On the Control of a Rotary-Linear Switched Reluctance Motor

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***Abstract*—In several advanced industrial applications both rotary and linear movements are required. But in many cases, mainly due to space limitations it is difficult to use two motors to ensure the two types of motion. For such applications the rotary-linear motors are ideal solutions. The proposed switched reluctance rotary-linear motor practically combines three identical rotating motors with a linear one. It can be used in precise two degrees of freedom motion control systems, as pick and place equipment, robotics, instrumentation, automotive applications, etc. In the first part of the paper the proposed motor is described together with its control system. In the second part results of simulations are given for the rotational, translational and combined rotating-linear movements. All these results emphasize the correct design of the motor and its capability to perform both the two types of movements.**

I. Introduction

Since the usual motors produce only one dimensional motion (linear or rotary), two dimensional motion control systems often require more than two motors to fulfill the required motion profiles. The most typical industrial applications where combined linear and rotary movements are required are: parts assembling, component insertion and electrical wiring equipment. Usually in these applications the high-performance manufacturing machines use cascaded X-Y tables driven by rotary motors and rotary-to-linear mechanical couplings. Even if this is the most widely used method, it has several disadvantages as the complex mechanics, great space requirement, frequent mechanical adjustments, high manufacturing/maintenance costs, low reliability, etc. [1], [2].

For such applications the rotary-linear motors could be better solutions. These are able to execute by a single unit both rotating and linear movements independently or also simultaneously.

Generally the rotary-linear motors are developed upon usual electrical machine's designs. For example the permanent magnet linear and rotary actuator cited in [3] is based on a Vernier-type permanent magnet synchronous machine. Helical motion induction machines are also reported in literature [4], [5].

The switched reluctance motor (SRM) also stand on the basis of diverse rotary-linear motor structures because they have the simplest structure as possible. The relatively easy control and low manufacturing and maintenance costs at high reliability are other advantages of SRMs.

The rotary-linear SRM cited in [6] is practically obtained by combining a three-phase tabular linear SRM motor with a four-phase rotary SRM. It has a quite complicated structure formed by two rotation and three propulsion stators and a long toothed tubular rotor.

II. The Proposed Rotary-Linear SRM

The proposed rotary-linear SRM is a multi-stack machine. Its multi-segmented construction is similar to the modular stator of the multilayer SRM cited in [7], but it is designed to perform also linear movements.

The complex structure of the rotary-linear motor in discussion can be seen in Fig. 1, where the iron cores of the machine are given [8].

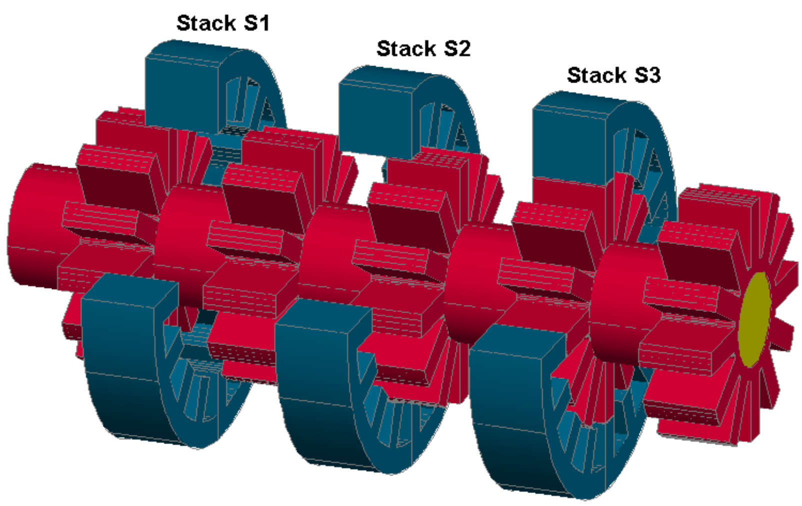


Fig. 1. The basic structure of the proposed rotary-linear SRM's iron core

The stator of the machine has a multi-segmental design, practically being composed of three, precisely shifted, classical 16 poles SRM stators, Fig. 2.

