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On a Rotary-Linear Switched Reluctance Motor

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***Abstract*--In the paper a switched reluctance rotary-linear motor is proposed and investigated. It is mechanically robust, simple to construct and easy to operate also in hostile industrial and automotive environment. The stator is built up modularly from correctly shifted three usual 8 poles switched reluctance motor stators. The mover is constructed of several common 6 poles SRM rotor stacks. The motor is able to ensure both rotating and linear movement. Its complex structure is analyzed in depth by means of finite element method based three dimensional numeric field computations. The proposed rotary-linear motor is expected to be useful in diverse advanced industrial and automotive applications where both linear and rotary motion is required and the space at disposal is reduced.**

***Index Terms*--rotary-linear motors, switched reluctance machines, variable reluctance principle, finite elements method, field computations, digital simulation.**

I. Introduction

In several advanced automotive and industrial applications both rotary and linear movements are required. But in many cases, mainly due to space limitations, it is difficult to place two motors to ensure both types of motion. For such applications the rotary-linear motors seems to be the best solutions. Their use is efficient since they do not have complex mechanical structure needing frequent mechanical adjustments. The proposed rotary-linear motor has low manufacturing and maintenance costs at high reliability due to the applied switched reluctance motor technology.

II. The Rotary-Linear SRM

Several years ago switched reluctance motors (SRM) were considered as an unpopular choice for high-precision and high-speed motion applications, because they were difficult to control and their output had high torque ripples. This was due to the fact that the actuator characteristics were highly dependent on its complex magnetic circuit, which is difficult to model, simulate, and control.

But in the recent years a general resurge of interest in the SRMs can be widely observed [1]. This is mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of simplifying the mechanics through complex control strategy.

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It must be emphasized that most of these developments were directed towards general speed/torque control of only the rotary SRMs [2].

The proposed rotary-linear motor is a direct-driven machine. The mechanical energy is directly transferred to the load. Thus any mechanical couplers (gears or belts) can be eliminated from the motion chain. Other advantages of such motors are their fast response, high flexibility and their drive and control system may be simple.

In the paper a novel, high performance, direct-driven rotary-linear motion system is proposed. The motor is based on the variable reluctance principle. It aims to replace the traditional rotary-linear systems with a higher performance and lower cost alternative.

The complex iron core structure of the rotary-linear SRM in discussion is given in Fig. 1.

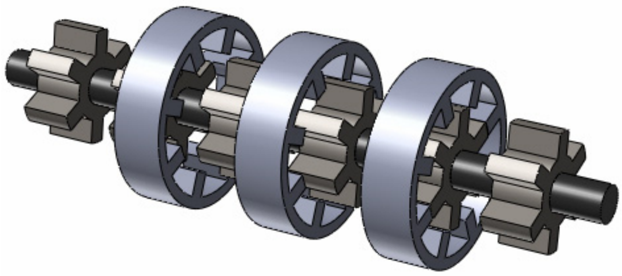

Fig. 1. The iron core structure of the proposed motor.

As it can be seen in the figure the stator is built up modularly of three correctly shifted ordinary SRM stators having 8 poles each, as that given in Fig. 2.

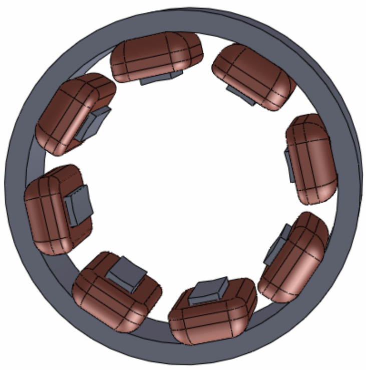

Fig. 2. One stator stack of the motor.

The mover is constructed of several common 6 poles SRM rotor stacks mounted on a common shaft. The toothed structure of each mover stack ensure appropriate flux path along the stators, air-gap and the mover. The mover may both rotate and move on the axial direction.

The design of the motor follows the usual steps established for classical rotary and linear SRMs [1], [3].

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III. SIMULATION OF THE MOTOR

The two types of movements were studied separately by means of numeric field computations.

A. The simulation of the rotary movement

When rotation is required two coils on each stator stack are fed function of the mover position and the imposed current pulses sequence. The stator which has its poles aligned in the axial direction with the mover 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 the axial forces developed by them will be equal, but of opposite direction. Hence their sum will be nil, therefore no linear movement will be produced [4].

For the study of the rotary movement a two dimensional finite elements method (FEM) based numeric field analysis was performed by using the Flux 2D program.

