New linear hybrid reluctance actuator

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***Abstract* -- In this paper a new type of hybrid reluctance actuator is presented. This linear hybrid reluctance actuator is a two phase double sided actuator in which the stator is composed by four normalized U cores, each with a coil wrapped around the yoke connecting the two arms of the core or with two coils wound on each of the arms and a permanent magnet placed near the air gap between and in contact with both arms. The mover is comprised of rectangular poles without connecting iron pieces between them but mechanically joined by non-magnetic mounting parts. The magnets are arranged so that their flux is in parallel to the flux created when the coils are energized, both fluxes are added and the total reinforced flux links the stator and the mover. But when no currents flow through the coils no flux crosses the air gap, and the flux of the magnets is closed through the back iron that supports them. An analysis and simulation of the motor using 2 D finite element and MATLAB Simulink is carried out. Finally, a comparison of this type of actuator with respect a linear reluctance stepper motor of the same size is shown.**

***Index Terms*-- Finite element analysis, linear electric actuators, linear hybrid reluctance motors, linear stepper motors, linear switched reluctance motors, machine design.**

I. INTRODUCTION

NOWADAYS there are many applications where it would be desirable to change the hydraulic or pneumatic drives or electric drives combined with mechanical transmission systems by linear electric actuators. These actuators convert directly electric energy into a linear controlled movement. They consist of coupled magnetic and electric circuits in relative motion [1]. Electric actuators are formed by a fixed part or stator and a moving part or mover both parts can contain coils, permanent magnets or bars. Among the different types of linear electric actuators linear switched reluctance motors and linear reluctance stepper motor are an attractive alternative due to their simple construction, robustness and good fault capability nevertheless their weak point is the low force/mass ratio. In order to alleviate this drawback, permanent magnets are inserted in the magnetic structure of the reluctance actuators resulting linear hybrid reluctance actuators. Usually the permanent magnets are placed in such a way that their flux in series reinforces the flux created by the excited coils crossing the air gap and linking the stator and the mover, even when through the coils do not flow current [2-3]. Szabó and Viorel [4] proposed a variant of the Sawyer motor with an additional parallel magnetic path in which the coil is wrapped around. In this linear motor the flux of the magnet is in parallel to the flux created when the coils are energized, both fluxes are added and the total reinforced flux links the stator and the mover. However when no currents flow through the coils no flux crosses the air gap, and the flux of the magnets is closed through the back iron that supports them.

This paper presents a new type of linear hybrid reluctance actuator with a behavior close to the variant of the Sawyer motor before mentioned but with a complete different arrangement of the coils and magnets. The paper is organized as follows. Section II gives a description of the proposed actuator. Section III introduces improvements in the design of the actuator. In section IV, first finite element analysis of the actuator is performed and then simulation of the actuator is reported using Matlab-Simulink. In section V a comparative of the proposed linear hybrid reluctance actuator and a linear reluctance stepper actuator of the same size is shown. Finally in Section VI the conclusions from this study are drawn.

II. DESCRIPTION OF THE LINEAR HYBRID ACTUATOR

This paper proposes a simple low cost actuator able to produce linear forces in the range of 200 to 300 N at a speed of 0.15 m/s, Fig. 1. The linear hybrid reluctance actuator is a two phase double sided actuator in order to balance the normal forces. Two phase actuator is a good choice if, as in this case, has to start in predetermined positions and force ripple is not a drawback, however a three phase actuator should be considered in any other circumstance.

