TORQUE CONTROL AND TORQUE RIPPLE MINIMIZATION OF SWITCHED RELUCTANCE MOTORS

By

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ABSTRACT

Simple power electronic drive circuit and fault tolerance of converter are specific advantages of SRM drives, but excessive torque ripple has limited its use to special applications. Due to the nature of the torque production in SRM, the torque generated in any individual phase is discontinuous. To generate a ripple free output torque, there must be a overlapping between phases. To obtain a constant torque, the summation of the torque generated by the phase currents must be the same. In this work, a torque factor is defined to determine the torque required in each phase during overlapping to make a ripple free resultant torque according to the rotor position and the specified turn-on/turn-off angles. Then the torque command is converted into current command according to the inductance based SRM model. Finally voltage-chopping technique is used to generate voltage pulses for each phase to maintain the phase current around the desired value. Simulations show satisfactory results of the proposed method.

Keywords: Torque Ripple Minimization, Torque Control, Torque Factors, Optimal Current Profiling, Inductance Modeling, Switched Reluctance Motor.

INTRODUCTION

The simple and rugged construction, and low cost makes the Switched Reluctance Motor (SRM) a viable candidate for various general purpose adjustable speed applications [1]. The simple power electronic drive circuit requirement and the fault tolerance of the converter are specific advantages of SRM drive for applications requiring a high degree of reliability. The output power of an SRM is higher than that of a comparable induction motor and the torque-inertia ratio is also higher due to the absence of rotor windings.

The primary disadvantage of an SRM is the higher torque ripple compared with the conventional machines, which contributes to acoustic noise and vibration [2]. The origin of torque pulsation in an SRM is due to the highly nonlinear and discrete nature of torque production mechanism. The total torque in an SRM is the sum of torques generated by each phase, which are controlled independently. Torque pulsations are most significant at the commutation instants when torque production mechanism is being transferred from one active phase to another.

The minimization of the torque ripple is essential in high performance servo applications, which require smooth operation with minimum torque pulsation. The excellent positive features of an SRM can be utilized in a servo system by developing torque ripple minimization techniques. These types of drives have extensive applications in hybrid electric vehicles, direct drive machine tools, and automotive industries, etc.

There are essentially two primary approaches for reducing the torque pulsations: One method is to improve the magnetic design of the motor, while the other is to use sophisticated electronic control. Machine designers are able to reduce the torque pulsations by changing the stator and rotor pole structures, but only at the expense of motor performance. The electronic approach is based on selecting an optimum combination of the operating parameters, which include the supply voltage, turn-on and turn-off angles, current level and the shaft load.

In this work, an inductance based model of a four phase 8/6 SRM is used. The torque generated by the SRM can be computed directly from the phase currents and rotor position. This provides a convenient way to control the output torque.

In this paper torque factors are defined and used to determine the desired torque produced by each phase during overlapping to make a ripple free resultant torque. Then the torque command is converted into current command according to the inductance based SRM model. Then hysteresis current control technique is applied to maintain the phase current within an acceptable range around the reference current.

The above torque control technique is simulated in Matlab / Simulink environment to test the performance. Simulations show satisfactory results of the proposed scheme.

1. Mathematical Model for SRM

The inductance based model of switched reluctance motor is used in this work. Since the phase inductance changes periodically with the rotor position angle, it is expressed as a Fourier series with respect to rotor position angle [5]

$$L(\theta, i) = \sum_{k=0}^{m} L_k(i) \cos(kN_r \theta) \qquad (1)$$

where N_r is the number of rotor poles.

If three terms are used in the Fourier series, then the three coefficients L_0, L_1, and L_2 can be computed from L_{0° (aligned position), L_{30° (unaligned position), and L_{15° (midway between the above two positions). Since

$$\begin{bmatrix} L_{0^0}(i) \\ L_{15^0}(i) \\ L_{30^0}(i) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \cos(6*15^0) & \cos(12*15^0) \\ 1 & \cos(6*30^0) & \cos(12*30^0) \end{bmatrix} \begin{bmatrix} L_0(i) \\ L_1(i) \\ L_2(i) \end{bmatrix} \qquad (2)$$

We can have

$$L_0(i) = \frac{1}{2}\left[\frac{1}{2}\left(L_{0^0}(i) + L_{30^0}(i)\right) + L_{15^0}(i)\right]$$

$$L_1(i) = \frac{1}{2}\left(L_{0^0}(i) - L_{30^0}(i)\right)$$

$$L_2(i) = \frac{1}{2}\left[\frac{1}{2}\left(L_{0^0}(i) + L_{30^0}(i)\right) - L_{15^0}(i)\right] \qquad (3)$$

The inductance variation at aligned position ($L_{0^\circ}(i)$), unaligned position ($L_{30^\circ}(i)$), and at midway position ($L_{15^\circ}(i)$) of the phase winding is estimated from the standstill test results [6].

