

# Modular Fault Tolerant Switched Reluctance Machine – Design and Dynamic Simulations

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**Abstract**-Electrical machines and drives used in various critical fields must be of special design in order to achieve the required fault tolerance level. In the paper a modular fault tolerant switched reluctance machine is proposed and studied by means of dynamic simulations. It is proved that the machine in study is able to have continuous operation also despite of five severe winding fault conditions.

## I. INTRODUCTION

Fault tolerance is the ability of a system to continue performing its intended function in spite of different faults. The fundamental problem is that, as the complexity of a system increases, its reliability drastically deteriorates, unless compensatory measures are taken [1].

An advanced fault tolerant electrical system has to be capable to detect its faults and to adequately compensate them [2].

Fault tolerance is obligatory in many safety-, mission- and business-critical applications:

- i.) Safety-critical applications are those where loss of life or environmental disaster must be avoided (such as medical and military applications, power plants, etc.).
- ii.) Mission-critical applications stress mission completion, as in case of a spacecraft, airplane or vehicle.
- iii.) Business-critical applications are those in which keeping a factory operating is a key issue and downtimes could cause severe losses. The most typical examples are the advanced industrial systems [3].

Hence the electrical machines and drives used in such systems must be of high fault tolerance. Switched reluctance machines (SRM) seems to be the one of the best solutions for high reliability applications.

It is well known that the SRM is inherently more fault tolerant than other machines, because it can continue operating and producing torque also with one or more faulty phases [4]. This is due to its independent concentrated windings. Its brushless and permanent magnet free closed construction enables a maintenance free utilization even in high temperature, dusty, dirty and vibrations exposed harsh environments [5].

Several methods exist for improving the fault tolerance of a SRM. As a first step the stator poles and phase numbers can be increased [6], [7].

Another usual solution is the division of the phases into individual coils called channels [8]. This way a 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 solu-

tion is that a more complex power converter is required, having as many branches as channels.

Combining the fault tolerance increasing solutions with the modular construction concept a novel SRM was developed, which is high reliable and quickly repairable.

Its fault tolerance is highlighted by means of dynamic simulations performed by a program set up in the MATLAB<sup>®</sup>/Simulink<sup>®</sup> environment. In the simulation program the flux and torque computations are substituted with data extracted from two look-up tables containing the machine's flux and force characteristics obtained via finite elements method (FEM) based numeric field computations [9].

All the obtained results emphasize the high fault tolerance of the proposed SRM.

## II. THE MODULAR FAULT TOLERANT SRM

The proposed fault tolerant SRM is given in Fig 1.

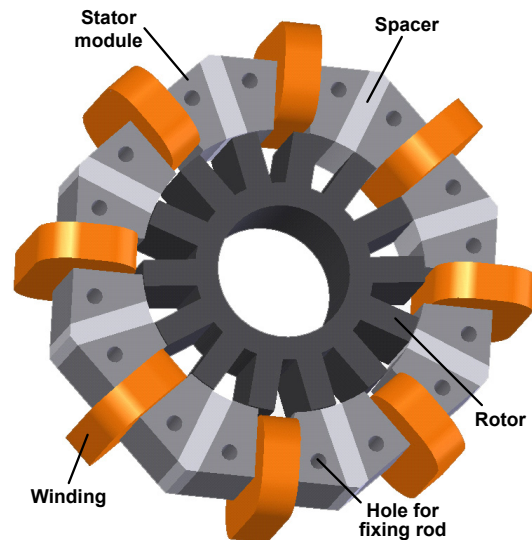


Fig. 1. The modular fault tolerant SRM in study

The aim of its design was to develop a highly fault tolerant innovative SRM which is able to develop 5 N·m torque at 600 r/min speed.

The machine has four phases, each divided into two channels. Each channel is wound on one of the eight module's yoke. The modules of a single phase are placed diametrically opposed (see the flux lines when a phase is fed and the poles are aligned obtained by means of numerical field computation in Fig. 2). The stator modules are separated by non-magnetic spacers, which also assure the correct shifting of the modules.

