

# Torque Ripple Minimization of a Switched Reluctance Motor

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**ABSTRACT** - This paper presents a simple technique to minimize torque ripple of a Switched Reluctance Motor. The technique is based on the control of the sum of the square of the phase currents by using only two current sensors and analog multipliers. The simulation results and a proposed circuit are given. The advantages and its limitations of the proposed circuit are explained.

## 1. INTRODUCTION

Switched Reluctance Motor (SRM) becomes an attractive alternative in adjustable speed drive due to its simplicity in both motor constructions and power converter. Excessive torque ripple, especially at low speeds is still one of the important reasons for Switched Reluctance Motor not to be acceptable in variable speed drive market. This torque ripple comes from motor's stepping nature and has undesirable effects to the bearing system and produces acoustic noise. It does not allow to use SR motor in servo applications.

Several efforts to reduce or eliminate the torque ripple of Switched Reluctance Motor are presented in literature. In [1,2] phase current shape is modulated to counteract the torque ripple. This technique requires a special motor geometry and pole shape design. A balanced commutator which works for accurate current tracking to reduce torque pulsations is reported in [3]. This technique needs computations and is based on measured motor data. The method described in [4] optimizes the commutation angle for torque ripple reduction. This work needs excessive memory to use recalculated optimal position - phase current values which are obtained from the nonlinear  $T=T(\theta, i)$  torque curves. Torque ripple minimization method given in [5] is based on the estimation of the instantaneous Switched Reluctance Motor torque from the flux linkage versus current and rotor position characteristic curve via bi-cubic spline interpolation. The estimation is achieved by a simulation model using a DSP. The application of a variable structure system theory to the speed control of Switched Reluctance Motor given in [6]

results that this control is also effective in reducing the torque ripple of the motor, compensating for the nonlinear torque characteristics. Only simulation results are given in that paper. Its practical implementation needs accurate dynamic speed measurements. Some small torque ripple exhibited in simulation are explained by temporary outgoing of the drive from sliding regime.

In this paper a simple technique is proposed to modulate phase currents to eliminate torque ripple by using only two current sensors. Simulation results are given, the advantages and limitations of the technique are explained.

The paper is organized as follows. In section two the mathematical model is given. Section three and four give simulation results with conventional and proposed methods. Experimental results are given in section five. Finally, section six concludes the work.

## 2. THE MATHEMATICAL MODEL

The Switched Reluctance Motor used in the simulation is a 8/6 SRM with C - Dump converter. Figure 1 shows the motor, the converter and the control.

The state equations of this system are

$$d\lambda_n / dt = V_n - R \cdot I_n \quad (n = 1, 2, 3, 4)$$

$$dV_c / dt = (-I_g \cdot u_g + I) / C_d$$

$$dI_g / dt = (V_g - R_g \cdot I_g) / L_g \quad (1)$$

$$d\omega / dt = (T_e - T_L - B \cdot \omega) / J$$

$$d\theta / dt = \omega$$

where,

- $\lambda_n$  flux of  $n^{\text{th}}$  phase, Wb
- $t$  time, s
- $V_n$  phase voltage of  $n^{\text{th}}$  phase, V
- $R$  per phase coil resistance,  $\Omega$
- $I_n$  phase current of  $n^{\text{th}}$  phase, A

