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THE DSPM: AN AC PERMANENT MAGNET TRACTION MOTOR WITH TRUE FIELD WEAKENING*

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Abstract: **The Doubly Salient Permanent Magnet Motor (DSPM) employs a stator and rotor structure similar to that of a standard switched reluctance machine. But in addition, it has a controllable level of magnetic field flux bias in the stator/rotor pole flux path. This flux bias is supplied by permanent magnets (PMs) and field coils, both contained in the stator structure. The level of bias flux is controllable since the field coil flux can aid or "boost" the PM field flux or buck or "weaken" the PM field flux. The DSPM is the only brushless PM machine structure which can be truly and easily field modulated. This property makes the motor ideal for vehicle drive applications, where it is desirable to produce near constant levels of output power over a range of vehicle speeds.**

INTRODUCTION

The primary attraction of PM electrical machines is their inherent efficiency advantage due to the lack of heating or I^2R losses in the creation of the exciting magnetic flux. However, with this efficiency advantage also comes the operational disadvantage of having to deal with a near fixed level of magnetic excitation. In variable speed applications, such as inverter fed traction drives, as the desired operating speed grows, so too does the machine internal voltage or back emf. This back emf is proportional to the product of the machine speed and the fixed level of excitation flux. When the internal back emf reaches the level of the inverter bus voltage the machine reaches the maximum operating speed. If a higher speed is required then either the bus voltage must be raised (and the switching devices upgraded), or the excitation flux must be reduced or "weakened".

In a DC machine with the PMs stationary and the armature windings rotating, it is quite simple to provide an additional DC field coil in the stator field circuit, which can be used to modulate (with the expenditure of some I^2R loss) the total field excitation flux. In an AC machine, however, the armature windings are stationary and at least a portion of the field circuit must rotate. The most common construction is to have the PMs mounted on or within the rotor structure. Thus if a DC coil is to be used to modulate the total field it too must be rotor mounted and supplied by a source of field current. This supply mechanism (brushes and slip rings, or rotating rectifiers) as well as the rotor windings themselves, would complicate the rotor construction to such a degree to make it impractical for all but the largest of machines.

An alternative method of field control in rotor PM AC machines is to use a component of the stator winding current, referred to as the d-axis current, to excite a synchronously rotating component of field flux. This stator supplied field flux flows in the same path (the d-axis circuit) as the flux produced by the rotor PMs, and thus modulates the total field. The problem with this method is that the magnetic circuit in the d-axis contains the magnets. These magnet segments appear as a large airgap within the circuit and therefore a large ampere turn supply from the stator coils is required to reach d-axis flux levels comparable to the PM flux. Thus the net I^2R loss due to the stator control of the field is excessive.

This paper discusses a new alternative PM AC machine structure which does not suffer the field control problem of existing designs. The machine, due to its construction, is termed the Doubly Salient Permanent Magnet motor or DSPM [1-4]. In this machine the permanent magnets as well as the DC field control coils are contained in the stator rather than the rotor. The rotor is a simple stack of shaped laminations and the stator phase coils are short end turn concentrated windings, wrapped around salient poles.

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In the next sections the operational details of the machine are presented as well as a comparison to its non PM excited predecessor, the Switched Reluctance Motor. Experimental results from prototype DSPMs are given and the required sizes for scaled high torque traction motors are detailed.

The Doubly Salient Permanent Magnet Motor: Brushless PM or Reluctance Motor?

The DSPM motor, gets its name from the shape of the magnetic core which is characterized by iron protrusions, or magnetic poles, on both the rotor and stator laminations (see Figure 1). At first glance, due to the doubly salient construction, the machine is thought similar to the switched reluctance motor, but the machine operates on a fundamentally different basis. The switched reluctance machine develops torque due to excited magnetic poles pulling into alignment. The excitation comes entirely from stator winding currents which create magnetic flux that flows from stator to rotor pole tips, resulting in a pulling of the rotor poles into alignment with the energized stator poles. The stator pole pairs are sequentially excited, step-pulling the rotor poles in synchronism with the stator winding drive. Fundamental to switched reluctance operation is excitation of only those stator poles with approaching rotor poles. Ideally in a 6/4 construction (6 stator poles, 4 rotor poles, similar to the construction shown in Figure 1), only two stator poles (one pair) are excited at any one time. One can think of this type of operation as utilizing only one third of the stator windings on a continuous basis.

