Paper

IPMSM with Adjustable PM Armature Flux Linkage for High Efficiency and Wide Range Operation

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With the rapid development of power electronic devices, rare earth permanent magnet (PM) and motor control technology, interior permanent magnet synchronous motor (IPMSM) is being widely used in various applications. In some applications such as electric vehicles and compressors, except for high efficiency, extensive constant-power operating range is also desired. This paper discusses an IPMSM with adjustable PM armature flux linkage by means of adapting flux-shortening iron pieces in the space of rotor's flux barriers. The performance of the proposed IPMSM is studied using normalized analysis for general meaning. It shows that the operating range of the proposed IPMSM can be greatly extended by lowering the PM armature flux level through the iron pieces. Due to the possibility of decreasing the PM armature flux linkage, the proposed IPMSM requires less *d*-axis armature current in the area of flux-weakening control, so the efficiency and power factor can be improved, especially at light load and high speed operation. The variations of efficiency relating to operating conditions and PM flux level are discussed. The efficiency and power factor map of the proposed IPMSM is presented. The maps show that the high-efficiency and high-power factor operating area of the proposed IPMSM is larger than that of the conventional one, indicating the advantage of the proposed IPMSM in improving efficiency. Based on the analysis of the efficiency performance at various decreasing rates of PM armature flux linkage, optimal decreasing pattern of PM armature flux linkage is obtained corresponding to various operating conditions.

Keywords: IPMSM, adjustable PM armature flux linkage, high efficiency, adjustable speed control, operating range

1. Introduction

With the rapid development of power electronic devices, rare earth permanent magnet and motor control technology, interior permanent magnet synchronous motor (IPMSM) is being used in various applications. There are many advantages for IPMSM such as no excitation loss, maintenance free, easy control and robust to circumstance, etc. Because of the possibility of utilizing the reluctance torque for IPMSM, compared with the surface permanent magnet synchronous motor (SPMSM), high efficiency and extensive constant-power operating range can be easily realized. For this reason, it is widely applied as the driving motor for compressors of air-conditioners and refrigerators. Recently, the application of IPMSM to electric vehicles (EV) begins to be studied with increasing interests [1][2]. For these applications of the IPMSM, extensive constant-power operating range is also required except for high efficiency characteristic under the limitation of supply voltage and current.

As the IPMSM obtains field excitation from permanent magnet (PM), direct control of the excitation level is not possible. Generally, the so-called flux-weakening control strategy which makes use of the equivalent flux-weakening effect by means of the armature reaction of *d*-axis current is applied in high speed constant-power operating region [3][4]. Because the flux-weakening effect is obtained by adjusting the armature current vector, large negative *d*-axis current is always needed no matter how much the load torque is. The power loss relating to the *d*-axis current causes the efficiency to decrease, and this situation becomes worse at light load and high-speed operation [5][6]. For the IPMSM with large amount of permanent magnet to obtain high-torque performance, the armature back electromotive force will be high, thus voltage saturation will occur at very low speed even when the flux-weakening control is applied. Contrarily, for the IPMSM with small volume of permanent magnet in order to obtain a wide operating range, the PM armature flux linkage is also small, the high- torque performance at low speed will thus be sacrificed.

The study of the relationship between the parameters of the IPMSM and the constant-power operating range under the constraints of supply voltage and current has been reported [3]. It has been known that the pattern of speed-output power characteristic is decided by the difference between PM armature flux linkage and the maximum *d*-axis armature reaction. According to the above conclusion, it is obvious that for an ideal adjustable speed IPMSM, it is desired to have large PM armature flux linkage at low speed to obtain high torque performance, and then to have decreased PM armature flux linkage at high speed to extend operating range.

This paper discusses an IPMSM with adjustable PM armature flux linkage by adapting movable flux-shortening iron pieces in the spaces of the rotor's flux barriers. With the movable flux-shortening iron pieces, it has been verified that the PM armature flux linkage can be effectively decreased to some extent. This makes possible for the motor to realize high torque performance at low speed. And meanwhile, at the high-speed operation, constant-power operating range can be greatly extended under certain constraints of the supply voltage and current. Furthermore, the *d*-axis current level required in the operating region of flux-weakening control can be effectively lowered due to the decreased PM armature flux linkage. Thus significant improvement in the efficiency as well as power factor can be expected.

