

## MULTI-LEVEL MODELLING OF A MODULAR DOUBLE SALIENT LINEAR MOTOR

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### Abstract.

The three-phase linear motor in discussion is basically a hybrid linear stepper motor having improved performances due to its novel modular construction. This linear motor is one of the best choices for industrial applications where fast and accurate linear motions under heavy loads are required.

In this paper a multi-level model of this motor will be presented. The model is built up by coupling units of three different types of analysis and simulation platforms. The basis of the whole model is built up in SIMULINK. The field computations were made using MagNet 6.0 FEM-based magnetic field analysis program. The obtained results, the static characteristics of the forces, were integrated in the SIMULINK model by easy-to-use look-up tables. The power converter's model was made in SIMPLORER, a widely used simulation program in the field of power electronics. The converter units were coupled into SIMULINK by the Sim2Sim link. This way all the parts of the model were implemented in the most suitable platform for each of them.

The obtained results are in good accordance with the theoretical expectations and with the results of analytical computations. This means that the overall performances of the combined simulation program are quite good. Therefore the idea of coupling units built-up in different simulation platforms into a single simulation program could be also applied for simulating other types of electrical machines.

### 1. Introduction

A mathematical model of an electric machine is based on a theoretical approach and can be used for easy performance prediction and control without prototyping. To be useful the model must be realistic and yet simple to understand, easy to manipulate and implement. The development of a practical model is not easy, because the above mentioned requirements are conflicting. Therefore a skilful mathematical model of a certain electrical machine can be very useful for prediction of its behaviour both in transient and steady state regime, and for testing several control schemes [1].

In this paper a coupled multi-level mathematical model and simulation program of a three-phase modular double salient linear motor is presented. The model couples several different simulation platforms (SIMULINK, SIMPLORER and MagNet), each one of them widely used in its field. Hence the main advantages of each platform were exploited, and the global efficiency of the entire simulation program is almost as high as possible.

### 2. The three-phase modular double salient linear motor

The three-phase modular double salient linear motor (Fig. 1) was previously presented [2, 3].

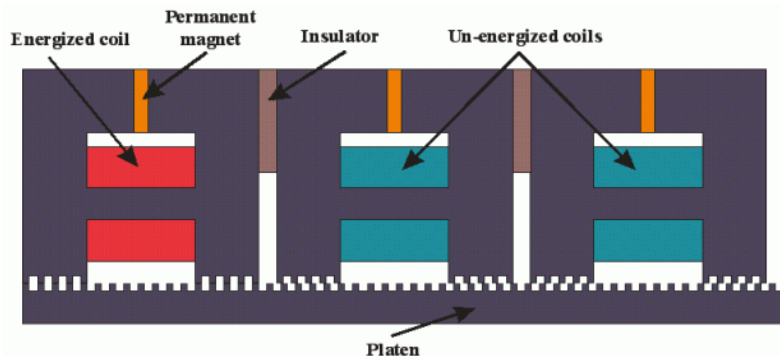


Fig. 1. The three-phase modular double salient linear motor

It is a direct-driven linear motor, which can replace rotational to linear movement translator devices. Therefore this motor is simple, efficient and has high positioning accuracy. Hence these motors are ideal for applications that require high position accuracy and repeatability.

The mover of the motor is a single stack composed of three modules, like that presented in Fig. 2. Each module has a rare earth permanent magnet, two salient teathed poles and a command coil. If the command coil is not energised, the flux generated by the permanent magnet 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 energised, the command flux produced by it 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 mover moves one step minimising the air-gap magnetic energy. By advanced control strategies the resolution of positioning can be increased significantly [3]. The modular linear motor eliminates several disadvantages of the "classical" hybrid linear stepper motors. Due to these benefits it is one of the best choices for industrial applications where fast and accurate linear motion under heavy loads are required.

