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Research on Electromagnetic Field Simulation of Permanent Magnet Synchronous Motor

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ABSTRACT

In the electrical engineering education, modelling and dynamic simulation represent tools in order to understand behaviours of the different components for electric drive-systems in transitory regimes. This paper proposes a method to simulate the electromagnetic field of Permanent Magnet Synchronous Motor (PMSM). Based on the fundamental principle of traditional magnetic circuit design, the simulation model of Permanent Magnet Synchronous Motor (PMSM) is established by the ANSYS software. The load magnetic field of the motor is calculated. The magnetic field distribution of the motor is obtained. The performance of the maximum torque output under the different number of magnetic pole pairs, the permanent magnet in different sizes and the different rotor core thickness are analyzed in detail. Finally, the simulation results can provide the theoretical foundation for optimization design of the permanent magnet synchronous motors.

Key words: Permanent magnet synchronous motor, electromagnetic field simulation, output torque, performance

INTRODUCTION

For Hybrid Electric Vehicle (HEV) and Permanent Magnet Synchronous Motor (PMSM) is widely used due to its high torque, low weight, high efficiency and compactness (Huang *et al*., 2014; Zeraoulia *et al*., 2005).

The Permanent Magnet Synchronous Motor (PMSM) has numerous disadvantages over other machines that are conventionally used for ac servo drives. The use of the permanent magnet in the rotor of the PMSM makes it unnecessary to supply magnetizing current through the stator for constant air gap flux, the stator current needs only to produce the torque. Hence, for the same output, the PMSM will operate at a higher power factor (because of the absence of magnetizing current) and will be more efficient. On the other hand, the excitation must have been done on the motor by the conventional wound-rotor Synchronous Machine (SM), which is often supplied by brushes and slip rings. This results the rotor loss and the regular brush maintenance, which will lead to the downtime (Zheng and Pi, 2013).

The key reason for the development of PMSM is to remove the prior disadvantages of the SM by replacing its field coil doing power supply and slip rings with a permanent magnet (Ji *et al*., 2006; Li *et al*., 2001; Jing *et al*., 2009).

The design of permanent magnet synchronous motor is mainly based on the traditional magnetic circuit method. However, this traditional method, which depends on the empirical formula and the empirical coefficient, often results a large calculation error (Wang *et al*., 2011).

Based on this reasons, this paper uses finite element method to simulate the motor magnetic circuit. By studying the relationship of permanent magnet parameters and the maximum output torque, a useful method to magnetic circuit optimization and a design of permanent magnet synchronous motor are proposed.

MATERIALS AND METHODS

The matter of electromagnetic field analysis is generally solved by the Maxwell equations which has been given the boundary conditions. The potential function is more easier to establish the boundary conditions than the field quantity and the potential function is used to analysis the following assumptions by the motor electromagnetic field, which has been established:

- Neglecting edge effect and end effect, the three-dimensional problem is converted into two-dimensional to analysis, which uses the surface current model
- Materials are isotropic, ignoring the hysteresis effect of ferromagnetic materials
- Magnetic field was merely limited to the interior of the motor, external boundary of the stator is considered to be zero vector magnetic potential line
- The motor air gap and its cross section structure are symmetric along the main pole axis

Electromagnetic torque is an important performance index of the motor. The calculation accuracy of the electromagnetic torque depends on the calculation accuracy of magnetic fields, which determines the calculation accuracy of motor starting performance. So it has a great influence on the final accuracy of calculation. The two basic methods of the calculation of electromagnetic torque are consist of the virtual displacement method and the Maxwell stress tensor method. The method of virtual displacement, due to the need for two finite element solutions to obtain energy variation, caused by the angular displacement. Thus the modeling, calculation and the distinguishing small changes among the high energy, those all require the reasonable selection of a computational step to determine appropriate angular displacement. Therefore, the current Maxwell stress tensor method is widely used in the calculation of electromagnetic torque. The Maxwell stress tensor method can calculate torques, which is deduced by the mechanical theory. In order to take the rotor to be the object of solving and the closed surface of motor air gap to be solving domain, the electromagnetic torque of motor can be calculated by the surface integral in Eq. 1:

$$T_m = \frac{1}{\mu_0}\oint_S \left[B_n r\times B - \frac{1}{2}B^2 r\times n\right]dS \tag{1}$$

where, μ_0 is air permeability, n is the unit normal vector of surface S, r is the distance between field point and the axis of rotation in the surface.

