Torque Ripple Minimization of Switched Reluctance Motor SRMDS 6/4

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***Abstract*- Due to the reluctant effect that exists between the stator and the rotor and its conception, the torque of Switched Reluctance Motor (SRM) has a ripple waveform. Hence it is necessary to reduce these undulations, which are undesirable and harmful for a best fonctionnement of system. In order to minimize these undulations, we present in the follow paper the current hysteresis control of the SRM supplied with half-bridge asymmetrical inverter. This is realized with a right angles commutations choice of the power converter.**

I. INTRODUCTION

Recently, Switched Reluctance Motor (SRM) become popular in industrial applications especially for low and medium drives. This is because SRMs have the advantages of low manufacturing cost, good friability, tolerance, wide range operation of speed, torque and good dynamic response [1].

The primary disadvantage of an SRM is the higher torque ripple compared with conventional machines; witch contributes to acoustic noise and vibrations [2]. In Switched Reluctance Motor, the individual phases excitations are synchronized with rotor position that necessitates position sensing. This is an other disadvantage of SRM drive. Usually, mechanical position sensors or optical encoders are employed for this purpose [3].

The torque production mechanism in SRM is based on the variation of reluctance. Because of the double saliency, the stator and the rotor pole tend to align together to offer minimum reluctance path for the main flux produced by the excited stator phase. Thus, by sequentially exciting the stator phases, a unidirectional torque can be generated and hence electromechanical energy conversion can be performed [4].

In order to obtained higher performance as desired torque and speed stably, the current commutation from one phase to an other should be accurately controlled. Control of the SRM can be done in different modes of operation, namely, voltage control, current control and single pulse control. Low speed operation in Switched Reluctance Motor requires current control to limit the phase current to the desired value. These; in order to minimize the torque ripple. Fig 1 shown the idealized profile of phase inductance and current. We refered to equation 6, it is clear if we maintained the current constant in the region of positive inductance variation, we obtained also a constant torque.

In current control, hysteresis controller is commonly used in switched reluctance motor (SRM) drives, operating in the low speed region, for limiting the current to the desired value.

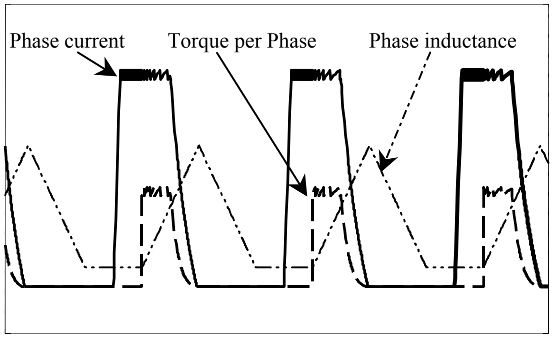


Fig. 1. The idealized phase inductance,phase current and torque waves

Not much attention has been paid in the literature on the effect of the size of the hysteresis current band on the performance of the SRM drive. On the other hand, this type of control gives fast response and good accuracy.

It can be implemented with simple and minimum of hardware. However, does not require knowledge of the load parameters [5].

II. TORQUE GENERATION

The double salient switched reluctance motors have independent phase windings on the stator and a rotor usually made of steel lamination. The machine produce torque on the basis of varying reluctance along the magnetic circuit. When a stator is energized, the stator pole pair attracts the closest rotor pole pair toward alignment of the pole.

Hence, torque is produce by this tendency of the magnetic circuit to adopt a new configuration with minimum reluctance and is independent of the current direction. By consecutive energization of all phases windings, continuous rotation in either direction is possible [3].

The relation of the instantaneous torque can be given as [6]:

$$T(\theta,i)=\sum_{j=1}^{3}T(\theta,\ i)=\sum_{j=1}^{3}\frac{\partial}{\partial\ \theta}W_j(\theta,\ i)\qquad j=1,2,3\qquad(1)$$

where T, i and θ represent the torque, current, and rotor position respectively.

The last term of (1) represent the variation of co-energy witch is depend of rotor position and current phase.

