

Simulation of Faults by means of Finite Element Analysis in a Switched Reluctance Motor

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Abstract

The influence of the presence of errors in the behavior of a switched reluctance motor is investigated in this paper. The dynamic response of a Switched Reluctance Motor (SRM) is analyzed by the coupled structural and electromagnetic Finite Element Method (FEM). The dynamic behavior of the motor under failure operation can lead us to non-invasive diagnosis of faults and rotor eccentricity in switched reluctance machines by monitoring the dynamic response of the system (Torque and Speed).

1 Introduction

In many safety critical applications it is desirable to have a drive which is fault tolerant. It is often assumed that the Switched Reluctance Motor (SRM) will be ahead in the election for a fault tolerant system as it possesses unique characteristics that promote the motor for fault tolerance capability – the ability to continue operation despite faulted motor windings or inverter circuitry.

The SRM itself consists of a stator with an even number of poles that can be energized and a rotor made of a ferromagnetic material. The motor operates by energizing the stator and establishing the magnetic flux that links the rotor structure. As a result, a torque is produced that aligns the closest poles of the rotor with those of the energized stator poles. To maintain rotation, the current stator poles are deenergized and the next sequential pair is energized.

The SRM possesses the fail-silent property, i.e. after one or several failures the drives exhibit quiet behaviour externally so that they stay passive by switching off, and therefore do not wrongly influence other components of the system. It also can operate under faulty phases. This capability is possible in the SRM for machine designs having high number of poles per phase, or for machines controlling individually the poles or pole pairs of every phases. These two characteristics demonstrate the validity of this drive as an ideal failure tolerant actuator.

The Switched Reluctance Motor drive system consists of the reluctance motor, the power converter, the rotor position detector and the controller. In the design of a fault tolerant system, the control should be based on a good knowledge of the operation of the reluctance motor drive under normal and fault conditions. Therefore, all the faults that can occur in the entire system have to be considered. There are no electrical faults in the rotor of the Switched Reluctance Motor drive since there is no magnet, no brushes and no windings in the rotor, but mechanical defects can lead the rotor to eccentricity (both static or dynamic). The concentrated windings of the stator may cause electrical faults in it, such as inter-turn short circuits, inter-phase short-circuits, ground short-circuits or open circuit. Overheating, over current or over voltage on the main switches and the freewheeling diodes are the principal cause of damage in the power converter. Also, electrical faults in the rotor position detector can produce errors in the trigger of the main switches and the drive could not be commutated normally. Intern-turn short circuits and eccentricity become the critical faults for the machine, as they are the most frequent and considerably reduce the performance of the machine, leading also to machine breakdown.

Scarce bibliography was found reporting failures in SRM, but concerning the simulation of some of them good examples can be found (Arkadan & Kielgas 1994, Sharma & Murthy 1998, Stephens 1991). Non-invasive monitoring techniques in order to diagnose problems within this machine have been studied by several authors. Switched Reluctance machines are inherently susceptible to noise and vibration by the nature of their torque production. Therefore, many papers are based on this property to detect the presence of failures (Anwar & Husain 2000, Anwar & Husain 2001, Colby & Mottier 1996) although only focused in the radial force calculation.

In this paper, a method to predict the performance characteristics of SRM drive systems under internal fault operating conditions (those related only to the motor) is presented. The paper shows a model where the performance of the motor, through a finite element analysis, can be studied under several fault scenarios. Four different situations are studied:

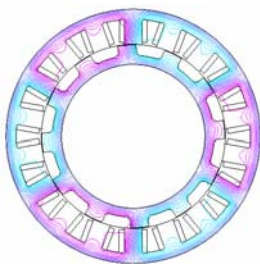
- Normal operation
- Non-centered rotor operation caused by static eccentricity
- Non-centered rotor operation caused by dynamic eccentricity
- Opened-Phase during operation

The paper also outlines a model that could identify characteristic dynamic responses of the system due to the considered failures. These responses can be used to diagnose problems in the switched reluctance machine. We will concentrate in the motor specific characteristics, as well as on the characteristics of fault simulation, detection, diagnosis and management of the failures in the machine.

