Research Report
**94 - 11**

# A Permanent Magnet AC Machine Structure with True Field Weakening Capability

A.J. Shakal, Y. Liao, and T.A. Lipo

Electrical & Computer Engineering
University of Wisconsin-Madison
Madison WI 53706-1691

**W**isconsin
**E**lectric
**M**achines &
**P**ower
**E**lectronics
**C**onsortium

University of Wisconsin-Madison
College of Engineering
Electrical & Computer Engineering Department
2559D Engineering Hall
1415 Johnson Drive
Madison WI 53706-1691

# A Permanent Magnet AC Machine Structure with True Field Weakening Capability

Andrew Shakal Yuefeng Liao Thomas A. Lipo
University of Wisconsin-Madison
1415 Johnson Drive, Madison, WI 53706 USA

**ABSTRACT - New doubly salient ac machines in which the field excitation is developed by stationary permanent magnets has recently been undergoing development at the University of Wisconsin. Because of the unique geometry of the stator, these permanent magnets are readily accessible. Therefore, for experimental purposes, simple iron blocks have been used to "short" a large portion of the permanent magnet flux and thus reduce the back emf developed within the machine. However, for practical applications, field weakening schemes involving miniature linear actuators or high torque stepper motors are being explored, as well as machine designs with combined PM and electrical excitation. Preliminary experimental results show that a substantial reduction in the back emf can be readily obtained thus lending credibility to the concept of weakening air gap fields produced by stationary permanent magnets.**

## 1. INTRODUCTION

The concept of field weakening in permanent magnet machines for the purpose of providing a constant power region at speeds above base speed has been an elusive goal for many decades. Weakening of wound field machines has, of course, been routinely done for many years, the separately excited DC machine being the most obvious example. In wound field machines the method by which the field is weakened simply involves a reduction in the field current. However, to weaken the field in machines were the excitation is provided by permanent magnets (PM's) is not so straightforward. The approach commonly used is to control the stator armature current in such a manner so as to produce an intentional component of MMF which acts in opposition to the PM field thereby reducing the field in the air gap [1]. However, this form of field weakening does not truly reduce the magnet field but only superimposes a second field which acts to reduce the net or resultant field. However, because of the large effective air gap imposed by the magnet, this type of weakening only a relatively small reduction in air gap flux can be achieved at a high cost in increased motor copper losses.

In the past several years work has begun on means to introduce field weakening in certain types of PM machines. In [2] and [3] for example, two different concepts were explored relating to field weakening in an Interior (or buried) Permanent Magnet (IPM) synchronous machine. In [2] it was demonstrated both by tests and by means of a new machine model that a cross coupling reactance (between the direct and quadrature axis) exists in an IPM machine and that this cross coupling term contributes to a certain amount of field weakening. In [3] it was shown that by proper control of the ratio of magnet emf divided by direct axis reactance (i.e. $E/X_d$) the field weakening range utilizing canceling armature ampere turns, can be extended to achieve any field weakening speed range desired. However, both of these methods can only be realized at the cost of a relatively oversized motor. This paper presents several new approaches, in which direct field weakening is obtained on the recently developed Doubly Salient Permanent Magnet (DSPM) machine in which the field is produced by stationary PM's, housed in the stator.

## 2. DESCRIPTION OF MACHINE

During the past two years work has progressed on a new type of doubly salient PM machine which employs magnets on either the stator or rotor [4-6]. Though similar in construction and appearance to that of a variable reluctance machine, this new type of machine employs high energy rare earth PM's to produce field excitation. Although work has been carried out on both a rotating PM machine [4] and a stationary PM machine version, [5] only the stationary PM machine has been built and tested to date. This form of the machine was found to be highly efficient and capable of relatively high torque densities. A cross section of this machine is shown in Fig. 1.

From this cross section, two properties of the DSPM machine should be noted. First note that the simplicity of the rotor can be especially appealing since it is identical to that of a variable reluctance machine. Secondly the location of the magnets on the stator can be noted making this machine a type of so-called homopolar machine. Clearly by placing the PM's on the stator, not only is the rotor freed from many problems at high speeds but the magnets are made accessible for manipulation. Both of these characteristics in turn make the DSPM machine particularly inviting for field weakening schemes.