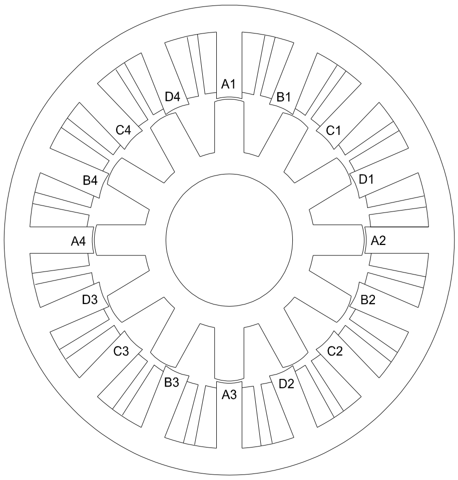


Fig. 2. The cross section of the proposed rotary-linear SRM

The proposed motor's rotor is constructed of several common 12 poles SRM rotor stacks. Its structure ensure appropriate flux path along the stators, the air-gap and the rotor. The rotor may rotate and also move on axial direction.

As its classical rotational and linear counterparts this motor is also based on the variable reluctance principle [9]. Its advantages are: their fast response, high flexibility and the simple drive and control system.

Due to its specific movement the motor requires also particular bearings. The linear-rotary bearings to be used are designed to permit the shaft to rotate smoothly and with low friction simultaneously during the straight line movement.

The proposed rotary-linear SRM is a direct-driven machine which directly transfers the mechanical energy to the load. Thus any mechanical couplings (gears or belts) can be eliminated from the motion chain.

Hopefully it will be able to replace the traditional complex rotary-linear systems with a higher performance and lower cost alternative.

III. THE CONTROL OF THE MOTOR

Each type of the movement (rotational and linear) has to be controlled independently. Only by imposing different energizing sequence for the windings on the three stators the different precise movements can be achieved [8].

When rotational movement is imposed four coils on each stator stack are fed simultaneously function of the rotor's position. The stator which has its poles aligned in the axial direction with the rotor poles will develop most of the torque. The other two stator stacks will also contribute to the rotational movement. As they are symmetrically unaligned on the axial direction in that position the axial forces developed by them will be equal but of opposite direction, hence their sum will be nil, hence no linear movement will be produced.

In Table I the sequence of the winding's feeding for a clockwise rotation from the initial position shown in Fig. 1 is given.

If linear movement is required the proposed motor will work similarly to a linear SRM [10]. Three of the four phases of one module will be fed and a rotor stack will be aligned upon the variable reluctance principle with the stator's poles.

The sequence of the winding's feeding for a linear movement to the left from the initial position seen in Fig. 1 is given in Table II.

As it can be seen in the tables at each moment of the motor's movement of any kind 12 windings are fed function of the moving armature's angular and linear position and the required type of movement.

Therefore the control strategy to be implemented is more complex than that usually applied for the classical rotating or linear SRMs.

TABLE I.
Sequence of the winding's feeding for the rotating movement

	Step 1			**Step 2**			**Step 3**			**Step 4**			**Step 5**		
Poles	**Stack S1**	**Stack S2**	**Stack S3**	**Stack S1**	**Stack S2**	**Stack S3**	**Stack S1**	**Stack S2**	**Stack S3**	**Stack S1**	**Stack S2**	**Stack S3**	**Stack S1**	**Stack S2**	**Stack S3**
A1	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0
A2	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0
A3	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0
A4	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
B1	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0
B2	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0
B3	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0
B4	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0
C1	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
C2	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
C3	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
C4	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
D1	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**
D2	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**
D3	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**
D4	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**