The color map of the flux density for aligned position is given in Fig. 3.

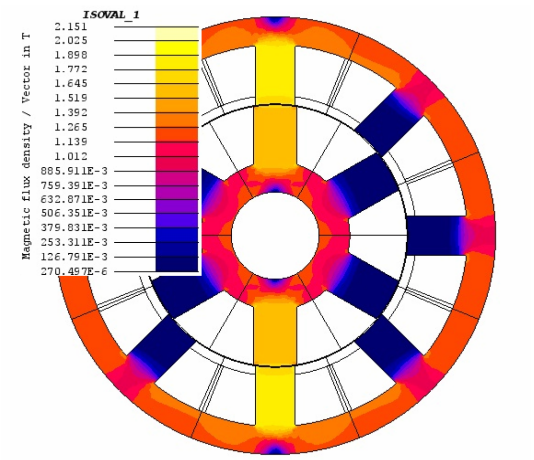

Fig. 3. Colour map of the flux density in aligned position.

Also the torque and flux curves versus current and angular position given in Figs. 4 and 5 were obtained by means of field computations. These curves can be used to model the machine in MATLAB-Simulink. They will be implemented in the simulation program as look-up table blocks.

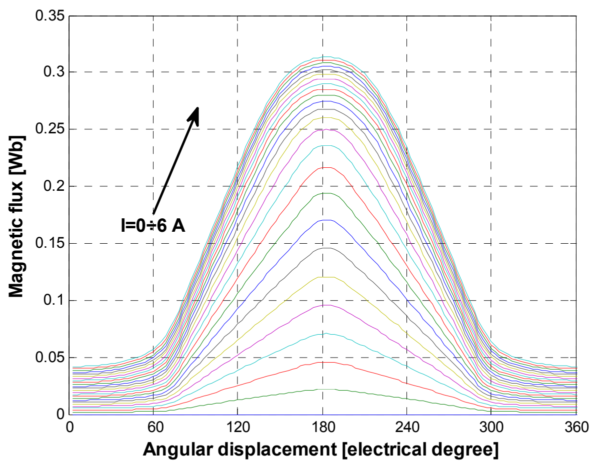

Fig. 4. Flux vs. position characteristics.

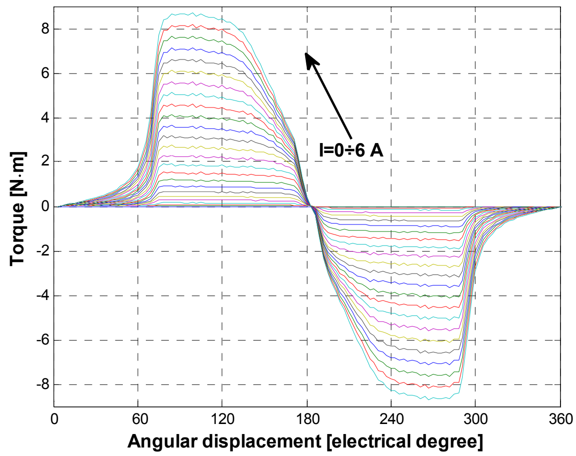

Fig. 5. Torque vs. position characteristics.

B. Simulation of the linear movement

If linear movement is required the proposed rotary-linear motor will work similarly to a linear SRM. Upon the required direction of movement almost all the phases of a stator stack will be fed. The mover stack will be aligned upon the variable reluctance principle with that stator poles [4].

To simulate the translation motion, obligatory three dimensional field computations must be performed due to the complex 3D flux paths inside the motor. These computations were performed by using Flux 3D.

The three dimensional model built up is given in Fig. 6. Due to the large amount of 3D mesh elements only a half of the motor was modeled and an adequate periodicity function was assumed.

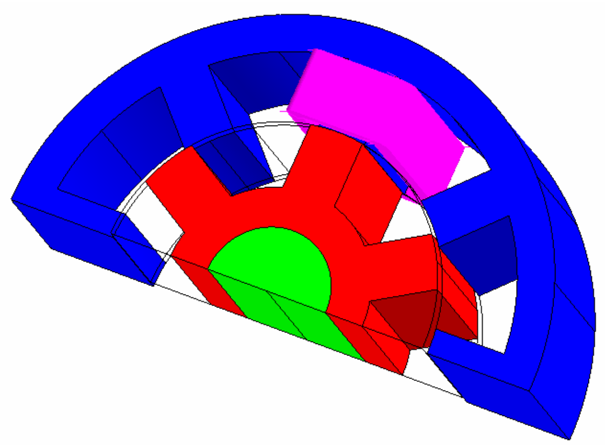

Fig. 6. The simplified 3D model of a part of the motor.

