Novel Modular Fault Tolerant Switched Reluctance Machine for Reliable Factory Automation Systems

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Abstract-**Electrical machines and drives used in diverse critical fields like advanced factory automation systems, automotive and aerospace applications, military, energy and medical equipment, etc.) require both special motor and converter topologies to achieve high level fault tolerance.**

In the paper a novel modular fault tolerant switched reluctance machine is proposed. Its stator is built up of simply to manufacture and to replace modules. The machine is able to have continuous operation despite winding faults of diverse severity. It is fed by a special power converter having separate half H-bridge leg for each coil. Thus a complex and high reliable electrical system is obtained. By advanced dynamic co-simulations (using a coupled Flux 2D and Simulink® program) the behaviour of the drive system under five winding fault conditions are studied. The obtained results prove the fault tolerant capacity of the proposed machine.

I. Introduction

In general, faults cannot be prevented. Instead they need to be tolerated to guarantee certain degrees of dependability. The fault tolerance by definition is a capability of a system to continue its uninterrupted operation also in the presence of faults, even for a limited period, with no significant loss of functionality or performance [1]. Originally it was used only in the informatics technology, but in our days fault tolerance became a basic requirement for numerous systems [2].

A system is reliable when it is capable of operating without material error, fault or failure during a given period in a specified environment. From another point of view a system is dependable if it is available, reliable, safe, and secure [3].

As it is well-known the failures of the electrical drive systems in factory automation systems can have disastrous effects on a plant's ability to function. Both the converter and motor faults can cause unscheduled downtimes which means production and revenue losses [4]. In other applications like in the automotive, aerospace, military, energy and medical fields the faults may have more catastrophic effects, and even human lives can be in danger.

Developing fault tolerant systems is an exciting engineering challenge and requires knowledge about all the possible faults that can occur and the system's response to them [5]. From the first approach of the fault tolerant concept till today several proposals emerged to improve the electrical machine's reliability. The fault-tolerant machine has to have a special design. An optimum solution has to be found taking into account all the advantages and drawbacks of the proposed machine structure.

Inherently by increasing the machine's fault tolerance the losses could be greater and its efficiency less than of its usual counterpart. Combining fault tolerance increasing solutions with the modular construction both high reliability, respectively quick and precise repairing of the machine was solved.

Thanks also to the improvements in the field of power electronics and to digital signal processing intelligent solutions could be provided for the drive system. The separate feeding of each coil and the improved control strategies applied smoothed the progress to high tolerance levels.

In the paper a novel modular switched reluctance machine (SRM) is proposed. The study on the machine's fault tolerance was performed by means of dynamic simulations. The entire electrical drive system (the machine together with its converter) was simulated using the latest technique, the co-simulation, by coupling together FLUX 2D and Simulink® [6]. This way it was taken advantage of the high precision machine analysis capabilities of FLUX 2D finite element method (FEM) based numeric field computation program and easy to use, but advanced Simulink®/MATLAB® environment [7].

II. The Novel Fault Tolerant Modular SRM

The increase of the fault tolerance level of an SRM requires changes in the existing structures. The first step should be the increase of the stator pole numbers and of the phase number [8]. A second solution can be the division of each phase into individual channels. This way a winding fault of a channel will not influence the operation of the other channels of the same phase or of other phases. The drawback of this solution is that a more complex power converter is required, having as many converter legs as channels.

The proposed modular fault tolerant SRM is given in Fig 1.