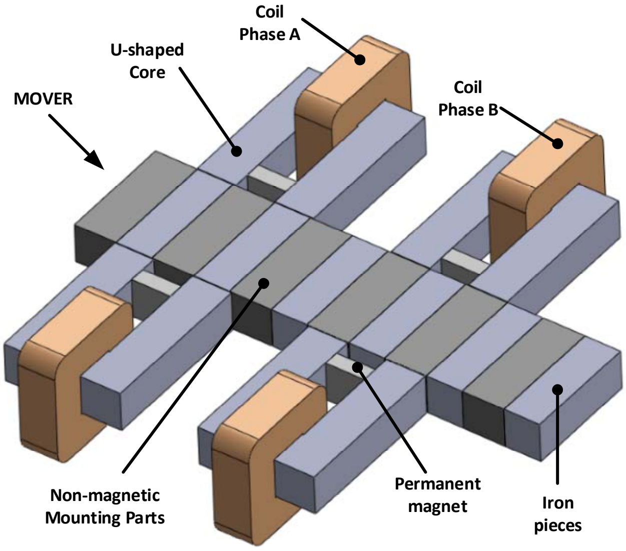

Fig. 1. View of the proposed linear hybrid reluctance actuator

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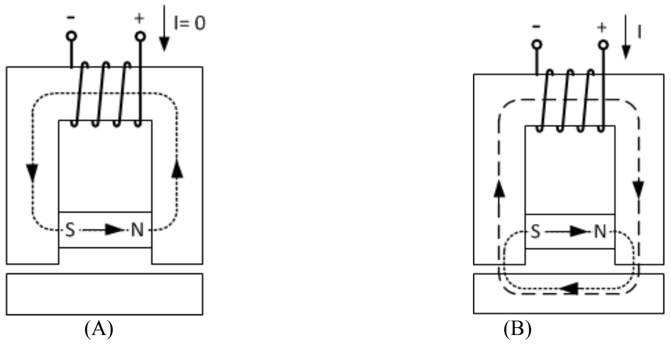


Fig. 2. Electromagnet with permanent magnet. (A) Flux distribution without current through the coil. (B) Flux distribution with current through the coil.

In this actuator the stator is composed by four laminated U-shaped cores, each with a coil wrapped on the yoke connecting the two arms of the core and a permanent magnet placed near the air gap between and in contact with both arms. This structure is an electromagnet with permanent magnet that has been described in [5-7].

The mover is comprised of rectangular poles without connecting iron pieces between them but mechanically joined by non-magnetic mounting parts. The operating principle of the electromagnet with permanent magnet is shown in Fig. 2, when no current flows through the coil the flux created by the magnet is closed through the yoke of the U core and does not cross the air gap as it is seen in Fig. 2A. But, when a current flows through the coil the flux of the magnet is added to the flux generated by the action of the coil, see Fig. 2 B, which originates an electromagnetic attraction force superior to that produced by a U core without the permanent magnet. Obviously, the permanent magnet has to be magnetized in such a way that its flux adds to the flux created by the energized coils.

The actuator is based on a previous design of a linear stepper reluctance actuator [8], with the same physical dimensions and of course without magnets and therefore with lower performances. In order to guarantee the displacement of the mover in the operating conditions a power converter, fed from the AC grid (single phase 230V, 50Hz) through a rectifier and a filter, must sequentially energize the phase windings of the actuator and reverse the sequence when it is required. The electronic power converter is an asymmetric converter, see Fig. 3, with two switches and two diode per phase.

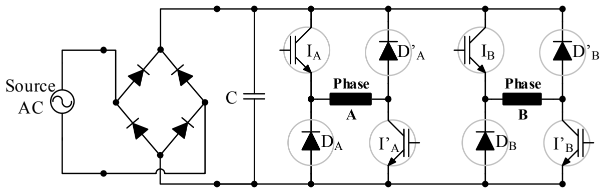


Fig. 3. Electronic power converter.

Each phase should be turned on at the point which its own inductance increases thus a device, such a logic sequencer that is able to consistently send the right firing signals to the gates of the power switches, is required, Fig. 4. In order to control the force of the actuator the current is regulated at each instant and at a reference value by means of a simple hysteresis controller that uses only one Hall-effect current sensor. The output signal of this controller is logically combined with the output signals of the logical sequencer in order to generate the firing signal that turns the power switches on and off. The direction, in which the actuator moves, depends on the sequence of phase excitation that is determined according to the state of two limit switches placed at the extreme positions the mover can reach [5]. A block diagram of this electronic control unit is shown in Fig. 5.

