A Rotary-Linear Switched Reluctance Motor for Automotive Applications

Loránd Szabó, Ioana Benţia, Mircea Ruba

***Abstract* -- In the paper a rotary-linear switched reluctance motor is proposed and investigated by means of advanced numerical simulations. The motor can generate two degrees of freedom movements: the same axis can both rotate and displace linearly. It is mechanically robust, simple to construct and easy to operate also in hostile automotive environment. The stator is built up modularly from precisely shifted three usual 8 poles switched reluctance motor stators and the rotor of several common 12 poles rotor stacks of the same machine. The complex structure of the motor is analyzed in depth by means of numeric field computations based on the finite element method analysis. The proposed rotary-linear motor machine is expected to be useful in diverse advanced automotive applications where both linear and rotary motion is required and the space at disposal is reduced.**

***Index Terms*--Electric machines, finite element methods, linear machines, numerical simulation, rotating machines, variable speed drives.**

I. Introduction

THE conventional electrical machines are playing an important role in motion control systems. But for diverse particular applications requiring higher performance the conventional machines seem to be difficult to fulfill the required sophisticated demands. Therefore new superior machines are expected to cause technological breakthrough in numerous advanced applications. Their development is widely recognized as one of the most important key technology for next generation [1].

The multi-coordinate electrical machines can achieve two, three or four degrees of freedom (DoF) movements (with *xy*-, *xφ*-, *yφ*- or *xyφ*-travel) having a compact single-mass moving armature [2]. Many and diverse such electrical machines are cited in the literature [3]: the helical motion induction machines [4], [5], permanent magnet variants [6] and also diverse variable reluctance constructions [7].

Such an electrical machine is also the proposed rotary-linear switched reluctance machine (SRM). In the first part of the paper the structure and the working principle are given. Also some details on the machine's control are highlighted. The paper also deals with the three dimensional magnetic field analysis of the machine. Its dynamic performances are studied by means of a SIMULINK program developed by using the static characteristics of the machine obtained via the numeric field computations. In the final part of the paper several possible automotive applications of the proposed electrical machine are detailed.

II. The Rotary-Linear SRM

The proposed electrical machine, as also its traditional rotational and linear counterparts, work upon the variable reluctance principle [8]. Practically it is an efficient combination of a usual rotational switched reluctance machine (SRM) and a special linear SRM having several mover modules on its shaft. It has all the advantages of the SRMs: mechanical robustness, constructive simplicity, low manufacturing and maintenance costs, high reliability and relatively easy control [9].

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

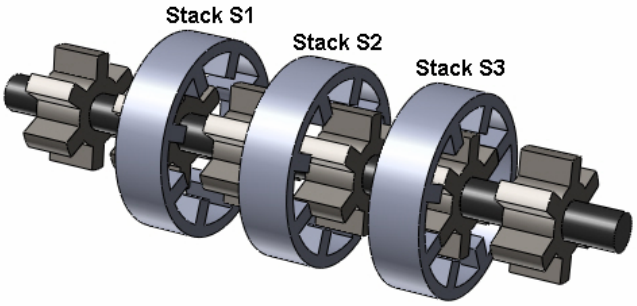


Fig. 1. The iron core structure of the proposed machine.

As it can be seen the stationary part of the machine is built up modularly of three precisely shifted common 8 poles SRM stators. Round the stators' poles concentrated coils are wound.

The iron core of a stator module together with a mover stack is shown in Fig. 2.

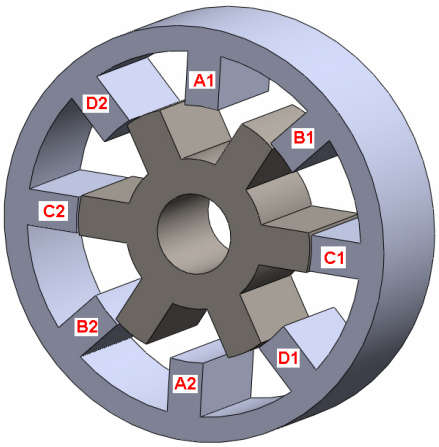


Fig. 2. One stator and rotor stack of the motor.

The mover armature is constructed of several common 6 poles SRM rotor stacks mounted on a common shaft, as shown in Fig. 3. The number of the mover stacks depends on the length of the required linear movement [10].

The paper was supported by the project "*Doctoral studies in engineering sciences for developing the knowledge based society–SIDOC*" contract no. POSDRU/88/1.5/S/60078, project co-funded from European Social Fund through Sectorial Operational Program Human Resources 2007-2013.

