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Torque Ripple in Switched Reluctance Motor Based on Asymmetrical Bridge Converter

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ABSTRACT

This paper presents an investigation of the torque ripple in 3-phase Switched Reluctance Motor (SRM) with 12 stator poles and 8 rotor poles driven by the asymmetrical bridge converter. The optimal control parameters are determined to reduce torque ripple by adjusting DC bus voltage and excitation angles. A DSP TMS320F28335 controller is used to create the PWM and to calculate the rotor position. The rotary torque instrument is used to measure the motor torque at a rated load of 1.4 Nm. The experimental results, the torque ripple depends on the phase current shape. The lowest torque ripple will be produce when the phase current shape is flatted-top.
Keywords : Switched Reluctance Motor, Torque Ripple, Asymmetrical Bridge Converter

I. INTRODUCTION

A Switched Reluctance Motor (SRM) is a doubly salient pole motor and no winding or permanent magnet on the rotor. Therefore, there is no copper loss in the rotor. Advantages of the SRM, it has simple structure, robust, low cost, high power density, high reliability, good controllability and high efficiency. The SRM is widely used for high-speed applications. However, a major disadvantage of the SRM is the large torque ripple, which produces acoustic noise and vibrations. The highly non-uniform torque is produced from magnetic saliency between stator poles and rotor poles [1]. Torque ripple minimization is introduced in [2-4]. The phase current profile is optimized and compared to constant the phase current profile [5]. The torque distribution function technique can moderate the torque ripple [6].

A symmetrical bridge converter is the most popular topology used to drive a SRM. It consists of two switching switches and two freewheeling diodes per phase. Merits of a symmetrical bridge converter are high efficiency, fast regeneration, phase independence, and high control capability. This paper investigates the torque ripple by adjusting DC bus voltage and excitation angles. Ultimately, the optimal control parameters are determined depending on the phase current.

II. PRINCIPLE OF SWITCHED RELUCTANCE MOTOR

The voltage equation (v_{ph}) in Eq. (1) is formulated from the electric circuit of the stator coil, which is shown in Fig. 1. The circuit's current is i_{ph}. The coil has an inductance $(L(\theta, i_{ph}))$, which is a function of the rotor position (θ) and current (i_{ph}). This coil has an internal resistance (R_{ph}).

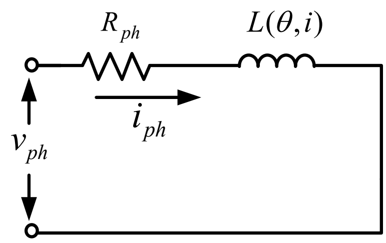


Figure 1. Electrical circuit diagram of the stator coil

$$v_{ph} = R_{ph} i_{ph} + \frac{d\lambda(\theta, i_{ph})}{dt} \quad (1)$$

The flux-linkage is given as

$$\lambda = L(\theta, i_{ph}) \quad (2)$$

Substituting Eq. (2) into Eq. (1)

$$\begin{aligned} v_{ph} &= R_{ph} i_{ph} + \frac{d(L(\theta, i_{ph}) i_{ph})}{dt} \\ &= R_{ph} i_{ph} + \frac{L(\theta, i_{ph}) di_{ph}}{dt} + i_{ph} \frac{dL(\theta, i_{ph})}{dt} \\ &= R_{ph} i_{ph} + \frac{L(\theta, i_{ph}) di_{ph}}{dt} + i_{ph} \frac{d\theta}{dt} \cdot \frac{dL(\theta, i_{ph})}{d\theta} \end{aligned} \quad (3)$$

ω_m is the rotor angular speed; $(\omega_m = \frac{d\theta}{dt})$, which is substituted in to (3). The yield is

$$v_{ph} = R_{ph} i_{ph} + \frac{L(\theta, i_{ph}) di_{ph}}{dt} + \frac{dL(\theta, i_{ph})}{d\theta} \cdot i_{ph} \cdot \omega_m \quad (4)$$

The voltage equation in Eq. (4) consists of 3 terms; the voltage equation of internal phase resistance $(R_{ph} i_{ph})$, the voltage equation of phase inductance coil $L(\theta, i_{ph}) \frac{di_{ph}}{dt}$, and the back EMF (e_{ph}) equation $\frac{dL(\theta, i_{ph})}{d\theta} \cdot \omega_m \cdot i_{ph}$, which describes in Fig. (2).

