IMPLEMENTATION OF A NEW SWITCHING STRATEGY FOR SWITCHED RELUCTANCE MOTORS

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Abstract **– This paper presents a new switching method for Switched Reluctance Motors (SRM) that may result in better results concerning control of torque and current compared to conventional methods, besides reduction in loss due to switching of semiconductors. The main objective of this new strategy is the constant monitoring of the motor current and, starting from its instantaneous value, a switching logic is applied to the converter, yielding minimum current ripple and, consequently, minimization of the torque ripple generated by the machine.**

Key Words **– Control, Motion, Switching, Switched Reluctance Motor.**

I. INTRODUCTION

The incessant search for efficient use of electrical energy, especially in the area of electromechanical energy conversion, makes strategies in start-up of electrical machines an important target as far as rationalization of electrical energy consumption is concerned.

Various switching methods are used in the start-up of electric motors. Switched Reluctance Motors (SRM), particularly, present features that require switching methods not only for their control, but also for their motion.

The switching methods, when properly applied, may result in low loss due to switching of the semiconductors in the command circuit of the machine, and in better output parameters such as torque.

The most usual switching methods for Switched Reluctance Motors are the *hard* and *soft switching* methods [6]. Both require high-frequency switching of power semiconductors of the motion circuit of the machine, which results in loss, which is proportional to the switching frequency. Besides, output parameters such as torque and speed may also be unsuitable due to the switched quality of the electrical energy fed to the machine.

A new method defined as *tri-state* system is introduced by LUK [1] and implemented only through computer simulations. Thus, the actual implementation of the new system proposed was carried out based on the results presented in [1].

Section II presents the motor along with its features and details of its motion, followed by Section III, which presents the most common SRM switching methods in greater detail, and the new system proposed is presented in Section IV. The experimental results obtained are presented in Section V, followed by concluding remarks.

II. SWITCHED RELUCTANCE MOTOR (SRM)

Switched Reluctance Motors are electric machines which were initially developed in the 1940's, when a prototype was designed in Scotland, meant as a traction drive for an electric locomotive [2].

The main features of SRM are that they are quite suitable for motion with speed variation, robust, require low maintenance, low cost, and have a broad range of uses, among which transport, industry, household, and aerospace stand out [3].

Figure 1 presents the cross section of an SRM with topology 6/4.

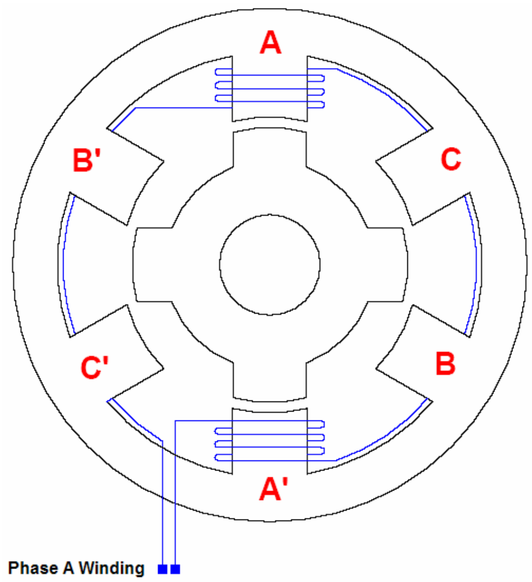

Fig. 1. Cross section of a Switched Reluctance Motor (SRM) with topology 6/4.

The topology presented in Figure 1 is classified as 6/4 because the machine has 6 magnetic poles in the stator and 4 in the rotor. A relevant feature of a Switched Reluctance Motor is the absence of coils wound on the rotor, as shown in Figure 1. This is one of the factors that contribute to the low cost of the machine. The coils are present only on the stator; in fact, more specifically, each winding is composed of two half windings around the poles diametrically opposed to the stator, according to Figure 1. However, in order to simplify the figure, only the winding of phase A of the motor is shown, because an SRM with topology 6/4 has just 3 phases. There are many other configurations of Switched Reluctance Motors as far as the number of phases and poles is concerned [4].

The Switched Reluctance Motor operating principle consists of the generation of torque through the rotor's tendency to move to a position where the magnetic circuit established – when one of the phases is energized – has a minimal reluctance (or maximal inductance). A variation in angular position θ of the rotor produces a variation in inductance L of the motor windings, as shown in Figure 2.