The co-energy can be calculated from:

$$W_j = \int_0^i \phi_j\,(\theta,\, i)\; di \qquad (2)$$

where ϕ_j represent the flux per phase witch can be given by:

$$\phi_j = L_j\,(\theta, i)\cdot i + \sum_{k\neq j} M_{jk}\,(\theta, i)\cdot i_k \;\;,\qquad k{=}1{,}2{,}3 \qquad (3)$$

L_j is phase inductance

M_{jk} is the mutual inductance between phases.

It is clear from (3) that flux phase depend of four parameters witch are three phase currents and rotor position. Under the simplifying assumption of linearity and the mutual inductances are zero, the flux per phase becomes:

$$\phi_j = L_j\,(\theta)\cdot i_j \qquad (4)$$

The idealized phase inductance profile of SRM is shown in fig. 1, with:

L_o : represent the phase inductance in unaligned position.

L_c : represent the phase inductance in aligned position.

θ_1 , θ_2 , θ_3 depend of the machine geometrical as shown in fig. 2, with:

β_r and β_s are stator pole arc and rotor pole arc respectively

N_r is the number of rotor pole.

$$L(\theta) = \begin{cases} L_0 & 0 \le \theta \le \theta_1 \\ \dfrac{L_c - L_0}{\theta_2 - \theta_1} & \theta_1 \le \theta \le \theta_2 \\ \dfrac{L_0 - L_c}{\theta_3 - \theta_2} & \theta_2 \le \theta \le \theta_3 \\ L_0 & \theta_3 \le \theta \le \theta_T \end{cases} \qquad \begin{cases} \theta_1 = \dfrac{\pi}{N_r} - \dfrac{\beta_r + \beta_s}{2} \\ \theta_2 = \dfrac{\pi}{N_r} - \dfrac{\beta_r - \beta_s}{2} \\ \theta_3 = 2\theta_2 - \theta_1 \end{cases} \qquad (5)$$

On this basic conditions, (1) can be simplified as:

$$T(\theta, i) = \sum_{j=1}^{3} \frac{1}{2} i^2 \frac{dL_j}{d\theta} \qquad (6)$$

The phase excitation currents are synchronized with the rising inductance region for motoring torque and with the decreasing inductance region for generating torque.

The optimum performance of an SRM depends on the appropriate positioning of the phase currents relative to the rotor angular position. This is can de deduced from (6).

The motor controller selects the turn-on and turn-off angles in such away that having appropriate output as the torque or speed.

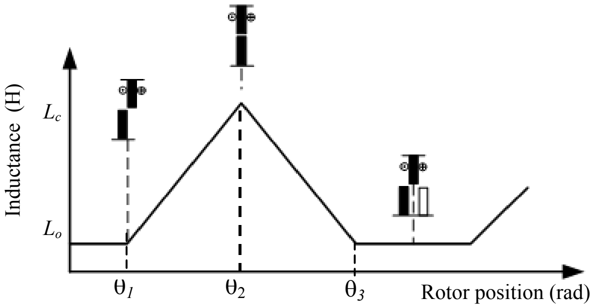


Fig. 2. The idealized phase inductance

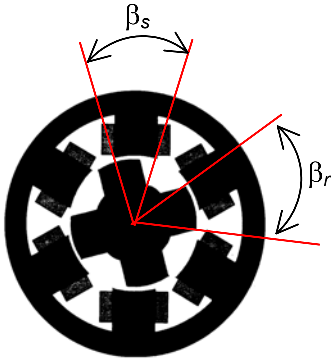


Fig. 3. Stator pole arc and rotor pole arc of the SRM 6/4

III. ELECTRICAL MODEL

When a current is following through stator winding the phase voltage is governed by [4]:

$$u = R_i\, i_j + \frac{d\phi_j}{dt} \qquad (7)$$

Where R_j is the phase coil resistance and u represents the input dc voltage. According to (4) and assumption concerning magnetic linearity and mutual inductances, (7) can be rewrite as follow:

$$u = R_i\, i_j + L_j(\theta)\frac{di_j}{dt} + i_j \frac{dL_j}{dt} \qquad (8)$$

Which can be also becomes:

$$u = R_i\, i_j + L_j(\theta)\frac{di_j}{dt} + i_j \omega \frac{dL_j}{d\theta} \qquad (9)$$

Where ω represents the angular velocity in radian per second. The last term in (9) is the back EMF of the SRM. At high speeds, the back EMF opposes the rise and the fall current in the phase winding, this is because the proportionality between back EMF and speed.

