ON FAULT TOLERANCE INCREASE OF SWITCHED RELUCTANCE MACHINES

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Abstract: **The Switched Reluctance Machine (SRM) is ideal for safety critical applications (aerospace, automotive, defense, medical, etc.) where it is desirable that the electrical drive system to be fault tolerant. The phase independence characteristics of the SRM enable it to operate (at lower power and higher torque ripples) also under partial phase failure conditions. Its reliability can be improved during its conception stage by applying special fault tolerant designs and in its exploit by monitoring its condition and applying fault detection techniques. In the paper first the most typical faults and their detection methods are summarized. In the second part of the paper a fault tolerant SRM structure is proposed and analyzed by means of simulations. The obtained results emphasize the usefulness of fault tolerant SRMs.**

Index Terms**: switched reluctance machine, machine faults, fault tolerant, cosimulation.**

I. INTRODUCTION

It is well-known that the switched reluctance machine (SRM) possesses unique characteristics that promote it for fault tolerance capability: the ability to continue its operation despite faulted motor windings or inverter circuitry. The only effects of a fault are the power reduction proportional to the number of faulted phases out of total phases and the increase of torque ripple.

Because of the magnetic independence of the SRM's phases and the circuit independence of the inverter phases, a fault in either a motor winding or an inverter phase can be detected and isolated with no effect on the other phases. Hence the SRM can continue its operation also with one or more phases disabled. Winding fault detectors can indicate the existence of faults, and these can be isolated by the intelligent motor controller.

In contrast, winding faults of a polyphase ac machines have more serious consequences. A fault in one phase seriously affects the operation of the other phases because of the mutual magnetic coupling of the stator windings. The dropout of a single phase (either by winding disconnection, or by power switch inaction) drops a three-phase machine to single-phase excitation [1].

Although it's inherent fault tolerant capability faults of diverse severity can occur in SRMs [2]. In the paper the main possible faults (both of the machine and of the power converter) are summarized. Also the effects and danger risks of these faults are highlighted.

The reliability of a SRM based drive system can be improved mainly by two ways:

i.) by permanently (preferably on-line) monitoring its condition and applying advanced fault detection methods

ii.) by using fault tolerant designs for both the machine and power converter.

A fault tolerant SRM together with its power converter is proposed in this paper. The use of a simple controller enables the increase of the currents of the healthy remained phases in a manner to diminish the torque decrease due to the faulty phases.

The fault tolerance of the proposed SRM is studied by means of simulation. The machine model was set up using a finite elements method (FEM) based on numeric field computation program (*Flux 2D*). The wildly used *MATLAB*®*–Simulink*® environment was used for modeling the inverter's control system and to simulate diverse winding faults. These two programs were coupled together by using the *Flux to Simulink Technology*.

Hence by means of cosimulation the behavior under healthy and faulty conditions of the SRM in discussion was studied. All the obtained results emphasized the usefulness and high fault tolerance of the proposed SRM.

II. FAULTS OF A SRM DRIVE SYTEM

The block diagram of a conventional SRM's control system is given in Fig. 1.

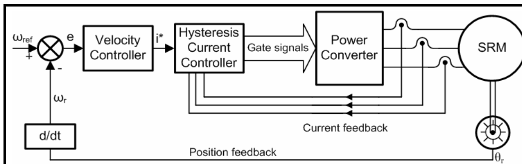


Fig.1 – Block diagram of a SRM drive system.

In this complex system all the components can fail: the machine, the power converter and also the control circuits [3]. In the paper we will deal only with the faults of the machine and of the power converter.

MACHINE FAILURES

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

SRM in its conventional construction seems to be the most reliable machine hence its passive and simple rotor structure, independent phase windings, etc. But in special situation also the SRM can fail.

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%) [4]. 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* are subject to insulation break-down caused by mechanical vibration, heat, age, damage during installation, etc.

As the windings of a SRM are independent and simple only two of the five possible winding faults (turn-to-turn, coil-to-coil, line-to-line, line-to-ground, and single or multi-phase open-circuit faults [5]) can occur: phase open and phase short. As the windings are placed in the stator the open phase faults are more common.

The phase winding may open typically due to manufacturing defects, or burnout of a weak link within the winding. When a phase winding is open, no excitation is available to that faulty phase, and there is no further contribution of torque from that phase. The controller has to increase the demand from the remaining healthy phases to maintain the constant speed of the SRM. The machine adapts to the faulty situation with increased torque and speed ripples.

The armature phase may be completely or partially shorted due mainly to the insulation failure. 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. 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 [3].