A three-dimensional (3-D) plot of inductance shown in Figure. 1 depicts the profile of inductance versus rotor position and phase current. At 0° and 60°, phase A is at its aligned positions and has the highest value of inductance. It decreases when the phase current

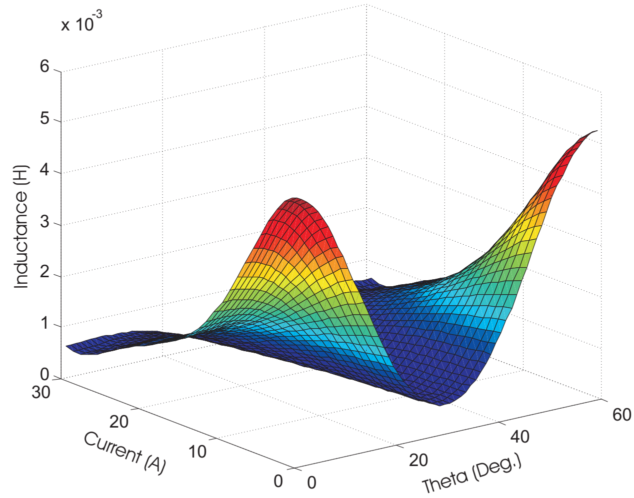

Figure1. Variation of phase inductance with current and rotor position

increases. At 30°, phase A is at its unaligned position and has lowest value of inductance. The inductance at unaligned position does not change much with the phase current and can be treated as a constant. The inductance at midway and aligned position decrease when current increases due to saturation.

Based on the inductance model described before, the phase voltage equations can be formed and the electromagnetic torque can be computed from the partial derivative of magnetic co-energy with respect to rotor angle θ [11].

The phase voltage equation can be expressed as

$$\begin{aligned} V &= Ri + \frac{d\psi}{dt} \\ &= Ri + \frac{d(Li)}{dt} \\ &= Ri + L\frac{di}{dt} + i\frac{\partial L}{\partial \theta}\omega + \frac{\partial L}{\partial i}\frac{di}{dt} \\ \text{and } \frac{di}{dt} &= f(\theta, i, \omega) + g(\theta, i, \omega)V \end{aligned} \qquad (4)$$

Where

$$f(\theta, i, \omega) = -\frac{R + \frac{\partial L}{\partial \theta}\omega}{L + i\frac{\partial L}{\partial i}} i$$

$$g(\theta, i, \omega) = \frac{1}{L + i\frac{\partial L}{\partial i}}$$

$$\omega = \frac{d\theta}{dt}$$

$$\frac{\partial L}{\partial i} = \sum_{k=0}^{m} \frac{\partial L_k(i)}{\partial i} \cos(kN_r\theta)$$

$$\frac{\partial L}{\partial \theta} = -\sum_{k=1}^{m} L_k(i)\, kN_r \sin(kN_r\theta)$$

The general torque expression is given by [11]

$$T_e \quad \frac{W_{co}}{\quad}_{i \ const} \tag{5}$$

where W_{co} is the co-energy. The co-energy is the area under the magnetization curve and is given by

$$W_{co} \quad \int_0^{i1} \quad ,i \ di \tag{6}$$

So the torque equation become

$$T_{e,j} \quad \int_0^{i1} \frac{\quad ,i}{\quad} di$$

$$\int_0^{i1} \frac{L \quad ,i \ i}{\quad} di$$

$$\int_0^{i1} \frac{\sum_{k\ 0}^{m} L_k \ i \ \cos kN_r \quad i}{\quad} di$$

$$\sum_{k\ 1}^{m} kN_r \sin kN_r \quad \int_0^{i1} L_k \ i \ i \ di \tag{7}$$

Figure 2 shows the torque variation with the rotor angular position at different values of phase current. Since the inductance gradient is negative from 0° to 30° the torque is negative and the inductance gradient is positive from 30° to 60° the torque is positive.

