Influence of Skewed and Segmented Magnet Rotor on IPM Machine Performance and Ripple Torque for Electric Traction

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Abstract- **The paper presents impacts of the stator slot with skew and segment magnet rotor on the performance of interior permanent magnet (IPM) machine for an electric traction. Comparisons of the average torque, torque ripples, cogging torque and no-load back EMF with skew and un-skew are given and how suitable a segmented rotor IPM machine and its torque characteristic and the field weakening capability are investigated. The results of the machine performance comparisons are based on comprehensive use of finite element analysis tools (Ansoft Maxwell 2D).One of the machine designs with one stator slot-pitch skew and no-segment magnet rotor for electric traction has been manufactured as prototype. From the FEA results, it shows that the IPM synchronous machine with two-teeth stator slots skewed and two-segmented magnet rotor has better performance than the conventional IPM synchronous machine.**

I. INTRODUCTION

The Interior Permanent Magnet（IPM）Machine drive has been widely used in high-performance applications due to its various attractive features such as high torque production and wide-speed range by flux-weakening. Reference[1] indicates proper machine design such as skewing and fractional slot pitch windings is the most effective means to minimize ripple torque of surface PM machine with Sinusoidal current excitation. Reference[2] gives the idea that segmentation magnet pole provides path flux canalization which is useful in flux-weakening and the segmented IPM machine is possible for wide constant power operation. However it does not give the suitable segmented number in IPM machine for Electric Traction. This paper investigates the impacts of the skewed and unskewed stator slots on the average torque , ripple torque, cogging torque and no-load back electromotive force(back EMF) .and gives how suitable the segmented IPM machine’s torque characteristic and its field weakening capability. The results of the machine performance comparisons are based on the comprehensive use of finite element analysis tools (Ansoft Maxwell 2D).One of the machine designs with one stator slot-pitch skew and no-segment magnet rotor for electric traction has been manufactured as prototype. From the FEA and measurement, it shows that the IPM machine with one stator slot-pitch skew and two-segment magnet rotor has better performance than the conventional IPM synchronous machine.

II. IPM MACHINE DESIGN

A. *Design Procedure*

The 7.5kW IPM design procedure is shown in Fig.1

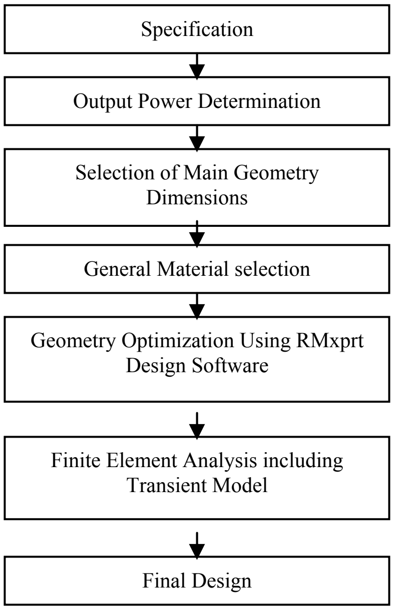


Figure 1. 7.5kW IPM design procedure

First, ANSOFT RMxprt software is used to develop the preliminary design. The input for this program includes basic electrical parameters (output power, frequency and voltage) and geometrical dimensions of the machine. The program allows specification of the magnetic and electrical properties of the materials. Also, the software can perform the optimization of the machine characteristics using the input parameters as independent variables. The output of the program gives the characteristics of the machine.

Second, ANSOFT Maxwell 2D software is used to create IPM transient model and to determine instantaneous solutions corresponding to three phase current or voltage excitation. Moreover, in order to get high torque value and low ripple torque and cogging torque, the PM size and shape of the magnets were adjusted.

The main preliminary parameters of the IPM machine designs are given in Table I.