IV. POWER CONVERTER TOPOLOGY

The converter needs to provide negative voltage during the phase turning off, making a fast decrease of the currents [7].

A power converter topology that presents these operation characteristics is the half bridge converter shown in fig. 4 with six MOSFET and six diodes. Each phase winding of the SRM is connected in series with two MOSFETs and two diodes.

It makes possible an individualized phase operation, uses three voltage levels (- u, 0 and u). If we considered one phase, the three operating modes associated with the power converter are defined as follow:

Mode a: $u_{ph} = u$ if S_1 and S'_1 turned on (fig 5.a)
Mode b: $u_{ph} = -u$ if S_1 and S'_1 turned off (fig 5.b)
Mode c: $u_{ph} = 0$ if S_1 and S'_1 turned off and $i = 0$ (fig 5.c)

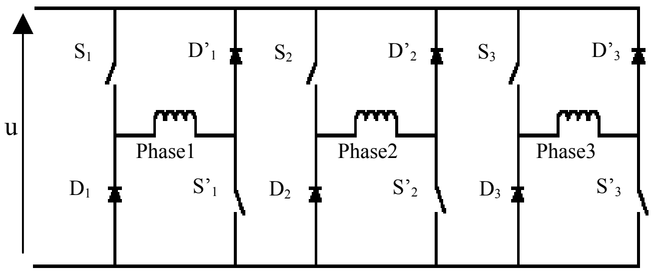


Fig. 4. Circuit topology of power converter

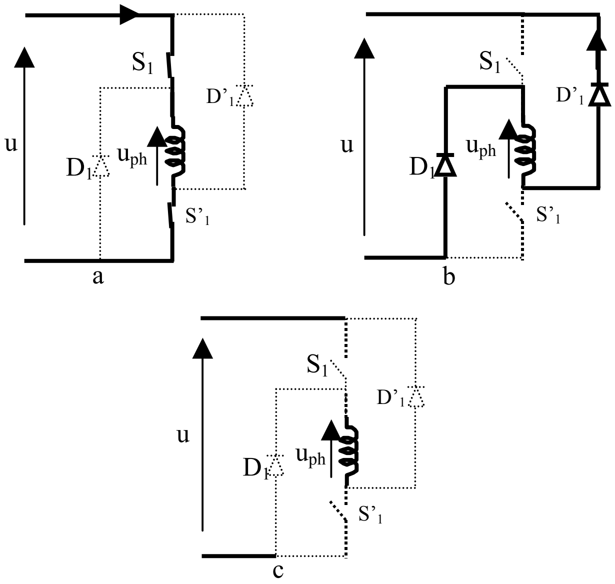


Fig. 5. Single phase circuit; Operating modes a, b and c

V. HYSTERISIS CURENT CONTROL

In order to maintain the motor torque to his constant value, we use the hysteresis strategy control. This is based on the supply of the SRM with predetermined currents according to a consign value of the torque in trapezoid wave form which ensures a desired torque over one complete period.

This strategy has been often carried out by means of the hysteresis current regulators.

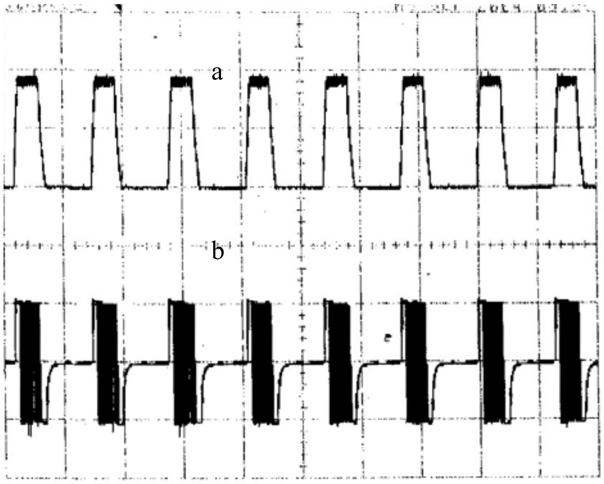
A typical hysteresis current controller is adopted, which is robust and fast. The shape of controlled current is characterized by turn on and turn off angles, reference current and by hysteresis band. Hence by switches turning on (θ_{on}) and turning off (θ_{off}), the current can be controlled around the reference current. Depending of hysteresis range the current ripple can be very small, reflecting in the resultant propulsion force. This situation is very important specially when the torque control is wanted [5].

