USING CO-SIMULATIONS IN FAULT TOLERANT MACHINE'S STUDY

Loránd Szabó
Mircea Ruba
Department of Electrical Machines
Technical University of Cluj
15, Daicoviciu str., RO-400020 Cluj, Romania
E-mail: Lorand.Szabo@mae.utcluj.ro

KEYWORDS
Fault tolerant electrical machines, switched reluctance machines, co-simulation, numerical field computation.

ABSTRACT

The Switched Reluctance Machine (SRM) is ideal for safety critical applications (aerospace, automotive, defense, medical, etc.) where it is desirable that the electrical drive system to be fault tolerant. During the design of a fault tolerant electrical drive system it is indispensable to use advanced simulation techniques. Finite elements method (FEM) based magnetic field computation programs are the most precise tools in simulating the electrical machines. These programs must be embedded in a general simulation platform.

The paper deals with the analysis of a proposed SRM's fault tolerant capacity. The study was performed by means of a coupled simulation program. The main program was built up in Simulink®, the most widely used dynamic system simulating platform. The SRM was modeled using the Flux 2D FEM based numerical field computation program. The machine's model was connected to the main program thru the Flux-to-Simulink link.

This co-simulation technique proved to be a very useful tool in the fault tolerance study of the proposed SRM.

INTRODUCTION

When designing a new technical system the flowchart given in Fig. 1 must be followed (Lewis 1974).

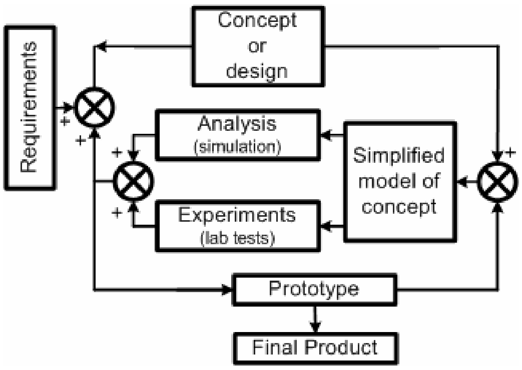


Figure 1: Design flowchart

The design is created firstly in the mind of the engineer. Later a list of specifications must be identified including with the envisions which would satisfy the design's requirements. In the next stage the designer creates (firstly in his own mind) a product that meets the specifications. Next the "mind model" of the new product must be transferred into a "symbolic" or "physical" model.

It is usually best to work with symbolic models at first, because they are less expensive than physical (laboratory) models. A symbolic model is a mathematical model of the system which describes its basic behavior.

By simulations (practically by solving the equations of the mathematical model) the entire behavior of the system can be studied, and important conclusions can be drawn on the way the designed system fulfills the requirements. Based on these conclusions modifications in the design have to be performed. This checking loop should be completed until the system is closed to that required.

Only in this stage of the design an experimental model of the system is worth to be built up. If both the results obtained via simulations and experiments are acceptable the prototype of the system can be built up and tested. The final decision on the correctness of the design shall be stated only based on the test results.

Upon these is clear how important the modeling and simulations are.

FAULT TOLERANT ELECTRICAL DRIVE SYSTEMS

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 (Blanke 2006).

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 (Isermann 2005). 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 (Laprie 1992).

Proceedings 23rd European Conference on Modelling and Simulation ©ECMS Javier Otamendi, Andrzej Bargiela, José Luis Montes, Luis Miguel Doncel Pedrera (Editors)
ISBN: 978-0-9553018-8-9 / ISBN: 978-0-9553018-9-6 (CD)

The fault tolerant design of complex electrical systems is becoming our days a necessity for a growing number of fields, far beyond its traditional application areas, like aerospace, military and vehicles.

For example a fault of an electric drive system used in propulsion applications can be critical, since an uncontrolled output torque may have an adverse impact on the vehicle stability, which ultimately can risk the passenger safety. A failure of an electrical drive system can have disastrous effects also on a plant's ability to function. Both the converter and motor faults can cause unscheduled downtimes that can result in lost production and revenue (Ruba 2008a and Suresh 2006).

These and similar applications stimulated the researches in the field of fault tolerant electrical machines and drives (Rene 1992).

In safety critical applications both the electrical machine and its power converter must be fault-tolerant.

