Proc. of the 5th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2005 (pp304-309)

Using Digital Signal Processor in Linear Switched Reluctance Actuator Driving and Control

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Abstract: - This paper presents the control strategy of a Switched Reluctance Actuator implemented in Digital signal processor TMS320F2812 from Texas Instruments. The work starts with a Linear Switched Reluctance Actuator (LSRA) analysis and characterisation based on device design project and main functional performance characteristics. One intends to establish some guidance on understanding actuator behaviour for it properly control and regulation. The actuator under analysis is a part of a complete electrical drive developed by the authors in the Electrical Machines and Power Electronics Laboratory of the University of Beira Interior, and is to be applied in a machine-tool or in a transportation system. The knowledge of a chosen set of experimental obtained characteristics, here presented, allows the proper actuator driving and control.

Key-Words: - Control, Digital Signal Processor, Linear Switched Reluctance Actuator, Design, Analysis and Construction, Finite Elements Analysis, Experimental Characteristics.

1 Introduction

Linear switched reluctance actuators (LSRA) are counterparts of rotary SRMs, that is, the linear configuration can be obtained to result from the rotary configuration, i.e., cut radially and unrolled.
Thus, the LSRA develops force (thrust) and motion by the tendency of a secondary to assume a position where the inductance of the dc excited primary is maximised [1,2].
This kind of linear electric machine is not compatible either with machine conventional design methodologies either with classical machine strategies.
In fact, the classical empirical parameters used in those approaches are, in this case, unknowns, as well as the magnetic flux density distribution and, consequently, the actuator performance [3,4]. This observation allows to conclude that classical control strategies can not be used, and new methodologies must be developed.
Analytical complexity of an electromagnetic actuator grows with it geometrical complexity and control strategy, as also with saturation effects. The always different machine topology, for different relatives positions between primary and secondary, relieve the actuator design out of strictly analytical analysis.
The magnetic circuit saturation for relative actuator positions tends to be higher for positions near the alignment, being significant even for small current levels. On the other hand, positions near the unalignment position are almost free of saturation effect, due to the leakage flux influence.
Thus, the finite element method (FEM) for numerical analysis of this kind of non-conventional machine is an important tool for models simulation. FEM allows the magnetic characteristics knowledge, as magnetic co-energy variation W_c, and magnetic energy variation W, for different relative positions between primary and secondary parts.
This paper concerns the actuator performance characterization, based on both already proposed and performed design, and analysis methodologies, [3]–[7], and on obtained experimental characteristics of a constructed linear switched reluctance actuator prototype. Obtained data, after detailed analysis, is used to develop actuator control strategy.

2 Machine Design and Experimental Performance Evaluation

For linear switched reluctance actuators the optimised design consists to obtain the best performances in terms of current and forces, with a minimum of construction materials volume and weight (magnetic iron and copper), that is to obtain the best specific force – longitudinal force or thrust to machine weight ratio.

Thus, the author's opinion is that the design should follow three steps, as stated in [3,7], that are:

– specification of main data, with main electrical and mechanical requirements, as are the rated thrust up to the base speed, the dc link voltage V_0, the number of phases, m and the topology (tubular or flat);

– analytical calculus, following a logic sequence to calculate electrical and mechanical parameters, performed by computer programs, changing and adapting different parameters, in order to obtain the required actuator performance, established by the designer;

– numerical analysis, being possible the determination of the effect of geometry changing, or the influence of excitation positions and current levels, in machine performance.

Fig.1 Actuator test branch

Fig.1 shows the actuator under study, mounted on a test branch, and also the primary (the mover) and the secondary (the stator).

Concerning the excitation current i and position x, the traction developed force F for this kind of machine has the relation with co-energy W_c:

$$F(i,x) = \frac{\partial W_c(i,x)}{\partial x} \tag{11}$$

The Finite Element Method (FEM) is now a popular method and are commonly used in Electrical Engineering [8]. Fig.2 shows a possible utilization of this kind of analysis, evaluating, in this example, the influence of different airgap length on the distribution of magnetic flux density, being also possible to know the critical points where saturations can occur.

