Comparison of Control Performance of PMSM of Different Rotor Structure

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***Abstract*-Two permanent magnet synchronous motors (PMSM) whose rotor magnetic circuit structures were radial and tangential were designed.vector potential and energy methods were used to calculate the electromagnetic parameters of the motors. Based on the mathematical model, the torque characteristics were calculated, control performances within constant torque and constant power control area were analysed and the corresponding control methods were given. Simulation results showed that dynamic performance and overload capacity of the radial structure were better while the flux-weakening speed expansion capacity of the tangential structure was better,which were consistent with the theoretical analysis.The final conclusions provided some reference for the design of the two kinds of PMSM.**

I. INTRODUCTION

Because of the global energy crisis, the new energy vehicles, especially electric cars get more and more attention and become the research hotspot in recent years. Permanent magnet synchronous motors (PMSM) are widely used in drive systems of electric vehicle and related equipments due to many advantages such as high power density, high efficiency, low manufacturing cost and wide constant power operating range. Motors used in electric vehicles require good control performance such as fast response, wide speed range and so on, thus, it has great significance to do some research on control performance of PMSM for the improvement of the performance of electric vehicles.The structure, shape and size of the permanent magnet have great effect on the electromagnetic parameters which are the determinant factor for the control performance of PMSM. Therefore, in order to know the control performance, it is necessary to calculate the electromagnetic parameters accurately. Different occasions require different control performance of motors,so the research of control performance of motors which have different rotor structure has an important reference value to the design of PMSM.This paper studied on the control performance of two PMSMS whose rotor magnetic circuit structures were radial and tangential.

II. CALCULATION OF ELECTROMAGNETIC PARAMETERS

Two 8-poles, 30-slots, 6.3Kw PMSMS whose rotor magnetic circuit structure were radial and tangential were designed.Their sides were all the same but the structure of magnets. Parameters were as follows: rated torque 40 N.m, rated voltage 41V, rated speed 1500rpm, stator outside diameter 176mm, inside diameter 118mm, Core length 145mm, Air-gap length 2mm, magnet thickness 5mm, width 24.5mm.

A No-load Magnetic Flux Leakage Coefficient

Magnetic flux leakage coefficient was defined as the ratio of the total outward flux provided by permanent magnet and the main magnetic flux of the outer magnetic circuit. Expression is as follow:

$$\sigma = \frac{\Psi_f}{\Psi_\delta} = \frac{\Psi_\delta + \Psi_\sigma}{\Psi_\delta} = 1 + \frac{\Psi_\sigma}{\Psi_\delta} \qquad (1)$$

σ not only changes with the permanent magnet materials, shape, size, and gap length but also changes with the load. The no-load value of σ is called no-load magnetic flux leakage coefficient.The no-load magnetic flux leakage coefficient is consisted of pole-to-pole flux leakage coefficent and end flux leakage coefficient. Since the latter is generally much smaller than the earlier ones, it is usually negligible.There are many factors affecting the no-load magnetic flux leakage coefficient and the distribution of magnetic flux leakage field is complex,so it is hard to calculate accurately. As the error of the analytical method is too large, it is usually only used as a rough estimate, while it is convenient to plot the distribution of magnetic field lines and find the magnetic flux by using the magnetic vector potential method and the accuracy is much better.In this paper, the magnetic vector potential method was used to do two-dimensional electromagnetic field computation to

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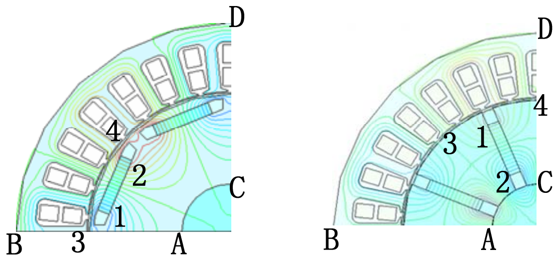
calculate the no-load magnetic flux leakage coefficient. The distribution of magnetic field lines and the solving planar field were shown in Figure 1 and the solving model was as follow:

$$\begin{cases} \Omega: & \frac{\partial}{\partial x}(\nu\frac{\partial A}{\partial x})+\frac{\partial}{\partial x}(\nu\frac{\partial A}{\partial x})=-J \\ \Gamma: & A=0 \\ \ell: & \nu_1\frac{\partial A}{\partial n}-\nu_2\frac{\partial A}{\partial n}=J_s \end{cases}$$