Other constructional advantages of this machine are apparent since the rotor is extremely simple consisting of simple laminations. Also the stator can be manufactured with bobbin wound coils in much the same manner as a variable reluctance machine. However, in addition, the magnets, being on the stator, can be inserted only after complete manufacture of the machine thereby avoiding the necessity of dealing with the large magnet forces while assembling the machine.

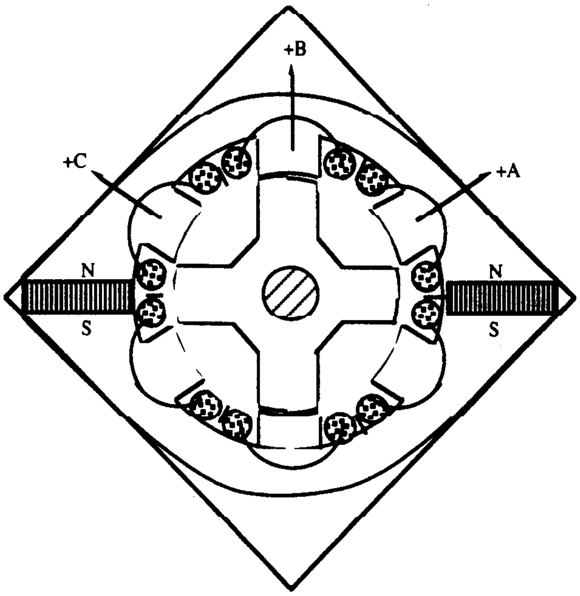

Fig. 1 Cross Section of Doubly Salient Permanent Magnet Motor with Stator Magnet Excitation.

## 3. BASIC PRINCIPLES OF OPERATION AND CONTROL

While Fig. 1 shows the cross-section of a 3-phase, 6/4-pole DSPM motor with stationary magnets, two phase or even single phase schemes can be conceived for use as a generator. For low speed and high torque applications, the machine can be constructed in repetitive fashion, for example a 12/8 pole configuration. It can be noted that the rotor of the DSPM machine is identical to that of the three phase variable reluctance machine (VRM). The stator structure is also similar to that of the VRM except that two pieces of PM are buried in the core and therefore introduced into the main flux path of the stator windings. In order to achieve a high flux concentration in such machines, use is made of the corners of the stator lamination which are normally discarded after punching. This changes the physical appearance of the motor to either a square or trapezoidal or even "football" shaped cross-section which adds slightly to the weight and space occupied by the machine. High performance PM material with a linear demagnetizing characteristic is used to sustain the magnetization and demagnetization of the armature reaction so as to keep a nearly constant flux level within the air gap. The stator pole arc is set to be $\pi/6$ mechanical radians and the rotor pole arc selected to be slightly greater than the stator pole arc to allow for current reversal. As configured, the airgap reluctance, seen by the PM excitation is invariant with rotor position if fringing is negligible. A linear variation of the PM induced flux linkage and thus a trapezoidal shaped back EMF is induced in each of the stator windings at no-load as shown in Fig. 2.