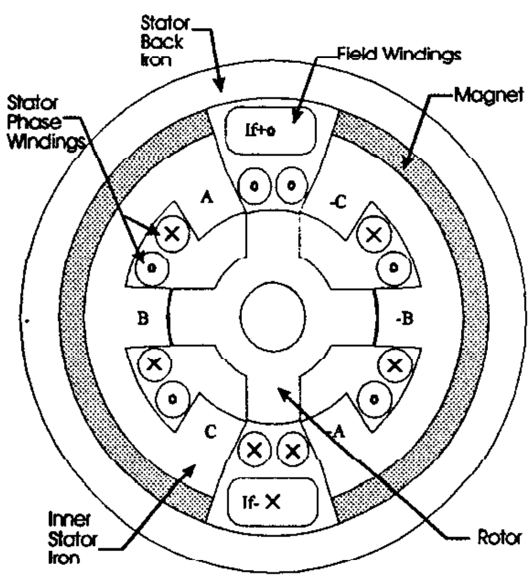

Figure 1 Doubly Salient Permanent Magnet Motor (DSPM)

The permanent magnets in the stator of the DSPM machine provide a constant level of magnetic flux "bias" which flows between the stator and rotor poles, independent of rotor position. This bias flux flows continually but its flow path switches between the different stator poles (on which are wound the different stator phase coils) depending on rotor pole positions. Thus there is a pulsating flow of permanent magnet produced flux through each stator phase coil which produces an induced voltage (or emf) in each coil. As a rotor pole comes into alignment with a stator pole the PM flux level within that stator coil rises, inducing one polarity of emf within that coil. As the rotor pole passes the stator pole and goes out of alignment, the PM flux level within the stator coil falls, inducing the opposite polarity of emf, see Figure 2. Thus an alternating emf (the machine back emf) is induced in each stator winding due to rotor motion and the permanent magnet bias. Based on this operating principle the DSPM should be regarded as a brushless DC machine rather than a switched reluctance machine.

Torque is produced in the DSPM machine by excited magnetic poles trying to align themselves (as in the switched reluctance machine) but due to the PM flux bias the entire rotor structure contributes to torque production rather than just a portion. Stator coils which "see" a rising level of bias flux due to rotor poles coming into alignment are excited to add flux to the bias flux, thus increasing the aligning force between that stator and rotor pole pair set. Stator coils which "see" a falling level of bias flux due to rotor poles passing the alignment point and going out of alignment are excited to subtract flux from the bias flux, thus weakening the reverse directed aligning force between that set of stator and rotor pole pairs. Without stator coil currents the forward and reverse directed aligning forces due to the presence of the PM bias flux cancel (ideally) at all rotor positions producing no net force. But with the correct

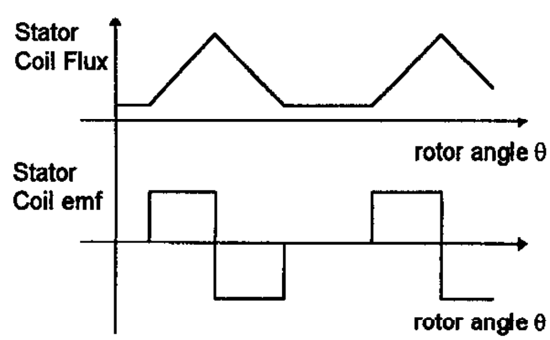

Figure 2 Ideal flux and back emf waveform for DSPM motor

drive of the stator coil currents the aligning force is strengthened at the coming into alignment set of pole pairs and weakened at the going out of alignment set of pole pairs (negative of a negative effect). Thus an apparent forward directed driving force is created at each rotor pole, and 4 out of 6, i.e. two thirds, of the stator structure is utilized at all times in torque production, doubling the stator utilization of the switched reluctance machine.

