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F. Leonardi*, Y. Li, T. Matsuo, T.A. Lipo, P. McCleer***

Wisconsin Power Electronics
Research Center
University of Wisconsin-Madison
Madison WI 53706-1691

*McCleer Power Inc.
2421 Research Drive
Jackson MI 49203

**Emerson Motor Co.
8100 W. Flourissant Ave.
PO Box 36912
St. Louis MO 63136

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

DESIGN CONSIDERATIONS AND TEST RESULTS FOR A DOUBLY SALIENT PM MOTOR WITH FLUX CONTROL

F. Leonardi[1] T. Matsuo[2] Y. Li[3] T.A. Lipo[2] P. McCleer[1]

[1]McCleer Power Inc., 2421 Research Dr., Jackson MI, 49203

[2]University of Wisconsin - Madison, 1415 Engineering Dr., Madison WI, 53706

[3]Emerson Motor Company, 8100 W. Flourissant Ave., PO Box 36912, St. Louis MO, 63136

Abstract: **A prototype of a new permanent magnet machine is presented in this paper, and its experimental tests fully documented. The motor incorporates the benefits of PM machines, namely the high power density and efficiency, overcoming some of its major disadvantages, such as high cost and limited speed range. Low cost is achieved due to the utilization of simple ceramic PM (ferrite) magnets but the unique flux concentrating magnetic structure allows for the maintenance of a high air gap flux density and consequently high power density. All the active material (coils and magnets) are placed in the stator, so that the rotor structure is very simple like that of the Switched Reluctance Machine (SRM). An extended speed range is obtained thanks to a field coil that can be used to weaken the PM field at high speed or to boost the field at low speed.**

INTRODUCTION

Doubly salient machines have attracted an increasing interest among the community of researchers in the electric machine field. The most popular machine of this family is the Variable (or Switched) Reluctance Motor which combines a simple structure, with excellent robustness and interesting performance. More recently PM excited doubly salient motors and generators were presented [1] - [4].

The doubly salient prototype presented in the past [1] uses rare earth magnets placed in the stator yoke. The proposed doubly salient PM motor instead has a large PM placed between the stator teeth and the stator yoke (fig. 1). This unique placement of the magnet allows for the concentration of the PM flux through one tooth at a time, thereby achieving an outstanding flux focusing property. The area available for the magnet is wide and therefore inexpensive ferrite magnets can be utilized without the performance penalty usually associated with their low residual flux density. In fact an air gap flux density in excess of 1.0 Tesla is easily achievable.

This magnet configuration allows for some extra space, located between the PMs, that can be made available for a field winding, used to weaken or boost the PM flux. It has been shown [2] that PM flux cancellation is limited only by the PM demagnetization, and, in case of ferrite material at room temperature or higher, the per pole flux can be reduced down to 10% of the PM flux. Flux boosting is limited by the iron core saturation and therefore is design dependent. A 50% increase in the per pole flux is readily obtainable [2].

A detailed analysis of the sizing equations of this kind of doubly salient machine is reported in [5] and will not be repeated in this paper.

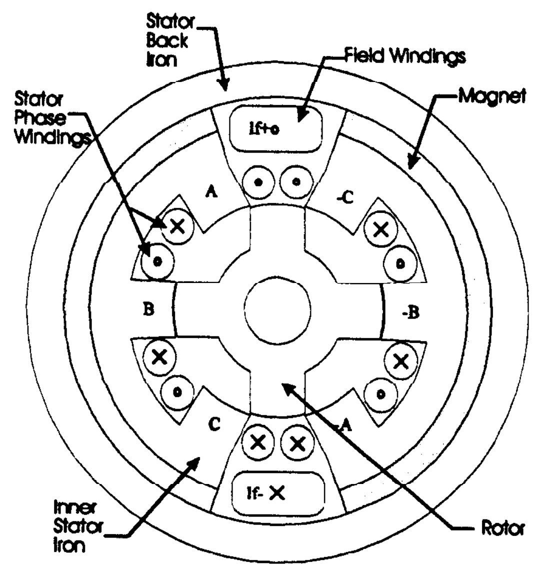

Fig. 1 Doubly Salient Permanent Magnet Motor (DSPM)

The doubly salient PM motor is generally immediately associated with the SRM for an evident similarity of the magnetic structure at the gap. The rotor and the stator coils are identical and the two machines start to differentiate in the vicinity of the outer diameter. In spite of these analogies, the basic operational principle of these two machines is completely different, and the Doubly Salient

Permanent Magnet motor (DSPM) should be regarded as a member of the brushless dc machine family more than of the Variable Reluctance Motor family. In fact for the DSPM the reluctance torque is, in most operating conditions, only a parasitic pulsating torque, and does not give any contribution to the motor output. The electromechanical power conversion is the result of the interaction between the PM flux and the coil current, as in every other PM machine.