In the two dimensional electromagnetic field, the area integral is simplified to the line integral of closed path T_{max} along the air gap is presented in Eq. 2:

$$T_{cm} = \frac{L_{ef}}{\mu_0}\oint_r r^2 B_r B_0 d\theta \tag{2}$$

Equation 2 provides a concise pathway to calculate the torque of the motor, as long as a closed curve is arbitrarily chosen in the motor, the air gap will calculate the total torque acting on the rotor. The Maxwell stress method is more sensitive to the density degree of subdivision, the accuracy of the solution depends on the quality of chosen integral route and the mesh generation.

RESULTS

One permanent magnet synchronous motor take as a example, which rated power is 5.5 kW. In order to take the whole motor to be the solving domain, it use the finite element method to simulate magnetic field and to study the relationship of the magnetic parameters and the maximum output torque.

Relationship between the number of magnetic poles P and maximum output torque: In the case of the same permanent magnet volume and thickness for the rotor core, it is important to study the maximum output torque of the motor under the different number of magnetic poles. Using ANSYS software, the properties, meshings, settings for solving of materials are designated through the process of creation of simulation model. In an attempt to simulate the motor magnetic field of the different number of poles, results of the motor internal flux density are shown in Fig. 1.

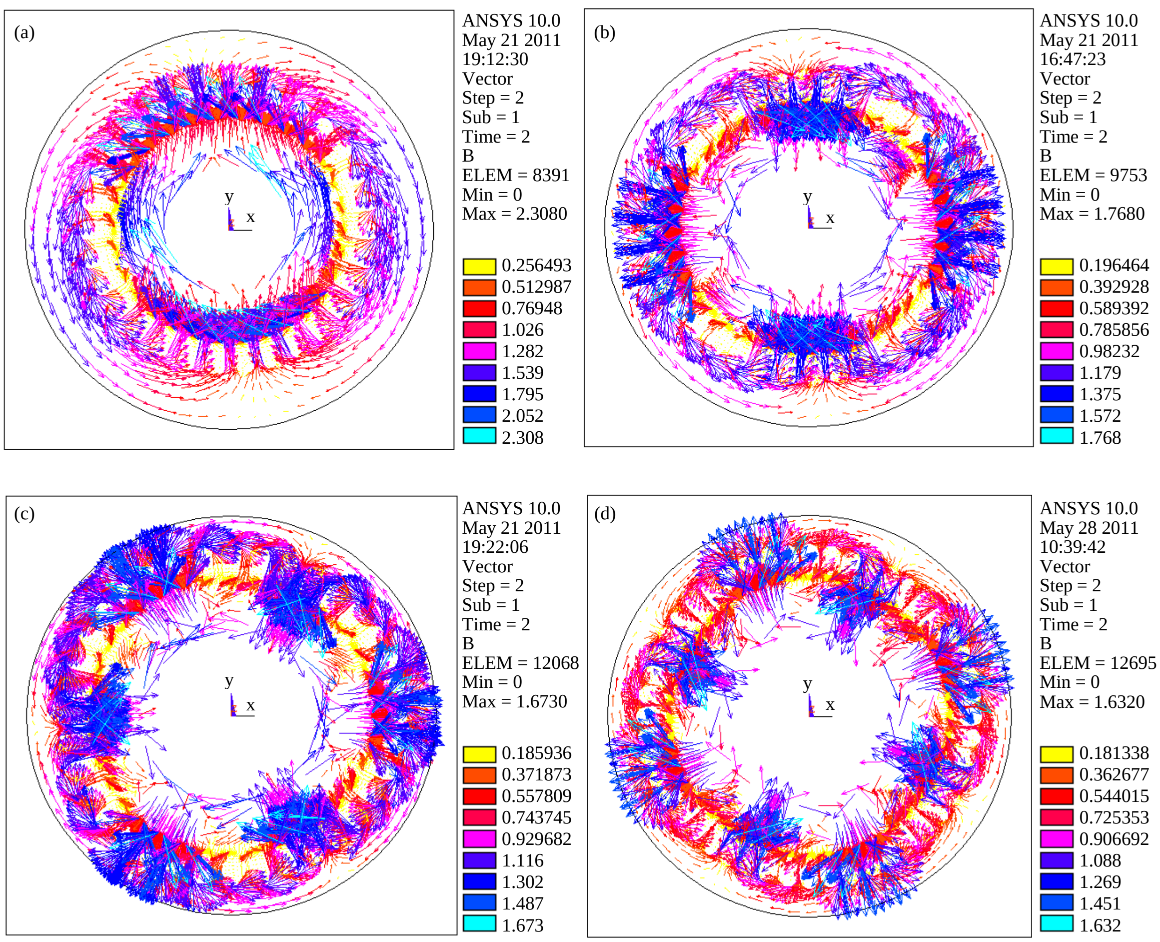

Fig. 1(a-d): Vector diagram of internal flux density (a) 2-pole motor, (b) 4-pole motor, (c) 6-pole motor and (d) 8-pole motor

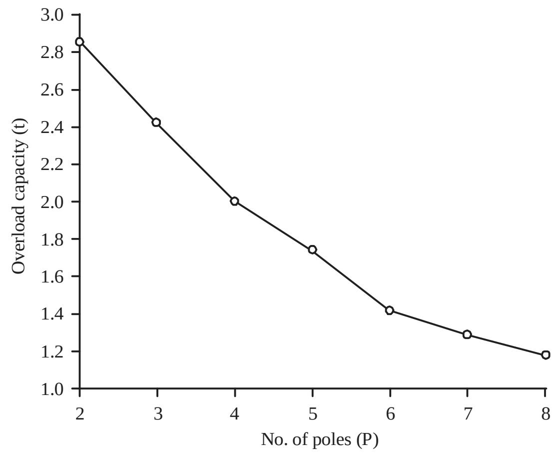

Fig. 2: Magnetic poles and overload capacity

When P = 2, the maximum output torque is 50.05 Nm, when P = 4, the maximum output torque is 70.45 Nm, when P = 6, the maximum output torque is 74.29 Nm and when P = 8 the maximum output torque is 79.81 Nm.