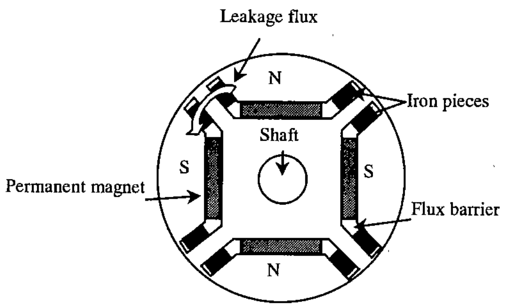
The performance of the proposed IPMSM is studied using normalized analysis for general meaning in this paper. The variations of efficiency relating to operating conditions and PM flux linkage level are discussed. Efficiency and power factor maps of the proposed IPMSM are presented to have a comparison with the conventional one. The maps show that the area of high efficiency and high power factor operation of the proposed IPMSM becomes larger, illustrating the advantage of the proposed motor in efficiency improvement. Based on the analysis of the efficiency performances at various decreasing rates of PM armature flux linkage, the optimal decreasing pattern of PM armature flux linkage is obtained corresponding to various rotating speeds and load torques.

2. IPMSM with Adjustable PM Armature Flux Linkage

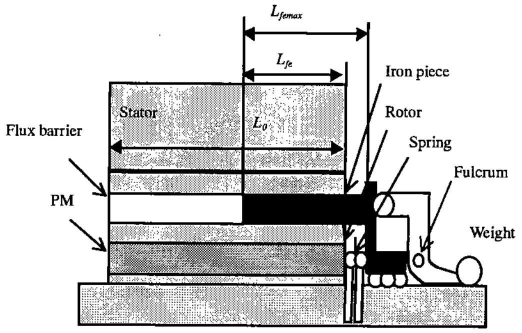
2-1 The Proposed IPMSM

From the consideration of adjusting the PM armature flux linkage, an IPMSM with flux-shortening iron pieces in the space of the rotor's flux barriers has been proposed [7]. Fig.1 (a) shows the rotor structure of the proposed IPMSM. Movable flux-shortening iron pieces are designed, which can be inserted into the flux barriers. Flux leakage paths will be formed when the iron pieces are inserted into the flux barriers, causing the armature flux linkage produced by the PM to decrease. The decreased amount of the PM flux will be decided by the inserted length of the iron pieces. Fig.1 (b) gives the experimental mechanism, which utilizes centrifugal force for inserting the iron pieces. With the increasing of rotating speed, the centrifugal force of the weight increases, pushing the iron pieces into the flux barriers. The inserted length or the position of the iron pieces will depend on the weight as well as the motor's speed. The merit of this mechanism exists in that no electrical supply is needed for the insertion of iron pieces. But it should also be awared that the complexities of the magnetic force and friction acting on the iron pieces makes it difficult for smooth insertion and endurance, and it can only realize one inserting pattern for each designated value of the weight. To obtain arbitrary inserting pattern for the iron pieces, using an actuator may be one solution. Although the use of actuator may add cost and make the system to be complicated, for the large motor, the save of energy and the improvement of operating performance will be very significant. We mainly discuss the possibility and the advantages of the IPMSM with adjustable PM armature flux linkage in this paper, other possible mechanisms to realize PM flux adjustment are being considered and will be reported later.

Fig.2 gives the FEM calculation result for the proposed IPMSM with no armature current. The figure shows that when there are iron pieces in the flux barriers, the PM flux flowing into the armature will be decreased. It has been reported in [7] that with the insertion of the iron pieces, the PM armature flux linkage decreases, d,q-axis inductances increase, and the difference between d and q-axis inductances remains almost constant. Fig.3 gives the variations of these parameters calculated by FEM method with the insertion of the iron pieces, which have been partly verified by experiments [7]. It can be known that for the experimental motor of this paper, the PM armature flux linkage can be decreased by about 25% at most, with the iron pieces been totally inserted.



