# Effects of Winding Faults on the Switched Reluctance Machine's Working Performances

Rareş Terec[1], Ioana Benţia[1], Mircea Ruba[1], Loránd Szabó[1], Pavol Rafajdus[2]
[1]Technical University of Cluj, Romania
Rares.Terec@mae.utcluj.ro
[2]University of Žilina, Slovak Republic
pavol.rafajdus@kves.utc.sk

***Abstract*—The switched reluctance machine (SRM) is considered to be ideal for numerous safety-critical applications (in aerospace, automotive, defense, medical, etc.) where it is desirable that the electrical drive systems 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. The paper deals with the most frequent faults of the SRMs and their detection. By means of numeric field analysis the effects of winding faults are also investigated. By using advanced co-simulation techniques the dynamic behavior of the SRM in healthy and several faulty conditions are also studied in the paper. The overall conclusions highlight the advantage of using such electrical machines in applications where an unwanted shutdown could have catastrophic effects on the entire system.**

## I. Introduction

The switched reluctance machine (SRM) is a double salient electrical machine with a passive rotor. The stator winding consists of coils placed on the stator poles, usually one coil on each pole. A phase comprises of two coils on opposite poles connected in series. Each phase is independent and the excitation must be a sequence of voltage/current pulses applied to each phase in turn. The passive rotor is made usually of conventional laminations without any kind of winding, excitation, squirrel-cage or permanent magnet. Its operating principle is based on the variable reluctance principle [1].

In motor mode the torque is produced by the tendency of the rotor to reach a position where the inductance and the flux produced by the energized stator windings are maximized. The control system requires rotor position information for an optimal phase excitation in order to achieve as smooth as possible continuous torque and high efficiency [2].

Due to their very simple construction the SRMs are robust and reliable, therefore there are ideal for safety-critical applications (aerospace, automotive, defense, medical, etc.) where it is desirable that the electrical drive system to be fault tolerant.

Unfortunately despite their robustness and reliability faults can appear during they exploitation. Their phase independence characteristics enable them to operate (of course at lower power and higher torque ripples) also under partial phase failure conditions.

In the safety-critical applications mentioned above it is very important to detect a fault in its incipient phase in order the operator to be able to make the correct decision regarding the effects of the fault on the entire system.

In the paper a short overview is performed regarding the most frequently faults of the SRMs and the fault detectors cited in literature. By means of advanced numeric field computations the effects of faults on the machine's performances are analyzed and also the effectiveness of the detection circuits are taken into study. In the last part of the paper the dynamic behavior of the SRM will be investigated under several stator winding fault conditions.

## II. Faults of the SRM

Unfortunately no statistical data on SRM faults can be found in the literature. Hence the induction machines failing statistics should be considered also in this case [3]. 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 can have several defects [5]:

i) short circuit in one coil of a phase
ii) a whole coil is bridged by a short circuit
iii) the whole phase is short circuited
iv) open circuit in one coil 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.

The 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].

Mechanical unbalance due to different eccentricities can arise when the rotor is not properly centered in the stator, by giving rise to different air-gap lengths on opposite sides of the machine. In these cases the machine will strongly vibrate [7].

To avoid the harmful effects of faults on the systems in which the SRMs are used it is necessary to detect the faults already in their incipient phase [8].

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## III. FAULT DETECTION

The winding faults of the SRM can be sensed by several failure detectors [9].

In a first approach a simple fault detection device can be applied: the over-current detector given in Fig. 1 [10]. Its efficiency is limited due to insufficiently fast response time and the inability to detect all types of faults.

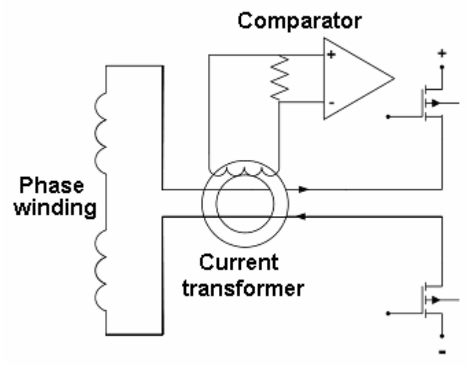



Figure 1. The current differential detector

Another simple detector, the flux differential one is shown in Fig. 2.