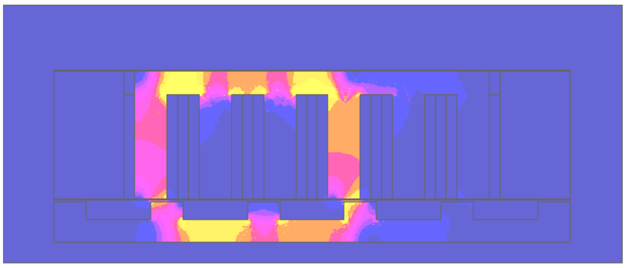

Fig.2 Distribution of magnetic flux density for an excitation current of 3 A on phase 1.

Taking into account the simulated obtained characteristics, trough the application of FEM [10,11], the machine prototype was submitted to experimental tests.

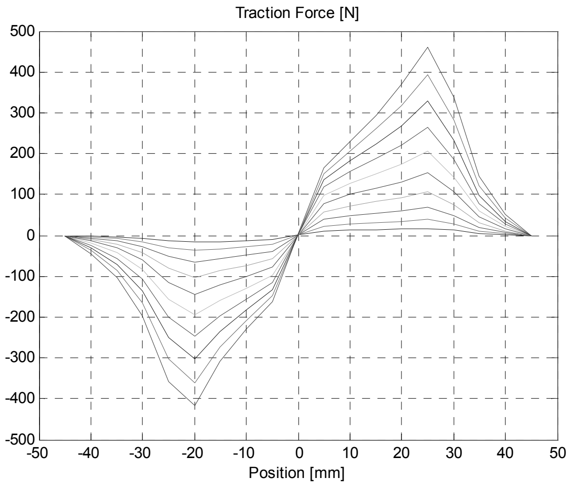

Fig.3 Characteristics of maximum traction force for different relative positions and for different excitation currents.

Fig.3 shows the traction force for different secondary relative positions, for a 2 mm airgap length and for a set of excitation current levels. Note that the represented as positive and negative force values correspond to different directions of machine movements, that is to right and left, respectively. Using this actuator information is possible to know how to apply power to actuator in order to displace the moving part.

3 Machine Instrumentation

The instrumentation of the LSRA was made with the goal of its signal position, current and voltage acquisitions [9]. Only the first one is used for control purpose, the others two are used for study proposes.

The optic sensor is an incremental encoder presenting one of two states that can be obtained, for example, considering a two colours band (black and white). The main parts of this sensor are an emission diode and a photoreceptor. The photoreceptor absorbs different light reflex, depending on the colour of the band that is on the influence of the emission diode, being this way generated an impulse train. As smaller is the space between bands, higher is the sensor resolution. A disadvantage of this method is that is not possible to determine the direction of the movement, and that's why it was been adopted a quadrature encoder, where two different black and white bands are positioned with 90º displacement, being possible to known the movement direction, with two optic sensors. In the presented work, a spaced band of paper of 2 [mm], with colours black and white, positioned in the test branch (Fig.4), allows the generation of wanted pulses, when the sensor is passing trough the band. On the same figure, a larger paper band can be seen, giving a lower resolution solution, 5 [mm], that the one used as initial developing point. As we will latter show this resolution will be improved taking advantage from DSP QEP internal circuitry.

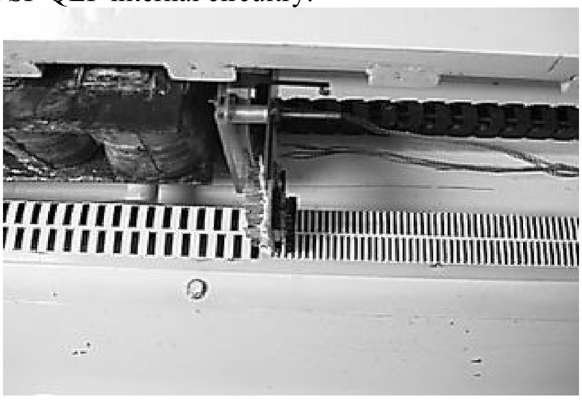

Fig.4 Detail of the actuator acquisition system

For position acquisition, two optic sensors OPB704, joint together with actuator's secondary part, were adopted, as shown in Fig.4.

The designed circuit for the position signal acquisition is shown in Fig.5, where a rectangular wave, with levels 0 and 3 Volts, is obtained. The position and direction is obtained trough this data.