(a) Theoretical rotor structure of the proposed IPMSM.



(b) Experimental inserting mechanism for iron pieces.
Fig.1. IPMSM with adjustable PM armature flux linkage.

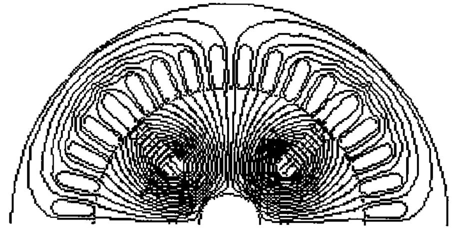


Fig.2. Flux of the IPMSM with iron pieces at no load.

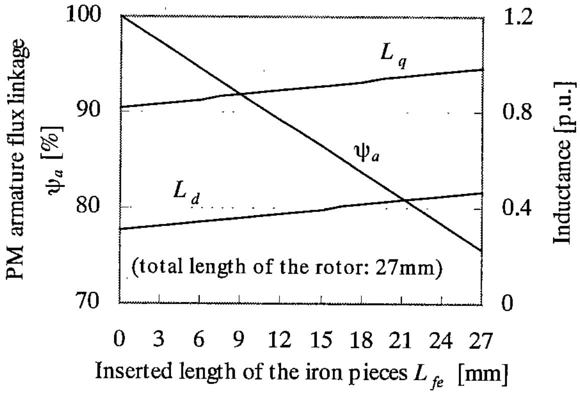


Fig.3. Parameters of the proposed IPMSM.

2-2 Mathematical Model

When taking into account the iron losses, the mathematical model of the IPMSM at d-q co-ordinate and the constraints of supply voltage and current can be described as follow [8]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = (1+\frac{R_a}{R_c})\begin{bmatrix} \frac{R_a R_c}{R_a+R_c} & -\omega L_q \\ \omega L_d & \frac{R_a R_c}{R_a+R_c} \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + (1+\frac{R_a}{R_c})\begin{bmatrix} 0 \\ \omega\psi_a \end{bmatrix} \quad (1)$$

Table 1. Parameters of the IPMSM without iron pieces.

PM armature flux linkage ψ_a	0.597 [p.u.]
d-axis inductance L_d	0.308 [p.u.]
q-axis inductance L_q	0.816 [p.u.]
Armature resistance R_a	0.150 [p.u.]
Equivalent iron loss resistance R_c	23.815 [p.u.]

$$T = \psi_a i_{oq} + (L_d - L_q) i_{od} i_{oq} \tag{2}$$

$$i_{od} = i_d - i_{cd} \qquad i_{oq} = i_q - i_{cq} \tag{3}$$

$$I_a = \sqrt{i_d^2 + i_q^2} \le I_{alim} \qquad V_a = \sqrt{v_d^2 + v_q^2} \le V_{alim} \tag{4}$$

Here, v_d,v_q: d,q-axis armature voltages, i_d,i_q: d,q-axis total armature currents, i_{od},i_{oq}: d,q-axis total armature currents L_d,L_q: d,q-axis inductances, i_{cd},i_{cq}: d,q-axis current of the equivalent iron loss resistance, R_a: armature resistance, R_c: equivalent iron loss resistance, ψ_a: PM armature flux linkage, ω: angular velocity of the motor, p: differentiator, T: output torque, I_a,V_a: armature current and voltage, I_{alim},V_{alim}: constraints of armature current and voltage. All quantities above are in per unit in order to have a general consideration. The normalization is based on the equations listed in the appendix.

Several control strategies have been suggested based on the above mathematical model of the IPMSM. In this paper, maximum torque control algorithm is used when the speed of the motor is below the base speed, and flux-weakening control is employed above the base speed [9][10]. Table 1 gives some parameters of the test IPMSM. The data listed above are of the test motor with no iron piece inserted into the flux barriers.