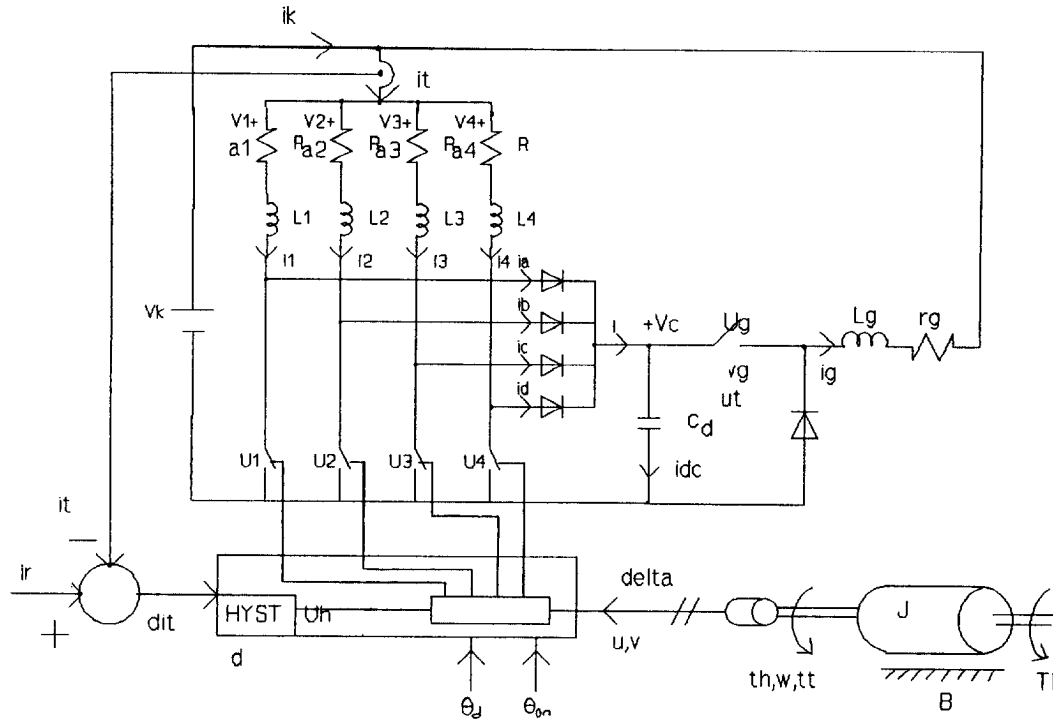


Fig. 1 C - Dump Converter of a four-phase SRM

- $V_c$  C - Dump capacitor voltage, V  
 $I_g$  inductor current in C - Dump circuit, A  
 $u_g$  C - Dump converter control signal, (1 or 0)  
 $I$  sum of energy recovery diodes currents, A  
 $C_d$  C - Dump capacitor, F  
 $V_g$  voltage across the inductor in C - Dump circuit, V  
 $L_g$  inductor in C - Dump circuit, H  
 $R_g$  resistance of  $L_g$ ,  $\Omega$   
 $\omega$  angular speed, rad/s  
 $\theta$  rotor position (angle), rad  
 $T_e$  electrical torque, Nm  
 $T_L$  load torque, Nm  
 $B$  coefficient of viscous friction, Nm s/rad  
 $J$  moment of inertia, kg m<sup>2</sup>

$$T_e = \sum_{n=1}^4 0.5(dL_n / d\theta) I_n^2 \quad (2)$$

where,

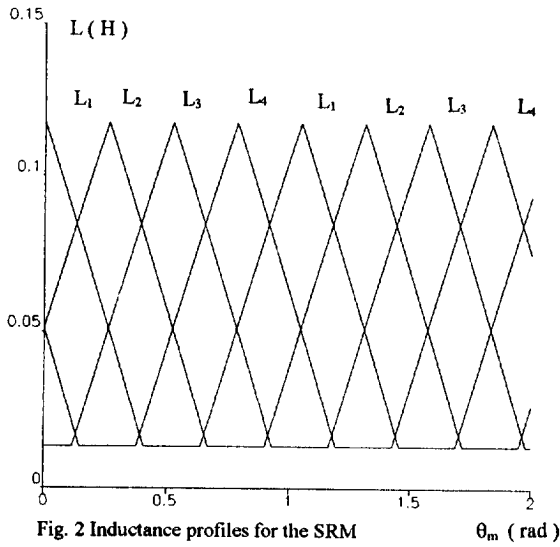
$L_n$  is phase inductance of  $n^{\text{th}}$  phase.

Following assumptions are made in the above model.

- The mutual inductances between phases are zero.
- The motor works in the linear region of its magnetic characteristics. The inductance profiles of phases are given in figure 2. The currents  $I_n$  can be calculated from fluxes by,

$$I_n = \lambda_n / L_n \quad (3)$$

Electrical torque is,



$V_g$  and  $V_n$  in equation ( 1 ) are defined according to the control strategy.

### 3. SIMULATION

The simulation is achieved with Simnon Version 3.10 by using the mathematical model given in the equations ( 1 ). Simnon is a simulation program for non-linear systems [ 7 ]. Runga - Kutta method is chosen to solve the state equations.

In practice, voltage source is used to drive the motor and current is controlled. This can be done by controlling the total current as

$$i_1 + i_2 + i_3 + i_4 = I_{ref} \quad (4)$$

with only one current transducer.

The torque variation, corresponding currents, inductances and their slopes which were obtained trough simulation are given in Figure 3 and 4.

The torque dip in figure 3.a can be explained by equation ( 2 ). The tail of phase current is not controlled. During commutation the rising edge of phase current is modulated to satisfy ( 3 ). However, this does not make the torque constant.

