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Speed Control Scheme Analysis of Switched Reluctance Actuator

Abstract. *This paper presents the implementation of a nonlinear model of a Linear Switched Reluctance Actuator (LRSA) in Simulink/ SimPowerSystems environment. The model is based in an already implemented motor model for the rotating machine, which was improved and adopted to be applied in the analysis of a linear actuator. Both the magnetic information from experimental data and results obtained from Finite Element Analysis (FEA) were used to perform that analysis. The model is used in the assessment of several control schemes.*

Streszczenie. *Przedstawiono nieliniowy model liniowego siłownika reluktancyjnego LRSA z wykorzystaniem środowiska Simulink/SimPowerSystem. Do analizy wykorzystuje się dane eksperymentalne i obliczone przy wykorzystaniu metody elementu skończonego. (**Analiza sterowania szybkością w siłowniku reluktancyjnym**)*

Keywords: Linear Switched Reluctance Actuator; Performance Simulation; Control Analysis, Dynamic Simulation.
Słowa kluczowe: siłownik reluktancyjny, symulacja.

Introduction

The investigation in linear actuators and respective methodologies of control, command and regulation is to gain more attention, having this type of actuator wide application in traction and positioning of industrial processes. In this group of machines (linear actuators) are outstanding those whose working principle relies in the magnetic circuit reluctance variation.

The Linear Switched Reluctance Actuator (LRSA) is a doubly salient machine in which force (thrust) is produced by the tendency of the translator to travel to a position where the inductance is maximized. Its extreme constructive simplicity, the capacity to operate in high speed, the raised precision reached with relatively low costs and the high force/weight ratio without permanent magnets are the main attractive features [1]. Opposing the recognized virtues of these actuators, control difficulties arise as challenges to be exceeded. In fact, the highly nonlinear magnetic characteristics that distinctively characterize the functioning of the LSRM, the requirement to sequentially activate and deactivate the phases of the machine, the noise and the force oscillations that elapse from this excitation form, turn the control study of these actuators an interesting subject to be analysed.

This paper presents a study on the performance of a tri-phase 6/4 LSRA operating in variable speed condition, using simulation approach with nonlinear model based on actual magnetization characteristic of the machine [2].

This work has as well as objective the inquiry around the development, evidence and validation of LSRM control algorithms for effective prediction of speed and position. The implemented speed control algorithms have two closed cascade loops. The actual velocity is compared with speed reference resulting in speed error. The speed control produces a current reference which is compared with actual phase current. The supply converter works in accordance with current error and the x_{on} and x_{off} commutation positions, being the LSRA fed by a tri-phase asymmetrical power converter [3]. With this configuration, the phase currents can be independently controlled. The current control is accomplished by a hysteresis band controller. The specific machine under analysis is a prototype that was designed and built for force development studies and the necessary data for model was available from previous FEA [4], [5].

The speed controllers under analysis are: (1) conventional PI controller; (2) Fuzzy controller and (3) Sliding mode controller.

The paper is organized as follows: in Section II the LSRM dynamic characteristics are outlined. Section III contains the nonlinear model description in the Simulink--SimPowerSystems environment. Section IV details the performance simulation analysis and Section V concludes the paper.

II. LRSA Dynamic Characterization

A. Review Stage

The dynamic behavior of LSRA is fully described by the electromagnetic, force and mechanical equations [1], [6].

If the mutual effect of the phases is neglected, the voltage applied to one phase of the machine can be expressed as:

$$v_j = r_j \cdot i_j + \frac{d\lambda_j}{dt}, \; j = 1 \ldots \mathrm{m}. \tag{1}$$

where v_j is the voltage applied to phase *j*, i_j the current flowing in phase *j*, r_j the resistance of phase *j*, λ_j the flux linkage of phase *j* and m the machine phase number. In the LSRA, flux is a function of current and translator position, meaning that equation (1) becomes:

$$v_j = r_j \cdot i_j + \frac{\partial\lambda_j}{\partial i_j}\cdot\frac{\partial i_j}{dt} + \frac{\partial\lambda_j}{\partial x_j}\cdot\frac{\partial x_j}{dt}, \tag{2}$$

where x_j is the translator position. The phase current can be expressed as follows:

$$\frac{\partial i_j}{dt} = \left(\frac{\partial\lambda_j}{\partial i_j}\right)^{-1}\cdot\left(v_j - r_j\cdot i_j - \frac{\partial\lambda_j}{\partial x_j}\cdot\frac{\partial x_j}{dt}\right). \tag{3}$$