For the permanent magnet synchronous motor, the maximum of motor output torque is also known as the pull out torque. If the load torque exceeds this value, the motor will not maintain the synchronous speed. Generally, the ratio of motor maximum output torque to the rated torque $T_N(t = T_{max}/T_N)$ is defined as the pull out torque multiple, which is used to measure the overload capacity t of motor. Let's take a permanent magnet synchronous motor as example, which rated power is 5.5 kW. The relationship between the multiple pull out torque and the pole number is shown in Fig. 2.

As shown in Fig. 2, under the same circumstances of the same permanent magnet volume and thickness for the rotor iron core, the number of motor poles has a direct effect on the output torque. When numbers of magnetic poles are less, the flux density is low and the output torque is less. With the magnetic pole number raising, the maximum output torque T_{max} will increase. But the motor overload capacity t will declining with the increase of the number of magnetic poles.

Relationship between center angle of permanent magnet and the maximum output torque T_{max}: As the width of magnetization direction for permanent magnet (b_M) plays an important role on the magnetic flux of permanent magnets, the output torque of motors has a close relationship with it, especially when the motor with a high magnetic loading, the selecting appropriate b_M is critical. But b_M has relate to the selection problem in the coefficient of pole arc, the suitable coefficient of pole arc can make a air gap flux density waveform when the track of motors is close to sine wave. The rotor structure of surface mount type, when the coefficient of pole arc is too large will cause the induced potential harmonic component increasing. which may cause the fluctuation and the loss of the torque increase, at the same time the magnetic leakage in inter electrode will rise.

In the process of simulation, in order to simplify the computation and the optimization of magnetic circuit, the change of b_M is equivalent to variable quantity of center angle ($\Delta\varphi$) in a single pole arc permanent magnet. Taking the 4 poles motor as a example, when the width (b_M) of magnetization direction for permanent magnet is different, the vector of internal magnetic flux density is shown in Fig. 3 and the central angle and maximum output torque (T_{max}) in Fig. 4.