2. Torque Control And Torque Ripple Minimization

At any time, the resultant output torque of SRM is the summation of the torque in all phases:

$$T \quad \sum_{j\ 1}^{N} T_j \tag{8}$$

where N is the number of phases, and T_j is the torque generated in phase j, which is a nonlinear function of phase current i and rotor position θ. From Figure.2, it is clear that high torque is not available near aligned/unaligned position even when high phase current

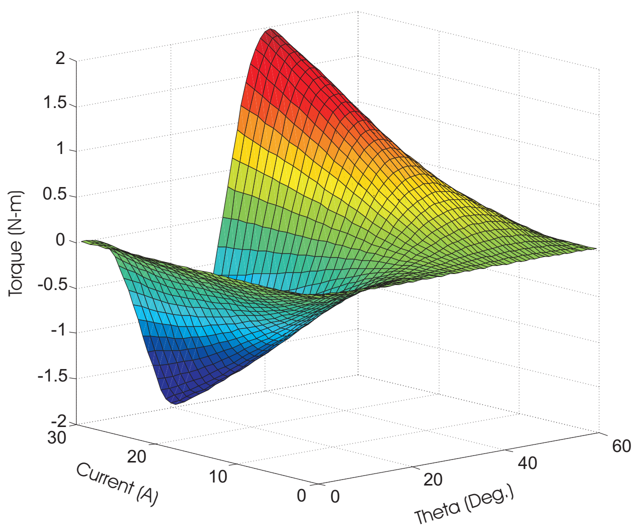

Figure 2. Variation of Torque with current and rotor position

is presented. To generate a ripple-free output torque, there must be overlapping between phases.

During phase overlapping, the current in one phase is decreasing, and that in the other phase is increasing. To obtain a constant torque, the summation of the torque generated by these currents must equal to the torque generated in non-overlapping period. To determine the desired torque produced by each phase, torque-factors are introduced, which are defined as

$$T \quad \sum_{j\ 1}^{N} T_j \quad \sum_{j\ 1}^{N} Fact_j(\quad) T_{ref} \tag{9}$$

where $Fact_j(\theta)$ is the torque factor for phase j at rotor position θ, and Tref is the reference torque.

The motor used in this work is a four phase 8/6 switched reluctance motor. To generate desired torque, the torque factor must meet the following requirements:

$$\sum_{j\ 1}^{N} Fact_j(\quad) \quad 1 \tag{10}$$

$$Fact_j(\quad) \quad Fact_j(\quad \frac{\quad}{3}) \tag{11}$$

$$Fact_j(\quad) \quad Fact_k(\quad (j \quad k) \ \frac{\quad}{12}) \tag{12}$$

For 8/6 SRM, the inductance increasing/decreasing period for each phase is $\pi/6$. The conduction angle is chosen as $\pi/8$. This means,

$$_{off} \quad _{on} \quad \frac{\quad}{8} \tag{13}$$

So the phase overlapping for each two adjacent phases is $\pi/8 - \pi/12 = \pi/24$. During phase overlapping, the total torque is distributed in the two phases according to a sine function of the rotor position. The torque factor for phase j is expressed as follows,

$$Fact_j(\theta) = \begin{cases} \frac{1}{2} - \frac{1}{2}\cos 24(\theta - \theta_{on\,j}) & for\ \theta_{on\,j} \le \theta < (\theta_{on\,j} + \frac{\pi}{24}) \\ 1 & for\ \left(\theta_{on\,j} + \frac{\pi}{24}\right) \le \theta < \left(\theta_{off\,j} - \frac{\pi}{24}\right) \\ \frac{1}{2} + \frac{1}{2}\cos 24\left(\theta - \theta_{off\,j} - \frac{\pi}{24}\right) & for\ \left(\theta_{off\,j} - \frac{\pi}{24}\right) \le \theta < \theta_{off\,j} \\ 0 & otherwise \end{cases} \tag{14}$$

The turn-on and turn-off angles (θ_{on} and θ_{off}) for phase A for forward motoring operation are chosen as -30° (or 30°) and -7.5° (or 52.5°) respectively. The turn-on and turn-off angles for the other phases can be obtained by phase shifting of a multiple of $\pi/12$.

The torque factors for all four phases in forward motoring operation are shown in Figure 3. In this Figure, the thick dotted line represents the summation of all the four torque factors which is 1 at any rotor position.

