Fault Tolerant Modular Linear Motor for Safe-Critical Automated Industrial Applications

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Abstract* – In various safe-critical industrial, medical and defence applications the translational movements are performed by linear motors. In such applications both the motor and its power converter should be fault tolerant. To fulfil this assignment redesigned motor structures with novel phase connections must be used. In the paper a modular double salient permanent magnet linear motor is studied. Its phases are split into independent channels. The study on the fault tolerant capability of the linear motor was performed via cosimulation, using the Flux-to-Simulink Technology. The conclusions of the paper could help the users to select the optimal linear motor topology for their certain application, function of the required mean traction force and its acceptable ripples.

***Keywords:* fault tolerance, linear motor, modular construction, cosimulation.**

I. INTRODUCTION

Due to technological achievements the degree of automation of industrial plants continuously increased in the last decades. High reliability, fail-safe and fault tolerance become an essential part of the advanced electromechanical systems.

An electromechanical system is considered to be:

i) *reliable* if no failure and malfunction could result in an unsafe system
ii) *safe* if it causes no injury or damage to the operator, environment and system itself
iii) *fail-safe* if the system could be stopped safely after the failure
iv) *fault tolerant* if the system could complete its task safely after any failure.

Faults or failures correspond to any condition or component (subsystem) degradation that affects the performance of a system such that the system cannot function as it is required [1].

Nowadays the application of the advanced electromechanical systems expands to areas such as highly dynamic/unstructured or space/remote environments, medical and high-speed applications, the necessity for the system to be *failsafe* (could stop with no harm to the environment, operator, and itself) and *fault tolerant* (tolerate the failure and complete the assigned task) increases [1].

An electromechanical system is *fault tolerant* if after any failures there will be no interruption in the operation of the system. Fault tolerance and high reliability can be achieved by using high quality components, through specific designs and control strategies, and by incorporating redundancy in the design of the systems.

A generic standard, IEC 61508, was developed to improve functional safety aspects of all electrical, electronic and programmable electronic safety-related systems (E/E/PES) [2].

The permanent magnet modular linear motor [3] is suitable for advanced safe-critical automated industrial electromechanical systems. It is a direct-driven linear motor, which eliminates gearboxes, ball screws, belts, couplings, or other rotary-to-linear motion converters between motor and load, offering high speed, acceleration, positioning accuracy, and rapid strokes, compared to systems based on rotary motors [4].

As any fault-tolerant machine it 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. Unfortunately by increasing the machine's fault-tolerance its losses could be greater and its efficiency less than its usual counterpart [5].

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 systems. The separate phase feeding and control of the machines allow an easier approach of the fault tolerant tasks and offer better results.

The fault tolerance study of the proposed modular linear motor 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 one of the latest coupled simulation technique (FLUX-to-Simulink). The coupled simulations allowed precise analysis of the motor's behaviour both in normal and faulty operation cases.

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II. THE FAULT TOLERANT MODULAR LINEAR MOTOR

The fault tolerant linear motor in study emerges from the three-phase modular double salient linear motor that of the hybrid linear motor [3]. A three-phase variant of this motor is given in Fig. 1.

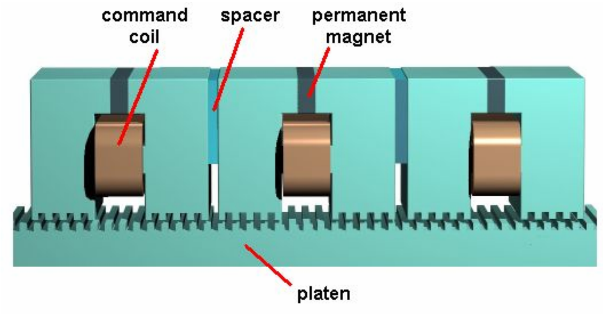

Fig. 1. The three-phase modular linear motor

Each module has a permanent magnet, two salient teethed poles and a command coil. Its working principle is given in Fig 2.