TABLE II.
Sequence of the winding's feeding for a linear movement

No. of poles	Step 1			Step 2			Step 3			Step 4		
	Stack S1	Stack S2	Stack S3	Stack S1	Stack S2	Stack S3	Stack S1	Stack S2	Stack S3	Stack S1	Stack S2	Stack S3
A1	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
A2	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
A3	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
A4	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
B1	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
B2	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
B3	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
B4	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
C1	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
C2	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
C3	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
C4	0	**1**	0	**1**	0	0	0	0	**1**	0	**1**	0
D1	0	0	0	0	0	0	0	0	0	0	0	0
D2	0	0	0	0	0	0	0	0	0	0	0	0
D3	0	0	0	0	0	0	0	0	0	0	0	0
D4	0	0	0	0	0	0	0	0	0	0	0	0

The block scheme of the proposed rotary-linear SRM's control system is given in Fig. 3.

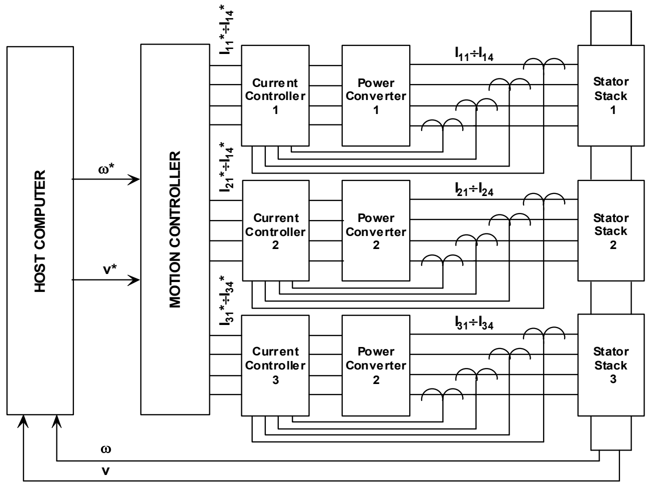


Fig. 3. The block scheme of the rotary-linear SRM's control system

Both the angular and linear speeds (ω^* and v^*) are imposed for the motion controller by the host computer. Upon the required speed profiles the motion controller imposes the 12 currents in the phases of the machine. The currents in the four phases of each stator module are controlled via four-phased current controllers and power converters. The feedback speed signals (ω and v) are given by the rotational and linear velocity sensors located on the moving armature of the machine.

IV. The Sample Machine

The main data of the simulated rotary-linear machine are: 500 W rated power, 300 V rated voltage and 6 A rated current. It is capable to develop 7.5 N·m torque (when rotating) and 30 N axial force (at linear movement).

The outer diameter of the stator is 210 mm and the length of a stator stack is of 15 mm.

V. The Simulation Program

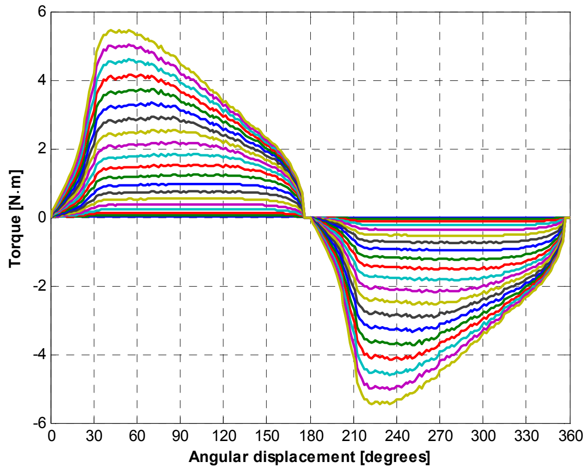
To be able to study the complex operation of the proposed rotary-linear SRM and to verify the designed control system dynamic simulations of the motor in different conditions should be performed [11].

The simulations were carried out by a complex program set up in the MATLAB®/Simulink® environment, the most widely used dynamic system simulating platform [12].