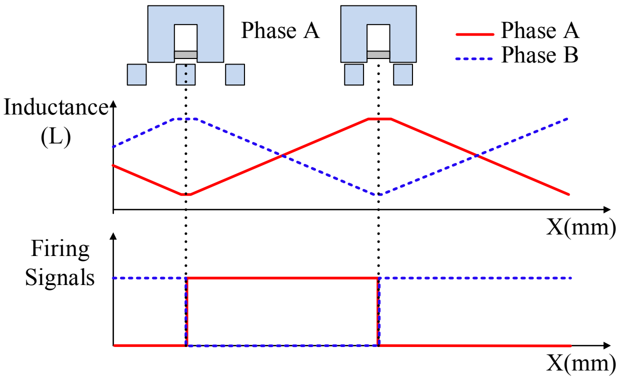


Fig. 4. Variation of inductances and firing signals.

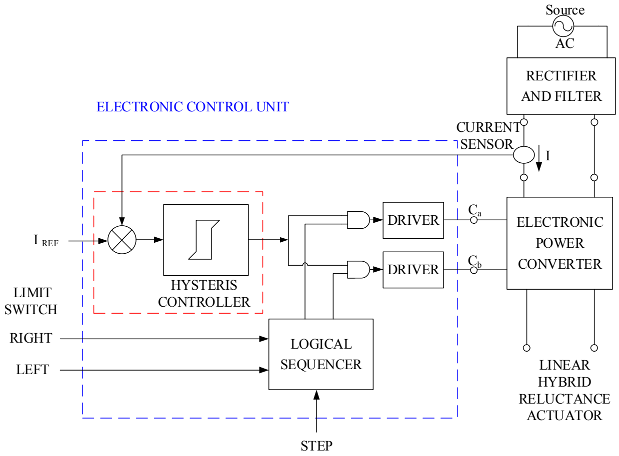


Fig. 5. Block diagram of the electronic control unit.Introduction

III. IMPROVED LINEAR HYBRID RELUCTANCE ACTUATOR

With the aim to obtain better performances, reduce the mass of the mover and ease its construction some changes are introduced in the former design. The dimensions of the U-cores are the same but the coil is split in two parts, both with the same number of turns, and placed around the arms of the core. The mover is optimized with the objective to obtain the highest average force in this regard, Fig. 6, shows, for a current of 5 A, the average force for given values of the mover pole widht versus mover pole length. These results demonstrate that the mover pole lenght can be as short as possible consistent with mechanical considerations therefore a pole lenght of 25 mm is taken in the improved design. In contrast, Fig. 7, for a current of 5A, shows that for a given pole lenght of 25 mm the average force decreases as the mover pole widht increases thus a mover widht of 21 mm is the selected value in the optimized design. A view of the improved actuator is depicted in Fig. 8. The main dimensions and parameters of the former actuator and of the improved version are given in the appendix.

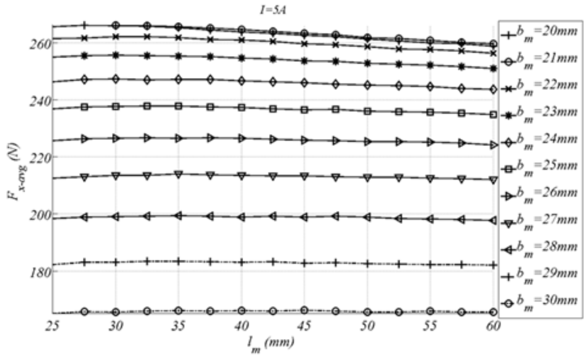


Fig.6. Average force (current of 5 A) for given values of the mover pole widht versus mover pole length

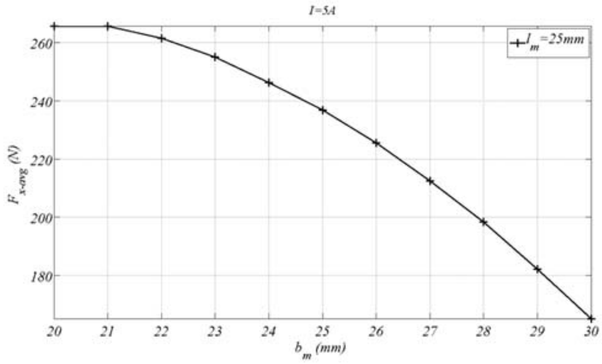


Fig. 7. Average force (current of 5 A) for a mover pole length of 25 mm versus mover pole width.