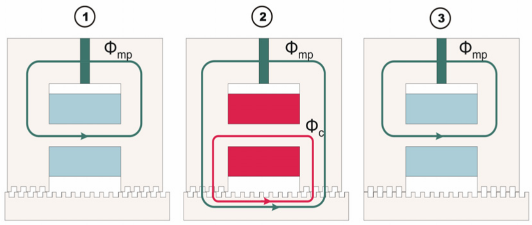

Fig. 2. The working principle of the motor

If the command coil is not energized, Fig. 2-1, the magnetic flux generated by the permanent magnet, Φ_{pm}, passes through the core branch parallel to the permanent magnet due to its smaller magnetic resistance. In this case there is no significant force produced.

If the coil is energized, Fig. 2-2, the command flux produced by it, Φ_c, directs the flux of the permanent magnet to pass through the air-gap and to produce significant forces.

Due to the tangential component of the force the moveable armature moves one step minimising the air-gap magnetic energy, Fig. 2-3.

The tooth pitch and the number of modules determine the motor's resolution. By advanced control strategies the resolution of positioning can be increased significantly.

Usually the modular linear motor offers particularly strong benefits in those industrial applications where fast and accurate moves under heavy loads are required (flexible manufacturing systems, robotic systems, machine tools, conveying systems, linear accelerators, turntable drives, automated warehousing etc.).

Achieving a fault tolerant variant of a usual electrical machine requires modified topologies. First of all the windings of the machine has to be redesigned. When designing such a machine also its losses have to be optimised.

The fault tolerant variant of the modular linear machine is obtained practically by doubling the number of its modules (as shown in Fig. 3).

Each phase of the fault tolerant variant of the modular linear motor is compound of two channels, each channel placed on different modules, relatively shifted with the same calculated displacement.

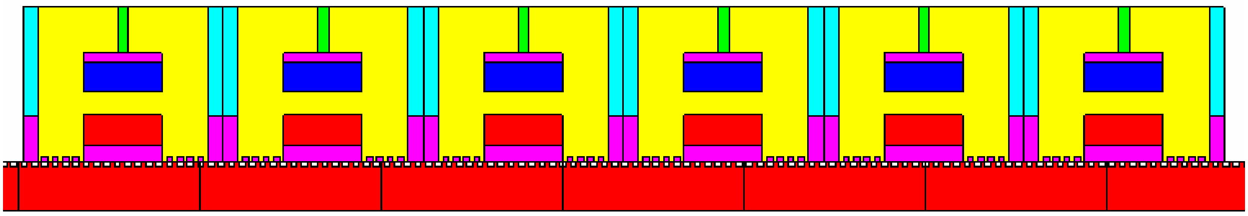

Fig. 3. The fault tolerant linear machine with 6 modules

At each time two modules operate synchronously.

Hence its operation despite of winding faults becomes possible. If a winding fault occurs in one channel of a phase, the second channel will still operate.

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 tangential force can be held at its rated value, but of course the force ripples will be greater.

Of course this solution can be used only if the windings and the cooling system of the machine are designed to support the greater currents.

The modular linear machine is controlled by a half H-bridge type power converter. The current of the coils is controlled using PWM technique. Each module uses one half H-bridge to generate the current for the required force.

By the parallel connection to the common main bus bars of each bridge the faulted windings can be totally isolated from the rest of the circuit. The implemented intelligence of the converter allows this isolation of the faulted module.

Each half H-bridge is controlled separately by opening/closing the power switches. The control of the power switches is performed by a command strategy using the instantaneous position of the motor and the measured phase currents.

The power converter of the new fault tolerant modular motor is given in Fig. 4.