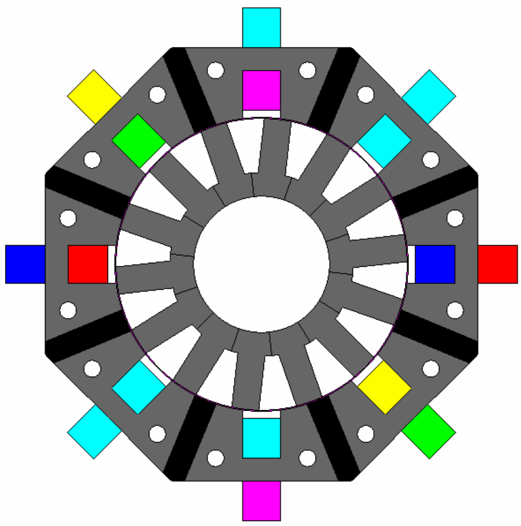

Figure 1. The cross section of the modular fault tolerant SRM

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The machine has four phases, each divided into two channels (coils). Each channel is wound on the yoke of a module; hence the total number of modules is 8. The modules of a single phase are placed in the stator diametrically opposed (see the flux lines obtained by means of numerical field computation in Fig. 2). This way the machine's forces during normal operation of are correctly balanced.

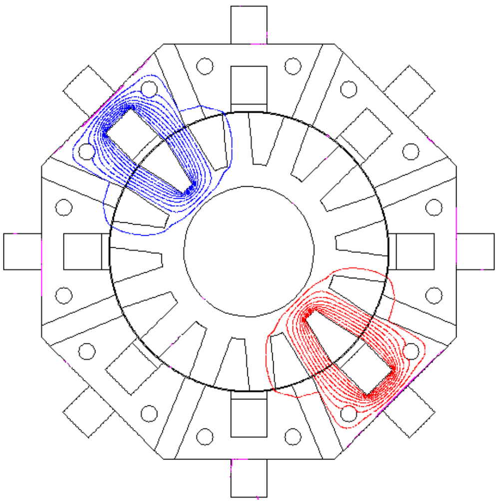


Figure 2. Flux lines in the modular fault tolerant SRM

The modular construction allows an easy manufacturing of the machine and fast replacement of the damaged modules in case of a winding failure.

The design of the modules implies many restrictions. First of all they must be sized in a way to fit into a closed circle, and to ensure that the modules are shifted correctly one relatively to the others. Also the winding must fit in the slot of the module. An other restriction is connected to the electromagnetic separation between two adjacent modules. This can be achieved by placing spacers of nonmagnetic material between them (see the construction of the machine in Fig. 3).

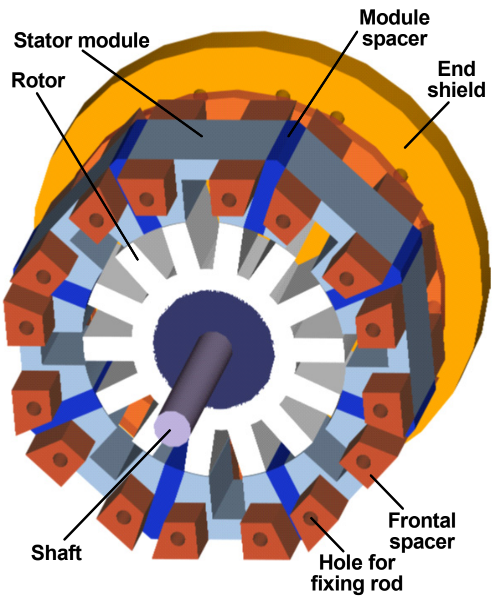


Figure 3. The construction of the machine

The thickness of the spacer has to be more than 20 times the air-gap length of the machine, to assure the exact electromagnetic separation of the neighboured modules.

Each module is built of laminated sheets pressed together by nonmagnetic metal fixing rods. These rods also keep the modules in their place and fix the two end shields.

In case of a winding fault only a single end shield and the rods of the faulted module has to be detached. Hence the module can be easily pulled out and replaced. This way there is no need of decoupling the machine from its load during the repair, a major advantage in industrial environment.

The number of rotor poles (Q_R) is computed upon the number of stator modules (N_{mS}) and the number of the phase to channel division (n_{div}):

$$Q_R = n_{div} \cdot N_{mS} - n_{div} \tag{1}$$

The stator yoke's height is obtained from the stator pole width b_{sP}:

$$h_{yS} = 0.85 \cdot b_{sP} \tag{2}$$

The flux density in the yoke can reach 1.9 T assuring fast current fall at the end of each conduction period.