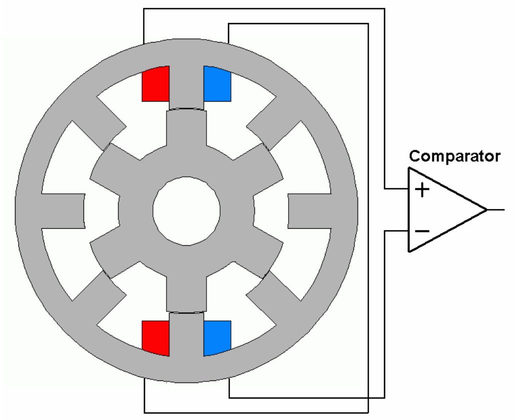



Figure 2. The flux differential detector

It requires additional 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 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 voltage that can be detected with a bidirectional comparator. This can sense ground faults, phase-to-phase faults and the short circuit faults, which cannot be detected by the over-current detector mentioned above.

This detector seems to be the most adequate in almost all of the cases. Its drawbacks are that they may be oversensitive and require additional coils to be placed on poles.

More complicated is the rate-of-rise sensing detector. It consists of a linear magnetic coupler placed around the upper phase-winding lead with the core, as shown in Fig. 3. It is made of a magnetic material which is linear in the entire range of operation.

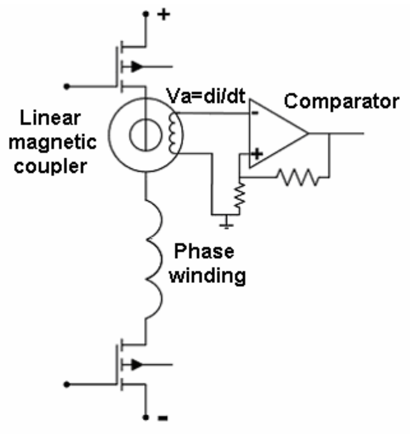



Figure 3. The rate-of-rise detector

The output voltage of the linear coupler is proportional to the time-rate-of-change of the phase current, which is modifying due to winding faults [10].

## IV. EFFECTS OF FAULTS ON THE EMFS GENERATED IN THE WINDINGS OF THE SRMS

All the winding faults of a SRM cause unsymmetrical field distribution inside the machine. The best way to emphasize these changes is to perform a numeric field analysis of a sample SRM [11].

The main data of the simulated simple SRM is:

i.) Rated power 350 W
ii.) Rated voltage 300 V
iii.) Rated current 6 A
iv.) Rated speed 600 1/min
v.) Number of stator poles 8
vi.) Number of rotor poles 6

The cross section of the SRM in study is given in Fig. 4.