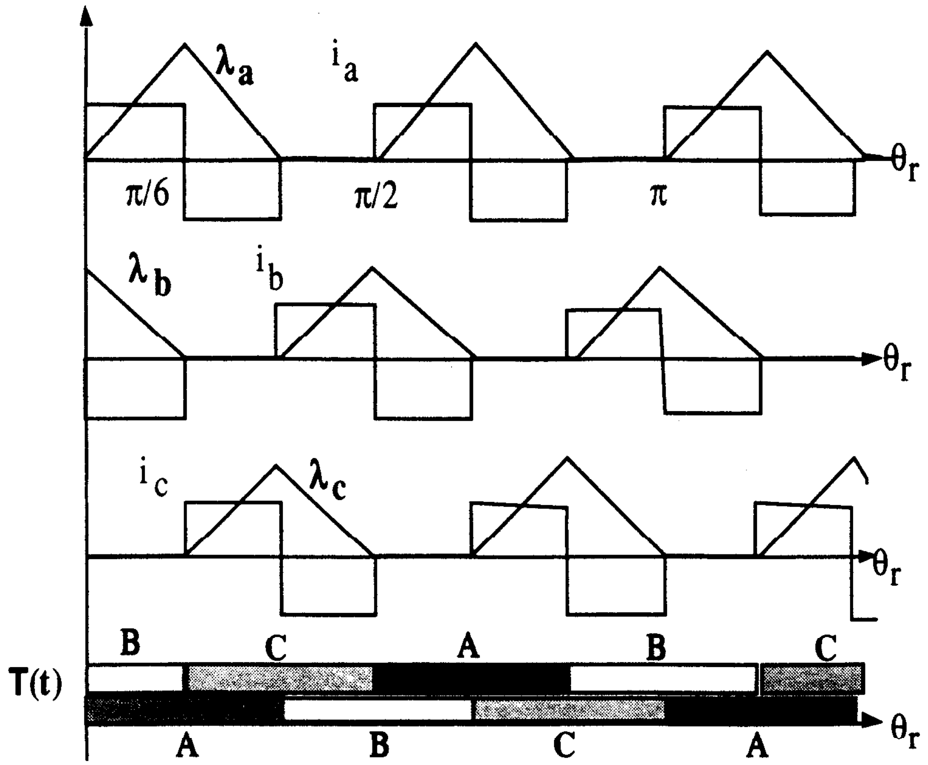

Fig. 2 Idealized Flux Linkage and Current Waveforms for DSPM Machine.

When the machine is loaded, armature reaction flux is produced in the windings in addition to the PM induced flux. It is important to note, however, that the existence of the PM constitutes a very high reluctance path for the armature reaction flux and thus forces the bulk of the armature reaction flux to circulate through another overlapped pole pair. As a result, the active stator phase winding will possess relatively small inductances at both the aligned and unaligned positions, and the maximum inductance appears when the poles is, in fact, essentially half overlapped, as illustrated in Fig. 3. In contrast to the VRM this small aligned inductance makes it possible to reverse the current rapidly at the aligned position. Therefore, torque can be produced both by applying positive current to the winding when its PM-induced flux is increasing and by applying negative current while the flux is decreasing, as shown in Fig. 2.

## 4. TORQUE PRODUCTION IN THE DSPM MACHINE

Beginning with Faraday's Law, it is not difficult to determine that the torque produced by any stator phase can be written as the sum of two components

$$T = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta_r} + i \frac{\partial \lambda_m}{\partial \theta_r}$$