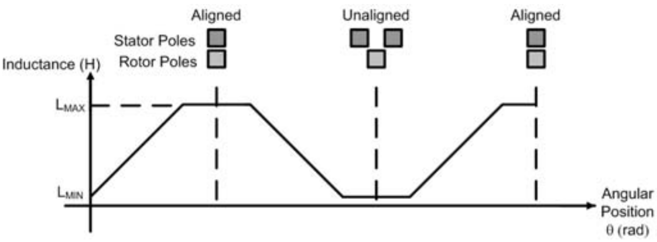

Fig. 2. Variation of inductance with angular position.

The equation that defines torque generation for SRM is [2]:

$$T = \frac{1}{2} \cdot i^2 \cdot \frac{dL(\theta)}{d\theta} \qquad (1)$$

where:

T – Torque generated by motor.

i – Current applied at one of the phases.

L – Inductance at one of the phases.

θ – Angular position of rotor.

Thus, according to (1), torque generation occurs when current is applied to the machine windings (and its direction is irrelevant once in (1) current i is shown raised to the second power). However, (1) also shows that torque generation depends on the inductance variation rate L in relation to rotor's angular position θ. So, to produce positive average torque current is applied to the winding that has increasing inductance. Optical sensors connected to the machine shaft indicate this condition.

When the sensor of a given motor winding detects the most suitable position to apply current to this phase, semiconductors of the circuit in Figure 3 relative to the respective phase are taken to the state of saturation, allowing the connection of the DC link with the winding of that phase.

The power converter shown in Figure 3 is an *Asymmetric Half Bridge*.

The power converter in Figure 3 is composed of MOSFET semiconductor switches, more specifically the 2SK557. The free-wheeling diodes are SKN20/04.

The process of detecting inductance increase in a certain phase and applying current to the respective phase is carried out continuously and separately for the three phases of the motor.

Figure 4 shows the graph of torque of the SRM used for implementation of the new switching strategy. Such graph was obtained through simulations using the Finite Element Method (FEM).

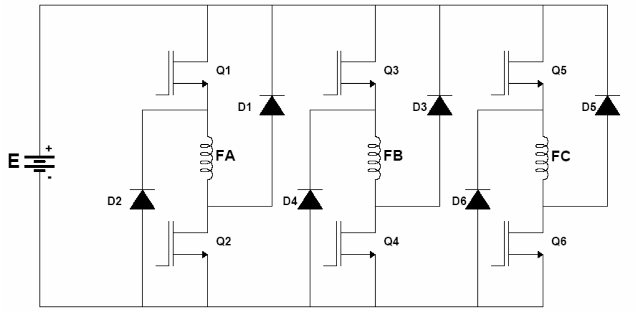

Fig. 3. Power converter for start-up of SRM.

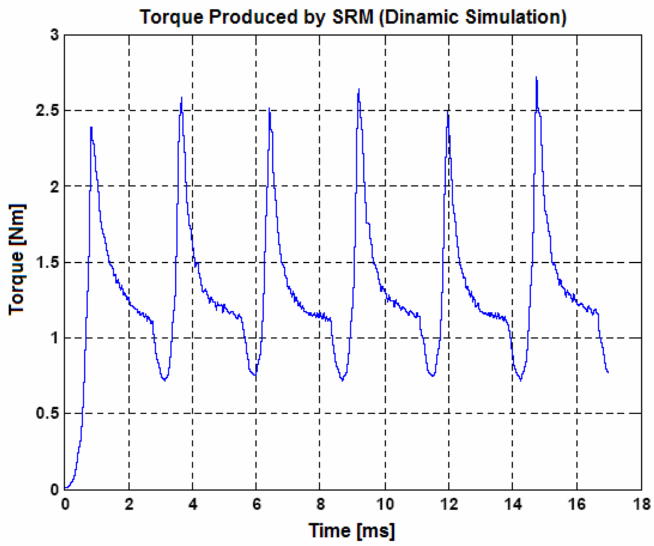

Fig. 4. Behavior of torque in SRM used – curve obtained through simulation using the Finite Element Method.

III. CONVENTIONAL SWITCHING METHODS

The conventional methods for start-up of Switched Reluctance Motors are shown below:

A. Hard-Switching

The *hard-switching* method consists of, during detection of inductance increase in a given motor winding, applying a switched signal of high frequency to both switches of the power converter relative to that respective phase, as shown in Figure 5.

