Fault Analysis of Switched Reluctance Motor Drives

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Abstract[1]– **The switched reluctance machine (SRM) is uniquely reliable for its fault tolerance capabilities. More has been discussed in the literature about fault tolerance of switched reluctance machine than has actually been analyzed. This paper will present a model for various fault analysis which is general enough to be applied to any type of SRM drive as an evaluation tool. The post-fault performance characteristics of the SRM will be presented here in terms of torque and speed ripples to show its fault-tolerance capabilities.**

I. INTRODUCTION

The SRM is a prime candidate for various automotive and aerospace applications primarily because of its fault tolerance capabilities. The unique phase independence characteristics of the machine enable the SRM to operate under partial phase failure conditions. Moreover, the location of the phase windings in series with the converter phase switches makes shoot-through faults impossible in SRMs. The discussion on the fault-tolerance of SRMs in the published literature has mostly been on the conceptual level without any detailed analysis. The literature fails to provide an analytical tool to quickly analyze and predict the performance under faulted conditions. The detection and management of SRM faults reported by C. Stephens is based on experimental results only [1]. Arkadan's approach is finite element based, which is extremely time consuming [2]. Most of the results presented were machine specific and not general enough to be applicable as an evaluation tool. During faults the performance deterioration in terms of torque-speed characteristics and speed and torque ripples have never been analyzed before. This paper will present a generalized method of predicting the post-fault performance of SRMs after identifying the various faults that can occur. The fault analysis for SRMs in the motoring mode will be presented in this paper, while fault analysis in the generating mode and the excitation requirements will be presented in a companion paper.

II. DYNAMIC MODELING OF SRM

The phases in an SRM are independent and there is negligible mutual coupling between phases [3]. Therefore, the SRM can be conveniently described by its phase flux-angle-current and torque-angle-current characteristics with appropriate phase shifting for the different phases. Either the table of these characteristics obtained from the finite element analysis or the static measurements, or the analytical expressions for flux linkage $\lambda_{ph} = f_{\lambda}(i_{ph},\theta)$ and torque $T_{ph} = f_T(i_{ph},\theta)$ can be used to model the machine. The analytical models developed by Art Radun [4] has been used to model these characteristics of an SRM in this research, since the model results matched the experimental data for a series of tests that were conducted. Either the phase flux or the phase current can be used as a state variable for dynamic modeling of SRMs. Care must be taken to use the incremental inductance in the state space representation when current is used as a state variable, since saturation cannot be neglected in an SRM. The applied phase voltage in an SRM is given by

$$V_{ph} = \frac{d\lambda_{ph}}{dt} + i_{ph}R_{ph}. \tag{1}$$

The *di/dt* expression for the state variable i_{ph} can be derived from the above equation as follows

$$\frac{di_{ph}}{dt} = \frac{1}{\partial\lambda/\partial i}\left(V_{ph} - i_{ph}R_{ph} - \frac{\partial\lambda}{\partial\theta}\omega\right) \tag{2}$$

where the incremental inductance $\partial\lambda/\partial i$ and $\partial\lambda/\partial\theta$ can be easily derived from the closed form expression of $\lambda(i,\theta)$ given in [4]. The phase torque in SRM is obtained from the co-energy W_m', which can also be calculated from the phase flux linkage using the following expression.

$$T_{ph} = \left.\frac{\partial W_m'}{\partial\theta}\right|_{i=cons.} \quad \& \; W_m'(i_{ph},\theta) = \int_0^i \lambda_{ph}(i',\theta)di' . \tag{3}$$

The required expressions have been derived through simple algebra and a symbolic package, but not included here because of their length. However, the derivation is straightforward as outlined here. The superposition of the individual phase torque gives the total electromagnetic torque T_e with m number of phases.

$$T_e = \sum_{j=1}^{m} T_{ph}(i_j,\theta_j). \tag{4}$$

The mechanical part for state space representation of the electromechanical system is

$$\frac{d\theta}{dt} = \omega \; and \; \frac{d\omega}{dt} = \frac{1}{J}\left(T_e - T_L\right). \tag{5}$$

Equations (2) and (5) represent the state space model of the SRM with i_{ph}, θ and ω being the state variables.

[1] This work was supported by grants from the National Science Foundation (grant No. ECS 9702370) and the Ohio Board of Regents.

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III. SRM DRIVE

A 3-ϕ 6/4 SRM [4], a 2-switch per phase bridge converter topology and a PI speed controller have been chosen as the SRM drive system. A block diagram of this drive system is shown in Fig. 1.