TABLE I
7.5KW IPM MACHINE PARAMETERS

Design Parameter	Value
Rated output power (kW)	7.5
Rated voltage(V)	115
Rated torque($N \cdot m$)	22.4
Number of poles	8
Number of stator slots	48
Rated speed(r/min)	3195
Outer diameter of stator(mm)	175
Inner diameter of stator(mm)	120
Axial length of stator core(mm)	75
Inner diameter of rotor(mm)	38
Air gap(mm)	0.5
Thickness of magnet(mm)	5.5
Magnet material	NdFeB
Rated current(Arms)	46

B. 2D FEA Models.

The FEA model of conventional IPM machine is shown in Fig.2. It is excited with three phase balanced sinusoidal currents producing the characteristic synchronously rotating magneto motive force (MMF). Fig.3 shows flux density simulation results for two poles transient model with current I_{Rms}=46A and control angle is at 45 electric degree.

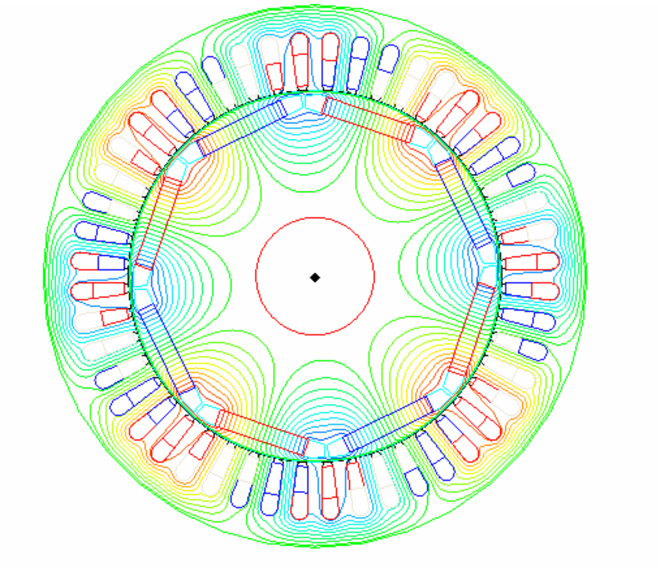


Figure 2. Cross-section of the 8-pole 7.5kW IPM machine

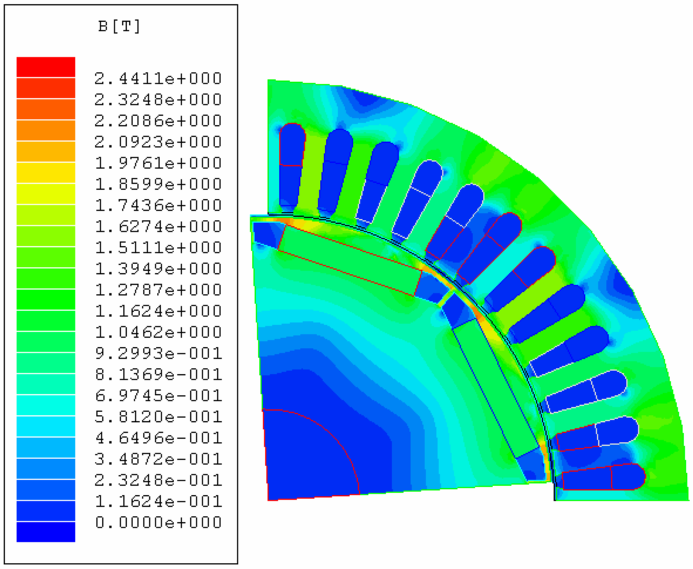


Figure 3. Flux density of two poles transient model.

III. INFLUENCE OF SKEW AND SEGMENTED MAGNET ON RIPPLE TORQUE AND BACK EMF

A. Torque Calculation

The IPM machine is also called hybria permanent magnet reluctance motor. Its salient structure generates the extra reluctance torque. The existence of the reluctance torque is positive to improve the motor's overload ability and power density. Further more, it makes the motor more easy to adjust the speed by weakening the d-axis flux-linkage. The torque equation is given as:

$$\begin{aligned} T &= \frac{3}{2}p(\lambda_d I_q - \lambda_q I_d) \\ &= \frac{3}{2}p[\lambda_m I_q + (L_d - L_q)I_d I_q] \\ &= \frac{3}{2}p[I_s\cos\theta + \frac{1}{2}(L_d - L_q)I_s^2\sin(2\theta)] \end{aligned} \tag{1}$$

where p is the number of pole-pairs, λ_d and λ_q are the d- and q-axis flux-linkages, λ_m is the PM flux-linkage, L_d and L_q are the d- and q-axis inductances. θ is the current control angle[3].