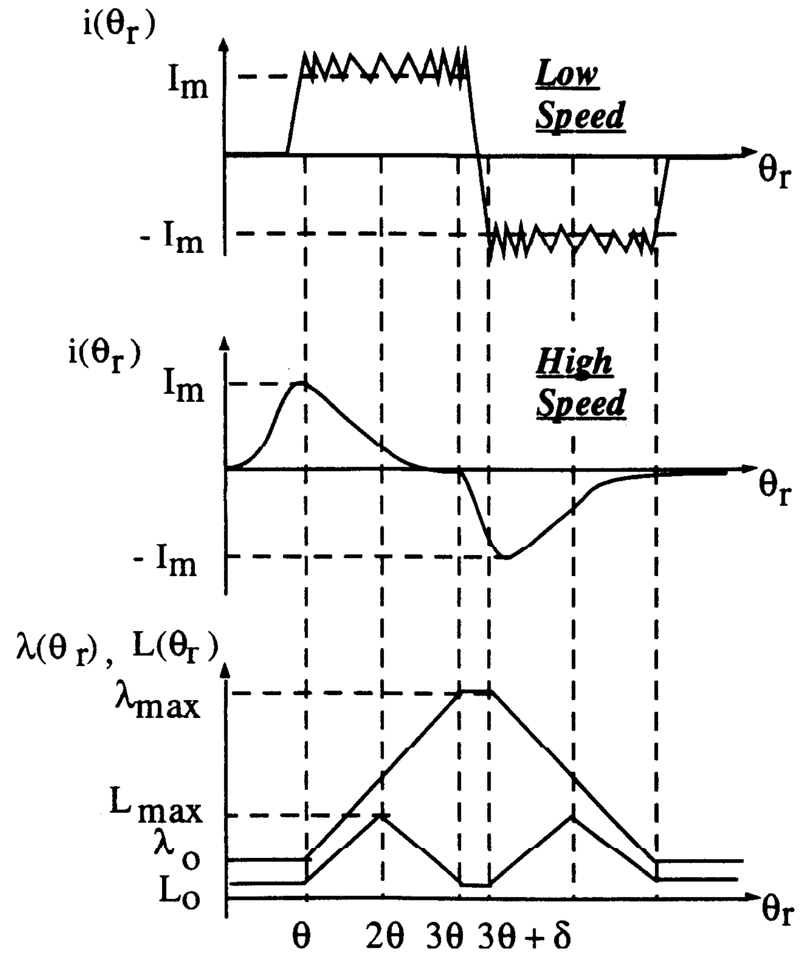

Fig. 3 (a),(b) Current Waveforms of the DSPM Motor at Low and at High Speed as Function of Rotor Position, (c) Corresponding Variations of Flux Linkage and Inductance.

or,

$$T = T_r + T_m \qquad (1)$$

where $\lambda_m$ is the flux produced by the magnet linking the phase, $i$ is the phase current, $L$ is the phase inductance and $\theta_r$ is the rotor mechanical angle. Also, the field energy is

$$W_f = \frac{1}{2}Li^2 \qquad (2)$$

Careful examination of (1) and (2) reveals the following features of the DSPM motor:

(i) The presence of a reaction torque $T_m$, which is the dominant torque component, can be produced by applying either a positive current to a phase winding when its flux linkage is increasing or, alternative, while its emf is positive ($e_m = \partial\lambda_m/\partial\theta_r > 0$), and a negative current when the flux linkage is decreasing ($e_m = \partial\lambda_m/\partial\theta_r < 0$);

(ii) The presence of a reluctance torque $T_r$, although relatively small, is responsible for the torque ripple at low speed. Because of the triangular-shaped variation of the stator winding inductance, the reluctance torque will have a zero average value if the current amplitude is kept constant during one stroke. However, the net reluctance torque will be non-zero if the current is varying;

(iii) The armature reaction field energy $W_f$, which is to be recovered during current commutation, is small because of the relatively small value of the stator inductance. Therefore, the energy conversion ratio is attractive.

It is clear that at low speed, the DSPM motor is, in principle, similar to the PM brushless DC (PM-BLDC) motor with a 120° quasi-square current waveform. The only difference is that the two 120° conducting current blocks are drawn together in the case of the DSPM motor. It should be realized that a sufficient interval between the two current blocks must be provided in the design of the DSPM motor to ensure current reversal. At high speed, the current cannot be maintained constant due to the excessive PM induced back EMF. In this case the current peaks in the first half stroke where the inductance is increasing and drops rapidly in the second half stroke where the inductance is decreasing. This uneven distribution of the phase current, however, gives rise to a considerable amount of reluctance torque which ultimately contributes to extending the constant power capability of the DSPM motor. This performance advantage clearly distinguishes the DSPM motor from the PM-BLDC motor.

It is useful to compare the torque production of the DSPM motor with that of the conventional VRM. In this case, both machines are assumed to have identical main dimensions and stator windings. To visualize the difference between the VRM and the DSPM motor, it is helpful to look at the flux vs. current loci for both motors, as shown in Fig. 5. Two cases are shown in the graph, one for slightly saturated machines (small machines) and the other for highly saturated machines (large machines). To generate the same heat in the two motors, the stator current for the DSPM motor is scaled down to $\sqrt{2}/2$ of that for the VRM. The torque produced in one stroke is represented by the area W for the VRM and W' for the DSPM machine. The area W' is clearly much greater than W due to the fact that: (i) The restored field energy is only a small fraction of the total field energy; (ii) The turn-off angle can be pushed much closer to the aligned position due to the smaller inductance encountered; (iii) Bi-directional operation brings about an improvement in torque production.

