A New Design Concept of Permanent Magnet Machine for Flux Weakening Operation

Longya Xu, *Senior Member, IEEE*, Lurong Ye, *Student Member, IEEE*, Li Zhen, *Student Member, IEEE*, and Ahmed El-Antably, *Member, IEEE*

***Abstract*—In this paper, a new design concept of a PM machine for flux weakening operation is proposed. The feasibility of strong flux weakening capability without permanently demagnetizing the permanent magnet is investigated. Results from the finite element analysis on the proposed PM machine structure are presented to verify the new design concept.**

I. Introduction

PERMANENT Magnet (PM) machines are attracting growing attention for a wide variety of industrial applications for a number of reasons. Because the excitation of a PM machine is provided by permanent magnets, brushes and slip rings are eliminated, resulting in a simple and rugged structure. Also, the excitation provided by permanent magnets is current-free and lossless, enabling PM machines to have more efficiency and to be higher in power density as compared to other electric machines. The structure and unique operation mode of a PM machine give additional advantages to the control of its speed and position. Since the armature field and the rotor of a PM machine are always synchronized, and the armature field can be precisely controlled, it is very convenient to implement precise speed and position control on a PM machine. In addition, by utilizing the back EMF of the nonconducting winding, the speed control of a PM machine can be realized without using a position sensor, which is of particular importance to certain applications where the use of a rotating encoder may be prohibited.

However, the application of a PM machine is limited by the fixed excitation from permanent magnets. By utilizing a new concept of flux weakening, this paper contributes to expanding the speed range of PM machines greatly without introducing major negative effects. In traction and spindle drives, constant power and variable speed operation in a wide speed range are required. With dc and synchronous machine drives, this requirement can be easily achieved by appropriate reduction of the field current as speed increases. In a PM machine, however, the magnet flux is fixed and the airgap flux weakening is usually accomplished by applying a large demagnetizing current in the d-axis of the permanent magnets. Flux weakening obtained by this method not only increases conduction losses but has a risk of demagnetizing the permanent magnet irreversibly [1], [2]. When an excessive d-axis current is applied, the permanent magnets will be forced to operate in the irreversible demagnetization region and will never be able to recoil back to its original operation point after the d-axis current is removed. Consequently, the torque capacity of the PM machine is permanently reduced [3], [4]. It is clear that for a variable speed PM machine, the achievable speed range is seriously limited by the largest allowable demagnetizing current specified by the demagnetization characteristics.

The power converter capability imposes additional limiting factors to the flux weakening operation and, hence, to the speed range of a PM machine. For instance, whether the converter can provide sufficiently large demagnetizing current to the PM machine is questionable because the power converter current and voltage are always finite.

How to fully utilize the finite converter current and voltage to increase the flux weakening range without demagnetizing permanent magnets is always of great interest as well as challenging to both PM machine designers and control engineers [5], [6]. In this paper, a concept of altering the flux path of the permanent magnets for flux weakening operation is proposed. The new concept is aimed at minimizing the required demagnetizing current for a given level of flux weakening. In this way, not only can we reduce the associated copper losses but also eliminate the risk of damaging permanent magnets. In addition, by reducing the demagnetizing current, we can extend the flux weakening region so that a wide speed range can be achieved. The contents of the paper are organized as follows. In Section II, the structure, equivalent circuit, and phasor diagram of a normally designed PM machine are reviewed to discuss the conventional methods of flux weakening. In Section III, the new design concept is introduced and the structure of a PM machine implementing the new design concept is presented. The strong flux weakening capability without permanently demagnetizing the permanent magnets is discussed. Finite element analysis results of the new PM machine structure are included in Section IV to verify the new design concept.