a.radial b.tangential

Figure 1 magnetic field lines distribution and the solving planar field

Where v is magneto-resistance ratio, A is magnetic vector potential, J is source current density, ζ is boundary of equivalent surface current of permanent magnet, which were marked 12 and 34. Ω is solving planar field.The magnetic vector potential of all the points within the magnetic field of PMSM can be got by doing FEA in Maxwell 2D.After that σ_0 can be calculated by the following formula:

$$\sigma_0=\frac{|A_1-A_2|}{|A_3-A_4|} \quad (2)$$

The no-load magnetic flux leakage coefficient changed with the length of permanent magnet magnetized direction and the length of air-gap was shown in Figure 2.It can be seen from the figure, σ_0 of the tangential structure was larger than the radial structure.The longer of permanent magnet magnetized direction and shorter of air-gap,the larger the σ_0 was.

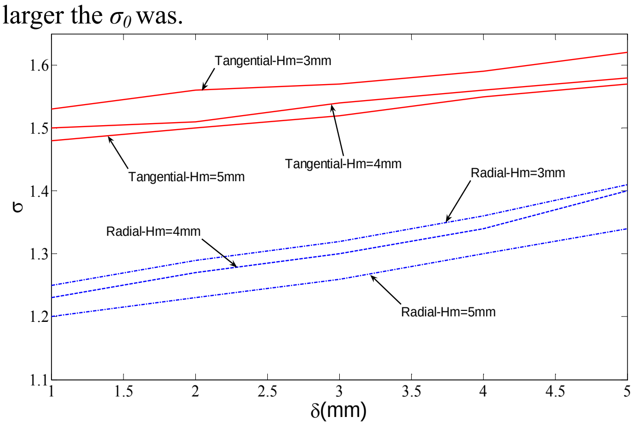


Figure 2 no-load magnetic flux leakage coefficient changed with structure parameters

B D-q Axis Inductance

The d-q axis inductances of PMSM have decisive effect on the ability of flux-weakening speed expansion, torque output and power output,so,it is very important to calculate them accurately.Just as the no-load magnetic flux leakage coefficient, the analytical method's error is too large,which is not appropriate for accurate calculation. The energy method was used to calculate the d-q axis inductance in this paper.Energy within a motor can be calculated by the following formula:

$$W_{AV}=\frac{1}{4}\int_v B\cdot H^* dv \quad (3)$$

If the magnetic field energy of permanent magnet is ignored, the whole energy within a motor is the storage energy of inductance when there are currents flowing through the winding. If current I(a) flows through an inductance L(a), the average storage within a cycle can be calculated by the following formula:

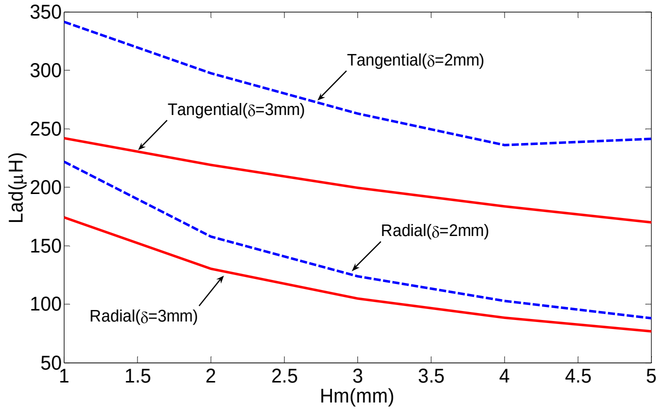
$$W_L=\frac{1}{T}\int_0^T\frac{1}{2}L_a*i^2(t)dt=\frac{1}{2}L_aI^2 \quad (4)$$

Therefore,if only d-axis or q-axis current flows through the winding and the permanent magnet excitation magnetic motive force is set to zero, the energy within a motor can be calculated by the following formula:

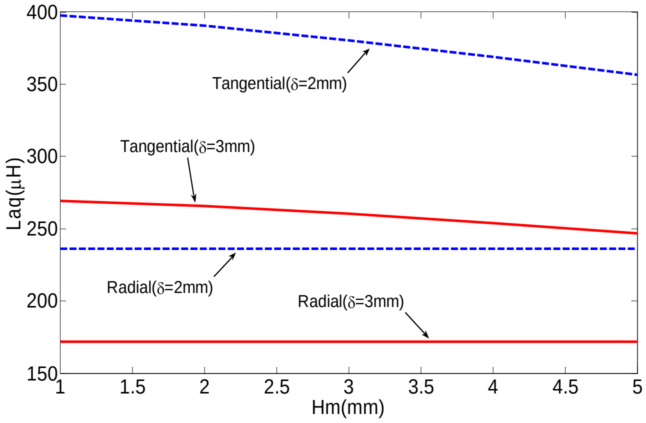
$$\begin{cases} W_{AV_d}=W_{L_d}=\frac{1}{2}L_dI_d^2 \\ W_{AV_q}=W_{L_q}=\frac{1}{2}L_qI_q^2 \end{cases} \quad (5)$$