As in (1), the first part is the permanent magnetic torque which is proportional to $\cos\theta$,so the maximal value of the permanent magnetic torque is at $\theta = 0$ electric degree, while the maximal value of the second part:the reluctance torque which is proportional to $\sin(2\theta)$ is at $\theta = 45$ degree. So the maximal value of the total torque is at θ_m , $0^\circ < \theta_m < 45^\circ$ .Fig.4 shows the torque versus the current control angle.

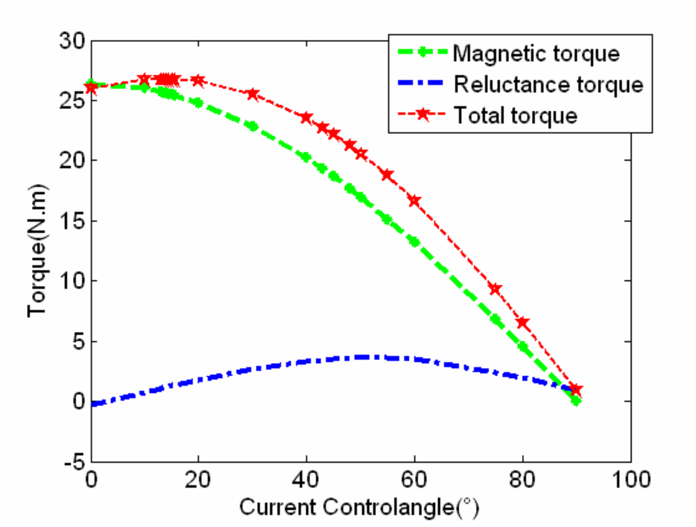


Figure 4. Torque compositions of IPM machine

B. Elimination of the Cogging torque

The ripple torque of IPM machine is generated by the interaction of the stator current magneto motive force and rotor electromagnetic properties, while the ripple torque can even be in existence without winding excitation which is called Cogging torque. Its expression is as in(2).

$$T_{cog}=\sum_{i=1}^{\infty}K_{sk}T_i\sin(iN_p\theta_m+\phi_i) \qquad (2)$$

Where

T_i,ϕ_i are the cogging torque harmonic amplitude and phase angle respectively.

N_p is the lowest common multiple of the stator tooth number Q and pole pair number p,

θ_m is the mechanical angle between the stator axis and the rotor axis,

K_{sk} is the skew factor, which is decided by the formula as follows

$$K_{sk}=\frac{\sin(iN_p\pi\alpha_{sk}/Q)}{iN_p\pi\alpha_{sk}/Q} \qquad i=1,2,3\ldots\ldots \qquad (3)$$

where α_{sk} is the ratio of the skew pitch to teeth width

There are many means to reduce the cogging torque, such as skewing stator slots, enlarging slots number, minishing brush's width and so on. However the most prevailing method is just skewing stator slots, and mostly skewing one stator slot pitch [4]. This method can eliminate the cogging torque completely in theory. Because after skewing one slot pitch as in Fig.5,the half of the conductor is under the S pole of the cogging harmonic magnetic field, and the other half is under the N pole when the conductor cut the cogging harmonic magnetic field. The two induce the same amplitude but the opposite phase of electromotive force. So the combined cogging harmonic electromotive force of the whole rotor conductor is zero, and the cogging torque is eliminated as well.

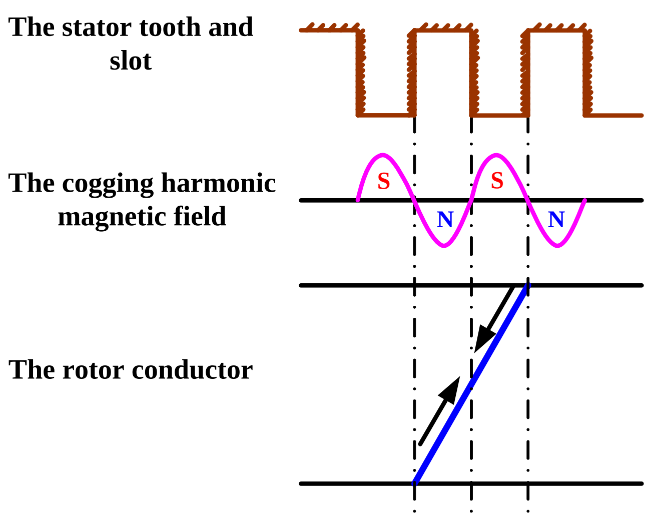


Figure5. The principle of eliminating cogging torque through skewing slot

Fig.6 shows the simulation results of cogging torque comparison between the stator skewing and without skewing, and the cogging torque is nearly eliminated after skewing two-tooth stator slots.