In the last decade several proposals to improve the electrical machine's reliability had been published. The fault-tolerant machine must have a special design. Inherently by increasing the machine's fault tolerance its losses could be greater and its efficiency less than those of its usual counterpart (Ivonne 2008).

Thanks also to the improvements in the field of power electronics and of 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 are the most frequently used methods to achieve the required fault tolerant capacity (Heimerdinger 1992 and Zhang 2003).

THE PROPOSED FAULT TOLERANT SWITCHED RELUCTANCE MACHINE

The SRM in study having a 12/14 pole structure is shown in Fig. 3 (Ruba 2008c). This structure emerged from the classical 12/8 model (Krishnan 2001), as that could be transformed relatively easily in a fault tolerant variant.

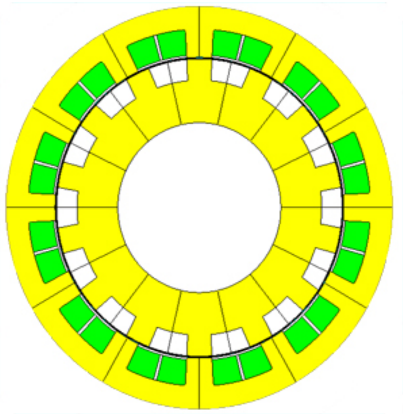


Figure 3: The proposed fault tolerant SRM

The proposed modifications were implying both the rotor structure (Ruba 2008b) and the connection of the stator windings.

The winding scheme is a six phase duplex type. Practically each phase is split into two channels. At each time two channels, diametrically disposed, are fed (see Fig. 2). Hence at each moment two pairs of adjacent stator poles are contributing to the torque development. In case of a fault on one channel this will not contribute anymore to the torque generation. The second channel connected in parallel is independent of the faulty one and will continue its operation. This winding connection helps the motor to overrun the poles with faulty phases and to minimize the torque ripple.

As it can be seen in Fig. 2 the proposed SRM has shorter flux paths as its classical counterpart, which means less iron losses.

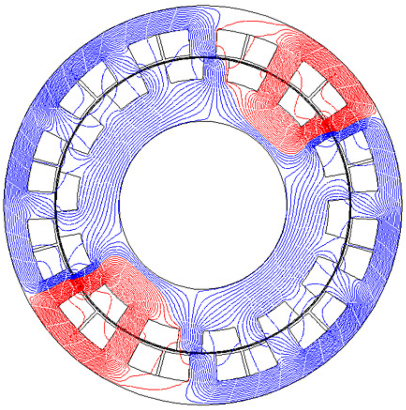


Figure 2: The flux lines in the SRM

The machine is fed from a special power converter (see Fig. 4), which has a separate half H-bridge circuit for every channel in order to be able to control each one independently, as requested by the fault tolerant design.

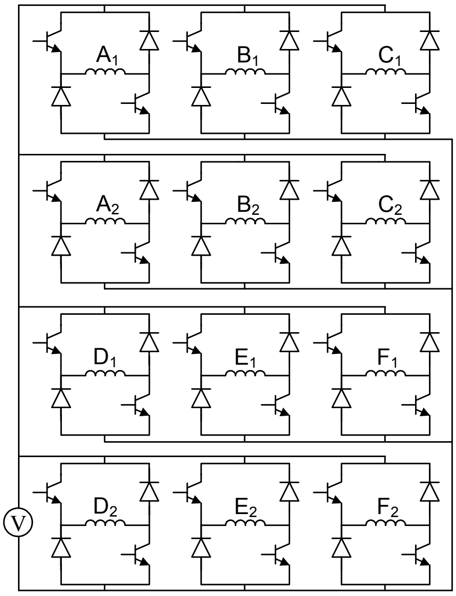


Figure 4: The converter of the proposed SRM

A main disadvantage of the proposed 12/14 fault tolerant SRM is its power converter (Szabó, 2008). This to be also fault tolerant has to be complex, and able to detect and isolate the defects. It has 24 power switches and 24 reverse current diodes. The separate command of each channel will increase its costs.

THE COUPLED SIMULATION PROGRAM

Modeling complex electromechanical systems is a rather difficult task, because such systems often have sub-systems, components and aspects whose structure, as well as behavior cannot be described in a single comprehensive formalism. Different approaches to model such complex systems are possible (Vangheluwe 2002):

i.) A single super-formalism may be constructed which subsumes all the formalisms needed in the system description.

ii.) Each system component may be modeled using the most suitable formalism and tool. To investigate the overall behavior of the system, co-simulation can be used. In this approach, each component model is simulated with a formalism-specific simulator. In this case the co-simulation engine orchestrates the flow of input/output data in a data-flow fashion.