Thus
$$\begin{cases} L_d=2W_{AV_d}/I_d^2 \\ L_q=2W_{Av_q}/I_q^2 \end{cases} \quad (6)$$

According to the calculation model,the post-processing macros were recorded in the Maxwell 2D, and then parametric analysis was done to find the d-q axis inductance by energy method.The impact of d-q axis currents on inductance was ignored,because the d axis inductance L_d which has greater effect on the control performance of PMSM is neally linear. Therefore the inductance value of rated condition also can reflect the control performance of PMSM well. The d-q axis inductances of the two prototypes changeed with the length of permanent magnet magnetized direction and the length of air-gap was shown in Figure 3.It can be seen from the figure, d-q axis inductances of the tangential structure were larger than the radial structure,and the longer the permanent magnet magnetized direction and air-gap,the smaller the d axis inductance was.While the q axis inductance was nearly remained constant and did not change with the parameters.



a. d-axis inductance



b. q-axis inductance

Figure 3 d-q axis inductance changed with structure parameters

III. ANALYSIS OF ELECTROMAGNETIC TORQUE

Torque characteristic is an important indicator of motor performance and has decisive effect on the control performance of PMSM. Expression is as follow:

$$T_{em} = \frac{P_{em}}{\Omega} = T_e + T_r = \frac{mpE_0U}{\omega X_d}\sin\theta + \frac{mpU^2}{2\omega}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\theta \quad (7)$$

Where T_e is permanent magnet torque, which is produced by the interaction of armature reaction between the permanent magnet air-gap magnetic field and the stator magnetic field.T_r is reluctance torque, which is produced by asymmetry of the d-q-axis magnetic circuit.It can be seen from (7), T_e is direct proportion to the value of E_0/X_d .Larger permanent magnet torque is better for the use of magnetic energy of permanent magnet and the heighten of power density.The greater difference between the d-q axis inductance,the larger reluctance torque is.Larger reluctance torque is better for the ability of overload, beening pulled into synchronization and flux-weakening speed expansion.

The electromagnetic torque situation of prototypes were shown in Figure 4,where 40 N.m was rated toque.In the case of equal volume of permanent magnet, the reluctance torque ratio of total electromagnetic torque of the radial structure was 57.5%,but the one of tangential structure was 28.8%.If the reluctance torque is all applied,the total electromagnetic torque of the radial structure is 86 N.m and the one of tangential structure is 63 N.m. Thus it can be seen that the radial structure can produce larger reluctance torque, which makes the ability of overload, beening pulled into synchronization and flux-weakening speed expansion of it stronger.

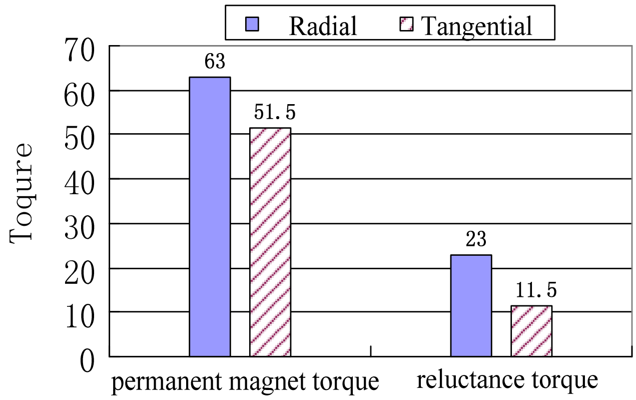


Figure 4 Reluctance and magnetic torque components of prototypes

IV. ANALYSIS OF CONTROL PERFORMANCE

A Constant Torque Control Area

Radial and tangential structures are all belong to the salient-pole struture,d and q axis inductances are not equal. The best control strategy within the constant torque control area is the maximum torque per ampere (MTPA) control which can get the minimum current under the same torque and has some advantages such as reducing copper loss, improving efficiency of the system and reducing the workload of inverter.