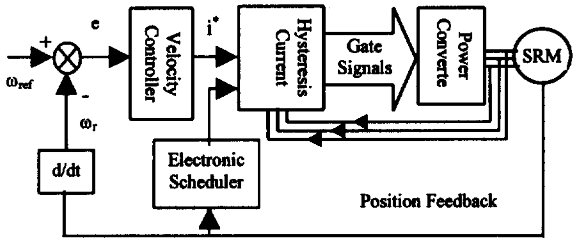

Fig. 1: Block diagram of the SRM Drive.

The controller has an inner current control loop and an outer speed control loop. The velocity controller generates a current command based on the error between the reference speed and the motor speed. A proportional-integral (PI) compensator has been used inside the velocity controller. An electronic scheduler identifies the most appropriate phase for positive torque production. The current in the designated phase is regulated at the reference level by hysteresis control. A torque ripple minimizing algorithm or torque/ampere maximizing algorithm could have been added to the controller for control sophistication and further analysis. The following section on faults outlines all the modifications that has been carried out to simulate faults in the system.

IV. FAULT MODELING

The faults in a SRM can be broadly classified as machine faults (a. armature phase open, b. armature phase short, c. partial phase short and d. multiple phase fault) and converter faults (a. phase switch open, b. phase switch short, c. multiple phase fault and d. DC voltage drop). A brief description of the SRM faults are presented below.

A. Armature Phase Open

When phase winding in a SRM is open, no excitation is available to that faulty phase and there is no further contribution of torque from that phase. The controller increases the demand from the remaining healthy phases to maintain the constant speed. The machine adapts to the faulty situation with increased torque and speed ripples. The phase winding may open due to manufacturing defects or burnout of a weak link within the winding. Simulation of armature phase open can be conducted by disconnecting the gate signals to the faulted-phase at the instant of fault.

B. Armature Phase Short

Armature phase may be completely or partially shorted due to the insulation failure. In case of short circuit, a high current limited only by the contact and winding resistances will flow through the faulted phase during the designated conduction period. Eventually, the switch of the converter fails or a fuse in series with the winding/switch blows out and the faulted-phase stops producing torque. During the time when the fault occurs and the fuse blows out, the speed of the machine may increase or decrease drastically depending on the timing of fault occurrence. Once the transient is over, the remaining healthy phases maintain the constant speed again by increasing their torque contribution to the system. The complete short situation of a phase can be simulated by replacing that particular phase by a short circuit resistance value.

C. Converter Switch Open

When a switch in the converter is open-circuited, it stops supplying excitation current to the corresponding phase winding. This case is similar to the armature phase open case and can be simulated by stopping gate signals to that phase at the instant of fault.

D. Converter Switch Short

When a switch in the converter is short-circuited, the corresponding phase winding receives continuous excitation irrespective of the rotor position and controller logic. This faulty excitation results unlimited current through the phase supported only by the small winding resistance and back-emf of the machine. Eventually, the switch or the fuse blows out and the faulted-phase stops producing further torque. In a converter with bridge topology of two switches per phase, both the switches of the phase are to be shorted for the short circuit fault. So, the scenario of faults depends on the converter topology used, since a wide variety of converter topologies are available for SRM.

E. DC Voltage Drop

When the supply DC voltage drops, the speed decreases momentarily and then returns to the previous value drawing more line current from the source. The line current increases to compensate for the decreased supply voltage, and hence, to satisfy the input-output power conservation relationship at a constant speed. However, speed regulation is only possible up to a certain maximum amount of voltage drop. If the supply voltage drops below the maximum limit, the phase current reaches its upper limit and the speed settles at a value lower than the commanded speed.

V. RESULTS

The performance characteristics of SRM under different machine/converter faults are presented here showing the waveforms of motor speed (rpm), net torque (N-m), and torque and current (A) in the faulty/healthy phases. The machine analyzed is a 3-phase, 6/4 60 kw SRM. The rated voltage is 270 volts. All the faults were simulated at a rated constant speed of 1500 rpm with a load torque of 10 N- m. Results for the faults of armature phase open and armature phase short are given here.

A. Armature Phase Open

Fig. 2 shows the simulation results for the armature phase-open condition that occurs at 0.2 sec during steady state