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. [6]. 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 centered in the stator, giving rise to different air-gap lengths on opposite sides of the machine. In these cases the machine will strongly vibrate [7].

CONVERTER FAILURES

Several faults can appear also in power converters. When a *switch in the converter is open-circuited* it does not lead to any catastrophic failure; it only stops supplying current to the corresponding phase winding. This case is similar to the open phase case. It practically means that the corresponding phase stops generating any torque.

A more frequent and much more dangerous fault is when a *switch in the converter is short-circuited*. In this case the corresponding phase winding receives continuous, uncontrolled excitation irrespective of the rotor position and controller logic. This faulty excitation results unlimited current through the phase. Eventually, the switch or the fuse (if it exists) 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 such faults depends on the converter topology used.

When the *supply DC voltage drops*, the speed of the machine 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, in a way 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 [3].

III. FAULT DETECTION IN SRM

Simple fault detection devices can be applied for SRMs.

One of the simplest one is an overcurrent detector, operating from the current sensor signal, setting a comparator having a threshold above the normal operating range of the phase currents (see Fig. 2).

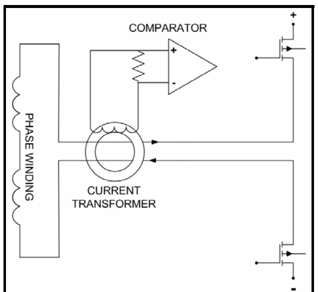


Fig.2 – Current differential detector.

This detector is easy to implement, but unfortunately is not acting fast enough, because the fault indication cannot be set until the phase current is already very high, and it is unable to interrupt a fault in progress. Since the detector operates from the current sensor it is not capable to detect all kinds of faults which could occur [1].

Another simple detector, the flux differential one, is given in Fig. 3. It uses search coils wrapped around the stator poles. The search coils of each phase are connected in series opposing. Hence during normal operation the induced voltages of the search coils are equal and opposite, leaving a net zero voltage at the terminals of the series pair. When a fault occurs the imbalance in the pole fluxes induces a voltage in one search coil that is greater than the voltage in the other coil, producing a net voltage that can be detected with a bidirectional comparator. This detector can sense ground faults, phase-to-phase faults, and the shorted-turn faults, faults that the previously mentioned current differential detector could not detect. The drawbacks of this detector are that it is oversensitive (it may respond to faults also in other phases) and requires additional coils to be placed on the poles [1].

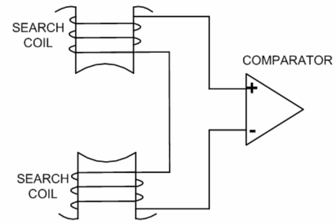


Fig.3 – Flux differential detector.

More sophisticated detectors are also cited in literature. Using a combination of them practically all the winding faults of the SRM can be relatively easily detected.

The electrical or mechanical unbalance due to open phases of the SRM generates force unbalance which results practically in vibrations and supplementary noise. Both vibrations and noises are frequently used in fault detection and condition monitoring of electrical machines. The techniques and apparatus used for other types of electrical machines (mainly of induction machines) can be also applied in the case of SRMs [8].

IV. THE FAULT TOLERANT APPROACH

The simplest definition of fault tolerance is that a fault in a component or subsystem does not cause the overall system to malfunction [9]. The fault tolerance of a given system can be quantified in terms of reliability and availability.

Generally, *reliability* means an attribute of components and systems that will not need to be repaired. It is often measured in terms of mean time to failure (MTTF), the mean time until a system or one of its components first fail. The mean time until a failure assumes that the device cannot be repaired or it cannot resume anyway to it's normal regime.

Availability is simply measured in terms of the expected proportion of time that the system will be available for use.

Special design and redundancy are commonly applied to improve the fault tolerance of electrical machines and drives.

The *special design* is based on the idea that the chances of operating close to the failure limit can be reduced by over-sizing the system's components.

The concept of *redundancy* means that if a part of the system fails, there is an extra or spare part that is able to operate in place of the failed unit, such that the operation of the system is uninterrupted.

Although these two approaches are the surest ways to increase the fault tolerance of an electrical machine drive system, they greatly increase the cost and complexity of the system. Moreover, redundancy may not be practical for an application that has a severe restriction on the installation space.

As alternatives to these approaches *fault diagnosis* and *fault-tolerant operating strategies* have been proposed in the literature [10].

The purpose of condition monitoring is to detect in time incipient failures in order to prevent the system from catastrophic breakdowns.

Fault tolerant operating strategies are based on the concept that a faulty system can maintain its uninterrupted operation with the assistance of a modified topology or control algorithm.