2 Analysis Procedure and Model

While an analytical model would give estimations for the response of the system, a finite element analysis is required to obtain more accurate results due to the inherent non-linearity of the motor. Since the past showed the fact that the implementation of prototypes is very time consuming, it is tried in a first step to handle the questions by means of simulations, characterizing the typical failures by means of Finite Element Techniques.

Our modeling environment consists of two main components. The first is a Finite Element FEMLAB Model of our 18/12 SR Motor (Figure 1) to represent the inherent non linear electro-magnetic behavior of the motor. The second component is a Simulink model to simulate the dynamics of the system. The dynamics are expressed in the equations (1) and (2).



$$V = Ri + \frac{d\psi(\theta_m, i)}{dt} = Ri + \frac{\partial\psi(\theta_m, i)}{\partial\theta_m} \omega_m + \frac{\partial\psi(\theta_m, i)}{\partial i} \frac{di}{dt} \quad (1)$$

$$T_e - T_l = J \frac{d\omega_m}{dt} + B\omega_m \quad (2)$$

Fig. 1. Electromagnetic Analysis of the 18-12 SRM

V represents the terminal voltages for all phases of the SRM, i is the phase current, R gives the phase resistances, ω_m is the mechanical rotational speed, θ_m is the rotor position, t is the time and ψ is the flux generated in the motor. The first term of the right hand side of (1) represents the resistive (Ohmic) voltage drops in the windings, the second term represents

the energy storage (transformer voltage component), and the third term represents the effects of motion (rotational voltage component). The inductances vary nonlinearly as a function of rotor position and load condition and their values are computed using finite element methods. The torque and rotor speed relations are expressed in (2) where T_e is the developed torque, B is the viscous coefficient of friction, J is the inertia of the motor and T_l is the load torque.

The data obtained from the Finite Element Model as an interpolation table are introduced in the previous equations through MATLAB/SIMULINK, as usually done by other authors (Miller 1993, Miller 2001, Stephenson & Corda 1979, D'hulster & Belmans 2003, and Soares & Branco 2001) but unlike them, torque and flux data during a failure are also computed. **a**

Under fault conditions, the values of L and R change, reflecting changes in currents required to maintain the desired level of operation. SRM's are highly nonlinear devices because the magnetic materials go in and out of saturation as the SRM operates, as well as due to changing winding inductances as a function of currents and rotor position. Further, operating the system under fault conditions results in different behaviours because the motor is operated at more extreme quiescent points. It should be noted that any change in parameters, operating conditions, or system topology requires repetition of the finite element field analysis and state space simulation. The estimated engineering effort required to set up each simulation is approximately one day.

3 Faults Analysis

The prediction of the flux-linkages and its variation with the current and position as well as the torque contributions, (see figure 2), in every phase as a function of the angle and current is needed to determine the magnetic and mechanical behaviour, which is required for the current control strategy.

The variation of the geometrical and/or construction characteristics (conductivity and permeability of the material, number of turns in the coil, coils full-factor), the range of work of the motor (intensity of the current and speed) and the introduction of the electrical and/or mechanical conditions derived from the presence of errors will be introduced in the Finite Element Model to obtain the different performances of the motor.

Four cases are studied:

- Normal Operation, with the motor rotating at 500 rpm
- Eccentric rotor with several displacements (25, 50 and 75%) from the centred position at $t=0$ sec exhibiting static eccentricity
- Eccentric rotor with several displacements (25, 50 and 75%) from the centred position at $t=0$ sec exhibiting dynamic eccentricity
- Open-phase during operation

Internal Faults are simulated through the Finite Element Analysis, introducing the data of the defects in the previous Finite Element Model and connecting this data with the Power Electronic part of the model to observe the dynamics of the system under fault conditions.