L. Szabó, I. Benţia and M. Ruba are with Electrical Machines and Drives Department, Technical University of Cluj, 28 Memorandumului str, 400114 Cluj, Romania (e-mails: Lorand.Szabo@mae.utcluj.ro, Ioana.Bentia@mae.utcluj.ro, respectively Mircea.Ruba@mae.utcluj.ro).

978-1-4673-0141-1/12/$26.00 ©2012 IEEE

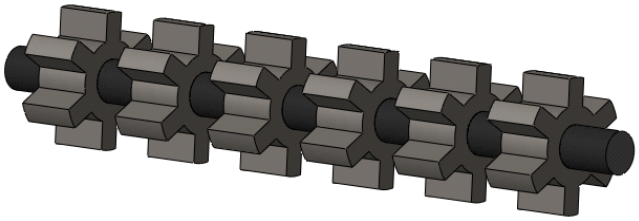


Fig. 3. The mover armature.

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 [11].

The rotation or axial movement of the motor depends on the feeding sequence of the coils placed on the stator stacks.

III. The Control of the Motor

Each type of the movement (rotational and linear) has to be controlled independently. The different precise movements can be achieved by imposing different energizing sequences for the windings on the three stators [10].

When rotation is required two coils from diametrically opposed poles on each stator stacks are fed function of the mover's position and the imposed current pulses sequence. The stator which has its poles aligned in the axial direction with the mover's poles will develop most of the total torque. The other two stator stacks will also contribute to the rotational movement. As they are symmetrically unaligned on the axial direction the thrusts developed by them will be equal, but of opposite direction. Hence their sum will be nil and no linear movement will be produced.

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

If the machine has to perform a movement in the axial direction it will work similarly to a linear SRM [12]. In this case almost all the phases of a single module will be fed. Only the coils of the completely un-aligned poles are not energized. The closest mover stack will be aligned upon the variable reluctance principle with the poles of that stator stack. By feeding in a right sequence the coils of the stator stacks continuous linear movement can be achieved.

For a linear movement to the left from the initial position seen in Fig. 1 the winding feeding sequence is given in Table II.

TABLE II.
Sequence of the Winding's Feeding for Linear Movement

	Step 1			Step 2			Step 3		
No. of poles	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
A2	0	0	0	0	0	0	0	0	0
B1	0	**1**	0	0	0	**1**	**1**	0	0
B2	0	**1**	0	0	0	**1**	**1**	0	0
C1	0	**1**	0	0	0	**1**	**1**	0	0
C2	0	**1**	0	0	0	**1**	**1**	0	0
D1	0	**1**	0	0	0	**1**	**1**	0	0
D2	0	**1**	0	0	0	**1**	**1**	0	0

As it can be seen in the tables at each moment of the motor's movement of any kind at least six windings are fed function of the moving armature's angular and linear position, respectively the required type of movement. Additionally when linear motion is performed the correct feeding sequence also depends on the angular position of the mover (which poles are unaligned). Therefore the control strategy to be implemented is more complex than that usually applied for the classical rotating or linear SRMs.

The block scheme of the proposed machine's control system is given in Fig. 4 [13].

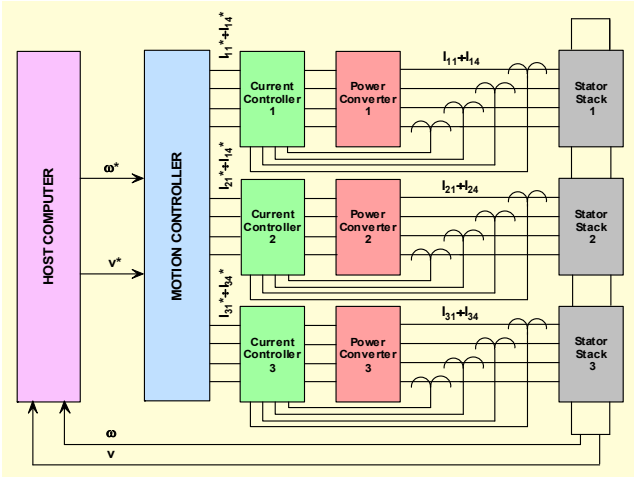


Fig. 4. The block scheme of the control system.

Both the angular and linear speeds (ω^* and v^*) are imposed for the motion controller by the host computer.

