STUDY OF FAULT TOLERANT MODULAR VARIABLE RELUCTANCE LINEAR MACHINE

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ABSTRACT

In numerous vital industrial, medical and defence applications the translational movements are performed by linear electric motors. In such applications both the linear 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 three-phase fault-tolerant modular variable reluctance linear motor will be studied. The motor is built up of six modules and its phases are split into 2 independent channels. The comparative study of the proposed motor was performed via co-simulation, using the Flux-to-Simulink Technology. The final 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.

INTRODUCTION

The fault tolerant concept emerged for the first time in information technology. 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 [1].

The result was an operational unit having certain fault tolerant level, as a sum of the safety levels of each equipment of the system. From another point of view a system is dependable if it is available, reliable, safe, and secure [2]. Advanced systems with embedded linear motors are desirable not only in industry, but also for several other (e.g. medical and defence) applications [3]. The variable reluctance permanent magnet modular linear motor [4] is suitable for such applications. It is a direct-driven motor, which eliminates gearboxes, ball screws, belts, couplings, or other rotary-to-linear motion converters between the motor and load assuring high speed, acceleration, load-positioning accuracy, and rapid stroke cycling, as compared to systems based on rotary motors.

To be fault-tolerant it has to have a special design [5]. Multiplying the number of the modules in the motor was the first step in achieving fault tolerance. The second one involved a special design of the power converter. Separate command of each phase and the parallel connection of the modules also contribute to the fault tolerant capability of the linear motor. The transient regime simulation of the entire motion system (the machine and its converter) was performed using one of the latest simulation techniques, the co-simulation (by means of FLUX-to-Simulink link). The coupled simulations allowed precise analysis of the machine's behaviour both in normal and faulty operation cases [6], [7].

THE FAULT-TOLERANT MODULAR LINEAR MOTOR

The studied linear modular motor's structure emerges from that of the hybrid linear motor [8]. A three-phase variant of this motor is given in Fig. 1.

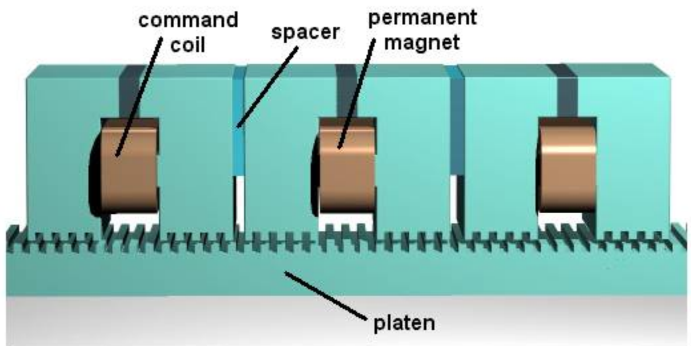


Fig. 1.
The three-phase modular linear motor

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

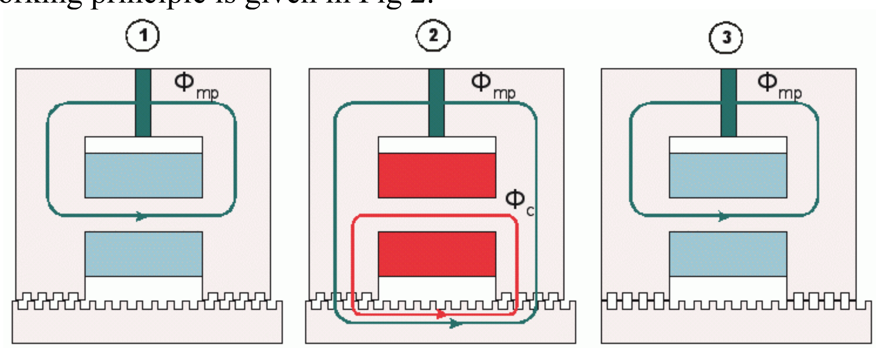


Fig. 2.
The working principle of the motor

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, as shown in 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. 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.).

There are several control possibilities for the three-phase modular linear motor from the simplest open-loop control schemes to the most sophisticated and powerful variable speed drive systems. In order to achieve maximum average tangential force and to reduce as much as possible the it's ripple the control system has to assure the change of excitation of the three module's command coils at a specific displacement, the optimal commutation angle (α_o), before reaching the intermediate equilibrium points [9]. The modular linear machine is controlled by an H-bridge type power converter. The current of the coils is controlled using hysteretic modulation technique. Each module uses one H-bridge to generate the current for the required force [10]. By the parallel connection to the common main bus bars of each bridge the faulted windings can be totally isolated from the other ones. The implemented intelligence of the converter allows this isolation of the faulted module. The control of the power switches is performed by a strategy using the linear position of the motor and the measured phase currents.