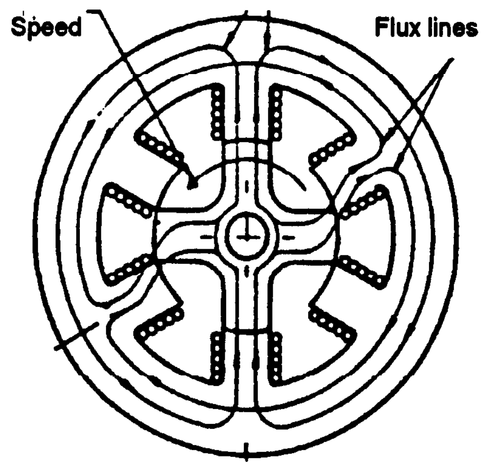

Fig. 2 Switched Reluctance motor section

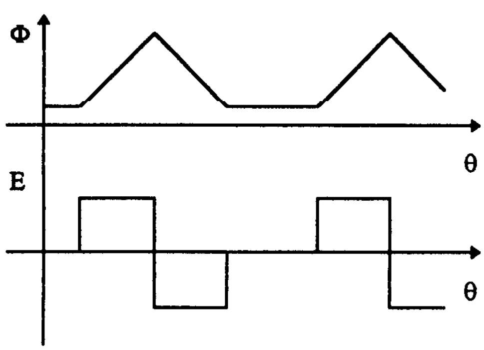

Fig. 3 Ideal flux and back emf waveform for DSPM motor

INDUCED VOLTAGE

Perhaps the main difference between the DSPM and the rotating magnets PM brushless motors is that the variation of the flux in the gap is induced by a permeance variation and not by the magnet rotation. The PM flux tends to flow through the stator poles that are aligned with the rotor poles: as the alignment is a function of the rotor position so becomes the air gap flux distribution. The stator coils link a pulsating flux and therefore an alternating emf is induced in the coils. The direction of the flux density in the stator poles never reverses but oscillates between a maximum value (at full alignment) and a minimum value when the poles are not aligned. The corresponding back emf is ideally a square waveform as shown in fig. 3. It is very important for the effectiveness of the design that the leakage flux be kept under control, for two main reasons. First, because this flux component reduces the useful flux for a given magnet volume. Second because the leakage flux linked by the armature winding in the unaligned position reduces the flux difference:

$$\Delta\Phi = \Phi_{aligned} - \Phi_{unaligned} \qquad (1)$$

that is responsible for the induced voltage. This induced voltage can be approximated by:

$$E_{emf} = N_{se} \cdot \frac{\Delta\Phi}{\Delta\theta} \cdot \omega_e \qquad (2)$$

where:

N_{se} is the turn number in series per phase

$\Delta\theta$ is the angle between the minimum and maximum flux position

ω_e is the electrical angular speed.

A low leakage factor has already been demonstrated for a broad range of pole numbers (from 2 to 8 magnets and 6 to 24 stator teeth, corresponding to 6 to 24 pole pairs of a conventional ac machine), but ratios $\Phi_{aligned}/\Phi_{unaligned}$ as low as 2 are possible for very high pole number (>32). Some provisions must, however, be considered in this case to avoid performance deterioration.

Another important difference between conventional PM machines and the DSPM is the flux control capability, made possible by the insertion of a dc coil in the stator. This dc coil shares the same magnetic path with the PM and therefore its flux can be added or subtracted to the main exciting flux, according to the dc current polarity. Since the dynamic response of this coil must only be fast enough to anticipate the rotor speed changes, only a moderate di/dt is required. Hence a low power converter is sufficient to drive the flux controlling current.

The effect of the field current on the machine induced voltage is shown in fig. 4, where the prototype open circuit voltage waveforms with 10A boosting current, no field current and 10A field weakening current are compared. The resultant emf for a continuum of field current is shown in Fig. 5.

