# Direct Control of Air-Gap Flux in Permanent-Magnet Machines

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***Abstract*—A new field weakening and adjustment technology for PM machines by direct control of air-gap fluxes is introduced. This new technology requires no current decomposition by the inverter eliminating the need for a position sensor. Demagnetization, which normally occurs during field weakening, does not occur with this new method. The field-weakening ratio can reach 10:1 or higher. This technology is robust and particularly useful for, but not limited to, electric vehicle drives and PM generators.**

***Index Terms*—Field weakening, field control, permanent-magnet (PM) machines, motors, generators, electric vehicle, drives.**

## I. Introduction

PM machines are desirable for applications that require high power density. One undesirable property is that it is not easy to field weaken them if it is necessary to drive them at a constant power output above base speed where the back electromotive force (emf) equals the line voltage. By weakening the field the back emf can be reduced thereby allowing PM motor operation to continue; however, existing approaches for field weakening PM motors are relatively complex.

A technology for directly controlling PM generator's terminal voltage and the PM motor's back emf has not been available. If the PM field could be directly controlled the buck-boost converter, which now controls a PM generator's output voltage at the direct current (DC) link, could be eliminated.

Morimoto *et al.* [1] stated that direct control of the magnet flux in the PM motor is not available. However, the direct-axis armature current can weaken the air-gap flux. In this mode of operation, magnet demagnetization due to the direct axis armature reaction must be prevented, because it can irreversibly decrease the magnet torque.

Soong and Miller [2] based their study on the work by Morimoto *et al.* For the maximum torque field-weakening control they concluded that the optimal high-saliency interior PM motor design is the most promising for applications requiring a wide field-weakening range.

Manuscript received June 16, 1999.

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Prepared by the Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, managed by Lockheed Martin Research Corp. for the U.S. Department of Energy under Contract DE-AC05-96OR22464.

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Publisher Item Identifier S 0885-8969(00)11018-6.

Namuduri and Murty [3] focused their discussion on the pulse-width-modulation (PWM) strategy and the microcontroller system that implements the phase angle control scheme. The authors concluded that, though the PM motors were not designed for field weakening by phase angle control, experiments showed that the torque at no-load speed can be increased significantly with phase advance, at the expense of increased motor losses.

Sozer and Torrey [4] presented an approach for adaptive control of the surface mounted PM motor over its entire speed range. The adaptive flux-weakening scheme is able to determine the right amount of direct-axis current at any operating condition.

Sebastian and Slemon [5] proposed that with optimum alignment of the stator and magnet fields maximum torque per ampere is achieved up to a break-point speed. Operation at higher speeds with reduced torque is achieved by adjustment of the current angle to reduce the effective magnet flux i.e., the equivalent of field weakening.

This study suggests a new direct control of the air-gap flux of PM machines through the magnitude and direction of the DC control current fed to a field-weakening control coil. There is no special requirement on the inverter to control direct and quadrature-axis current components and a position sensor on the rotor is not necessary. Under a normal control range, the field-weakening control coil does not demagnetize the PMs. A 10:1 field-weakening ratio can easily be obtained. This new method is robust and particularly useful for, but not limited to, electric vehicle drives and PM generators. The same principle can be used for either axial- or radial-gap PM machines.

## II. Principle of Equalization of Air-Gap Flux Densities for Field Weakening

The principle of equalization of air-gap flux densities for field weakening of the new type of PM machines is explained through the air-gap fluxes acting on the coil edges as shown in the following figures.

Fig. 1(a) shows a conventional coil in a PM machine where the air-gap fluxes of opposite polarities are acting on the coil edges 1 and 2. A back emf is induced when there is a relative movement between the coil and the air-gap fluxes. Fig. 1(b) shows what happens when the direct-axis current component weakens the field in a conventional PM machine. The magnitudes of the air-gap fluxes at both coil edges are equally weakened in opposite polarities thereby inducing a smaller back emf.