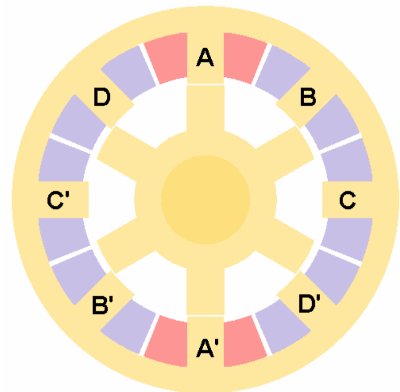
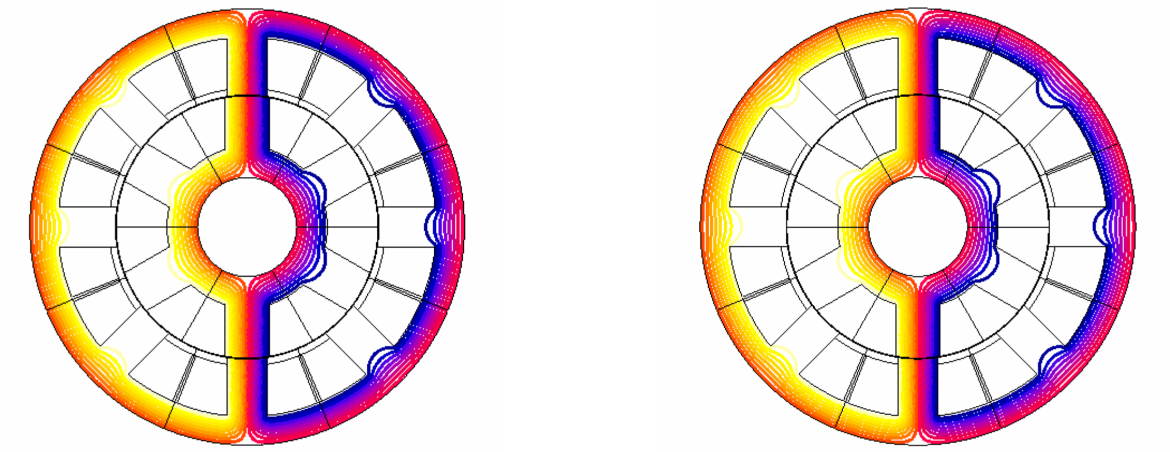



Figure 4. The cross section of the SRM in study

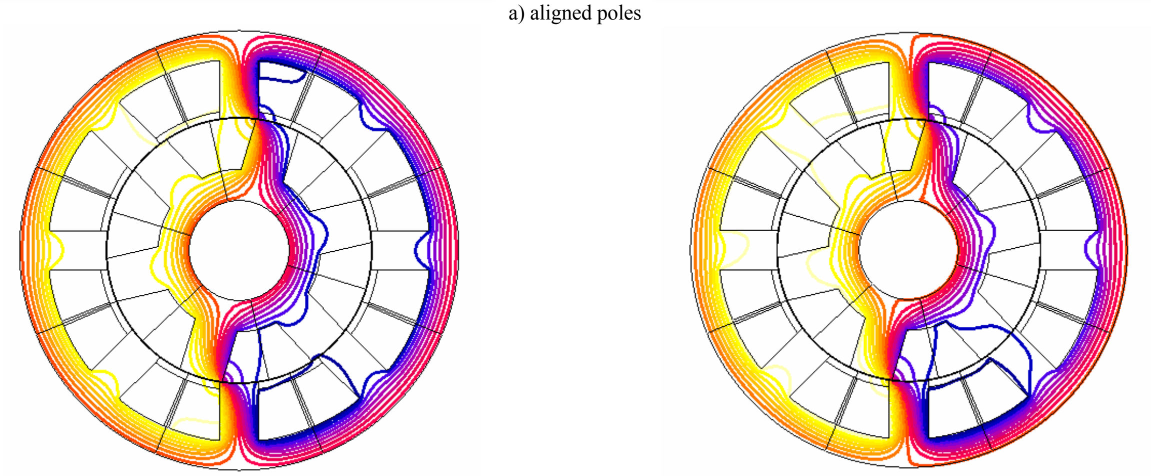
The numeric field computations were carried out by using the finite elements method (FEM) based Flux 2D program package [12].

The simulation based study was performed for the healthy machine and for a faulty condition where 20% of the *A* winding's turns were shorted.