Some data for the above simulation results are as follows

Reference current.....:  $I_{ref} = 3.4 \text{ A}$   
 Speed.....:  $\omega = 30 \text{ rad/s}$   
 Load torque.....:  $T_L = 1.2 \text{ N.m}$   
 Source voltage.....:  $V_K = 300 \text{ V}$   
 C-Dump voltage.....:  $V_C = 600 \text{ V}$

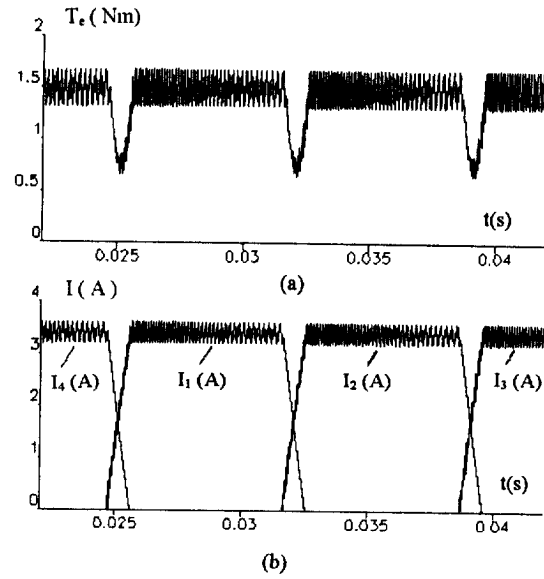


Fig. 3 Simulation results  
 a) Torque variation  
 b) Phase currents  $I_1$ ,  $I_2$  and  $I_3$  variation

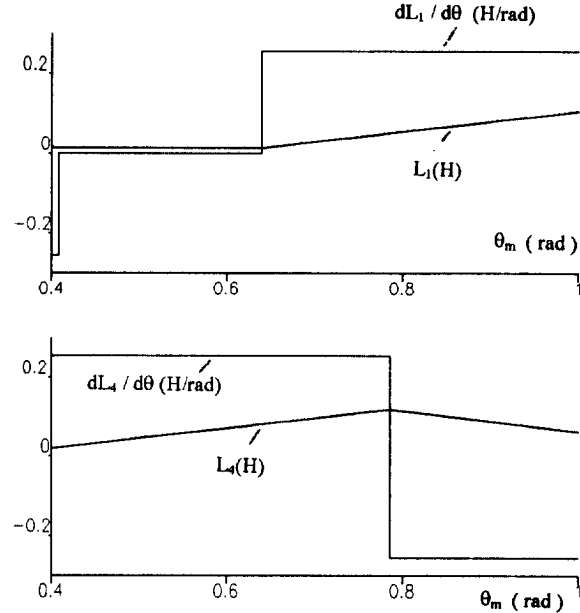


Fig.4. Phase inductance  $L_1, L_4$  and their slopes  $dL_1/d\theta$ ,  $dL_4/d\theta$

Phase voltage on time.....:  $\theta_{on} = 0^\circ$   
 Phase voltage width.....:  $\theta_C = 15^\circ$   
 C-Dump switching freq.....:  $f_c = 5 \text{ kHz}$

#### 4. THE PROPOSED METHOD

Note that the commutation from  $I_4$  to  $I_1$  occurs in positive torque production period of both  $L_4$  and  $L_1$  in figure 3 and 4. Therefore the following control is more logical according to the equation (2) where the torque is proportional with the square of the currents.

$$i_1^2 + i_2^2 + i_3^2 + i_4^2 = I_{ref}^2 \quad (5)$$

The proposed method based on the equation (5). This control is simulated with the same data used in the above section and the results are shown in Figure 5. It is seen that the torque dip is appreciably eliminated. The ripple shown in the figure comes from the hysteresis current control and can be made as small as possible by reducing hysteresis band and increasing switching frequency.

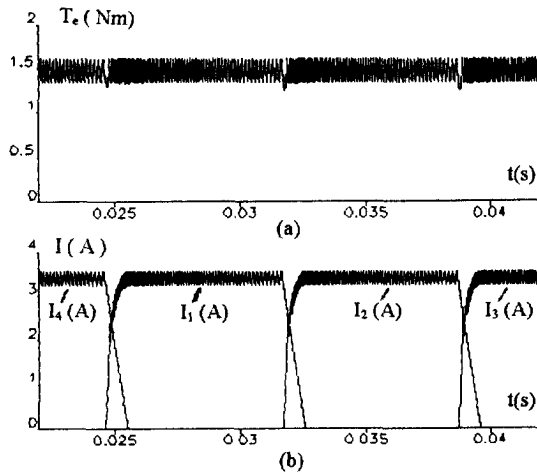


Fig. 5. Simulation results with proposed control method  
a) Torque variation  
b) Phase currents  $I_4$ ,  $I_1$  and  $I_2$  variation