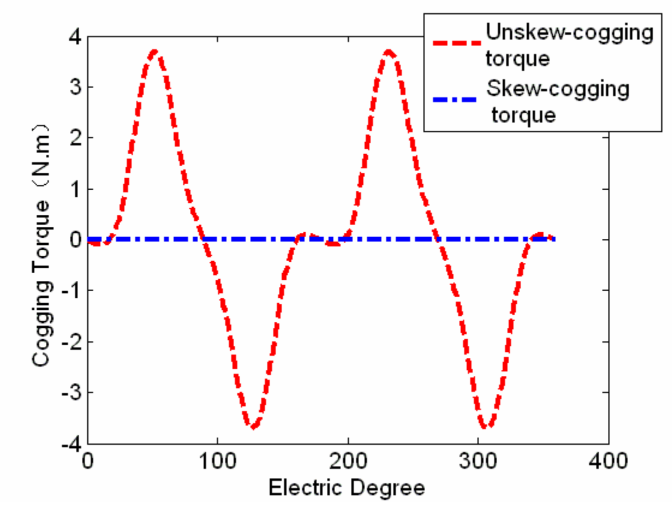
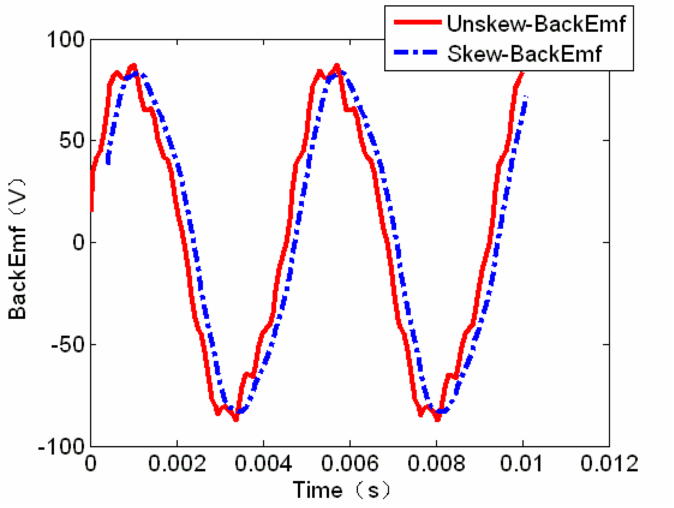


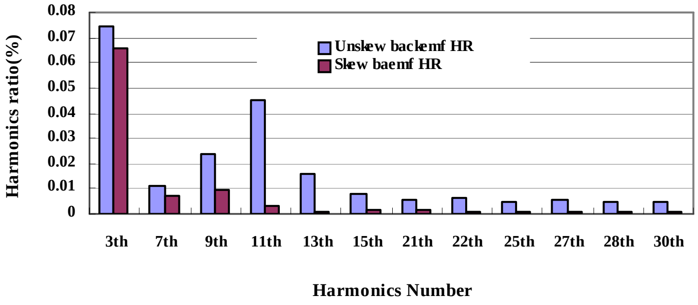
Figure 6. Cogging torque versus rotor position

The simulation result of the no-load back EMF based on Maxwell 2D can not consider the influence of the skewing slot, however we can apply a method of fragment calculation to compute it[5].The step is as follows: first, The air flux density is fragmented into several segments along the motor axial direction. In every fragment, the stator slot are assumed to be unskewed, then every fragment's magnet field is calculated separately based on the 2D FEA . At last, the calculated value of every fragment's flux-linkage is combined and then averaged. The no load back EMF considering the skewing slot influence is obtained.