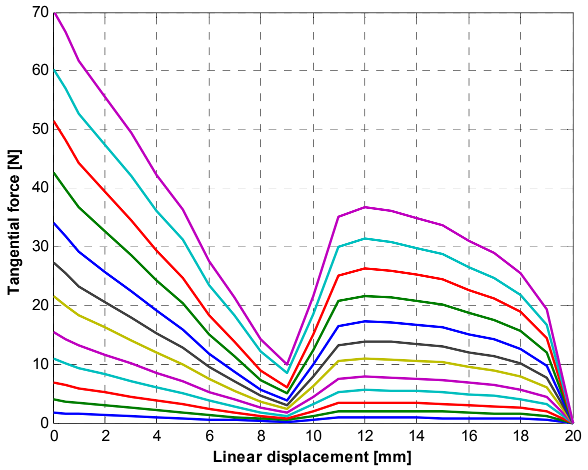
The static characteristics of the machine are the starting point in developing the complex simulation program. These characteristics are set up separately for the rotary and linear movement. The main static characteristics are the torque, respectively the tangential (axial) force, plotted versus the angular / linear displacements having different control current values as parameters. Also the magnetic flux thru the energized coils versus the currents and the angular, respectively the linear positions of the moving armature characteristics are required.

These all were set up by using advanced three-dimensional numeric field computations performed via Flux 3D finite elements method (FEM) based program.

Two of these static characteristics computed for phase currents between 0 and 8 A are given in Fig. 4.



a) rotational movement



b) linear movement

Fig. 4. The static characteristics computed via numeric field analysis for different currents and rotational / linear positions of the mover

The main window of the Simulink® simulation program is given in Fig. 5.

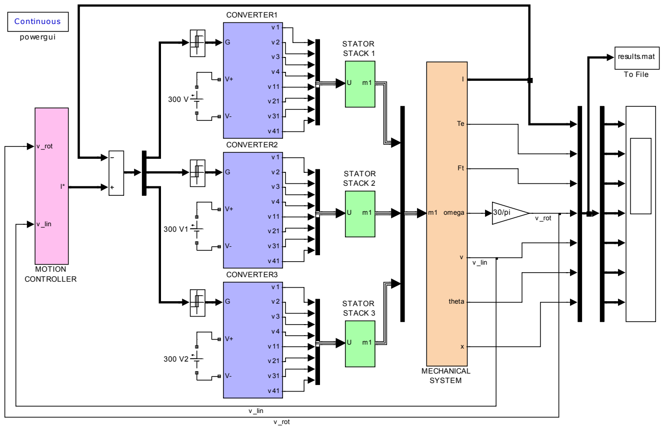


Fig. 5. The main window of the simulation program

As it can be seen in the figure the basic structure of the program follows the block diagram of the machine's control system given in Fig. 3.

The motion controller block generates the imposed currents for the 12 windings of the machine placed on the three stator stacks. The currents are imposed function of the required movement (rotary, linear or combined) and the measured rotational and linear speed of the motor. The hysteresis current controllers are modelled by simple *Relay* blocks. The models of the three four-phase power converters of the system are built up by using blocks from the SimPowerSystems™ blockset.

Each model of a stator module is compound of two parts, one modelling the rotational movement, the other one the linear one. In Fig. 6 the model of the rotational movement is given. The two look-up tables (*Flux* and *Torque*) embedded in the model can be easily observed. In the *Mechanical System* block the speed and displacement of the two types of movement are computed, respectively several internal signals required by the coordination of the movements are generated.

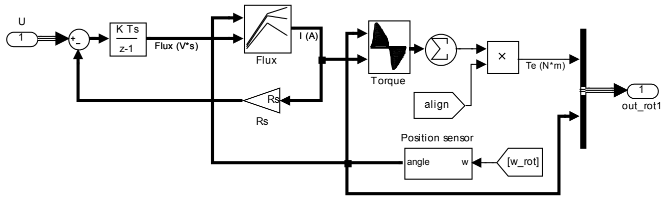


Fig. 6. The model of the rotational movement of one of the machine's stator

The main results of the simulation are: the phase currents in the windings, the generated torque and axial (tangential) force, respectively the angular and linear speed and displacement of the moving armature. These signals are both displayed by using a *Scope*-type block and exported in the *results.mat* file for future processing. All the results given in this paper were plotted in MATLAB® by using the data saved in these files.