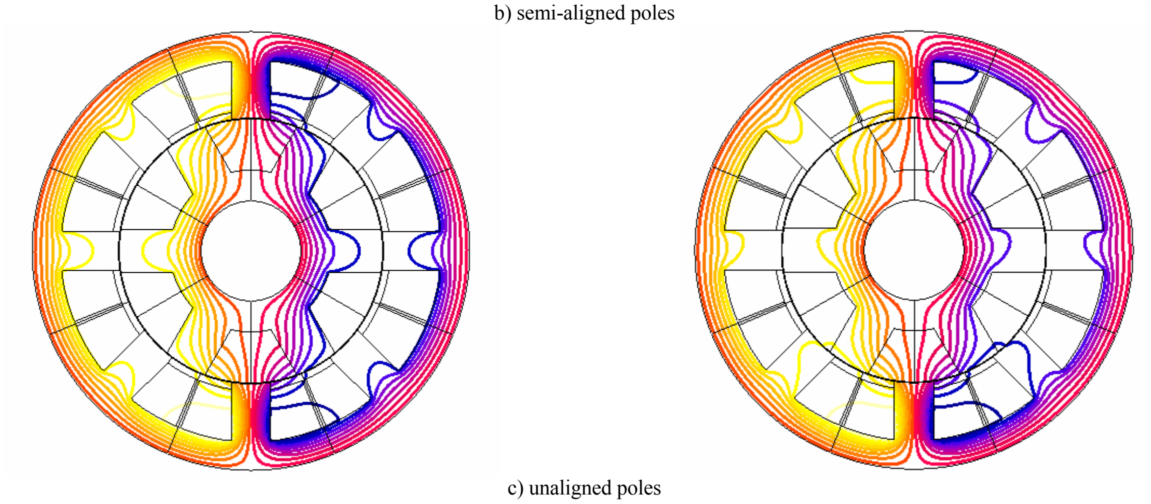
The magnetic flux distribution in the three significant rotor positions of the SRM (aligned, semi-aligned and unaligned) are given in Fig. 5.




a) aligned poles



b) semi-aligned poles



c) unaligned poles

Figure 5. The magnetic flux distribution in the SRM in study at different rotor positions and machine conditions

As it can be seen in the plots the changes in the magnetic flux distribution due to the minor stator winding fault taken into study are not too significant, but there can be sensed by finely tuned detection circuits.

By performing a time-stepping numeric field analysis the variation of the magnetic flux in pole *A* can be computed for diverse rotor positions [13]. The results were plotted versus the rotor's displacement (see Fig. 6). In position *0* pole *A* is perfectly aligned with a rotor pole.

The decreased magnetic flux due to the shorted turns in coil *A* can be clearly observed.

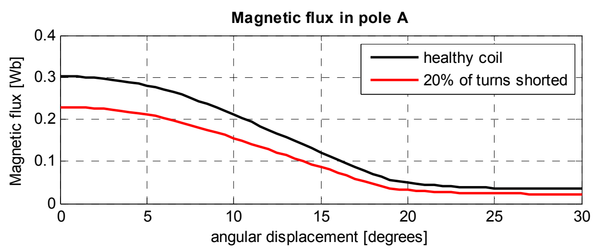



Figure 6. The variation of the magnetic flux vs. rotor displacement

By having computed also the variation of the magnetic flux function of time, the emf induced in the search coils having 200 turns round pole *A* can be plotted (see Fig. 7).

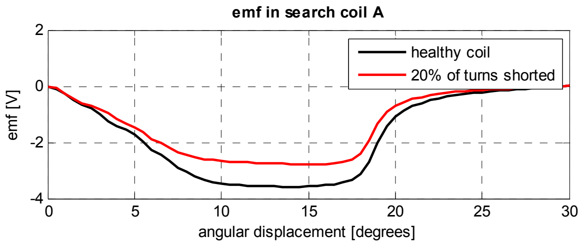



Figure 7. The variation of the emf vs. rotor displacement

By computing the emf in both search coils placed on opposite poles (*A* and *A'*) the voltage differences to be sensed by the detector given in Fig. 2 can be plotted for both machine conditions taken into study (see Fig. 8).