II. Flux Weakening of PM Machine

A. Review of Normally Designed PM Machines

For convenience of discussion on flux weakening operation, the structure, equivalent circuit and phasor diagram of a normally designed permanent motor are reviewed in this section. In general, a PM machine has a stator of a typical

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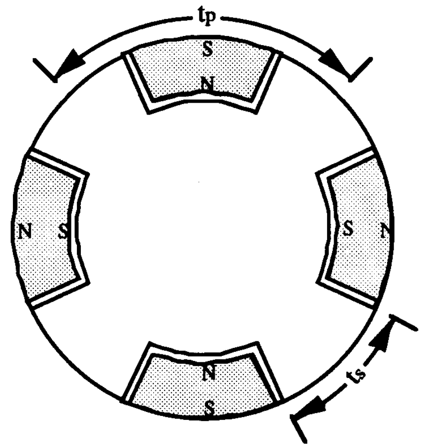

Fig. 1. Normally designed rotor structure of a PM machine.

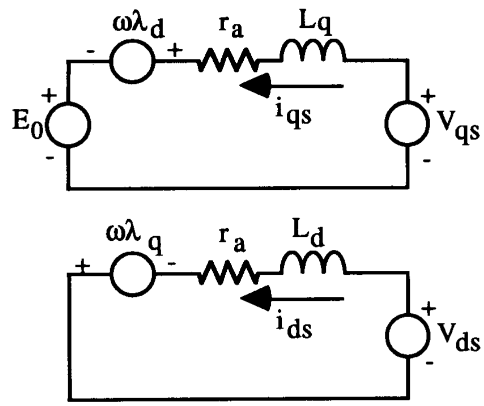

Fig. 2. Equivalent circuit of a PM machine.

three-phase ac machine. The rotor may be in surface or internal magnet mounting style depending on the location of permanent magnets. Without loss of generality, a typical surface mounted rotor is shown in Fig. 1 and the magnets are oriented toward the rotor surface. Note that the magnetic permanence along the d-axis of the magnets in a PM machine is extremely low, as compared to the other types of ac machines, due to the existence of permanent magnets.

The equivalent circuit of the PM machine shown in Fig. 2 is very similar to that of a conventional synchronous machine except that the internal induced voltage, E_0, is due to the rotation of the magnets instead of the field winding, and that the reactance X_d is much smaller than X_q due to the permanent magnets. The governing equations of the PM machine are in the form of

$$v_{ds} = r_a i_{ds} + \frac{d\lambda_d}{dt} - \omega\lambda_q \tag{1}$$

$$v_{qs} = r_a i_{qs} + \frac{d\lambda_q}{dt} + \omega\lambda_d + E_0 \tag{2}$$

where

$$\lambda_q = L_q i_{qs}, \qquad \lambda_d = L_d i_{ds}$$

and E_0 is the EMF due to the magnet generated flux linking the stator windings.

The phasor diagram shown in Fig. 3 can be utilized to characterize the steady state operation of a PM machine. To complete the PM machine description, the characteristics of the permanent magnets are given in Fig. 4. Note that the demagnetizing curve of the magnet can be divided into three regions by three lines, called no-load, rated-load, and excessive load lines. The three lines are denoted as 1, 2, and 3, respectively in the figure. As indicated, if the demagnetizing current is near or beyond line 3, the permanent magnet is in danger of being damaged.

B. Conventional Flux Weakening Methods

The accurate meaning of flux weakening of a PM machine is that in high-speed range, the airgap flux is weakened so that the back EMF can be adjusted to a proper level matching the supply voltage. According to the phasor diagram of a PM machine as shown in Fig. 3, the effect of flux weakening is represented by the vector, $I_d X_d$. Physically, flux weakening can be accomplished through three means:

1) Increasing I_d to directly demagnetize the permanent magnet. The demagnetizing current, I_d, however, is limited by the converter capability and copper losses of the PM machine. Also, this method is very risky because it is possible to demagnetize the permanent magnets irreversibly.
2) Increasing X_d to enhance the effect of the armature current. This is usually done by modifying the PM machine structure. Unfortunately, X_d cannot reach a substantial value for a normally designed PM machine because of the existence of permanent magnets.