When each phase of the LSRA is excited it produces an instantaneous force, being all the instantaneous forces produced by the phases added to achieve the total force induced in the translator, which can be found by

$$F_j = \frac{\partial W_{Cj}\left(i_j, x_j\right)}{\partial x_j}\Big|_{i_j = constant}, \tag{4}$$

where W_{Cj} is the co-energy, and can be written as follows:

$$W_{Cj} = \int_0^{i_j} \lambda_j \cdot \left(i_j, x_j\right)\cdot di_j \;\Big|_{x_j = constant}. \tag{5}$$

If equation (5) is substituted in equation (4), the representation of instantaneous force of one phase is:

$$F_j = \int \frac{\partial \lambda_j (i_j, x_j)}{\partial x_j} \cdot di \,. \tag{6}$$

The total force F_e produced by the actuator can be calculated by considering the instantaneous forces produced by all phases, as follows:

$$F_e = \sum_{j=1}^{m} F_j (i_j, x_j) \,. \tag{7}$$

The mechanical equations can be expressed as follows:

$$F_e - F_l = M \cdot \frac{dv}{dt} + B \cdot v \,. \tag{8}$$

Here F_l is the load force, v is the velocity, M and B are respectively the mass and the viscous friction coefficient. Equation (8) can be re-arranged in the form:

$$\frac{dv}{dt} = \frac{1}{M} \cdot (F_e - F_l - B \cdot v). \tag{9}$$

B. LSRA Dynamic Model

The LSRM dynamic model is obtained by the combination of the electric models of all phases with the mechanical model. In this work the model is derived from data obtained with the FEA and experimental tests performed in a constructed LSRA, with parameters shown in Table 1.

Table 1. LSRA Parameters

Symbol	Quantity	Value
F	Rated thrust	250 N
V	Base speed	0.8 m/s
V_0	Dc link voltage	200 V
m	Number of phases	3
M	Mass	20 kg
	Topology	Flat
Fx	Thrust density	2 N/cm^2

The flux-current-translator position characteristics, with map shown in Fig. 1, and the thrust–current–translator position characteristics, with map shown in Fig. 2, were accounted in the form of lookup tables in the Simulink environment to perform the different control approaches and analysis.

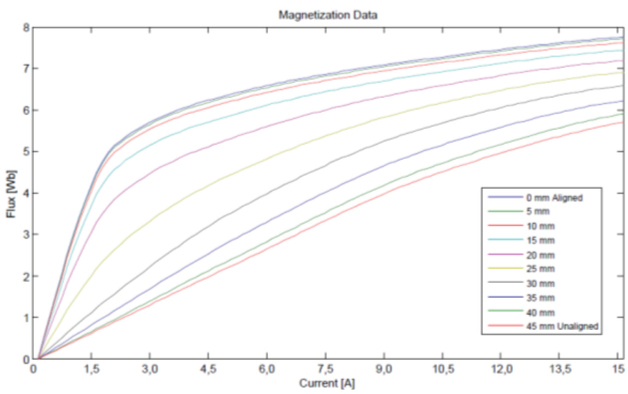

Fig. 1. Flux-Current-Translator Position Characteristics

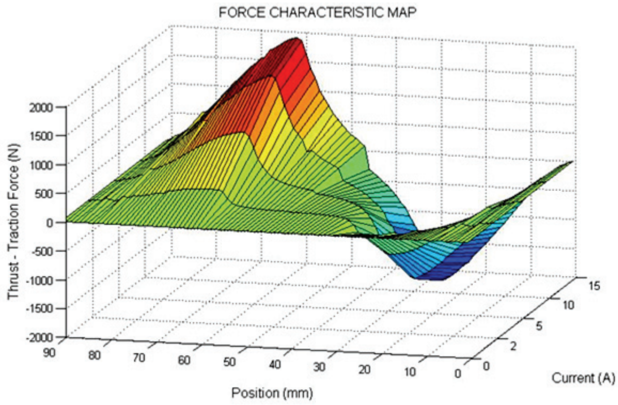

Fig. 2. Force-Current-Translator Position Characteristics

III. Nonlinear model description in Simulink

The nonlinear model was implemented in Simulink as illustrated in Figs. 3 to 5.