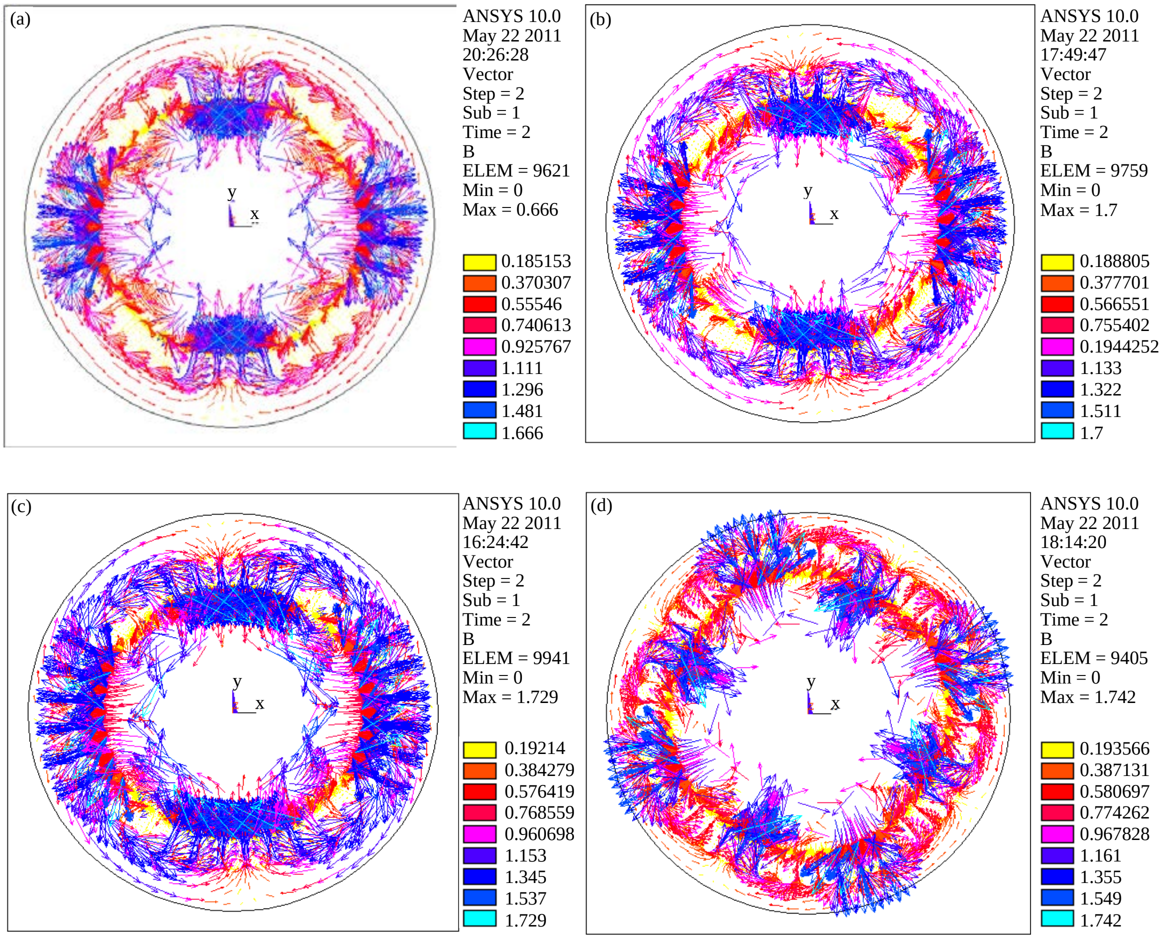

Fig. 3(a-d): Vector diagram of magnetic flux density (a) $\Delta\varphi = 45.478°$, (b) $\Delta\varphi = 54.522°$, (c) $\Delta\varphi = 65.478°$ and (d) $\Delta\varphi = 74.522°$