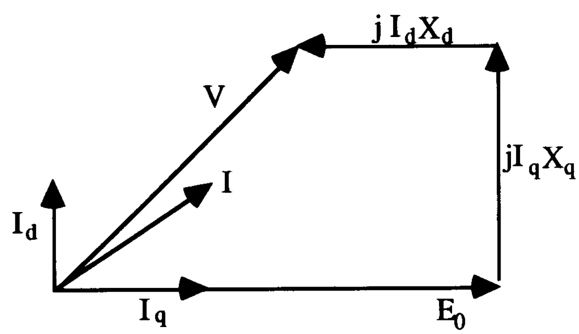

Fig. 3. Phasor diagram for the PM machine in steady state.

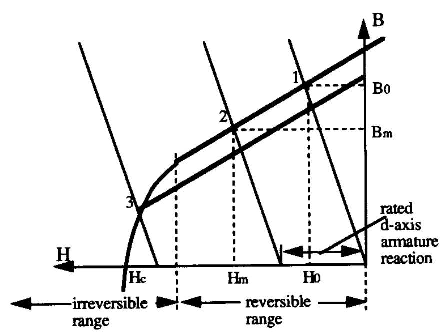

Fig. 4. Demagnetization curve for permanent magnet.

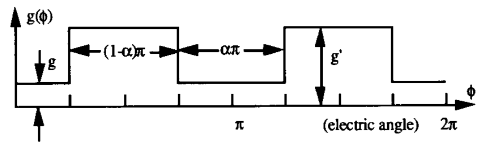

Fig. 5. Gap function for the normally designed PM machine.

3) Increasing I_d and X_d simultaneously. It will be made clear in later discussion that the difficulty in realizing (3) is almost the same as that met in (1) and (2).

The following calculation is used to quantitatively discuss the dilemma that we are facing in a normally designed PM machine for flux weakening operation. The equivalent gap functions for calculating X_d and X_q are shown in Fig. 5. In the figure, g is the effective gap including tooth effect, while g' denotes the gap measured along the d-axis with the magnets being removed. α is the arc space, τ_s, between magnets normalized by the pole pitch τ_p. That is,

$$\alpha = \frac{\tau_s}{\tau_p}. \tag{3}$$

According to the machine design theory, the d-axis magnetizing inductance is given by

$$L_d = \mu_0 \frac{3Dl}{2} \left(\frac{K_{w1}N_t}{P}\right)^2 \int_0^{2\pi} \frac{\cos^2(\phi)}{g(\phi)}\, d\phi \tag{4}$$

where,

N_t the number of turns of one phase winding in series,
l the effective length of the rotor (m),
D the diameter of the rotor (m), and
P the number of poles.

Upon evaluating (4), we can readily show that

$$L_d = 3\mu_0 \left(\frac{K_{w1}N_t}{P}\right)^2 \frac{Dl}{g} \frac{\pi}{8} K_d \tag{5}$$

where

$$K_d = \left[\left(\alpha - \frac{\sin(\alpha\pi)}{\pi}\right) + \frac{g}{g'}\left(1 - \alpha + \frac{\sin(\alpha\pi)}{\pi}\right)\right]. \tag{6}$$

In a similar fashion, the q-axis inductance is calculated as

$$L_q = 3\mu_0 \left(\frac{K_{w1}N_t}{P}\right)^2 \frac{Dl}{g} \frac{\pi}{8} K_q \tag{7}$$

where

$$K_q = \left[\left(\alpha + \frac{\sin(\alpha\pi)}{\pi}\right) + \frac{g}{g'}\left(1 - \alpha - \frac{\sin(\alpha\pi)}{\pi}\right)\right]. \tag{8}$$

The gap functions given in Fig. 5 are used in (6) and (8).

