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Loránd Szabó, Mircea Ruba, Csaba Szász, Virgil Chindriş, Géza Husi

Fault Tolerant Bio-Inspired System Controlled Modular Switched Reluctance Machine

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Original scientific paper

Fault tolerance is an obligatory feature in safety critical applications (aeronautical, aerospace, medical and military applications, power plants, etc.), where loss of life, environmental disasters, equipment destructions or unplanned downtimes must be avoided. For such applications, a novel bio-inspired motion control system is proposed. All its three components (the switched reluctance machine, the power converter and the control system) are designed to be as fault tolerant as possible. This paper describes all these three fault tolerant components: the bio-inspired control system having self-healing capabilities, the power converter with an extra leg and the fault tolerant modular machine. The theoretical expectations and simulation results are validated by means of laboratory experiments.

Key words: Fault tolerance, Bio-inspired system, Artificial cell, Embryonic machine, Motor control, Switched reluctance machine, Modular construction

Upravljanje otporno na kvarove modularnim prekidačko-reluktantnim strojem nadahnuto prirodom. Otpornost na kvarove je nužnost u sigurnosno kritičnim aplikacijama (aeronautičke, zrakoplovne, medicinske i vojne aplikacije, elektrane itd.), gdje je potrebno izbjeći smrtne slučajeve, prirodne nepogode, uništenje opreme ili neplanirane prekide u radu. Za takve aplikacije, predložen je novi slijedni sustav nadahnut prirodom. Sve tri komponente (prekidačko-reluktantni stroj, pretvarač i sustav upravljanja) su projektirani da budu što je više moguće otporni na kvarove. Ovaj rad opisuje sve tri komponente: sustav upravljanja nadahnut prirodom sa samoliječećim svojstvima, pretvarač s dodatnom granom i modularni stroj otporan na kvarove. Teoretska očekivanja i simulacijski rezultati su provjereni laboratorijskim eksperimentima.

Ključne riječi: otpornost na kvarove, sustav nadahnut prirodom, umjetna stanica, embrijski stroj, upravljanje motorom, prekidačko-reluktantni stroj, modularna konstrukcija

1 INTRODUCTION

Fault tolerance is the ability of a system to continue performing its intended function in spite of different faults, expectedly occurring in any system. As the complexity of a system increases, its reliability drastically gets worse, unless compensatory measures are taken [1].

An advanced fault tolerant electrical system has to be capable of detecting its faults and able to adequately compensate the failures [2]. Fault tolerance is an obligatory feature in almost all of the safety-critical applications, where loss of life or environmental disasters must be avoided (aeronautical, aerospace, medical and military applications, automated manufacturing systems, power plants, vehicles, etc.) [3].

Hence, also the electrical motion control systems (compound of the motor, the power converter and the control unit) used in such applications must tolerate faults. The high fault tolerance of these components can be achieved in different ways.

In the field of fault tolerant electrical machines two main research directions can be observed nowadays: one dealing with permanent magnet (PM) motors [4], [5] and the other one with fault tolerant switched reluctance machines (SRMs) [6]. Each variant has its advantages and drawbacks. A detailed survey on fault tolerant electrical machines can be found in [7].

The most inherently fault tolerant electrical machine is the SRM [8], [9]. Additionally, it does not have costly permanent magnets. Therefore, our study focused on this type of machine. The fault tolerance of the SRM can be improved by a novel modular construction, by feeding all of its coils separately.

The applied power converter is also of increased fault tolerance due to its extra redundant converter legs.

As it was stated already it is equally important also the fault tolerance of the SRM's control system. For such purposes, the proposed bio-inspired control system is a good choice to improve the dependability of the classical control units.

Bio-inspired control systems have already been proposed for diverse applications, as for manufacturing systems, robotics, IT applications [10], [11], [12], etc. To control electrical machines directly by bio-inspired self-healing systems is a new approach not yet cited in the literature.

In the paper, all three constituents of the SRM based fault tolerant motion control system are described in details. Their unified analysis from the fault tolerance's point of view is new in the literature; therefore, it could be of real interest for all the specialists working in this field.

2 THE MODULAR SWITCHED RELUCTANCE MACHINE

The SRM is the most fault tolerant electrical machine, because it can develop torque, within certain limits; even when one or more coils are faulty [13], [14], [15]. This is mainly due to its independent concentrated windings. Its brushless and permanent magnet free simple construction enables a reliable and maintenance free utilization even in high temperature or in dusty, dirty and vibrations exposed harsh environments [16].

Several methods exist for improving the fault tolerance of a SRM. In the first approach, the stator poles and phase numbers can be increased [17], [18]. Another usual solution is the division of the phases into individual coils [19], this way a fault of a coil will not influence the work operation of the other coils 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 coils [20].

To combine the advanced fault tolerance solutions with the modular construction concept, a novel SRM was developed, which is highly reliable and quickly repairable. The proposed modular SRM is given in Fig. 1.