TABLE I.
Sequence of the Winding's Feeding for Rotation

	Step 1			Step 2			Step 3			Step 4		
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
A1	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0
A2	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0
B1	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0
B2	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0
C1	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
C2	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0
D1	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**
D2	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**

Upon the required speed profiles it imposes the 12 currents in the phases of the three stator stacks. The currents in the phases of each module are controlled via four-phased current controllers and power converters. The feedback speed signals (ω and v) are given by the angular and linear velocity sensors located on the mover of the machine.

IV. Tridimensional Numeric Field Analysis

A profound and precise analysis of the rotary-linear SRM taken into study can be achieved via the finite elements method (FEM) based three dimensional (3D) numeric field computations [14].

The analysis was performed for a sample machine having the following rated data:

i.) Voltage: $U_N = 300$ V
ii.) Current: $I_N = 5$ A
iii.) Power: $P_N = 350$ W
iv.) Angular and linear velocity: $n_N = 600$ r/min, $v_N = 0.5$ m/s
v.) Torque and axial force: $T_N = 5.5$ N·m, $F_N = 25$ N (for a single module).

The three dimensional model of the machine was developed by using the Flux 3D software [15]. As the analysis requires a huge number of elements and accordingly very long simulation times, respectively due to the rotary-linear SRM's symmetrical construction only a half of the machine was modeled (see Fig. 5). Proper periodicity conditions were set in the model.

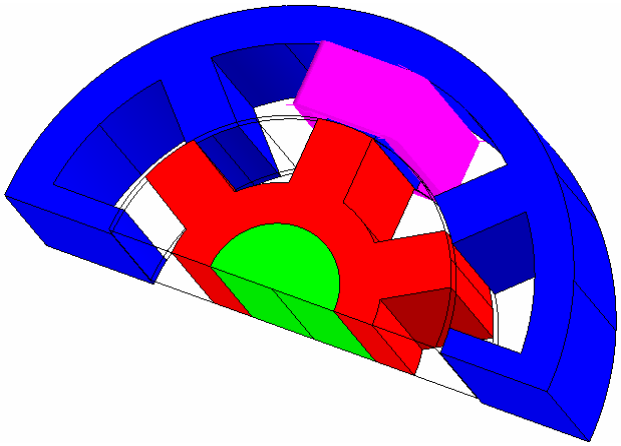


Fig. 5. The 3D model of the RLSRM.

The automatically generated solution mesh is given in Fig. 6.

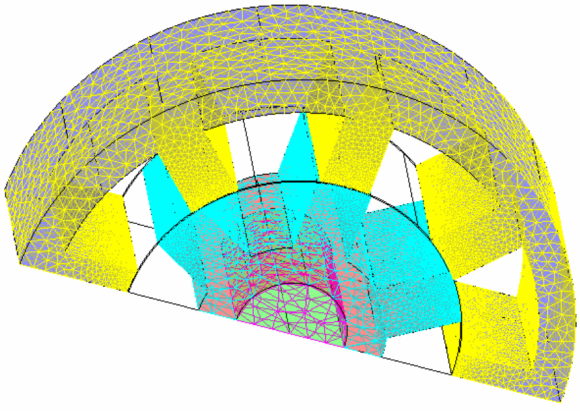
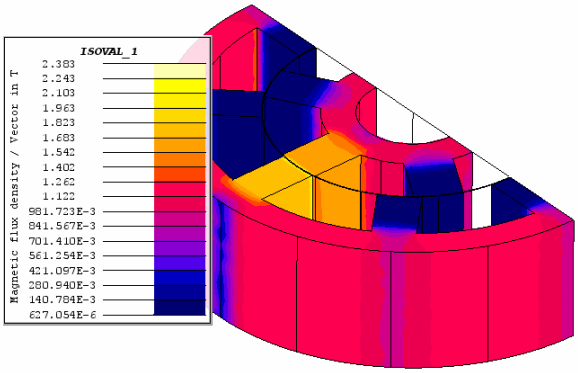


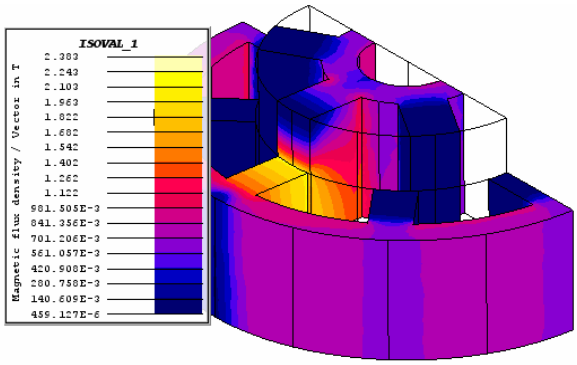
Fig. 6. The solution mesh generated by Flux 3D.