To implement such approaches it is required to design an electrical drive system which carries out the following tasks:

i.) fault detection or identification
ii.) fault isolation if possible
iii.) remedial (emergency) actions after fault detection

V. THE PROPOSED FAULT TOLERANT SRM DRIVE SYSTEM

The most common way to more enhance the fault tolerant capacity of a SRM is to increase the redundancy of the winding-converter configurations.

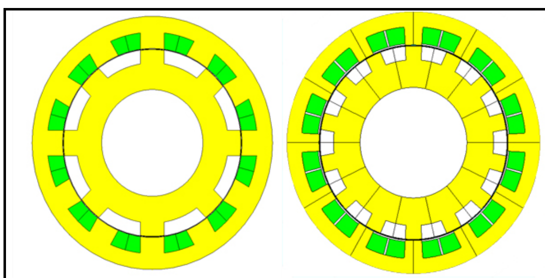
The phase of the SRM usually consists of two coils placed on opposite poles. The two coils can be connected in series, in parallel and independently.

The series connection is the most common arrangement. The currents in the two pole-coils are automatically equal under normal conditions. The parallel arrangement can be useful for high-speed machines, because it permits the use of thinner conductors and more turns per pole. A greater security is assured by the independent connection of the coils, when each of them has its own independent half-bridge controller.

To increase the redundancy of the windings each coil can be doubled. The doubled windings can be connected in series and in parallel. In both cases the magnetic and mechanical unbalance is eliminated when one section is faulted [2].

Beside these several other solutions are cited in literature [1], [11], [12].

Next a novel fault tolerant SRM will be presented (see Fig. 4b). The starting point was a classical 12/8 poles SRM, Fig. 4a. The proposed machine has 14 rotor poles.

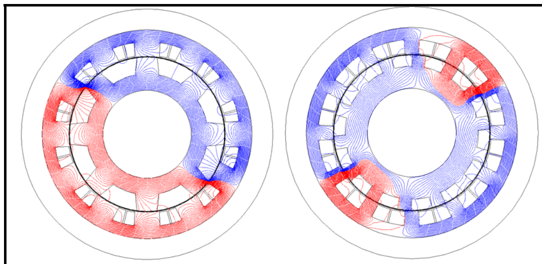


a) initial (12/8) b) proposed (12/14)

Fig.4 – The SRM structures.

The winding scheme is a six phased duplex type (each of the six phases is practically doubled). In case of fault of one channel, the second one still will contribute to the torque generation. At each time two adjacent phases are fed (practically in total 4 coils), hence 2 pairs of adjacent stator poles contribute to the torque development at each moment. This connection helps the motor to overrun the poles with faulty phases and to minimize the torque ripple.

By shorting in this manner the magnetic flux paths (see Fig. 5), also lower iron losses can be achieved.



a) initial (12/8) b) proposed (12/14)

Fig.5 – The field lines in the SRMs.

The proposed power converter has a separate H-bridge for each channel in order to be able to control each one independently, as requested by advanced the fault tolerant designs (see Fig. 6) [13].

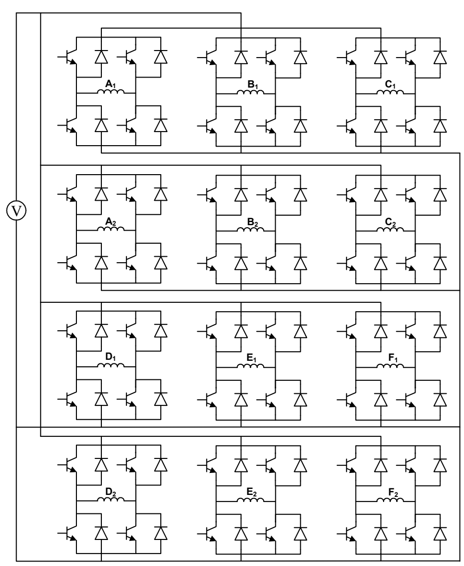


Fig.6 – The proposed power converter.

VI. THE SIMULATION PROGRAM

The simulations were performed using the cosimulation technique, by coupling two simulation environments to work together.

The model of the SRM and the electric circuits of power converter were built up in *Flux 2D* [14]. The control strategy was implemented in *SIMULINK*®, the most widely used platform in dynamic simulations.

The two programs were connected together using the *Flux-to-Simulink*® coupling technology. The finite elements model of the SRM is embedded in the SIMULINK® program via an S-type function called "*Coupling with Flux2d*".

