Research Report

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Reluctance Motor Control For Fault-Tolerant Capability

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Abstract - A synchronous reluctance motor (SynRM) is investigated for the possibility of fault-tolerant operation. Recent work suggests that for common SynRM, fault-tolerant operation, which is important for high-performance applications, can be achieved by proper control of the currents fed to the machine to produce a satisfactory average torque. Both simulation and experiment are carried out.

I. INTRODUCTION

For high-performance applications, the capability of fault-tolerant operation is an important requirement for many applications. It is well known that switched reluctance machines (SRMs) have inherent fault-tolerant capabilities [1]-[2], however their inherent disadvantages such as ripple torque and acoustic noise are difficult to eliminate. Normal permanent magnet (PM) machines have high torque density and efficiency but have, regrettably, no inherent fault-tolerant capabilities. A fault-tolerant permanent magnet machine has been developed with an innovative deep slot structure [3]-[4] which has a similar degree of fault-tolerance as switched reluctance machines. However, there is a reduction of torque density associated with this design. Also, the thermal limitation of the permanent magnets still exert an limit on the machine performance.

In the past synchronous reluctance machines were considered to have low torque density and efficiency. However with a modern rotor structure of axial laminations, this class of machine can achieve a torque density and efficiency approaching the induction machine [4]. In addition, the torque pulsation and acoustic noise problems, so intractable in switched reluctance motors, can essentially be eliminated in a SynRM. In this paper, it will be shown that a common SynRM also has fault-tolerant capability by proper control of the currents.

II. FAULT-TOLERANT DRIVE REQUIREMENTS

The concept of a fault-tolerant drive concerns the ability to operate in a satisfactory status after sustaining a fault. The term "satisfactory" implies a minimum level of performance once being faulted. Using an EV as an example, this would be related to the ability to continue to operate at a modest speed to finish the trip or, at least reach a repair shop. The principal electromagnetic faults which may occur within the electrical drive are:

- winding and/ or power device open-circuit
- winding and/ or power device short-circuit

To develop a drive which can continue to operate with either of these faults, it is clear the most successful design approach requires a multiple-phase drive in which each phase may be regarded as a single module. The operation of any one module must have minimal electrical, magnetic and thermal influence upon the others. Thus in case of one module failure the others should be able to continue to work unaffected. This philosophy must extended to both the machine and the power converter.

Switched reluctance machine drives almost naturally satisfy these requirements. However the SynRM has appreciable electrical, magnetic and thermal interactions among phases. To meet the above requirements implies a modified structure with associated performance much like those of the fault-tolerant PM machines which would greatly reduced the cost effectiveness of the SynRM. Hence, as an alternative, it is interesting to investigate the possibility of introducing a fault-tolerant capability for the SynRM simply by means of an intelligent controller.

III. SynRM FAULT-TOLERANT DRIVE

As shown in Fig. 1, the proposed SynRM fault-tolerant drive is almost exactly the same as the conventional SynRM drive. However, it must be noted that because of the necessity of independent current control of each stator phases, the neutral access is essential, which may be selected through a switch. Also note the necessity of each single-phase bridge of converter to drive each phase of the machine. While this doubles the number of the power devices, it only marginally increases the total devices volt-ampere rating.

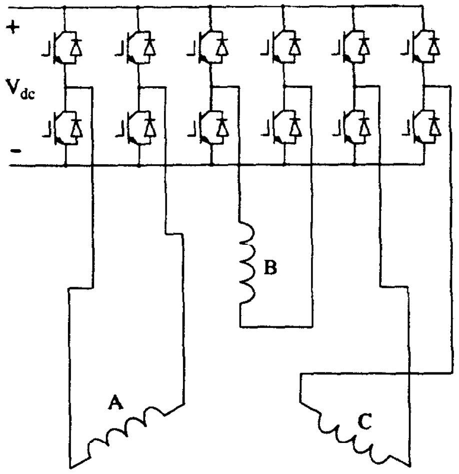

Fig. 1: SynRM fault-tolerant drive

For the case of a one phase open-circuited fault of either machine winding or power device, it is not difficult to show that the drive can be operated in a two-phase manner by control the other two healthy phases [1,2]. Roughly two-thirds of the original rated output can be produced. For the case of a converter short-circuit by one power device, it is also possible to operate the machine with two healthy phases by merely turning off the gate signal to the faulted switching device.