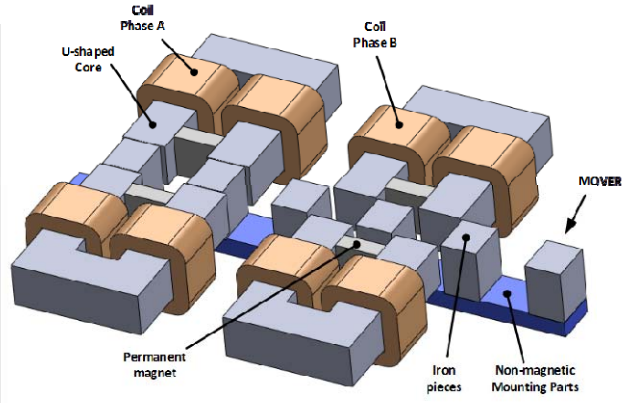


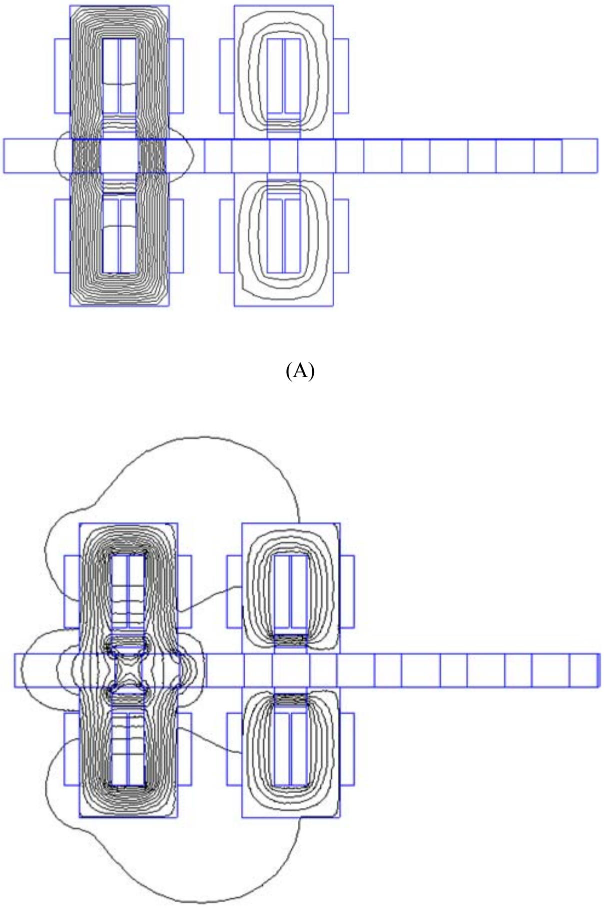
Fig.8. View of the improved linear hybrid reluctance actuator

IV. SIMULATION OF THE HYBRID RELUCTANCE ACTUATOR

In order to verify the operation of the proposed hybrid reluctance actuator, first, electromagnetic simulation using finite element software is performed, and then simulation of the whole actuator is made using Matlab-Simulink [6].

A. *Finite Element Analysis of the Hybrid Reluctance Actuator*

The electromagnetic behavior of the proposed actuator has been analyzed using 2D finite elements method. In Fig. 9 the distribution of field lines in different positions of the mover are represented. Fig. 9 A shows the distribution of field lines for the position of alignment, in which the stator poles of one phase are completely aligned with the mover poles while in Fig. 9 B is depicted the distribution of field lines for the position of non–alignment, being the displacement between the position of alignment and the position of non-alignment of 25 mm. It is important to note that in both cases the flux of the magnet in the non-excited phase closes through the yoke and do not cross the air gap therefore there is no detent force. The magnetization curves, flux linkage (ψ) vs current (I) for different relative positions between stator and mover (x), from the position of alignment (x = 0 mm) to the position of non-alignment (x = 25 mm) are shown in Fig. 10. Static force curves, force vs relative position between the stator and the mover for different values of current, are represented in Fig.11.