All the control signals computed in SIMULINK® are multiplexed and enter this block. The main characteristics computed via Flux 2D (currents in all the phases, torque and speed) are returned to SIMULINK® through another multiplexed signal line [15].

The main window of the Simulink® program is given in Fig. 7.

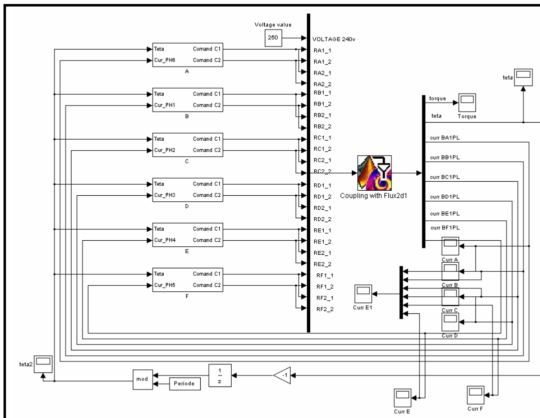


Fig.7 – The simulation program.

Different cases were studied by means of simulation in order to compare the two machine's geometries and to check their fault tolerance capability:

i.) normal operating mode,
ii.) open circuit of one channel,
iii.) open circuit of one phase,
iv.) open circuit of two channels from different phases,
v.) open circuit of one phase and one channel from a different phase (worst case in study).

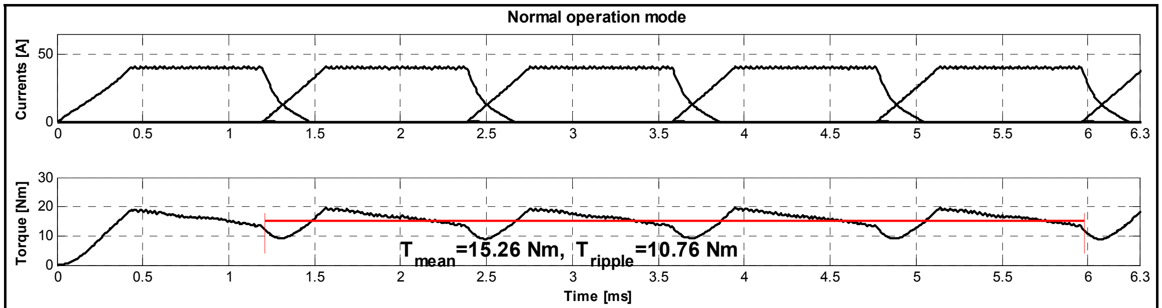
The obtained results are given in Fig. 8, where the phase currents and the torque of the SRM are plotted versus time for each case in study.

In all the cases also the mean value of the generated torque, respectively the torque ripple was computed. These values were computed for a four periods long time interval, as marked on the figures.

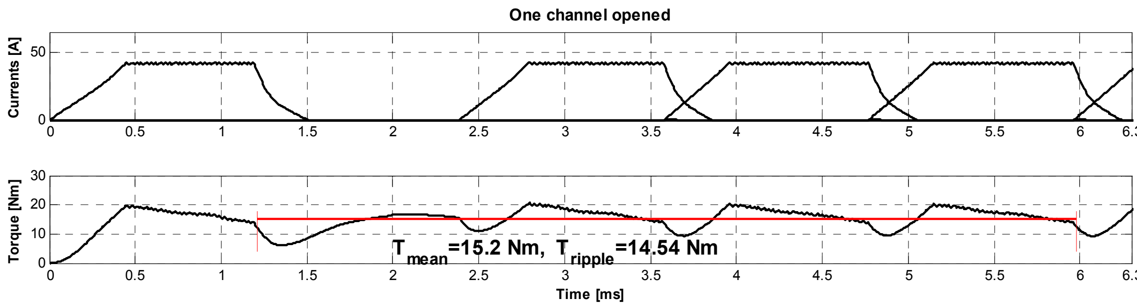
If only a single channel is opened (Fig. 8b), the most probably faulty case, practically the SRM will develop at unchanged currents near the same mean torque as in the case of the healthy machine (Fig. 8a). The single effect of the fault is the increase of the torque ripples by less than 4 Nm. If two cannels of different phases are opened the currents must be increased by 10% to achieve the rated mean torque (Fig. 8d).

If an entire phase is opened the current has to be increased by over 30% to achieve the rated mean torque, and the torque ripples in this case are greater by 2.5 times, as shown in Fig. 8c.

