Comparative Study on Switched Reluctance Machine Based Fault-Tolerant Electrical Drive Systems

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***Abstract*-The Switched Reluctance Machine (SRM) based electrical drive systems are ideal for critical applications (aerospace, automotive, defense, medical, etc.) where the fault tolerance is a basic requirement. The phase independence characteristics of the SRM enable it to operate also under partial phase failure conditions also in its classical construction. Its reliability can be improved by applying special fault-tolerant designs, respectively monitoring its condition and applying fault detection techniques. The SRMs used in such safe electrical drive systems has to be fed from power converters having also fault-tolerant capability.**

In the paper two SRMs are proposed together with their converters. The fault tolerance capacities of the two electrical drive systems are compared by means of simulations. Two advanced simulation platforms were coupled together to simulate the drive system. The results of the comparative study emphasize the usefulness of the proposed fault-tolerant electrical drive system. The conclusions of study help the users to select the best fitted variant for they specific application.

I. Introduction

The fault tolerance by definition is a basic characteristic of a system that ensures its continuous function even after a fault occurs, that would cause a normal similar system to malfunction [1].

The fault-tolerant concept emerged for the first time in information technology (IT). It meant an increased level of continuous operation of computer equipment. Later more and more fault-tolerant equipments were connected together in order to form a fault-tolerant system [2]. The result was an operational unit having certain fault-tolerant level, as a sum of the safety levels of each equipment 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 [3].

The fault-tolerant design of complex electrical systems is becoming our days a necessity for a growing number of companies, far beyond its traditional application areas, like aerospace, military and telecommunications [4].

As it is well-known the failures of the electrical drive systems can have disastrous effects on a plant's ability to function. Both the converter and motor faults can cause unscheduled downtimes, which can result in significant lost production and revenue [5].

In the field of electrical drives both the machine and the power converter must be fault-tolerant [6]. From the first approach of the fault-tolerant concept till today several proposals to improve the electrical machine's reliability had been published. The fault-tolerance of electrical machines means the rise of the operating level, and also increase in safety of the system that incorporates the electrical machine. As the machines evolution reached a high tech level, the fault tolerance level also required to be increased [7].

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 changed machine structure. Inherently by increasing the machine's fault-tolerance its losses could be greater and its efficiency less than its usual counterpart [8].

Thanks also to the improvements in the field of power electronics and to digital signal processing today intelligent solutions can be provided in designing a fault-tolerant electrical drive system. The separate phase feeding and control of the machines allow an easier approach of the fault-tolerant tasks and offer good results [9], [10].

The fault tolerance capability of two SRMs is studied in the paper. The two machines are compared via co-simulation. Flux 2D was used for modeling the machine by means of numerical field computation based on finite elements method (FEM). The MATLAB®-Simulink® environment was applied for modeling the inverter's control system and to impose the machine faults in study. These two programs were coupled together using the Flux-to-Simulink Technology. This way it was possible to study in details all the typical faulty conditions of the two machines.

II. Fault Tolerant SRM Based Electrical Drive System

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

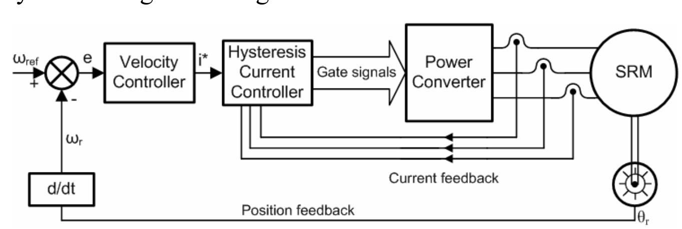


Figure 1. Block diagram of a SRM's control system

In this complex system all the components can fail: the machine, the power converter and also the control circuits [11].

The most common way to more enhance the fault tolerant capacity of these components is to increase the redundancy of the windings and converter legs [12].

The redundancy of the SRM can be increased simply by doubling its windings. The doubled windings can be connected in series or in parallel [13]. In both cases the magnetic and mechanical unbalance is eliminated when one section is faulted. Also several other solutions are cited in the literature [14].

The starting point of the design was a classical 12/8 poles SRM structure, as that shown in Fig. 2.