The simulations were performed for various phase currents, respectively angular and linear positions of the mover.

From the several results here only two color maps of the flux densities are given. The maps were generated for the positions when the mover and stator poles are perfectly aligned on both directions of movement (Fig. 7a), respectively when the two poles are aligned only on the radial direction (Fig. 7b). In both cases the current was set to its rated value.



a) poles aligned on both directions of movement



b) poles aligned only on the radial direction

Fig. 7. The color maps of the flux densities obtained by Flux 3D.

Studying the saturation in the cores it can be stated that in all the cases taken into study it does not exceed the designed levels.

In order to analyze the dynamic behavior of the proposed machine its static characteristics (the magnetic flux and the torque, respectively the axial force function of the mover's displacement and phase currents) has to be computed. The obtained parametric plots of the torque and the axial force are given in Figs. 8 and 9.

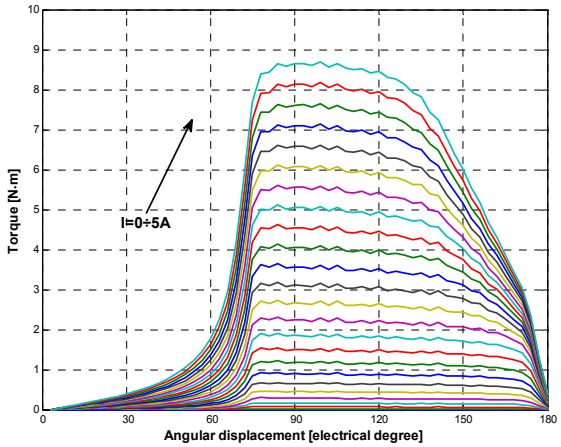


Fig. 8. The torque vs. position characteristics.

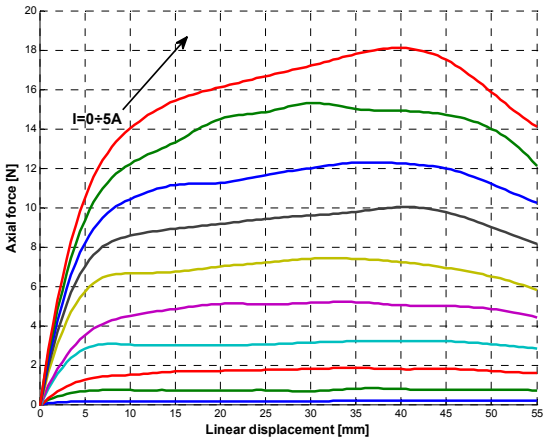


Fig. 9. The axial force vs. position characteristics.

All the obtained static characteristics will be integrated in the SIMULINK model as look-up tables [16].

V. Dynamic Simulations

To study the dynamic behavior under different conditions of the proposed rotary-linear motor a SIMULINK model was developed.

For easy understanding and use the model was built up modularly, as shown in Fig. 10. The model is hierarchical, which allows using both top-down and bottom-up approaches.

The block imposing the speeds, the motion controller, the models of each phase of the power converters, respectively of the stator stacks and of the machine's mechanical system can be easily distinguished.

Several external MATLAB files are used by the simulation program (for generating the motor's main parameters, for the look-up tables, for computing the commutation angles, etc.).

The main results of the simulation are: the phase currents in the windings, the generated torque and axial force, respectively the angular and linear speed and displacement of the moving armature. These are both displayed directly in SIMULINK 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 this file.

Numerous studies were performed by using the above presented simulation program. Next some of the most relevant and interesting results will be detailed. In a first approach the two kinds of movements were studied separately.

Firstly the rotational movement of the RLSRM was studied. For a profound analysis of the machine at the beginning only a single stator and mover stack was considered. In the machine at a time only the poles of one stator stack can be aligned with the mover's poles on the axial direction. Therefore it should be interesting to study the torque development capability of the machine also if the poles on the two armatures are not completely aligned on the axial direction.

The results in Fig. 11a and 11b are for the totally, respectively 33% aligned poles on the axial direction. When the poles are aligned the mover is accelerated rapidly to the imposed rated speed (600 r/min). The mean value of the developed torque during the constant speed working regime is about 5.6 N·m, very close to the rated torque of the machine. Due to the reasonably great number of poles and the correct computation of the commutation angles the torque ripples are relatively small.