FEATURES OF THE DSPM

The construction features of the DSPM machine which make it attractive for traction drives are:

1. The rotor is a simple stack of punched, steel laminations, containing no windings or permanent magnets whatsoever. The rotor construction is exactly the same as in a switched reluctance machine, even more rugged and easier to fabricate than the rotor of the squirrel cage induction machine.

2. The permanent magnets which provide magnetic bias excitation for the machine are mounted within the stator structure. This is one of the few PM AC machines in which the magnets do not rotate. This feature contributes to both the ruggedness and the ease of manufacture of the motor. In addition, there is a flux concentrating effect in which the flux produced by the relatively large cross sectional ceramic PMs flows through the relatively small cross sectional area pole faces. The air gap flux density can approach that created by much costlier rare earth permanent magnets used in high performance brushless DC machines. Thus there is no performance penalty for using the far less costly ceramic magnet material.

3. A DC field coil is inserted in the stator structure, to

Figure 3 Stator and rotor cores of a 6/4 DSPM prototype

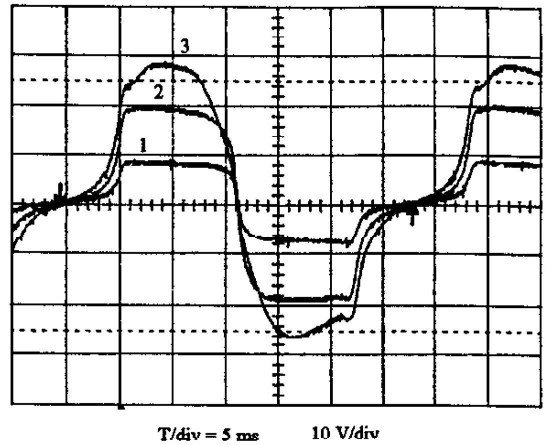

Figure 4 Open circuit voltage for three different field currents

produce magnetic flux in the same magnetic path as the permanent magnets. It can be driven (with DC current) to enhance the magnetic excitation of the machine achieving a boost of the PM flux. Even more importantly, simply by reversing the DC current, it can be driven to weaken the magnetic excitation and thus allow the motor to operate over a wide speed range at rated voltage and rated current (i.e. rated power). This is the only PM AC machine which can be truly and easily field weakened. The lack of this capability has always hindered PM excited machines in traction applications.

SOME TEST RESULTS FROM DSPM PROTOTYPES

Five DSPM prototypes have been built at the McCleer Power Inc. facilities with financial support from the Electric Power Research Institute (EPRI) and the collaboration of the University of Wisconsin-Madison [5]. Their power ratings range from 4 to 5 hp at speeds of 1500 to 4000 rpm, and voltage ratings from 36VDC for battery driven electric vehicle to 150 VDC for line rectified applications. Figure 3 shows a photograph of an unwound stator stack (showing the bias PMs) and rotor stack for the battery vehicle motor. This construction is typical of all the prototype 6/4 machines.

Figure 4 shows the field control capability of one of the machines: three open circuit voltage waveforms taken at the same speed but with different field (DC) currents are superimposed. The resulting modulation of the induced voltage in the phase coils is clearly visible. The field current excitation can reduce the open circuit voltage to 50% of its value without field current during weakening, or increase it to 120%

during field boosting, achieving a modulation range of 1:2.4.

Figure 5 shows the phase current waveforms at rated torque and relatively low speed (900rpm) for one of the battery operated machines. The current shape differs from conventional three phase brushless DC motors, where the conduction period is centered in any one half of the electrical period. In the DSPM the negative current period follows the positive current period with no zero current interval, matching the back emf waveform. The phase currents of a brushless DC motor contain only odd harmonics, while in a DSPM motor, the currents contain odd and even harmonics.

At higher speeds the DSPM current waveform deteriorates from the square like behavior of Figure 5 because of higher back emf and phase impedance. The performance can be maintained, however, by controlling the firing angle of the currents, in a fashion similar to the Switched Reluctance advance angle control [6].