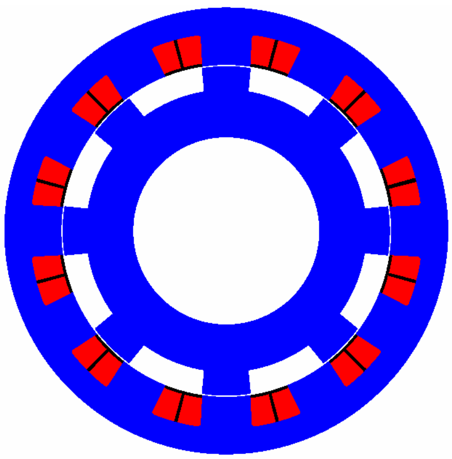


Figure 2. The initial SRM structure

The machine has 12 concentrated stator windings around each pole. All the windings are split in two parallel connected coils (called channels). Two windings from opposite poles are connected together to form a phase. Hence this SRM has 6 phases.

This structure was preferred because it can be transformed relatively easily in an efficient fault tolerant variant. The proposed modifications are implying both the rotor structure and the connection of the stator windings [15].

The modified SRM has a similar stator as the machine given in Fig. 2, but more (14) rotor poles, as shown in Fig. 3.

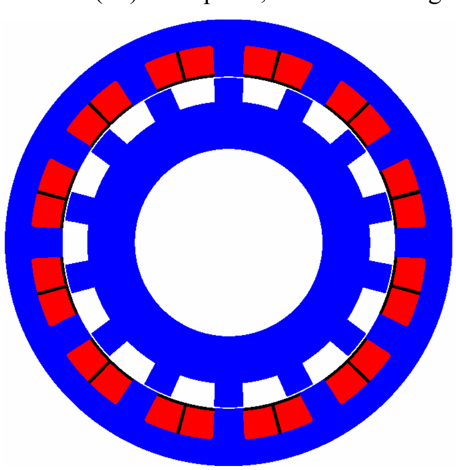
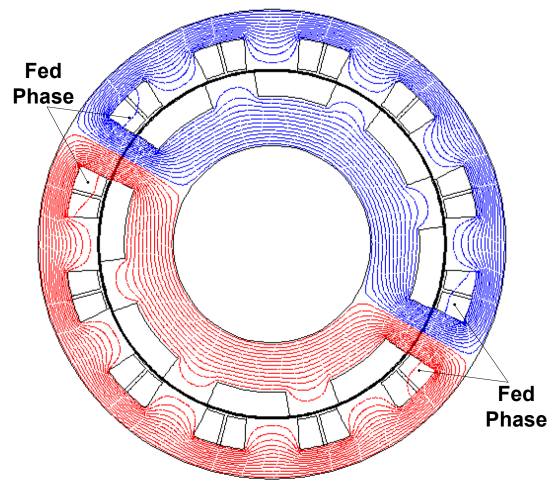


Figure 3. The proposed SRM structure

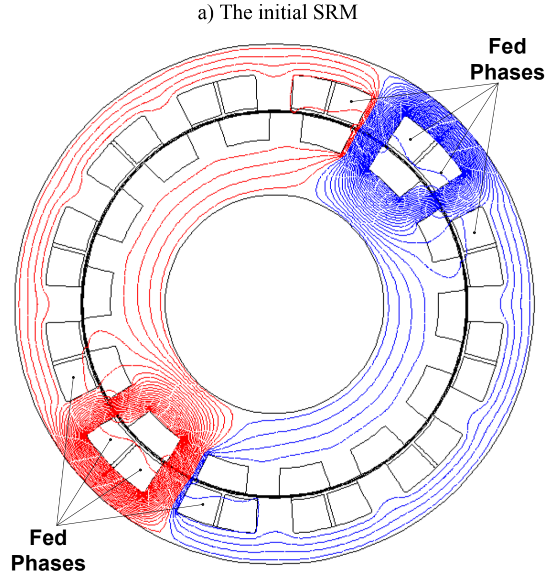
The increase of the rotor poles enhance the fault tolerance in means of torque development and safe operation and reduce the torque ripples under faulty conditions.