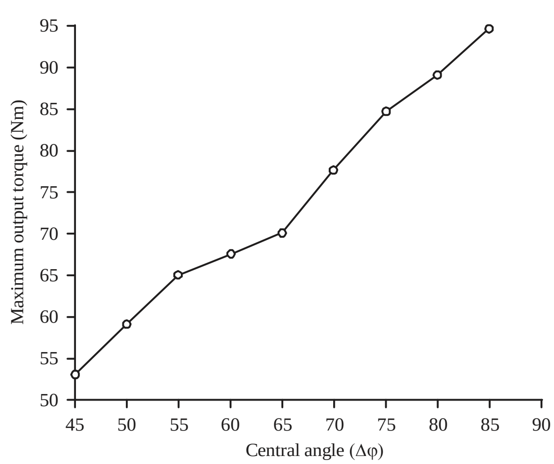

Fig. 4: Center angle and the maximum output torque T_{max}

Relationship between the length of magnetization direction for permanent magnet h_M and the maximum output torque T_{max}: Reluctance of the permanent magnet is close to air and the permanent magnet series in straight axis magnetic circuits, the length of magnetization direction for permanent magnet has a great effect on the straight axis performance of motor. On the other hand, the permanent magnet provides magnetic potential in the magnetic circuit and the air gap flux density in the magnetic circuit and the output torque increase. In the term of the performance, h_M should make the motor straight axis reactance X_{ad} more reasonable and in the point of technology, the permanent magnet should work at the best operating point. If the design of h_M is too thin, it will lead to the increasing of the reject rate and it is easy to demagnetize, which will influence the service performance of motor.

Let's take a 4-pole motor as example. When the length h_M of magnetization direction for permanent magnet is different, the vector of internal magnetic flux density is shown in Fig. 5.

Relationship between the different magnetization direction length of permanent magnet h_M and the motor maximum output torque is shown in Fig. 6.