In the worst case, when the poles are only in 33% aligned on the axial direction at the same currents the torque development capability of the machine is also reduced near the third of the rated torque (T = 1.9 N·m), as it can be seen in Fig. 11b. Also in this case the mover can achieve the imposed speed, but in a longer time. The torque ripples are a little bit larger than in the previous case.

As in normal working regime during the rotation of the machine all its stator stacks are contributing to the total torque development it is of interest to simulate also the rotation of the machine having all the three stator stacks active. The obtained results are given in Fig. 12. The dynamic behavior of the rotary-linear SRM in study is better than in the case shown in Fig. 11a and the torque generated is increased by near 66%.

In Fig. 13 the main results of a linear movement's simulation are given.

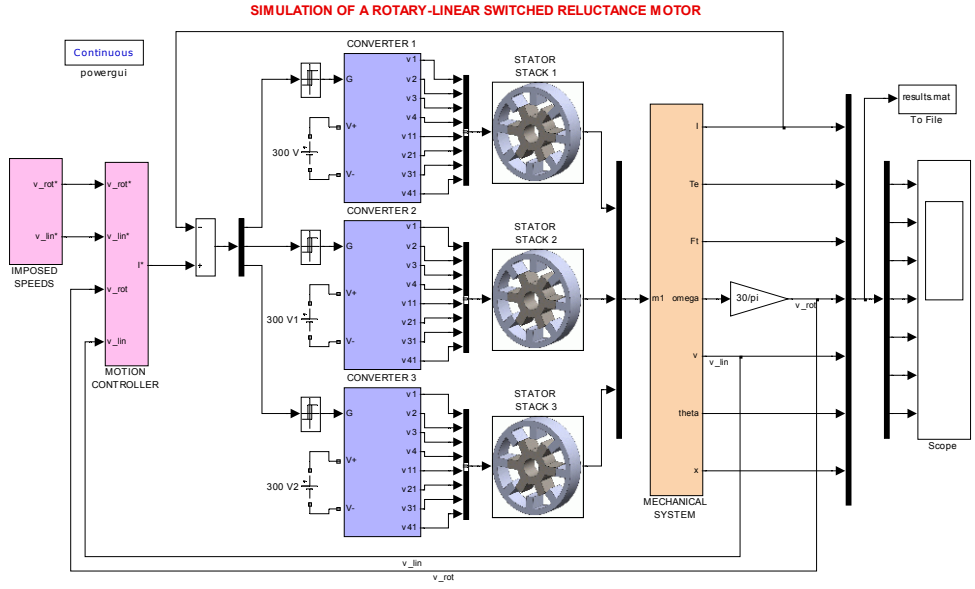
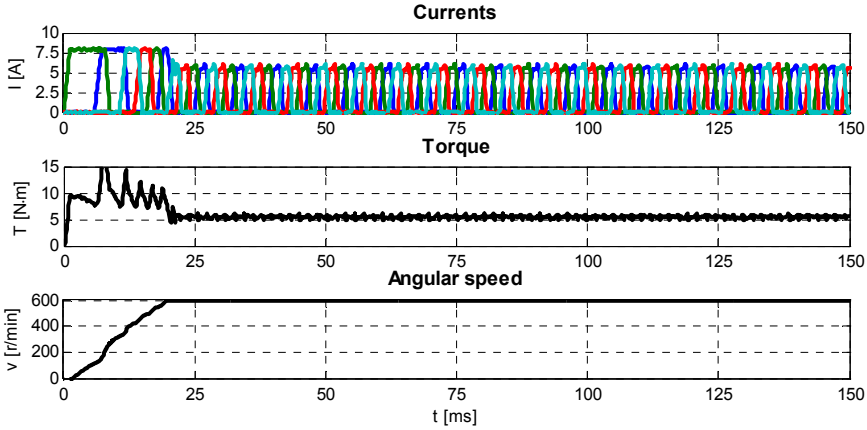
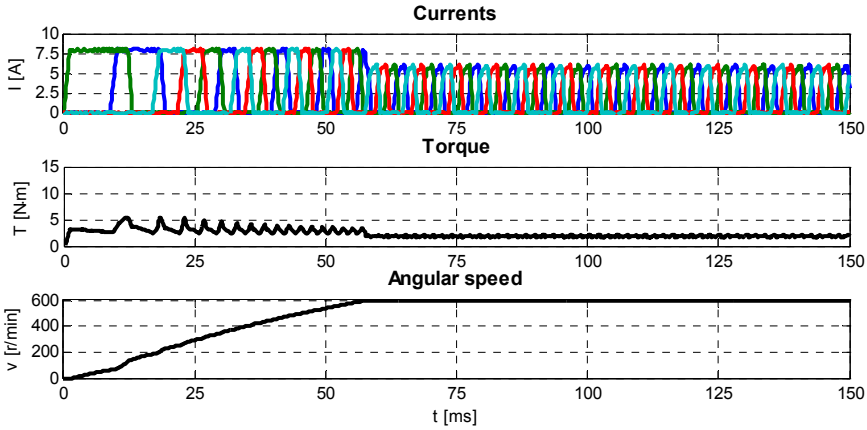