3. Operating Range

When the control strategy stated above is applied, the pattern of speed-output power characteristic of the IPMSM depends on the minimum d-axis armature flux linkage $\psi_{dmin}(=\psi_a-L_dI_{alim})$, so the operating range is decided by the parameters of the machine [3]. There exist three operating regions for the maximum output power control, they are, Region I; Current-limited region with constant maximum torque, Region II; Current-and-voltage-limited region, and Region III; Voltage-limited region. Region III only exists in case of $\psi_{dmin}\le 0$, where the speed limitation does not exist. For IPMSM with $\psi_{dmin}>0$, the maximum possible angular velocity ω_c is: $\omega_c=V_{om}/\psi_{dmin}$, where $V_{om}(V^2_{om}=V^2_{alim}-R^2_aI^2_{alim})$ is the practical armature voltage limitation taking into account the armature resistance.

Fig.4 gives the variations of the minimum d-axis armature flux linkage ψ_{dmin} and maximum possible angular velocity ω_c of the proposed IPMSM with the decreasing in the PM armature flux linkage ψ_a. Here, the decreasing rate of the PM armature flux linkage is represented by α. It can be noticed that with the decreasing in ψ_a, ψ_{dmin} decreases and ω_c increases. For the test IPMSM in this paper, with ψ_a been decreased by 10%, operating range can be enlarged to about 1.8 times of that of the conventional IPMSM. With ψ_a been decreased by 25%, ψ_{dmin} becomes below zero, thus theoretically the speed limitation does not exist. From the output power characteristics shown in Fig.5, it can be known that with decreased PM armature flux linkage, although the proposed IPMSM delivers slightly lower output power at low speed, it will exceed the conventional IPMSM at high speed operation. There is no significant difference between the maximum output capabilities if the decreasing rate of PM flux is not too large. It also can be observed in Fig.5 that the constant-power operating range of the proposed IPMSM extends greatly with the increasing of PM armature flux linkage decreasing rate α.

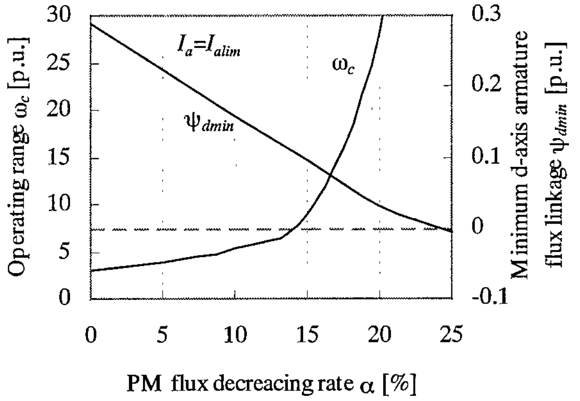


Fig.4. Operating range with decreased PM flux.

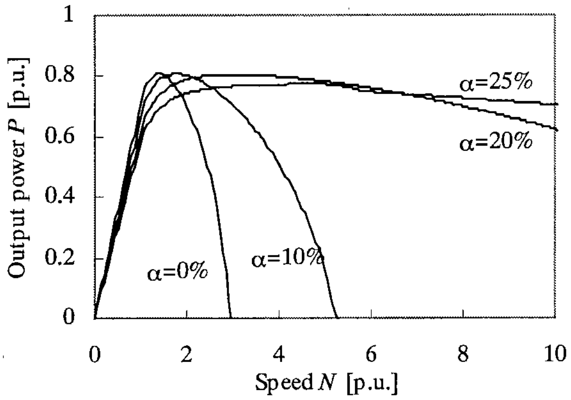


Fig.5. Output power performance.

4. Improvement in Efficiency

For IPMSM, it is possible to extend operation range to some extent by applying flux-weakening control above the base speed, which makes use of the demagnetizing armature reaction of d-axis current. But, because of the necessity of supplying large d-axis current no matter how much the load torque is, power loss due to the d-axis current makes efficiency performance to be degraded. The drop in efficiency will be more significant when the load is very light and the speed is very high. If the PM armature flux linkage is decreased, the d-axis current needed to weaken the armature flux to meet the voltage and current constraints under flux-weakening control will become smaller, thus the improvement in efficiency can be expected.