Due to the high-frequency switching of the signal applied to the base of the semiconductors of the power converter, there is significant energy loss through their heat dissipation [5]. This loss is proportional to the switching frequency. Besides switching loss, this method presents a higher level of ripple in the waveforms of the current applied to the machine windings, also producing greater torque ripple. Despite these downsides, the *hard-switching* method is a workable strategy regarding current control for the machine working as a generator.

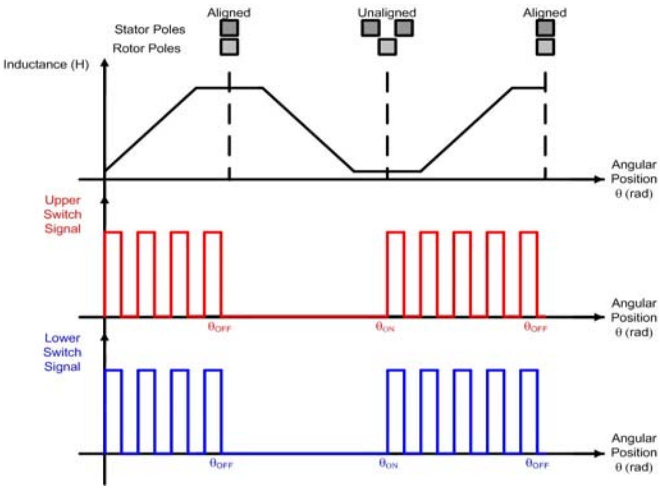

Fig. 5. *Hard-switching* method.

B. Soft-Switching

The *soft*-switching method consists of keeping the lower switch of the power converter relative to the respective phase in state of saturation while the upper switch receives a switched signal in high frequency during the detection of inductance increase of a certain phase, as shown in Figure 6.

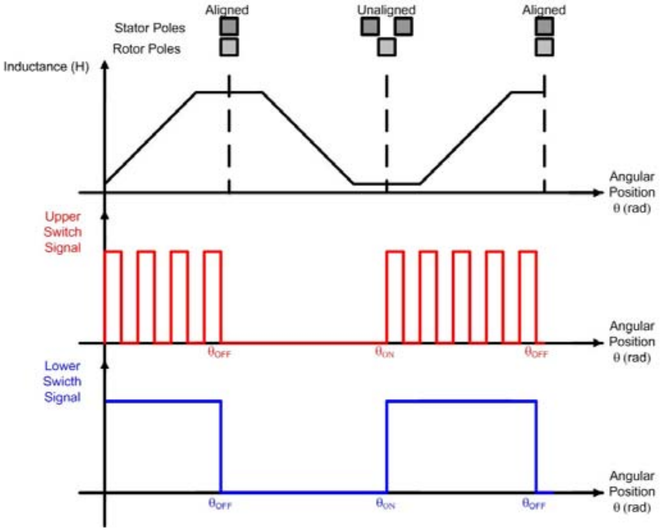

Fig. 6. S*oft-switching* method

Unlike the *hard-switching* method, in this case high-frequency switching is applied to only one of the two power semiconductors relative to each phase, which provides lower switching loss. Besides, the current ripple of the windings is from 5 to 10 times lower than that in the *hard-switching* method [2]. The *soft-switching* method also has the advantages of lower acoustic noise and electromagnetic interference [5].

IV. THE SWITCHING METHOD PROPOSED

The main objective of the switching method proposed, the *tri-state*, consists of applying signals that make the control of the energy supplied to the windings of the machine also possible, but doing that through low-frequency switching signals, aiming at minimizing loss in the semiconductors which, as has been shown, is proportional to the switching frequency.

The operating principle of this method consists in monitoring the instant value of the current of the winding which is being energized (increasing inductance) and, from the monitored value, acting upon the upper and lower switches of the power converter relative to the respective phase.

Acting upon semiconductor switching is done accordingly two previously established values in a micro processed system. Such values are a lower (I_{INF}) and an upper (I_{SUP}) current values, and the objective is to keep the current of the motor windings in the hysteresis gap established by these values, as shown in Figure 7.

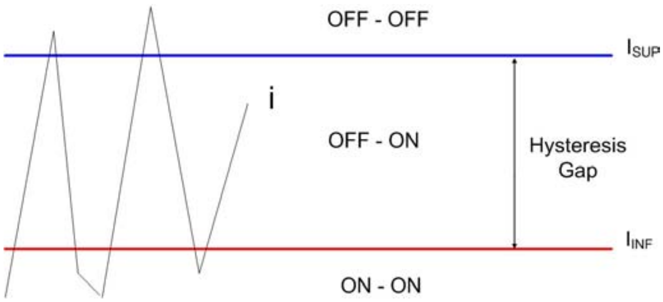

Fig. 7. *Tri-State* switching method.