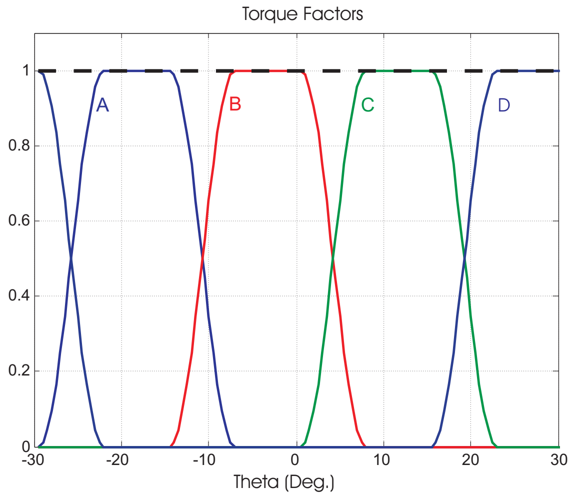

Figure 3. Torque factors for forward motoring operation

Once the torque factors are defined, the reference torque to each phase can be calculated from the motor reference torque (T_j = $Fact_j(\theta)T_{ref}$). The current required to produce the reference torque in each phase at any rotor position can be calculated from the torque expression (Eq. 7). In this work, the values of phase currents required to produce different output torque at different rotor positions are calculated and stored in the 2-D lookup tables. These lookup tables supplies the reference currents to each phase corresponding to the reference torque and rotor position. Then hysteresis current control technique is applied to maintain the phase current within an acceptable range around the reference current.

3. Simulation Results

Simulations were carried out using Matlab/Simulink® with and without torque ripple minimization method on a four phase 8/6 switched reluctance motor by using nonlinear inductance model. Figure 4 shows the Matlab/Simulink model for SRM with torque ripple minimization. The results, shown in Figure 5 – Figure 7, have been achieved using hysteresis current control for turn-on angle θ_{on} = -30°, turn-off angle θ_{off} = -7.5°, constant speed n = 500 rpm and a fixed current reference of I_{ref} = 12 A. Figure 5 shows the currents in each phase, Figure 6 shows the torques produced by each phase and Figure 7 shows the total torque produced by the motor without torque ripple minimization.