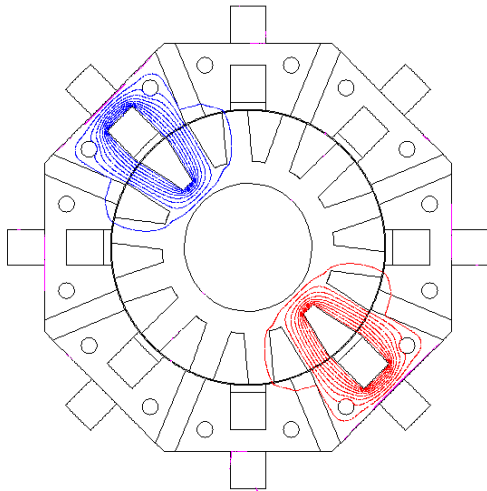


Fig. 2. The flux lines in the SRM in study

As it can be seen the magnetic flux is closed between two adjacent poles of the machine, and it is not passing through the central part of the rotor. Hence due to the shorter flux paths the losses in the machine are less than in its classical counterpart. Also the forces are better balanced.

The modular construction allows both easy manufacturing and fast replacement of the damaged modules in case of a winding failure. Only a single end shield and the two fixing rods of the faulted module have to be detached and the module can be easily pulled out and replaced. This way there is no need of decoupling the machine from its load, a major advantage in industrial environment [10].

The machine's power converter given in Fig. 3 has a separate half H-bridge for every channel. The current in each channel is controlled separately by means of PWM techniques. During the conducting period one switch of the half-bridge is opened permanently, and the other one is commanded via a hysteresis current controller function of the imposed current.

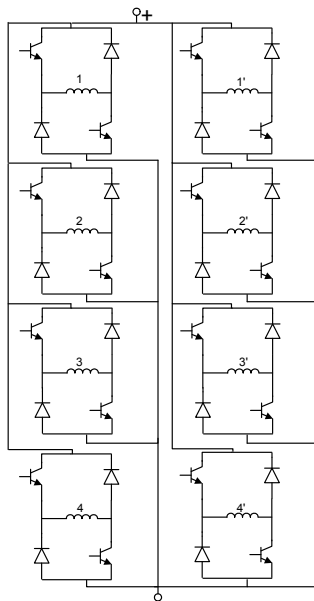


Fig. 3. The power converter

The control system of the machine 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 by the faults [10]. A first answer of the system to an open circuit fault is the increase of the currents in the remaining healthy coils up to a predefined value, which was taken into account when the windings were designed.

The four phase sample machine to be simulated has 350 W. Its rated voltage and current are 300 V and 6 A. It is capable to develop a rated torque of 5 N·m.

The main data of the sample machine are:

- i.) Module height 35 mm
- ii.) Rotor pole height 26 mm
- iii.) Air-gap 0.5 mm
- iv.) Module and rotor yoke height 11 mm
- v.) Rotor and stator pole width 13 mm
- vi.) Winding height 19 mm
- vii.) Outer diameter 210 mm
- viii.) Number of turns of a channel 220.

### III. THE SIMULATION PROGRAM

To be able to study the fault tolerance of the proposed machine dynamic simulations in different operational conditions should be performed.

In a first approach co-simulation technique was applied [11]. The main program was built up in Simulink<sup>®</sup>. The SRM was modelled via the Flux 2D, a FEM based numerical field computation program [12]. The machine's model was connected to the main simulation program thru the Flux-to-Simulink link.

This program was not useful in the case of simulating the machine in an advanced control system due to the long computation times required.

Therefore another approach was applied for the dynamic simulation of the speed control system with the fault tolerant SRM in study.

The model is based on two main characteristics of the machine (the torque and the magnetic flux thru the energised coil versus the rotor position and current as given in Figs. 4 and 5), preliminarily computed by means of field computations performed using the Flux 2D program [13].

