Various control strategies on Torque Ripple Minimization for Switched Reluctance Motor

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Abstract: A Matlab-Simulink environment used to build a model of a 6/4 Switched Reluctance Motor (SRM) to study and explore methods for minimizing the torque ripple. Various control strategies were reviewed and a simulation studies were carried out for the following control methods: Current control, Torque control, Torque and flux control, and Torque and speed control were the obtained results analyzed, evaluated, and compared to each other. The simulation results confirmed that torque ripple minimization was achieved; discussions, conclusions, and suggestions were presented in this study.

Keywords: Switched Reluctance Motor, Torque Ripple, Torque Control, Current control.

1. Introduction

Switched Reluctance Motor (SRM) has a fail-safe characteristic due to its simple structure as the rotor has no winding, own the following positive features: operation in extraordinary temperatures or in extreme temperature variations, low cost with absence of permanent magnet in the structure gaining great tolerances and robustness. The torque production in switched reluctance motor comes from the tendency of the rotor poles to align with the excited stator poles due to the variance in magnetic reluctance for magnetic field lines between aligned andunaligned rotor position [1]. Main downside of switched reluctance motor drives are torque ripple and acoustic noise as effects of the geometric doubly salient structure, concentration of excitation windings round the stator poles and the magnetic saturation operational approach to exploit the torque per mass proportion and pulsed magnetic field achieved by feeding sequentially the different stator windings. The phase current commutation is the foremost source of the torque ripple that shall be minimized through magnetic circuit design in a motor design stage [2] or by using torque control techniques [3]. In contrast to rotating field machines, torque control of switched reluctance machines is not based on model reference control theory, such as field-oriented control, but is achieved by setting control variables according to calculated or measured functions. The goals of diverse categories of control tactics proposed to control torque of switched reluctance motor are: squat torque ripple, sound decrease and achieved higher efficiency. Srinivas, P and Prasad, P V N [4] presented direct instantaneous torque control scheme realized torque ripple minimization for low speed applications. Mir, S., Elbuluk, M. E. & Husain, I [5] and Henriques, L., Rolim, L., Suemitsu, W., Costa Branco, P. J., and Dente, J. A [6] presented a novel method of controlling the motor currents to minimize the torque ripple, using a neuro-fuzzy compensator were a compensating signal is added to the output of a classical PI controller, in a current-regulated speed control loop. Baldu’i Blanqu’el, Arnau D’oria-Cerezo1, [7] presented the desired current references in order to minimize the torque ripple for a Switched Reluctance Motor. A full-order nonlinear controlled was developed using the port-controlled...
Hamiltonian (PCH) systems theory for the purpose of torque ripple reduction and characteristic improvement was presented by [8].

2. Equivalent circuit of Switched Reluctance Motor

In this study a switched reluctance motor represented by a circuit of resistance and inductance ignoring nonlinearities aspects of the system. This linear investigative model defined by the following three differential equations: the voltage equation, the motional equation and the electromagnetic torque equation depicted in equations (1-3) respectively [9] as shown in Figure 1.

\[ V = R_i + \frac{d\lambda(\theta, i)}{dt} \] \hspace{1cm} (1)

Where \( V \) is potential difference applied across phase, \( e \) is back electromagnet moto force, and \( R \) is the phase resistance. Normally, \( e \) is the function of both rotor position and phase current, and reluctance \( \lambda \) calculated from product of inductance and winding current:

\[ \lambda(\theta, i) = L(\theta, i) i \] \hspace{1cm} (2)

From equations (1) and (2) get:

\[ V = R_i + \frac{d\lambda(\theta, i)}{di} \cdot \frac{di}{dt} + \frac{d\lambda(\theta, i)}{d\theta} \cdot \frac{d\theta}{dt} \] \hspace{1cm} (3)

\[ \text{Figure 1. Equivalent circuit of SR motor} \]

To describe the stored magnetic energy \( W_f \) and the co-energy \( W_c \) nonlinear analysis of electromechanical energy conversion included saturation of the magnetic circuit as:

\[ W_f = \int i d\psi \] \hspace{1cm} (4)

\[ W_c = \int \psi di \] \hspace{1cm} (5)