The machine has four phases, each divided into two coils. Each coil is wound on one of the eight module's yoke. The modules of a phase are placed diametrically in opposition to the stator's core. The accurate distance between the two neighboring modules is set by nonmagnetic spacers. The entire modular construction is tightened by 16 rods, 2 through each module, as shown in Fig. 2.

The modular stator is placed between the two end shields. Nonmagnetic spacers keep the stator centered in the middle of the motor. The rotor has a usual construction built of laminations. An encoder is placed on the machine's shaft for the precise measurement of the rotor position required by the control system.

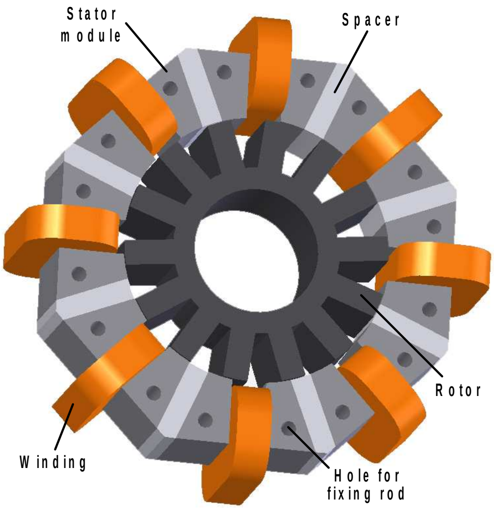


Fig. 1: The modular SRM in study.

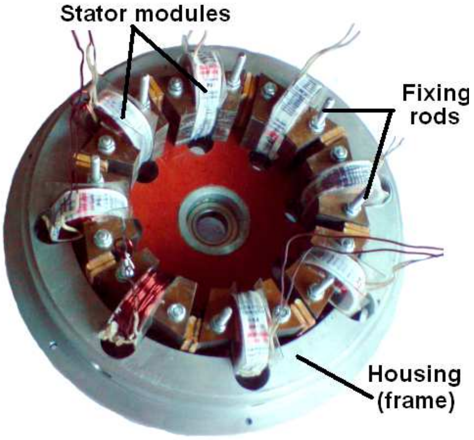


Fig. 2: The frame of the SRM with themodules placed around.

The prototype of the fault tolerant modular SRM built up in our laboratory is given in Fig. 3.

One of the main advantages of the novel modular SRM construction is emphasized by the flux lines obtained via numeric field analysis, which is performed by using Flux 2D finite elements method (FEM) based software package.

Figure 4 shows that the magnetic flux lines are closed between the two poles of a single module, hence it does not pass through the central part of the rotor, similarly to the SRM described in [21]. Due to the shorter flux paths, the losses in the machine are less than in a classical 4-phase

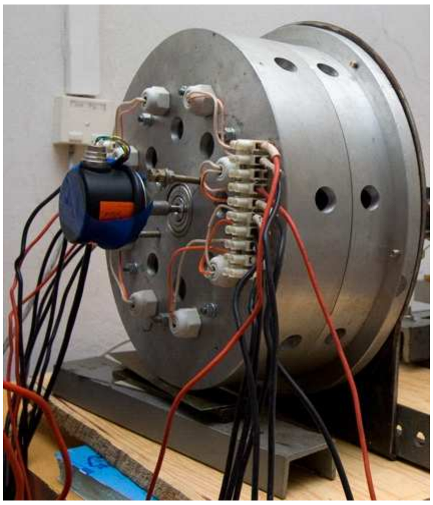


Fig. 3: The prototype of the modular SRM.

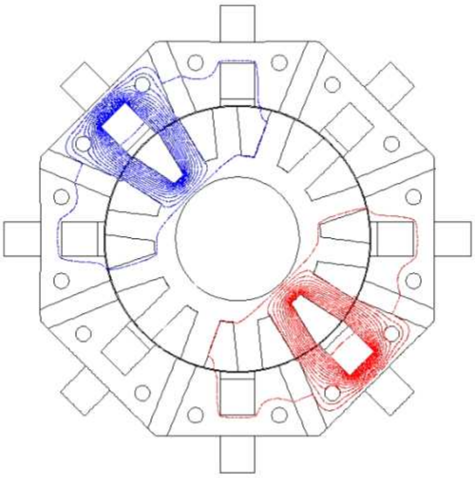


Fig. 4: The flux lines in the SRM for aligned position obtained by means of numeric field computations.

SRM. Furthermore, the balance of the forces is better in the machine.

The modular construction enables 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 [22].

The fault tolerance of the motor was studied previously by means of the most advanced simulation tools [23]. The machine's model was built up in the Flux 2D FEM based numerical field computation program and it was connected to a main Simulink program thru the Flux-to-Simulink link [24].

