American Journal of Applied Sciences 2 (4): 791-795, 2005
ISSN 1546-9239

Estimation of Vibrations in Switched Reluctance Motor Drives

S. Balamurugan and R. Arumugam
Power System Engineering Division, College of Engineering
Guindy, Anna University, Chennai, India-600025

Abstract: This study discusses a simple algorithm for estimation and reduction of Vibrations in a Switched Reluctance Motor (SRM) using magnetic circuit simulation in MATLAB/SIMULINK Environment. A Non-linear model is developed using magnetic circuit equations, wherein non-linearity is added using a inductance profile with back EMF. Dynamic characteristic of the SRM is simulated and the same is being verified experimentally. In this simulation, both current and voltage control techniques are used to control the SRM. Fast Fourier Transform is used to analyze the electromagnetic torque in Frequency domain, which gives the mechanical and magnetic vibration frequencies and their dB magnitude. The complete simulation and experimental results are presented.

Key words: SRM, Vibration Frequency, Nonlinear-model, MATLAB/SIMULINK, Electromagnetic Torque

INTRODUCTION

The switched reluctance motor is a mechanically rugged machine, due to the simplicity of its construction and stator winding arrangement. It has the capability to run from zero speed to base speed and enter into the field-weakening region[1, 2]. The switched reluctance motor is, hence, receiving increased attention in applications where cost reduction and variable speed are required. SRM requires rotor position encoders and has a considerable amount of torque ripple, which causes vibration and acoustic noise.

The vibration in the SRM is due to the control strategies and geometric design of the motor[3-7]. The geometric design approach refers mechanical design related to vibration behavior. The stator part of SRM is particularly designed to avoid resonance frequencies and associated mode shapes excited by a harmonic magnetic force. In dynamic operating conditions control strategies are used to run the motor with reduced vibrations for a better control of the SRM, it is required to predict the vibration frequencies of the SRM at different operating conditions.

The existing literature much attention has paid to the mechanical design of stator yoke and pole shape related to vibration behavior. In this geometric design, SRM designed using Finite Element Analysis (FEA) packages has reduced resonance at the operating range of speeds due to harmonic magnetic forces[6-11]. The second is vibration is produced in the SRM due to control strategies. It found from current waveform, turn-on and turn-off times of the SRM. In this study, a new algorithm is proposed to estimate vibration produced in the SRM for different control strategies.

In this study a novel method to predict the vibration frequencies SRM from the measured electrical parameters at operating conditions. This method has been developed for the simulation and verified experimentally. In simulation method, a nonlinear model is developed in the MATLAB/SIMULINK environment using inductance profile. Dynamic characteristic of SRM is simulated and the results are verified experimentally with the developed prototype SRM. From the dynamic characteristic of the SRM, electromagnetic torque is found and it is analyzed using time domain to frequency domain analysis tool FFT. Using this tool, vibration frequencies and their magnitudes are found for the SRM in dynamic and transient operating condition. These estimated vibration frequencies for different control strategies are tabulated and compared with the experimental results.

Modeling of SRM:

Modeling Equations of SRM: MATLAB/SIMULINK model of the SRM is developed from the voltage equation of the SRM. The phase voltage equation is (1):

$$v_{ph} = r_{ph}.i_{ph} + L_{ph}\frac{di}{dt} \qquad (1)$$

Where:

v_{ph} = The voltage applied to the phase
r_{ph} = The phase resistance
i_{ph} = The phase current
$L_{ph}\frac{di}{dt}$ = The induced voltage in the self-inductances.

The induced voltage $L_{ph}\frac{di}{dt}$ is defined by the magnetic flux linkage ψ_{ph}, which is the function of the phase current i_{ph} and the rotor position θ_{ph}. So the induced voltage can be expressed as:

$$L_{ph}\frac{di}{dt}=\frac{d\psi_{ph}\left(i_{ph},\theta_{ph}\right)}{dt}=\frac{\partial\psi_{ph}\left(i_{ph},\theta_{ph}\right)}{\partial i_{ph}}.\frac{di_{ph}}{dt}+\frac{d\psi_{ph}\left(i_{ph},\theta_{ph}\right)}{\partial\theta_{ph}}.\frac{d\theta_{ph}}{dt} \qquad (2)$$