The analytical solution of the current found from equation (3). The electromagnetic torque equation is:

\[ T_e = \frac{\partial W_c}{\partial \theta} = \frac{\partial W_c(\theta + \Delta \theta) - \partial W_c(\theta)}{\Delta \theta} \] \hspace{1cm} (6)

From equation (6), an analytical solution for the torque can be obtained. \( W' \) is the co-energy, which can be expressed as:

\[ W_c = \int_0^i \lambda di \] \hspace{1cm} (7)

And the motion equation is:
\[ T_e = J \frac{\partial W_e}{\partial t} + D \omega + T_L \] ........ (8)

\[ \omega = \frac{d \theta}{dt} \] ........ (9)

Where TL, Te, J, \( \omega \) and D are load torque, electromagnetic torque, rotor inertia, rotor speed and friction coefficient respectively.

3 Torque control strategies

Control of the switched reluctance motor can be done using one of the following techniques: Current control method, Torque control method, and Torque & Flux control method to control timing and width of the voltage pulses using a Hysteresis control method [10 & 11]. In method of Current control if the assessed current differs from the reference more than acceptable tolerance, the transistors of the adjustable frequency drive are turned off and on in such a way that the current will return in its tolerance band as fast as possible. In method of Torque control if the projected torque diverges from the reference more than permissible tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the torque will return in its tolerance band as fast as possible. For Torque & Flux control method if either the estimated flux or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the flux and torque will reoccurrence in their tolerance bands as fast as possible. For Torque & Speed control method if either the estimated speed or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the speed and torque will homecoming in their tolerance bands as fast as possible.

4 Simulation Results and Discussion

To investigate the success of the suggested simulation model based on Matlab and Simulink, some simulation results for various control techniques are presented and compared with each other. The following motor parameters were used to build the simulation model as: 6/4 3 phase, power rate = 60kw, stator resistance = 0.05 ohm, inertia = 0.05 Kg.m^2, friction = 0.02 N.m.s. Various control strategies were studied, the Matlab-Simulink models, and the simulation results were analyzed and discussed as follows [12 & 13]:

4.1 Current Control

In this section the block diagram model of the current control method for the specified motor was built in Simulink as shown in Figure 2.

![Figure 2. Block diagram of SRM with Current Control](image-url)
Samples of the simulation results are presented in Figure 3 shown the stator flux, stator current, rotor speed and electromagnetic torque. Figure 4 zoomed in section of the simulation results for detailed investigations which shows that the band of the torque ripple is approximately from 10 to 60 Nm when the reference torque is set to 30 Nm.

**Figure 3.** SRM performance with Current Control  
**Figure 4.** SRM performance with Current Control

### 4.2 Torque Control

In this section the block diagram model of the torque control method for the specified motor was built in Simulink as shown in Figure 5 and the torque reference value was set to 30Nm.
Samples of the simulation results are presented in Figure 6 shown the stator flux, stator current, rotor speed and electromagnetic torque. Figure 4 zoomed in section of the simulation results for detailed investigations which shows that the band of the torque ripple is approximately from 28 to 32 Nm which is in comply with torque hysteresis band. The obtained results show great reduction in the torque ripple compare to the results obtained from the current control method.
4.3 Torque and Flux Control

In this section the block diagram model of the torque and flux control method for the specified motor was built in Simulink as shown in Figure 8 and the torque reference value was set to 30 Nm when the reference torque is set to 30 Nm.

Figure 8. Block diagram of SRM with Torque and Flux Control

Samples of the simulation results are presented in Figure 9 shown the stator flux, stator current, rotor speed and electromagnetic torque. Figure 10 zoomed in section of the simulation results for detailed investigations which shows that the band of the torque ripple is approximately from 28 to 32 Nm which is in comply with torque hysteresis band. The obtained results show great reduction in the torque ripple compare to the results obtained from the current control method, but achieved small improvement compare to torque and flux method and better results expected for higher speed.

Figure 9. SRM performance with Torque and Flux Control

Figure 10. SRM performance with Torque and Flux Control
4.4 Torque and Speed Control

In this section the block diagram model of the torque and speed control method for the specified motor was built in Simulink as shown in Figure 11, the torque reference value was set to 10 Nm, and the reference speed set to 500, 1000 and 1500 with a step changes.