All the performed simulations demonstrated that the machine is able to maintain its movement also in severe faulty conditions (four coils opened in different phases of the machine, or an entire phase opened). The modular SRM can develop also in these conditions near 50% and 75% of its rated torque, respectively. Certainly, in such circumstances, the torque ripples are higher and the machine can only work at reduced speed. However, it can fulfill the main requirement in a safety-critical application: not to stop due to the faults.

3 THE POWER CONVERTER

As it was already described, in an advanced fault tolerant electrical drive system the power converter must be fault tolerant, too. In the literature, three main approaches are cited concerning the fault tolerance of the power converters [25]:

i.) applying a special design (with redundant spare legs)

ii.) without redundant power switches or diodes, but adding to the converter external electromagnetic switches, which can introduce possible additional connections between the legs of the converter [26]

iii.) by using adequate control strategy to avoid the fault's influence as much as possible [16], [27].

As the modular SRM in study requires only bipolar current pulses, each coil of the machine can be supplied through a separate half H-bridge converter leg. Additional redundant backup legs are provided in order to undertake the role of the eventually faulted legs, as shown in Fig. 5.

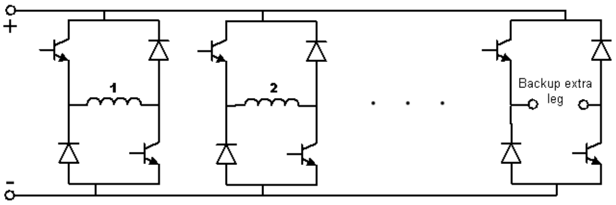


Fig. 5: The fault tolerant power converter.

It should be mentioned that each inverter leg from the converter given in Fig. 5 is itself fault tolerant because it eliminates the possibility of a rail-to-rail short circuit [16].

4 THE BIO-INSPIRED CONTROL SYSTEM

As it is well known, the nature suggests the best models for advanced control systems [28]. For example, the immune system of higher order biological organisms is a distributed and multilayered system. It is robust and it is able to identify infectious pathogens, injury, diseases or other harmful effects. Therefore their properties and abilities – mainly like self-healing or surviving – could serve as models also in the case of the modular SRM's control system, were robustness and fault tolerant operation are basic requirements.

The proposed bio-inspired system is modeled on a POE-type (Phylogeny, Ontogeny and Epigenesis) embryonic structure, developed in analogy with the evolutionary processes of biological systems [29], [30].

Phylogeny (P) explains genetically the evolution of species. In engineering sciences, this corresponds to the genetic algorithms and evolvable hardware. Ontogeny (O) involves multi-cellular organization, cellular division and differentiation from the mother to the daughter cell (each cell owns a copy of the original genome). Finally, Epigenesis (E) is concerned with learning and adaptation processes (for example nervous and immune system, etc.) [31], [32].

In accordance with the POE-type model, the embryonic systems derive from the multi-cellular structure of complex living organisms with strong hierarchical organization from molecular to population levels, as shown in Fig. 6 [33].

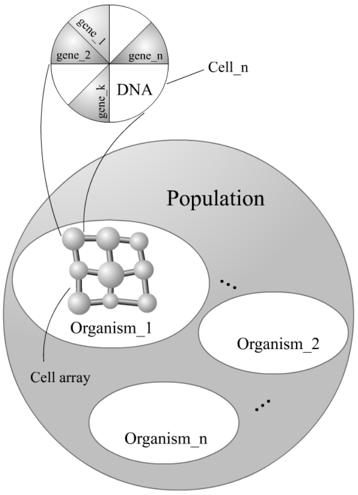


Fig. 6: Living organism's evolution process as model for POE-type artificial immune hardware systems development.

All multi-cellular organisms start their life as a single cell, which divides repeatedly to generate numerous identical copies of it. Each cell contains all the information necessary to create the entire entity, the genotype (DNA). As the number of cells grows, cell differentiation takes place, when some of them start to change to provide different or specialized functionality. In this case, the appropriate gene (or genes) is selected based upon the cell's position inside the cell network, as well as other factors.

Based on this theoretical approach, the modular SRM's control system based on an embryonic array structure was developed.

A homogeneous array of programmable logic units (called artificial cells) were considered, which use their location within the network to extract appropriate configuration data. Each such "artificial cell" contains all the configuration details of all cells and hence can perform any cell's function as required.

The simplest possible system composed of 9 cells was considered. It is organized in macro-groups of "cell networks" named "clusters", as shown in Fig. 7.

Fig. 7: Artificial cells in a cluster structure.

At the same time only a part of them are active, having active genes (for example those highlighted in light blue in Fig. 7). All the other cells can be considered as spare cells. Using the active genes, a wide range of industrial control tasks can be performed.

The control system was implemented by using FPGAs (Field Programmable Gate Arrays) because their specific internal architecture circuits seem to be the most appropriate for such purposes [34] due to their massive parallel computation abilities. Furthermore, an FPGA-based system can be easily reconfigured to best fit any specific application.