SCALING OF THE DSPM

As the rating of a DSPM grows, say above 5 HP for standard speed machines (i.e. less than 4000 rpm), it becomes beneficial to repeat the basic 3 stator pole - 2 rotor pole structure by even number multiples to prevent excessive back iron requirements for the magnetic flux paths. For example, in Figure 6, we show the cross section of a preliminary design of a continuously rated 100 HP, 3000 rpm, 12/8 DSPM motor. The OD of this machine is 10.5 inches and the stack length will be approximately 12 inches, assuming liquid cooling at the stator outer surface. The upper speed limit (at 100 HP) for this machine is calculated to be in excess of 10,000 rpm, but this must be confirmed experimentally.

For even larger machines, a 18/12 stator/rotor pole structure becomes advantageous. Figure 7 shows a summary of preliminary design results for large 18/12 machines as a function of rated torque. Simple design rules have been followed to obtain these results; the most important of which are: stack length to airgap diameter ratio held constant at 1.5, 10 mm thick ceramic magnet segments, airgap length 1.0 mm, stator phase winding current density not to exceed 10 A/mm^2, stator to rotor tooth radial length ratio held constant at 1.5, and rated torque to be achieved with no field boost. For military applications, mechanical shock requirements would force larger physical airgaps which would require corresponding (but not excessive) increases in the radial thickness of the PMs and rated phase currents. For a more detailed comparative sizing analysis of DSPM machines see [7].

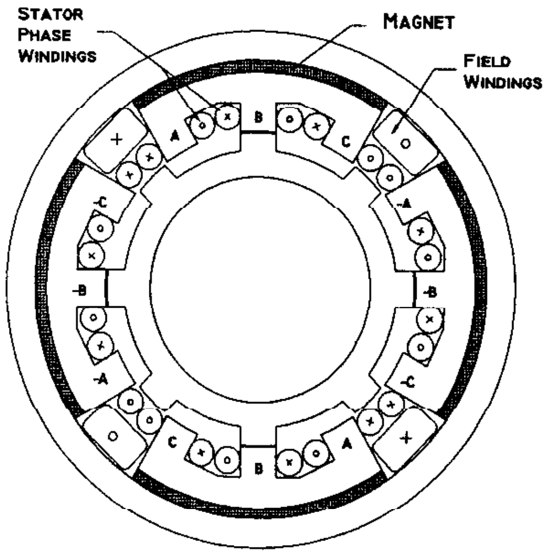

Figure 6 Doubly Salient PM 12/8 motor for high power application

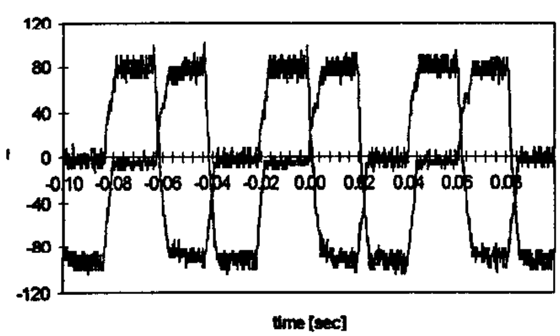

Figure 5 Phase current (Amp) waveform at low speed, rated torque

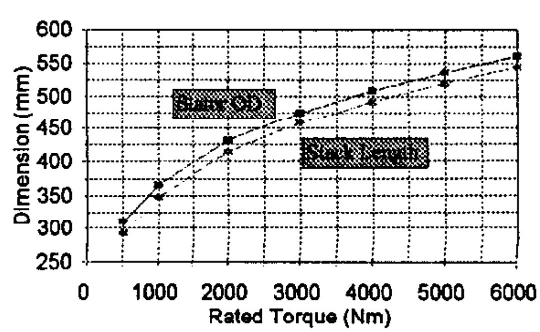

Figure 7 Size vs rated torque of a 12/18 DSPM

Conclusion

This paper has detailed the operational principles, the prototype performance and the potential of the Doubly Salient Permanent Magnet Motor, a new member of the family of PM excited AC machines. The DSPM has stator mounted permanent magnets and a stator contained field coil, the combination of which enable controlled field excitation. The rotor of the DSPM is identical to the rugged, salient, punched lamination stack used in the Switched Reluctance Motor. Due to its PM excitation efficiency advantage and its field weakening ability, this machine is an ideal candidate for traction applications.

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