FEM Based Studies on Fault Tolerant Modular Linear Motors

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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 modular linear motor structures will be studied. All of them have their phases split into independent channels. The comparative study of the proposed motor variants was performed via cosimulation, 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.

1. 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. 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 [2].

Advanced systems which embedded linear movement motors are desirable not only in industry, but also for medical and defence applications [3].

The permanent magnet modular linear motor [4] is suitable for such applications. 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 superior speed, acceleration, load-positioning accuracy, and rapid stroke cycling, compared to systems based on rotary motors.

Its separate phase command and feed allows its operation despite winding faults. In addition the complex power converter fulfils the assignment of fault detection, isolation and masking. Hence the joint system will become a fault tolerant system.

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

Doubling or tripling the number of the modules in the motor was the first step in achieving a fault tolerant linear motor. 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 comparative study 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).

It was taken advantage of the high precision machine analysis capabilities enabled by the FLUX 2D finite element method (FEM) based numeric field computation program and easy-to-use, but also advanced Simulink/MATLAB simulation environment [6].

The coupled simulations allowed precise analysis of the machine's behaviour both in normal and faulty operation cases [7].

2. The design of the 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.

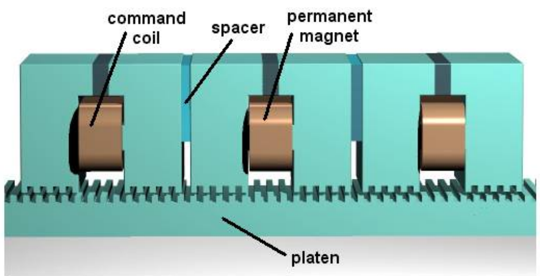


Fig. 1. The three-phase modular linear motor

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

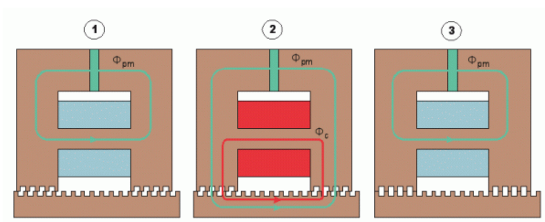


Fig. 2. The working principle of the motor

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, 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.).

2.1. Design of the linear modular motor

The design algorithm is based on several relationships obtained from a simplified analytical motor model and on some existing experience in this field. The analytical model is built up upon the simplified equivalent magnetic circuit (see fig. 3) of the module and of the platen segment under it.

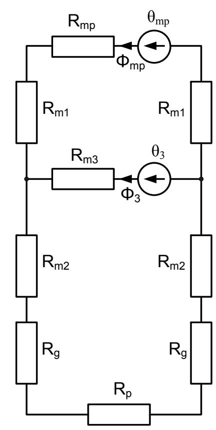


Fig. 3. The simplified equivalent magnetic circuit

The circuit consist of two MMFs (θ_{mp} and θ_3) of the permanent magnet, respectively of the command coil. There are 9 reluctances in the circuit: R_{pm} of the permanent magnet, R_{m1} and R_{m2} of the pole, R_{m3} of the core branch with the command coil, R_g of the variable air-gap and R_p of the platen segment under the mover module.

In the first stage of the design procedure the following required design inputs must be prescribed depending on the application in which the motor will be used: number of modules, maximal tangential force to be developed by the motor, the resolution of the positioning, the length and the width of the running track

The control coil design has to be made as a function of its MMF. It must be so great as to force all the permanent magnet's flux through the poles and the air-gaps. Also in this case a simple optimization process can be applied. As numerous products of number of turns and current can give the same MMF, it must be chosen that combination which will produce the less I^2R loss in the command coil. This way both the electrical input and thermal dissipation of the command coil are minimized.

2.2. The control of the linear modular motor

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 the last case the speed can be modified from zero to many meters per second. The motor's speed capability can be determined by design and depends on the supply frequency. The stopping, starting and reversing of the motor are all easy to implement. From the numerous possibilities available the right decision must be made as to trade off the overall cost of the control system, maintaining the required control capabilities. In order to achieve maximum average tangential force and to reduce as much as possible the tangential force 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 angel (α_o), before reaching the intermediate equilibrium points. This value may be determined theoretically and depends on the number of modules coupled together to form the mover [9].

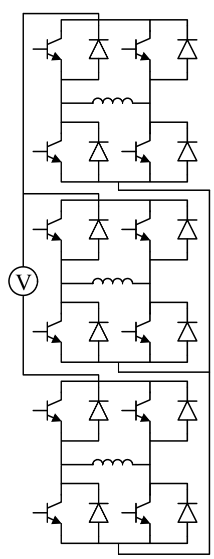


Fig. 4. The power converter of the motor

The modular linear machine is controlled by an H-bridge type power converter. The current of the coils is controlled using PWM 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. Each H-bridge is controlled separate by opening/closing the power switches. The control of the power switches is performed by a strategy using the linear position of the motor and the measured phase currents.