In order to analyze the fault tolerance of the proposed SRM adequate simulation programs are required. Hence, the electrical machine and its electronic converter must be simulated by means of coupling two software packages.

The MATLAB/Simulink® environment is perfectly suited for the platform that simulates the converter and imposes the different working regimes and machine conditions. Flux 2D solve numeric field computation problems, like modeling electrical machine structures. By coupling these two platforms, simulations suitable for in depth analysis can be accomplished.

It should be mentioned that the co-simulation term has also other meanings. It is also used for the joint simulation of the hardware and the software. In this case the co-simulation is usually applied to substantiate heterogeneous specifications, or to validate the hardware and software parts of a complex electrical system and their interactions (Ruelland 2001). In other cases this term covers the association of a numerical (digital) and continuous models of a complex system (Belhadj 2003).

Firstly the machine's geometry was built up using the graphical commands of Flux 2D. Also in this pre-processing stage the materials were assigned to each subdomains (stator and rotor iron core, windings, etc.).

Next the mesh required by the FEM was generated. This is an essential stage hence both the precision and the computation times depend on the correct generation of the mesh. It must be dense enough for precise calculation and also optimal for not consuming a lot of the computational time (Hameyer 1999). The most attention was paid to the mesh round the air-gap, the most important part of an electrical machine.

In the next step the electrical circuit attached to the machine's model was set up. The proposed 12/14 SRM structure has 6 phases, each split into 2 channels. The electrical circuit for a single channel of the machine in study is given in Fig. 5.

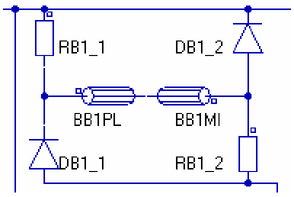


Figure 5: Electric circuit of one channel

The circuit follows the arrangement of a classical H-bridge topology. The power switches are replaced by resistors. These resistors can be easily controlled 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.

Usual coils components (like BB1PL and BB1MI in Fig. 5) are used to link the two faces of each channel from the geometrical design with the attached electrical circuit. Their characteristics (conductor material, number of turns, etc.) were set in accordance with the real winding arrangements. For each channel of the SRM two such components are used: the "come" and "go" sides (faces) of the winding.

As it was stated previously at each time two channels (4 coils) are fed by the two corresponding H-bridges. The H-bridges are connected in parallel to the main bus bars, and they are commanded separately, but synchronously.

The block diagram of the coupled simulation program is given in Fig. 6. The imposed simulation task is solved by means of time stepping method.

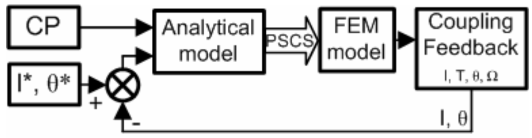


Figure 6: The block diagram of the coupled simulation program

The FEM model of the SRM is embedded in the main SIMULINK® program. The analytical model of the drive system is computing at each time step the power switches command signal (PSCS), which are practically setting the values of the resistors from the machine's circuit model. The computations are performed using several constant parameters (CP) as being inputs in the system, respectively the current (I) and the angular position (θ) error signal. 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 (T), the mechanical speed (Ω) and the angular position of the SRM at that time step.

The main window of the simulation program is given in Fig 7.