Or:

$$L_{ph}\frac{di}{dt}=\frac{\partial\psi_{ph}\left(i_{ph},\theta_{ph}\right)}{\partial i_{ph}}.\frac{di_{ph}}{dt}+\frac{d\psi_{ph}\left(i_{ph},\theta_{ph}\right)}{\partial\theta_{ph}}.\varpi \qquad (3)$$

where, ϖ is the angular speed of the motor the torque The phase equation can be expressed as:

$$v_a=r_a.i_a+\frac{\partial\psi_a\left(i_a,\theta_a\right)}{\partial i_a}.\frac{di_a}{dt}+\frac{\partial\psi_a\left(i_a,\theta_a\right)}{\partial\theta_a}.\varpi \qquad (4)$$

T_{Mph} is generated by on phase can be expressed as:

$$T_{Mph}=\int_0^{I_{ph}}\frac{\partial\psi_{ph}(i_{ph},\theta_{ph})}{\partial\theta_{ph}}di_{ph} \qquad (5)$$

(or):

$$T=\frac{1}{2}I^2\frac{dL}{d\theta}\bigg|_{I=Cons} \qquad (6)$$

The one phase model of a three phase 6/4 SRM with current loop control is shown in the Fig. 1.

Current Block: The flux linkage of SRM/phase, which includes the back emf is written as follows:

$$\psi=\int(v-ir-E_b)dt \qquad (7)$$

The current-flux linkage-rotor position characteristics of 6/4 SRM are shown in Fig. 2. The complete parameters and dimensions of the SRM are given in appendix-1. The obtained current-flux linkage-rotor position characteristics from the MAGNET6.1 are used to model the ANN for SRM model. ANN has two inputs and one output. The inputs are flux linkage and rotor position and output is current. The modeled current block using ANN is shown in Fig. 3.

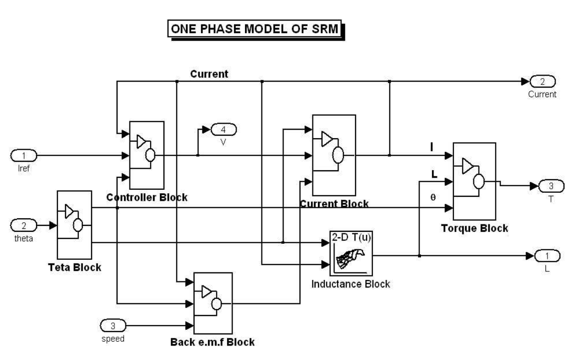

Fig. 1: One Phase Model of SRM

Rotor Position Block: The theta block is used to find the position of the rotor for a given input. The rotor position block is shown in the Fig. 4. The initially rotor position of the SRM should be defined using an initiation file that should execute before the simulation starts.

Inductance Block: Inductance profile of the SRM is obtained from the FEA and its values are tabulated. These tabulated values are used to model SRM using MATLAB/SIMULINK environment. The inductance value used in lookup table includes the non-linearity of SRM model. Inductance block of SIMULINK model is shown in Fig. 5.

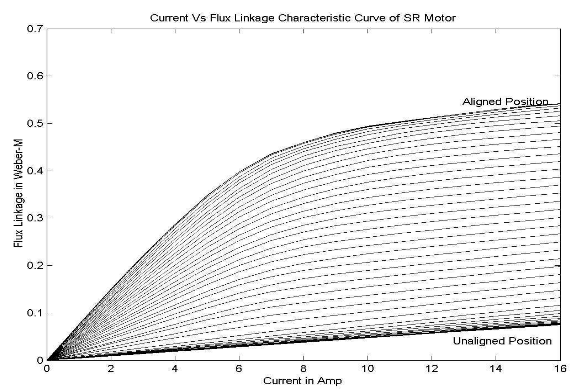

Fig. 2: Flux Linkage (Ψ)- Current (i) Characteristics of a 6/4 Pole Switched Reluctance Motor

