Fault Detection in Switched Reluctance Machines

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Abstract* – Switched reluctance machines (SRM) are widely used in safety-critical applications due to their well-known inherent fault tolerance abilities. Despite of this some faults are possible to occur, hence fault detection circuits can be useful components of the SRM's control system. The first part of the paper is an overview of the SRM's faults and their detection systems. Also the causes and the effects of the most typical faults are detailed. In the second part the effects of the SRM's winding faults are studied by means of advanced co-simulation techniques.

***Keywords:* switched reluctance machine winding faults, fault tolerance, fault detection, numeric field computation, co-simulation.**

I. INTRODUCTION

Switched reluctance machines (SRM) are inherently fault tolerant due to the high number of poles per phase which allows for individual control of the coils or of the coil pairs. Therefore they can continue their movement also having one or more faulty phases [1], [2]. The winding or power converter faults cause only a power reduction of the machine proportional to the number of faulted phases out of total phases and inherently the increase of torque ripple.

The brushless and permanent magnet free rotor construction of the SRM enables a maintenance free utilization at high temperatures even in dusty, dirty and vibrations exposed harsh environments [3].

The SRM can be used either as a motor or as a generator in automotive and aerospace applications, including advanced industrial drives, actuators, adjustable speed drive systems and integrated starter-generators.

It also possesses fail-silent properties, 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.

In the literature several fault tolerant SRMs are cited. Also the post fault analysis on several fault occurrences for further evaluation of the SRM abilities, respectively fast and accurate fault predictions methods upon the performance of the SRM under normal and faulty operations had been studied [4].

II. FAULTS OF A SRM DRIVE SYTEM

A SRM drive system (see its block diagram in Fig 1) consists of the motor, the power converter, the rotor position detector and the controller [2].

Practically almost all the components of an electrical machine are susceptible to failures (windings, bearings, etc.).

In this complex system any of the components can fail. In the paper the machine faults are presented in detail.

Unfortunately no statistical data on SRM faults could be found in the literature. Hence the induction machines failing statistics should be considered also in this case. The squirrel cage induction machine's most frequent fails are in the stator winding (30%) and in its bearings (40%) [5], [6]. This data can be extrapolated also for SRM. Therefore it can be stated that the most frequent fails of a SRM are the winding and the bearing faults.

The windings can have several faults [7]:

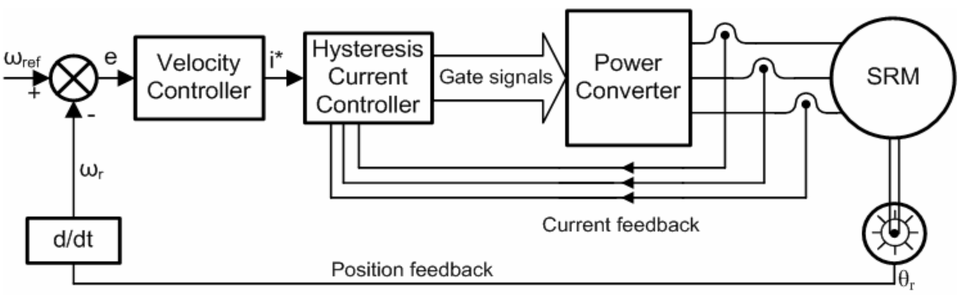


Fig. 1 Block diagram of a SRM drive system.

i) open phase
ii) short phase
iii) partial short phase
iv) multiple phase faults.

In [8] a more detailed classification of the winding faults is given:

i) short circuit in one winding of a phase
ii) a whole winding is bridged by a short circuit
iii) the whole phase is short circuited
iv) open circuit in one winding of a phase
v) a short circuit between two different phases
vi) a short circuit from one winding to ground.

The windings failures may be caused by mechanical vibration, heat, age, damage during installation, power converter fails, etc.

Machine bearings are subject to excessive wear and damage caused by inadequate lubrication, asymmetric loading, or misalignment. All the components of a bearing can fail: the outer and inner race, the rolling element and the cage. The most typical bearing damages are numerous: flaking, peeling, spalling, smearing, creeping, stepped wear, speckles and discoloration, indentations, chipping, cracking, seizing, fretting and fretting corrosion, electrical pitting, rolling path skewing, damages of the retainers, etc. [9]. A correct maintenance plan can assure a long life for the machine's bearings.