3. The fault tolerant linear motor design

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 its modules (as shown in fig. 5).

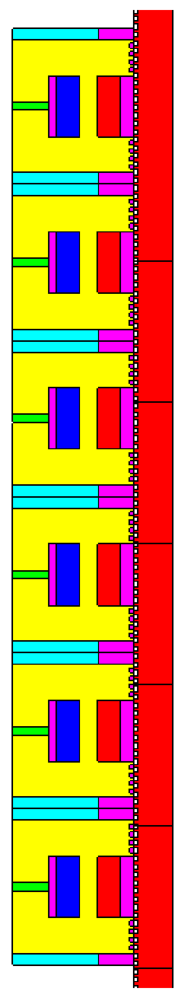


Fig. 5. The fault tolerant linear machine having 6 modules

At each time two modules operate synchronously. Hence, each phase is compound of two channels, each channel placed on different modules, relatively shifted with the same calculated displacement.

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 imposing increased current control, the lack of the faulted channel can be compensated.

The power converter attached to the new modular motor is obtained practically by doubling the converter given in fig. 4.

4. The coupled simulation program

The model of the linear modular motors were 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. A compromise had to be made between the imposed mesh density, the computation accuracy and the available hardware. A detail of the generated mesh is given in fig. 6.

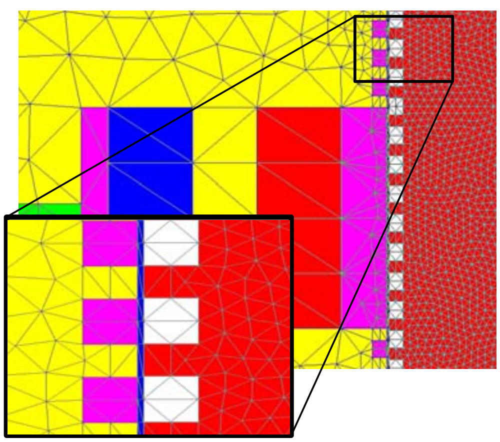


Fig. 6. The mesh generated in Flux 2D

A second attention had to be paid to the special mesh type for translational movement models in Flux 2D. The comprehensive areas at the two extremities of the armatures were set as mapped type mesh. This will allow correct computation and displacement of the translating component of the model.

The electric circuit attached to the FEM model of the fault tolerant linear modular motor in study is given in fig. 7.

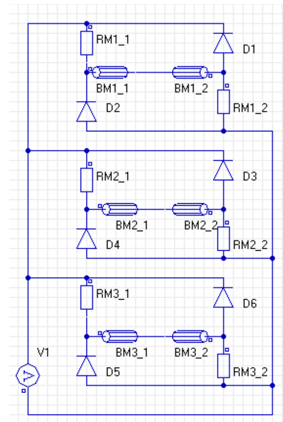


Fig. 7. The electrical circuit in Flux2D

As it can be seen each phase of the machine is modelled by two coils, the ingoing and the returning coils [6].

The solid-state power switches are replaced by resistors in the circuit. The ON/OFF states of the switches are modelled simply by changing the resistance from 100 kΩ to 4 mΩ.

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. 8, where the main window of the simulation program is given. This control system will generate signals with reference values for the resistances for each branch.

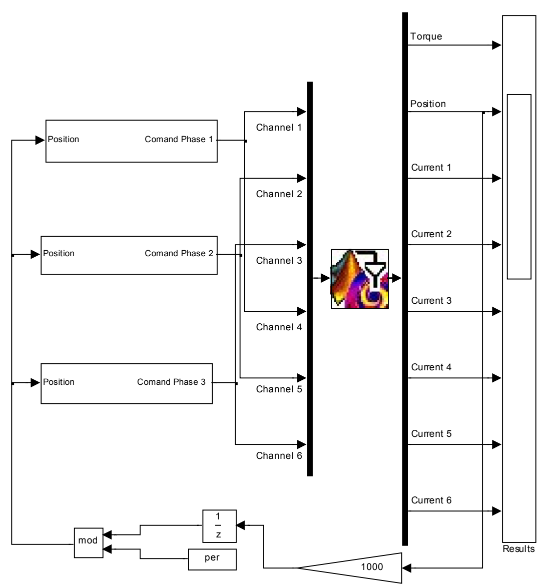


Fig. 8. The coupled simulation program

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 (practically the signals to be transferred to Flux 2D) are the resistance values for each branch. The S-function block will receive the output signals after the field computation (the torque, the phase currents and the rotor position) and will transfer them to Simulink. Using these values the parameters of the next simulation step will computed.

This way the task of simulation will be computed step by step till the time limit is reached.