In order to keep current of the windings within the hysteresis range shown in Figure 7 as often as possible, the semiconductor switching logic implemented was the one presented in (2).

$$[Q1,Q2] = \begin{cases} ON-ON, & if \quad i < I_{INF} \\ OFF-ON, & if \quad I_{INF} < i < I_{SUP} \\ OFF-OFF, & if \quad i > I_{SUP} \end{cases} \tag{2}$$

Where I_{INF} e I_{SUP} are the limit current values which establish the hysteresis range, also shown in Figure 7, and i is the instantaneous current value in a given motor winding. The logic presented in (2) is applied continuous and separately to the three phases of the SRM in issue.

Compared to the *hard-switching* method, the *tri-state* scheme avoids abrupt variations in the current waveforms by keeping it within the hysteresis gap. Compared to the *soft-switching* method, the *tri-state* method provides better current ripple [1], keeping it nearly constant during the inductance growth interval, which also benefits control of the machine when operating as a generator [1]. The fact that semiconductor switching to keep current within the hysteresis range is lower than in the *hard* and *soft-switching* methods, providing lower loss due to semiconductor switching, is also relevant.

V. RESULTS OBTAINED IN IMPLEMENTATION

As stated previously, *tri-state* method was only implemented through simulations as in LUK [1], obtaining the graphs shown in Figure 8 as result.

The first graph in Figure 8 shows inductance curves in one of the SRM simulated by LUK [1]. The second graph shows the curve of the torque generated by the SRM for a *tri-state* switching. The SRM is a machine that has a high level of torque ripple, as can be observed in Figure 4. However, the graphs obtained with computer simulation of the *tri-state* method carried out by LUK [1] show that the fact that the new switching strategy keeps the current within a narrow range of values reduces the torque ripple generated by the machine.

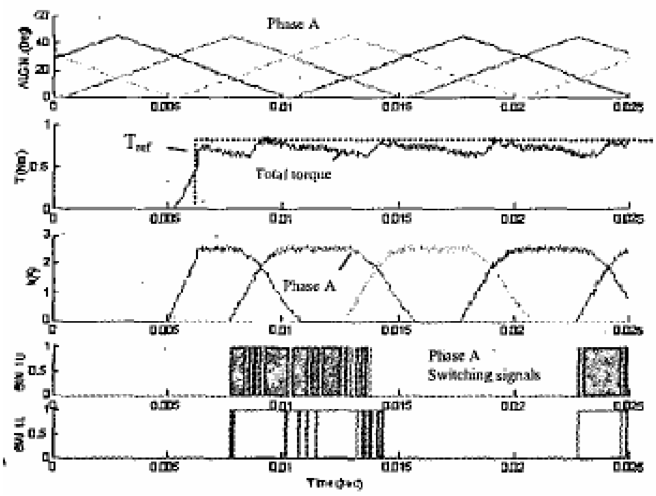

Fig. 8. Results obtained through simulation of the *tri-state* method implemented by LUK [1].

Thus, the *tri-state* method was physically implemented for an SRM with topology 6/4 in order to verify the computational results obtained by LUK [1].

The block diagram of the implemented system is shown in Figure 9.

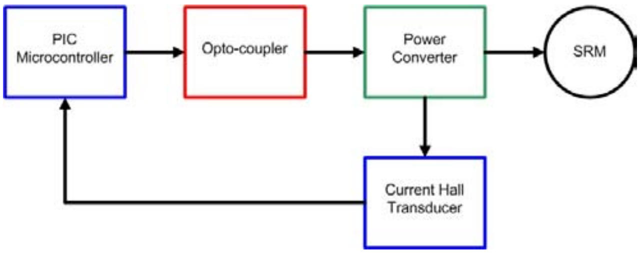

Fig. 9. Block diagram of *tri-state* system

The current waveform in one of the windings is shown in Figure 10.

Figure 10 shows the pulses of command applied to the upper and lower switches of the power converter of an SRM operating with the *tri-state* method, as well as the current in one of the windings of the machine. As stated in item IV, the instantaneous value of current in each SRM winding is monitored in order to apply the switching method described in (2).