Mechanical unbalance due to different eccentricities can arise when the rotor is not properly centred in the stator, giving rise to different air-gap lengths on opposite sides of the machine. In these cases the machine will strongly vibrate [10].

In a SRM drive system mainly 3 types of converter faults can occur [2]:

i) A switch in the converter is open-circuited
ii) A switch in the converter is short-circuited
iii) The supply DC voltage drops

In some circumstances also the control circuits can fail [4].

III. EFFECTS OF THE FAULTS

The main effect of an open winding fault in a SRM consists of the loss of torque production from one phase or more [8]. The flux can become unbalanced due to different magnetic pull between healthy and faulty phases. The converter can suffer from short or open circuits which lead to the reduction of the torque from the associated phases, etc. Also some comfort effects can rise up in terms of noise, vibrations, usually due to rotor eccentricity etc. Further analytical studies on torque reduction can be found in [8].

In case of short circuit a very high current will flow through the faulted phase during the designated conduction period. Hence the switch of the converter can also fail due to the high current, or in better case a fuse, if exists, in series with the winding or the switch blows out. In this case the faulted phase stops producing torque in a similar manner as in the case of an open circuit [11].

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 regime is over, the remaining healthy phases have to maintain the constant speed by increasing their torque contribution to the system [4].

When dealing with an eccentricity of the rotor, apart from the noise and vibration factors, the concentration of flux in one side will produce a bigger attraction force in this direction and the ripples in the torque will be bigger.

Several converter fault were described in detail in [11].

IV. FAULT DETECTION

The winding faults of the SRM can be sensed by several failure detectors [12]. In the paper three such devices are presented [13].

Due to its less complicated construction than of other machines, very simple fault detection devices can be applied for SRMs, such as the overcurrent detector given in Fig. 2. The detector is explained in details in [14].

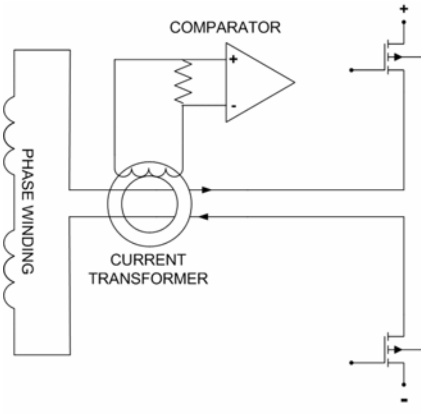


Fig. 2 The current differential detector

Its efficiency is limited due to insufficiently fast response time and the inability to detect all types of faults.

Another simple detector, the flux differential one is given in Fig. 3 [14].

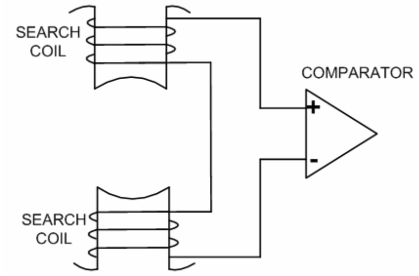


Fig. 3 The flux differential detector

This detector can sense ground faults, phase-to-phase faults, and the shorted-turn faults, which cannot be detected by the overcurrent detector. However, this one is oversensitive and requires additional coils to be placed on poles.

Therefore combined use of the two detectors mentioned above is suggested in the literature.

The third detector in study, the rate-of-rise one, shown in Fig. 4, consists of a linear magnetic coupler placed around the upper phase-winding lead with the core being made of a magnetic material, linear in the range of operation. The output voltage of the linear coupler is proportional to the time-rate-of-change of the phase current [14].

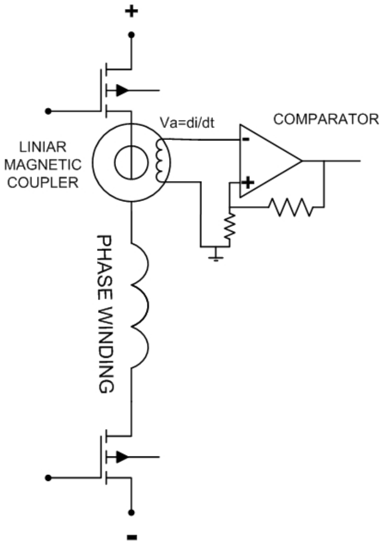


Fig. 4 The rate-of-rise detector

V. THE SIMULATIONS

In the paper a simple 8/6 SRM structure (given in Fig. 5) was studied by means of simulation.

