Fault Tolerant Switched Reluctance Machine Study

Mircea RUBA, Technical University of Cluj-Napoca, Romania
Dr. Markus ANDERS, Maccon GmbH, München, Germany

Abstract

A lot of industrial, medical, aeronautical, military, etc. applications demand for high level safety operation. Therefore, it is impetuous to ensure the continuous work also of the electrical machines and drives included in it. In this paper a fault tolerant switched reluctance machine will be presented. It has a 24/18 pole structure and a special 4 channel triplex winding. The behaviour of the proposed machine under different fault conditions was studied by means of simulations. The machine model was built up in Flux 2D, and its control system in Simulink®. The advanced Flux-to-Simulink Technology was used for linking together the two platforms in order to perform transient regime co-simulations. All the obtained results emphasize the correct right design of the machine.

1 Introduction

The *fault tolerant concept* appeared first rose up in the field of computer science. The fault tolerant system is designed to continue operating reliably despite faults that produce hardware failures or software errors. A fault tolerant system can detect faults in its components, and has the ability either to correct a fault (for example, by switching to a backup unit when the main one fails), or to circumvent one (for example, by reconfiguring the system).

An equipment is built up by interconnecting several systems. If each composing system can provide a certain level of safety in operation, the final product will be also able to operate continuously in case of fault occurrence [1]. The resulting operational unit may have certain fault tolerant levels, as a sum of the safety levels of each component of the system.

A system is reliable when it is capable of operating without material error, fault or failure during a specified period in a specified environment. From another point of view a system is dependable if it is available, reliable, safe, and secure [2].

An electromechanical system is driven by a unit formed of the power converter and of the electrical machine. Both must be able to offer an imposed fault tolerance level. The machine's fault tolerance design has to be in a manner to assure as smooth as possible output parameters in case of fault occurrence.

From the inverter's point of view, as the evolution of the power electronics hit an exponential slope, the separation, command and control of each phase will set the wanted fault tolerance level [3].

Switched Reluctance Machine (SRM) tends to take over several applications where an electric machine is needed. Hence an increasing demand on its safe operation in various fields can be observed.

A solution for increasing the reliability of a SRM drive system is to use motors with fault tolerant design. A four-phased fault tolerant SRM having 24/18 poles was designed. By an advanced control system setting the correct firing angles for each power switch set corresponding to the triplex winding a good torque characteristic with low ripple was obtained [4].

The behaviour of the motor under different fault conditions was studied by means of simulations. The machine model was built up in Flux 2D, a high performance finite elements method (FEM) based magnetic field computation platform.

The motor's advanced control system was modelled in Simulink® and the Flux-to-Simulink Technology was used for linking together the two platforms. In this way it was possible to study all the faulty states of the motor, as in deep as possible [5].

2 The fault tolerant switched reluctance machine

The fault tolerant SRM in discussion has 24 poles on the stator and 18 on its passive rotor. It has a specific four-phase triplex winding, as shown in Fig. 1.

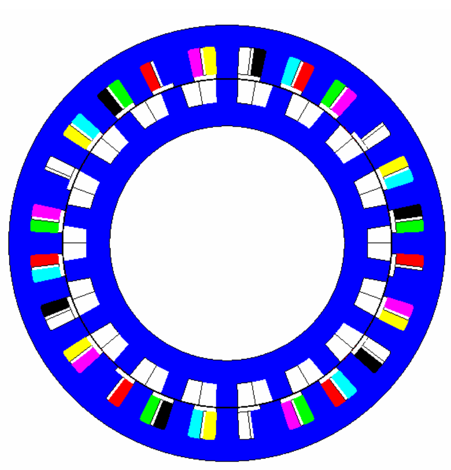


Fig. 1 The fault tolerant SRM

The spatial displacement of the stator and rotor teeth is made in accordance to maximize the torque development and balance the forces.
The winding of one phase is divided in four coils. For example, in Fig. 1. the coils corresponding to a single phase are wound round those stator poles, which are aligned with the rotor ones.
As the number of stator poles is relatively high, the torque ripple both in normal operation and faulty one, is smooth.
The stator frame of the machine is 5 mm thick. The outer diameter of the SRM is 190 mm. The stator end caps were also sized 5 mm thick. The machine length is 60 mm. Taking into account the given number of the stator teeth, the stator pole arc was selected to be 7.5° and also the rotor pole arc is the same, 7.5°.
The rotor pole arc may be extended to reduce torque ripple. But this way the rotor inertia should be greater, and the reduced rotor inductance will degrade the torque production capacity of the machine.
To control the machine an intelligent power converter must be used. The specific control strategy, which assures the fault tolerant operation of the SRM, must be implemented on the converter. Also fault detection functions must be added to the converter's intelligence. To improve the overall performances of the system supplementary a torque optimization unit has to be coupled.
As in the case of usual SRMs a feedback signal of the rotor position is also needed to ensure the correct commutation of the phases.
PWM technique was proposed for controlling the phase currents through the fault tolerant machine's multi-phased windings.