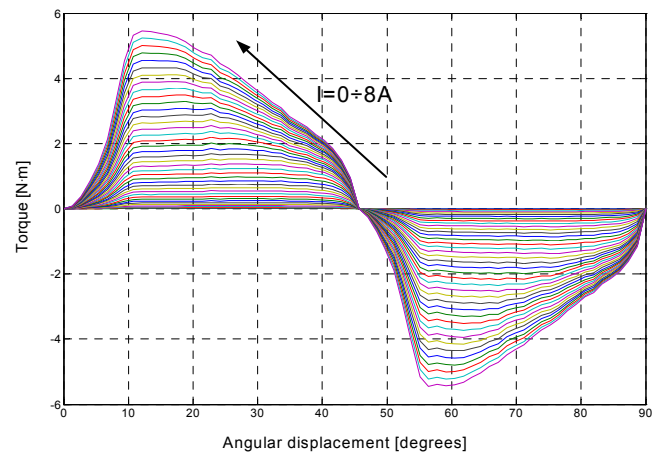


Fig. 4. The torque of the SRM computed for different rotor positions and currents

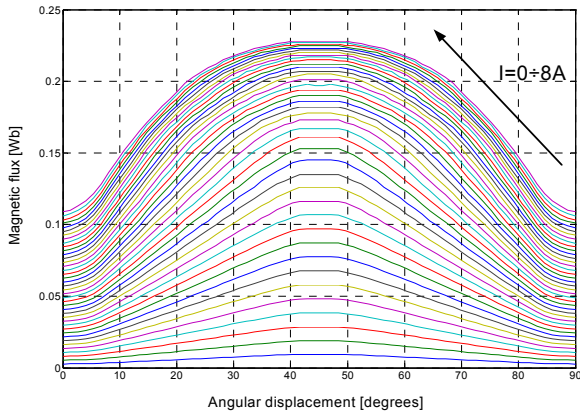


Fig. 5. The flux of the SRM computed for different rotor positions and currents

The two tables containing these data were integrated in the Simulink<sup>®</sup> program by 2-D Look-up Table-type blocks [14]. The main window of the simulation program is given in Fig. 6.

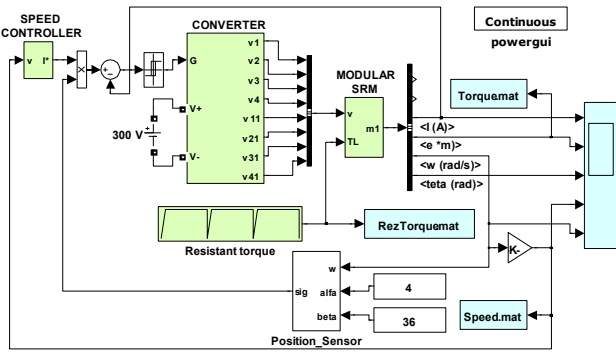


Fig. 6. The main window of the simulation program

In the modularly built up program the main units of the speed control system (the speed controller, the power converter and the modular SRM) can easily be distinguished.

The speed controller is of PI type. The power converter is built up of SimPowerSystems blocks. The machine's model with the two look-up tables is given in Fig. 7.

In the *Mechanic System* block the motion equation is implemented. The trapezoidal shape of the resistant torque is an input parameter of this block. The proper inertia of the rotor was computed during the numeric field analysis of the machine. Also the inertia of the load is taken into account.

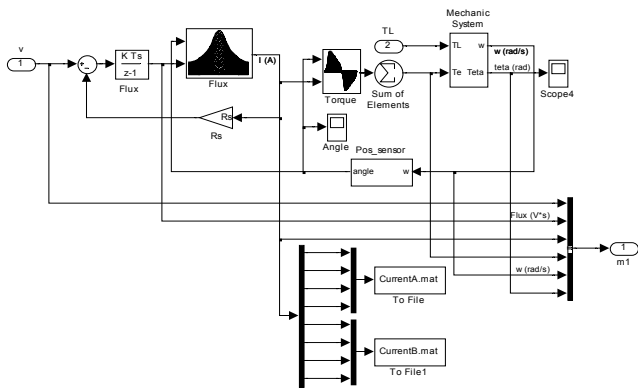


Fig. 7. The model of the SRM

#### 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:

- normal operation mode;
- one channel open;
- two open channels;
- three open channels;
- four open channels;
- one completely faulty (open) phase.