(A)

(B)

Fig.9. Field lines distribution for phase A, current of 5A. (A) Aligned position. (B) Non-aligned position.

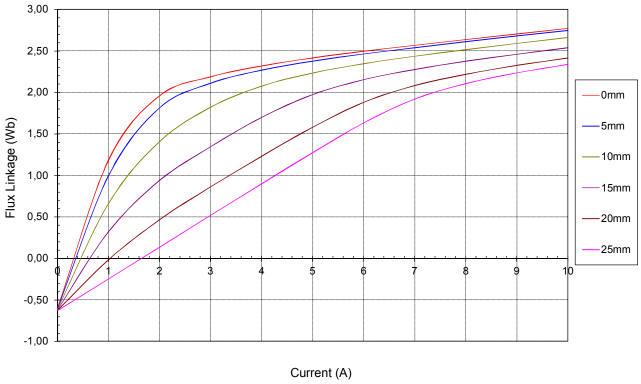


Fig. 10. Magnetization curves of the hybrid reluctance actuator.

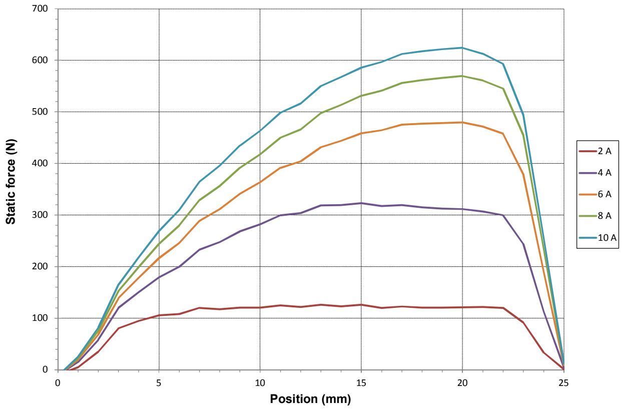


Fig. 11. Static force-position curves for the hybrid reluctance actuator.

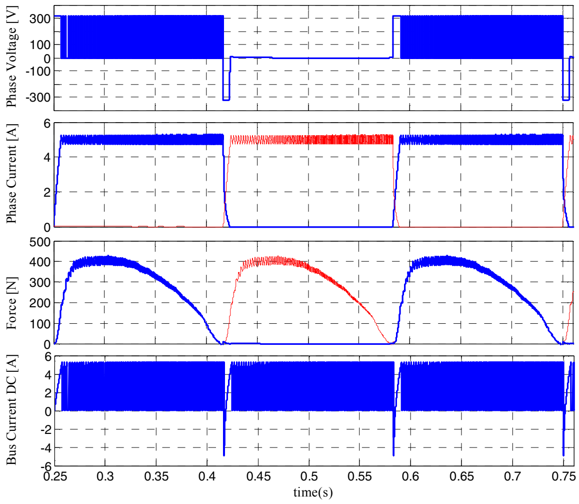


Fig. 12. Waveforms of phase voltage, phase current, force and D.C. bus current at 0.15m/s.

B. *Matlab-Simulink Simulation of the Hybrid Reluctance Actuator*

Simulation of the hybrid reluctance actuator considering the electromagnetic actuator, the electronic power converter and the control is implemented using Matlab-Simulink coupled with the results obtained of the previous finite element analysis [9]. Fig. 12 shows the waveforms of phase voltage, phase current, phase force and total force, and DC bus current at 0.15 m/s an with a turn-on position, $x_{ON} = 0$ mm, that coincides with the non-aligned position of the poles of the stator and the mover, and a turn-off position, $x_{OFF} = 25$ mm, for a regulated current of 5 A and a speed of 0.15 m/s.