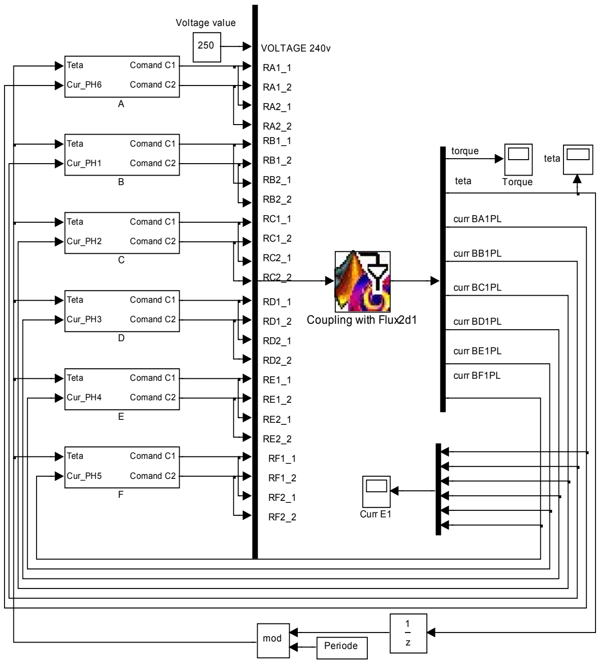


Figure 7: The main window of the simulation program

As it can be seen 6 sub-systems (blocks) are controlling the phase currents upon the PWM technique. The commutations of the power switches are set upon the rotor position. Each block is built up using logical, switch and hysteresis blocks, as shown in Fig. 8.

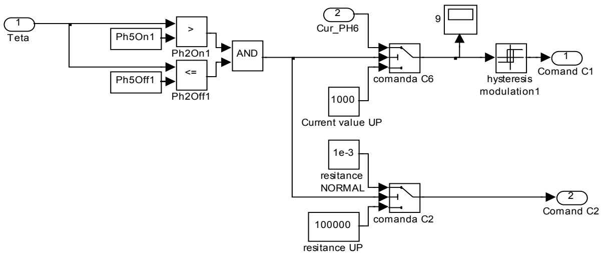
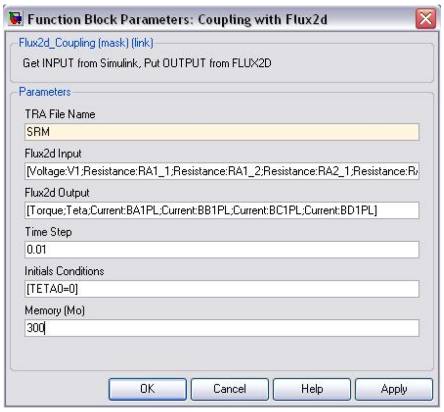


Figure 8: The phase current controller block

The FLUX 2D model of the SRM is embedded in the main program via an S-type function called *Coupling with Flux2d*. Its mask is shown in Fig 9.


Function Block Parameters: Coupling with Flux2d

Flux2d_Coupling (mask) (link)

Get INPUT from Simulink, Put OUTPUT from FLUX2D

Parameters

TRA File Name: SRM

Flux2d Input: [Voltage:V1;Resistance:RA1_1;Resistance:RA1_2;Resistance:RA2_1;Resistance:R

Flux2d Output: [Torque;Teta;Current:BA1PL;Current:BB1PL;Current:BC1PL;Current:BD1PL]

Time Step: 0.01

Initials Conditions: [TETA0=0]

Memory (Mo): 300

Figure 9: The mask of the coupling block

All the control signals computed in SIMULINK® and entering this block are multiplexed. The outputs of the field computations are returned to the main program through another multiplexed signal line.

RESULTS OF SIMULATIONS

The main data of the SRM in study are:

i.) Voltage: 250 V
ii.) Reference phase current: 40 A
iii.) Input phase power: 10 kW
iv.) Phase resistance: 1.2 Ω
v.) Number of turns per phase: 100

Constant velocity was imposed (600 r/min) during the time stepping simulation. The fault tolerance capacity of the SRM was studied in steady-state regime was considered.

The proposed SRM was simulated under different conditions in order to check its fault tolerance capability:

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

In all the cases the simulation time 8 ms in no-load conditions. The mean torque developed in normal operating mode was the reference value in this study.

The current and torque waveforms versus time for the healthy and for all the four faulty conditions of the proposed SRM are given in Fig. 10.

As it can be seen in the figure a short transient period is required still the current reaches its maximum value.

In the plots the effects of faults can be observed as missing currents and decreasing torques, due to the faulty windings.