The proposed SRM has at each time two adjacent phases fed, which means in total 4 windings ("two phase on" feed technique). Hence at each moment two pairs of adjacent stator poles are contributing to the torque development. This connection helps the motor to overrun the poles with faulty phases and to minimize the torque ripple. By shorting the magnetic flux paths also lower iron losses can be achieved.

To emphasize the difference between the two SRM variants in study the flux lines obtained by means of numeric field computations are given in Fig. 4.



a) The initial SRM



b) The proposed SRM

Figure 4. The flux lines in the SRM machines

The power converter for the proposed SRM has a separate H-bridge for each channel in order to be able to control each one independently, as requested by the fault tolerant design (see Fig. 5) [16].

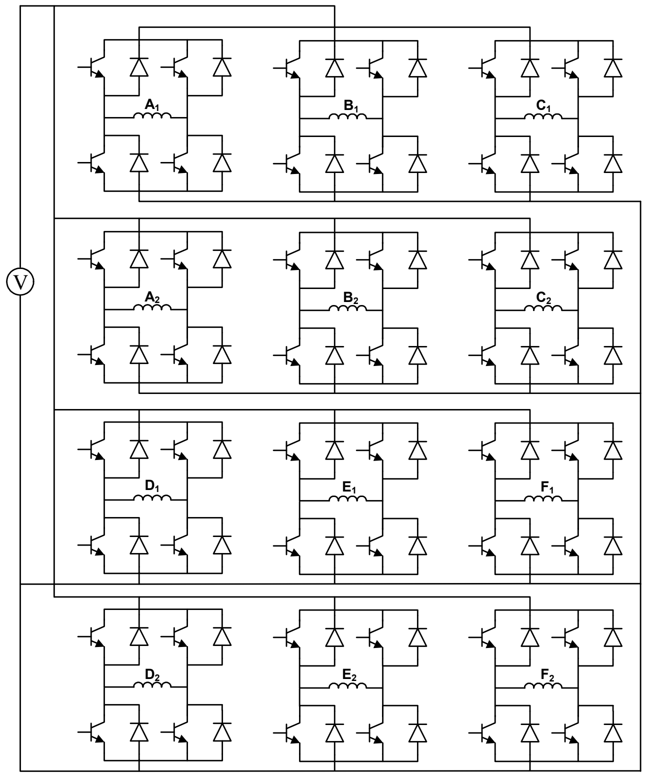


Figure 5. The proposed power converter topology

This topology is a quite complex one: 36 solid-state power switches are required. Beside this each branch needs separate control and protection circuit.

A direct short circuit can occur if the top and bottom switches of the same branch are turned on at the same time. In normal conditions the top and bottom stages of a half of the H-bridge of a single branch are never on at the same time, unless a malfunctioning command is received from its control system. This can be avoided by monitoring the work of the control system.

A more severe fault is when a power switch is short circuited. In this case the solution is the total isolation of the entire branch by opening permanently all the remaining power switches of that bridge. This way practically the damaged branch is physically separated [17].

III. The Simulations

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

The model of the SRM and the electric circuits of the power converter were built up in *Flux 2D* [18].

The generated mesh for the 12/14 poles SRM variant is given in Fig. 6

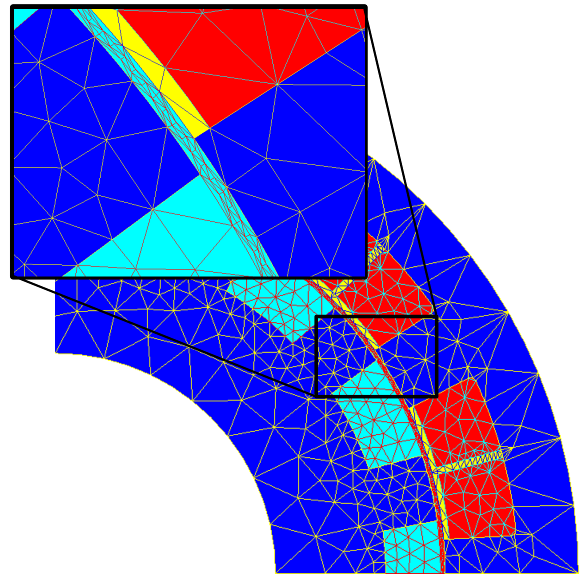


Figure 6. The mesh generated for the proposed SRM

The electrical circuit for a single channel of the machine is given in Fig. 7.