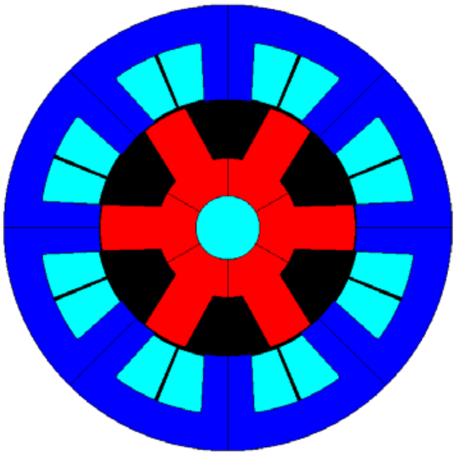


Fig. 5 The 8/6 SRM structure in study

The machine has 8 concentrated coils wound around each stator pole. Two coils from opposite poles are adequately connected together to form a phase. Hence there are 4 phases. This structure was selected for the simulations because it is very common and having four phases is more fault tolerant than the three phased variants.

The SRM's power converter (see Fig. 6) has a separate half H-bridge leg for each coil of every stator pole in order to be able to control each one independently, as requested by the fault tolerant design.

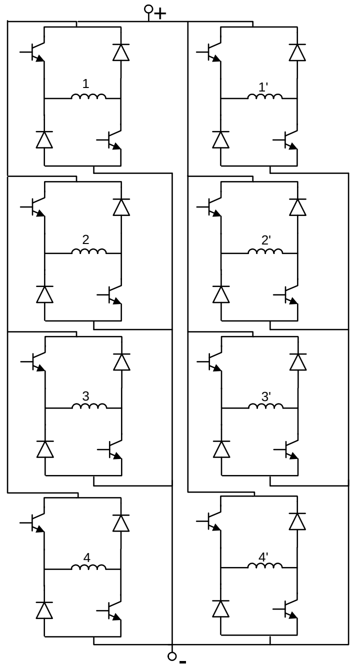


Fig. 6 The power converter

The control system of the SRM has the ability to detect the fault, to isolate and remedy it, in such a way as the fault to have as little influence as possible on the SRM. In the fault tolerant concept, this is the main imposed task for a drive.

The simulation program was built up using two specific software packages.

Flux 2D program was used for modelling the machine using finite element method (FEM) based numeric field computations. The MATLAB-Simulink environment was applied for modelling the power converter's control system and to generate the faults for the different working conditions taken into study [15].

A current differential fault detector was added to the control system.

The mesh generated automatically by Flux 2D is shown in Fig. 7.

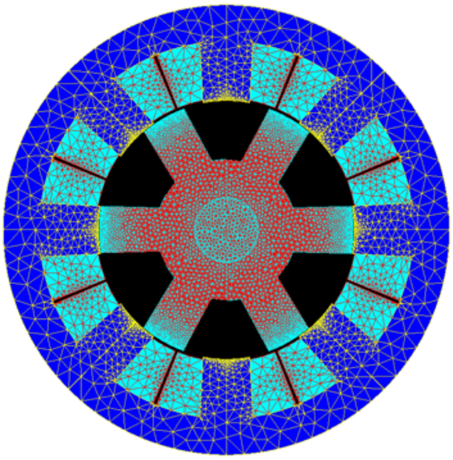
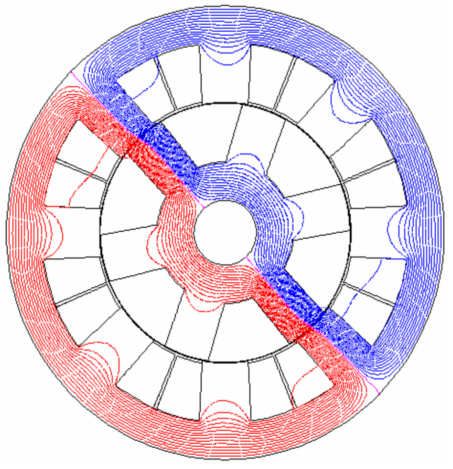
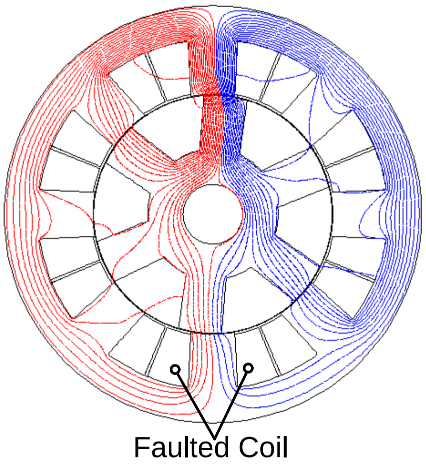