Fig. 2 illustrates that a small back emf can be generated even when the magnitudes of the air-gap fluxes remain high. In this

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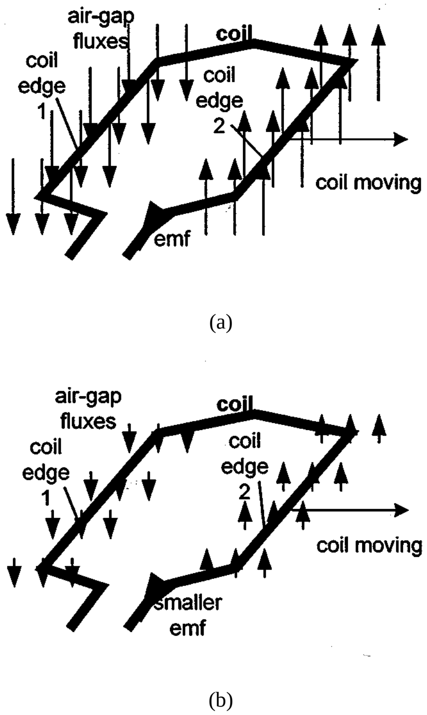


Fig. 1. Conventional field weakening. (a) Normal situation. (b) Conventional field weakening.

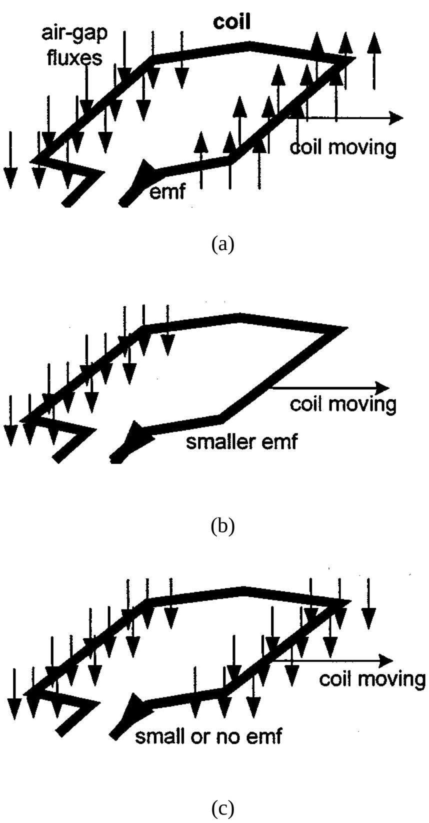


Fig. 2. Field weakening based on equalization of air-gap flux densities. (a) Normal situation. (b) Partial equalization of air-gap flux densities. (c) Equalization of air-gap flux densities.

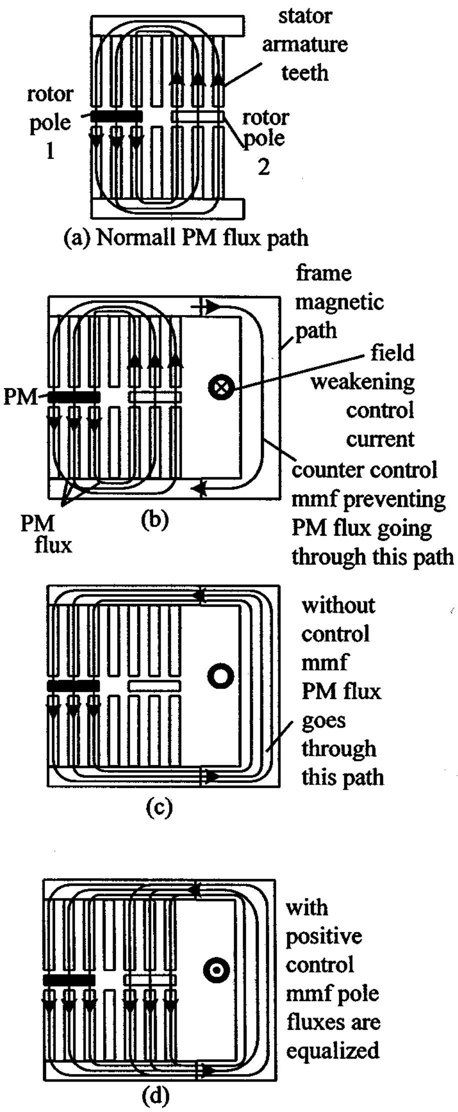


Fig. 3. An axial-gap field-weakening PM machine.

technology the polarities of the air-gap fluxes play an important role for weakening the back emf. Fig 2(a) shows a conventional PM coil, which is the same as that explained for Fig. 1(a). However, if the flux acting on a coil edge is taken away as shown in Fig. 2(b), the back emf is reduced. The back emf can be very small as shown in Fig. 2(c) when the air-gap fluxes acting on both coil edges have nearly equal magnitudes and polarities.