All the simulations were performed in identical conditions. The simulation time was 1 s. The resistant torque is increased constantly up to 5 N·m in 0.1 seconds.

A variable speed profile is imposed to the speed control system. The imposed speed and resistant torque vs. time are given in Fig. 8.

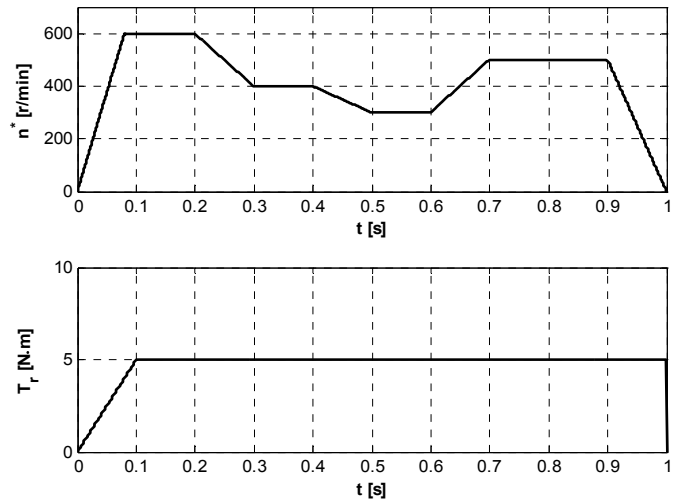


Fig. 8. The imposed speed and the resistant torque vs. time

The results of the simulations are shown in Figs. 9 and 10. In all the six cases two sets of currents (those in the first, respectively second channels of all the phases), the speed and the developed torque were plotted versus time.

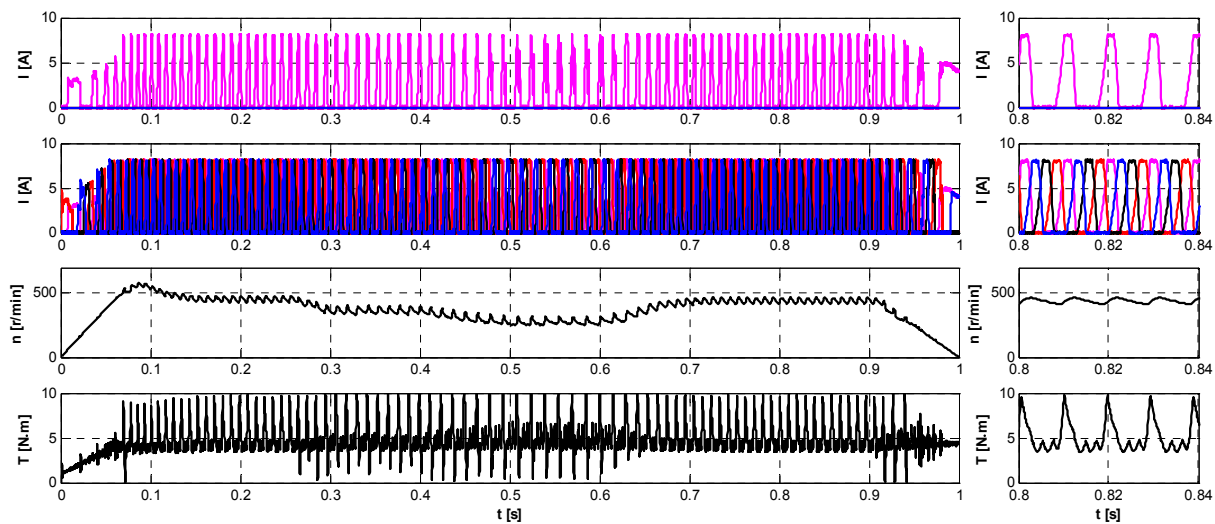
In the left of each plot a zoom taken between 0.8 and 0.84 s is given.