3.1 Normal Operation

When the machine is operating normally, with no faults, the flux and the characteristic torque produced by the SRM look as follows:

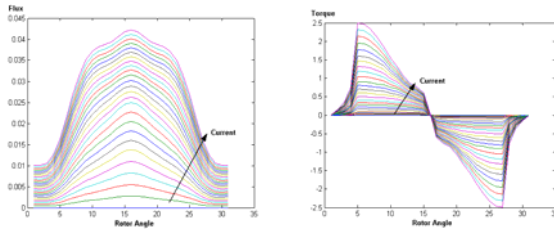


Fig. 2. Flux and Torque Characteristics in Normal Operation

We introduce this data in our system (SRM + Control), that is developed to achieve flat torque response. The load of the system is 0.5 Nm. As seen in Figure 3 the response of the system is as expected, when the rotor is centred and no faults applied. After the transient start-up, the system reaches the steady-state.

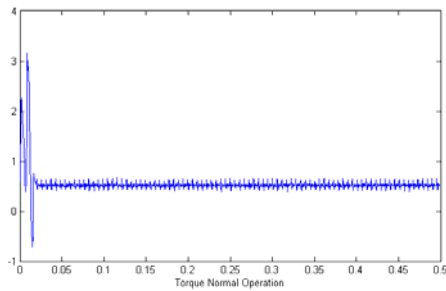


Fig. 3. Torque under Normal Operation

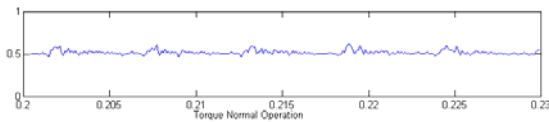


Fig. 4. Ripple in the Torque

However a small ripple can be observed in the torque response. The torque ripple is a typical characteristic of the SRM and one of their biggest disadvantages, while several control models are developed to correct it. If we make a zoom into the Figure 3, we can observe (see Fig. 4) the mentioned ripple, which is around 10% average, acceptable and normal for this kind of motors.

3.2 Static Eccentric Rotor

In this case, the machine is operating with a rotor in an eccentric position. Figure 5 illustrates a motor whose rotor axis is moved 0.075, 0.15 and 0.225mm right from its original position, what represents a 25, 50 and 75 % of eccentricity (A zoom in opposite poles is made to appreciate the displacement).

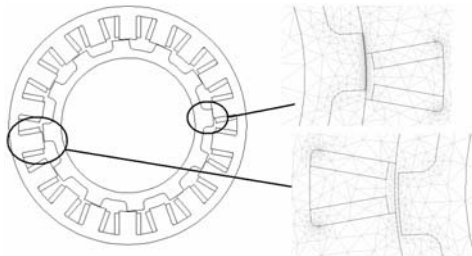


Fig. 5. Zoom on opposite poles in an eccentric motor

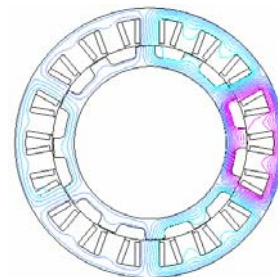


Fig. 6. Electromagnetic behavior in an eccentric rotor

The rotor is rotating on its own axis - this is termed static eccentricity. Analyzing the electromagnetic response, the first thing that can be observed in Fig 6 is that the density of the flux lines is higher in the right section of the motor. This is because the reluctance in the

right section of the airgap is now less. The concentration of flux in one side will produce a bigger attraction force in this direction and the peaks in the torque will be bigger.

Flux and torque data of the eccentric motor are also computed in the new model (Fig. 7) in order to introduce them in the dynamics model.