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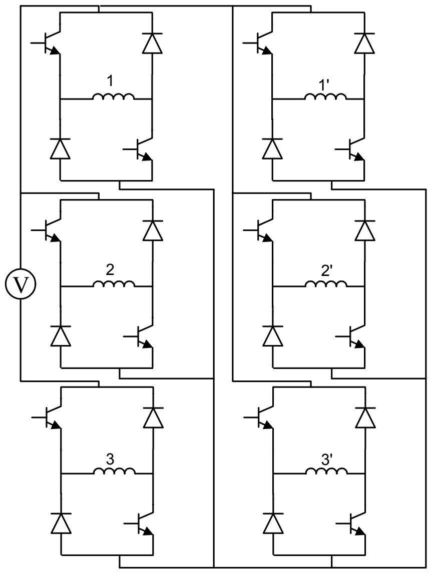


Fig. 4. The power converter

III. THE SIMULATION PROGRAM

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

The model of the fault tolerant modular linear motor and the electric circuits of its power converter were built up in Flux 2D. The generated mesh for the linear motor in study is given in Fig. 5.

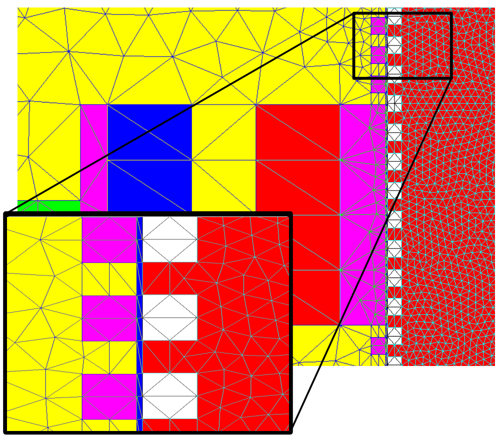


Fig. 5. The mesh generated in Flux 2D

The electrical circuit for a single channel of the machine is given in Fig. 6.

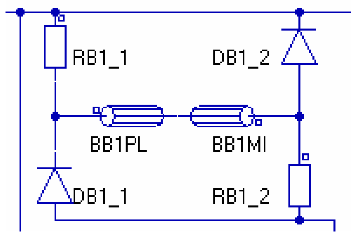


Fig. 6. Electric circuit of one channel

The circuit follows the arrangement of the half H-bridge topology. Common coil components (like BB1PL and BB1MI) are used to link the two faces of each channel to the circuit. In the model 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 [6]. 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, forces and speed) are returned to the main program through another multiplexed signal line.

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

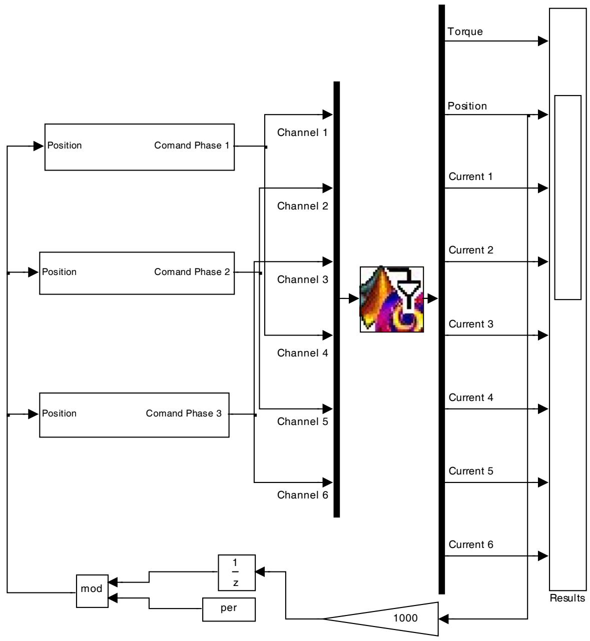


Fig. 7. The main window of the simulation program

Several healthy and faulty regimes of the modular linear motor in study were simulated by the means of this program.