Fig. 7 The mesh generated by Flux 2D

To emphasize the effect of an open coil on the magnetic flux distribution in the machine the flux lines for the healthy machine and for one having an open coil are given in Fig 8.



a) healthy machine



b) machine having one open coil

Fig. 8 Flux lines in the SRM obtained via Flux 2D

As it can be seen in the healthy machine due to the two oppositely placed coils fed, the magnetic flux lines are concentrated through these two poles.

If one of the two coils is opened the flux generated by the single fed healthy coil is distributed through the three poles being overlapped with the rotor poles. Unfortunately two of these poles are generating negative torque, hence the overall performance of the machine is reduced.

This harmful effect can be diminished by increasing the fault tolerance of the machine [16].

The dynamic behaviour of the machine and its power converter was studied by means of co-simulation, by coupling together the Flux 2D model of the machine with the Simulink model of the control system and of the power converter. The two programs were linked together by means of the advanced Flux-to-Simulink Technology [17]. This way practically the FEM model of the SRM is embedded in the main Simulink program.

The main window of the simulation program is given in Fig. 9. A similar simulation program was described in detail in [18].

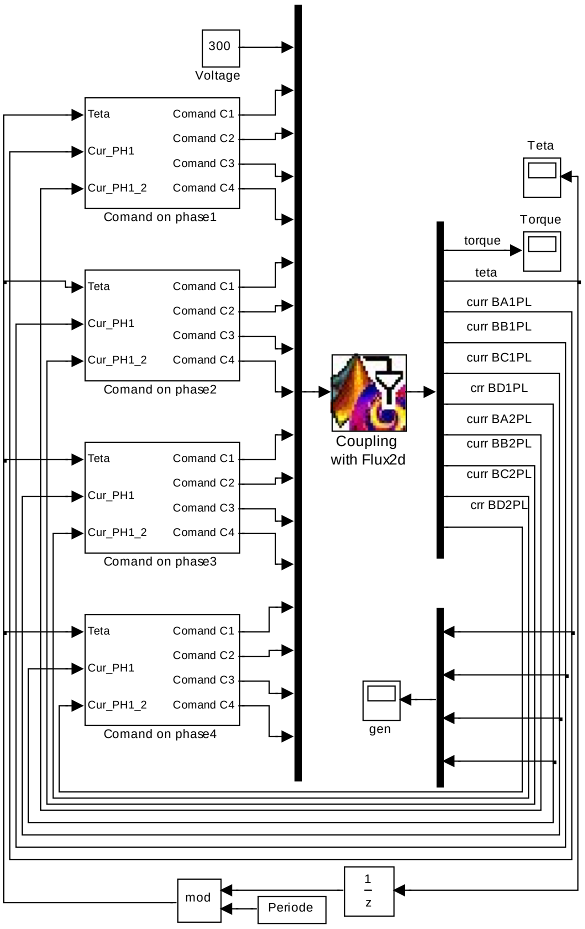


Fig. 9 The main window of the simulation program

In this program a supplementary fault detection block was added. In order to be able to study the effects of the fault all the currents from each phase was monitored. The sub-system of this fault detection block is given in Fig. 10.

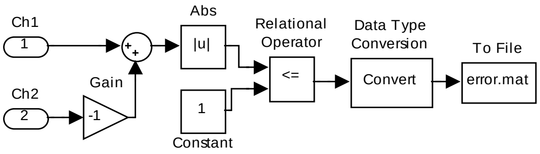


Fig. 10 The fault detection sub-system

A threshold of 1 A was established as the difference tolerance between the currents in the coil pairs monitored. The logical signal of the fault is saved in a separate file (*error.mat*).

The simulation time was set 0.03 s. Both the healthy and one open coil conditions of the machine were taken into study. At 0.005 s a first coil is open and at 0.015 s a second one.

The simulation took roughly 10 hours on a PC equipped with a Quad Core processor and 4 GB of RAM memory.