Several external MATLAB® files are used during the simulation (for generating the motor's main design data and the date required for the look-up tables, for computing the commutation angles, etc.).

V. Results of Simulations

Several studies were performed by using the above presented simulation program. Next some of the most relevant and interesting results will be detailed.

In Fig. 7 the main results of a linear movement's simulation are given: the phase currents in the windings from the active stator module, the developed tangential (axial) force, respectively the speed and the linear displacement of the moving armature. A 0.5 m/s speed step was imposed by the motion controller. At the beginning higher tangential forces are required to accelerate the mover. In about 120 ms the mover's speed reaches the imposed value. After this both the command currents and the tangential force are lower, as to maintain the constant speed linear movement of the machine. The force ripples are high, as it could be expected for a linear SRM.

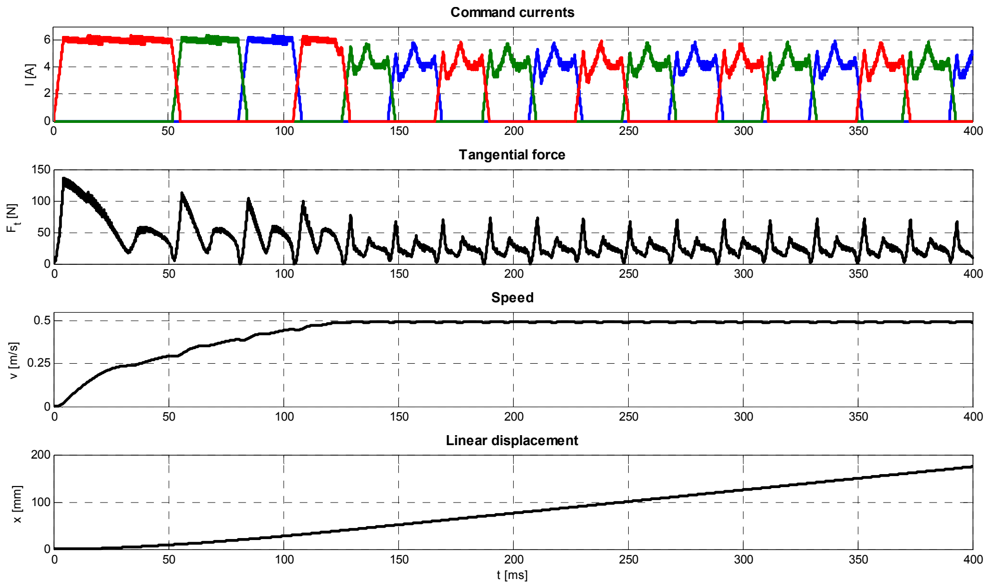


Fig. 7. The results of the linear movement's simulation

The results of the motor's rotational movement are given in Fig. 8. In the first stage only a single stator module's work was simulated. As in the machine, at a time, only one stator module can be perfectly aligned with one of the rotor's stack it is interesting to study the torque development capability also of the un-aligned stator modules. The results in Fig. 8a are for the perfectly aligned stator module. The rotor is speeded up rapidly to the imposed speed (400 1/min). The mean value of the developed torque is about 5 N·m, the rated torque of the motor. Due to the relatively great number of poles the torque ripples are quite small.