The stator module height is computed taking into account the number of turns per channel and the isolation between the winding and the stator slot. The active stack length is given by:

$$l_a = \frac{\pi}{2} \cdot \frac{1}{\sqrt[3]{Q_R^2}} \cdot D_g \tag{3}$$

The first two terms of the equation are the aspect coefficient. Q_R is the number of the rotor poles, and D_g is the mean diameter (the diameter in the middle of the air-gap). Each channel has 220 turns, and the rated current is 6 A. The rated power and voltage are 350 W, respectively 300 V. The proposed fault tolerant modular machine can develop a rated torque of 5 N·m.

The machine was designed by means of complex mathematical methods [9], [10], [11], [12]. The developed design program was used both for the precise geometrical sizing and also for the machine's characteristics (torque, losses, flux density, flux leakage, heating, etc.) computation.

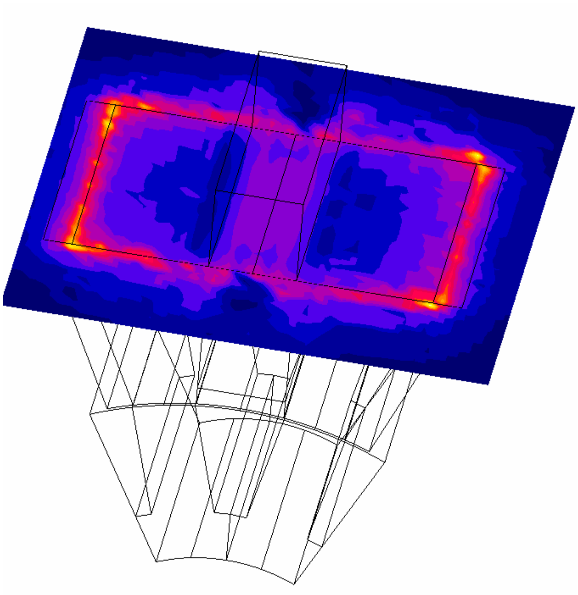
The main computed geometrical dimensions are given in Tab. I.

TABLE I
MACHINE GEOMETRY

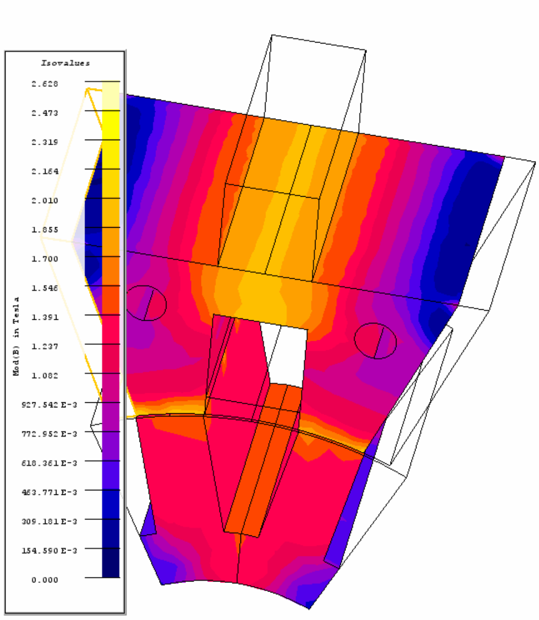
	Dimensions [mm]
Module height	35
Rotor pole height	26
Air-gap	0.5
Module yoke	11
Rotor yoke	11
Rotor and stator pole width	13
Winding height	19
Outer diameter	210

Because the winding are placed on the stator yoke it was expected that the leakage flux could be greater than in the classical SRMs. Therefore the leakage flux was computed both analytically and via 3D FEM based methods

A part of the three dimensional (3D) field computation's result obtained by means of Flux 3D package are given in Fig. 4.



a) cut plane for computing the leakage flux



b) flux density in a module and the corresponding rotor pole pair

Figure 4. Graphical results obtained by means of Flux 3D

The cut plane in Fig. 4a was created to be able to compute the flux leakage in the outside of the module. In Fig. 4b the 3D flux density distribution in a module and the corresponding rotor pole pair is given. As the colour map shows the flux density values are close to the analytically computed ones [13].