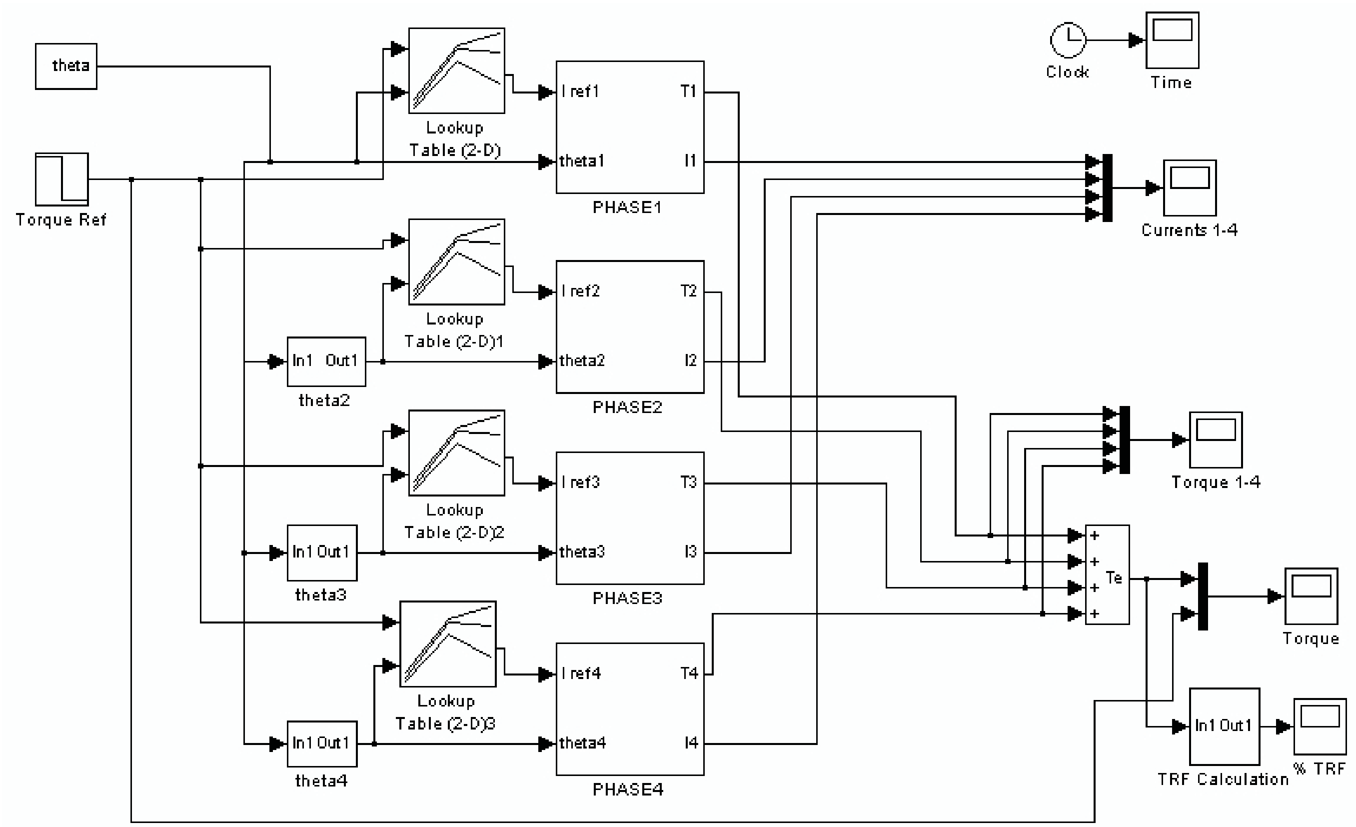

Figure 4. Matlab/Simulink model for SRM with torque ripple minimization

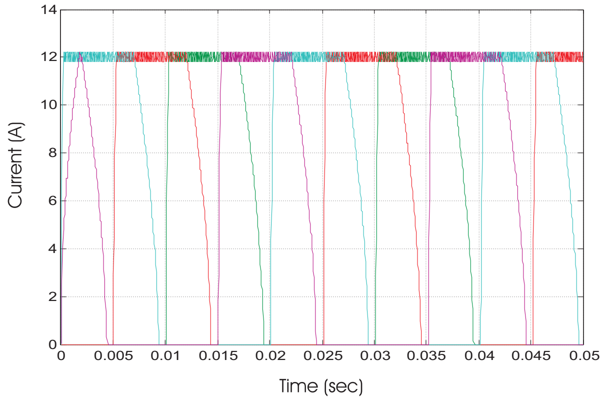

Figure 5. Currents in each phase of SRM in normal operation

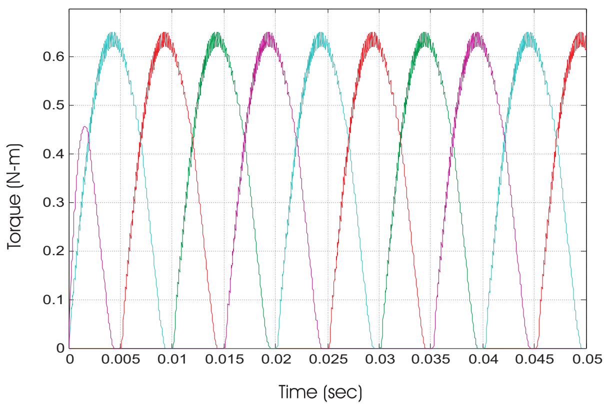

Figure 6. Torques produced by each phase of SRM in normal operation

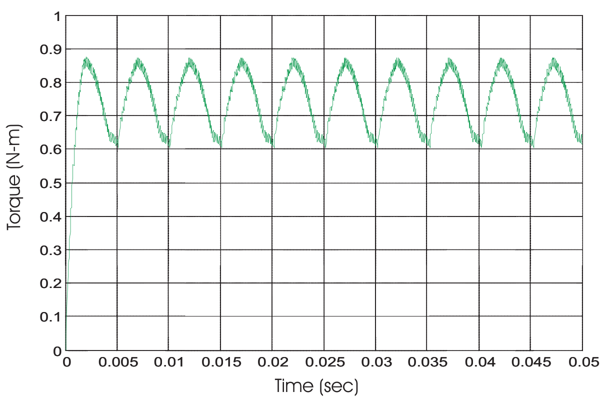

Figure 7. Total Torque produced by SRM in normal operation

Here a Torque Ripple Factor (TRF) is used to measure the ripple of the torque produced by the motor. It is defined as follows.

$$\% \, TRF = \frac{\text{RMS value of } [T(t)-T_{avg}]}{T_{avg}} \times 100$$

Without torque ripple minimization method the TRF of the motor torque is observed as 15 - 20 %.