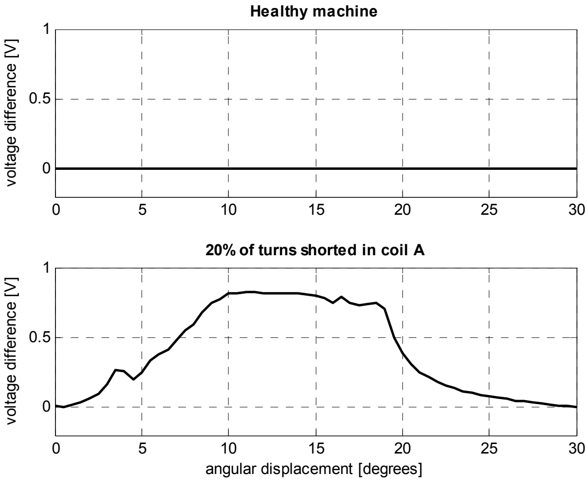



Figure 8. The variation of the voltage differences sensed by the detector

As it can be seen from figure 8, the voltage difference in case of shorted winding turns conditions is enough significant to be sensed by a precise differential detector.

## V. Dynamic Simulation of SRMs with Winding Faults

Dynamic simulations are one of the best choices to emphasize the effects of different winding faults on the SRM's behavior [14]. For this purpose the same SRM as in the previous case was simulated. The machine and its power converter must be simulated by means of coupling two software packages [15].

The MATLAB-Simulink environment is perfectly suited for simulating the converter and it can be easily used also for imposing the different operating regimes and machine conditions. The model of the SRM was built up in Flux 2D.

The FEM model of the SRM is embedded in the main Simulink program. The Simulink model of the drive system is computing at each time step the power switches command. At every time step data are exchanged between Simulink and Flux 2D. The FEM model is returning to the main program four signals: the phase currents, the electromagnetic torque, the mechanical speed and the angular position of the SRM at that time step.

The main window of the simulation program is given in Fig. 9.

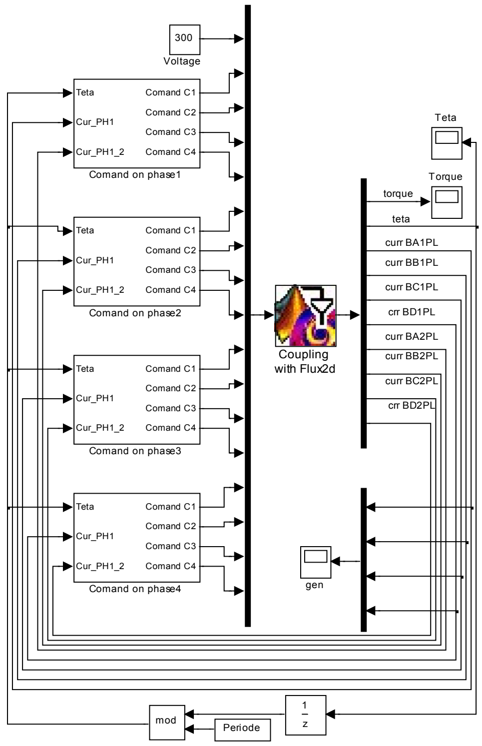



Figure 9. The main window of the coupled simulation program

The phase currents are controlled based on the rotor position by four closed-loop hysteresis modulation technique based current controllers.

For each phase four signals are sent to the machine's model to control the power switches of the converter (2 pairs of signals for each coil of the phase). All these signals are multiplexed.

They are the inputs of the Flux-To-Simulink coupling S-function type block (*Coupling with Flux2d*), which practically is the studied machine's embedded model built up using Flux 2D program. This block assures the connection between the two environments by maintaining the correct data transmission between them during the co-simulation.

Six conditions of the SRM were taken into study:

i.) healthy machine (normal operation mode)
ii.) one coil opened
iii.) two opened coils from different phases
iv.) three opened coils from different phases
v.) four opened coils from different phases
vi.) one opened phase.