Fig. 10. The main window of the SIMULINK program.



a) stacks aligned on axial direction



b) stacks partially aligned on axial direction

Fig. 11. The simulation results of the rotational movement

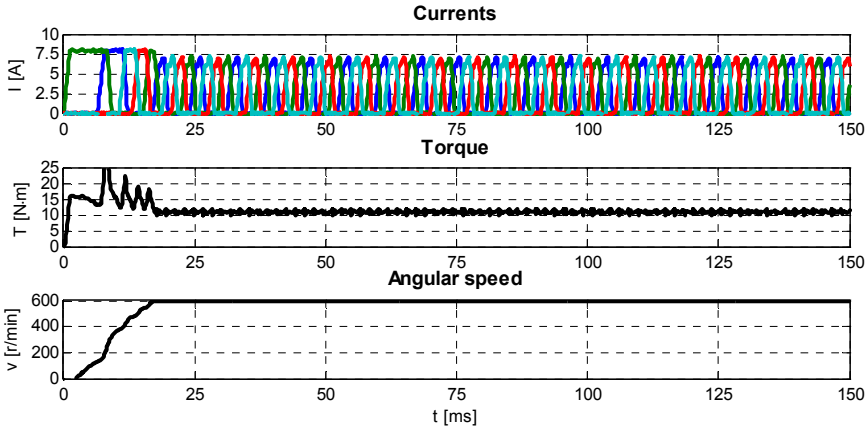


Fig. 12. The simulation results of the rotational movement, when all the stator stacks are active

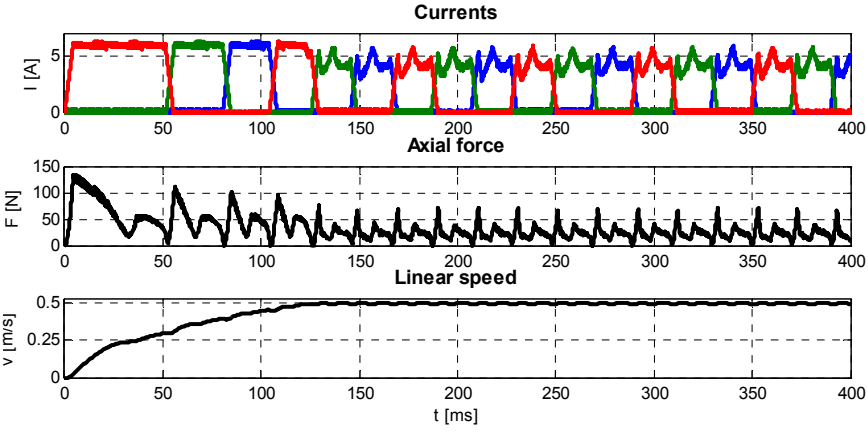


Fig. 13. The simulation results of the linear movement

In Fig. 13 the phase currents in the windings from the active stator module, the developed axial force, respectively the speed and the linear displacement of the moving armature are plotted versus time. A rated (0.5 m/s) speed was imposed by the motion controller. At the beginning higher axial 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 axial 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 with only three stator poles.

The behavior of the motor in study during the combined rotational-linear movement is of much interest. Therefore in Fig. 14 the results for such working regime are given.

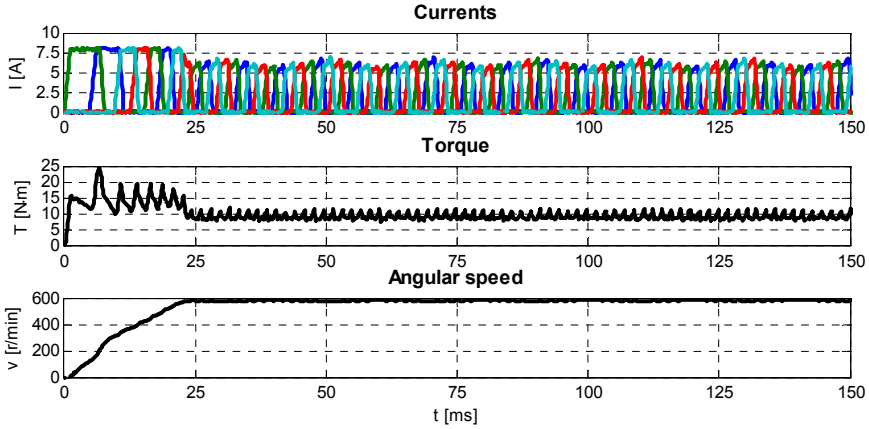


Fig. 14. The simulation results of a combined rotational-linear movement

In this case all of the stator modules are working. During its 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 (600 r/min).