The most difficult scenario appears to be the condition in which a short-circuit occurs in one machine phase. In this case, the machine can not be simply operated in a two-phase manner since the strong magnetic coupling between the faulted and the healthy phases will induce significant current in the shorted phase to further damage the drive system.

The issue of single phase short-circuit fault-tolerance will be discussed in detail in this paper. The principle to be employed is to make the shorted current sufficiently small while, at the same time, producing enough torque by control the currents of the other healthy phases to satisfy the requirements of an emergency operating mode.

For a three phase SynRM, the mutual inductances between phases A and B and between phase A and C have the following form, respectively:

$$M_{ab} = -\frac{1}{2}L_0 - L_2\cos(2\theta - 120^o) \qquad (1)$$

$$M_{ac} = -\frac{1}{2}L_0 - L_2\cos(2\theta + 120^o) \qquad (2)$$

where L_0 and L_2 are constants for the SynRM, and θ is the relative position of rotor d-axis to phase A axis. Assuming phase A as the faulted phase and has been reduced to zero, the mutual flux linkage in phase A is:

$$\lambda_{am} = M_{ab}i_b + M_{ac}i_c \qquad (3)$$

where i_b and i_c are the currents in phases B and C, respectively.

Assuming that the power fed phase A is cut as result of short circuit detection the remaining i_b and i_c must be controlled to induce a constant flux linkage in phase A so as to prevent induced current in the faulted phase. In addition i_b and i_c should also capable of producing an appreciable torque.

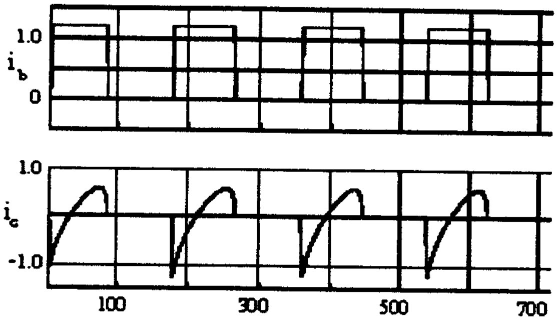

Fig. 2: Current waveforms of working phases. Currents in per unit corresponding to rotor position θ in electrical degrees.

Since induced current will flow if the flux linkage in the shorted phase should change, λ_{am} must be maintained as zero. In this case i_b and i_c has the wave forms shown as Fig. 3 constrained by the following relation:

$$i_c = -\frac{M_{ab}}{M_{ac}}i_b = -\frac{-0.5L_0 - L_2\cos(2\theta - 120^o)}{-0.5L_0 + L_2\cos(2\theta + 120^o)}i_b \qquad (4)$$

Note for every 180 electrical degrees, a range of 90 can be used to control the phase B and C currents with desired waveforms to produce positive torque. For the other 90 degrees, phase B and C currents are zero or negative torque will be produced.

IV. COMPUTER SIMULATION

A computer simulation study was carried out with MATLAB with the dynamic model of a SynRM under the condition of one phase shorted. The machine selected is a 300w machine developed at WEMPEC which has a high saliency ratio of 7.0. While this value is beneficial for normal operation, analysis shows it is not ideal for short-circuit operation. By maintaining the total loss below rated value and the phase A short current under control, the study shows that 15 percent of the rated torque output can be achieved. Figs. 3 and 4 show the currents and torque waveforms for this case, respectively. Note that during each 180 electrical degrees, an appreciable torque is produced over a range of 90 degrees. The current in the shorted phase remains very small.

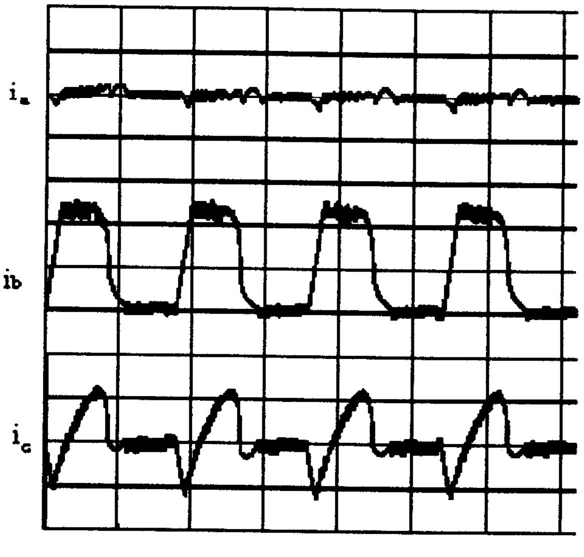

Fig. 3: Three phase currents as a function of rotor position. The amplitude of phase B current is 2.0 per unit.