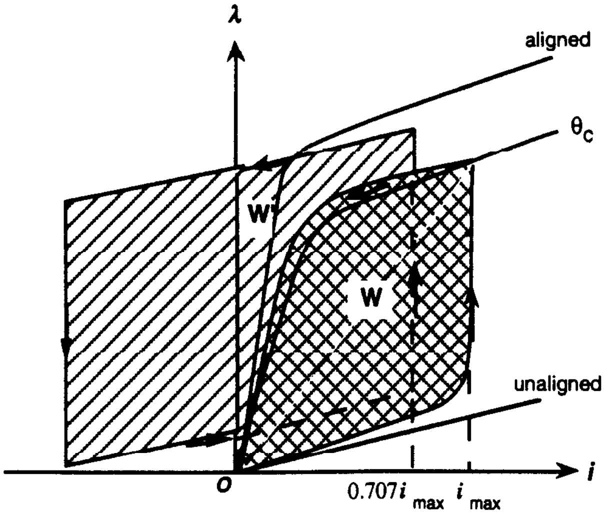

Fig. 5 Comparison of Torque Production between the VRM and the DSPM Motor

## 5. FIELD WEAKENING METHODS

Several methods of weakening the PM field of a DSPM machine can be identified [7]. One method would be to simply "short circuit" the PM flux by placing pieces of ferromagnetic material around the protruding corners (which house the magnets) as shown in very simplified form in Fig. 6. However, relatively large forces must be overcome to position the magnet accurately. While perhaps not feasible in practice, this method is suitable for experimental purposes as detailed below.

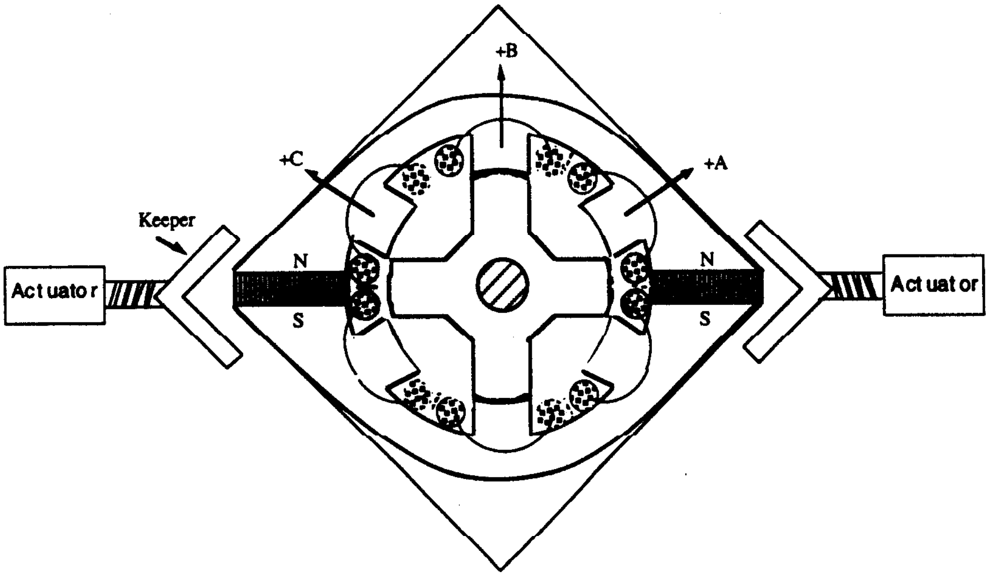

Fig. 6 Field Weakening of DSPM Machine Derived by a Movable Magnetic Shorting Piece.

Perhaps the most practical scheme in terms of implementation is the magnetic/non magnetic shell shown in Fig. 7 which surrounds the stator and moves (rotates) with respect to the stator. (Although shown partially here for clarity the shell actually covers most of the stator outer surface). Assume first that the non-magnetic surface is in contact with the magnets. In this case the reluctance seen by the magnets is large and thus most of the flux passes through the air gap, thereby linking the stator windings (which are not shown here for simplicity). When the shell is rotates, the magnetic section begins to short out the magnet starting from the right hand portion of the shell rotates in the direction shown. When the shell has rotated sufficiently far (say 30 degrees,) which depends upon the width of the magnetic section and the "skew" of the magnetic/non-magnetic pieces), the magnets will be completely shorted. Note that it is not necessary to continuously rotate the shell and only asmall movement of (say) 30 degrees back and forth will be necessary to transition from a non shorted condition to a completely shorted condition.