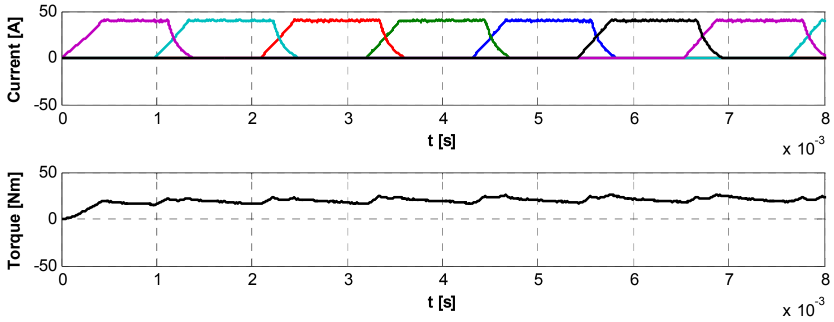
The current and torque plots for the healthy machine operating under normal conditions are given in Fig. 10a. As the machine has higher number of phases and stator poles than the usual 12/8 topology the torque ripples are relatively lower (Ruba 2008c).

If one channel is open (Fig. 10b) due to the missing channel's currents the torque is lower than in the previous case and torque ripple is higher.

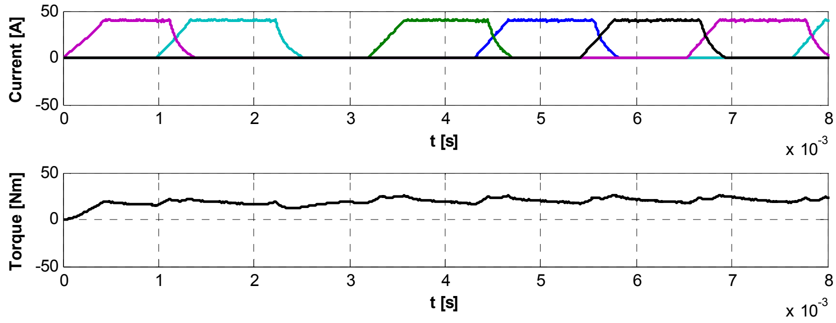
When an entire phase is faulty (Fig. 10c) there are moments when the torque is falling to zero, because the load inertia and the resistive torque are nil, at no-load conditions.

In the situation of the faults on two different channels from two different phases, Fig. 10d, the torque ripple is greater.

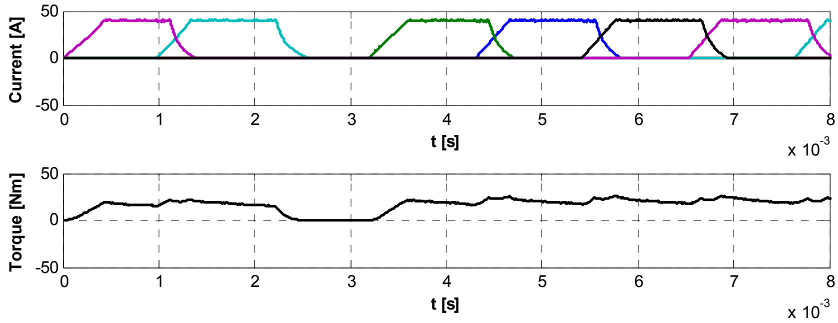
The worst case in study is the fault of an entire phase, and a second fault on one channel from different phase (Fig. 10e). The torque ripples in this case are the highest.



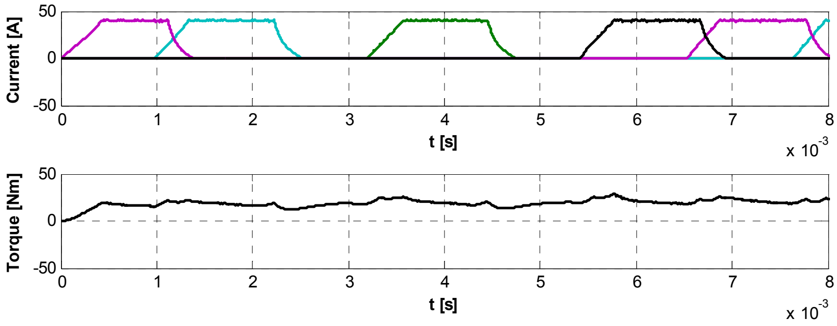
a) normal study case



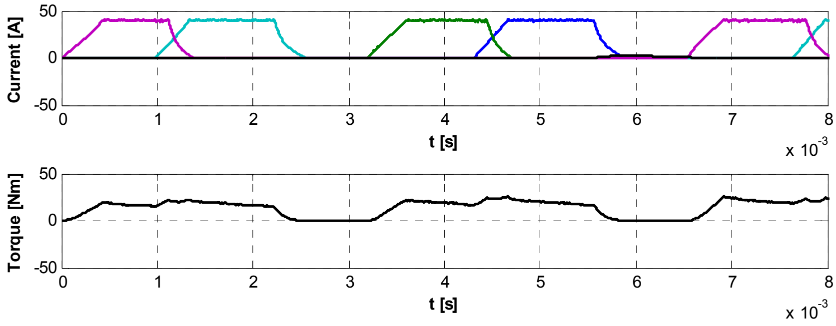
b) one channel open circuit



c) one phase open circuit



d) two channel open circuit



e) one phase and one channel open circuit

Figure 10: Current and torque plots of the SRM in study under different faulty conditions

