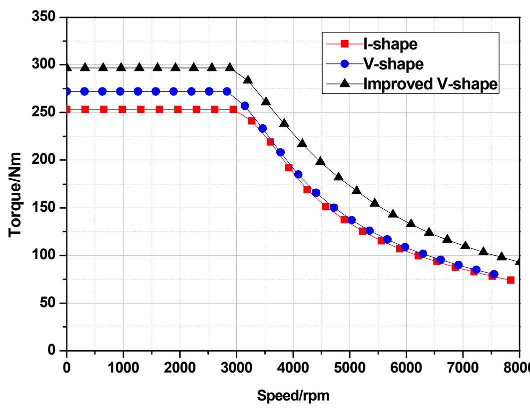


Figure 8(a). N-T curves of the magnet arrangement

As can be seen from Figure 8, because of the similar flux under no-load, the corner speed of three magnet arrangement is almost the same. Due to the bigger output torque, the Improved V-shape has better output performance. The peak power of Improved V-shape is nearly 96kW. It is about 15.7% bigger than I-shape, and 12.9% than V-shape. As a result, improving the reluctance torque is an effective way to expand the external characteristics of the IPM motor.

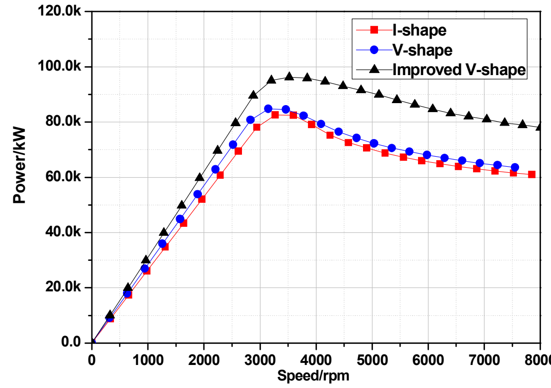
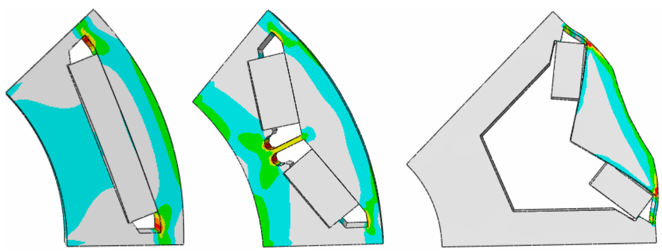


Figure 8(b). N-T curves of the magnet arrangement

3. *Risk of Improved V-shape*

According to the analysis of the performance, the Improved V-shape has a better output capability. Because of the special rotor shape, there is a risk in structure strength.

The high speed motor are under greater inertial force, sometimes the inertial force may exceed several times of the own weight. Thus, the strength analysis is a very critical link of the motor design. In order to avoid strength damage, the maximum stress value must be less than the ultimate strength of the material. In order to not affect the performance of the motor, the Max. radial deformation value must be far less than the size of the air-gap. This paper did the strength calculation of the three motor structures under centrifugal load at 120000 rpm, and Figure 9 shows the results of strength calculation of three magnet arrangement.



(a) I-shape (b) V-shape (c) improved V-shape

Fig. 9. Results of strength calculation under centrifugal load at 12000 rpm.

TABLE IV

RESULTS OF STRENGTH CALCULATION UNDER CENTRIFUGAL LOAD AT 12000RPM

		I-shape	V-shape	Improved V-shape

Max.stress	Mpa	267.3	269.4	419.7
Yield strength	Mpa	460	460	460
Max.stress< Yield strength		√	√	√
Max.Displacement	mm	0.0315	0.0294	0.1007
Air-gap	mm	1.00	1.00	1.00
Max.Displacement		√	√	√

As the results listed in the Table IV, the strength calculation of three motor structures is all within the scope of the material allows, and the maximum stress of Improved V-shape is the biggest, we can improve it in the future optimized design. The maximum displacement results are all far less than Air-gap, Three motor structures all meet strength requirements.

III. CONCLUSIONS

In this paper, a IPM motor using 48 slots and 8 poles with distributed winding is designed for electric vehicle with a peak torque of 280Nm and peak power of 80kW. Three different arrangement of magnets are compared by electric-magnetic performance for electric vehicles. Only the Improved V-shape design can achieve the target of requirements.

Improved V-shape arrangement of magnets can provide the biggest output torque and power , and its usage of magnets is nearly half of the others. But, Improved V-shape still has some problem on the electromagnetic field harmonic, the bigger torque ripple, it needs a further research to solve the problems.

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