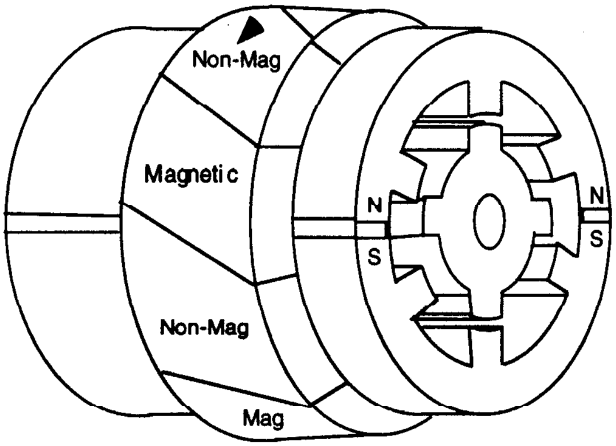

Fig. 7 Field Weakening Using a Magnetic/Non-Magnetic Collar Driven by an Actuator.

Although clearly achievable, the mechanical aspects involved in the field weakening methods described above, puts these methods at a disadvantage, as compared to any method of a strictly non-mechanical nature. With this in mind, two machine structures have been devised, in which field weakening could be accomplished, but purely by electrical means. These designs, in essence, are combinations of the present DSPM machine and a DSPM type machine where the magnets are replaced by field coils. The first of these hybrid machines is shown in Fig. 8. From this figure, it should be clear that, in a sense, this machine could be thought of as four separate machines, each with six stator poles and four rotor poles, separated from each of the other machine segments by flux barriers. As shown, two stator poles from each quadrant belong to one phase giving a total of eight poles per phase. By connecting the respective phase windings of each quadrant in series, one can obtain composite phase windings, each having four back EMF sources, two of which are controllable via the current in the field windings, thus providing for overall field control. The reasons for the pole numbers used in this machine are two fold. First, in order to keep the PMs operating point fixed, a 6/4 pole combination is required for each quadrant. Second, four such quadrants are needed to make the composite machine balanced, that is free from unbalanced torques.