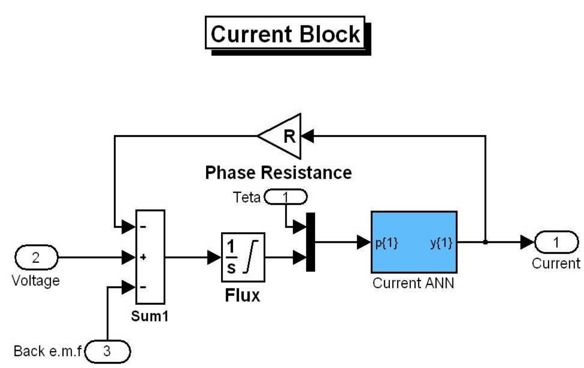

Fig. 3: Current Block

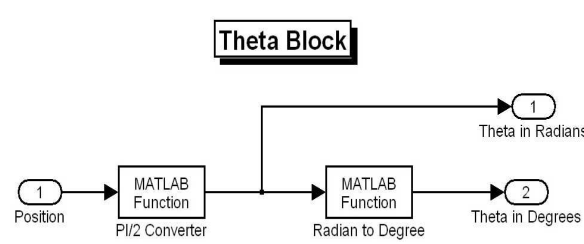

Fig. 4: Rotor Position Block

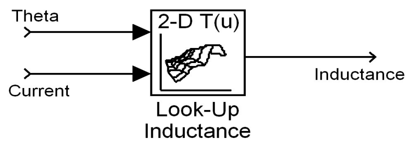

Fig. 5: Inductance Block

Torque Block: For dynamic simulation electromagnetic torque produced to be found w.r.t. time. The instantaneous torque produced on SRM can be calculated using equation (6). And it is shown in the Fig. 6.

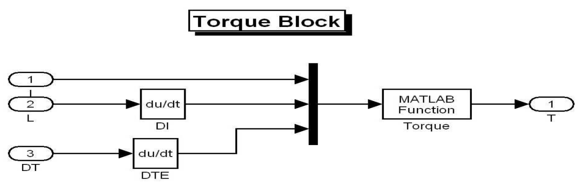

Fig. 6: Torque Block

Back e.m.f. Block: It is more important to include the back e.m.f of the motor for realistic simulation of the SRM. In this model instantaneous induced back e.m.f is found and added to the voltage equation. The significance of this study is that the effect of back emf is accounted while modeling the SRM. Figure 7 shows the e.m.f block of the motor.

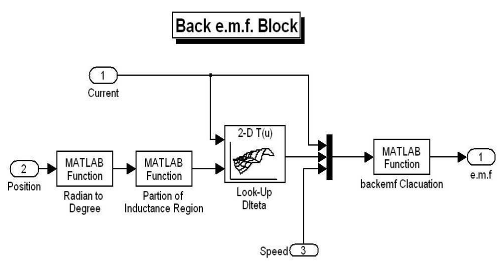

Fig. 7: Back e.m.f Block

Controller Block: SRM has got two control strategies. One is a single pulse operation or high-speed operation and another is low speed or current control. The most popular current control strategy is hysteresis current control, wherein actual phase current is allowed to vary between upper and lower bands of the set current values. The current control block is shown in Fig. 8.

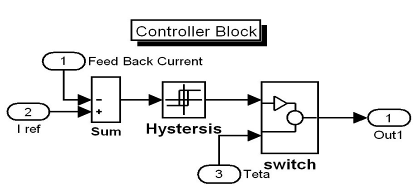

Fig. 8: Current Controller

To complete one revolution of the 6/4 pole SRM, it is required to have 12 switching. Figure 9a-d shows the inductance profile for instantaneous current, phase current, phase voltage and torque. Figure 10 shows phase current and voltage during single pulse operation during simulation and Fig. 11 shows phase current and voltage during experimentation on single pulse operation.

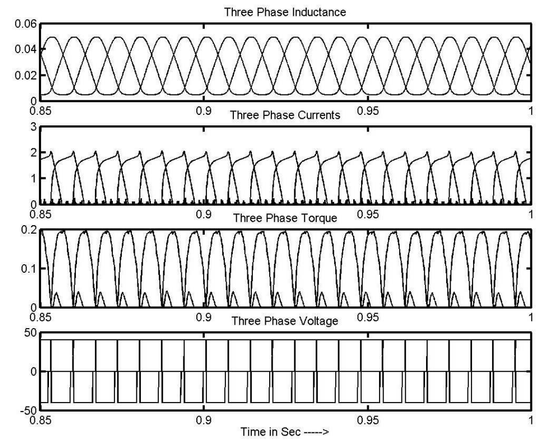

Fig. 9: Dynamic Characteristic of Sr Motor Current Control Mode (a) Inductance Profile (L (θ, I)) (b) Current (I) (c) Torque (d) Voltage