The linear movement can be achieved by using two feeding methods. Upon the first one the two coils of the aligned poles are energized. In the case of the second feeding method six of the eight coils on a stator stack are energized in the same time..

For the first case the obtained results are visualized as color maps of the magnetic flux density in Fig. 7. As it can be seen the distribution of the flux density is quite closed to that computed via Flux 2D (Fig. 3). This emphasizes the correct modeling during both the two and three dimensional numeric field computations performed within the study.

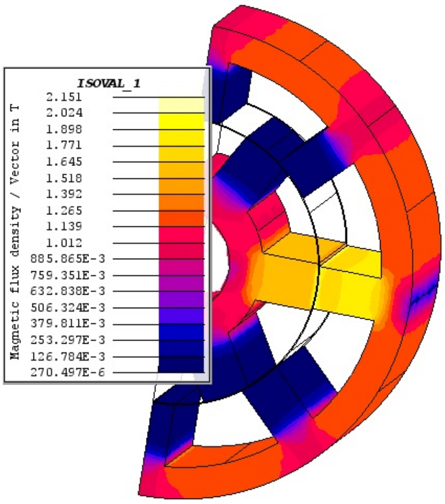

Fig. 7. 3D colour map of flux density in aligned position.

Also for this control method the static characteristics of the machine, the axial force and flux function of current and linear displacement were plotted. To obtain these plots several simulations were performed for different currents and linear positions.

The initial position was considered when the poles of the stator and mover are perfectly aligned, as shown in Fig. 7. As the stator stack length is 55 mm the simulations were performed for a half pole pitch equal to this value. The current values were varied from 0 to 5 A.

The static characteristics obtained are given in Figs. 8 and 9.

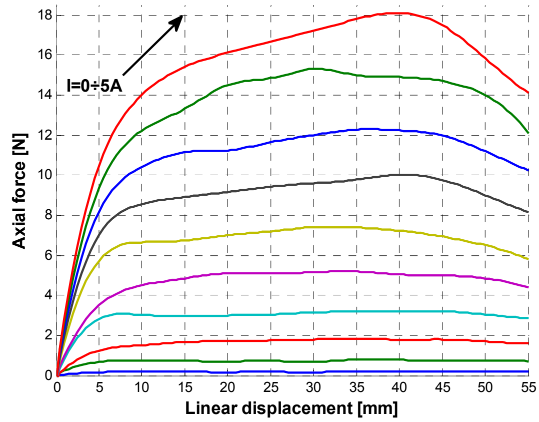

Fig. 8.Axial force vs. linear position characteristics.

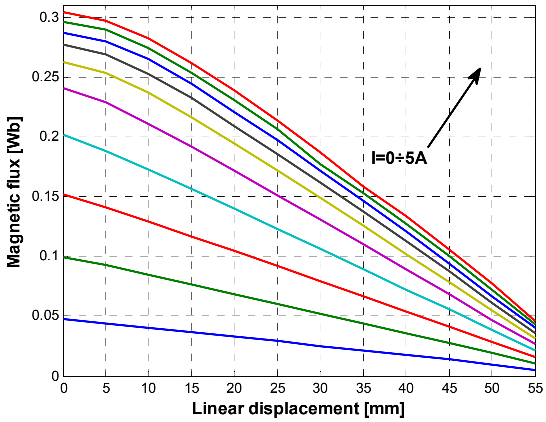

Fig. 9. Flux vs. linear position characteristics.

As it can be observed in Fig. 9 the maximum flux value is quite the same as the one obtained via the 2D field computations (see Fig. 4).

The second way to feed the machine during the linear movement is to energize 6 of the total 8 coils of the stator at one time. Two of the poles are aligned with the mover poles; respectively four of them are only partially aligned. It is considered that due to symmetry the sum of torque produced by the four partially aligned poles will be nil and no rotary movement will result.

The advantage of this more complex feeding is the higher axial force obtained.

The flux density color map for this feeding method and when the stator and mover poles are aligned is given in Fig. 10.