Fig.6 gives the simulated efficiency perofrmance of the proposed IPMSM with several fixed decreasing rates of the PM armature flux linkage, when the motor is operating at load torque 0.14 [p.u.]. Mechanical loss is considered in the simulation. It shows that at low speed, with the PM armature flux linkage been decreased, the efficiency is slightly lower than that of the conventional IPMSM. This is because the proposed IPMSM need a little larger current to provide the same load torque. With the increase in the rotating speed, the armature voltage will reach the value of limitation, so flux-weakening control is needed to maintain operation. In the flux-weakening operating region, the efficiency of the proposed IPMSM exceeds that of the conventional one. The larger the decreasing rate of PM armature flux linkage is, the higher the efficiency becomes. For example, at speed 1 [p.u.], the efficiency of the proposed IPMSM with 7.6%, and 12.6% PM armature flux linkage decreasing rate α is respectively 0.62% and 2.2% lower than that of the conventional IPMSM. It however becomes 8.4% and 11.1% higher at speed 2.9 [p.u.]. Meanwhile the conventional IPMSM cannot operate beyond speed 2.9 [p.u.] at this load torque, but the proposed IPMSM can still operate with reasonably high efficiency. The improvement of efficiency can be predicted to be more significant with lager α.

5. Efficiency Optimization

From the above discussion on the efficiency improvement for the proposed IPMSM, it can be known that with adjustable PM armature flux linkage, significant efficiency improvement effect can be realized. In this chapter, we discusses the relationship between the efficiency and operating condition of the proposed IPMSM, and then the optimal PM armature flux linkage decreasing pattern to realize maximum efficiency operation.

5-1 Efficiency and Operating Condition

The efficiency of the IPMSM will vary with operating conditions, such as load torque and rotating speed. For the proposed IPMSM with adjustable PM armature flux linkage, the efficiency performance also relates to the PM armature flux linkage decreasing rate α. It is useful to obtain the relationships among the efficiency, operating conditions and the decreasing rate of PM armature flux linkage for high-efficiency operation. For simpicity, the mechanic loss of the motor is neglected in the following analysis.

Unfortunately, the relationships among the efficiency, operating conditions and PM armature flux linkage decreasing rate α are very complicated. Fig.7 gives some of the relationships at several load torques. The proposed IPMSM shows slightly lower efficiency at very low speed in all load conditions with different PM flux decreasing rates. If the load is light, the efficiency of the proposed IPMSM will soon exceed that of the conventional IPMSM, and may keep operation with high efficiency till very high speed, at which conventional IPMSM cannot maintain operation. With the increasing in the load torque, the efficiency of the proposed IPMSM will exceed that of the conventional IPMSM at a higher speed than in the situation of lower load torque. There is almost no significant difference between the efficiencies if the load torque is comparatively high.

For convenience, the areas with efficiency greater than 80% and 70% of the proposed IPMSM at several values of α are given in Fig.8. Although at low speed the efficiency of the IPMSM with decreased PM armature flux linkage is slightly lower than that of the conventional IPMSM, high-efficiency operating area extends significantly. It is obvious that the proposed IPMSM is able to keep operation with high efficiency in a much wider region, especially at light load torque. Although the maximum torque available in the IPMSM with decreased PM armature flux linkage is somewhat lower, it does not mean lower output power capability. In fact, the output power keeps reasonably large at high speed. This is benefit for the IPMSM that operates at constant-power load. The performance of power factor also shows a similar tendency (Fig.9).