The wave form of the back emf of a coil edge is a direct reflection of the air-gap flux distribution of its adjacent pole. In this technology because the air-gap fluxes do not have equal magnitudes with alternating polarities, the short pitch approach for harmonic cancellation is not as effective as the distribution approach.

## III. Magnetic Paths and Machine Structures

### A. Sample Magnetic Path

An example of the new field-weakening technology is shows in the axial-gap PM machine of Fig. 3. The rotor is situated between two stators as shown in Fig. 3(a). Rotor pole 1 is made of PM material, and pole 2 is made of ferromagnetic material. The magnetic flux starts from rotor pole 2 and goes in a counter clockwise direction. The flux traverses the air gap, the stator armature teeth, the stator back iron, the stator teeth facing rotor pole 1, the air gap, the PM rotor pole 1, the air gap, the lower stator teeth, the lower stator back iron, the lower stator teeth, and the air gap returning to rotor pole 2. The PM must have sufficient thickness in order to push the desired flux through both sets of air gaps facing pole 1 and pole 2. This configuration is similar to a conventional PM motor that has both poles made of PM material but with half the thickness of the pole-1 PM.

Fig. 3(b) shows that the frame of the PM motor acts as a third magnetic path. To prevent flux going through the frame, the control current in the field-weakening control coil produces a countering magnetopotential. Because the PM flux can go through the rotor pole 2, this magnetopotential only prevents the PM flux going through the frame and does not demagnetize the PM. This situation corresponds to the case shown in Fig. 2(a). The highest back emf would be produced. For electric vehicle drive, this situation is most suitable for the low speed and high torque operation.

Fig. 3(c) shows that when the field-weakening control coil has no current, the PM takes the least reluctance path through the stator frame. The air-gap fluxes are in a situation similar to that shown in Fig. 2(b). This configuration is most suitable for electric vehicles running at medium speed with a medium torque requirement.

Fig. 3(d) shows the case for which the field-weakening control coil is fed with a control current that produces equal magnitude air-gap fluxes at both pole 1 and pole 2 in the same direction. Though both air-gap fluxes remain strong, their back emfs induced in the coil edges of a coil cancel to produce a value that is nearly zero, just as if the field had been weakened. This corresponds to the situation shown in Fig. 2(c). It should be noted that under no situation is the PM subjected to demagnetization due to this field weakening. The new PM machine structure that utilizes this flux equalization principle is not limited to this example.

### *B. Sample Machine Structure*

Fig. 4 shows a possible new PM machine structure of eight poles. The field-weakening control coils are wrapped around the shaft axis in a toroidal form. The machine frame is made of mild steel to serve as the additional flux path. In order to prevent shaft flux, nonmagnetic bearing inserts, a nonmagnetic shaft, and nonmagnetic bearings should be used. Two axial-gap stators are mounted inside the frame. The stators have their individual yokes for their normal flux return paths. The armature coils are wound inside the slots between the teeth, which project axially toward the rotor from both sides.

The rotor view shows that the PMs are located at every other pole between the ferromagnetic poles, which are not made of PM material. The rotor poles are mounted in the holes of a nonmagnetic structure, which is attached to the shaft. A banding on the rotor outer periphery may be used to increase the rotor strength for high-speed operations.

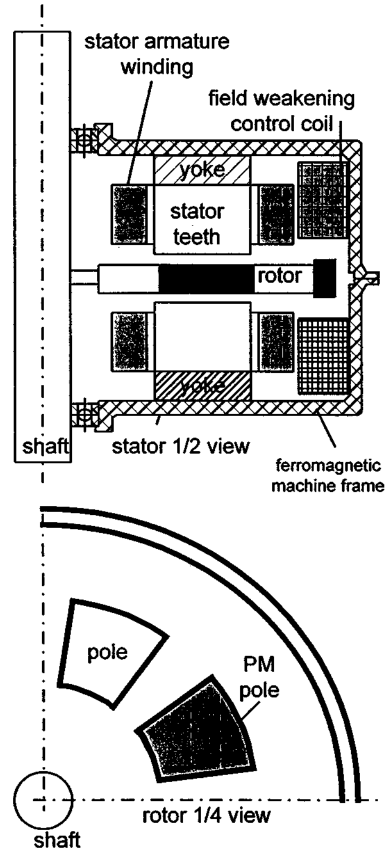


Fig. 4. A possible new PM machine structure.