The results, shown in Figure 8 – Figure 10, have been achieved using torque ripple minimization technique explained in this paper for the same turn-on/turn-off angles and at the same speed. Figure 8 shows the phase currents, Figure 9 shows the torques produced by each phase of SRM, and Figure 10 shows the torque produced by the motor along with the reference torque. With the implementation of the torque ripple minimization method, the TRF of the motor torque is $< 3\%$ which is acceptable in most of the applications.

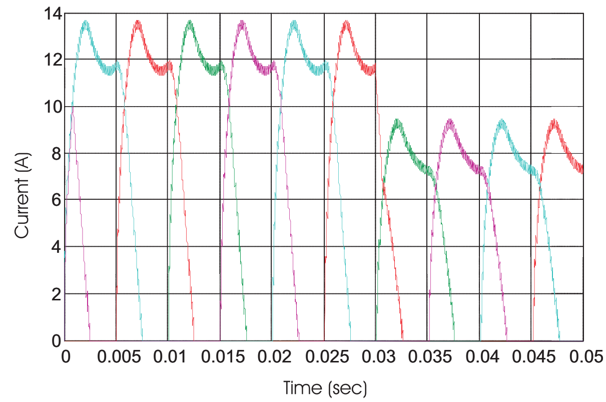

Figure 8. Currents in each phase in torque ripple minimization method

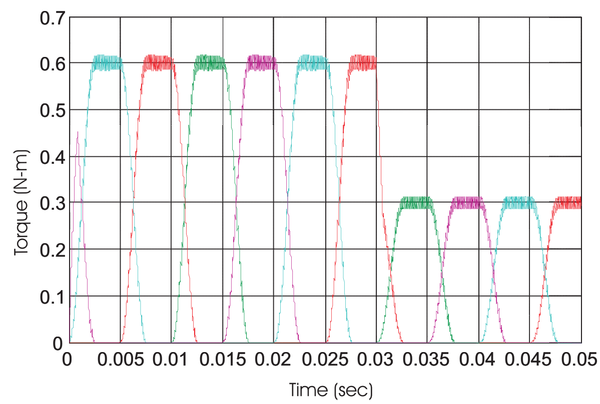

Figure 9. Torque produced by each phase in torque ripple minimization method

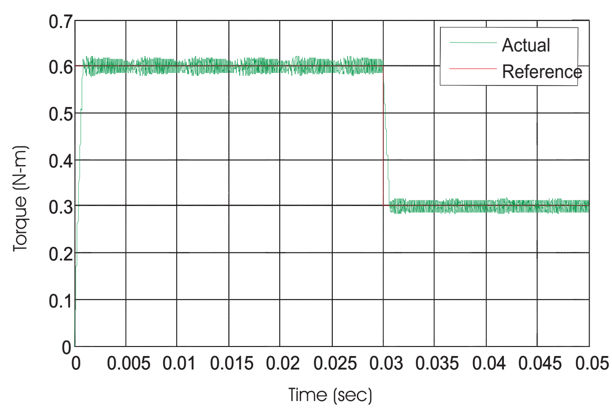

Figure 10. Total Torque produced by SRM in torque ripple minimization method

Conclusions

Switched reluctance motors have a significant torque ripple. This is not desired for several applications. To minimize the torque ripple, phase overlapping is necessary and the determination of torque generation in overlapping phases is very important. In this paper, a torque factor is defined to determine the torque required in each phase according to the rotor position and the specified turn-on/turn-off angles. Then the torque command is converted into current command according to the inductance based SRM model. Finally hysteresis current control is used to maintain the phase current around the desired value. The SRM model with torque ripple minimization technique is simulated in Matlab / Simulink environment using hysteresis current controller. The simulations show satisfactory results of the proposed method to minimize the torque ripple of the switched reluctance motor.

Appendix:

Motor Parameters

Power = 1000 W

Maximum Current = 50 A

No. of phases = 4

No. of stator poles = 8

No. of rotor poles = 6

Phase winding resistance = 0.2996 Ω

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