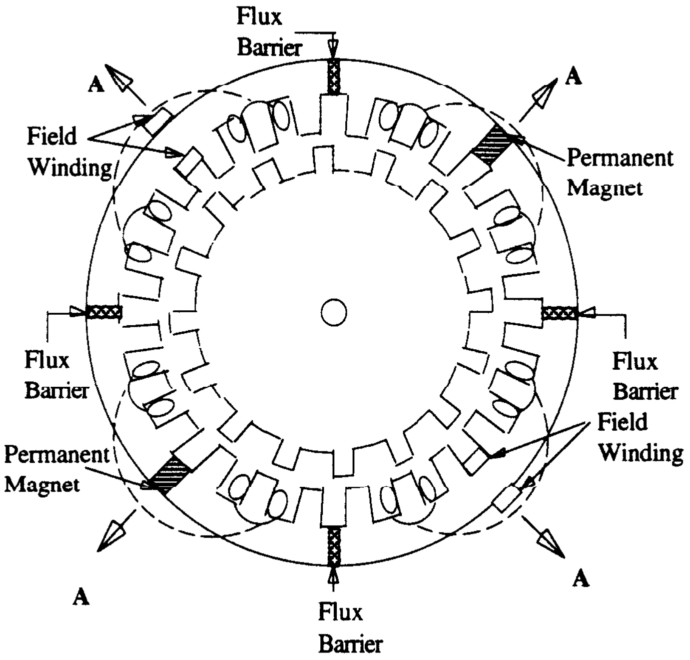

Fig. 8 Four Quadrant Machine with Semi-Controllable Field

The second design which incorporates pure electrical weakening, operates in precisely the same manner as the four quadrant machine discussed above. The only difference is the means in which the machine is structured. Instead of having a machine in which PM and electrically excited segments are placed on the same periphery, as in the four quadrant machine, this "two sided" machine places the segments end to end, as shown in Figs. 9a-9c. Shown in Fig. 9a, is a cross section of that side of the machine which is excited by a field winding, while Fig. 9b depicts that portion of the machine excited by PMs. But while the two sides of the machine are physically, in a sense, in parallel, as far as the armature windings are concerned, whereas magnetically they are again in series. This is true since each armature winding links both PM flux and field coil flux, as depicted in Fig. 9c. Clearly with this machine design as well, the total field flux is controllable, making high speed, field weakening operation feasible with this machine structure.

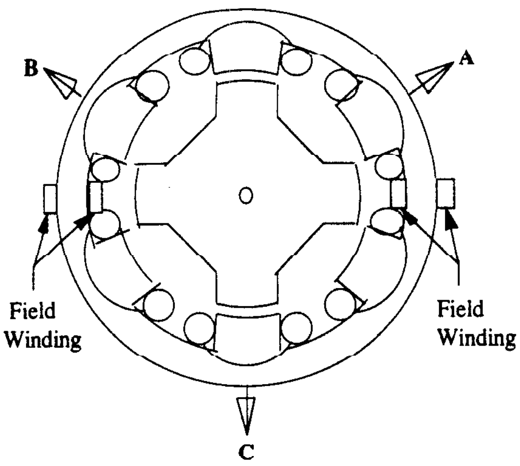

Fig 9a Electrically Excited Side of Two Sided Machine

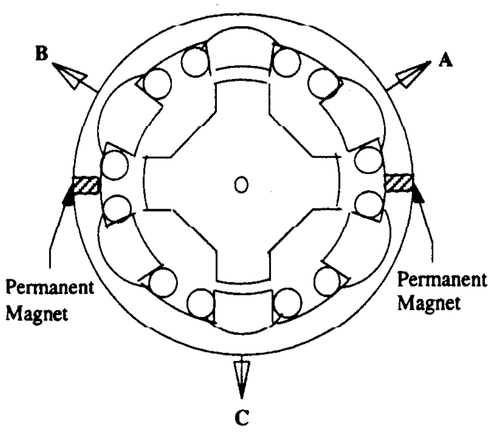

Fig. 9b PM Excited Side of Two Sided Machine

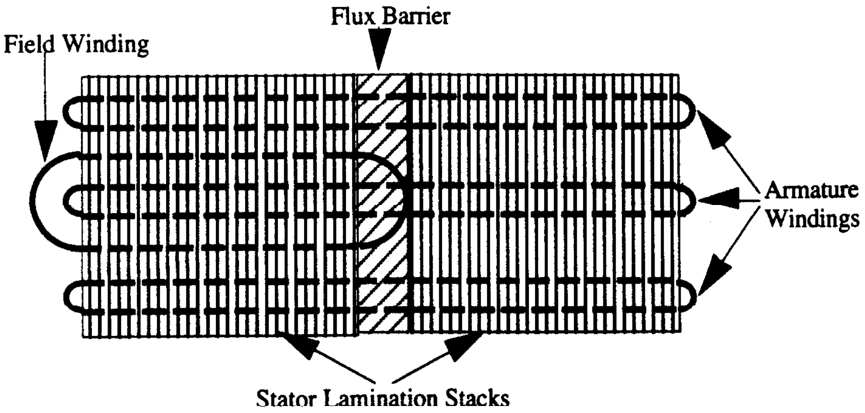

Fig. 9c Top View of Doubly Excited Two-Sided Machine, with Semi-Controllable Field

## 6. TEST RESULTS

For experimental purposes, the first of these weakening methods was chosen to exemplify the degree of field weakening that can be obtained with this structure. To "short" the PM flux, two blocks of iron were machined so as to fit perfectly over the aforementioned stator "corners" containing the magnets. In order to obtain a plot of the back emf verses the amount of weakening, the iron blocks were spaced away from the stator using plastic shims of various thicknesses. The resulting values of back emf vs. shim thickness are shown in Fig. 10. The maximum amount of field weakening was, of course, obtained when the iron blocks were directly placed over the stator corners containing the magnet. With the blocks in this position the back emf was found to be reduced by a factor of over 4.5. This, of course, is a very substantial reduction and it lends credence to the concept of field weakening a stationary magnet machine. Clearly, it would be very difficult to obtain such a comparable reduction in a rotating magnet machine due to the fact that the PM's themselves develop very high field intensities which act in a magnetic path with a very large air gap.