Both computation methods proved that the leakage fluxes are relatively small [14]. The flux losses due to flux leakage are about 12% of the total flux generated.

The computed flux densities in different regions of the machine are given in Tab. II.

TABLE II
FLUX DENSITIES IN DIFFERENT REGIONS OF THE MACHINE
(FEM VS. ANALYTIC CALCULATIONS)

	FEM	Analytic
Flux leakage	$8 \cdot 10^{-5}$ Wb	$7 \cdot 10^{-5}$ Wb
Yoke flux density	1.81 T	1.55 T
Air-gap flux density	1.21 T	1.18 T
Rotor pole flux density	1.25 T	1.15 T
Stator pole flux density	1.20 T	1.17 T
Rated torque	5.69 N·m	5.57 N·m

Also the machine's losses were computed both via analytical and numerical methods to ensure the correctness of the design. The losses of the proposed machine are given in Tab. III.

TABLE III
LOSSES IN THE MACHINE

	Losses [W]
Iron losses in the modules	6.22
Rotor iron losses	3.72
Winding losses	24.5

Taking into account these losses the machine's efficiency was calculated to be of 0.83.

III. THE PROPOSED CONVERTER AND THE SIMULATION

The control system must have the intelligence to detect the fault, to isolate and remedy it, all to ensure that the machine's behaviour is influenced as less as possible [15], [16]. In the fault tolerant concept, this is the main imposed task for a drive. For this purpose the complete separation of the channels was an obligatory requirement [17].

The proposed converter has a separate half H-bridge for every channel in order to be able to control each one independently, as requested by the fault tolerant design (see Fig. 5).

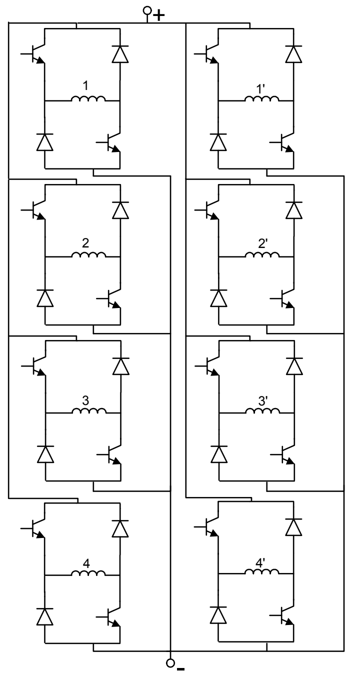


Figure 5. The power converter

Only one switch of an inverter branch is commanded via a hysteresis current controller. The second one is held open for the whole conducting period.

The separate feeding of each channel is a second achievement that sets the fault tolerance to a high level. The simulation of the power converter was performed by using an electrical circuit built up in Electriflux, Flux 2D's circuit editor, attached to the FEM model of the machine. The electrical circuit corresponding to one phase is given in Fig. 6. As it can be seen each channel of one phase is modelled using two electrical coils, corresponding to the "come and go" sides of the winding.

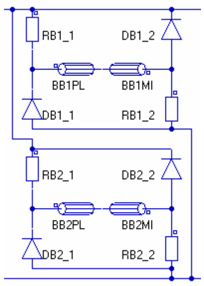


Figure 6. The electrical circuit model of one phase

In the electric circuit model the power switches were replaced by resistors. Their resistance are set at a high value (OFF state of the switch) or at a low one, corresponding to the ON state of the transistor.

The dynamic behaviour of the machine in study and its power converter was simulated using co-simulation, by coupling together Flux 2D and Simulink® by means of Flux-to-Simulink Technology [18]. The main window of the simulation program is given in Fig. 7.