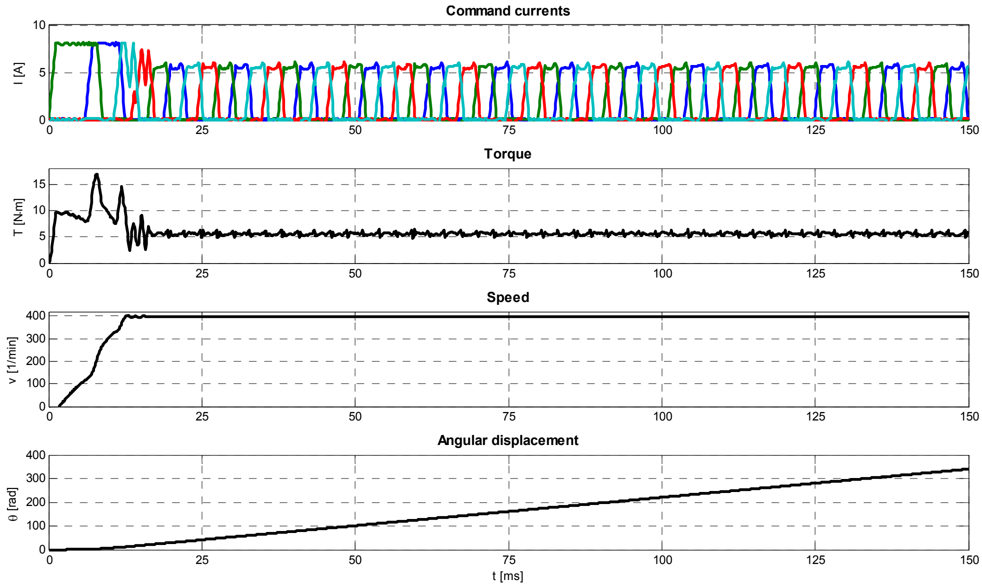
In the worst case only 33% of the stator stack is aligned with the rotor stack. The results of simulation for this case are given in Fig. 8b. As it can be seen also in this case the mover can achieve the imposed speed. Of course the torque development capability of the stator module is reduced, to about 3 N·m. The torque ripples are a little bit larger than in the previous case.

The behavior of the motor in study during the combined rotational-linear movement is of maximum interest. Therefore in Fig. 9 the results for such working regime are given. In this case all of the stator modules are working. They are contributing together to the torque production of the machine.

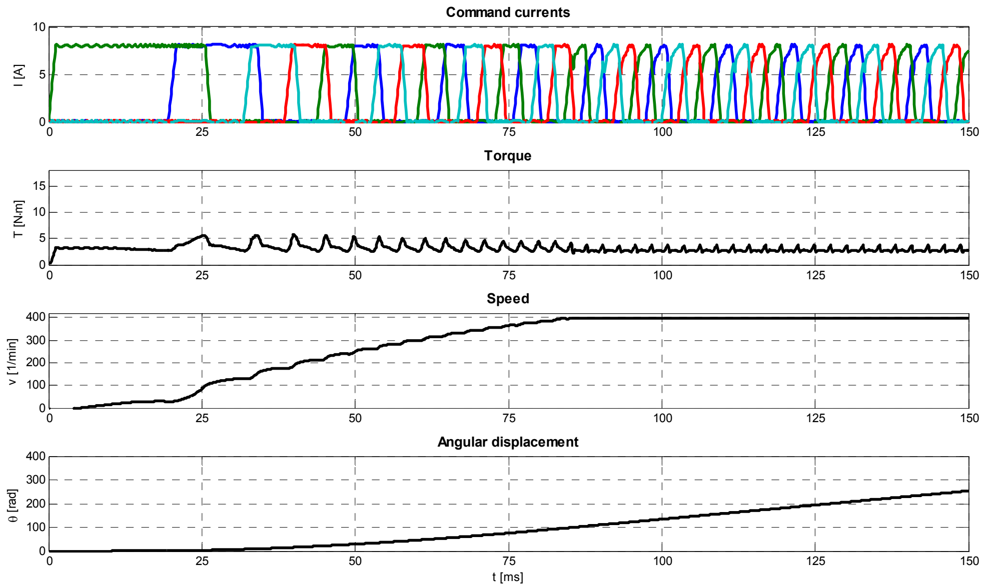
During the rotation the mover also has a linear displacement at 0.5 m/s speed. For the rotational movement the same speed was imposed as in the previous cases in study (400 1/min).