In the caption of the figures the mean speed, the mean torque and the torque ripple are given for all the conditions in study. These were computed during the constant speed movement of the machine between 0.75 and 0.85 s.

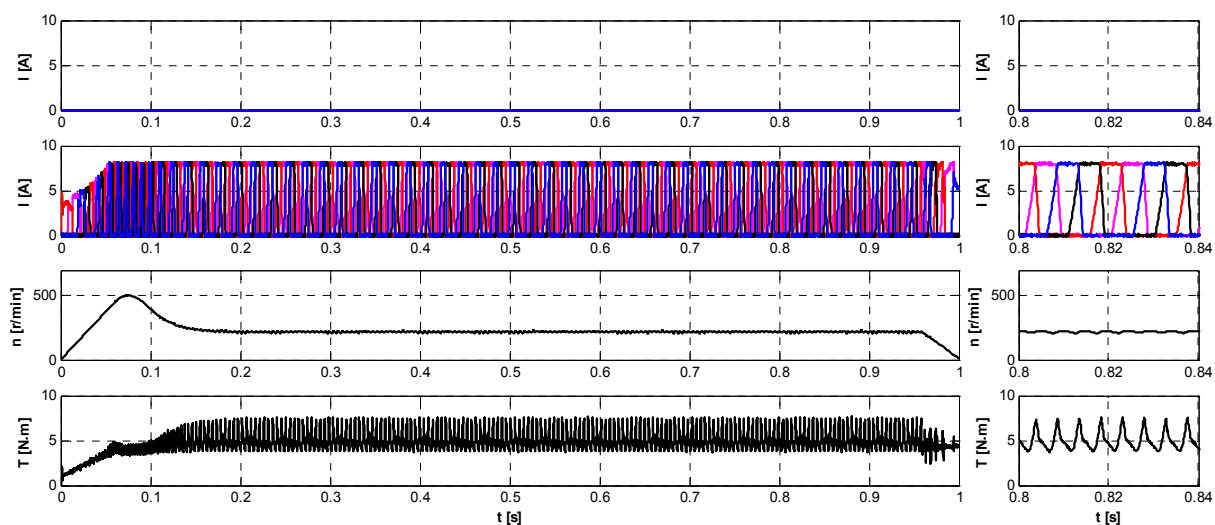
The results of simulation for the healthy machine are given in Fig. 9a. As it can be seen the current pulses are of 6 A, the rated value of the current. The imposed speed profile is quite closely followed. Inherently the machine has a visible torque ripple, this being one of the main drawbacks of SRMs.

The behaviour of the machine at one and two faulted channels can be studied in Fig. 9b, respectively 9c. As it can be seen the currents were increased up to 8 A to compensate the lack of torque due to the opened channels. The torque ripple is obviously much greater than in normal condition. Due to these high torque ripples the speed of the machine also has small fluctuations round the imposed values.