5. The simulations performed

The performances of the two above presented modular linear motors 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 of the motor having 6 modules four cases were considered:

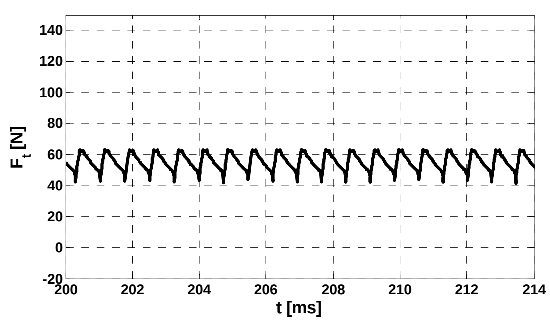
a) normal operating mode;

b) open circuit of one channel;

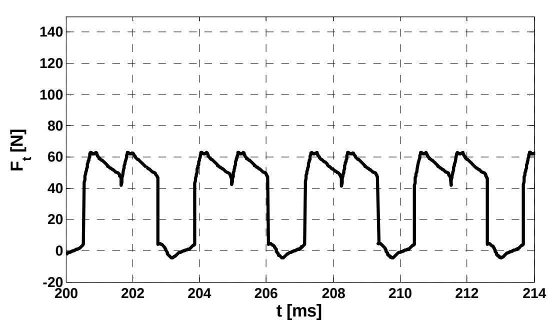
c) open circuit of two channels of different phases;

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

In Fig. 9 the tangential force versus time plots for the original 3 modules linear motor variant for its healthy and faulty conditions are given.



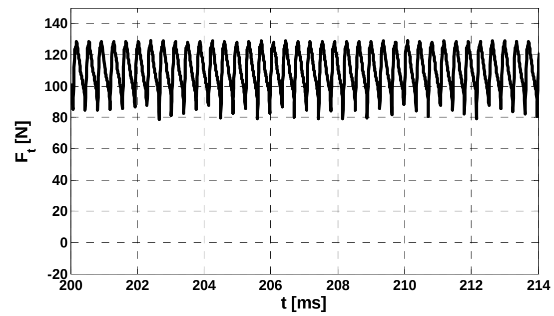
a) normal operating mode



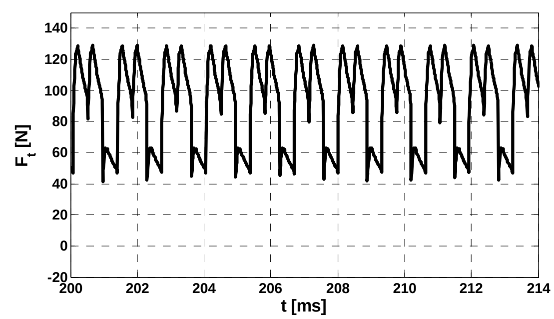
b) open circuit of one phase

Fig. 9. Results for the 3 module machine

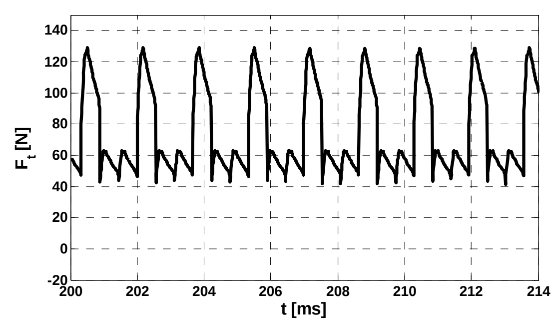
In fig. 10 the force plots for the fault tolerant variant of the modular linear motor under the studied conditions are given.



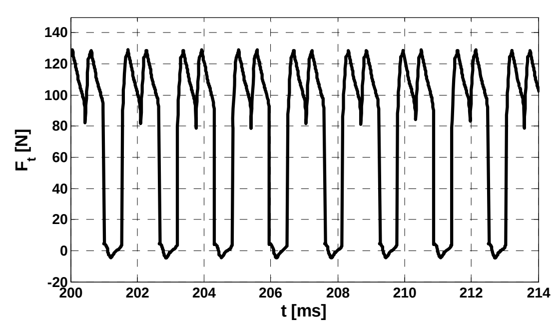
a) normal operating mode



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. 10. Results for the motor having 6 modules

The first case (fig. 10a) 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.

In fig. 10b 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.

The open circuit of two channels from two different phases was the third case in study (see ig. 10c). 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).

The last fault is study is the most severe one: the opened circuit of two channels belonging to the same phase (see the result in fig. 10d). 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 case.

6. 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 modular linear motor is proposed. In accordance with the application the complexity and of course the tolerance level can be increased, taking into account also the costs, too.

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.

Finally it can be stated that in the paper an optimal solution for applications that demand both increased safety operation and linear displacements was proposed.

7. Literature

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