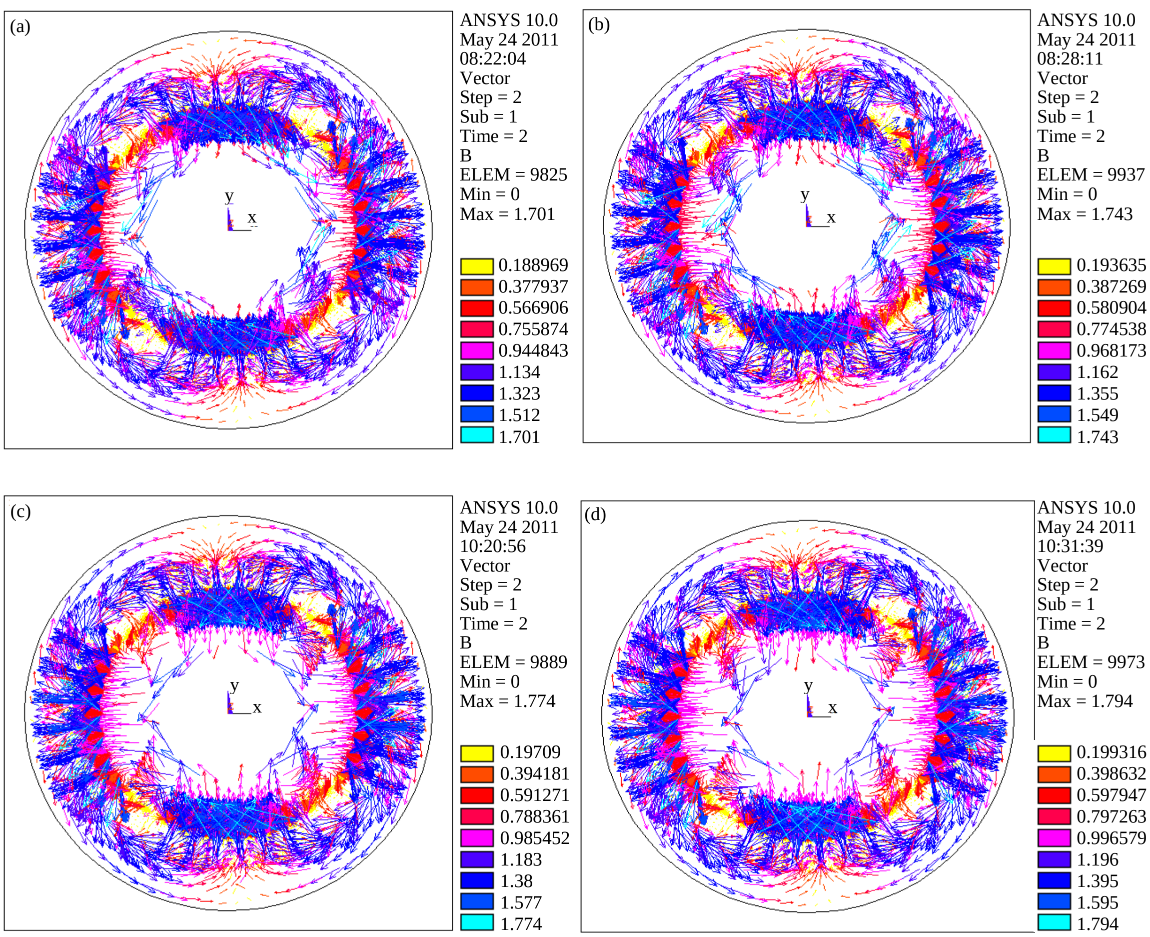

Fig. 5(a-d): Magnetic flux density vector diagram (a) h_M = 10.6 mm, (b) h_M = 13.6 mm, (c) h_M = 16.6 mm and (d) h_M = 18.6 mm

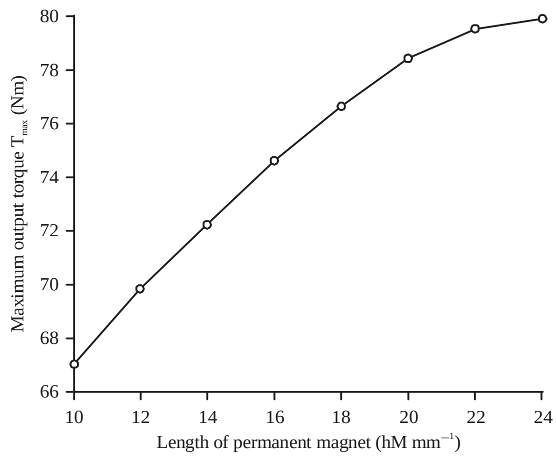

Fig. 6: Length of magnetization direction and the maximum output torque T_{max}

As shown in Fig. 5 and 6, for the sake of ensuring the rotor core unsaturated, with the increase of h_M, the value of torque increases is more fast. When h_M reaches to a certain thickness, the value of the torque increases much slow. The reason is that the air gap flux density of the motor will increase with the increasing of h_M and the magnetic potential, reluctance and magnetic flux leakage increase as well. When the thickness increases to a certain value, it will reduce the coefficient of the pole arc and result the waveform of air-gap flux density distorting. Therefore, in order to improve the utilization rate of the permanent magnets, h_M should not be too large.

Relationship between thickness of rotor core d and the maximum output torque T_{max}: Rotor core is used to prevent the interference of external magnetic fields. The distribution of magnetic flux density is changable, thus it will distribute in some places where they are most needed in the design of rotor. When P = 4, the magnetic flux density equivalent nephogram in thickness of different rotor cores is shown in Fig. 7.

As shown in Fig. 7, when the thickness of rotor iron core varies from 7-5 mm, the magnetic saturation of core becomes more and more obvious. As shown in Fig. 8, the magnetic saturation makes reluctance increasing and the air gap flux density decreasing. Finally, the output torque is reduced, when increasing the thickness of core, the reluctance will be reduced and the air gap flux density and the output the torque will be increased. When the thickness of iron core increases to a certain value and then increase the thickness of iron core again, the torque output begins to decline. Besides, the more thick core will make the rotational inertia of rotating part increasing. Thus, if the starting torque of motor increases, the unstable factors of operating component will increase too. Therefore, it requires a reasonable thickness selection value for the rotor iron core.

DISCUSSION

Using the finite element method of permanent magnet synchronous motor parameters and performance pointed out, that as the permanent role of the permanent magnet motor is always present, the past does not count the permanent role, excluding AC-DC axis cross coupling effects calculated separately AC-DC axis armature field is unreasonable (Zhou *et al*., 1994; Rahman and Zhou, 1994). Kurihara proposed the use of field-circuit coupling step when the element analysis of