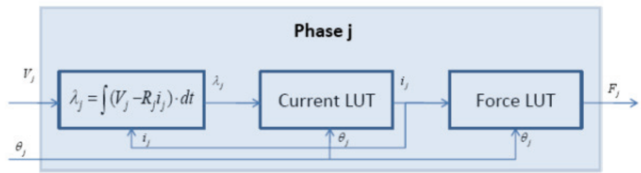

Fig. 3. Electric model of one phase

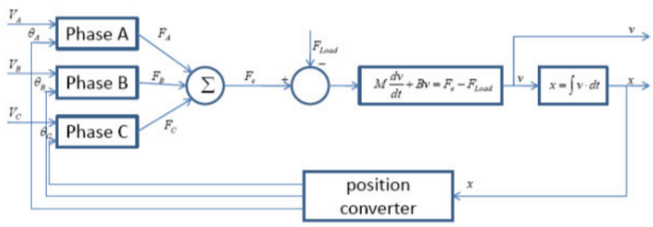

Fig. 4. Combination of the electric model of all phases with the mechanical model

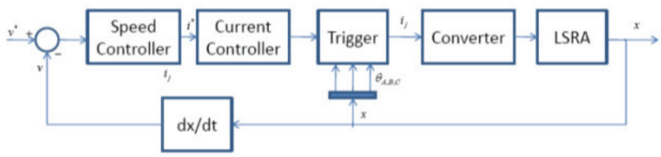

Fig. 5. Complete simulation model implementation in Simulink/ SimPowerSystems

IV. Speed controller performance analysis

To produce positive thrust it is expected that the current pulses occur somewhere in the rising part of the phase self-inductance curve. To obtain maximum traction force, turn--on should be near the minimum inductance position and turn-off near the maximum. The LSRA under analysis is of type 6/4 poles and the chosen commutation values were X_{on}=45 mm (unaligned position), X_{off}= 82,5 mm.

The different controllers were analyzed in scenarios of variable speed (taken as reference) and variable load with commutation at fixed positions [7], [8].

The fuzzy controller acts in accordance with the error and error change, being the output the reference for the current controller (hysteresis), with characteristics shown in Fig. 6, and rule data base listed in Tab. 2.

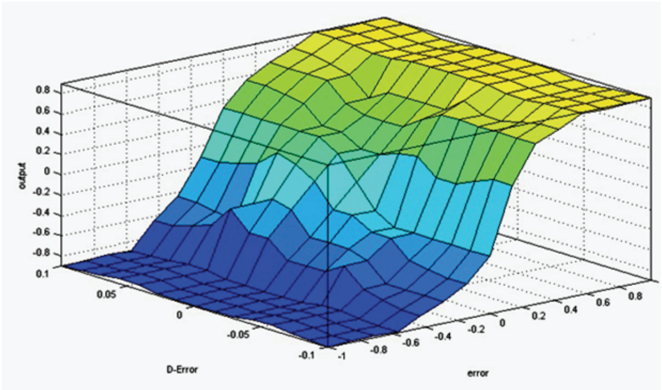

Fig. 6. Fuzzy controller's "Rule Map"

Table 2. Rule Data Base

CE \ E	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*
NB	NB	NB	NM	NS	PM	PB	PB
NS	NB	NB	NS	NS	PM	PB	PB
ZE	NB	NB	NS	ZE	PS	PB	PB
PS	NB	NB	ZE	PS	PS	PB	PB
PB	NB	NB	NS	PS	PM	PB	PB