Achieving fault tolerance for a usual electrical machine requires modified topologies. The fault tolerant variant of the modular linear machine is obtained practically by doubling its modules (as shown in fig. 3). Each phase is compound of two channels; each channel placed on different modules equally shifted each of the others. At each time two modules are fed synchronously (*A* and *A*, *B* and *B*, respectively *C* and *C*). Hence its operation despite of winding faults becomes possible. If a short circuit or an open circuit occurs on one channel of the phase, the second channel will still operate. By applying current control (increasing command current in the channels in parallel with open-circuit channels, the effects of the faults can be diminished.

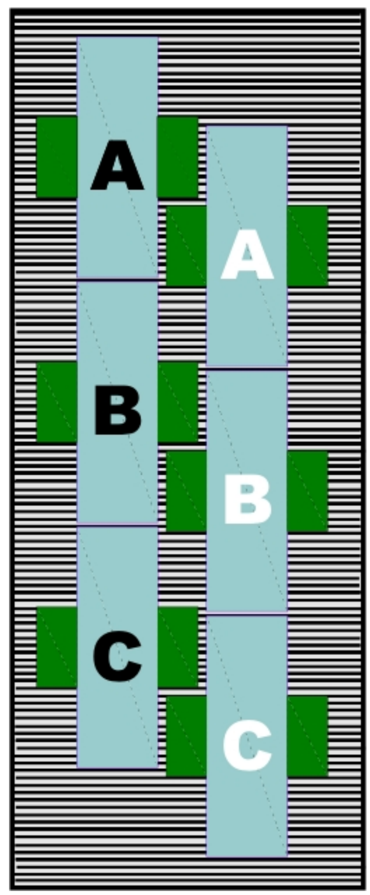


Fig. 3.
The fault tolerant linear motor

THE COUPLED SIMULATION PROGRAM

The model of the linear modular motor was built up using the Flux 2D finite element method (FEM) based electromagnetic field computation software.

As the study is performed for transient regime with translation motion a mesh optimization was required in order to reduce computation times [11].

A second attention had to be paid to electric circuit attached to the FEM model of the fault tolerant linear modular motor in study. Each phase of the machine is modelled by two coils, the ingoing and the returning coils [7]. The solid-state power switches are replaced by resistors in the circuit.

The control system of the modular linear motor is built up in MATLAB - Simulink environment [5]. Flux 2D and Simulink are communicating using the advanced Flux-to-Simulink coupling method, as it can be seen in Fig. 4, where the main window of the simulation program is given.

The linear motor's Flux 2D model is embedded in the Simulink program by the *Coupling to Flux2D* S-function type block. The input values of the block are the resistances for each power switch.

The S-function block will receive the output signals of the field computation (the torque, the phase currents and the rotor position) and will transfer them to Simulink.

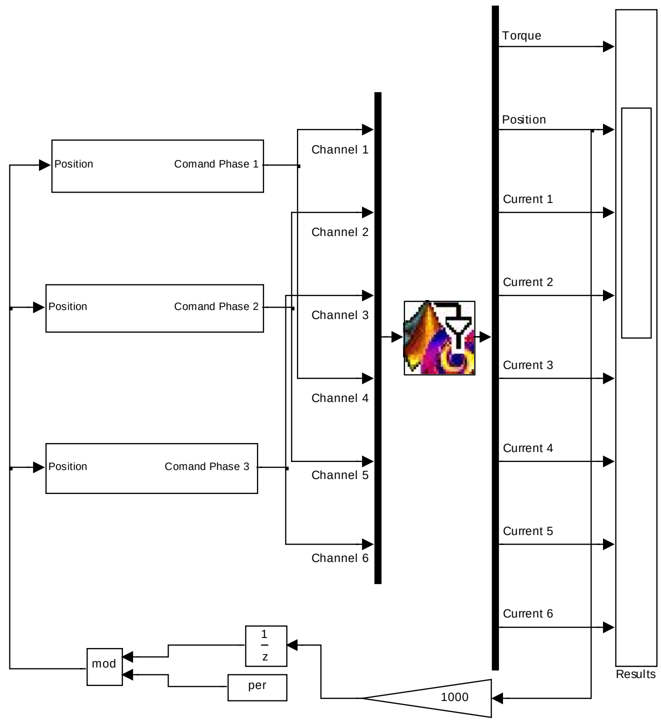


Fig. 4.
The coupled simulation program

Using these values the parameters of the next simulation step will computed. This way the simulation task will be computed step by step.