Fig.7(a) gives one-phase Back EMF waveform comparison of skewed model and unskewed model.Fig.7(b) compares the harmonic ratio(HR). It obviously shows that the back emf is more close to sine wave and harmonics is reduced greatly after skewing the stator slot. The total harmonic distortion (THD) is also reduced from 9.55% to 6.75%.



(a) A-phase Back EMF versus time



(b)Harmonic ratio comparison of A-phase back EMF

Figure 7. The comparison of backemf for skew and unskew

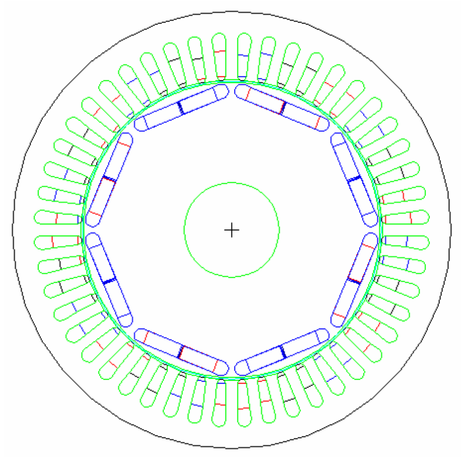
C. *Reduction of the ripple torque*

The ripple torque is defined as in (4)

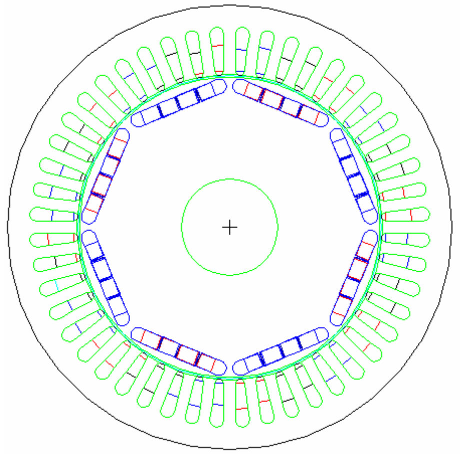
$$T_{rip} = (T_{\max} - T_{\min}) / T_{ave} \qquad (4)$$

where $T_{\max}$ is the maximum torque of one period, $T_{\min}$ is the minimum torque and T_{ave} is the average torque.

Segmenting the magnet is an available way to reduce the ripple torque. But how many sections the magnet should be segmented into is suitable:two or four? To resolve the question, we construct the other two segmented FEA models in allusion to the conventional one. The three models have the same stator parameters but have different magnet rotor. Fig.2 is conventional model whose magnet rotor is not segmented. Fig.8(a) is two-segmented model whose magnet is segmented into two sections ,and the four-segmented model whose magnet is segmented into four sections is Fig. 8(b).



(a) Two-segmented FEA model



(b) Four-segmented FEA model

Figure 8. The segmented FEA models

From Fig.9 , it can be seen that the ripple torque of the segmented model is lower than the conventional model's[6], and the ripple torque is reduced from 18.11% to 7.81%. However, the average torque of the four-segmented model is largely lower than the previous two models'. So the two-segmented model is selected.

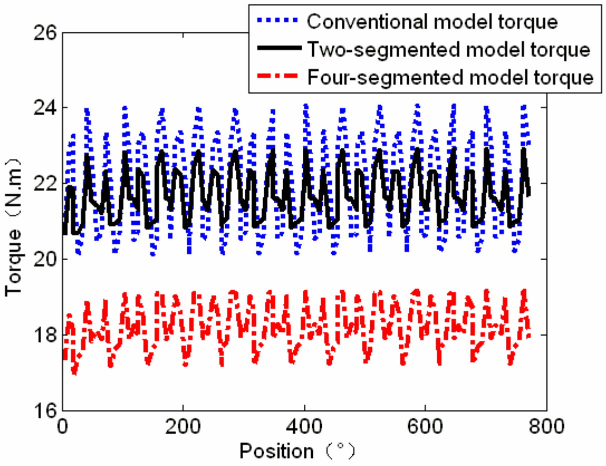
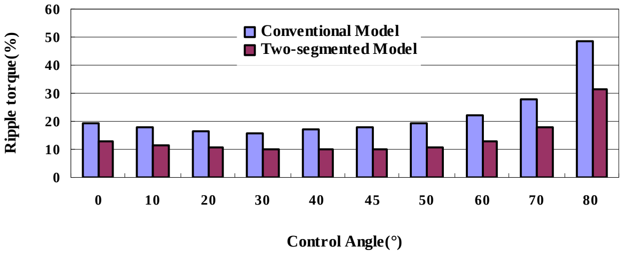
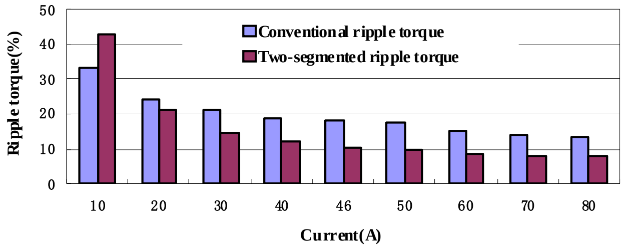