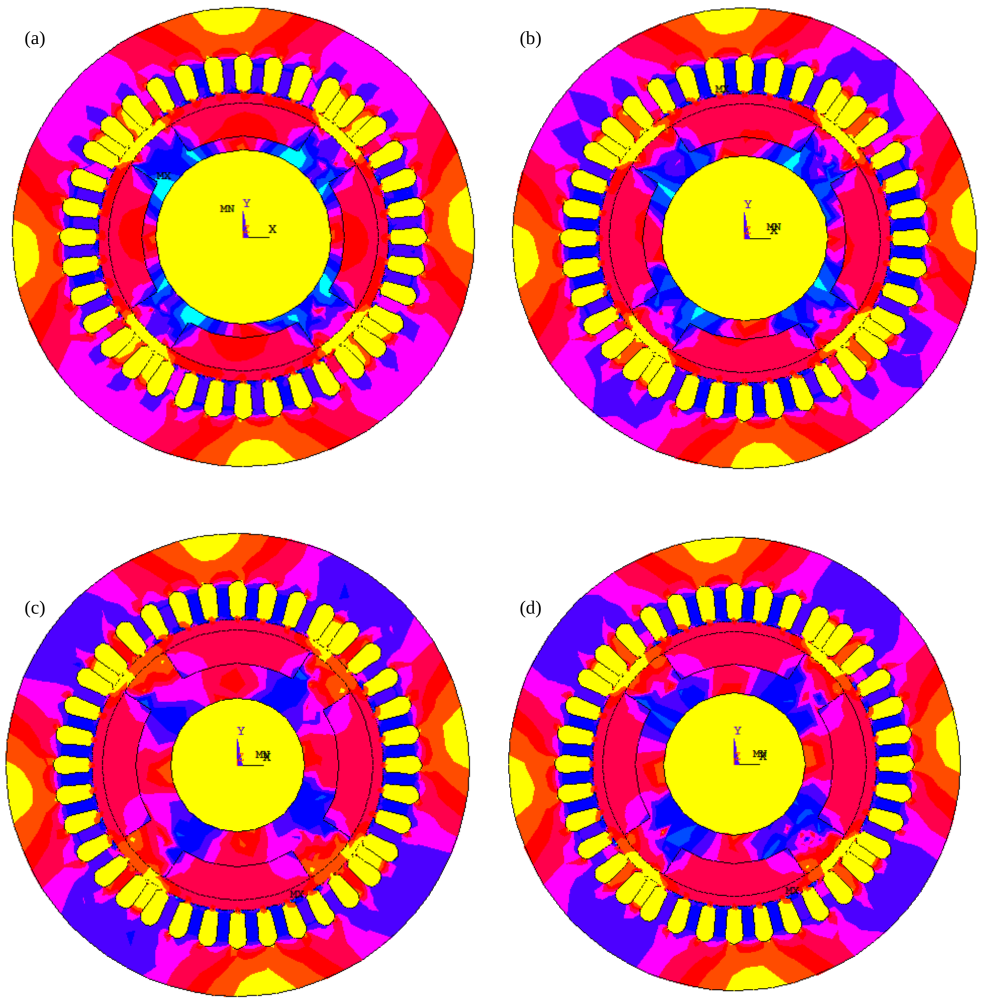

Fig. 7(a-d): Magnetic flux density equivalent nephogram (a) d = 5 mm (B_{max} = 1.652T), (b) d = 7 mm (B_{max} = 1.714T), (c) d = 11 mm (B_{max} = 2.001T) and (d) d = 13 mm (B_{max} = 1.978T)

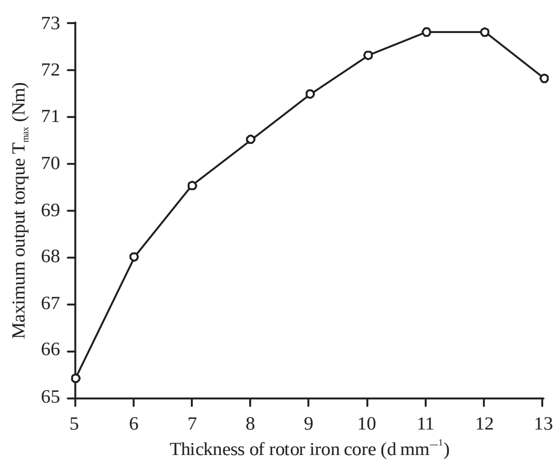

Fig. 8: Relationship between thickness of rotor iron core d and the maximum output torque T_{max}

steady-state performance of permanent magnet synchronous motor was limited and the magnetic field was explored due to current harmonics and torque fluctuations was caused by the presence of harmonics. At the same time, they opened a new research method of permanent magnet synchronous motors (Kurihara *et al*., 1994). But the application of the field-circuit mathematical model of a squirrel-cage rotor was not given in the various branches of constraint satisfied. In 1995, Craiu presented a method about using the finite element method of permanent magnet DC motor (Craiu *et al*., 1995). Permanent magnet DC motor researching is no longer confined the static magnetic field analyzing, but the paper did not consider the armature windings, the commutation of the problem and the widely using of the low power motor commutation torque generated fluctuate, which are the article deficiencies.