As it can be observed studying the results the required rotational motion is fulfilled also in the case of the simultaneously linear displacement of the mover.

During of one pole pitch long linear movement the overall torque development capability of the three stator stacks is varying between 133% and 166%. When a stack is perfectly aligned (100% of the rated torque is produced) the two others



a) stator stack perfectly aligned with the rotor stack



b) stator stack 33% aligned with the rotor stack

Fig. 8. The results of the rotational movement's simulation

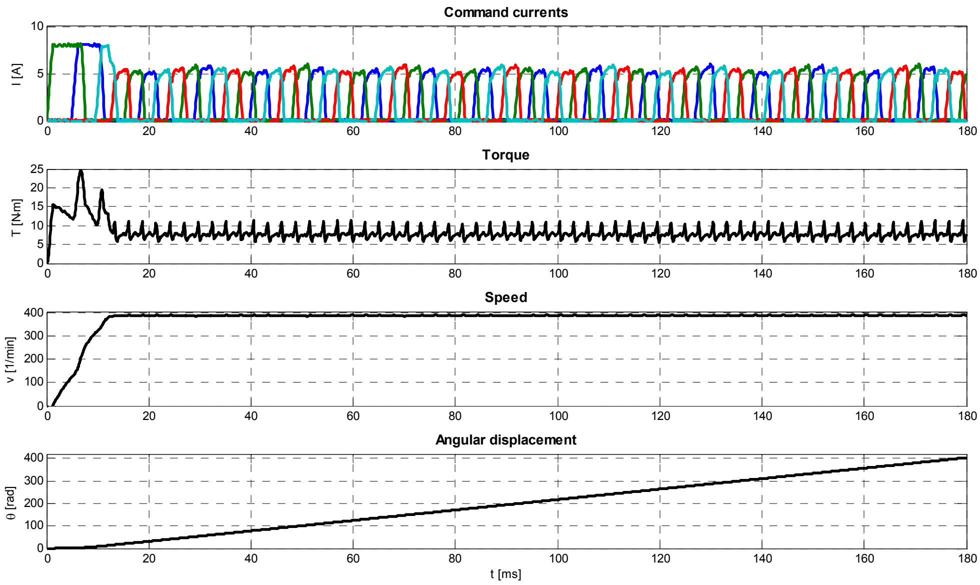


Fig. 9. The results of the simulation for a combined rotational-linear movement

ones are aligned 33% (see Fig. 1) and they can develop both nearly the same ratio of the rated torque.

Therefore during the linear movement the torque development capability of the motor is changing within 33% of the rated torque. This phenomenon is emphasized in Fig. 10, where the simulation results are given for the rotating movement combined with a 160 mm long linear displacement.

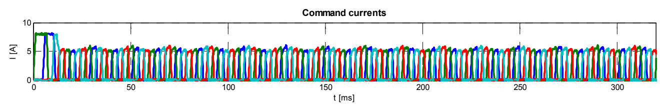


Fig. 10. The phase currents in a stator module during rotation and a 160 mm long linear movement

It can be clearly seen as the peak values of the phase currents have an oscillation. When the torque development capability of the motor is lower greater currents are required to maintain the constant torque of the machine.

Conclusions

The combination of a rotary and a linear movement on the same axis is frequently required in diverse industrial systems. For such applications the proposed rotary-linear SRM seems to be an excellent solution.

The developed control system enables precise control of three types on movement (linear, rotational and combined linear-rotational).

The proposed advanced simulation program was proved to be very useful in studying the diverse complex working regimes of the proposed machine.

All the simulation results presented in the paper emphasize both the usefulness of the proposed machine and the effectiveness of the developed control system.

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