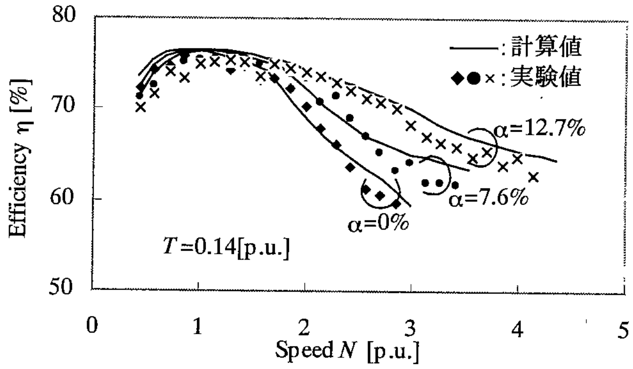
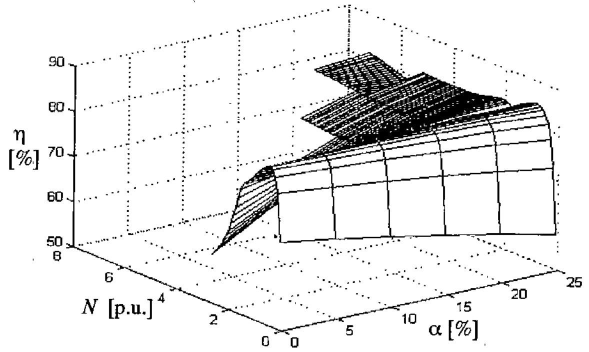
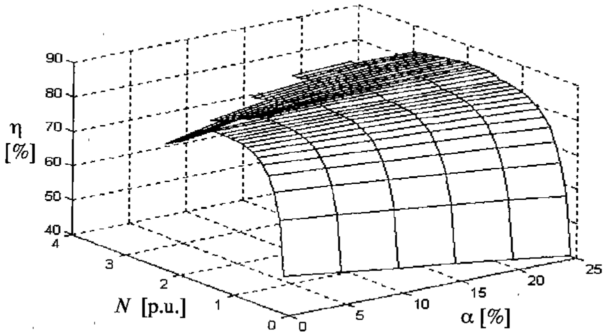


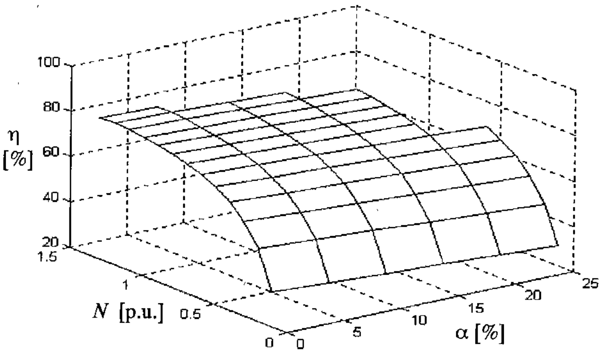
Fig.6. Efficiency performance.



(a) T=0.1 [p.u.]



(b) T=0.2[p.u.]



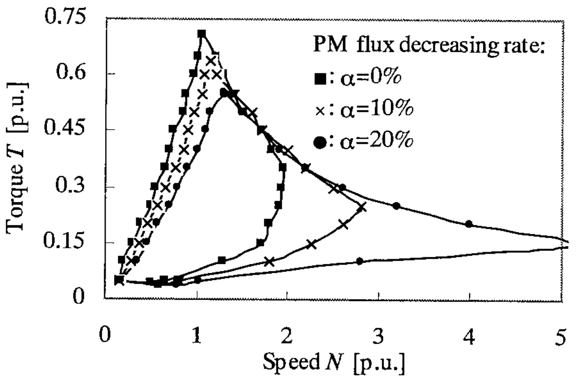
(c) T=0.5[p.u.]

Fig.7. Efficiency varies with operating condition and α.

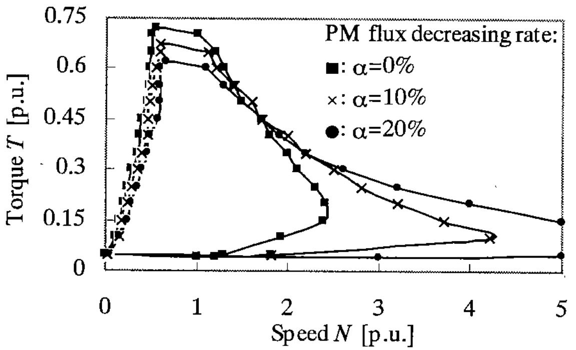
5-2 Optimal Decreasing Pattern of PM Flux