The results of the simulations are given in Fig. 11. The currents in the two faulty channels, the logical output of the two fault monitoring units and the torque of the SRM in study are plotted versus time.

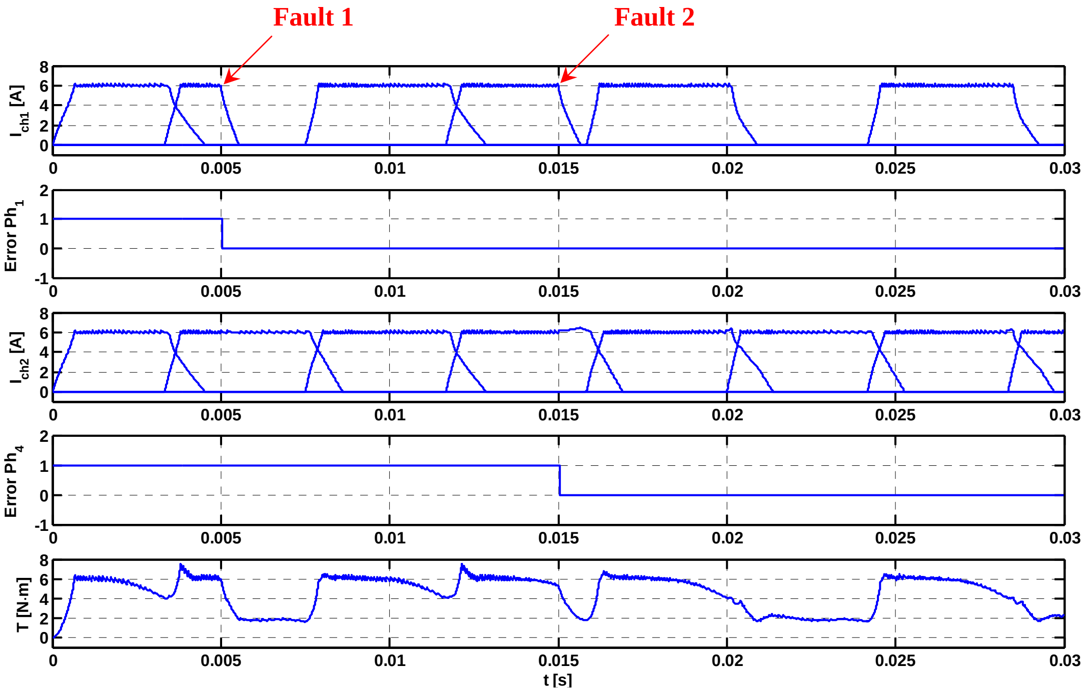


Fig. 11 Simulation results

As it can be seen both winding damages are sensed by the fault detection circuits (see the $ErrorPh_1$ and $ErrorPh_2$ signals).

The presence of a transitory regime after both winding faults can be noticed. During this the current in the opposing channel increases over the normal values.

VI. CONCLUSIONS

Although the SRM is inherently one of the most fault tolerant electrical machines several faults can decrease its performances.

In the paper the possible faults, their effects and three fault diagnosing circuits were summarised.

The behaviour of the SRM during open coil faults was studied by means of simulations.

The applied simulation program, a coupled one connecting two software platforms (Flux 2D and Simulink) was useful in studying the effects of the winding faults on the torque developing capacity of the SRM. The computing power of Flux 2D thus joined the facilities of Simulink in simply describing the different working regimes of the SRM drive system taken into study.

This paper provides a list of the possible faults within the SRM drive system, their causes, direct effects and a simulation illustrating a very common fault which might occur within the system. Future research involves testing different topologies by means of simulation under different fault regimes in order to increase the level of fault tolerance in the SRM.

To improve the fault tolerance capacity of the SRM several solutions can be adopted.

A first solution could be the multiplication of poles and phase numbers. Having more phases the SRM could more easily overrun the positions corresponding to the poles with open windings.

An other way to further enhance the fault tolerant capacity of a SRM is to increase the redundancy of the windings, respectively the converter configurations. The simplest solution is to double each coil. The doubled coils can be connected in parallel to more increase the fault tolerance of the SRM.

Future works regard changes in the machine's structure (new placement and connection scheme of the windings), improvement of the fault detection circuits and the development of an advanced intelligent control system (based on complex bio-inspired electronic architectures), which will be able to detect the faults, to isolate them and to act upon the power converter in such a manner as to diminish the negative effects of the faults.

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