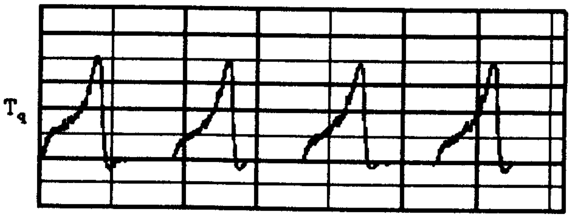

Fig. 4: Output torque as a function of rotor position. The torque ranges from -0.07 to 0.6 per unit.

The control scheme is also feasible for starting with a maximum torque load of 0.25 per unit. The starting process is shown in Fig. 5.

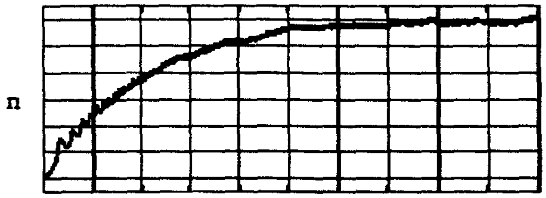

Fig. 5: Starting process with partial load. Speed from 0 to 300 rpm versus time from 0 to 10 sec.

V. EXPERIMENTAL VERIFICATION

Experimental confirmation has been realized with a Motorola 56001 DSP system and a six phase dc link converter, of which four arms are used to control the SynRM with phase *A* shorted. A dc generator is used as load. The results are in accordance with those the simulation. The three phase currents from oscilloscope is shown in Fig. 6, and Fig. 7 shows the starting process.

It should be noted that during each 180 electrical degrees, there is a range 90 degrees in which no torque is produced. Hence, the machine can not be started in this region. However before starting, the rotor can be positioned in a desired location by controlling phase B and C currents to provide a suitable spatial MMF.

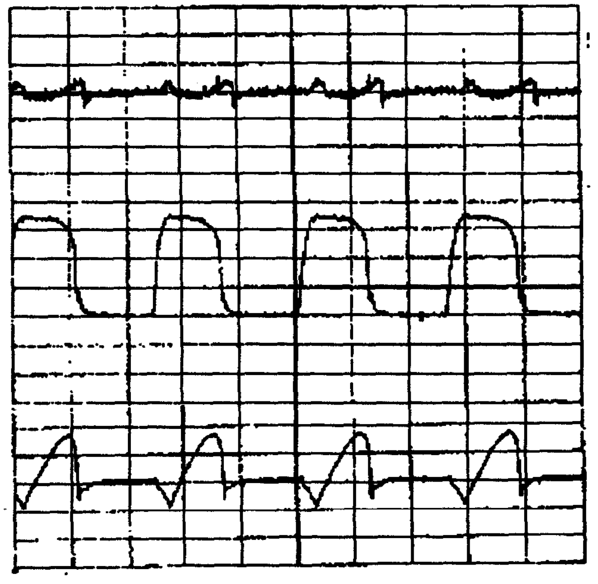

Fig. 6: Experimental results of phase A, B and C currents, from top to bottom with phase B current amplitude of 2.0 per unit.

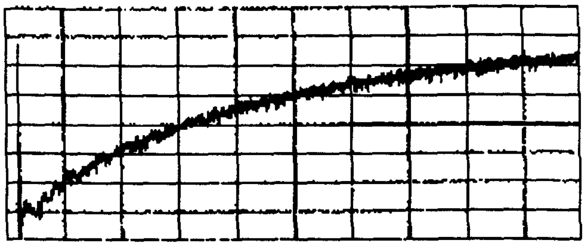

Fig. 7: Experimental result of starting process corresponding to the simulation.

VI CONCLUSION

The paper has shown that the SynRM has a certain degree of fault-tolerance by proper current control. This capability may be important in some high performance applications, such as for electric vehicles. Analysis also shows the possibility to optimize the control and thus to produce more torque. It is clear that this work also demonstrates that with any number of coils of one phase being shorted instead of an entire phase, fault-tolerant operation is also achievable.

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