3 The coupled models

The model of the SRM was built up using the Flux 2D finite element method (FEM) based electromagnetic field computation software.
As the study is performed in transient with motion regime a mesh optimisation was required in order to reduce computation times. A compromise had to be made between the imposed mesh density, the computation accuracy and the available hardware. A detail of the generated mesh is given in Fig. 2.

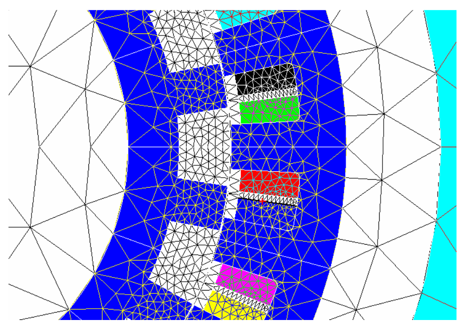


Fig. 2 The generated mesh in Flux 2D

The electric circuit attached to the FEM model of the fault tolerant machine in study is given in Fig. 3.

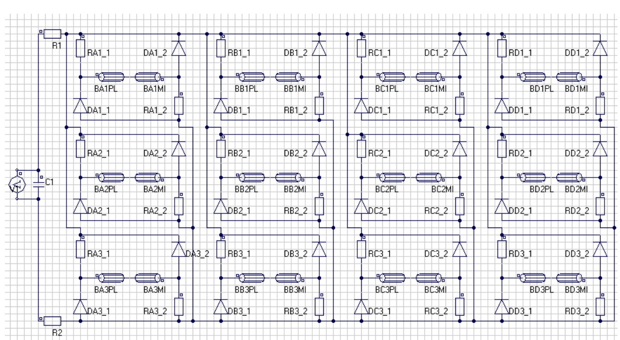


Fig. 3 The electric circuit of the machine

As it can be seen each phase of the machine is modelled by two coils, the ingoing and the outgoing coils. The diodes connected to all the branches are for ensuring the flow of the inverse current.
The solid-state power switches are replaced by resistors in the circuit. The opening / closing of the switches is modelled simply by changing the resistance from 100 kΩ to 4 mΩ.
The command of the electrical circuit is accomplished using MATLAB-Simulink® environment. The communication between Flux 2D and Simulink® is solved using the Flux-to-Simulink® coupling method, as it can be seen in Fig. 4 showing the main window of the Simulink® model.
The command system will generate signals with reference values for the resistances for each branch.
The link between Simulink® and Flux 2D is implemented by the *Coupling Flux2D* S-function type block. The input values of the block (practically the signals to be transferred to Flux 2D) are the resistance values for each branch.
The S-function block will receive the output signals after the field computation (the torque, the phase currents and the rotor position) and will transfer them to Simulink®. Using these values the parameters of the next simulation step will computed.
This way the next step of simulation, and so on, will be computed step by step till the time limit is reached.