Each cell was implemented by an autonomous FPGA array, with special functions inside the organism, defined through an instruction set (program) and called the "cell's gene". Each cell has a copy of all genes from the organism (operative genome) and depending on the cell's position inside the organism, only one cell has an operative gene (the cell's differentiation properties).

Based on these ideas, an artificial organism was built up by interconnecting 9 cells (see Fig. 8).

There are 4-bit data buses on each lattice for source-cluster identification X and Y coordinates code, destination-cluster identification X and Y coordinates code, destination- and source-cell identification code, and for the implemented genes code (A, B, C, D, and E). Cell operation state (active, or faulty) is specified through *Alive*-type

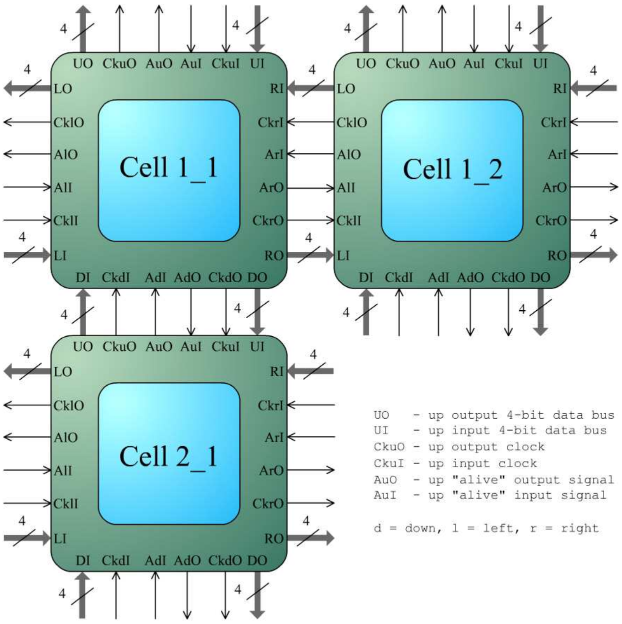


Fig. 8: Network structure of the embryonic system.

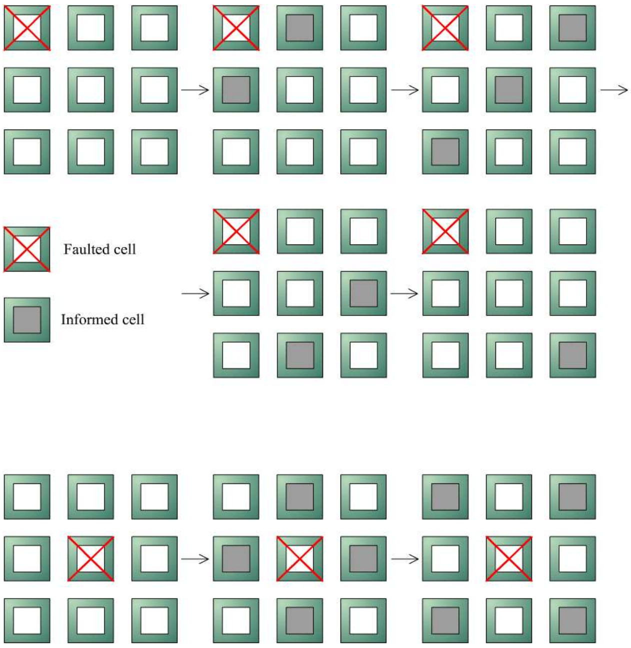


Fig. 9: Detection and information about faults taken place.

signals (*Alive* = 1 active, *Alive* = 0 means faulty cell), and all communication data are synchronized by clock (*Clk*)-type signals.

As it is known, a biological immune system never tries to provide a fault free functionality, typically by killing infected cells. The biological entity can easily accommodate this due to the huge quantity of redundancy inside the organism. In contrast, the hardware immune systems require some inherent fault tolerance, where even if there are many faults inside the system, there are sufficient spare cells, which can handle the arisen physical errors and damages.

A typical fault detection process is shown in Fig. 9, where the neighbored cells that discover damage (*Alive* = 0 on each lattice of one cell) pass through a sequential process this information to entire network. In this way, all artificial cells become aware almost instantaneously of this error or damage.

For example, faulting the *Cell 1_1*, its neighbor cells, *Cell 1 _2* and *Cell 2_1*, detect the fault through *Alive*-type signals. They are highlighted in Fig. 9 with a grey fill, as *informed cells*. These two cells, which detect the fault, pass the information to their other neighbor cells. In turn, these new informed cells pass the information further within the cluster until all cells of the cluster receive it. After finishing this process, all active cells in the cluster calculate the coordinates of the spare cell, which replaces the faulted cell. Fig. 10 describes the process of cell replacement.

At the beginning, the first cluster contains 4 spare cells (having no active genes). In case of a fault (for example in the cell *E*) all buses on the 4 lattice of the cell are released and the neighboring spare cell takes over all the functionality of the faulty cell.