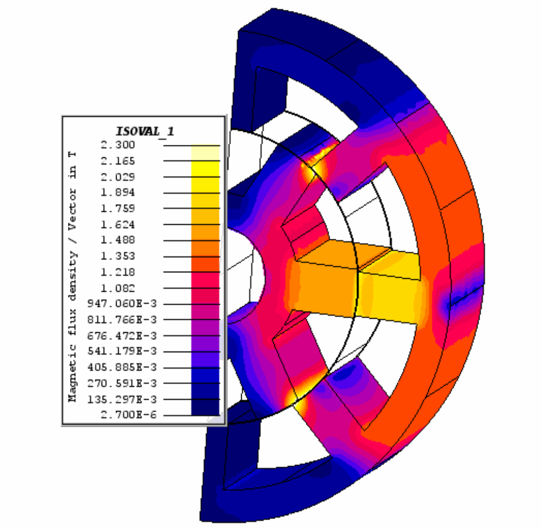

Fig. 10. Flux density map for the second method of feeding.

As it can be clearly seen the flux distribution is quite different from that obtained for the other feeding method (see Fig. 7). The flux lines are not passing through the entire stator and mover yoke. They have a shorter path between the two partially aligned poles and the aligned pole.

For a comparison in Fig. 11 the axial force versus linear displacement characteristics are plotted for the two feeding methods (two, respectively six coils fed simultaneously on a stator stack) at a 5 A phase current.

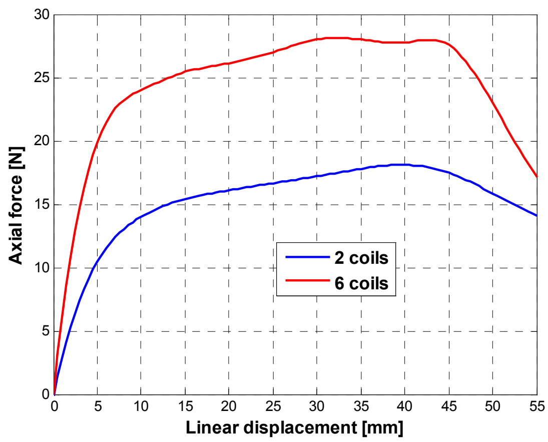

Fig. 11. The tangential forces obtained by the two feeding methods.

As it can be seen the axial force in the case of the second feeding method is higher with about 55 % than the one obtained for the other case.

Hence, the way of feeding the machine and the current value are set depending by the application where this machine is used and by needed values for torque and force.

C. *Comparison of the flux densities*

It could be of interest to compare the magnetic flux densities obtained via 2D and 3D numeric field computations with those computed analytically during the design. The values obtained by means of the three methods are in Table I.

TABLE I. COMPARISON OF MAGNETIC FLUX DENSITIES

Region	3D analysis	2D analysis	Analytical
Stator pole	1.92 T	1.89 T	1.79 T
Stator yoke	1.33 T	1.29 T	1.27 T
Rotor pole	1.71 T	1.64 T	1.58 T
Rotor yoke	1.16 T	1.13 T	1.12 T
Air gap	1.83 T	1.81 T	1.75 T

As it can be seen the results obtained analytically and via the 2D numeric field computations are quite closed. The 3D simulations are less precise because due to the long simulation times the mesh could not be enough refined.

IV. APPLICATIONS

Rotary-linear machines can be useful in diverse industrial and automotive applications where on a single axis both rotational and linear movements are required.

For example they can actuate the active-wheels or control the gearshifts in automated transmissions.

The concept of active wheel appeared due to the high degree of compactness reachable with the modern electromechanical actuators and the demand of a large space for the compartment push toward the installation of the apparatuses executing the vehicular functions into the wheels. An active wheel may be equipped with a suited set of electrical drives and coupling mechanical devices used to locally manage up to 4 basic vehicular functions: propulsion and active braking, passive braking, steering and active suspension [5], [6].

Transmission manufacturers have attempted to obtain the most advantageous solution by combining the best characteristics of manual transmissions and automated transmissions into Automated Manual Transmissions (AMTs) and Dual Clutch Transmissions (DCTs) to reduce overall system losses [7]. Currently, for this transmissions, is preferred a system based on hydraulic and electro-hydraulic actuation technology. Due to a continuous need of efficiency improvement, high precision and fast response, while minimizing costs, the demands for actuation system are increasing. All this requirements can be fulfilled using a combined rotary-linear actuation system. The linear motion is used to control the gear engagement and the rotation one controls the rail selection [8].

Advanced manufacturing lines also require combined precise rotary and linear motion for parts assembly, drilling process, electrical wiring and component insertion, etc. [9].

V. CONCLUSIONS

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

The 2D simulations compared with 3D simulation prove both that the machine is well designed and the usefulness of the proposed motor.

Also it is highlighted that different axial force can be achieved by two feeding methods, function by the requirements of the application.

Future work is related to the development of a laboratory model of the machine and of the control system capable to enable well-coordinated dual motion.

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