VI. EXPERIMENTAL RESULTS

Thus to evaluate the performances and the efficiency of this strategy, we present the experimental results by adjusting the three essential parameters which are: the turn on angle which is taken to the maximum of unaligned between the stator pole and the rotor one of the excited phase, the turn off angle which is taken at the medium point in the torque production zone and the dwell angle estimated at 30° [8].

The first case is carried out by feeding each phase of the SRM alone with a supply voltage of 50V.

The experimental results given by fig. 3 shows the waves forms of current and the voltage through the excited phase C and it is identical for the two other phases A and B. We notice that the phase current is maintained constant and follows perfectly its reference 0.9A around a band of 0.1A.

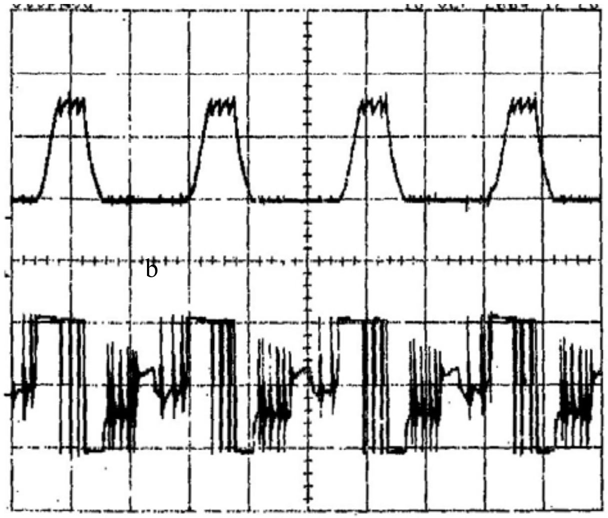


a- The phase C current 0.5A/div, 20ms/div
b- The phase C voltage 50V/div, 20ms/div

Fig.3. Experimental results when only the phase C is excited with a supply voltage of 50V

Experimental results given by fig. 4 shows the waves forms of currents in each phase. Then in fig.5 one gives the phase current and the phase voltage corresponding at the phase C. We notice that the phase current is maintained constant and follows perfectly its reference 0.9A around a band of 0.1A .

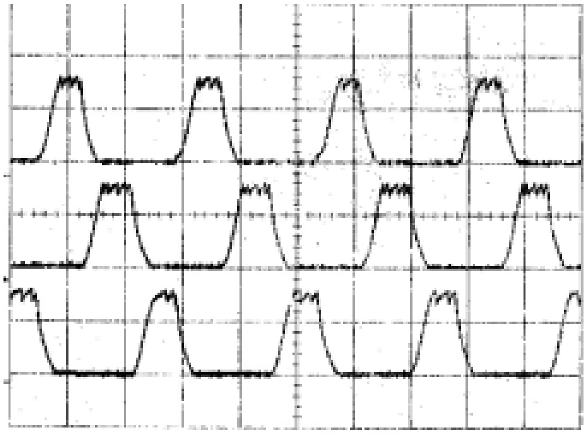
Comparing the voltage wave form of the phase C between the first case with only one phase excited and the second case of the three phases excited, we remarque the deformation of to voltage wave form that is explained by the effects of the induced e.m.f. created by the two other excited phases A and B. We notice that the phase current is maintained with an increase in its frequency compared to that obtained during the first cases that the developed torque by the three phases excited increases as well as the speed which reaches 1200 rpm.