Permanent magnet motors with the high efficiency, the high performance, etc., which has become the new trend of development of the motor industry. Finite element method is a powerful tool that has been widely used in motor performance analysis even though deficiencies of permanent magnet motor finite element analysis model has been existing. In this paper, the basic theory of electromagnetic field, the using of the finite element method and the permanent magnet motor parameter calculation and performance analysis have been commenced study.

CONCLUSION

In this study, finite element method is used to simulate the electromagnetic field of permanent magnet synchronous motor, analysis the effects of some parameters on maximum output torque of motor, compared with traditional magnetic circuit method, numerical calculation method can effectively judge rationality of the electromagnetic design for motor, which improves the calculation precision and can further optimize the designed motor, the main conclusions are as follows.

- With the number of magnetic pole becoming larger, both the density of magnetic flux and the value of maximum output torque (T_{max}) all increases, while the overload capacity of motor decreases
- With the increasing of the center angle for permanent magnet, the density of the magnetic flux will increase and the value of the torque increases faster
- In the situation that the rotor core is unsaturated, in a certain range, with the increasing of h_M, the torque value increases faster; when h_M added to a certain thickness, the torque value increases slower. When the thickness increases to a certain value, the coefficient of pole arc will be reduced, the waveform of air-gap flux density is distorted. So the degree of magnetic saturation for motor increases and the increasing of the magnetic potential almost all consumed in the increased reluctance and magnetic leakage, thus the contribution to torque is very small. Therefore, in order to improve the utilization rate of the permanent magnet, h_M should not be too large
- With the increase of thickness for core, the reluctance is reduced and the air gap flux density and the output torque are increased; when the thickness of iron core increase to a certain value, the thickness of iron core will be increased. When the torque output begins to decline, the too thick core will make the rotational inertia of rotating part increasing, thus the starting torque of motor and the unstable factors of operating component are increased

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REFERENCES

Craiu, O., N. Dan and E.A. Badea, 1995. Numerical analysis of permanent magnet DC motor performances. IEEE Trans. Magnet., 31: 3500-3502.

Huang, W., Y. Zhang and X. Zhang, 2014. Design of PMSM drive system for HEV application. Micro-Motors, 47: 52-56, (In Chinese).

Ji, J., F. Kong and X. Kong, 2006. Overview of the development of canned pump. Pump Technol., 1: 15-20, (In Chinese).

Jing, B., F.Y. Kong, X.F. Zhang and C.L. Gao, 2009. Electromagnetic design for permanent magnet canned motor of canned pump. Micromotors, 1: 28-31.

Kurihara, K., G. Wakui and T. Kubota, 1994. Steady-state performance analysis of permanent magnet synchronous motors including space harmonics. IEEE Trans. Magnet., 30: 1306-1315.

Li, G., D. Li and X. Yang, 2001. Feature of design of shields induction motor. J. Shenyang Univ. Technol., 23: 295-297, (In Chinese).

Rahman, M.A. and P. Zhou, 1994. Field-based analysis for permanent magnet motors. IEEE Trans. Magnet., 30: 3664-3667.

Wang, Y., Y. Huang and H. Lin, 2011. Research of servo design of high speed permanent magnet synchronous motor line-starting with load. J. Southeast Univ. (Nat. Sci. Edn.), 41: 538-542, (In Chinese).

Zeraoulia, M., M.E.H. Benbouzid and D. Diallo, 2005. Electric motor drive selection issues for hev propulsion systems: A comparative study. Proceeding of the IEEE Conference on Vehicle Power and Propulsion, September 7-9, 2005, Brest, France, pp: 1756-1764.

Zheng, W. and Y.G. Pi, 2013. Research of servo drive based on SERCOS bus in PMSM. Modular Mach. Tool Automat. Manuf. Technique, 1: 54-56.

Zhou, P., M.A. Rahman and M.A. Jabbar, 1994. Field circuit analysis of permanent magnet synchronous motors. IEEE Trans. Magnet., 30: 1350-1359.