Model was built in matlab for simulation.The solution diagram for directive value of i_d^* and i_q^* was shown in Figure 5 and the simulation result was shown in Figure 6.

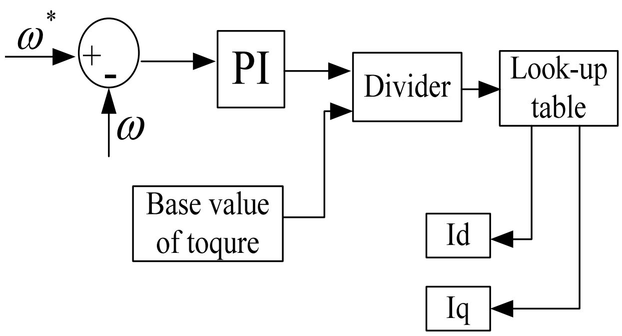
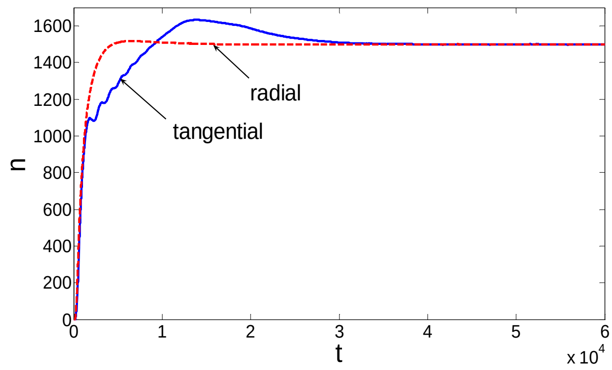
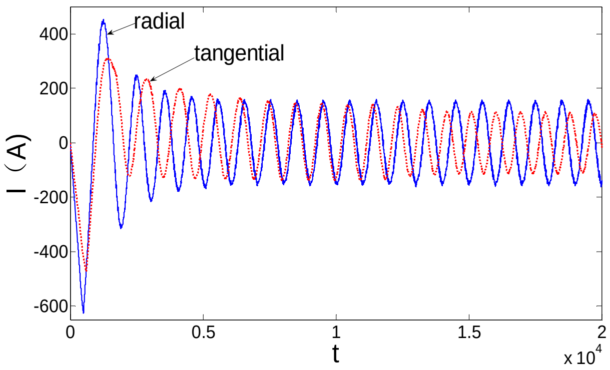


Figure 5 solution diagram for directive value of i_d^* and i_q^* of MTPA



a. speed curve



b. line current curve

Figure 6 simulation result within the constant torque control area

It can be seen from the speed curve that radial structure was pulled into synchronization at 0.1s and the tangential structure was 0.3s, which showed that ability of beening pulled into synchronization and dynamic response speed of the radial structure was better, consistent with the results of the analysis above. It can be seen from the line current curve that, achieving the same torque, the required current of tangential structure was smaller. That is because the magnetic flux under each polar was provided by the adjacent two poles in parallel, which can generate greater induced emf.

B Constant Power Control Area

PMSM goes in the constant power control area when the voltage of it reaches the limited voltage of inverter.When the voltage and current of PMSM reach max ,component of current is all d-axis current and ignores the effect of stator resistance,the ideal maximum speed of flux-weakening control is as follow:

$$\Omega_{max} = \frac{U_{lim}}{p(\psi_f - L_d I_{lim})} \qquad (8)$$

It can be seen from (8), in the case of equal number of pole pairs, limit voltage and current, the factors affecting the ability of flux-weakening speed expansion are Ψ_f and L_d .Smaller Ψ_f and greater L_d make stronger ability.The value of no-load magnetic flux leakage coefficient and reluctance torque will affect the value of Ψ_f.Known from (1), when the main magnetic flux Ψ_δ keeps constant, Ψ_f. and σ are inverse relationship. The permanent magnet torque can be designed smaller with larger reluctance torque. Thus, smaller σ and larger reluctance torque make stronger ability of flux-weakening speed expansion. Known from the analysis above, σ of the radial structure is smaller and reluctance torque of it is larger than the tangential structure,which is beneficial to the ability of flux-weakening speed expansion.While,it can be seen from figrue 3,the d axis inductance of the radial structure is smaller than the tangential structure,which is not conducive to the ability of flux-weakening speed expansion.Thus, comparing the ability of flux-weakening speed expansion, two aspects mentioned above have to be considered through (8).The ideal maximum speeds based on DC-side bus voltage 72V and fundamental RMS of phase current 110A are 5150rpm of radial structure and 8900rmp of tangential structure.U_d^* can be deduced from the d-q axis Mathematical model of PMSM,as follow:

$$u_q = -\omega\left[\frac{2T}{3P}\cdot\frac{\omega L_d}{U_d}\cdot\frac{L_q}{L_d - L_q} + \psi_f\frac{L_q}{L_d - L_q}\right] \qquad (9)$$