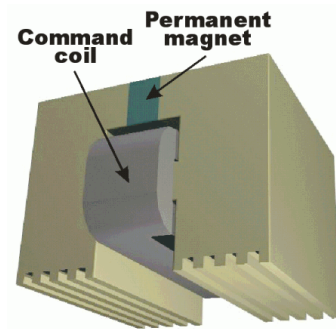


Fig. 2. The mover module

### 3. The simulation program of the motor

The simulation program of the motor in discussion is a compound of three coupled units; each implemented in different analysis and simulation platforms. Its block diagram is given in Fig.3.

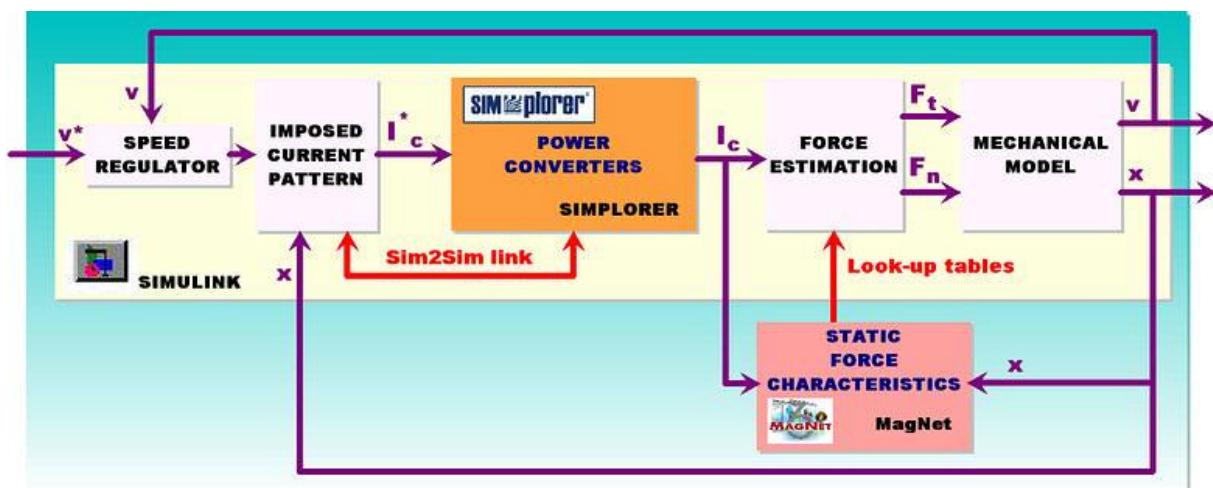


Fig. 3. The block diagram of the coupled simulation program

The first unit is a finite element method (FEM) based magnetic field analysis module. Upon these computations, made in MagNet 6.0 off-line the simulations, the static characteristics of the motor are computed: the total tangential and normal forces of the motor for different command currents and mover positions. The results are stored in look-up tables to be used in the SIMULINK unit. The FEM analysis is far the most precise method for determining these characteristics. It is time consuming, but these computations must be done only once for a given motor. The use of the static characteristics of the forces instead of their in-line computation shortens considerably the simulation times [4].

The main simulation program is built up in SIMULINK, an intensely used platform for simulating different dynamic systems. The entire simulation task is driven from this program. In this program the velocity and displacement of the motor are computed from the forces taken from the above mentioned look-up tables. Also in this part of the program is included the speed controller of the drive system and a logical unit generating the imposed command current pattern upon the required speed and the motor's position. The plotting of the results are commanded from this platform, because this is the most powerful in graphical visualisations (plots, diagrams, etc.). The power converter's model was implemented in SIMPLORER and this model was linked into the SIMULINK model through the SIM2SIM link.

The described program uses the almost best simulation platform for each kind of task. This way the accuracy of the entire simulation is high, and the simulation times are radically reduced. Using this

program diverse dynamic regime of the motor can be easily studied. It can be useful during design stage or for testing different motor variants. It is also advantageous in testing, without prototyping, different control strategies of the motor.