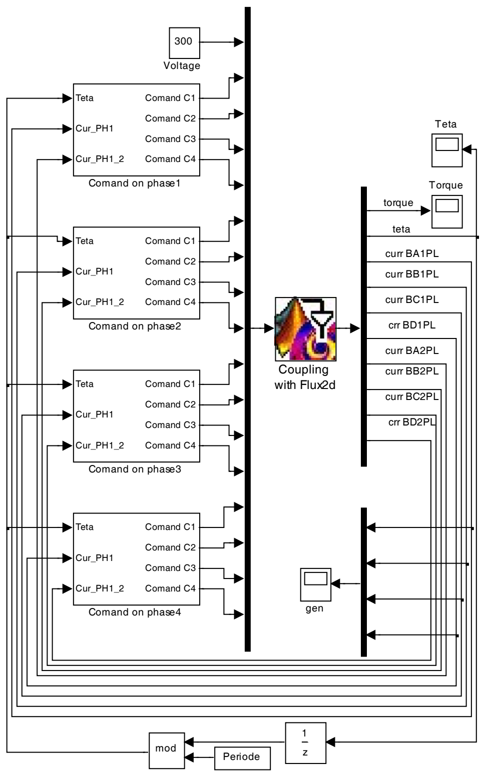


Figure 7. The main window of the simulation program

As it can be seen there are 4 blocks generating the phase currents upon the hysteresis current control technique. When a step is computed in Simulink® the results are sent to the Flux 2D model, and the response (concerning the position, torque and phase currents) is obtained after the field computations, and is sent back to the Simulink® model. The next step is computed based on these feedback values, so the system operates in closed reaction loop. The firing angles are defined upon the rotor position and the maximum phase current. The ON/OFF signals sent to the switches are: the resistance of 100 kΩ (OFF state) or 0.004 Ω (ON state).

In order to perform the coupled simulations some parameter adjustments were required, because the coupled programs need high computer resources. Therefore a compromise had to be taken when lowering the mesh density in order to obtain affordable computation time but, in meantime, not to decrease the precision of the results [19].

IV. The Results of Simulations

In order to emphasize the machine's behaviour both in normal and faulty operation mode several simulations were performed for the following conditions of the machine:

a) normal operating mode;
b) one channel open;
c) two open channels;
d) tree open channels;
e) four open channels;
f) one completely faulty (open) phase.

The simulation time for all the cases was set to 0.03 s. The obtained results are given in Fig. 8. In all the 6 cases in study the developed torque and two sets of currents (in the first, respectively second channels of the phases) were plotted versus time.

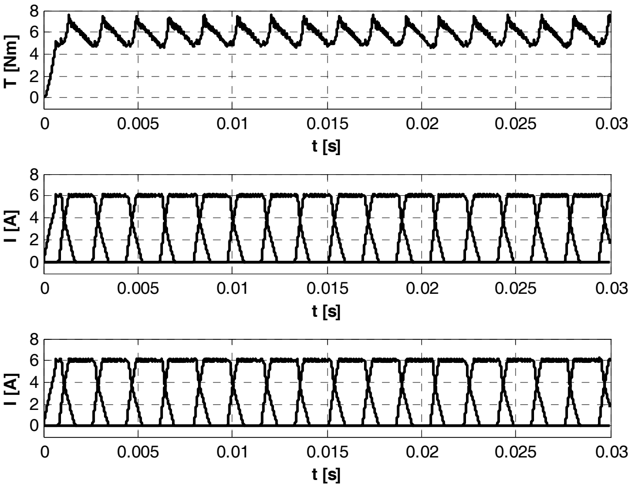
The open circuit faults were simulated by imposing OFF state for both switches of the corresponding converter branch.

In all the cases the mean developed torque was computed. A ratio of the mean torque vs. the rated torque was also computed (see Tab. IV).