As suggested by (6), we can increase α to increase K_d and, thus, L_d and X_d. However, the flux from the magnets will be reduced because the magnet surface is reduced. Under such circumstances, the number of turns in series has to be increased to compensate for the reduction of flux, resulting in larger copper losses and a poorer slot space utilization. Meanwhile, increasing α means increasing X_q. In the constant power operation regime, I_q is almost a constant. The magnitude of the vector, I_qX_q, will be increased, indicated by the dash line in Fig. 6, resulting in an increase of X_dI_d. As a result, I_d remains almost unchanged (not reduced), or equivalently the

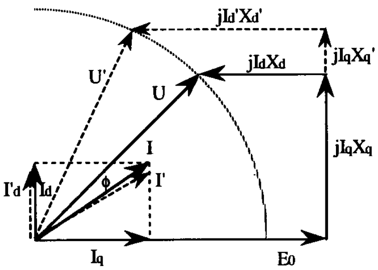

Fig. 6. Phasor diagram for the PM machine in steady state.

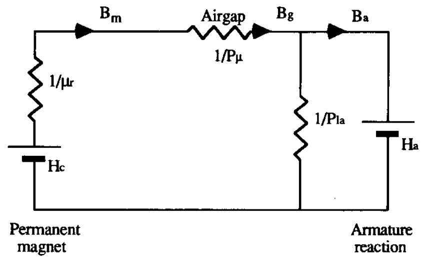

Fig. 7. d-axis magnet circuit for normally designed PM machines.

demagnetizing MMF along the d-axis is not reduced because of the increase of α or X_d. From this derivation, it is clear that we cannot protect the permanent magnet from being demagnetized.

With an appropriate selection of α, another approach to increase X_d suggested by the equations is to decrease g' and, at the same time, to increase g. The result is that X_d increases significantly and X_q decreases slightly. This approach, unfortunately, necessitates the reduction of the thickness of permanent magnets. As a result, the magnets will be more vulnerable to the demagnetizing current, I_d.

Structure modifications for a normally designed PM machine can be further illustrated concisely by the magnetic circuit in Fig. 7, similar to the one suggested in [7]. Note that in order to have a large flux weakening range for a normally designed PM machine, we can either increase H_a, equivalent to increasing I_d, or reduce the thickness or width of the magnets, equivalent to increasing X_d. In both cases, the flux from the permanent magnets is actually reduced to produce airgap flux weakening. In addition to the increase of copper losses, the permanent magnets are inevitably in danger of being permanently demagnetized.

III. New Concept for Airgap Flux Weakening

A. Flux Weakening by Altering Flux Path

As opposed to the direct reduction of flux from permanent magnets for airgap flux weakening, we propose a new PM machine structure to realize the following concepts:

1) The airgap flux is weakened by applying I_d current. This current, however, is not used to reduce the magnet flux. Rather, the current is used to alter the path of flux so that the flux from the permanent magnet linked by the armature winding is reduced while the flux from the permanent magnets preserved.

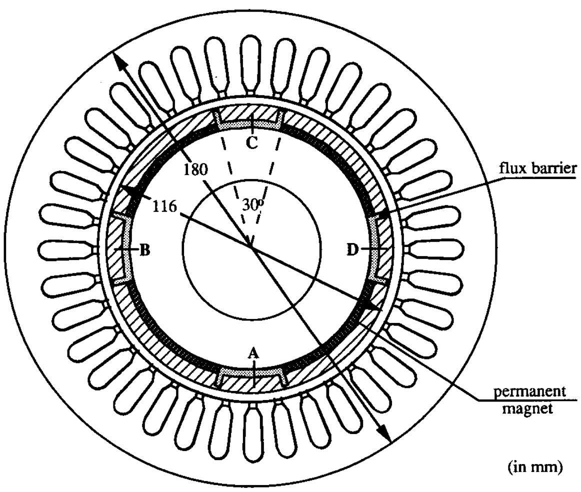

Fig. 8. Cross section of the PM machine.

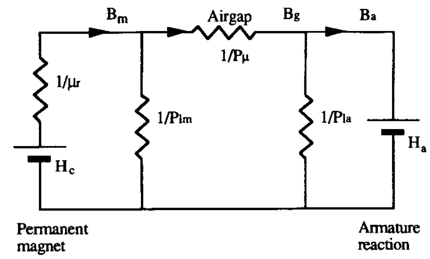

Fig. 9. Equivalent d-axis magnet circuit for the new PM machine.