For a better comparison all the simulations were performed for identical conditions (600 1/min imposed speed and 0.03 s simulation time).

For all the cases the developed torque, respectively the currents in the eight coils of the SRM were plotted versus time. The obtained results are given in Fig. 10.

In the case of the healthy SRM (see Fig. 10a) the symmetrical currents in the eight coils can be clearly observed. It must be also mentioned the inherently existing torque ripples.

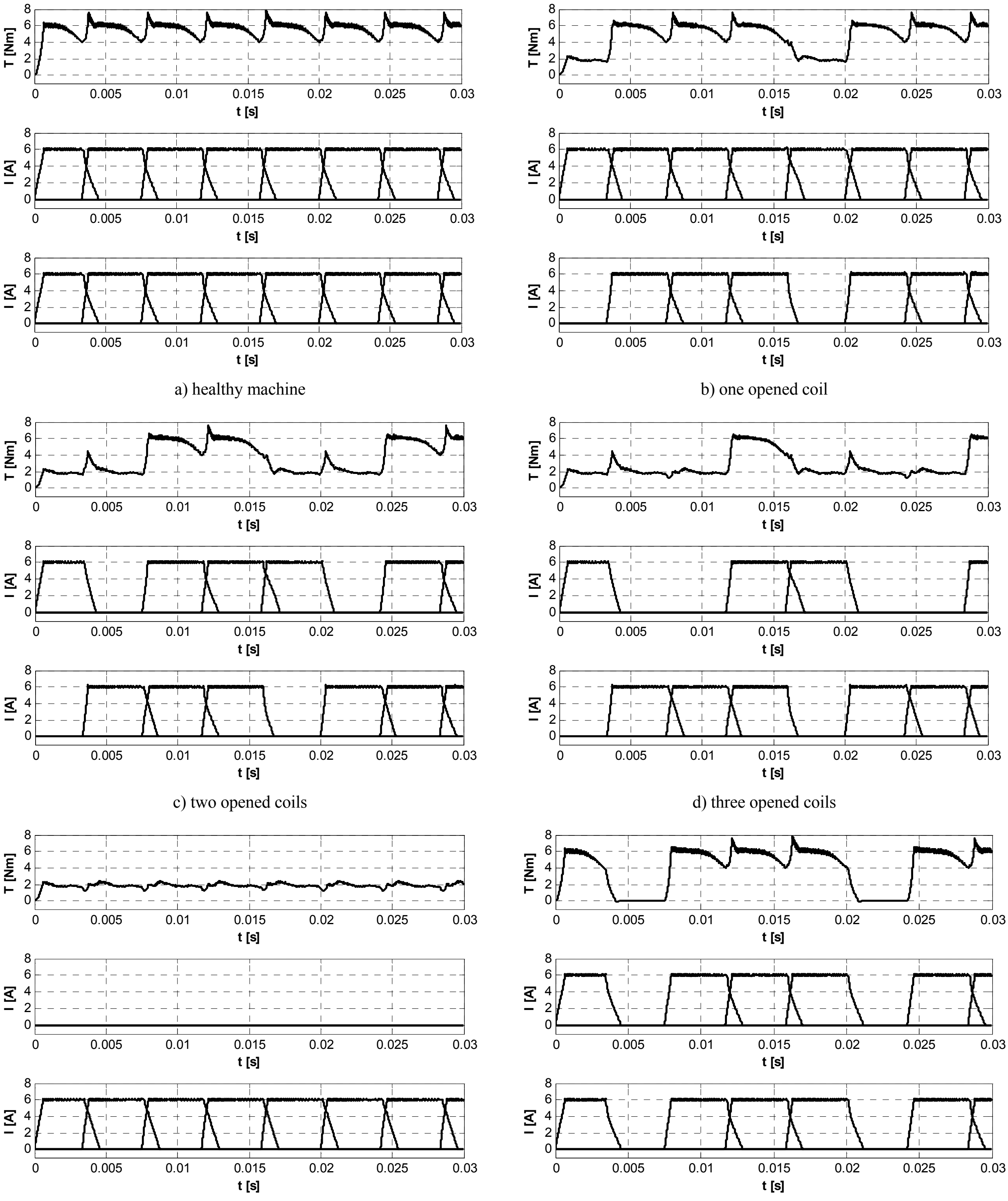
In the case of one opened coil fault (see Fig. 10b) half of one phase is opened. When the faulty phase is turned on the torque is falling to near 2 N·m. In this case the SRM develops a mean torque of 4.6 N·m, about 82% of the rated value.