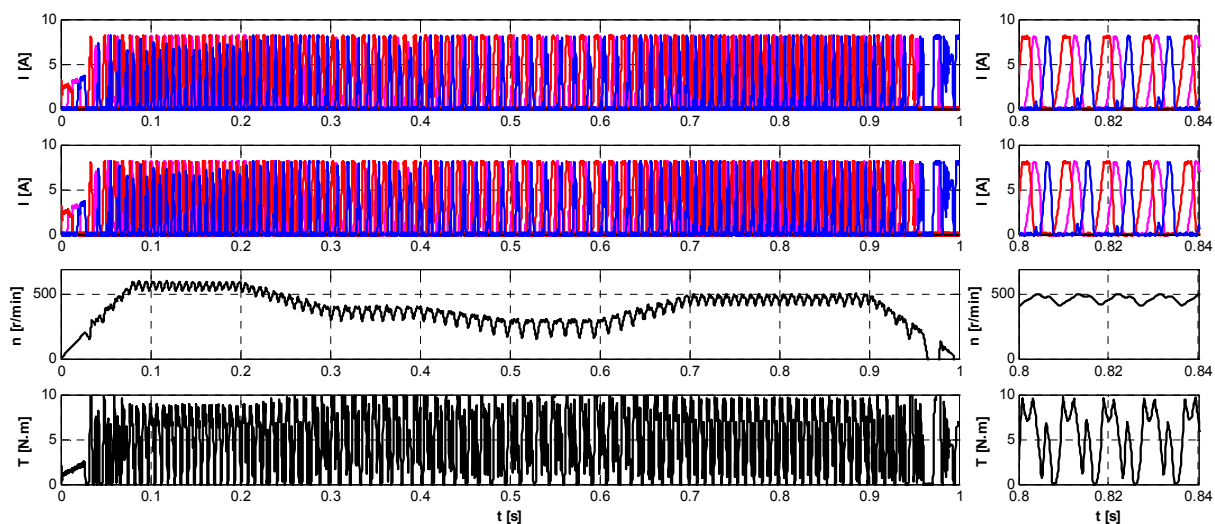




a) three open channels ( $v_{mean} = 440.1$  r/min,  $T_{mean} = 5.1$  N·m,  $T_{ripple} = 6.41$  N·m)



b) four open channels ( $v_{mean} = 219.4$  r/min,  $T_{mean} = 5.04$  N·m,  $T_{ripple} = 3.85$  N·m)



c) one entire phase open ( $v_{mean} = 466.6$  r/min,  $T_{mean} = 5.06$  N·m,  $T_{ripple} = 9.76$  N·m)

Fig. 10. The currents, speed and torque vs. time for different motor conditions

At more severe faults, when three, respectively four channels of different phases are opened the torque ripples remain high (see Fig. 10a and 10b). The control system is no more able to assure precisely the imposed speed. When four channels are opened (practically only half of the machine is operating), the modular SRM in study can run only at about 200 r/min at the rated torque, but it is still rotating. At such damage or the load should be reduced to keep the imposed speed, or the machine will slow down to ensure the torque required.

If an entire phase is faulted (both of its channels opened) the machine can run over the poles with the missing excitation due to the rotor's and the load's inertia (as seen in Fig. 10c). The torque ripples in this case are the greatest ones, due to nil torque developed by the poles with the faulty coils. The speed fluctuations are high, but in certain limits the speed can be controlled.

### CONCLUSIONS

The innovative fault tolerant modular SRM topology completes the few structures cited in literature and can be interested both for researchers working in the field of SRMs and in fault tolerant systems.

The design of the proposed structure was performed accurately taking into account all electromagnetic phenomenon of such a complex structure [15]. The number of poles was increased and the phase windings were split into two separately fed channels. The FEM based numeric computations were in accordance with the analytical ones [10], which proved the correctness of the design.

The MATLAB<sup>®</sup>/Simulink<sup>®</sup> model of the machine in study was proved to be a useful tool in dynamic simulations of diverse conditions of the machine. The integration in the Simulink<sup>®</sup> model of the tables computed via FEM based numeric field analysis increased the precision of the simulations. Hence, in short time numerous simulations could be performed for various operation conditions.

All the obtained results proved the fault tolerant capability of the proposed modular SRM. In very severe conditions (with up to the half of the channels faulted) the main task of a fault tolerant machine was fulfilled: to continue its movement. Of course in such conditions the torque ripples are higher and the speed is reduced.

Beside its fault tolerance another advantage of the machine is its simplicity. The modules can be manufactured separately and the stator can be easily assembled. The rotor is passive, it do not have neither windings, nor permanent magnets. The machine can be quickly repaired if winding faults occur without removing it from the load.

The main drawback of the proposed SRM is the complexity of its power converter. By splitting each phase into two channels, the number of the power converters branches was also doubled.

The machine 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.).

In the future more faulty conditions will be studied (short circuits, power converter faults, etc.). Special attention has to be given to the torque ripple minimisation. This can be improved by increasing the number of poles (and inherently the number of converter legs) or by applying more advanced control techniques [16].

### ACKNOWLEDGMENT

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