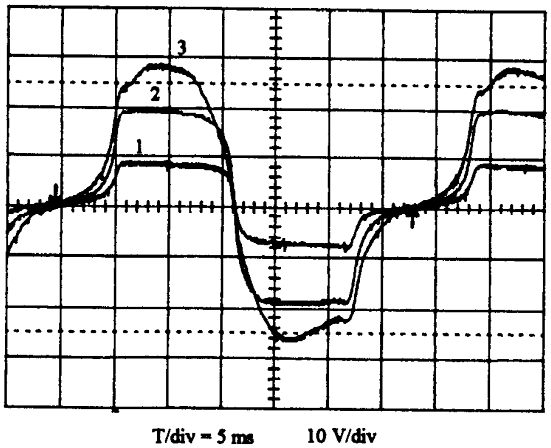

Fig. 4 PM induced voltage at 900 rpm 20 V/div for different If (field coil current): 1 @ If=-15 Amp, 2 @ If=0 Amp; 3 @ If=15 Amp

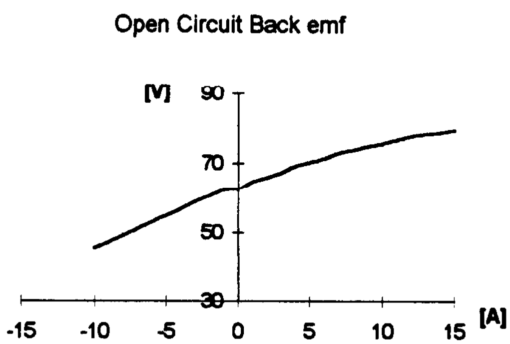

Fig. 5 Rms value of the PM induced voltage vs field coil current at 2000 rpm

In this machine the magnets were mounted non magnetized and then magnetized in place utilizing the field coils and all the phase coils in series. This strategy eases the mounting procedure but the magnetization is limited by the iron core saturation. In spite of several efforts made to increase the steel available for the magnetizing flux the residual flux at the end of the magnetization is about 70% of the design value. The design value can still be reached if the field coil is used to boost the magnet flux.

MACHINE PARAMETERS

During the normal operation of a DSPM motor, two phases are active at the same time, one being pulled toward alignment, the other pushed away. The reluctance torque caused by the self inductance variation is therefore mainly canceled. This principle reduces the torque ripple that is a significant drawback for many doubly salient machines. However a non-negligible pulsating torque will still arise due to mutual inductance variation and to the non ideal flux and current waveforms.

The phase winding inductance, shown in fig. 6, is a critical parameter for the DSPM. The self inductance of phase B is a little higher (5%) than the self inductance of the other two phases because the armature reaction flux has a slightly different magnetic path. The mutual inductance also reflects this asymmetry (fig. 7).

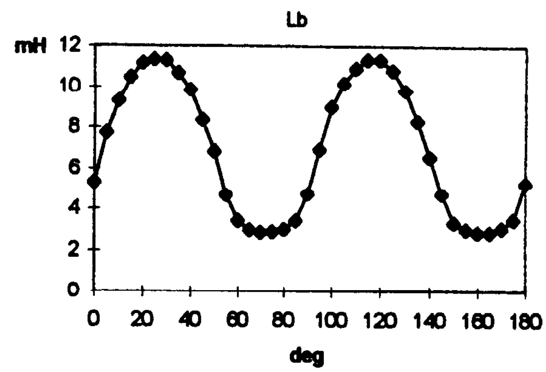

Fig. 6 Measured Inductance waveform for phase B (mH vs mechanical degrees)

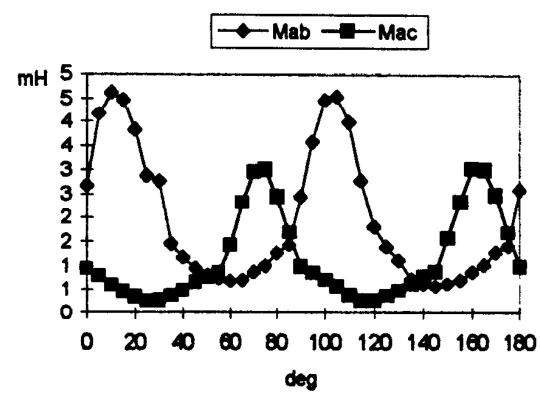

Fig. 7 Magnitude of measured mutual Inductance

A figure of merit for a the DSPM is given by:

$$Q = \Phi^2 / L \qquad (3)$$

where Φ is the per phase flux per unit of axial length [Wb/m], and L is the self inductance per unit of axial length [H/m]. If the stator resistance is neglected Q is directly proportional to the power deliverable by a DSPM generator, with a resistive load. Even for a DSPM motor Q can be used to judge the quality of a motor design.