Figure 9. Torque comparisons of three IPM machine

Fig.10 presents the comparison between conventional and two-segmented machine for the ripple torque variation versus current and current angle, which further validate the forward conclusion.



(a)Ripple torque versus Current angle



(b)Ripple torque versus Current

Figure 10. The ripple torque comparisons of conventional and two-segmented machine

IV. INVESTIGATION OF SEGMENTED MAGNET ON IMPROVING FLUX WEAKENING PERFORMANCE

A. *The torque- and power- speed characteristic of IPM machine*

IPM machines are widely used in electric traction motor because of its wide-speed range . The terminal voltage V_s is directly proportional to speed. So we can heighten the speed ω by enlarging V_s. However, the motor operates under both voltage and current limitations imposed by the inverter as in (5) and (6). Thus the maximum terminal voltage $V_{\max}$ provides a constraint over maximum speed. In order to enable the motor performance at higher speed, we can weaken the flux to adjust the speed. The detailed method is to increase the negative d-axis current I_d or reduce the q-aixs current I_q .However, the q-axis current should be reduced while increasing the d-axis current to assure that the current I_s not to be larger than the current limit $I_{\max}$ .It is necessary for increasing d-axis current to weaken the flux and widen speed range.

$$\begin{aligned} V_s &= \sqrt{V_d^2 + V_q^2} \\ &= \omega\sqrt{\lambda_d^2 + \lambda_q^2} \\ &= \omega\sqrt{(L_d I_d + \lambda_m)^2 + (L_q I_q)^2} \le V_{\max} \end{aligned} \tag{5}$$

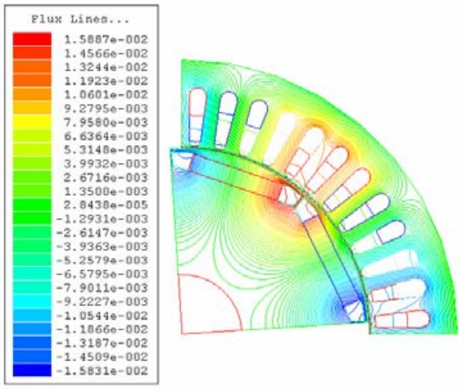
$$I_S = \sqrt{I_d^2 + I_q^2} \le I_{\max} \tag{6}$$

$$\begin{aligned} P_o &= \omega T \\ &= \frac{3}{2}\omega P[I_s \cos\theta + \frac{1}{2}(L_d - L_q) I_s^2 \sin(2\theta)] \end{aligned} \tag{7}$$

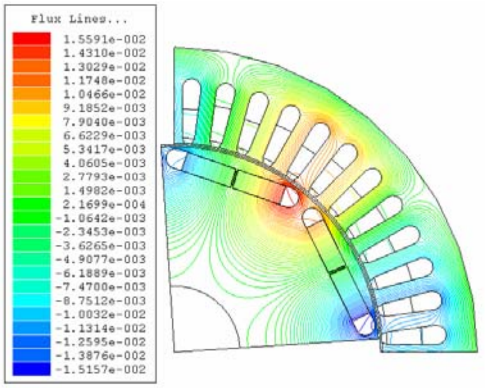
Where V_d, V_q is the d- and q- axis voltages, ω is the mechanical angular velocity, and P_o is the output power.Equation(7) shows that, during the flux-weakening range , θ is increasing until 90 degree to limit the voltage ,and when $\theta = 90^\circ$,output power P_o is zero. Thus for each motor design there is a limit over the speed at which output power will ultimately become zero.