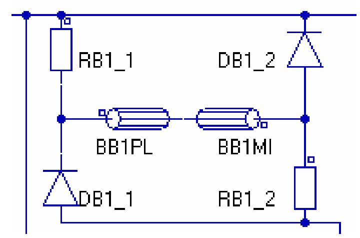


Figure 7. Electric circuit of one channel

The circuit follows the arrangement of a classical H-bridge topology. Usual coils components (like BB1PL and BB1MI) are used to link the two faces of each channel. The power switches are replaced by resistors. These can be easily set from outside the circuit. For the ON / OFF states of the power switches a low (0.004 Ω), respectively a high value (100 kΩ) for the resistance is imposed.

The main program was built up in Simulink®, the most widely used platform for dynamic simulations. Here was also implemented the control strategy for the SRMs.

The two programs were connected together using the Flux-to-Simulink® coupling technology [19]. The finite elements model of the SRM practically is embedded in the Simulink® program via an S-type function block called "Coupling with Flux2d". All the control signals computed in Simulink® are multiplexed and enter in this block. The main characteristics of the machines computed via Flux 2D (currents in all the phases, torque and speed) are returned to the main program through another multiplexed signal line.

The main window of the Simulink® program is given in Fig. 8.

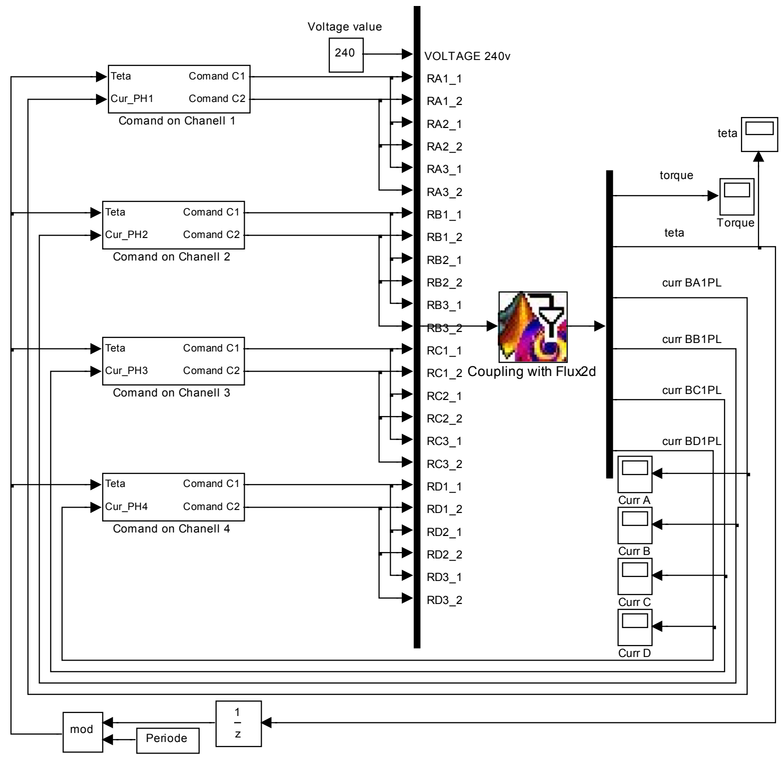


Figure 8. The main window of the simulation program

Six sub-systems (blocks) are simulating the control of the phase currents upon the PWM technique (see Fig. 9). The commutations of the power switches are set upon the rotor position.

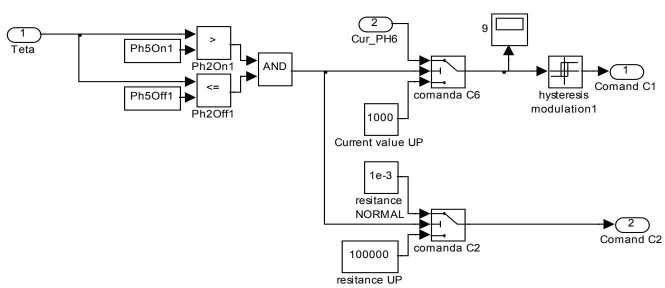


Figure 9 The phase current controller block

Using the above presented coupled simulation program two sample motors were simulated, a 12/8 and a 12/14 poles fault tolerant SRM.