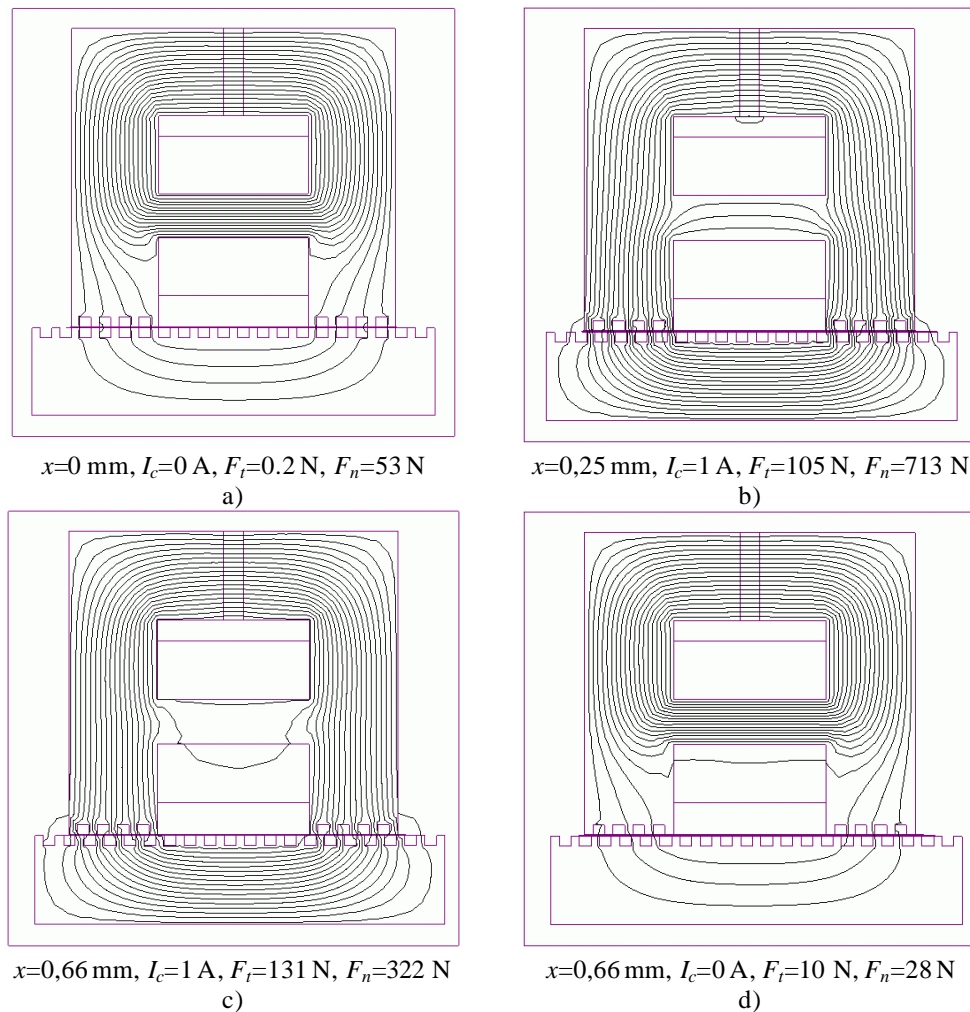
#### 4. The FEM based magnetic field analysis

The FEM based numeric field analysis of the three-phase modular double salient linear motor was performed using the MagNet 6.10 package [5]. Only a single module of the motor, with the platen part above, was analysed.

In order to determine the motor's static characteristics several computations were made. Different control currents (in the range of 0÷2 A) and distinct relative displacements of the mover with a step of 0.1 mm were considered. From the numerous results obtained only some one are presented, just to illustrate the motor's behaviour. The given results of the field analysis were obtained for the following mover positions and command current values:

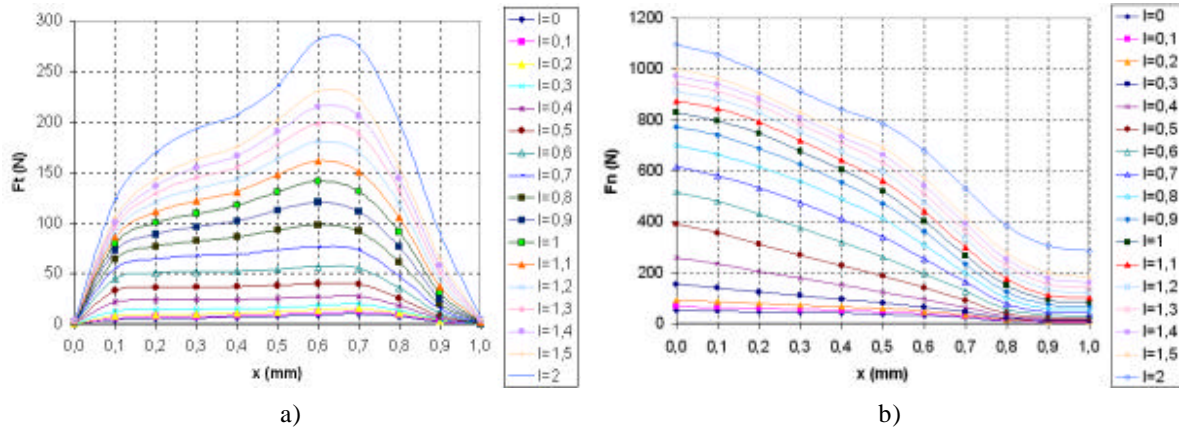
- a)  $x=0$  mm,  $I_c=0$  A (initial position, command coil not energised)
- b)  $x=0,25$  mm,  $I_c=1$  A (intermediate position, command coil energised)
- c)  $x=0,66$  mm,  $I_c=1$  A (stable position after one step, command coil yet energised)
- d)  $x=0,66$  mm,  $I_c=0$  A (stable position after one step, command coil not energised)

In Fig. 4 the flux plots and the computed tangential and normal forces are given for the four cases mentioned above. As it can be seen, the obtained results are perfectly in accordance with the theoretical expectations. When the command coil of the module is not energised, only a few flux lines cross the air-gap. When the module is active (its command coil is energised) the magnetic flux generated by the permanent magnet is forced into the air-gap and significant tangential and normal forces are produced.



**Fig. 4.** Results of the field analysis

Upon the computed forces the static characteristics of the motor are determined: the total tangential and normal forces for different command currents versus displacement. These characteristics are given in Fig 5.



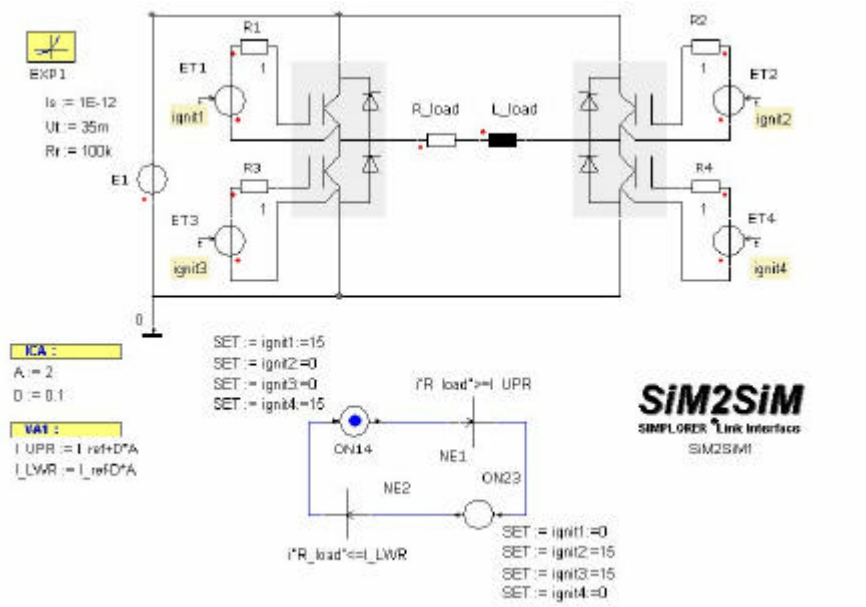
**Fig.5.** The static characteristics of the mover's tangential (a) and normal (b) forces

These characteristics will be used for the three-phase modular double salient linear motor's dynamic simulation model and will be loaded in the SIMULINK model as 2D look-up tables.