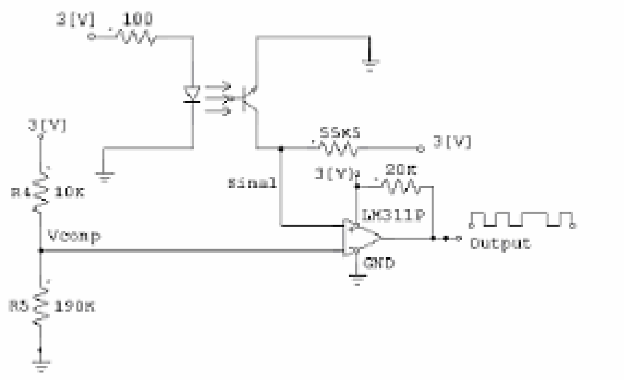

Fig.5 Electronic circuit used with each optical sensor

For current acquisition, three Hall effect sensors, one for each phase of the machine, were adopted (Fig.6). The voltage was obtained trough a circuit based on a voltage division circuit, with proper protection system, connected to the mentioned three machine phases.

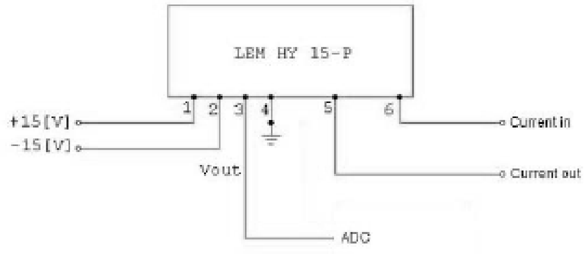

Fig.6 Electronic circuit used for current data acquisition

4 Machine Electronic Power Driver

The control circuits (Fig.7) are designed such a way that they are totally independent, being each circuit controlling each current flowing in phase coils.

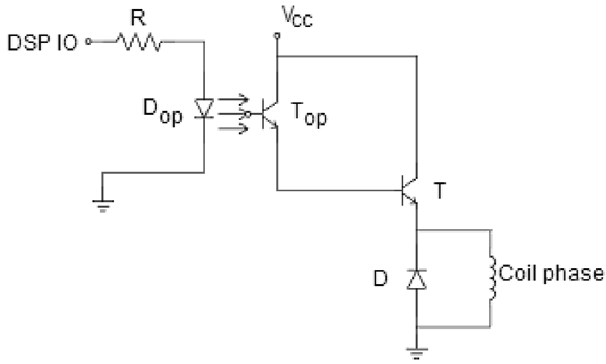

Fig.7 Power electronic circuit used for coil excitation

An output port from DSP is opto-isolated (D_{op}-T_{op}) from power driving transistor (T). After power transistor turn off, free wheel diode (D) will allow to dissipate energy stored on coil phase, protecting power transistor from overvoltages.

5 DSP based control

Control strategy was implemented in TMS230F2812 DSP from Texas Instruments [10-11]. This signal processor possesses several peripherals that justify it chose, also it processing capability (150 MIPS) and developing tools was determinants in chose.

All electronics of command and regulation was constructed around the eZdsp evaluation kit from Spectrum Digital, that uses Code Composer Studio as C/C++ software developing tool.

From all DSP peripherals and modules, the ones that more contribute for a rapid development are: QEP, EVMA, ADC, and IO. All software can be observed in Fig. 9.