This replacement can be repeated until there are free spare cells in the cluster. It can be observed that the embryonic array keeps its immunity during this process, having the same genotype (*A*, *B*, *C*, *D* and *E*) active. The faulty cell replacement process with spare cells is presented also through the time diagram of *Alive* signals shown in the bottom of Fig. 10.

This methodology can increase considerably the fault tolerance and self-healing properties of the embryonic ar-

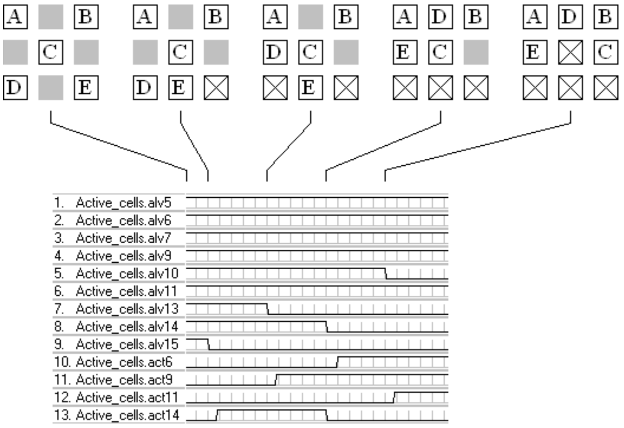


Fig. 10: The immunity of the embryonic hardware system.

ray, and is well-suitable for reconfigurable hardware implementation.

The developed bio-inspired control system was first tested by means of simulations. For this purpose a specially developed simulation software toolkit was developed, which could simulate in real-time complex VLSI circuits interconnected in network topologies [35].

5 THE IMPLEMENTATION OF THE CONTROL SYSTEM

The block diagram of the implemented control system is given in Fig. 11.

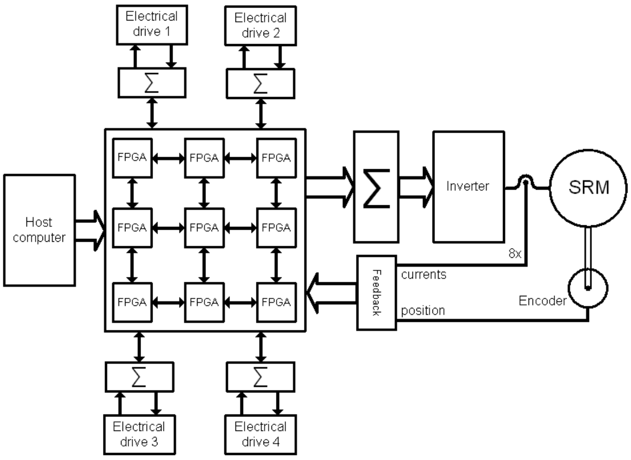


Fig. 11: The block diagram of the control system.

The designed control system is able to command simultaneously up to 5 electrical drive systems. For simplicity only a single one is shown in Fig. 11.

The "brain" of the entire system is the above detailed FPGA circuit-based artificial cell hardware structure, which was built up upon the scheme given in Fig. 12.

Each artificial cell was built up on an autonomous FPGA array (of Xilinx Spartan FPGA XC3S500E type). Basic communication rules between cells inside the network were defined.

The control system consists of an embryonic machine (hardware immune system) and a personal computer (supervisor of the digital control system).

A picture of the developed control system is given in Fig. 13.

The main role of the computer besides fulfilling the classical electrical machine's control tasks consists of monitoring the network communication and data transfer rate inside the artificial cell network, through specially designed software control panels. In addition, each occurred fault in the embryonic machine is detected in real-time and represented in the panel's window.

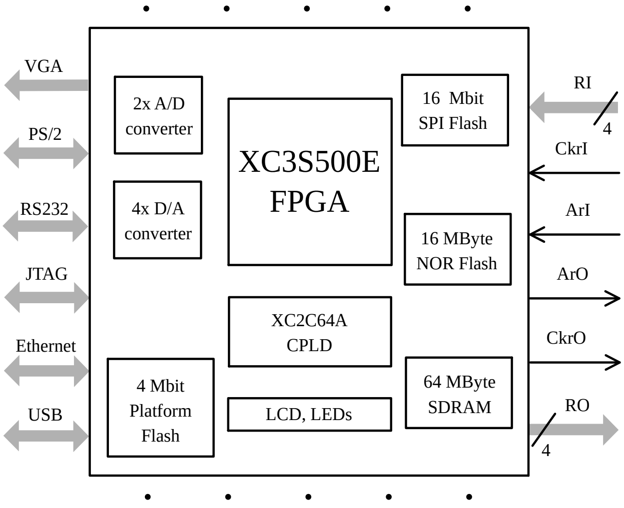


Fig. 12: Artificial cell block diagram.