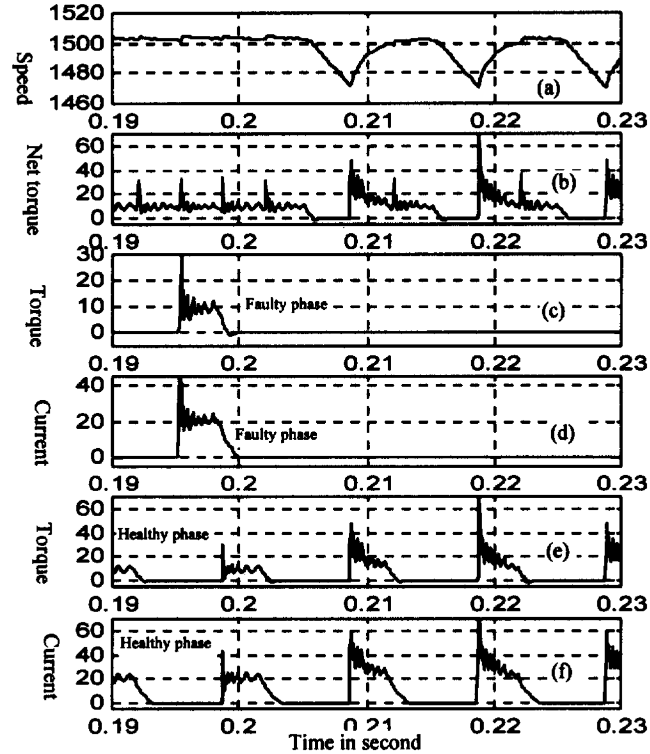

Fig. 2: Waveforms of SRM with one of the armature phases 'open' (fault occurred at t=0.2 sec). (a) speed response. (b) Net torque response. (c) Torque at the faulty phase (d) Current at the faulty phase (e) Torque at the healthy phase (f) Current at the healthy phase.

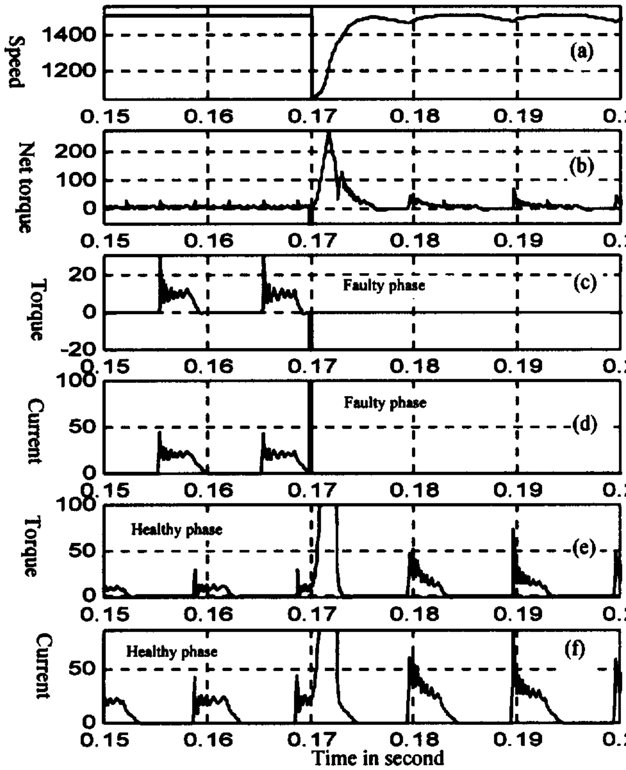

Fig. 3: Waveforms of SRM with one of the armature phases 'short' (fault occurred at t=0.17 sec). (a) speed response. (b) Net torque response. (c) Torque at the faulty phase (d) Current at the faulty phase (e) Torque at the healthy phase (f) Current at the healthy phase.

operation in one of the phases. Fig. 2(a) shows that the speed ripple increases from 0.2% to 2.33% due to the open circuit fault. Fig. 2(b) shows an increase in torque-ripple from 12 N-m to 43 N-m. The current as well as the torque developed by the faulted phase becomes zero after 0.2 sec and the remaining healthy phases increase their contribution as shown in Fig. 2(e).

B. Armature Phase Short

Fig. 3 shows the simulation results for the armature phase short condition in one of the phases that occurs at t=0.17 sec during steady state operation. Due to this fault the speed ripple increases from 0.2% to 2.35% and the torque-ripple from 25 N-m to 55 N-m. The current as well as the torque developed by the faulted phase becomes zero after the fuse or the device blows out in the shorted phase. At t=0.17 seconds there is a large impulse current that flows through the faulted phase. The speed at that time significantly decreases due to the fact that the short circuit current produces a very high breaking torque during that time. The motor then speeds up to 1500 rpm when all the other healthy phases are taking extra load to meet the net torque demand.

C. Other Faults

Further analysis showed that the machine was able to maintain constant speed up to a DC voltage drop of 40%, although with higher speed and torque ripples. A DC voltage drop of 60% reduced the speed by 40%. The speed dropped 80% due to a DC voltage interruption for 0.06 secs. The speed regained its steady state value when the interruption disappeared. An earth fault at the mid-tap position of a phase winding was also simulated. The steady state speed reduced by 50% due to the earth fault.

VI. CONCLUSIONS

The fault simulation methodology presented here makes it possible to investigate speed-ripple, torque-ripple, dynamic response, drive stresses etc. under various fault conditions in an SRM. The procedure is general enough to be applied to any type of SRM drive. The analysis showed that the SRM is capable of operating under various fault conditions, although the performance deteriorates.

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