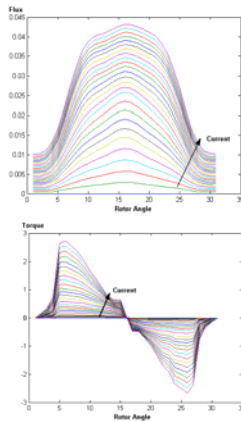


Fig. 7. Flux and Torque Characteristics with 50% of Static Eccentricity

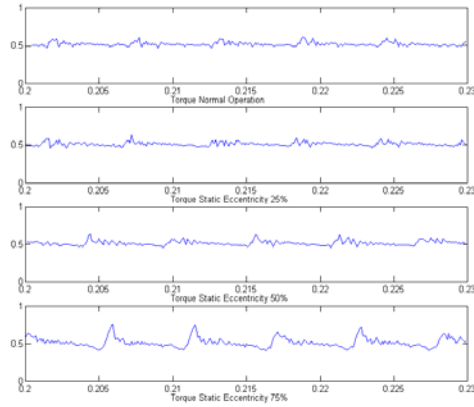


Fig. 8. Torque under Normal and Static Eccentricity Operation

Eccentricity is just a mechanical defect so no modification has to be made in the power electronics part. Figure 8 shows the torque response of the system under three different grades of eccentricity. We can observe that with bigger percentage of eccentricity, the ripple becomes also bigger, what can be dangerous for the system.

3.3 Dynamic Eccentric Rotor

In this case, the machine is operating also with a rotor in an eccentric position. Again the rotor axis is moved 0.075, 0.15 and 0.225 mm right from its original position, but now the rotor is rotating on the stator bore axis rather than its own axis – this is termed dynamic eccentricity. The density of the flux lines is still higher in the right section, but even higher as in the Static Eccentricity analysis and this is also reflected on the dynamic response of the system as the ripple of the torque is greater. Figures 9 and 10 show the re-calculated flux and torque characteristics of the motor and the dynamic response of the system under three different grades of dynamic eccentricity.

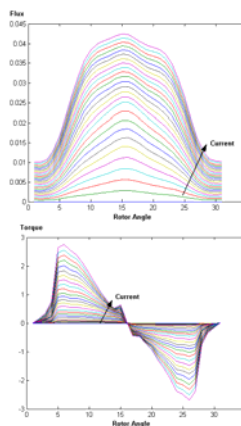


Fig. 9. Flux and Torque Characteristics with 50% of Dynamic Eccentricity

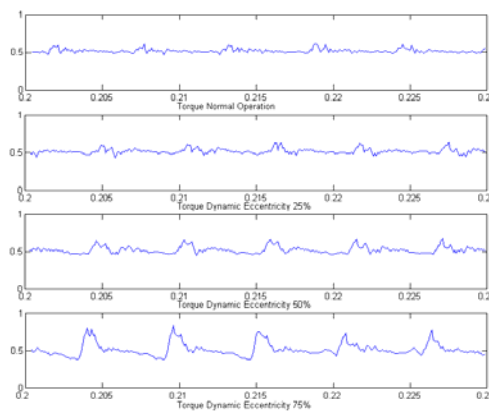


Fig. 10. Torque under Normal and Dynamic Eccentricity Operation

3.4 Opened-Phase

For the simulation of this fault, no modification has to be done in the Finite Element Model, but only in the power electronics circuit. The simulation starts in Normal Operation and after a preset time, one phase is deactivated. Later on the simulation, a second phase is deactivated too. Figure 11 shows the huge increase of the ripple as the two phases are deactivated.

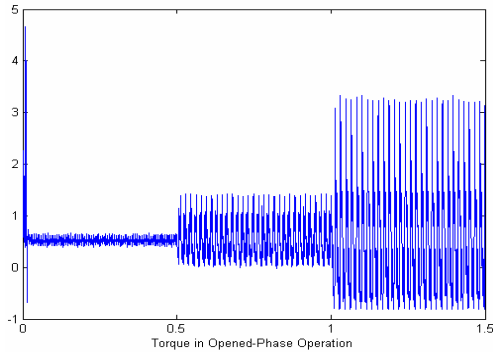


Fig.11. Torque under Operation with Deactivated Phases

4 Conclusion

This paper has illustrated the behaviour of an SRM under four different situations, including three different fault conditions. A torque dynamic response has been observed during the fault operations and its ripple has been also been recorded. Future work will involve the identification of characteristic ripple increasing associated with these fault and its quantification. In this way fault diagnosis tools can be developed, so that our system can manage them and adapt its control to the failure operation of the motor under fault conditions, achieving a real fault tolerant system. Dependent on the received results, these are to be validated by the construction of prototypes in a future step, as a SRM drive with an implemented fault detection and management system should be an ideal selection for reliability-premium drive systems in aerospace, industry and automotive.

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