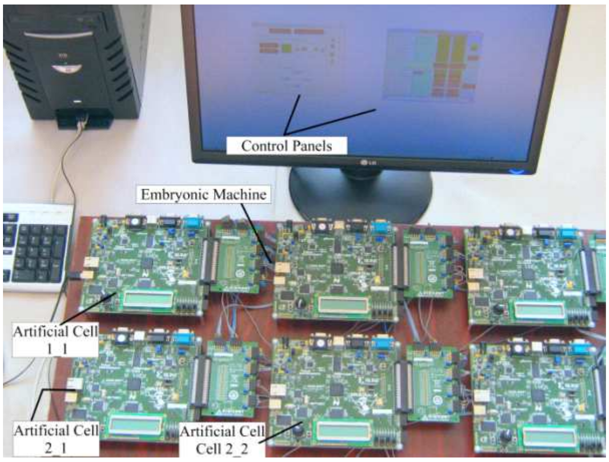


Fig. 13: The experimental embryonic control system.

The fault tolerant control system can be applied in a complex device able to control up to five electrical machines. The complete connection scheme of the system is given in Fig. 14. It contains a cell group (cell cluster) and the five controlled systems (motors with their power converters). The peripheral circuit (*External Device*) is an interface between artificial cell matrix and the PC. The multiplexer for control buses is a passive circuit that transmits the control signals generated by the artificial cells to the inverters. The scheme shows the possibilities of connecting a group of artificial cells to the controlled systems. Depending on application needs, these controlled systems may be fewer, in which case the cells that are not used to control these systems can be used, for example, for various data processing tasks.

The block diagram for the application in study (control

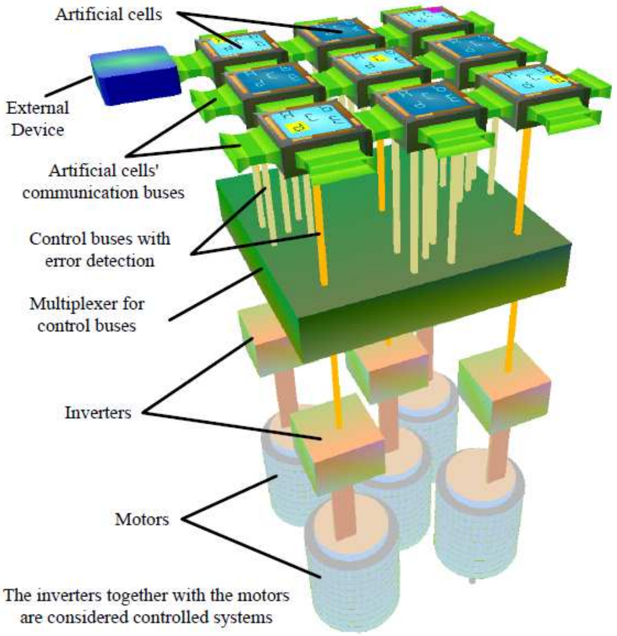


Fig. 14: Control possibilities with a group of artificial cells.

of the modular SRM) is given in Fig. 15.

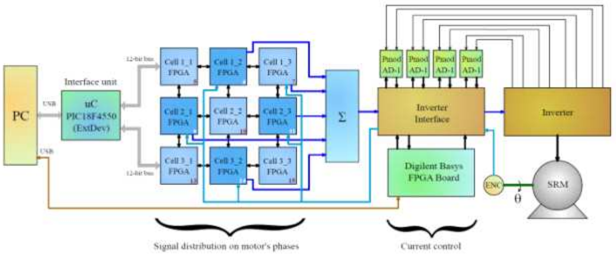


Fig. 15: The experimental embryonic control system.

6 THE LABORATORY MEASUREMENTS

For testing the proposed bio-inspired control system of the modular SRM a test bench was built up.

The main parts of the test bench were:

i.) the four-phase modular SRM to be tested;

ii.) an induction machine for loading purposes, fed through an autotransformer;

iii.) a four-phase power converter of particular design;

iv.) the embryonic control system;

v.) a PC;

vi.) measuring instruments as: a position encoder on the axis of the SRM fed from a dc source, high precision LEM current sensors connected to a data acquisition board inside the PC and a torque meter.

In Fig. 16 a photo taken of the test bench is given.

Fig. 16: The measurement unit of the laboratory setup.

The laboratory setup is perfectly suited for testing the fault tolerance of the modular SRM in study. The open-circuit faults were imposed by disconnecting different coils. Having the possibility to measure the currents, the torque and the speed of the machine its behavior in different conditions could be analyzed.

In order to be able to compare the results, all measurements were carried out under the same conditions. The control system was set as to ensure the rated current (6 A) in the coils of the machine. The resistant torque generated by the induction machine was controlled in a manner as to assure the rated speed (600 r/min) of the modular SRM in all the conditions taken in study.