Concerning Figure 10, the acquisition of the current waveforms, both for presenting results and for conditioning for the microprocessed system used, was made by means of a current hall transducer with a conversion ratio of 1:1000. In order to avoid very low voltage values, 5 coils were used for the main conductor in the transducer and the secondary current was applied to a 100 ohm resistance. It causes the voltage value shown in the screen of the oscilloscope to be half of the real value of the winding current in the machine. So, as the voltage shown in Figure 10 varies between 1.2V and 1.4V, the winding current in the machine at the moment it was measured actually varied between 2.4A and 2.8A. This result is close to the one which was expected, as the microprocessed system was designed to keep the current between 2A and 2.5A.

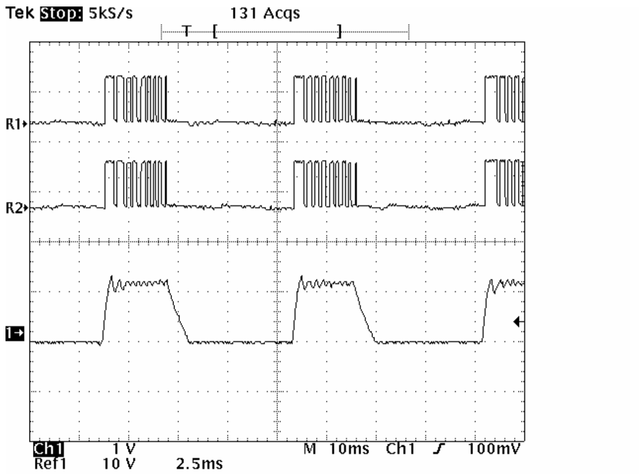

Fig. 10. Pulses of commands of power converter switches of the SRM and current in one of the windings in operation with the *tri-state* method

Figure 11 shows the current in a given motor winding, as well as its respective voltage. It is possible to observe the inversion of polarity when both switches are turned off. When we observe the winding in phase A in Figure 3, for example, when switches Q1 and Q2 are turned off, the converter operation changes to the free-wheeling state through diodes D1 and D2. This is done so as to provide a more pronounced rate of decrease in the winding current, because it prevents the current from entering the region of decreasing inductance, which would cause the generation of negative instantaneous values of torque.

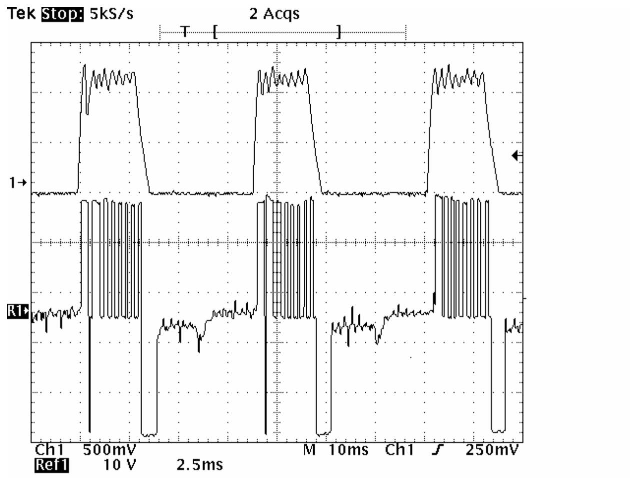

Fig. 11. Current and voltage in a given motor winding (*tri-state* method)

According Figure 9, the instantaneous value of the current was monitored through a microprocessed system with a PIC microcontroller. Through a process of analog/digital conversion, the microcontroller would detect the instant value of the current of the winding which was being energized at that moment and apply the *tri-state* switching as specified in its program.

Table 1 presents the SRM characteristics.

TABLE I
Characteristics of SRM used

Parameter	Value	Unit
Number of Phases	3	Phases
Number of Poles in Stator	6	Poles
Number of Poles in Rotor	4	Poles
Resistance per Phase	3,11	Ω
Minimal Inductance per Phase	30	mH
Maximal Inductance per Phase	135	mH
Nominal Voltage	180	V
Nominal Current	3,2	A
Nominal Speed	1800	RPM

VI. CONCLUSIONS

As a conclusion, the new switching strategy for switched reluctance motors, the *tri-state,* initially implemented through simulations by LUK [1] and confirmed by the results obtained in this work, through the physical implementation of the system for an SRM with topology 6/4, can be distinguished. The new switching strategy keeps the current in the windings within a range of desirable values, which implies in the reduction of torque ripple generated by the SRM. Besides, the *tri-state* strategy implements command signals to the semiconductors of the SRM power converter less frequently than it happens with the *hard* and *soft-switching* methods, which contributes to minimization of loss due to switching.

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