### *C. PM Machines With Non-Ferromagnetic Frame or Radial-Gap*

The shaft of a nonferromagnetic-frame PM machine can be used to substitute the ferromagnetic frame for the flux return path. Under this situation the flux conducted by the shaft must be sufficiently high for the desired field-weakening ratio. The principle can be applied to radial-gap PM machines.

## IV. PROTOTYPE MACHINE AND TEST

### *A. Prototype Machine*

The upper schematic of Fig. 5 shows a cut view of the four-pole prototype machine and the lower schematic shows the rotor. The rotor of this particular prototype machine is sandwiched between two axial-gap stators. Two of the rotor poles are made of mild steel. The other two poles are made of PMs. These two PM poles have the same polarity and a thickness sufficient for pushing the air-gap fluxes through the PMs and the mild-steel poles to form a complete magnetic path. The poles are mounted in an aluminum rotor structure that is attached to a nonmagnetic shaft made of stainless steel. The round shape of the PMs and the ferromagnetic poles results from the use of available round PMs to fill a normal pole shape shown in dotted lines. It is expected that the use of two round PMs and two round ferromagnetic pieces, which comprise each other pole, will cause harmonics in the back emf. However, a

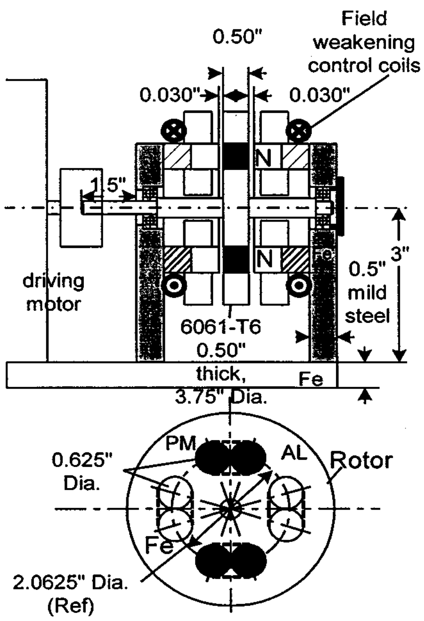


Fig. 5. A prototype PM machine for testing the back emf using direct control of air-gap flux in generator mode.

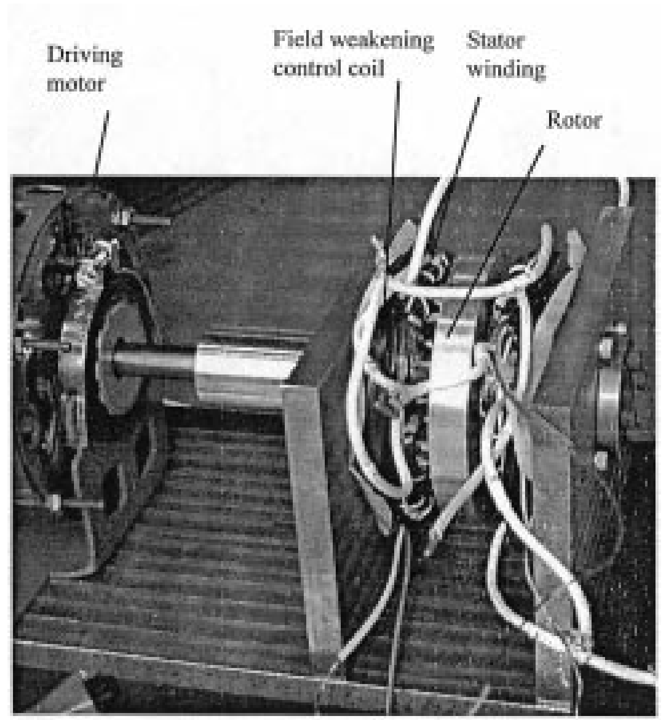


Fig. 6. A prototype PM motor with direct control of air-gap flux.

pole cap, that follows the dotted line of a rotor pole shown in Fig. 5, can be placed on top of the round PMs to reduce the air-gap-flux harmonics.

Two field-weakening control coils wound in toroidal shapes are placed between the stator winding and the steel frame of the machine. They are approximately 100 turns each. Like a field coil of a shunt-wound DC machine, more turns of the field-weakening control coils require less excitation current. Normally, the field coil power is roughly 3 percent of the full-load power of a shunt-wound DC machine. The prototype stator has 12 slots, and the coils are of full pitch with one coil per pole per phase.

The steel support frame of the machine is made of $1/2''$ mild steel. It is expected that the thickness of a round steel frame would be significantly reduced because the peripheral of a frame is about three times the outer diameter of a machine.