As it can be observed the proposed motor is able to simultaneously perform the two types of motion

During of one pole pitch long linear movement the overall torque development capability of the three stator stacks is varying between 133% and 166% of the rated torque of a single module.

When a stack is perfectly aligned (100% of the rated torque is produced) the two other ones are aligned 33% (see Fig. 1) and both they can develop nearly the same torque. Therefore during the linear movement the torque development capability of the motor is changing within 33% of the rated torque.

It can be clearly seen in Fig. 14 as the peak values of the phase currents have an oscillation due to the above mentioned phenomena. When the torque development capability of the motor is lower greater currents are required to maintain the constant speed of the machine.

VI. Applications

The combination of a rotary and a linear motion along the same axis is used in several industrial applications. Such applications are the precise parts assembling systems, component insertion machines, electrical wiring equipment, etc.

But in many cases, mainly due to space limitations it is difficult to place two motors to ensure the two types of motion. For such application the rotary-linear motors are the best solutions.

Rotary-linear machines can also be useful in diverse automotive applications, too.

For example in electrical/hybrid vehicles, a field with an increasing interest, they can actuate the active wheels or they can 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 machines and coupling mechanical devices used to locally manage up to 4 basic vehicular functions: propulsion and active braking, passive braking, steering and active suspension [6].

As each of the above 4 basic driving functions is governed by means of one DoF, usually the employ of one dedicated actuator per each of them is assumed. However, the use of multi-DoF machines (as that detailed in this paper) may potentially provide benefits in terms of system simplicity, compactness and lightweight by permitting to integrate more functions into a single motor [17], [18].

Another application where the rotary-linear motor can be used is the control of the gearshifts transmissions. 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 [19].

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 the 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 the rail selection [20].

The proposed rotary-linear motor could be used also in active all-wheel-steered (AWS) steer-by-wire (SBW) suspension mechatronic control systems. These active suspensions can provide superior performance by using properly designed multi DoF actuators [21].

VII. CONCLUSIONS

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

The rotary-linear motor developed has a shaft that can practically extend and retract, generating linear movement while rotating, providing this way two independent degrees of freedom in motion control.

By using the proposed rotary-linear SRM a decrease in the number of actuators necessary for the realization of the same degrees of freedom is solved: a single electrical machine can assure both rotational and linear movements. As a consequence both the total weight and size of the rotary-linear motion system can be reduced. In addition it 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.

All the simulation results prove the usefulness of the proposed motor.

Future works include the development of the control for the combined rotary and linear movement, respectively the construction of a laboratory model of the machine in study.

VIII. REFERENCES

[1] T. Yano, "Actuator with multi degrees of freedom," in *Next-Generation Actuators Leading Breakthroughs*, T. Higuchi, *et al.*, Eds., ed London (UK): Springer Verlag, 2010.

[2] H.-D. Stölting, *et al.*, *Handbook of Fractional-Horsepower Drives*. Berlin (Germany): Springer Verlag, 2008.

[3] I. Benţia and L. Szabó, "Rotary-linear machines - A survey," *Journal of Computer Science and Control Systems,* vol. 3, pp. 11-14, 2010.

[4] T. Onuki, *et al.*, "Induction motor with helical motion by phase control," *IEEE Transactions on Magnetics,* vol. 33, pp. 4218-4220, 1997.

[5] J. Alwash, *et al.*, "Helical motion tubular induction motor," *IEEE Transactions on Energy Conversion,* vol. 18, pp. 362-369, 2003.

[6] P. Bolognesi, *et al.*, "A low-complexity rotary-linear motor useable for actuation of active wheels," in *Proceedings of the International Symposium on Power Electronics Electrical Drives Automation and Motion (SPEEDAM '2010)*, Pisa (Italy), 2010, pp. 331-338.