From the above discussion, we can know that the efficiency of the proposed IPMSM depends on the load torque, rotating speed and PM armature flux linkage decreasing rate. In order to realize maximum efficiency, it is necessary to find an optimal PM armature flux linkage decreasing pattern relating to the operating conditions. Supposing that the position of the iron pieces can be adjusted freely (for example by using an actuator), simulation is done to obtain such an optimal decreasing pattern, which is given in Fig.10. To obtain optimal efficiency, it can be known that at light load torque operation, even when the speed is lower than the base speed, it will be useful to decrease the PM armature flux linkage. The larger the load torque is, the higher the optimal beginning speed for decreasing the PM armature flux becomes. Because of the decrease in torque capability when the PM flux is decreased, the suitable maximum decreasing rate of PM flux will become smaller when the load torque becomes larger. However, beyond a certain load torque, there is no need to decrease the PM flux considering both the torque ability and efficiency.

Fig.11 shows the efficiency improvement effect of the proposed IPMSM with the optimal PM armature flux linkage decreasing pattern, at load torque 0.1 [p.u.]. With the optimal decreasing pattern of PM armature flux linkage, the efficiency is improved from the speed lower than the base speed. At light load operation as shown in the figure, it can be seen that the higher the rotating speed is, the greater the efficiency improvement effect can be realized. Similar tendency can also be observed in the power factor performance. For example, at speed 2.7 [p.u.], the efficiency and power factor of the proposed IPMSM is 21.5% and 0.34 respectively, higher than that of the conventional IPMSM. Also, the proposed IPMSM can maintain operation with efficiency greater than 80% and power factor greater than 0.84 till very high speed.



(a) The area with efficiency greater than 80%.



(b) The area with efficiency greater than 70%.

Fig.8. Efficiency map.

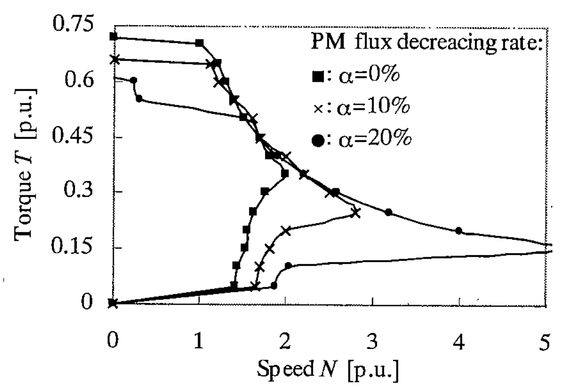


Fig.9. The area with power factor greater than 0.9.

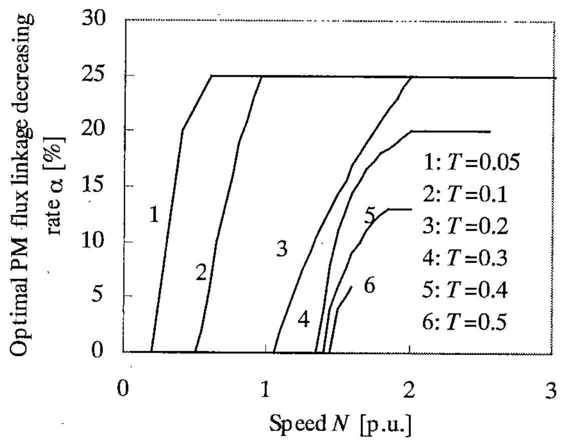


Fig.10. Optimal PM flux linkage decreasing rate.

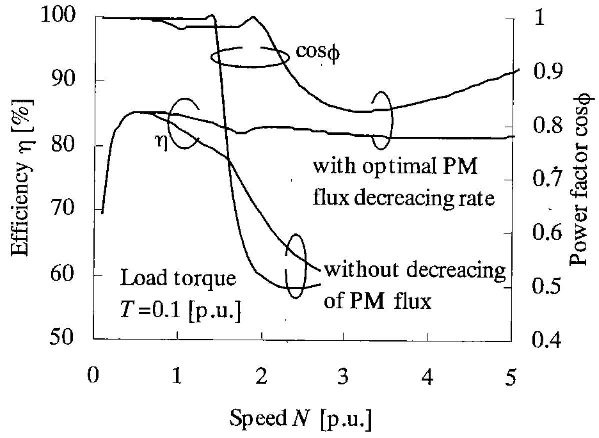


Fig.11. Efficiency improvement with optimal PM flux decreasing rate.