The common geometrical data of the two machines are:

- Stator outer diameter 190 mm
- Stator inner diameter 141 mm
- Stator pole depth 12 mm
- Rotor inner diameter 120 mm
- Active stack length 315 mm

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

i) normal operating mode,
ii) open circuit of one channel (faulty case 1),
iii) open circuit of one phase (faulty case 2),
iv) open circuit of two channels from different phases (faulty case 3) ,
v) open circuit of one phase and one channel from a different phase (faulty case 4, the worst in study).

For both machines the feeding voltage, the currents and the electric parameters of the windings were set identical, therefore a correct comparison of the two machines can be performed.

The obtained results are given in Fig. 10, 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 was computed and filled in the Table I.

TABLE I
RESULT COMPUTED UPON THE SIMULATIONS

	Studied cases	Mean torques [N·m] and percentage of the rated torque
12/8 SRM topology	Healthy case	52.21 (*100%*)
	Faulty case 1	49.10 (*94.04%*)
	Faulty case 2	35.27 (*67.55%*)
	Faulty case 3	46.31 (*88.69%*)
	Faulty case 4	33.36 (*63.89%*)
12/14 SRM topology	Healthy case	19.93 (*100%*)
	Faulty case 1	19.59 (*98.29%*)
	Faulty case 2	16.16 (*81.03%*)
	Faulty case 3	19.28 (*96.71%*)
	Faulty case 4	13.79 (*69.19%*)