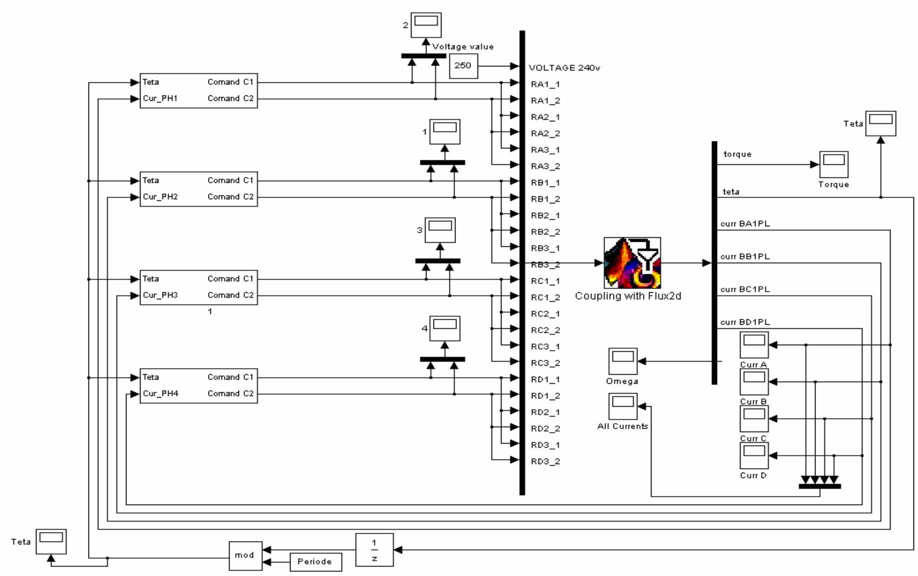


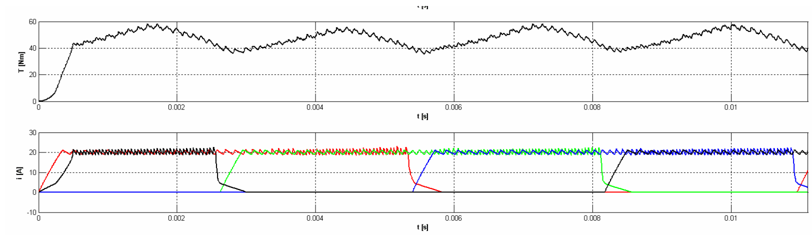
Fig. 4 The Simulink® model of the fault tolerant system

4 Simulations performed

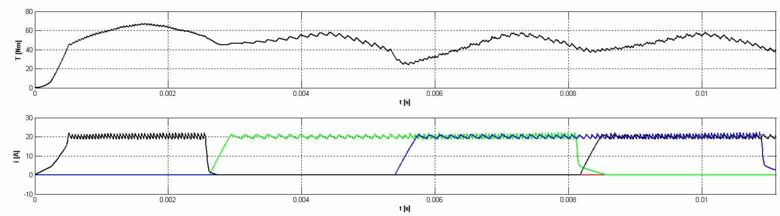
The operation under various winding faults of the proposed fault tolerant SRM was studied using the coupled simulation program.
Several faults depending on various reasons can appear in such machines. At this stage of the research only the most typical ones will be studied.
Five typical fault cases have been studied via simulation by changing the electrical circuit's structure and parameters:

i.) one channel open circuit
ii.) one phase (three channels) open circuit
iii.) one channel short circuit
iv.) one phase short circuit
v.) two phase open circuit

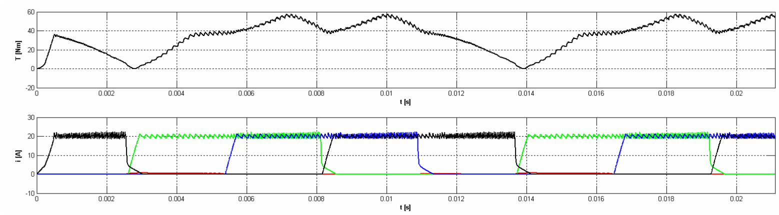
Current and torque wave forms for normal operation mode of the SR Machine can be seen in Fig. 5a. These will be reference values for the study of the faulted cases.



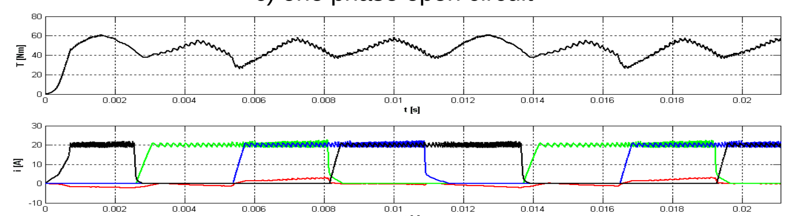
a) normal operation (no fault case)



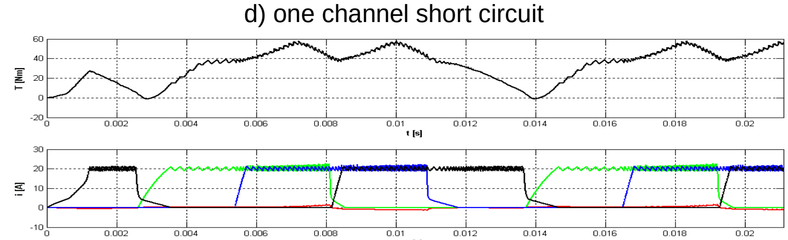
b) one channel open circuit



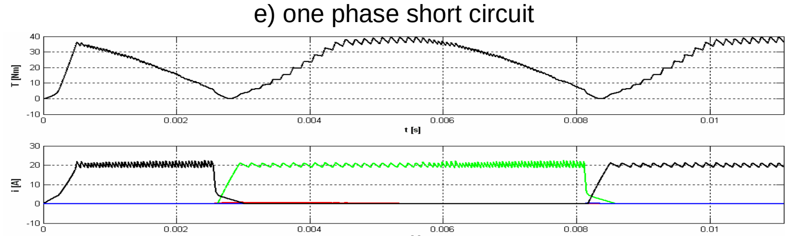
c) one phase open circuit



d) one channel short circuit



e) one phase short circuit



f) two phase open circuit

Fig. 5 The torque and phase currents of the SRM under different fault conditions

4.1. One channel open circuit failure

For simulating the open circuit failure a high value electrical resistance was inserted in series with the windings in the electrical circuit. This way, the machine will behave as having an open circuit winding on one phase.
The simulation time was set to 0.01 s.
The current having nil value in Fig. 5b is that of the faulty phase (in red colour), as the currents are plotted only for one channel. The torque has a small fall at the half of the period, corresponding to the missing current pulse.
Of course the mean and RMS value of the torque will be decreased due to this fault. All the torque's characteristics can be found In Table 1 from chapter 5.