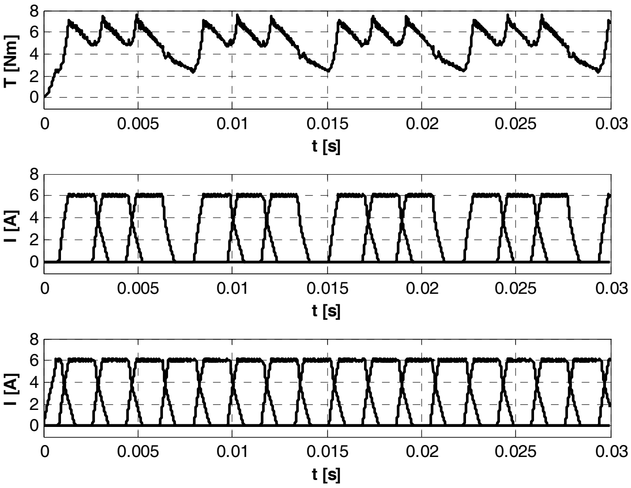
TABLE IV
Developed Torque Values In All the Studied Cases

Case in study	Mean value [N·m]	Mean/rated torque [%]
Normal operation	5.7	100%
One faulted channel	4.9	86%
Two faulted channels	4.3	75%
Three faulted channels	3.6	63%
Four faulted channels	2.8	51%
One faulted phase	4.3	75%

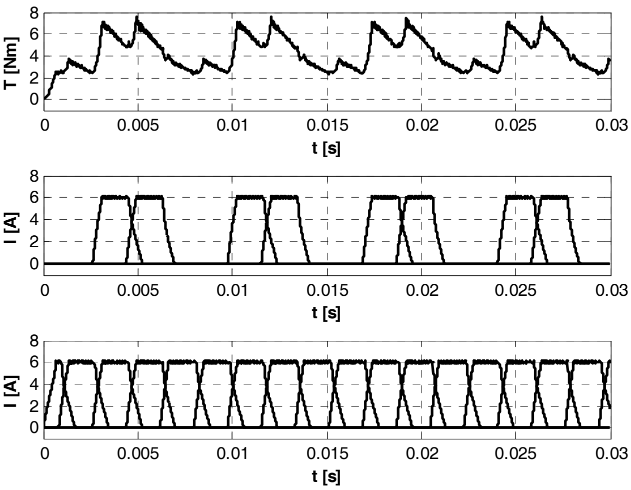
As it can be seen the mean value of the developed torque is decreasing as the winding faults are getting more and more severe. Practically when four channels are opened just a half part of the machine is working and developing half of the rated torque. If an entire phase is faulted the machine is still able to develop nearly 75% of its rated torque. Hence the machine can overrun the positions corresponding to the faulty windings due to its inertia.