The measurements were performed for the following machine conditions:

i.) healthy machine;

ii.) one coil opened;

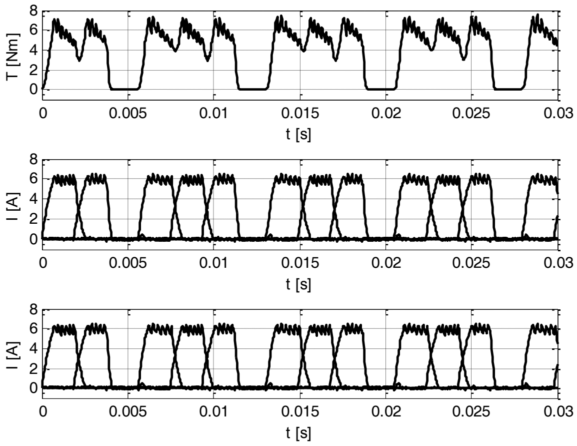
iii.) two coils opened (from different phases);

iv.) three coils opened (from different phases);

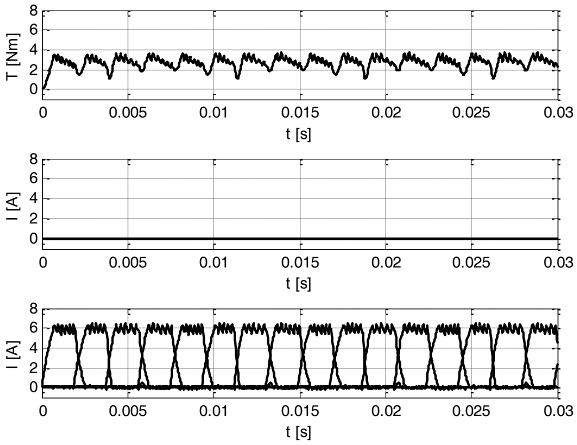
v.) four coils opened (from different phases);

vi.) one entire phase opened.

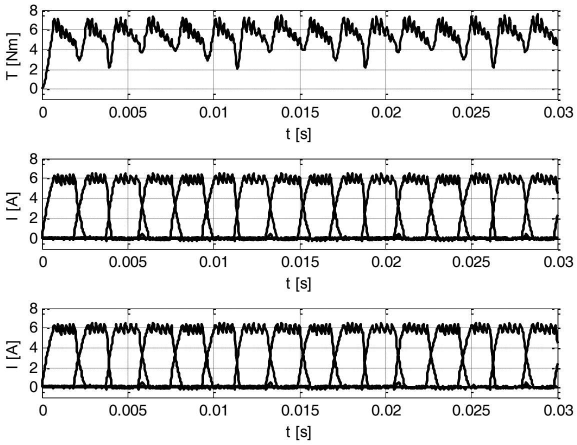
In Fig. 17 the results for three of the machine conditions taken in study are given: healthy, four coils and an entire phase opened. In all the cases three plots versus time



(a) healthy machine



(b) four coils opened condition



(c) one opened phase condition

Fig. 17: Results of the measurements.

for a period of 0.03 s are given: the developed torque and the currents in the first and the second coils of each phase.

When only a half of the machine works (Fig. 17), the torque development of the SRM is also reduced by 50 %. Due to the symmetrical faults, the torque ripples are in acceptable limits. When an entire phase is opened (see the lack of each fourth current pulse) the torque will have a drop down to nil when the faulty phase should conduct. Due to this damage the torque development is reduced by near 25 %, but the torque ripple is quite significant. The main results obtained for the case of the six machine conditions taken into account are given in Table 1. The torque ripples were defined as the difference between the maximum and minimum instantaneous torque expressed as a percentage of the average torque during steady state regime. These can be diminished by applying specific control techniques [36].

Table 1: Developed torques.

Case in study	Mean value [N·m]	Mean/rated torque [%]	Torque ripple [%]
Healthy machine	5.35	100%	92,5
One faulted coil	4.68	87%	115
Two faulted coils	4.05	75%	145
Three faulted coils	3.32	62%	193
Four faulted coils	2.65	50%	100
One faulted phase	4	75%	187

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 coils are opened, just a half part of the machine works and develops half of the rated torque. If an entire phase is faulted, the machine is still able to develop nearly 75 % of its rated torque. It can overrun the positions corresponding to the faulty windings due to its inertia.

Even in the worst-case taken into study (four faulted coils), the machine is able to develop about half of its rated torque. Hence, it can be stated that splitting of the phases into independent coils 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 coils) 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 coils when winding faults are detected. By this, the mean value of the developed torque can be maintained within certain limits relatively close to the rated value. Evidently, the windings and the cooling system have to be designed in a way to consider the greater currents.

7 CONCLUSIONS

In all the safety critical applications fault tolerance is an obligatory feature. The motion control systems used in such applications have to have obligatory all their components (the electrical machine, the power converter and the control system) fault tolerant.

In this paper, a novel fault tolerant modular SRM is proposed. It is supplied from a special power converter having extra legs, which can take over the role of an eventually faulted converter leg. The designed reconfigurable control system is of biological inspiration, having self-healing capacities.