LOAD TESTS

The main focus of this paper is on the bench test results of a prototype of the DSPM motor. Being a proof of concept machine, built mainly for comparison purposes, the motor was designed to fit in a standard 5 hp 4 pole induction motor frame (184T) with stator outer diameter of 8in (20.32cm). Thanks to the DSPM superior power density the frame is only partially utilized since the machine stack length is just 3.5 inches (8.9cm). The ferrite PM material is 'Ceramic 5' type, with nominal residual flux density of 0.35 Tesla at room temperature and relative permeability of 1.07.

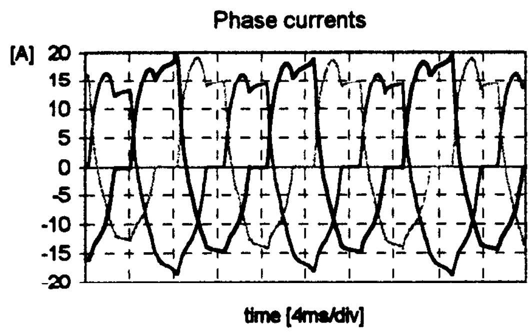

Fig. 8 Current Waveform at 1250 rpm, 100% duty cycle. Test set no. 1

Motor operation was evaluated with two different test setups: the first was a 150V DC Bus three phase inverter equipped with a sensorless position detection system. The inverter IGBTs were controlled by means of an 8 bit microcontroller. The limited dv/dt of the back emf in the zero crossing region makes this controller sensitive to noise. At low speed some instability may be generated by the jitter caused by the noise in the zero crossing detector output. Phase currents for motor operation at 1250 rpm, output torque of 7 Nm are shown in fig. 8. The three currents are slightly different because of the above mentioned phase asymmetry.

The second test setup was a ±160V dc bus 3 phase inverter, with split capacitor. The motor was equipped with a 12 bit optical encoder and four current sensors. A DSP controller is used to control the IGBT switches.

Fig. 9 shows the no load losses measured in motoring and generating mode with this new test setup. The different values reflect the presence of copper and pwm losses in the motoring operation. These losses are almost speed independent. The copper losses due to the rms value of the current however are only about 7 watts. The remaining loss difference should be regarded as additional losses in the copper and in the iron due to the pwm. The hysteresis band was very large if compared to the small value of the rms current necessary to overcome the losses. As shown in fig. 10 the switching frequency is high at low speed, even if a large hysteresis band is adopted.

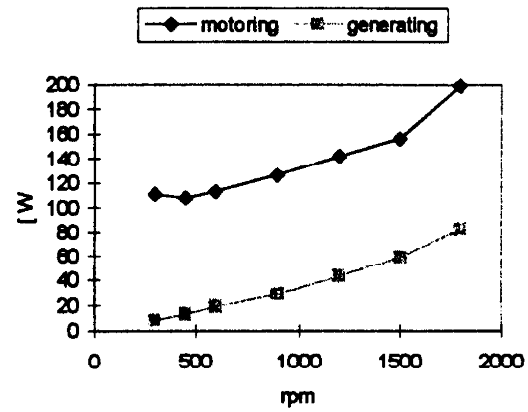

Fig. 9 No load losses in motoring and generating mode

These losses lower the efficiency of the motor especially at low speed. At high speed (fig. 11) when the inductance of the phase coils slows down the pwm frequency the efficiency is clearly improved.

The effect of pwm losses on the efficiency over the speed range is clearly recognizable in fig. 12.

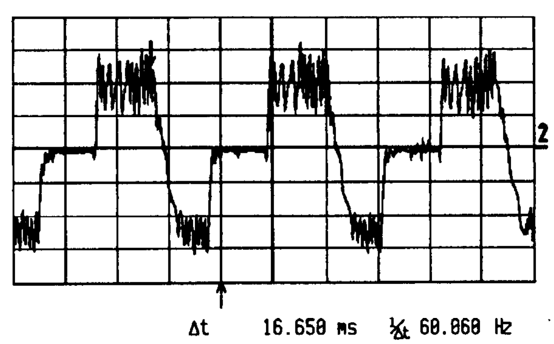

Fig. 10 Phase 1 current 10 amperes/div. 5 mS/div. 900 rpm. The field current. If=0 A. With phase shift of 7.47, 7.03, and 7.47 mechanical degrees, respectively, for firing, swap and turn off advance angle