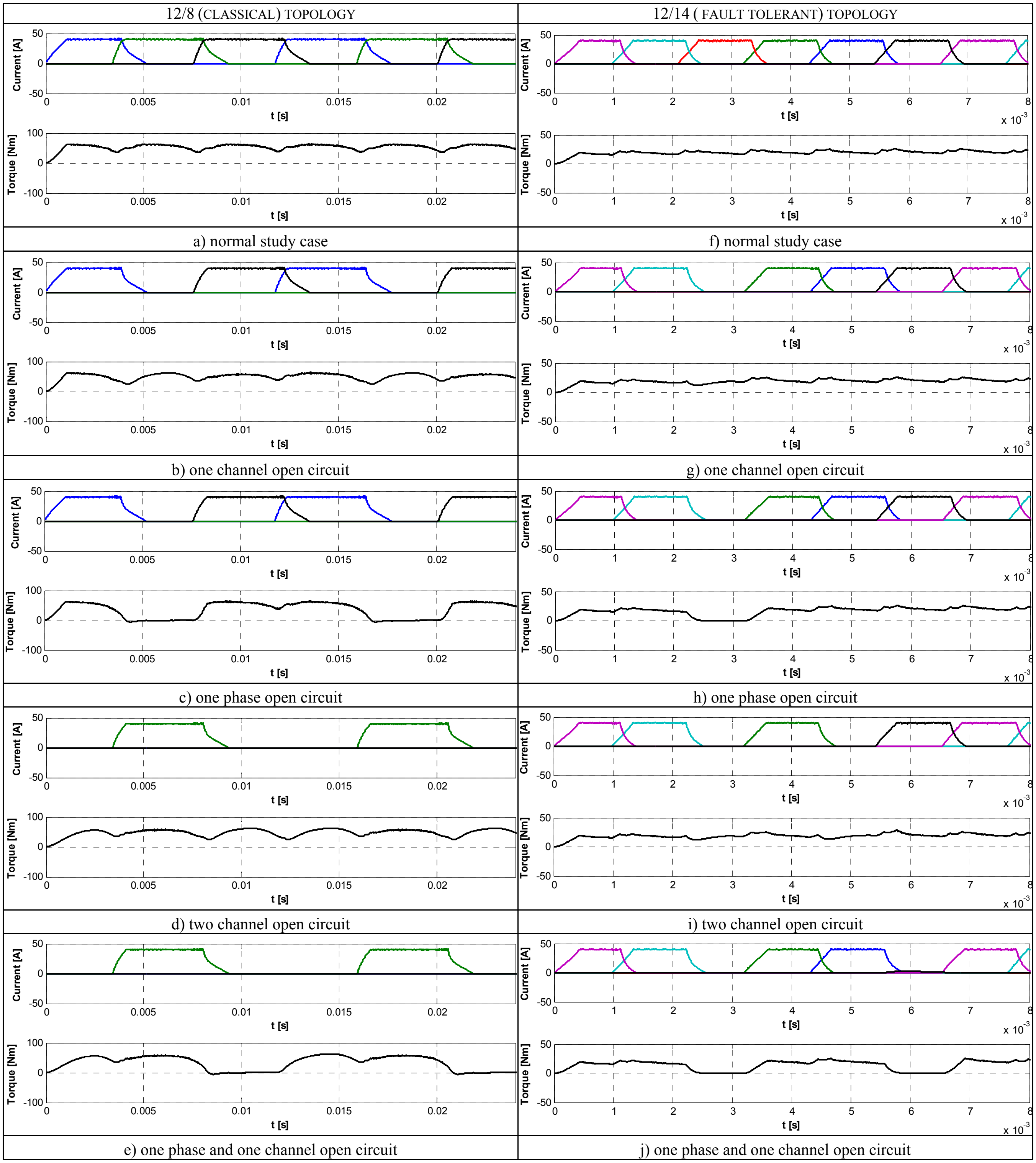


Figure 10 Current and torque plots of the two machines in study under different faulty conditions

Results for the normal operation mode are given in Figs. 10a and 10f. The obtained values are considered as references for the other ones. If only a single channel is opened (Fig. 10b and g), the most probably faulty case, practically both SRMs will be able develop at unchanged currents near the same mean torque as in the case of the healthy machine.

The worst case in study was the fault of an entire phase and a second fault on one channel from a different phase. In this case the torque of both SRMs has great ripples. But as it can be seen in the Table I the fault tolerant 12/14 SRM is still able to develop torque (around 70% of the rated torque) and continue its movement.

Comparing the results from Table I it can be observed that the proposed 12/14 poles SRM has higher torque generation capability at all the faults in study. The main disadvantage of this machine is the complexity of its power converter, hence it has 48 power switches and 48 reverse current diodes.

Separation of the command for each phase or channel increase the overall costs [20]. Upon the demands of specific applications, the electrical drive system (both the power converter and the machine) can be optimized, and a compromise between the required fault tolerance level and manufacturing costs can be achieved.

IV. Conclusions

The coupled simulation program connecting two software environments (FLUX 2D and Simulink®) was useful in studying the effects of different winding faults on the torque developing capacity of the SRMs in study. Thus the computing power of FLUX 2D joined the advanced facilities of MATLAB / Simulink® in simply describing the different working regimes of the machines and drives taken into study.

Problems were regarding the computation times. In order to obtain precise results in reasonable time the quality of the FEM model's mesh had to be optimized.

It was demonstrated by means of simulations that increasing the number of rotor poles, separating the phases/channels, setting new connections between the existing windings and using a complex control system all provide good solutions for the fault tolerant SRM based electrical drive system.

It was also proved that the proposed 12/14 poles SRM has better fault tolerant capacity than then the 12/8 poles SRM having classical construction. This increased fault tolerance unfortunately is achieved by more complex constructions (especially that of the power converter).

An improvement of the performances of the SRMs under faults will be studied in the future. After detecting the fault in a winding it has to be isolated and the current in the remaining healthy phases has to be increased. By this the average torque can be held at its rated value, but of course the torque ripples will be greater. This solution can be used only if the windings and the cooling system of the machine were designed to support the greater currents.

Acknowledgment

A part of the work was possible due to the support given by the Romanian National Center for Program Management (CNMP) under grant "*Parteneriate no. 12121 / 2008*" entitled "*Fault-Tolerant Equipment Controlled by Bio-Inspired Electronic Architectures*" (http://elbioarch.utcluj.ro/).

The authors should like to sincerely thank this way for the financial support.

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