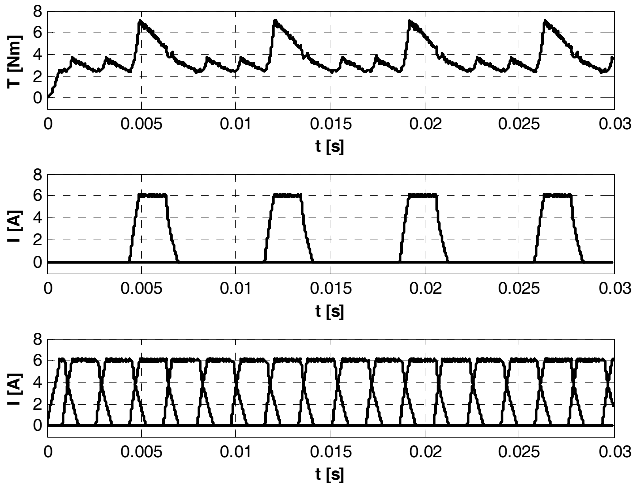
a) normal operating mode



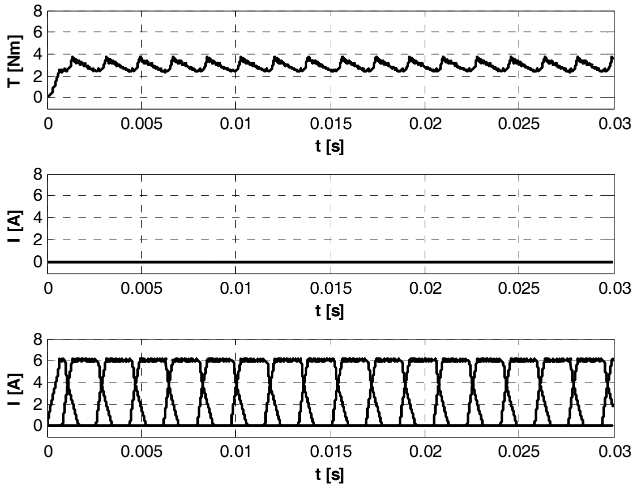
b) one channel fault



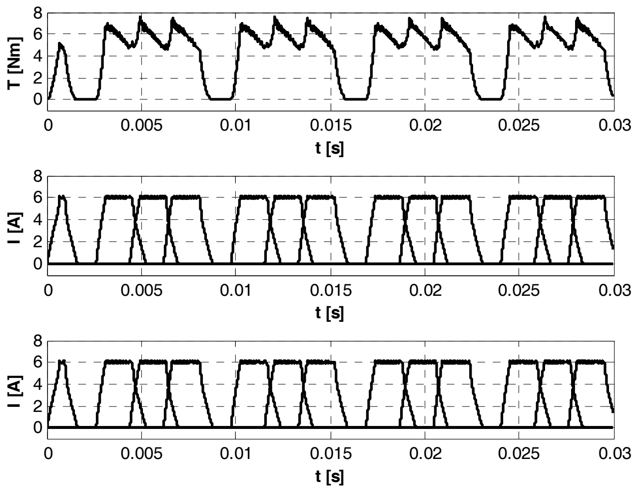
c) two faulty channels



d) tree faulty channels



e) four faulty channels



f) one faulted phase

Figure 8. The torque and current vs. time for all the cases in study obtained via simulations

Even in the worst case taken into study (four faulted channels) the machine is able to develop about 50% of its rated torque. Hence it can be stated that splitting of the phases into channels is a useful solution in achieving high fault tolerance.

In all the faulty cases the torque ripples are increased as compared with the healthy condition. The periods with low torque are longer as the number of missing current pulses (the number of open channels) is higher.

This drawback of the fault tolerant machine can be diminished by a current control system which is able to increase the currents in the healthy remained windings when opened channels are detected. By this the mean value of the developed torque can be maintained in certain limits relatively closed to the rated value. Of course the windings and the cooling system have to be designed taken into account the increased currents.

V. Conclusions

A novel modular fault tolerant SRM was proposed. Its modular construction simplifies both its manufacturing and repairing. It can be used in applications where the reliability is a key issue (advanced factory automation systems, automotive and aerospace applications, military, energy and medical equipment, etc.).

A particular design algorithm was developed. An easy-to-use design program was also written. Using it several similar machines can be easily sized.

The performances of the designed machine were tested both via analytical computations and FEM based numeric field computations. Results obtained by means of both methods proved that the design of the machine is in accordance with the imposed design data.

The fault tolerance of the proposed machine was performed by means of dynamic simulations. A coupled simulation program was used for this purpose. Two software environments (FLUX 2D and Simulink®) were coupled together using the Flux-to-Simulink Technology. Thus the ability of the MATLAB®/Simulink® environment to simulate the power converter, the control system and to impose the different working regimes and machine conditions was combined with the precise numeric field computation capability of Flux 2D. This simulation technique seems to be the best solution in such complex studies.

The main problem was how to reduce simulation times. In order to obtain both precise results and reasonable computation time the density of the FEM model's mesh had to be optimised.

The main advantages of the proposed machine are its fault tolerance and its simplicity. The modules can be manufactured separately and the stator can be easily assembled. The passive rotor is very simple.

The machine can be also quickly repaired if winding faults occur without removing it from the load.

In the future more faulty conditions will be studied (short circuits, power converter faults, etc.). Also an experimental model of the fault tolerant modular SRM in study is under construction and will be tested soon.

Acknowledgment

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