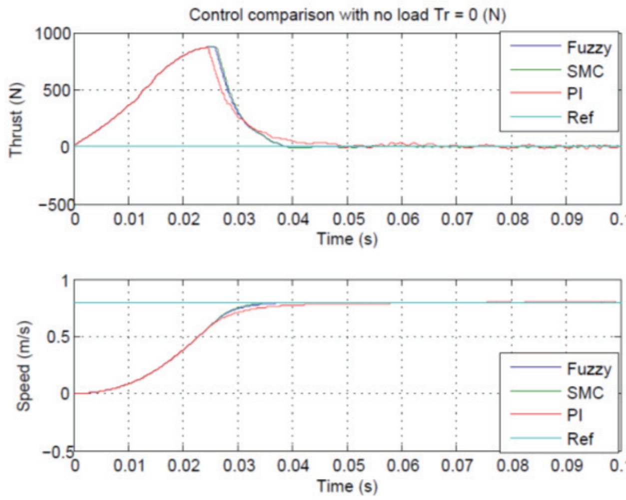

Fig. 7. Controller's comparative results for a speed reference of 0.8 m/sec without load

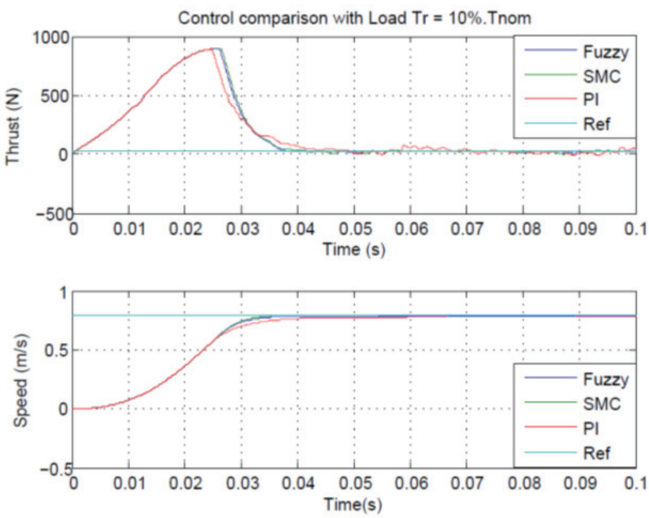

Fig. 8. Controller's comparative results for a speed reference of 0.8 m/sec with load $T_r = 10\%.T_{nom}$ (20N)

Some obtained illustration results are shown in Figs. 7 to 12. The controller's performance is first analyzed, for different load forces references. It were considered the value of 0 N, Fig. 7, 20 N, Fig. 8, 100 N, Fig. 9 and 200 N, Fig. 10, with the nominal speed of 0.8 m/sec. From the comparison between those obtained results, it can be concluded that the SMC controller can keep the speed reference, while the fuzzy and PI controllers can't.

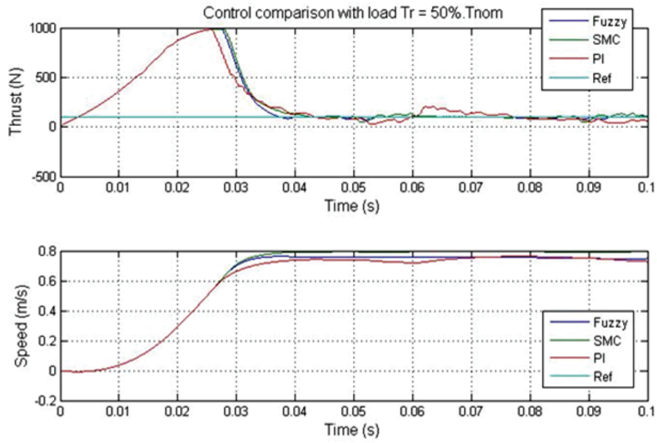

Fig. 9. Controller's comparative results for a speed reference of 0.8 m/sec with load $T_r = 50\%.T_{nom}$ (100N)