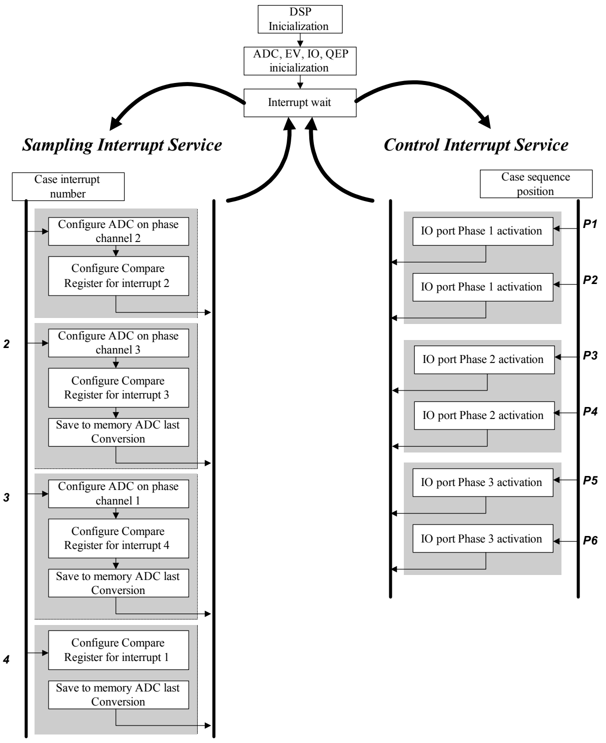

Fig.9 - DSP Software organization

Control strategy uses one of two Event Mananger (EV) modules from DSP. The EV modules include general-purpose (GP) timers, full-compare/PWM units, capture units, and quadrature-encoder pulse (QEP) circuits.

Timer 1 is used to generate sampling interrupts and use internal DSP clock as source, each time a match occurs between the Timer 1 Counter Register and corresponding Compare Register an interrupt is raised. Timer 2 use as input clock, the QEP output, and uses also corresponding Compare Register to generate interrupts. QEP circuit have the ability to increment Timer 2 if machine is moving to the left and decrement Timer 2 if machine is moving to the right. Also, QEP circuit is configured to generate a count pulse for each encoder pulses edges, duplicating optical encoder resolution.

Timer 1 acts like time counter and rules acquisition task, while Timer 2 acts like pulse counter and manages control task. These actions are parallel tasks that run in simultaneous.

After device initialization, DSP starts currents and voltages samples acquisition and place data in memory buffer. In simultaneous, control action sequentially active and inactive machine phases.

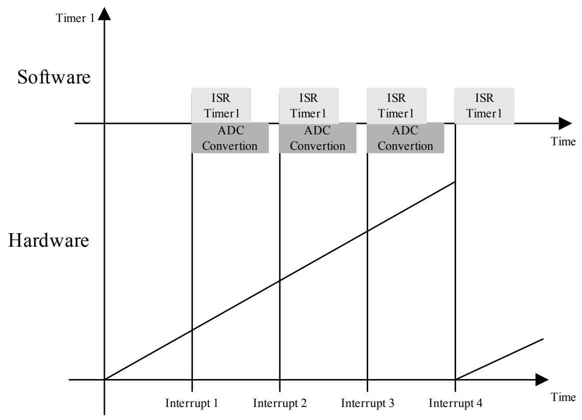

Fig.10 - Timer 1 sampling sequence

Each time Timer 1 generates an interrupt, a routine service is called and a specific task is executed. Fig.10 show the sampling sequence. On first interrupt ADC module, that was previously configured, starts to convert on channel phase 1 (hardware task). Using ADC shadow registers, that allow on fly configuration, next conversion, that will be performed on channel phase 2, is made. Also, Compare Register is loaded with a value for next match interrupt (software task). When second interrupt occurs, ADC automatically start conversion, while software save it to memory ADC last conversion and configures it to start conversion on machine phase 3 on third interrupt. When third interrupt occurs ADC data is recollected and stored in memory, and next interrupt is programmed. Fourth interrupt only have to collect and save ADC last conversion on memory, program next interrupt sequence, and configure ADC to phase channel 1.

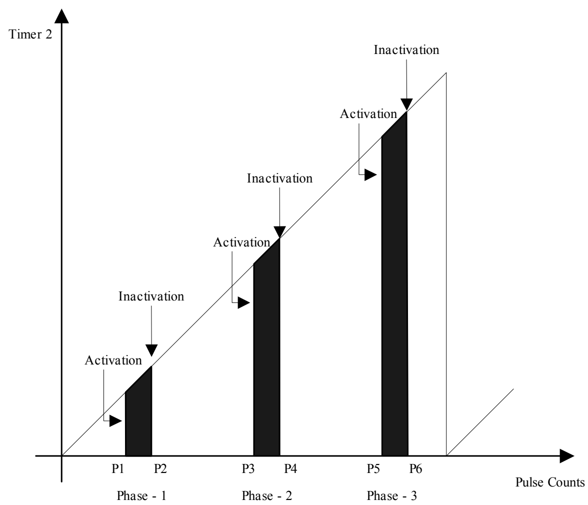

Fig.11 - Timer 2 firing position sequence

Control action is pictured in Fig.11. The procedure is identical to the one that rules acquisition sequence. Each time Timer 2 generates an interrupt, actuator position is evaluated and activation or

deactivation of machine phase is properly done. Also, next interrupt position is programmed in Compare Register.
Each machine phase power drive circuit is connected with a dedicated IO DSP port. When corresponding port is in logical level high the coil is feed with supply voltage, and when the logical level is low coil energy dissipates through free wheel diode.