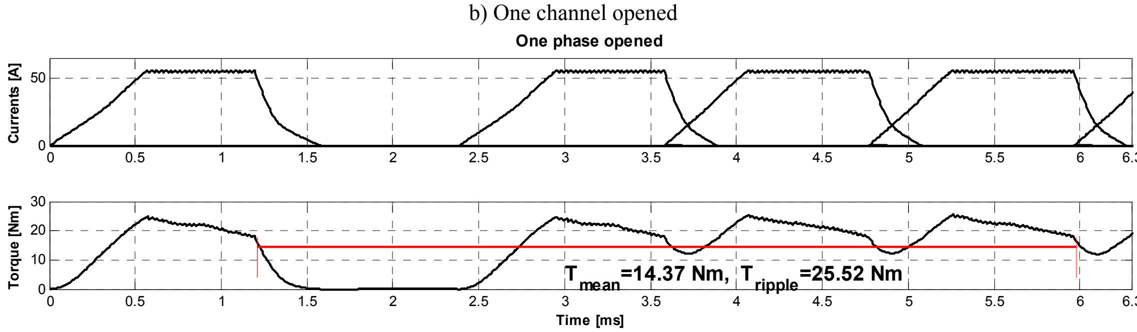
The proposed fault tolerant SRM is able to develop near its rated mean torque also in the worst case in study (Fig. 8e). In this case the phase current has to be increased by 1.5 times. The torque ripples are not much greater as in the case of a single open phase.



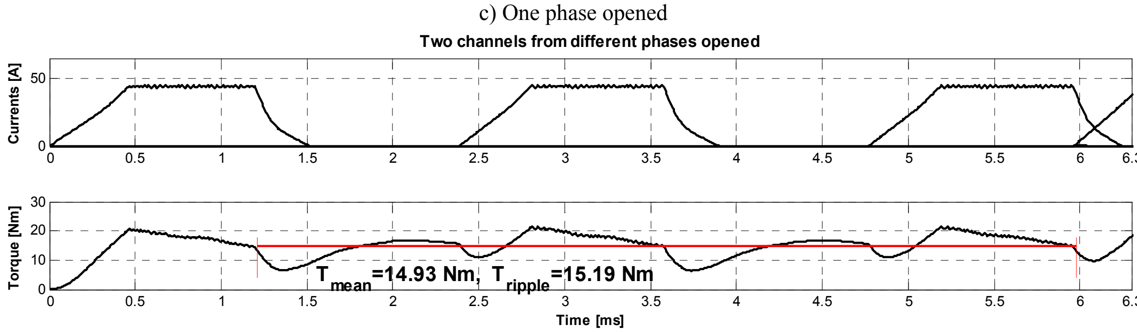
a) Normal operation mode



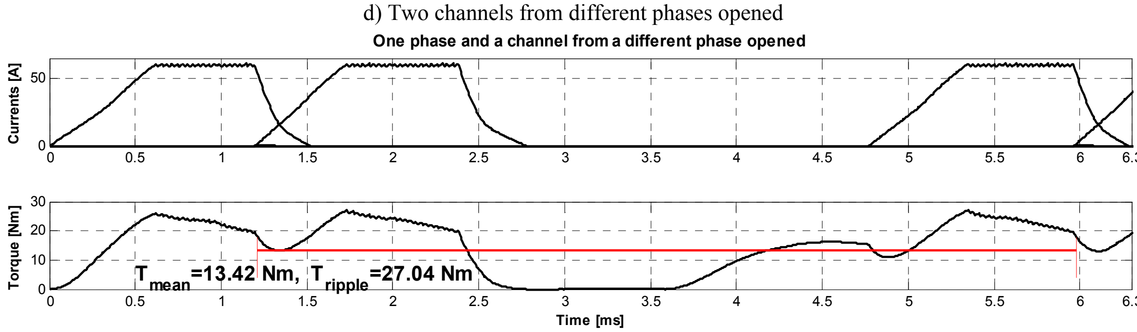
b) One channel opened



c) One phase opened



d) Two channels from different phases opened



e) One phase and a channel from a different phase opened

Fig.8 – Results of simulations. Currents and torque vs. time at different healthy and faulty regimes.

VII. CONCLUSION

It was proved by the results of simulation that the fault tolerance of the SRM can be improved by increasing the number of rotor poles, separating the windings in independent channels, setting new connections between the windings and applying an improved complex control system.

The complexity of the motor structure and the improved control system and power converter means of course higher costs. But these costs are reasonable if the importance of the applications is considered.

The applied simulation program, a coupled one connecting two programs (Flux 2D and SIMULINK®) was useful in studying the effects of different 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.

The main problems were concerning the computation times. In order to obtain yet precise results and reasonable computation time the mesh of the FEM model was lowered to an optimal level.

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

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