THE SIMULATIONS PERFORMED

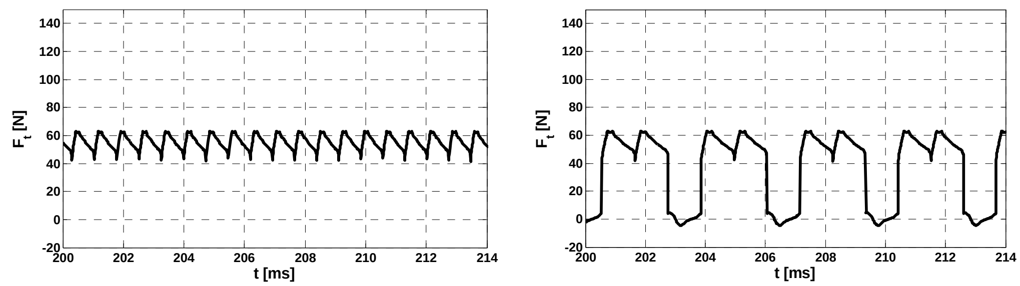
The dynamic performances of the two above presented permanent magnet variable reluctance modular linear motor variants were studied for different conditions.

The motor having 3 modules was studied for its normal and one open phase condition. For the fault tolerant variant with 6 modules four cases were taken into study:

i.) normal operating mode;
ii.) 0pen circuit of one channel;
iii.) open circuit of two channels of different phases;
iv.) open circuit of two channels of the same phase.

In Fig. 5 the tangential force versus time plots for the original 3 modules linear motor variant for its healthy and faulty conditions are given.

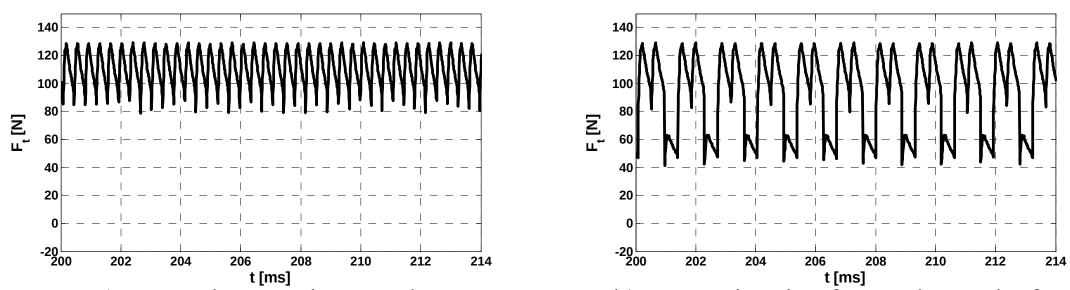
The results for the proposed fault-tolerant motor are given in Fig. 6. The first case (Fig. 6a) is the reference situation, when no winding faults are in the motor. The mean value of the tangential force in this case is 110.93 N, the double as in the previous case, because also the number of modules belonging a phase is doubled). In Fig. 6b the results of the simulation 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).



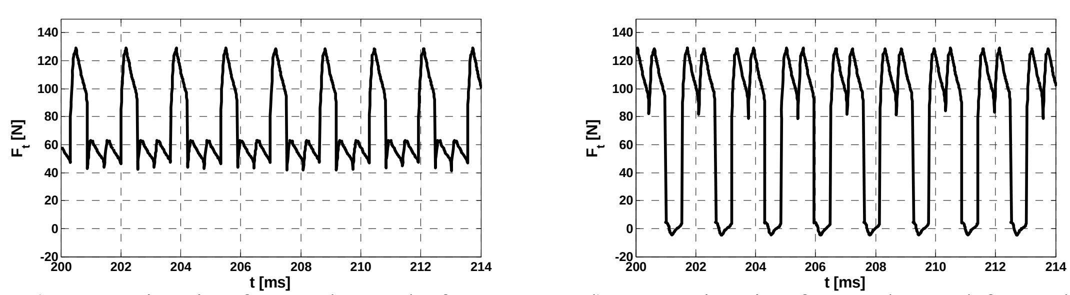
a) normal operating mode b) open circuit of one phase

Fig. 5.
Results for the 3 module motor

The open circuit of two channels from two different phases was the third case in study (see the results in Fig. 6c). The mean force developed in this case is 92.54 N (84% of the healthy machine's force). The generated force during two periods is falling to near 50 N, resulting in a mean tangential force of 73.50 N (about 66% of the force in healthy condition).



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. 6.
Results for the 6 module fault-tolerant motor

The last fault condition in study was the most severe one: the opened circuit of two channels belonging to the same phase (see the results in Fig. 6d). As it can be seen the tangential force ripples are quite high. The mean tangential force is in this case about 74 N, nearly the same as in the previously case. It can be stated that also in this case a significant tangential force is generated.

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 provide the best solution for the fault tolerant linear modular electrical drive system. In the paper a 6 modules permanent magnet variable reluctance modular linear motor is proposed. The coupled simulation program connecting two software environments (FLUX 2D and Simulink) was useful in studying the effects of different winding faults on the force developing capacity of the modular linear motor.

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