TABLE I

Rated Power (kw)	40	Max. 100
Rated Voltage (volts)	115	
Rated Current (amps)	140	Max. 300
Rated Speed (rpm)	10,000	Max. 16,000
Over Load Condition	100 kw at 16,000 rpm for 5 minutes	

2) The value of X_d is increased to enhance the effect of the demagnetizing current. In this way, the required I_d for flux weakening is reduced. The increase of X_d, however, does not rely on the reduction of the thickness or the width of permanent magnets.

It is evident that in order to implement the proposed concepts, a new magnetic structure of the permanent magnet machine is needed. It is necessary that as soon as d-axis current is applied, the flux from permanent magnets has an alternative path to flow with help from the armature current. Equivalently, the new design concept relies on chaneling the flux of the permanent magnet to an alternative path without passing through airgap and thus the airgap flux weakening is achieved. This is done instead of reducing the flux level of the permanent magnets directly.

B. Implementation of New Concept

The machine structure to realize the new design concept for airgap flux weakening operation is shown in Fig. 8. The specifications of the machine are listed in Table I. Compared to a conventionally designed PM machine, it is noticeable that an annular iron has been mounted on the surface of the magnets. To the annular iron, four iron sections, labeled as A–D in the figure respectively, and eight flux barriers are made.

The equivalent magnetic circuit in the d-axis of the new PM machine is drawn in Fig. 9 where P_{lm} represents the alternative path created by the added annular iron. It can be easily seen that iron sections A–D provide an alternative path to the flux produced by the permanent magnets and by the d-axis current as well. It is also interesting to note that for the flux generated by the d-axis current, the path does not include the permanent magnets resulting in a substantial increase of X_d in the presence of the permanent magnets. Whenever the d-axis current is applied, the flux lines from the permanent magnets are forced into P_{lm}. The airgap flux is, therefore, effectively reduced.

It can be observed that in the new structure, the dimensions of the eight flux barriers are very critical to the value of P_{lm}. Also, P_{lm} is highly nonlinear due to the saturation effect. Ideally speaking, we would like that by properly choosing P_{lm}, the airgap flux, B_g, is reduced substantially with a moderate value of I_d. Meanwhile, the flux of the magnet, B_m, only decreases slightly and the irreversible demagnetization of permanent magnets is completely avoided. Because of the complicated geometry and high nonlinearity related to P_{lm}, finite element analysis is utilized to quantitatively examine the flux weakening effect of the new PM machine structure.

IV. Finite Element Analysis Results

Finite element analysis is a powerful tool to be used in dealing with a magnetic field with highly nonlinear characteristics and a complicated geometry boundary. To substantiate the new design concept for airgap flux weakening operation, finite element analysis of the flux distribution has been applied to the PM machine specified in Table I. The actual dimensions of the PM machine and nonlinear B–H curve are input to the analysis to investigate the effects of the geometry and saturation to the alternative flux path. This path is represented in the equivalent magnetic circuit by the parameter P_{lm}. Three typical cases are chosen as in study.

In case 1, the PM machine is under no-load condition. The flux lines through both the airgap and the magnets have been examined by the flux plotting. As shown in Fig. 10, the majority flux lines generated by the permanent magnets travel through the airgap and link the stator windings. Only a small portion of the flux is shunted by iron sections A–D. Therefore, in no-load condition, the characteristics of the machine are very similar to those of a normally designed PM machine. Shown in the flux plot is also that the flux barriers of the annular iron are significant to block the flux leakage and to guide the flux lines traveling through the airgap.