6. Conclusions

This paper discussed an IPMSM which PM armature flux linkage can be adjusted by adapting flux-shortening iron pieces in the flux barriers of the rotor. Normalized analysis is applied to have a general survey on this kind of IPMSM. Iron piece inserted into the flux barrier provides a flux leakage path for the permanent magnet, so the PM armature flux linkage can be effectively decreased. The decreased amount of the PM armature flux linkage can be adjusted by controlling the inserted length of the iron pieces. At the same constraints of armature voltage and current, the proposed IPMSM has a much wider constant-power operating range compared with the conventional one. By suitably adjusting the decreasing rate of the PM armature flux linkage, it is possible for the proposed IPMSM to obtain both high torque capability at low speed and extensive operating range. Because of the possibility of lowering the PM armature flux level in flux-weakening operation region, less d-axis current is required to weaken the armature flux. This then minimizes the power loss due to the *d*-axis current. Thus the efficiency can be significantly improved, especially under light load, high-speed operation. Same tendency can also be observed in the power factor performance.

The efficiency of the proposed IPMSM depends on the operating conditions and the decreasing rate of PM armature flux linkage. The relationships among them are discussed in detail. The high-efficiency and high-power factor operating area of the proposed IPMSM is larger than that of the conventional one, indicating the advantage of the IPMSM with adjustable PM armature flux linkage. In order to realize maximum efficiency operation under various operating conditions, the optimal PM armature flux linkage decreasing pattern is obtained. With the optimal PM armature flux linkage decreasing pattern, efficiency and power factor performance can be improved significantly. Efforts are still needed for the design of the PM armature flux decreasing mechanism to make it suitable for practical industrial applications.

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Appendix

Normalization of the mathematical model of the IPMSM is executed based on the following equations:

$$\omega_{base}=\frac{V_{om}}{\psi_{01}} \quad (0\text{-}1) \qquad V_{om}=V_{a\,lim}-R_a I_{a\,lim} \quad (0\text{-}2)$$

$$\psi_{01}=\sqrt{(\psi_a+L_d i_{d1})^2+(L_q i_{q1})^2} \quad (0\text{-}3)$$

$$i_{d1}=\frac{\psi_a}{2(L_q-L_d)}-\sqrt{\frac{\psi_a^2}{4(L_q-L_d)^2}+\frac{I_{a\,lim}^2}{2}} \quad (0\text{-}4)$$

$$i_{q1}=\sqrt{I_{a\,lim}^2-i_{d1}^2} \quad (0\text{-}5) \qquad \psi_{an}=\frac{\omega_{base}\psi_a}{V_{a\,lim}} \quad (0\text{-}6)$$

$$R_{an}=\frac{R_a I_{a\,lim}}{V_{a\,lim}} \quad (0\text{-}7) \qquad L_{dn}=\frac{\omega_{base} L_d I_{a\,lim}}{V_{a\,lim}} \quad (0\text{-}8)$$

$$L_{qn}=\frac{\omega_{base} L_q I_{a\,lim}}{V_{a\,lim}} \quad (0\text{-}9) \qquad T_n=\frac{T\,\omega_{base}}{P_n V_{a\,lim} I_{a\,lim}} \quad (0\text{-}10)$$

Where P_n is the polar pairs, the variables with subscript *n* are normalized quantities. In this paper, *n* is neglected for simplicity.

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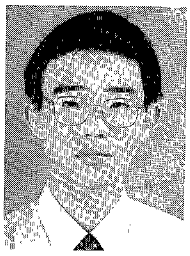

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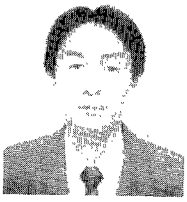

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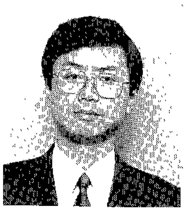

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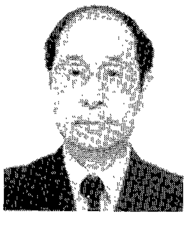

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