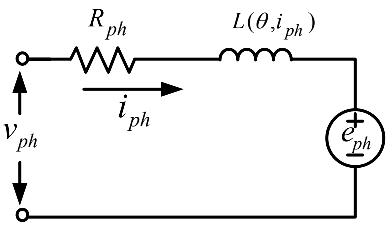


Figure 2. Electrical circuit diagram of the SRM

Input power can be expressed as

$$p_{in} = R_{ph} \cdot i_{ph}^2 + i_{ph}^2 \frac{dL(\theta, i)}{dt} + L(\theta, i_{ph}) \cdot i_{ph} \frac{di_{ph}}{dt} \quad (5)$$

The Eq. (5) is solved and rearranged as follows;

$$p_{in} = R_{ph} \cdot i_{ph}^2 + \frac{d}{dt}\left(\frac{1}{2} L(\theta, i_{ph}) \cdot i_{ph}^2\right) + \frac{1}{2} \cdot i_{ph}^2 \cdot \frac{dL(\theta, i_{ph})}{dt}$$

$$\begin{aligned} p_{in} = p_a &= \frac{1}{2} \cdot i_{ph}^2 \cdot \frac{dL(\theta, i_{ph})}{dt} = \frac{1}{2} \cdot i_{ph}^2 \cdot \frac{dL(\theta, i_{ph})}{d\theta} \cdot \frac{d\theta}{dt} \\ &= \frac{1}{2} \cdot i_{ph}^2 \cdot \frac{dL(\theta, i_{ph})}{d\theta} \cdot \omega_m \end{aligned} \quad (6)$$

The torque equation is given as follows:

$$p_a = T_e \omega_m$$

$$T_e = \frac{1}{2} \cdot i_{ph}^2 \frac{dL(\theta, i)}{d\theta} \quad (7)$$

where p_a is the mechanical input power. The mechanical equation is given by

$$T_e - T_L = J \frac{d\omega_m}{dt} + B\omega_m \quad (8)$$

where T_L is the load torque, J is the total inertia, and B is the total friction coefficient.

III. ASYMMETRICAL BRIDGE CONVERTER

The asymmetric bridge converter for 3-phase SRM is used as shown in Fig. 3. The converter consists of two power switches and two diodes per phase. Each phase of the converter is independent of others, so the external voltage control can be applied.

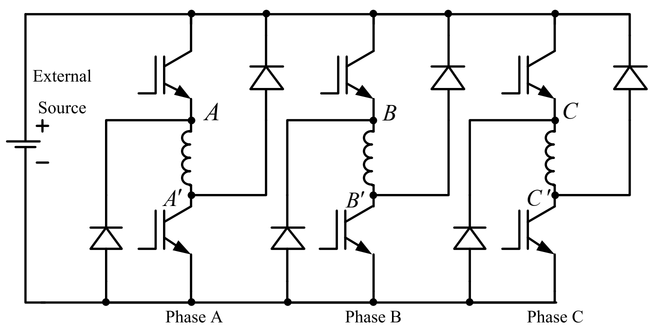


Figure 3. 3-phase asymmetrical bridge converter

The converter has three possible modes of operation. When both switching devices are turn-on, the external voltage is applied and the current rises rapidly in the winding. At low-speed operation, the current will exceed its demanded value fast. When one switch is turn-off and the current circulates through the other switch and one diode. This operation is the called free-wheeling mode, which employs a low demagnetizing voltage to the winding. If both switches turned off, the current circulates through two diodes and recharges the capacitor. The demagnetization process is faster than the freewheeling mode.

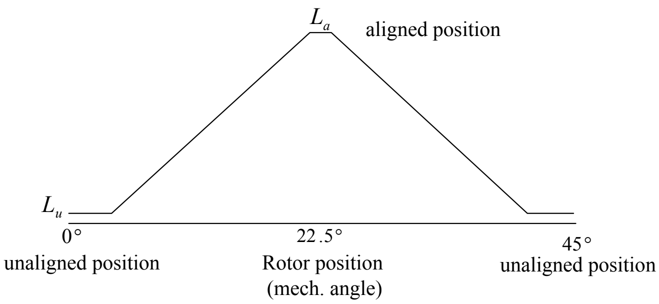


Figure 4. Inductance profile of the SRM

Fig. 4 depicts the inductance versus different rotor positions. For controlling the SRM, the converter needs the applied voltage to the winding between the turn-on angle and turn-off angle. The turn-on and turn-off angles must be in range 0° to 22.5° or while $\frac{dL}{d\theta}$ is increasing.

IV. EXPERIMENTAL RESULTS

The experimental setup is used to investigate torque ripple, when the SRM is controlled by asymmetrical bridge converter. It consists of 3-phase 12/8 SRM with resolver, 3-phase asymmetrical bridge converter with TMS28335DSP controller, external voltage source, torque meter, and 1.4 Nm load.