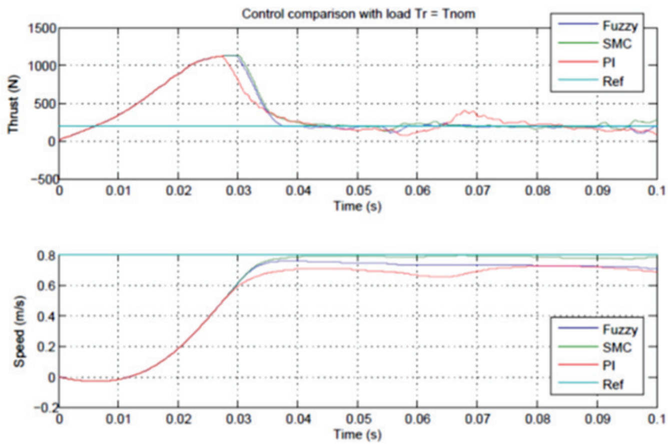

Fig. 10. Controller's comparative results for a speed reference of 0.8 m/sec with load $T_r = T_{nom}$ (200N)

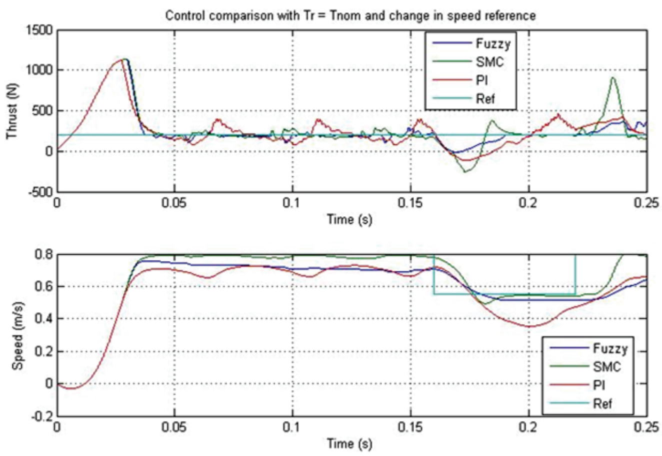

Fig. 11. Controller's comparative results for a change in speed reference from 0.8 m/sec to 0.55 m/sec, with load $T_r = T_{nom}$ (200N)

Figure 11 shows the results obtained from the application of the different controllers to the actuator, when a sudden change in speed reference from nominal speed (0.8 m/sec) to 0.55 m/sec and back occurs. The SMC controller seems to be more robust, exhibiting a faster response, when compared with the performance obtained from the application of the other two controllers (Fuzzy and PI), and a small overshoot in the lower reference speed value.

In Fig.12 the controller's response for an oscillating load force of 50% of the nominal amplitude is observed. The responses of Fuzzy and SMC controllers follow the speed reference, while PI controller exhibits a small oscillation around reference.

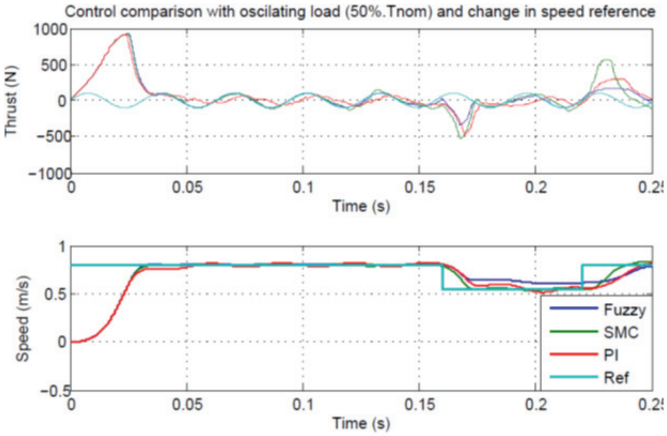

Fig. 12. Controller's comparative results for a speed reference of 0.8 m/sec, and an oscillating load $T_r = T_{nom}$ (200N)

V. Conclusions

The dynamic model of the Linear Switched Reluctance Machine was achieved, the adoption of different speed control strategies (PI, Fuzzy, Sliding Mode) were analyzed for comparative assessment, based on results obtained from the utilization of Simulink software.

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