Motors run in voltage limit circle within constant power control area, thus:

$$u_d^{\ 2} + u_q^{\ 2} = u_{max}^{\ \ 2} \qquad (10)$$

From (9) and (10), the follow equation was got:

$$i_q = -\frac{\omega L_d}{r} i_d + \frac{u_q - \omega\psi_f}{r} \qquad (11)$$

Thus, the directive value of i_d^* and i_q^* can be got,the solution diagram was shown in Figure 7 and the simulation result was shown in Figure 8.

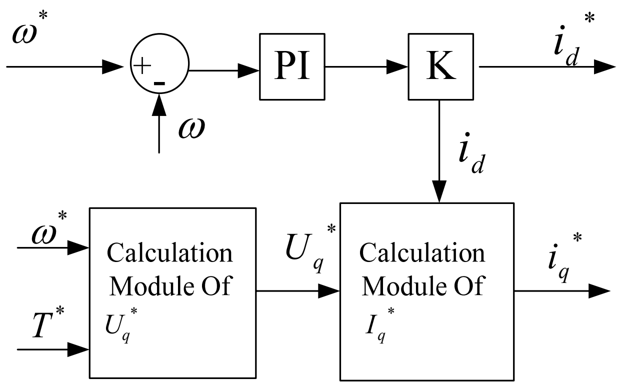
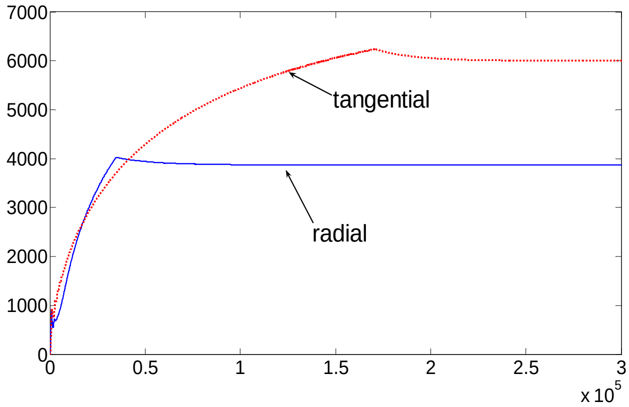
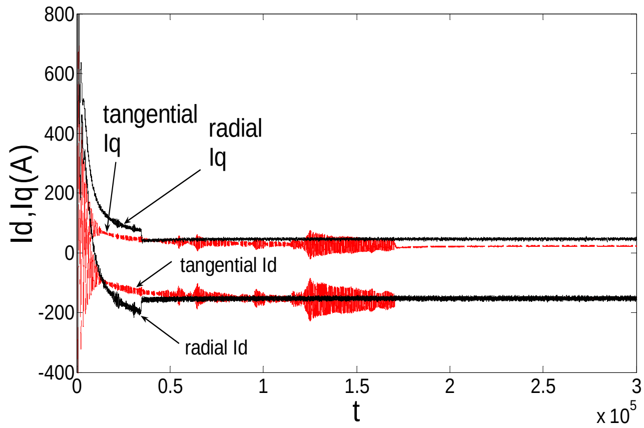


Figure 7 solution diagram for directive value of i_d^* and i_q^* of flux-weakening control



a. speed curve



b. I_d、I_q curve

Figure 8 simulation result within the constant power control area

It can be seen from figure 8, maximum speed of radial structure and tangential structure are 3870 rpm and 6000 rpm, which is consistent with the results of the analysis. Generally, the infection of ability of flux-weakening speed expansion by L_d is more sensitive than Ψ_f. Therefore, occasions required wide range expansion speed should adopt tangential structure, whose L_d is larger.

Ⅴ. CONCLUSION

This paper studied on the control performance of two PMSMS whose rotor magnetic circuit structure were radial and tangential.Simulation results showed that dynamic performance and overload capacity of the radial structure were better while the flux-weakening speed expansion capacity of the tangential structure was better. In practical applications,rotor structure should be selected according to different needs.Occasions required wide range expansion speed should adopt tangential structure and Occasions required high dynamic response speed should adopt radial structure.

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