![Figure 11. Block diagram of SRM with Torque and Speed Control](image)

Samples of the simulation results are presented in Figure 12 shown the stator flux, stator current, rotor speed and electromagnetic torque. Figure 13 and Figure 14 zoomed in section of the simulation results for detailed investigations which shows that the band of the torque ripple is approximately from 8 to 12 Nm which is in comply with torque hysteresis band. The obtained results show that the motor successfully tracking the desired speed with good dynamic response and the torque value kept within the torque hysteresis band when the motor is excited.
Figure 12. SRM performance with Torque and Speed Control

Figure 13. SRM performance with Torque and Speed Control
5. Conclusions
In this research a computer-based Matlab-Simulink modeling was presented to supplement the teaching of modelling subjects and enhance research exploration. The modelling allows learners to see the results of analysis and the possible remedial action. The program provides a better understanding of the SRM’s dynamic behavior and remedial action without the need to perform time consuming hardware experiments, which are also expensive to set-up. In this study, the results obtained from the dynamic analysis of a 6/4 SRM may be summarized as follows:

- The torque ripple when using current control method is larger compared to other used methods.
- Using Torque control method was significantly minimized the torque ripple as the torque variation was bounded within the torque hysteresis band.
- Little improvements were achieved by using torque and flux control method in compare with the torque control method, but further improvements expected for higher speed.
- A good speed variation tracking was achieved with torque and speed control method and the torque values were maintained within the predefined band when the motor is excited.
6. References

[1] Lawrenson, P J, Stephenson, J M, Blenkinsop, P T, Corda, J, and Fulton, N N, “Variable-speed switched reluctance motor,” *Proc. IEE*, vol. 127, pages (253–265).

[2] Torkaman, H & Afjei, E, “Comparison of Three Novel Types of Two-Phase Switched Reluctance Motors using Finite Element Method Progress in Electromagnetics Research, Vol. 25, pages(151-164), 2012.

[3] Cailleux, H, Pioufle, B Le, & Multon, B, “Comparison of control strategies to minimize the torque ripple of a switched reluctance machine,” *Electric Machines and Power Systems, vol.25*, no.10, pages(1103-1118), Dec. 997.

[4] Srinivas, P and Prasad, P V N, “Torque Ripple Minimization of 4 Phase 8/6 Switched Reluctance Motor Drive with Direct Instantaneous Torque Control”, International Journal on Electrical Engineering and Informatics Volume 3, Number 4, 2011

[5] Mir, S., Elbuluk, M. E. & Husain, I, “Torque Ripple Minimization in Switched Reluctance Motors Using Adaptive Fuzzy Control”, *IEEE Trans. Ind. Appl.*, 35(2), pages (461-468), 1999.

[6] Henrique, L., Rolim, L., Suemitsu, W., Costa Branco, P. J., and Dente, J. A “Torque Ripple Minimization in a Switched Reluctance Drive by Neuro- Fuzzy compensation”, *IEEE Trans. Magn.*, 36(5), pages (3592-3594), 2000.

[7] Schramm, D S, Williams, B W, and Green, T C, "Torque ripple reduction of switched reluctance motors by phase current optimal profiling", in *Proc. IEEE PESC' 92, Vol. 2*, Toledo, Spain, pages (857-860), 1992 .

[8] Amir Rashidi, Sayed Mortaza Saghaannejad, Sayed Javad Mousavi ,"Acoustic Noise Reduction and Power Factor Correction in Switched Reluctance Motor Drives", Journal of Power Electronics, Vol. 11, No 1, pages (37-44) , January 2011.

[9] Krishnan, R, “Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications”, *CRC Press*, 2001.

[10] Miller, T J E, “Switched Reluctance Motors and Their Control,” Magna Physics Publishing, *Hillsboro, OH*, and Oxford, 1993

[11] Miller, T J E, “Optimal Design of Switched Reluctance Motors” *IEEE Transactions on Industrial Electronics, vol. 49*, no 1, pp 160-170, Feb 2002.

[12] Matlab user manual, Math works Inc., 2014.

[13] Simulink user manual, Math works Inc., 2014.