When two coils are opened (see the results of simulation in Fig. 10c) the torque during the time periods corresponding to the operation of the faulted coils is falling to around 2 N·m, causing considerable ripples. In this case the machine is able to develop a mean torque of 3.71 N·m, about 67% of the rated torque.

When one more coil is opened only a single phase will remain healthy. As it can be observed in Fig. 10d the torque is falling three times during a period and the mean torque in reduced to 2.67 N·m, only about 48% of the rated one.

In Fig. 10e the results are given for the condition when all currents from the first coils of each phase of the machine are nil due to the opened coil faults. The mean developed torque of the machine now is 1.85 N·m, being only 33% of the rated torque.

When an entire phase of the machine is faulted is the most severe fault that the machine can still overrun. The simulated results in this case are given in Fig. 10f. In this




a) healthy machine

b) one opened coil

c) two opened coils

d) three opened coils

e) four opened coils

f) one opened phase

Figure 10. The results of dynamic simulations

case the SRM in study is still able to develop a mean torque about of 4 N·m, 72% of its rated torque.

For a better overview of the SRM's performances in the case of the six conditions taken into study the mean values of the torques are given in Tab. I.

TABLE I.
THE MEAN TORQUES FOR THE CONDITIONS TAKEN INTO STUDY

| Condition | Mean torques [N·m] and percentage of the rated torque |
|---|---|
| Healthy machine | 5.5 (100%) |
| One opened coil | 4.6 (83%) |
| Two opened coils | 3.75 (67%) |
| Three opened coils | 2.67 (48%) |
| Four opened coils | 1.85 (33%) |
| One opened phase | 4 (75%) |

All the results emphasize the inherent fault tolerant capability of the SRM. If winding faults appear during the machine's work this is able to overrun the poles having faulted coils. Of course due to the reduced number of coils contributing the torque generation the mean value of the developed torque is less and less as the number of opened windings is increased. Also the torque ripples are getting greater and greater as the severity of the faults is increasing.

But the main task of a machine used in safety-critical applications is fulfilled: not to stop due to the faults until the driven system is not in safe.

The fault tolerance of the SRM can be improved in several ways: by increasing the number of poles both on the stator and rotor [16] or by dividing the phase windings in separately fed coils (so-called channels) [17]. In [18] a modular SRM with improved fault tolerance is presented in details.

## VI. CONCLUSIONS

In the paper first of all the fault tolerance of the SRM was proved again by mean of numeric field computations. The field computations performed for static regime emphasized that a relatively minor winding fault (20% of the turns shorted in a coil) do not have significant effect of the performances of the machine.

A more in depth analysis was carried out by the dynamic simulation of the machine. For this purpose an advanced coupled (Flux 2D and Simulink) simulation program was built up. By studying six conditions of the SRM (healthy machine and five winding faults of diverse severity) it could be stated that these faults have effect both on the torque development capability of the machine and on the ripples of the torque, but the machine can continue its rotation also despite of these fault.

Therefore the SRMs are ideal solutions for various safety-critical applications in aerospace, automotive, defense, medical and other similar domains.

Having the effects of the faults clarified also the efficiency of the fault detection methods had been proved by means of the above mentioned simulation methods.

In the final part of the paper some solutions to improve the fault tolerance of the SRMs were detailed, too.

## ACKNOWLEDGMENT

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