V. COMPARATIVE OF THE PROPOSED HYBRID RELUCTANCE ACTUATOR AND A LINEAR RELUCTANCE STEPPER ACTUATOR

The hybrid reluctance actuator has been compared with a linear reluctance stepper actuator of the same size, in fact the same actuator with magnets or without magnets. The magnetization curves for the aligned and non-aligned position of both machines are shown in Fig. 13 and their static force curves versus position for a current of 5 A are shown in Fig. 14. The force waveforms of both actuators for a regulated current of 5 A and a speed of 0.15 m/s are depicted in Fig. 15. From the comparison of these figures, it is clear that the hybrid linear actuator can achieve higher values of force than a linear stepper actuator of the same size. A more thorough analysis shows that the average force in these conditions is of 276 N for the case of use permanent magnets and of 213 N without permanent magnets, that is nearly 30% higher. It is important to point out that as the current rises the increase in torque is clearly more pronounced in the case of the actuator with permanent magnet as evidenced in Fig. 16. This fact may be of interest to linear actuators requiring high thrust forces for very short periods of time. The authors are working to build a prototype to validate the obtained results.

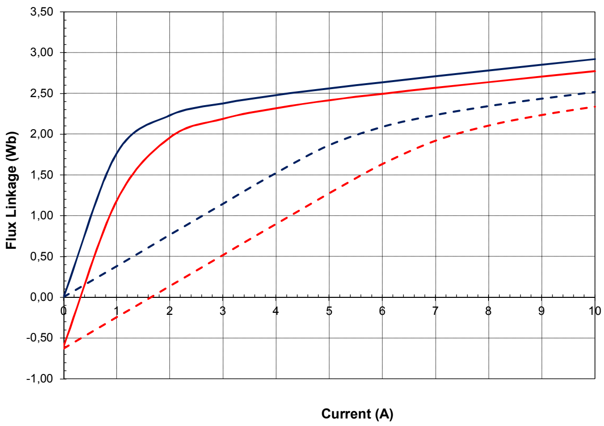


Fig. 13. Comparison of magnetization curves, aligned (solid lines) and non-aligned (dotted line) for linear hybrid reluctance actuator (red lines) and linear reluctance stepper actuator (blue lines).

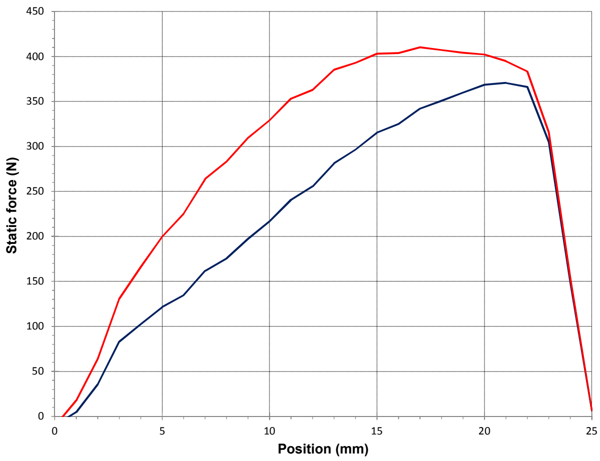


Fig. 14. Comparison of static force-position for a current 5 A for linear hybrid reluctance actuator (red line) and linear reluctance stepper actuator (blue line).

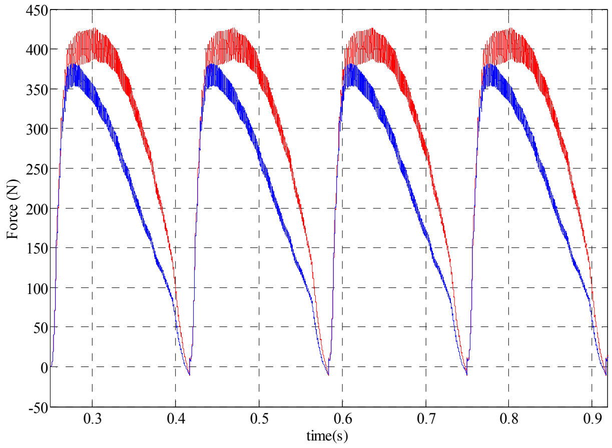


Fig. 15. Force waveforms for a speed of 0.15 m/s at a regulated current of 5 A for the linear hybrid reluctance actuator (red line) and the linear reluctance stepper (blue line).