### 5. The SIMPLORER unit

The power converter feeding the command coils of the three-phase modular double salient linear motor was modelled in SIMPLORER. This software package is frequently used for simulating comprehensive electric circuit components. SIMPLORER is very user-friendly, due to its graphic interfaces making even complex models easy to define [6].

The power converter unit is composed of three independently working one-phase inverters, built up using dynamic IGBTs. The SIMPLORER model of the single phase H-bridge inverter is shown in Fig. 6.



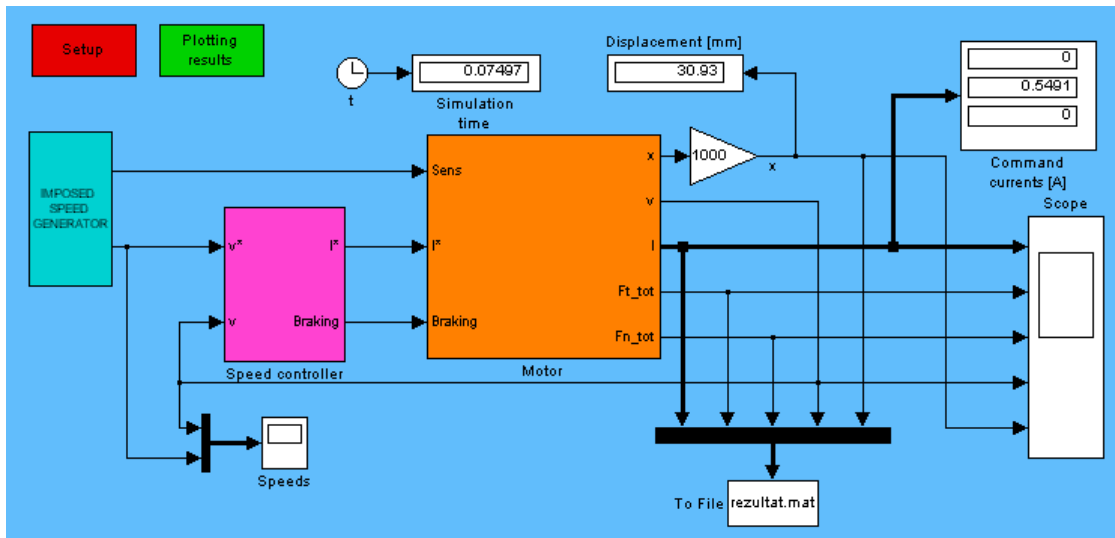
**Fig. 6.** The SIMPLORER model of a phase of the converter

The so-called SIM2SIM SIMPLORER–MATLAB/SIMULINK coupling's interface allows the exchange of each variable between a SIMPLORER and a SIMULINK model. The parameter exchanges are clearly arranged, so the different system quantities can be linked easily and quickly. During the simulation an automatic step width control in SIMPLORER and MATLAB/SIMULINK takes place.

The coupling element in SIMULINK is an S-Function-type block. After a multi-step setting process the link between the two different simulation platform can be easily established.