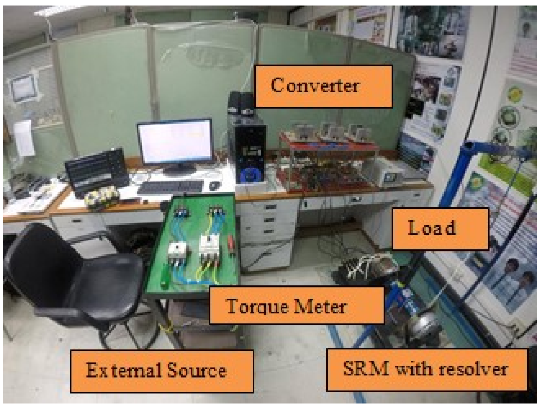


Figure 5. Experimental setup

To determine the optimum control parameters for lowest torque ripple, Figs. 6-9 show waveforms of average torque ripple and phase current A-C (from top to bottom). Table I – IV summarize the value of average torque ripple, when turn-on and turn-off angles were adjusted using DC bus voltage at 12VDC, 24VDC, 36VDC, and 48VDC, respectively.

(a) Turn-on angle at 0° and turn-off at 11°

(b) Turn-on angle at 1° and turn-off at 11°

(c) Turn-on angle at 2° and turn-off at 12°

(d) Turn-on angle at 3° and turn-off at 12°

(e) Turn-on angle at 4° and turn-off at 13°

(f) Turn-on angle at 5° and turn-off at 13°

Figure 6. Adjusting Turn-on/off angle with 12VDC

TABLE I

CONTROL PARAMETERS WITH 12V

Turn-on (°)	Turn-off (°)	Rotor speed (rpm)	Torque ripple (N.m)
0	11	1687	0.2700
1	11	1860	0.2610
2	12	2064	0.2955
3	12	2240	0.3060
4	13	2370	0.3140
5	13	2480	0.3130

(a) Turn-on angle at 0° and turn-off at 11°

(b) Turn-on angle at 1° and turn-off at 11°

(c) Turn-on angle at 2° and turn-off at 12°

(d) Turn-on angle at 3° and turn-off at 12°

(e) Turn-on angle at 4° and turn-off at 13°

(f) Turn-on angle at 5° and turn-off at 13°

Figure 7. Adjusting Turn-on/off angle with 24VDC

TABLE II

Control parameters with 24V

Turn-on (°)	Turn-off (°)	Rotor speed (rpm)	Torque ripple (N.m)
0	11	3532	0.3120
1	11	3364	0.2646
2	12	3235	0.4002
3	12	2972	0.4019
4	13	2764	0.4125
5	13	2576	0.4159

(a) Turn-on angle at 0° and turn-off at 11°

(b) Turn-on angle at 1° and turn-off at 11°

(c) Turn-on angle at 2° and turn-off at 12°

(d) Turn-on angle at 3° and turn-off at 12°

(e) Turn-on angle at 4° and turn-off at 13°

(f) Turn-on angle at 5° and turn-off at 13°

Figure 8. Adjusting Turn-on/off angle with 36VDC

TABLE III

Control parameters with 36V

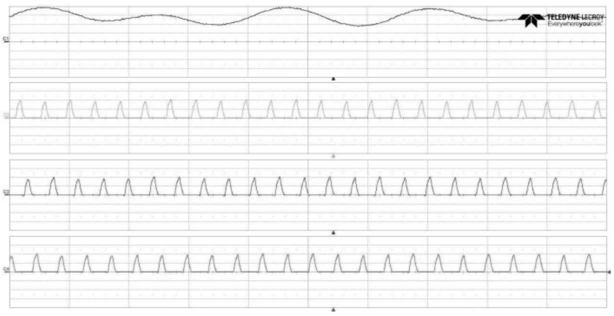
Turn-on (°)	**Turn-off (°)**	**Rotor speed (rpm)**	**Torque ripple (N.m)**
0	11	4220	0.3821
1	11	4382	0.4825
2	12	4312	0.8100
3	12	4150	0.9980
4	13	3785	1.1300
5	13	3563	1.2360

(a) Turn-on angle at 0° and turn-off at 11°

(b) Turn-on angle at 1° and turn-off at 11°

(c) Turn-on angle at 4° and turn-off at 13°

(e) Turn-on angle at 4° and turn-off at 13°



(f) Turn-on angle at 5° and turn-off at 13°

Figure 8. Adjusting Turn-on/off angle with 48VDC

TABLE IV
Control parameters with 48V

Turn-on (°)	Turn-off (°)	Rotor speed (rpm)	Torque ripple (N.m)
0	11	5621	0.4359
1	11	5439	0.4530
2	12	5228	0.5035
3	12	4951	0.6475
4	13	4787	0.9830
5	13	4557	1.0613

V. CONCLUSION

Average torque ripple value of the 3-phase 12/8 SRM using the asymmetrical bridge converter is investigated. Turn-on and turn-off angles were adjusted while the DC bus voltage was fixed. Experimental results, the lowest torque ripple will be occurred, when the shape of phase current is flatted-top as shown in Figs. 6-9. Ultimately, the optimal control parameters used to control the SRM that the shape of phase current is flatted-top. In this paper, the optimal turn-off angle is at 11° and the optimal turn-on angle is at 0° or 1°.

VI. REFERENCES

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