In case 2, the permanent magnet of each pole is removed and the reluctance of the air in these areas is assumed. With the d-axis current applied, the resultant flux distribution is plotted in Fig. 11. It is interesting to note that most of the flux lines generated by the d-axis current cross the flux barriers and continue in the iron parts A–D. These flux lines return to the stator without penetrating the permanent magnets. Only a small

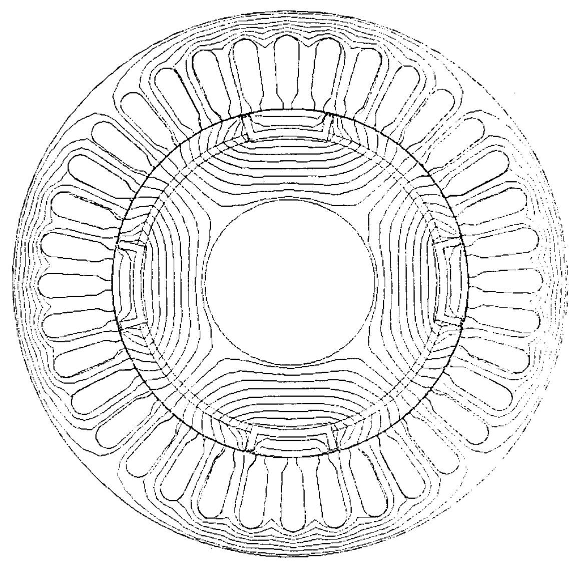

Fig. 10. Flux distribution in the new PM machine for no-load condition.

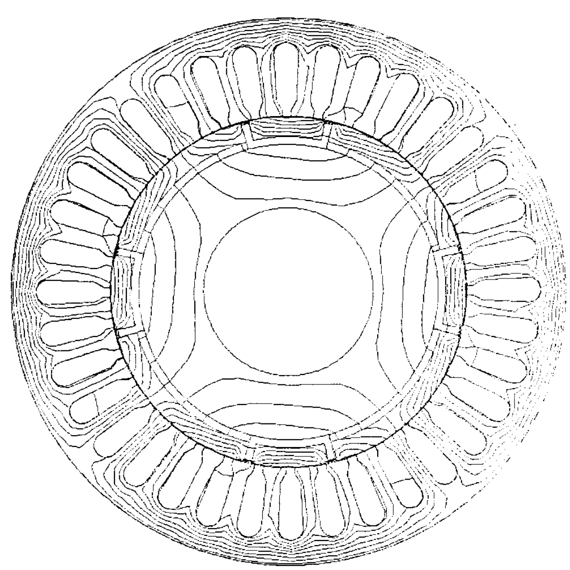

Fig. 11. Flux distribution in the new PM machine for case 2.

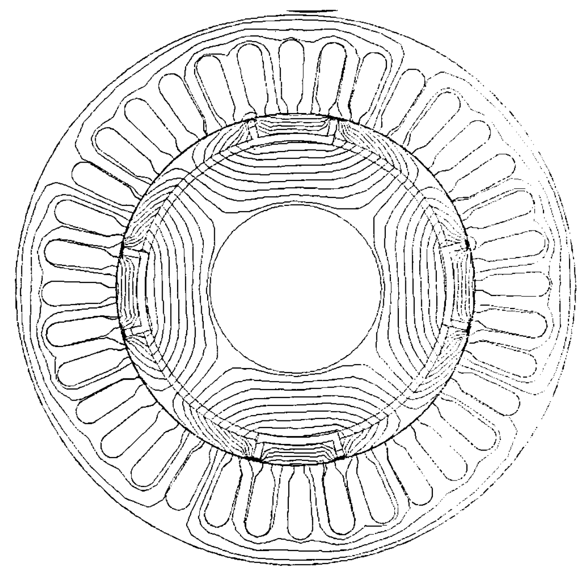

Fig. 12. Flux distribution in the new PM machine when demagnetizing current is applied.