a- The phase C current 0.5A/div, 5ms/div

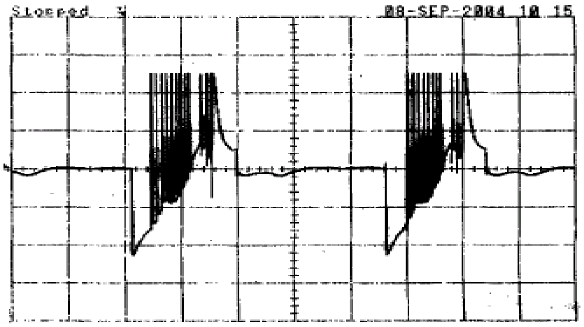
b- The phase C voltage 50V/div, 5ms/div

Fig. 5. Experimental results when all phases are excited with a supply voltage of 50V

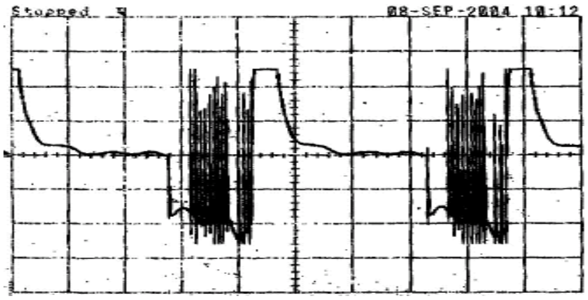


0.5A/div, 5ms/div

Fig. 4. Experimental results when all phases are exciting with a supply voltage of 50V



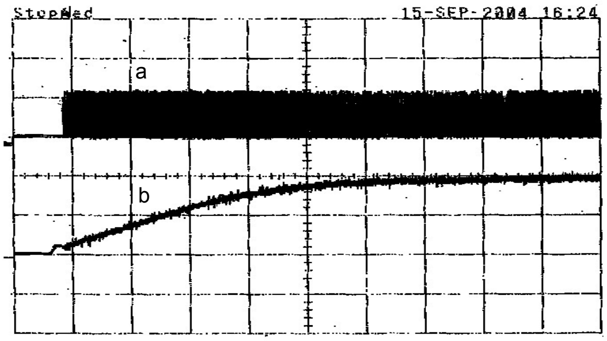
The induced e.m.f in phases A 20V/div, 5ms/div



The induced e.m.f in phases B 20V/div, 5ms/div

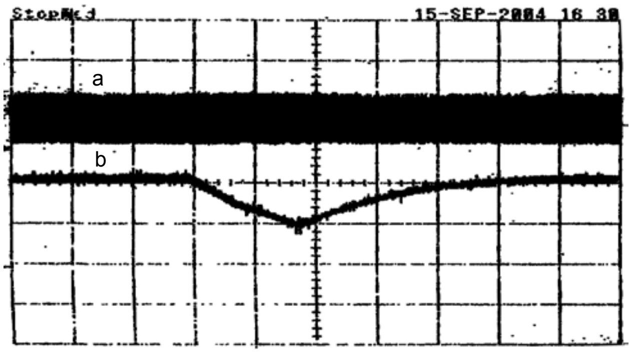
Fig. 7. Experimental induced e.m.f in phases A and B results by feeding the phase C alone witha supply voltage of 50V

Fig. 8 shows the dynamics of the three phases currents with the adjustment by hysteresis current control at the reference 1.2 A where the currents are maintained constant through this references in the various operations such that the starting and the load variation with as shown in the speed responses



a- phase current :1A/div, 2s/div

b- speed response :1000 rpm, 2s/div



a- phase current :1A/div, 2s/div

b- speed response :1000 rpm, 2s/div

Fig. 9. Rotor speed curve and current wave form under hystersis control at starting and load variation

VII. CONCLUSION

This paper shown that one can reach low speeds with a less torque ripple if one makes the optimum choice of the commutation angles. Adjusting the torque by the hysteresis currents. The results obtained showed that this technique ensures of good static and dynamic performances and achieve the consolidated objectif. It is especially characterized by its reliability and its simplicity where its realization has been choose.

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