In order to measure the back emf of the stator armature winding, the rotor of the prototype machine is driven by a small motor at 1200 rpm. The driving motor is shown on the left-hand side of Fig. 5. The two axial-gap stators were originally designed for a 50 000-rpm high-speed PM motor explaining why a low voltage was generated at 1200 rpm.

Fig. 6 shows the actual prototype motor driven by a low-speed motor for back emf measurement.

### B. Test Results

Fig. 7 shows the tested back emf values versus the control currents of the field-weakening coil. As mentioned before, the back emf is expectedly low because the driving motor runs at a low speed. Attention should be drawn to the range of the ratio of emf values to the minimum value as the control current is varied.

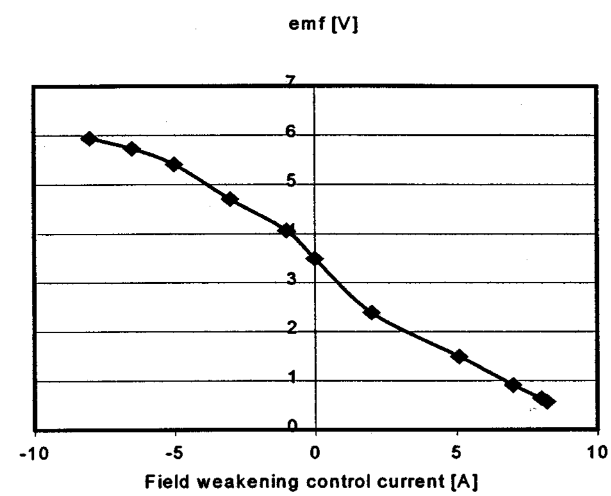


Fig. 7. Tested back emf values versus control currents of the field-weakening coil.

Test results show that a field-weakening ratio greater than 10:1 can be obtained.

Fig. 8 shows a significant control capability evidenced by the back emf traces of the prototype machine under various field strengths. Pole caps were used in this machine to reduce air-gap flux harmonics.

## V. Conclusion

- A new field-weakening and adjustment technology for PM machines is introduced.
- A field-weakening ratio greater than 10:1 can be obtained.

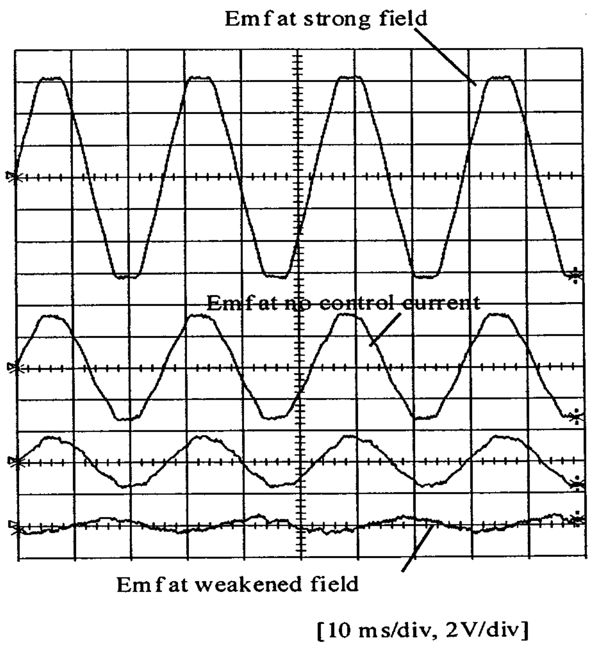


Fig. 8. Back emf traces under various field strengths.

- The air-gap fluxes are controlled directly by the field-weakening control coils.
- No control of the direct and quadrature-axis current components is necessary for the new PM machines.
- Under a normal control range, the demagnetization due to field weakening is not an issue with this new technology.
- This new technology is robust due to its simple operation principle.
- Either a ferromagnetic machine frame or
- The same principle can be used for either axial or radial gap PM machines.
- This technology is particularly useful for, but not limited to, electric vehicle motor drives and PM generators.

## ACKNOWLEDGMENT

The author appreciated the support funded by the Office of Advanced Automotive Technologies, Department of Energy. Encouragement from the Power Electronics Group headed by Mr. Donald Adams, the helpful discussions from Professor J. Milton Bailey and Dr. John McKeever, and the prototype building by Mr. S. Michael Jenkins are gratefully acknowledged.

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