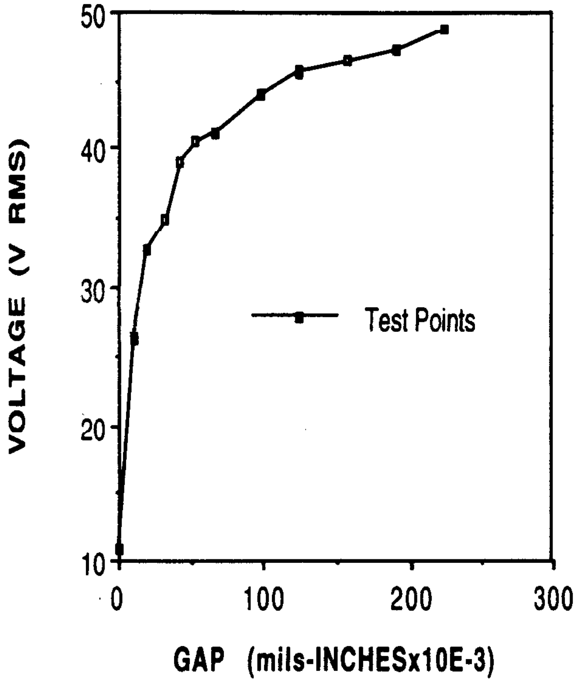

Fig. 10 Motor emf vs. Shim Thickness.

## 7. CONCLUSION

This paper has described possible field weakening schemes which can be realized with a stationary magnet DSPM machine. The optimum combination of stator geometry and these field weakening scheme is still being pursued. However, preliminary results show that a very substantial reduction can be obtained in the PM field which is attainable through simple means. The potential for field weakening this type of PM machine clearly makes it very attractive for use in applications such as electric vehicles where not only high torque but wide speed ranges are required.

## REFERENCES

[1] Jahns, T.M., "Flux-Weakening Regime Operation of an Interior Permanent-Magnet Synchronous Motor Drive", IEEE Transactions on Industry Applications, Vol. IA-23, No. 4, July/August 1987.

[2] Sneyers, B., Novotny, D.W., Lipo, T.A., "Field Weakening in Buried Permanent Magnet AC Motor Drives", IEEE Transactions on Industry Applications, Vol. IA-21, No. 2, March/April 1985.

[3] Schiferl, R. and T.A. Lipo, T.A., "Power Capability of Salient Pole Permanent Magnet Synchronous Motors in Variable Speed Drive Applications", IEEE Trans. on Industry Applications, Vol. 26, No. 1, January/February 1990, pp. 115-123.

[4] Yuefeng Liao and T.A. Lipo, "A New Doubly Salient Permanent Magnet Motor for Adjustable Speed Drives", 1992 Seminar on Power Electronics, Electrical Drives and Machines (SPEEDAM), Positano, Italy, 19-21 May, 1992, also in Electric Machines and Power Systems, Vol. 22, No. 2, 1993, pp. 259-270.

[5] Yuefeng Liao, Feng Liang and T.A. Lipo, "A Novel Permanent Magnet Motor with Doubly Salient Structure", IEEE IAS Annual Meeting, Houston TX, Oct. 5-8, 1992, pp. 308-314 (to appear in IEEE Trans. on Industry Applications)

[6] Liao, Y., "Design and Performance Evaluation of a New Class of Permanent Magnet Machines with Doubly Salient Structure"' Ph.D. Thesis, UW-Madison, Oct. 1992.

[7] Lipo, T.A., Liao, Y. and Liang, F., "Field Weakening for a Doubly Salient Motor with Stator Permanent Magnets", U.S. Patent pending.