4.2. One phase (three channels) open circuit failure

The fault is modelled also in this case by inserting of high value resistances in all the corresponding electrical circuit branches.
The phase currents in the case of open circuit that faults an entire phase are given in Fig. 5c. As the simulation was performed under no-load conditions, at the occurrence of the phase damage the generated torque will fall to nil. In order to have a better overview on the simulation results, in this case the simulation time was doubled to 0.02 s.

4.3. One channel short circuit failure

The study on the effects of short circuit in an electrical drive system must take into account the causes of the short circuit. When the short circuit appears in the power converter (for example by the damage of a power switch) the short circuit can affect in the worst case an entire phase, or a whole channel of the winding [6].
In our present study one of the worst cases, e.g. the short circuit of an entire channel was simulated.
To be able to compute this fault, the electrical circuit was modified. The short circuit was simulated using a low value resistance connected in parallel with the starting and ending terminal of the channel.
Through the short circuit almost the entire current of the phase will flow. Due to the small value of the resistance the phase current will rise fast and will reach great values (tens of amps). The current in the faulted phase will have small negative and positive values. This is because in the short circuited phase the only current will be that induced by the healthy phases. As it was expected, the generated torque is small when the current is negative (Fig. 5d).

4.4. One phase short circuit failure

A short circuit of all the channels of one phase, modelled by inserting low value resistances in parallel with all the channels, will decrease the mean value of the torque due to its fall to zero (see Fig. 5e).

4.5. Two phase open circuit failure

In our study it was intended to simulate also the worst case regarding the possible faults.
Considering the machine's complex structure, its worst damage case in study was the loss (open circuit) of two phases.
This was simulated by inserting in series high value resistances to "disconnect" from the feed bar the phases in discussion.
In this case the torque in the machine will be generated only by the single healthy remaining phase. Its plot versus time is given in Fig. 5f.
In this case the developed torque will have high ripples, reaching the maximum value of 40 Nm and the minimum of 0 Nm during the periods when the phase currents of the disconnected phases are nil.
Of course in this case the mechanical vibrations and noises of the machine will have higher values, causing a negative impact over the operation of the whole system.

5 Conclusions

To emphasize the effects of the different faults in study on the operation of the proposed fault tolerant SRM the characteristics regarding the developed torques can be found in Table 1. The torque development capability was computed versus the normal operating mean value of 46.7Nm.

Operating Modes	Developed torque values [Nm]				Torque development capability
	Min.	**Max.**	**Mean**	**Ripple**	**Percent of usable torque [%]**
Normal operating mode	36.3	58.2	46.7	21.89	100
Open channel fault	24.1	58.43	46.5	34.33	99.38
Open phase fault	0	57.68	35.5	57.68	75.65
Short circuit on one channel	26.29	61.28	46.5	34.99	99.04
Short circuit on one phase	0	57.87	38.3	57.87	81.62
Two open phases faults	***0***	***39.87***	***22.9***	***39.87***	***48.96***

Table 1. The torque values for different operating regimes of the SRM in study

As it can be observed, a high percent of the usable torque (that obtained in healthy operation mode) will be generated also when the machine has several faults. Hence, for an open channel failure, the usable torque can be considered unchanged, as the loss is only appr. 0.6%.

The same conclusion can be drawn when one channel is short circuited. In case of open circuit or short circuit for an entire phase, the torque loss is lower than 24.4%.

Regarding the torque ripple, the highest value can be observed in the case of one phase fault (both open and short circuit), when the torque falls to zero. In the case of one phase fault (again, both open short circuit), the ripple will be nearly equal for both cases (about 35,0 Nm).

Hence, for the one phase failure, the SR machine will behave nearly the same, both in open and in short circuit. This means, that the machine will "understand" the two faults in the same way, if the drive is able to mask them correctly.

Even in the case of the most severe fault in this study (two open phases) almost half of the unfaulted torque of the fault tolerant machine remains available.

This becomes a solid argument to sustain that the studied SR machine can respond positively to the requested tasks even in case of a serious winding failure occurrence. All the results of the simulations emphasize the correct concept and design of the proposed fault tolerant SRM.

References

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