Results concerning the torque development capability of the SRM in study are given in Table 1.

Table 1: The mean torques of the SRM for all the cases taken in study

Studied cases	Mean torques [N·m] and percentage of the rated torque
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%)

The torque ripples are different from a case to another and depend on the fault's severity.

As seen in the Table 1 the proposed fault tolerant 12/14 SRM topology is able to develop torque (around 70% of the rated torque) and continue its movement even at the hardest fault in study, when one phase and one channel from a different phase is damaged. Obviously the torque ripples are the greatest in this case. Of course heating and force distribution issues limit the operation in this faulty case

In the case of the first fault in study, nearly full torque is developed (more then 98% of the rated value). Also high mean torque is generated when two channels from different phases are opened (Fig. 10d).

A solution to improve the torque development of a machine in case of faulted windings is to isolate the defect, and to increase the current in the remaining healthy phases. By this the torque's average value can be held at the same value as in normal operation mode. Unfortunately this solution do not decrease the torque ripples.

Higher currents mean higher temperature and higher losses. Uncontrolled temperature rise can damage the healthy phases, on one side, and on the other, operation at higher currents demand higher power converters.

Hence this solution can be used only if the windings and the cooling system of the machine were designed to support the greater currents and over heating.

CONCLUSIONS

The study demonstrated that increasing the number of rotor poles and stator winding phases, separating the phases/channels, setting new connections between the existing windings, and using a complex control system all provided good solution for the fault tolerant SRM based electrical drive system.

The increased number of rotor poles and the more complex electronic system that drives and controls the machine means of course higher costs. These costs depend on the level of tolerance implemented in the system.

Upon the demands of specific applications, the electrical drive system (both the power converter and the machine) can be optimized and a compromise between fault tolerance level and manufacturing costs can be made.

The fault tolerance study of the proposed SRM was carried out upon the results of simulations. The transient regime simulation of the entire electrical drive (the machine and its converter) was performed using the advanced coupled simulation technique (FLUX 2D to Simulink®). This way it was taken advantage of the high precision machine analysis capabilities enabled by the FLUX 2D FEM based numeric field computation program and the easy-to-use, but advanced MATLAB/ Simulink® environment. In Simulink® it was very simply to impose different working regimes and faulty cases.

The use of co-simulation techniques offers several advantages:

i.) It is possible to have full system simulations even with mixed-signal parts.
ii.) It permits full system simulations reducing verifications and testing costs compared to full laboratory system testing in real hardware.
iii.) Simulink offers easy-to-use environment for simulations.
iv.) The use of the most proper simulation program for each system component.

Future works are regarding changes of the machine geometry by new placements and connections of the windings. The different constructions shall be compared by means of co-simulation techniques. The prototype of the best fault tolerant SRM variant is intended to be built up.

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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AUTHOR BIOGRAPHIES

LORÁND SZABÓ (M '04) received the B.Sc. and Ph.D. degree from Technical University of Cluj (Romania) in electrical engineering in 1985, respectively in 1995. Currently, he is a Professor in the Department of Electrical Machines of the same university. His research interests are in the areas of variable reluctance machines, fault detection, etc. He published over 140 scientific papers and books in these fields.

His e-mail address is: *Lorand.Szabo@mae.utcluj.ro* and his Web-page can be found at http://memm.utcluj.ro/szabo_lorand.htm.

MIRCEA RUBA received the B.Sc. and M.S. degree from Technical University of Cluj (Romania) in electrical engineering in 2007, respectively in 2008. He is a full time Ph.D. student working in the field of fault tolerant switched reluctance machines. His e-mail address is: *Mircea.Ruba@mae.utcluj.ro* and his Web-page can be found at http://memm.utcluj.ro/mircea_ruba.htm.