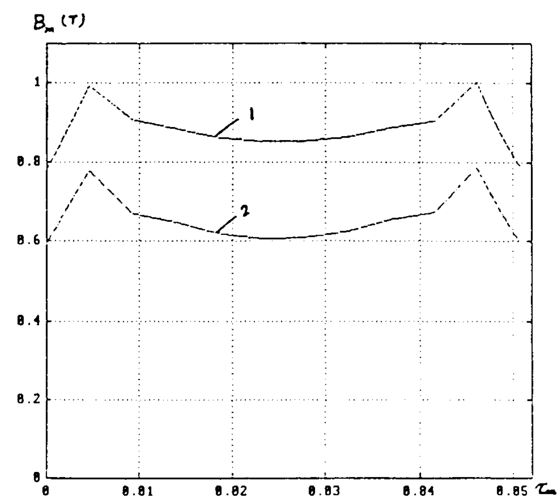

Fig. 13. Flux density along the surface of a PM pole. (Curve 1 at no-load condition and curve 2 at maximum demagnetizing current.)

portion of the flux goes through the permanent magnet, which means that the demagnetization effect to the magnets of the d-axis current is weak. It is also verified that the d-axis current has not been used to cancel magnet flux. The advantages of the PM machine with the new structure become evident.

In case 3, the permanent magnets of the rotor and d-axis current of the stator winding are both in place. The flux distribution over the machine cross section is plotted in Fig. 12. Because of the strong d-axis armature reaction, most of the flux lines generated by permanent magnets are bent over and pushed into iron sections A–D. These flux lines do not travel through the airgap to link the stator windings. By checking the number of flux lines in the airgap, it is seen that the flux density in the airgap is weakened effectively. In order to examine the demagnetization effect of the d-axis current, in Fig. 13, the flux density along the surface of the permanent magnet is plotted. From Fig. 13, it is evident that the flux density of the permanent magnets remains at 0.6 T, which is safely within the reversible range of the demagnetization curve. In summary, the FEM results verified the new design concept for flux weakening.

The results from finite element analysis on the new PM machine is also used to compare to those of the normally designed PM machine for the same rating. Table II summarizes the comparison of the airgap flux B_{g1}, magnet flux B_m, demagnetizing current I_d, and reversibility of the permanent magnets. It has also been found that for the PM machine designed according to the new concept, the constant power regime can be expanded to 5.6 times the rated speed, while

TABLE II

	B_{g1}(Tesla)	B_m(Tesla)	I_d(amps)	Reversibility
Normal design	0.18	0.18	228	no
New design	0.18	0.60	209	yes

for the normally designed PM machine, in terms of magnet safety, only two times.

V. CONCLUSIONS

The conventional flux weakening methods of a normally designed PM machine have been studied. The new design concepts for flux weakening operation of a PM machine have been introduced and verified by the field analysis using finite element analysis. Several important conclusions have been reached throughout our study.

1) The d-axis armature reaction inductance, X_d, has been increased substantially with the new design concept. The increase of X_d does not necessitate the reduction of the thickness or width of permanent magnets.
2) Strong airgap flux weakening is accomplished without applying an excessive d-axis current to reduce flux of the magnets. This significantly reduces the copper losses and prevents the permanent magnets from permanent demagnetization for operation in a wide range of speeds.
3) Since the flux from the permanent magnets is well preserved while in the flux weakening operation mode, the new design concept actually allows less permanent magnet materials to be used. As the result, a cost-effective, high-performance PM machine drive is made possible in a large power rating.

In effect, the new design concept introduced in this paper can be applied to many machine designs in which permanent magnets are used and a wide operation range is necessary. A prototype of the proposed PM machine is in progress and the experimental evaluation of the prototype will be reported in the future paper.

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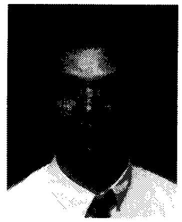

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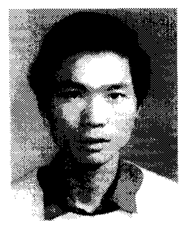

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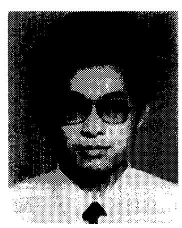

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