6 Experimental Results

After control implementation, performed experiments give results that can be observed at Fig.12. On channels *a* and *b* is possible to observe the sequence of pulses, generated by constructed optical encoder, quadrature relation between signals is observable. Also, a characteristic of reluctance machines is exhibited, velocity is not constant and change with displacement. This phenomenon gives origin to noise, provoked by actuator vibration.
At channels *c*, *d* and *e* is visible IO command sequence for each phase coil energizes. This sequence exhibits a time variable pulse width.

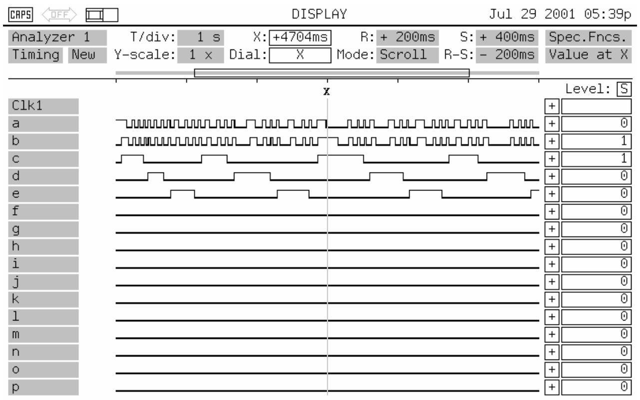

Fig.12 - Encoder signals (channel *a* and *b*), coils firing action (channels *c*, *d* and *e*)

Current and voltages of an actuator phase, obtained with acquisition system, is traced at Fig. 13. Voltage pulses applied to the phase coil is traced at channel 1, while on channel 2 is traced the phase current.
This plots allows to observe relevant aspects, pointed out perturbations are originated by other phase excitation actions. Each time that a phase is excited, the flux changing induces voltage on others phases; this occurs because magnetic path is shared. Induced voltage produces a current that flows in mesh path defined by the phase coil and the free-wheel diode.
In traction force applications these perturbations can be ignored, because its influence is minimal within respect with the force produced by excited phase.

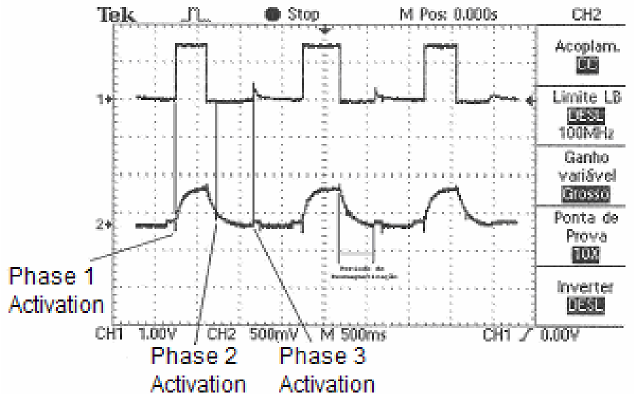

Fig.13 - Current and voltage phase signals

7 Conclusions

Reluctance machines usage in the past was difficult because of its control requirements, despite its simple functioning and construction. The aim of this work is to contribute for the LSRA understanding and characterisation, given guidance for control design methodology.
Developed Linear Reluctance machine was instrumented to collect data essential for actuator understanding and control.
A very simple power electronic driver was constructed, being the main idea to maintain simplicity and robustness, and for that contributes the components low count.
Using TMS320F2812 DSP a control strategy was implemented and tested. Processor possesses several internal peripheral components that turn easy to implement the proposed drive control strategy.
As it was demonstrated, this kind of control works properly, but it is not very versatile, just allows to control the displacement direction. This control scheme is under improvement. Present task main concern is the achievement of optimal turn on and turn off positions, for coils excitation actions. This procedure will allow to change, in real time, force produced by the LSRA and improve its performance.

Acknowledgment
The authors would like to thank the financial support provided by the University of Beira Interior and the CASE-Centro de Accionamentos e Sistemas Electricos da Fundação para a Ciência e a Tecnologia (FCT) of Portugal.

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