B. *Comparisons of IPM machines field weakening Capabilities*

In the two-segmented IPM machine, the magnet is segmented and a small iron bridge is placed between two segments for increasing the mechanical strength of rotor construction. When the stator current is applied, a part of the permanent magnet flux is canalized into the iron sections as in Fig.11(b) compared with Fig.11(a). Q-axis inductance increase evidently since more air is in q-axis direction though the segmented rotor improve d-axis inductance as well, as result, the saliency ratio of the machine become greater than conventional one. It has been revealed in [7] that higher is the saliency ratio, better is the reluctance torque contribution. During flux-weakening operation, the reluctance torque component of the IPM machine plays a crucial role by providing useful shaft torque.



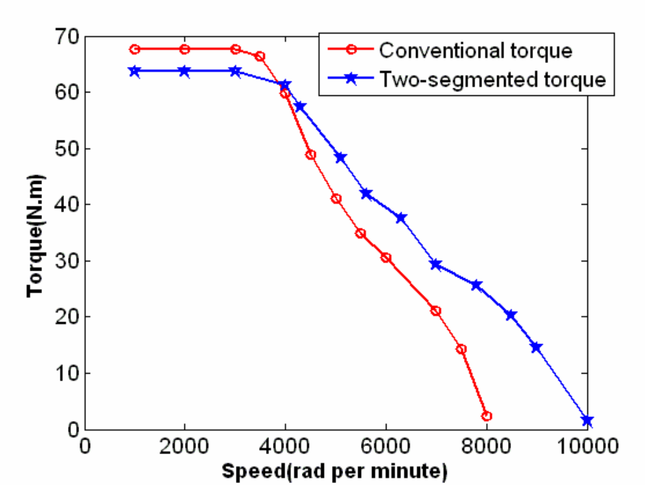
(a) Conventional model



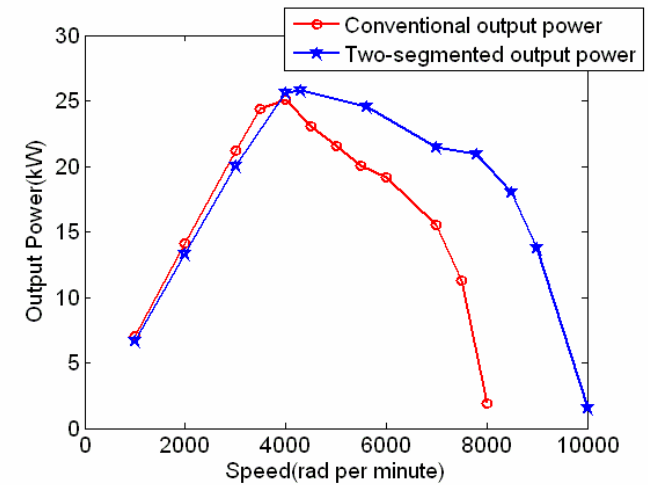
(b) Two-segmented model

Figure 11. Flux distribution of IPM machine

Fig.12 confirms that two segmented magnet rotor improved wide speed range and have higher field-weakening(FW) capabilities[8]~[10]. The constant output power speed range(CPSR) is improved from 3:10 to 4:10, while the maximum speed is improved from 8000rpm to 10000 rpm.



(a)Comparison of Flux weakening range



(b) Comparison of Output power

Figure12. Maximum torque /power –speed characteristics

V. CONCLUSION

This paper has investigated that whether stator slot skew or segmented magnet rotor IPM machine design can reduce cogging torque and ripple torque.And comes to the conclusion:

(1)Skewed and segmented magnet rotor machine design give possibility of better back-EMF waveform,and lower ripple torque,which make the machine run more smooth.

(2)As results of optimizing a 7.5kW IPM machine , FW performance characteristic is better than conventional IPM machine. And its CPSR improved 10 percent as well.

The goal of optimizing the performance of the IPM machine by skewing slot and segmenting magnet is realized .

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