IV. RESULTS OF SIMULATIONS

The regimes taken into the study were:

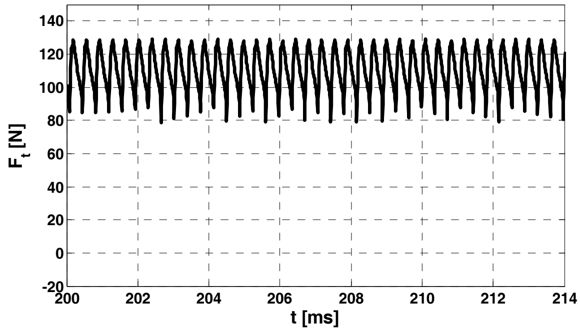
v) normal operating mode;

vi) open circuit of one channel;

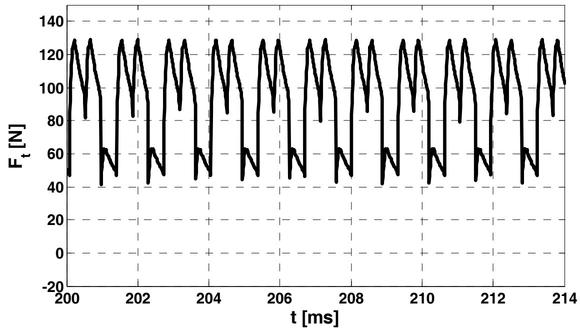
vii)open circuit of two channels of different phases;

viii) open circuit of two channels of the same phase.

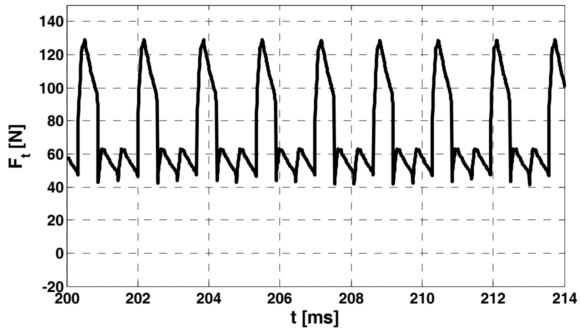
The main results (the tangential forces versus time) are given in Fig. 8.



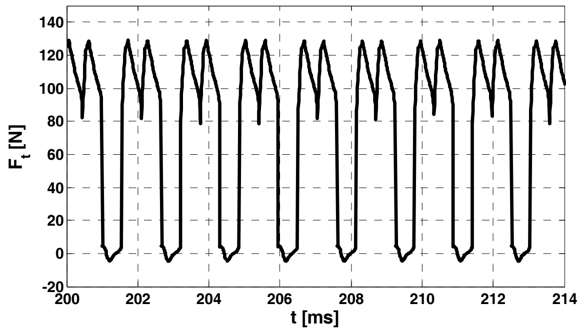
a) normal operating mode



b) open circuit of one channel of a phase



c) open circuit of two channels from different phases



d) open circuit of two channel from the same phase

Fig. 8. Results of simulation

The first case (Fig. 8a) is the reference situation, when no winding faults are in the motor. The mean value of the tangential force in this case is 110.93 N.

In Fig. 8b the results in the case of an open circuit of one channel are given. In this case the tangential force falls to about 50 N, corresponding to the lack of the faulted module. The mean force developed in this case is 92.54 N (84% of the healthy machine's force).

The open circuit failure of two channels from two different phases was the third case in study (see Fig. 8c). The generated force is falling to near 50 N during two periods, resulting in a mean tangential force of 73.50 N (about 66% of the force in healthy condition).

The last fault is study was the most severe one: the opened circuit of two channels belonging to the same phase (see the result in Fig. 8d). As it can be seen tangential force ripples are quite high. The mean tangential force is in this case about 74 N. It can be stated that also in this case a significant tangential force is generated, similar to the previous cases.

V. CONCLUSIONS

The study demonstrated that increasing the number of modules, separating the phases into channels, setting new connections between the existing winding arrangements and using a complex control system can all provide good solutions for increasing the fault tolerance of a linear motor.

In the paper a 6 modules permanent magnet fault tolerant linear motor is proposed. In accordance with a certain application the complexity and the tolerance level can be increased, taking also into account the costs.

The coupled simulation program connecting two advanced software environments was useful in studying the effects of different winding faults on the force developing capacity of the modular linear motor.

ACKNOWLEDGMENT

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