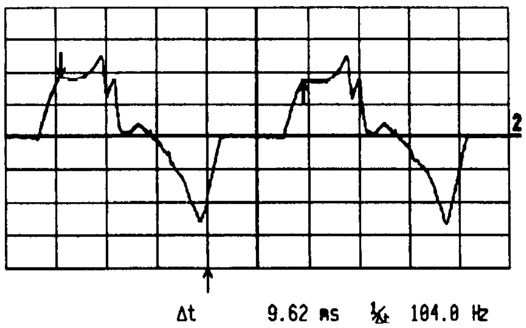

Fig. 11 Phase 1 current. 20 amperes/div. 2 mS/div. 1560 rpm at 20 Nm, 3265 W. . The field current If=15 A. With phase shift of of 4.92, 7.03, and 4.92 mechanical degrees, respectively, for firing, swap and turn off advance angle.

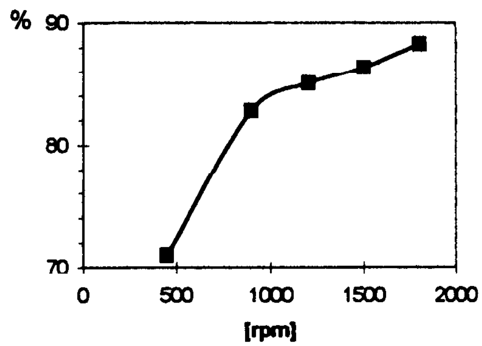

Fig. 12 Efficiency vs speed at 10 Nm

Other factors that influences the motor performances are the firing angle advance, the swap angle and the turn off angle i.e. when the phase is excited, when the phase current is reversed and when it is turned off with respect to the ideal timing. The ideal firing angle corresponds to the beginning of the stator and rotor pole overlapping. The ideal swapping happens at full alignment and the ideal turn off corresponds to the end of stator and rotor pole overlapping. As common practice for the Switched Reluctance motor the firing and turn off angles (and in our case also the swap angle) must be anticipated when increasing speed and current, to allow enough time to reach the desired current level with the minimum current - back emf phase shift. An automatic algorithm to estimate the optimal angles as a function of phase current and speed was not implemented in the controller utilized in these tests. The advance angle, as well as the current swap angle and the turn off angle were manually selected for each operating condition and therefore the results presented should be deemed as sub-optimal. The torque transmitted to the shaft is plotted in fig. 13 as a function of the firing angle advance, for 450 and 900 rpm.

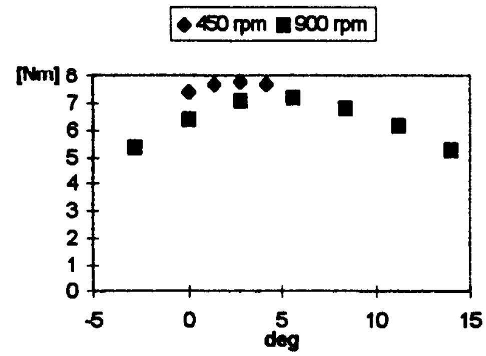

Fig. 13 Torque vs advance angle (mechanical degrees). Reference current set at 12.5A

As the phase current increases the iron cores are pushed into saturation and the torque per ampere ratio decreases. At the same time the increased motor losses cause an increase in motor temperature. As the magnet temperature increases the residual flux density decreases and so does the motor back emf. The effect on the efficiency caused by the iron core saturation and also by the magnet temperature increase can be seen in Fig. 14.

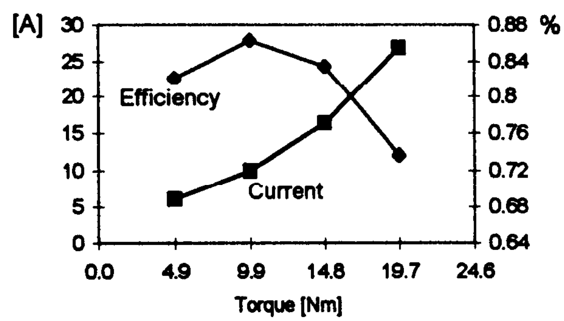

Fig. 14 Efficiency and current vs torque at 1500 rpm

CONCLUSIONS

Test results for a prototype of Doubly Salient PM machine were presented in this paper. The motor shows good power density if compared with conventional machines, at comparable efficiency. Superior efficiency is expected when higher grade, fully magnetized magnets are utilized in this topology.

The unique field control capability make this permanent magnet motor an interesting candidate for many applications such as traction motors for battery powered vehicles, and field regulated automobile and truck alternators.

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