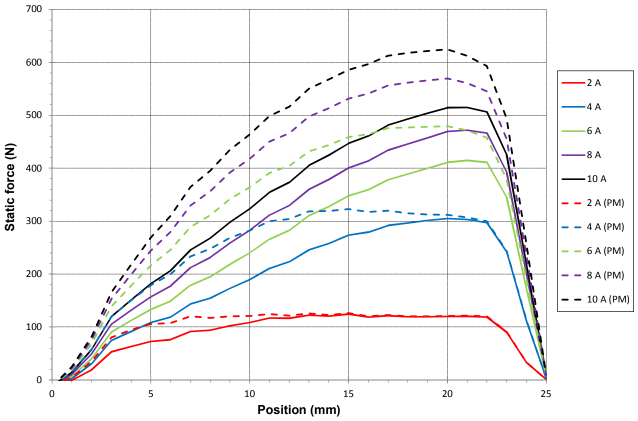


Fig. 16. Comparison of static force-position for different current values for the linear hybrid reluctance actuator (solid lines) and the linear reluctance stepper actuator (dotted lines).

VI. CONCLUSIONS

In this paper, a new type of hybrid reluctance actuator has been presented. The actuator is a two phase double sided actuator in which the stator is composed by four electromagnets with permanent magnets, each formed by normalized U cores with a permanent magnet placed near the air gap between and in contact with both arms. The mover is comprised of rectangular poles without connecting iron pieces between them but mechanically joined by non-magnetic mounting parts. In this actuator the flux of the magnets is in parallel to the flux created when the coils are energized, both fluxes are added and the total reinforced flux links the stator and the mover. In contrast, when no currents flow through the coils no flux crosses the air gap, and the flux of the magnets is closed through the back iron that supports them. From the study and simulation of the new hybrid reluctance actuator, performed by means of 2D finite element analysis and Matlab Simulink it can be concluded that the proposed actuator has nearly a 30% higher average force than a linear reluctance stepper actuator of the same size.

VII. APPENDIX

DESIGN SPECIFICATIONS OF THE LINEAR HYBRID RELUCTANCE ACTUATOR, FORMER AND IMPROVED VERSIONS

Description	**Value** **Form./(Imp.)**	**Units**
Average force (F_x)	250	N
Voltage DC bus (Vcc)	325	V
Current (I)	5	A
Speed (v)	0.15	m/s
Number of phases (m)	2	
Air gap (δ)	0.5	mm
Number of coils per pole (N_p)	1100	
Diameter of magnet wire (d_c)	0.8	mm
Laminated U-shaped core	125 x 75	mm
Magnetic steel	M 600-50A	
Stator pole width (b_s)	25	mm
Stator slot widht (c_s)	25	mm
Stator pole length (l_s)	75	mm
Stator yoke length (h_y)	25	mm
Mover pole width (b_m)	23 **(21)**	mm
Mover slot widht (c_m)	27 **(29)**	mm
Mover pole length (l_m)	73 **(25)**	mm
Stack length (L)	25	mm
Permanent magnet	NdFeB-32	
Permanent magnet width (a)	25	mm
Permanent magnet thickness (b)	10	mm
Permanent magnet length (c)	25	mm

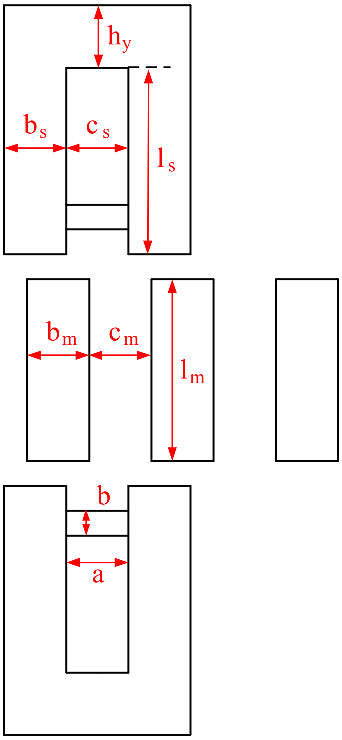


Fig. 17. Sketch of the linear hybrid reluctance actuator showing its main dimensions.

VIII. AKNOWLEDGMENT

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