#### 5. EXPERIMENTAL RESULTS

We assume that only two phases can conduct current simultaneously. Therefore

$$i_1 \cdot i_3 = i_2 \cdot i_4 = 0. \quad (6)$$

Then,

$$(i_1 + i_3)^2 + (i_2 + i_4)^2 = i_1^2 + i_2^2 + i_3^2 + i_4^2 \quad (7)$$

Equation 7 shows that the proposed control can be done by using only two current sensors. A circuit to implement this control is given in Figure 6. The freewheeling diodes and C-dump converter is not shown in that circuit for simplification. The multiplier circuits shown in the figure are not necessarily high accuracy one. In our circuit Analog Devices AD633 multipliers are used for squaring.

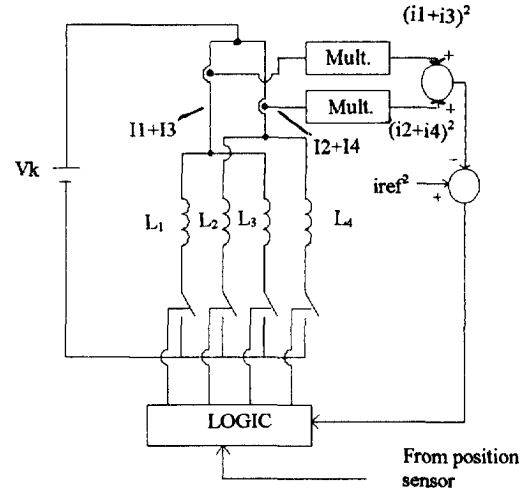


Fig.6. Proposed control circuit

Figure 7a and 7b shows the phase current waveforms taken from the oscilloscope without and with the proposed control is operated under the same conditions we used in simulation. Since we have no dynamic torque measurement system at this moment. The torque reduction is justified in two ways.

- a) The experimental and simulated current waveforms were in close agreement
- b) Audible noise was reduced.

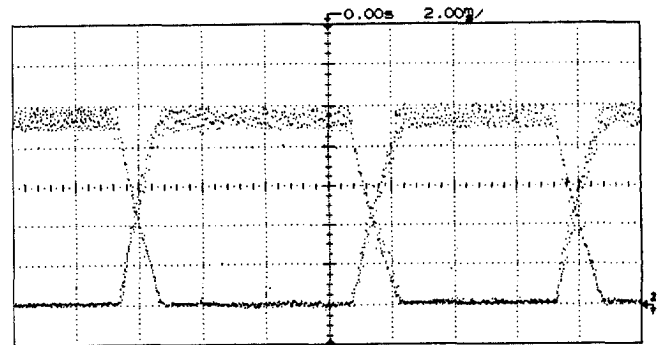


Fig. 7a Experimental phase current without the proposed control method  
Vertical 0.7 A/div Horizontal 2ms/div

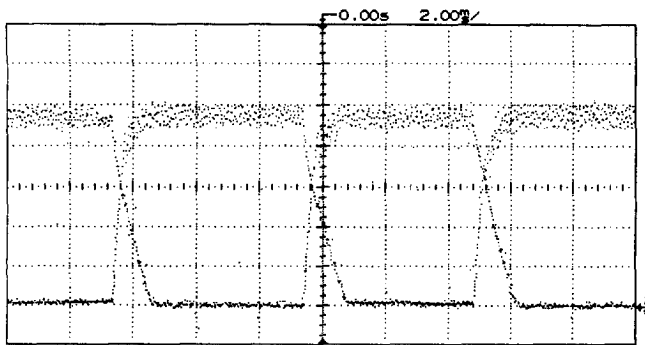


Fig. 7b Experimental phase current with the proposed control method  
Vertical 0.7 A/div Horizontal 2ms/div

## 6. CONCLUSIONS

A simple technique is given to minimize torque ripple of Switched Reluctance Motor. The proposed technique has the following advantages:

- 1 ) Only two current sensors are required to apply the method,
- 2 ) Accurate angle estimation or measurement is not needed,
- 3 ) It is simple. No look-up table or digital calculation is necessary,
- 4 ) No modification on motor or pole geometry is required.

But, there are some limitations for the proposed method to apply. These are:

- 1 ) Inductance versus angle variation is assumed linear in the positive torque production period ,
- 2 ) In any time only one or two phases have to conduct current.

However these limitations are easy to achieve especially at low speed. Therefore the technique given is very simple and helps to reduce torque ripple.

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