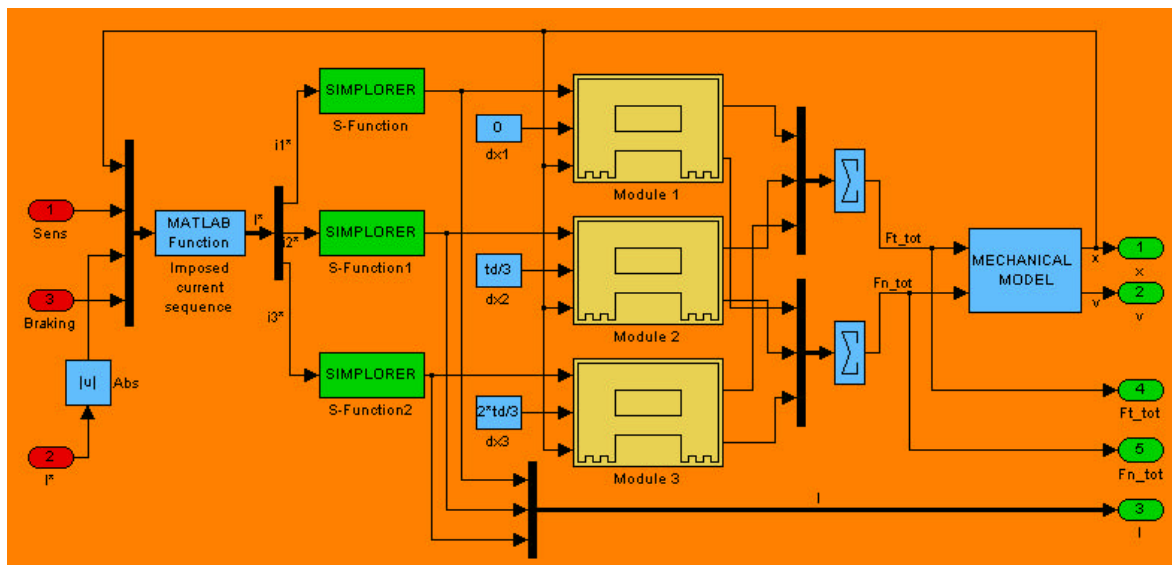
## 6. The MATLAB/SIMULINK model

The basic component of the coupled simulation program is implemented in MATLAB/SIMULINK. As it is well known, this environment is one of the best suited for the dynamic simulation of electrical machines. The main window of the simulation program is given in Fig. 7. As it can be seen, it is built up in a modular manner (using several sub-system type blocks). All the main components of the linear drive system can be clearly distinguished in the model. This way high transparency was assured for the users. Hence any changes in the program can be made quickly and easily. The program calls several MATLAB functions, e.g. for the setup (when the motor's main parameters are loaded from an M-file) or for the final plotting of the results. All the benefits of MATLAB (easy to write program lines, advanced graphical visualisations) and of SIMULINK (simple modular model building, easy to use graphical interface, etc.) are fully exploited [7, 8].



**Fig.7.** The main window of the SIMULINK model

The motor model subsystem is given in Fig. 7. This is also built up modularly: a subsystem is generating the three imposed command currents. In this subsystem are included the three S-Function type blocks obtained by the SIM2SIM linkage with SIMPLORER. These blocks are modelling the power converters feeding the command coils of the linear motor.



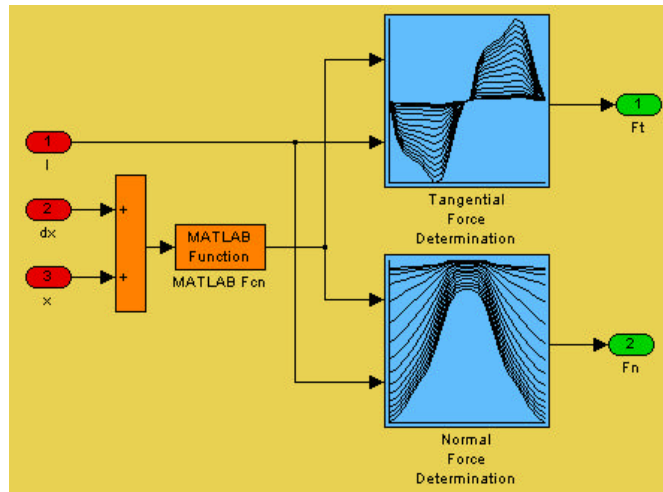
**Fig.8.** The **Motor** subsystem of the model



The models of the three modules of the motor were also grouped in a separate block (called **Module 1**, etc.) and are shown in Fig. 9.