[7] J. Pan, *et al.*, "Investigation of a rotary-linear switched reluctance motor," in *Proceedings of the XIX International Conference on Electrical Machines (ICEM '2010)*, Rome (Italy), 2010, pp. 1-4.

[8] G. Henneberger and I.A. Viorel, *Variable reluctance electrical machines*. Aachen (Germany): Shaker Verlag, 2001.

[9] T.J.E. Miller, *Electronic Control of Switched Reluctance Machines*. Oxford (U.K.): Newnes, 2001.

[10] I. Benţia, *et al.*, "A rotary-linear switched reluctance motor for advanced industrial applications," in *Proceedings of the International Conference on Power Electronics, Intelligent Motion and Power Quality (PCIM '2011)*, Nürnberg (Germany), 2011, pp. 947-952.

[11] R. Krishnan, *et al.*, "Design procedure for switched-reluctance motors," *IEEE Transactions on Industry Applications,* vol. 24, pp. 456-461, 2002.

[12] I.A. Viorel, *et al.*, "Speed-thrust control of a double sided linear switched reluctance motor (DSL-SRM)," in *Proceedings of the 18th International Conference on Electrical Machines (ICEM '2008)*, Vilamoura (Portugal), 2008.

[13] I. Benţia, *et al.*, "On the control of a rotary-linear switched reluctance motor," in *Proceedings of the 5th International Symposium on Computational Intelligence and Intelligent Informatics (ISCIII '2011)*, Floriana (Malta), 2011, pp. 41-46.

[14] K. Hameyer and R. Belmans, *Numerical Modelling and Design of Electrical Machines and Devices* vol. Ashurst Lodge (UK): WIT Press, 1999.

[15] "Flux3D User's Guide," ed: CEDRAT Group, 2011.

[16] I. Husain and S.A. Hossain, "Modeling, simulation, and control of switched reluctance motor drives," *IEEE Transactions on Industrial Electronics,* vol. 52, pp. 1625-1634, 2005.

[17] P. Bolognesi, *et al.*, "Dual-function wheel drives using rotary-linear actuators in electric and hybrid vehicles," in *Proceedings of the 35th Annual Conference of the IEEE Industrial Electronics Society (IECON '09)*, Porto (Portugal), 2009, pp. 3916-3921.

[18] M. Bertoluzzo, *et al.*, "A distributed driving and steering system for electric vehicles using rotary-linear motors," in *Proceedings of the 20th International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM '2010)*, Pisa (Italy), 2010, pp. 1156-1159.

[19] A. Turner, *et al.*, "Direct-drive electromechanical linear actuator for shift-by-wire control of an automated transmission," in *Proceedings of the IEEE Vehicle Power and Propulsion Conference (VPPC '2006)*, Arlington (TX, USA), 2006, pp. 1-6.

[20] A. Turner, *et al.*, "Direct-drive rotary-linear electromechanical actuation system for control of gearshifts in automated transmissions," in *Proceedings of the IEEE Vehicle Power and Propulsion Conference (VPPC '2007)*, Arlington (TX, USA), 2007, pp. 267-272.

[21] B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues. Volume II.* Dordrecht (Netherlands): Springer, 2011.

IX. BIOGRAPHIES

Loránd Szabó was born in Oradea (Romania) in 1960. He received the B.Sc. and Ph.D. degree from Technical University of Cluj (Romania) in electrical engineering in 1985, respectively in 1995. Currently, he is a Professor in the Department of Electrical Machines and Drives of the same university.

His research interests are in the areas of variable reluctance machines, linear and planar motors, condition monitoring and fault detection, etc.

He published over 190 scientific papers and books in these fields. His web page can be found at: http://memm.utcluj.ro/szabo_lorand.htm.

Ioana Benţia was born in Năsaud (Romania) in 1985. In 2009 she received the B.Sc. degree in electrical engineering from Technical University of Cluj (Romania), where she is currently a full time Ph.D. student.

Her research activities are focused on switched reluctance motors, especially on the ones with rotary-linear movement. In this field she published over 10 papers mainly in IEEE sponsored International Conference's proceedings. Her web page is: http://memm.utcluj.ro/bentia_ioana.htm.

Mircea Ruba was born in Satu Mare (Romania) in 1983. He received B.Sc., M.Sc. and Ph.D. degree from Technical University of Cluj (Romania) in electrical engineering in 2007, 2008, respectively in 2010. He is a researcher working in the field of switched reluctance machines. The results of his researches were published in more than 30 papers in journals and international conference proceedings. His personal web page can be found at: http://memm.utcluj.ro/mircea_ruba.htm.