The components of the fault tolerant system were tested formerly and independently by means of simulations. The prototype of the system was built up and tested.

The proposed bio-inspired control system due to its advanced self-healing capabilities offers much higher fault tolerance level as the classical or the artificial intelligence based ones [37]. In addition, the fault tolerance of the modular SRM is high, as it was proven also by the laboratory measurements.

Finally, the developed electrical drive system owns high fault tolerance level and it can be used in diverse safety-critical applications.

Future works include the testing of the bio-inspired control system in case of commanding five electrical machines, by setting up several fault conditions for all the subcomponents of the system (converter, control unit and the electrical machines). In addition, the control strategy of the SRM will be improved by increasing the currents in the machine after detecting faulted coils, as described in [38], [39].

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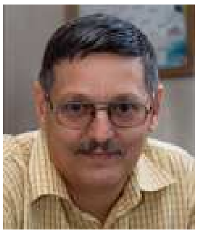

Loránd Szabó was born in Oradea, Romania, in 1960. He received the B.Sc. and Ph.D. degree from Technical University of Cluj (Romania) in electrical engineering in 1985, respectively in 1995. He joined in 1990 the Technical University of Cluj (Romania) as a research & design engineer. Since October 1999 he is with the Department of Electrical Machines and Drives of the same university, where he was a lecturer, associated professor and by now is a full professor. He is the director of the Centre of Applied Researches in Electrical Engineering and Sustainable Development (CAREESD). His current research interests include linear electrical machines, variable reluctance electrical machines, fault tolerant designs, fault detection and condition monitoring of electrical machines, etc. He published more than 220 papers in these fields.

Mircea Ruba was born in Satu-Mare, Romania, in 1983. He received the M.S. degree in electrical machines and drives from the Technical University of Cluj-Napoca in 2008, and the Ph.D. degree in electrical engineering from the same university in 2010. During 2010-2011 he worked 11 months as post doctoral researcher at Université Libre de Bruxelles, Belgium. Since fall of 2011 he is an assistant at the Department of Electrical Machines and Drives at the Technical University of Cluj-Napoca. His research is focused on the design and optimization of electrical machines, their control and power electronics.

Csaba Szász was born in Miercurea-Ciuc, Romania, in 1966. He received the B.S. and Ph.D. degrees in electrical engineering from the Technical University of Cluj, Romania in 1990 and 1999, respectively. He is currently a Lecturer at the Technical University of Cluj, Department of Power Electronics and Electrical Drives. In 2000-2002 he was a Visiting Researcher at Tokyo University of Agriculture and Technology, Department of Bio-Applications and Systems Engineering, Tokyo, Japan. His research interests include digital control systems and bio-inspired hardware systems development. He has authored or coauthored more than 115 publications in his research fields, including 11 books and 1 patent.

Virgil Chindriş was born in Sighetu-Marmaţiei, Romania, in 1984. He received the B.S., M.S. and Ph.D. degrees in electrical engineering from the Technical University of Cluj-Napoca, Romania in 2008, 2009 and 2012 respectively. He is currently a researcher at the Technical University of Cluj-Napoca, Department of Electrical Machines and Drives. His research interests include digital electronics, digital control systems, microcontrollers-based hardware systems, FPGA circuits (VHDL). He has coauthored 30 papers in his research fields, including 2 books.

Géza Husi was born in Debrecen, Hungary, in 1962. He studied at the University of Heavy Industry, Miskolc, Hungary and got his first degree as Mechanical Engineer in 1987 and his second degree as Engineer of Computer Integrated Manufacturing in 1993. He received his Ph.D. degree in the Zrínyi Miklós University of National Defense in 2006 and Ph.D. habil. degree in the field of informatics, mechatronics in 2012. His special fields of interest include robotics and mechatronics. Dr. Husi is appointed visiting professor in Ercyes University, Turkey and in the University of Oradea, Romania. He received István Harsányi Innovation Prize from the Hungarian Innovation Association in 2007. In 2011 he got the Audi Progressivity Prize and Audi Spirit Prize as the Head of the UD High Voltage research team.

AUTHORS’ ADDRESSES

Prof. Loránd Szabó, Ph.D.
Mircea Ruba, Ph.D.
Prof. Csaba Szász, Ph.D.
Virgil Chindriş, Ph.D.
Department of Electrical Machines and Drives
Technical University of Cluj-Napoca
400114 Cluj, 28 Memorandumului str., Romania
email: Lorand.Szabo@emd.utcluj.ro,
Mircea.Ruba@emd.utcluj.ro,
csaba.szasz@emd.utcluj.ro,
virgil.chindris@emd.utcluj.ro

Prof. Géza Husi, Ph.D.
Department of Electrical Engineering and Mechatronics
University of Debrecen
4028 Debrecen, 2-4 Ótemető str., Hungary
email: husigeza@eng.unideb.hu

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