Each block corresponding to a mover module has 3 inputs (the command current, the mover's displacement and the module's relative position within the mover armature) and two outputs (the tangential and the normal force). The forces of each module are added in order to obtain the total tangential and normal forces of the motor. In the **Mechanical model** subsystem the speed and the displacement of the motor are computed. These are the output signals of the entire model of the motor.

The values of the forces for certain currents and displacements are interpolated from two look-up tables, containing the results of the magnetic field analysis performed by the FEM based MagNet program. As it can be seen, the drawings on the mask of the look-up table type blocks are just the static characteristics shown in Fig. 5.



**Fig. 9.** A mover's model

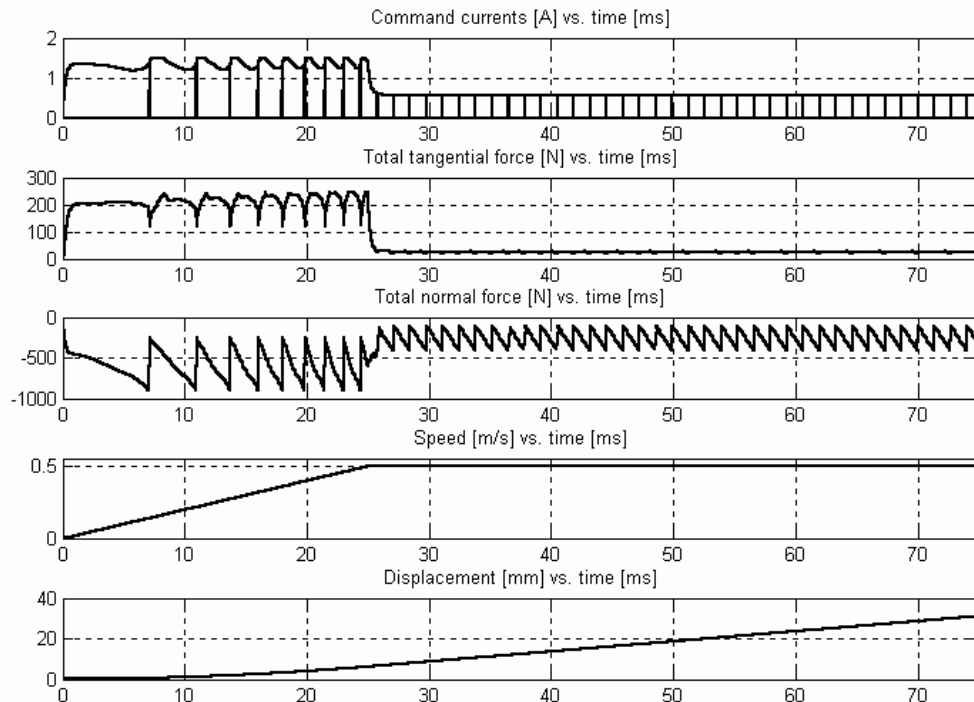
The above-presented model can be used for simulating any dynamic regime of the motor. All the motor characteristics can be obtained and plotted in order to make easy its study.

## 7. Simulation results

Numerous dynamic regimes were studied using this model of the three-phase modular double salient linear motor. Here only the results obtained for the starting of the motor with an imposed speed ramp will be given.

The sample three-phase motor's rated command current, respectively tangential force is 1 A and 135 N. Its step size is 0,66 mm.

The main results of the simulation are given in Fig. 10. The command currents, the total tangential and normal forces, the speed and the displacement are plotted versus time.



**Fig.10.** Results of simulation

As it can be clearly seen in Fig. 10, the ramp-type imposed speed was precisely followed. High tangential forces were needed for accelerating the mover. Due to the high force required for this stage of motion, the command currents also have significant values. After the mover was accelerated, its imposed constant speed may be maintained by low tangential force.

All the obtained results for diverse regimes are in good accordance with the theoretical expectations and also with the results of analytical computations. The basic idea of coupling in such a manner the different simulation platforms could be successfully applied to any other electric motor.

## 8. References

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