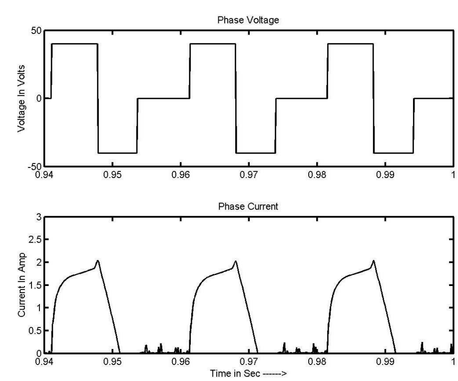

Fig. 10: Phase current and voltage of SRM

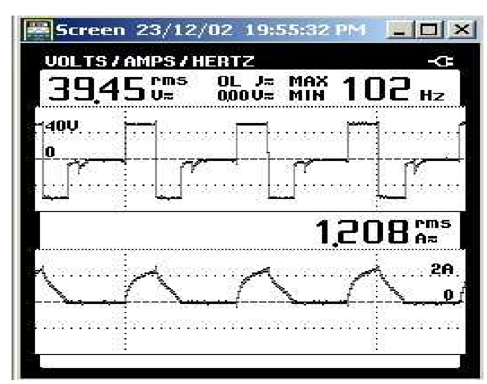

Fig. 11: Experimental Waveforms of Phase Voltage and Phase Current

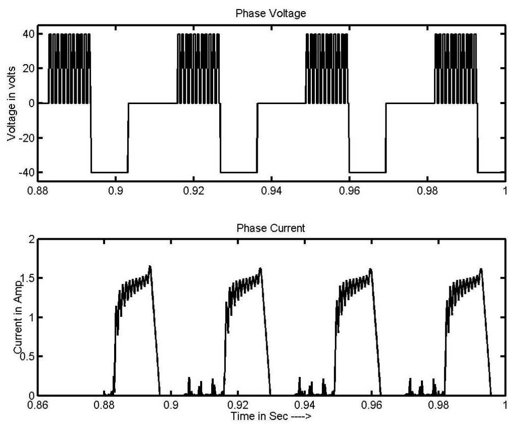

Fig. 12: Phase Current and Voltage Phase of SRM for PWM Control

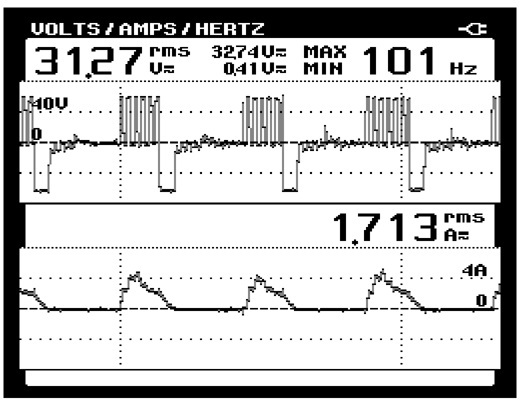

Fig. 13: Experimental Waveforms of Voltage and Phase Current for PWM Control

Figure 12 and 13 shows the input voltage is for SRM using PWM signal from simulation and experimental setup. In this control current profile is modified and vibration produced SRM is also reduced.

Estimation Vibration Frequency: Vibration frequency of the SRM is computed from electromagnetic torque produced by it. The electromagnetic torque produced by the motor is a continuous time domain variable. In order to get the vibration frequency, it is necessary to do the frequency transformation. Fourier Transform achieves the frequency transformation of the time domain variable. The Fourier transform, a pervasive and versatile tool, is used in many fields of science as a mathematical or physical tool to alter a problem into one that can be more easily solved. The Fourier transform decomposes or separates a waveform into sinusoids and coincides of different frequency. The sum of sinusoids and coincides of different frequency gives the original waveform. It identifies or distinguishes the different frequency sinusoids and their respective amplitudes. The Fourier transform is defined as:

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt \qquad (7)$$

and its inverse transform is defined as:

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(\omega)e^{j\omega t}\,dt \qquad (8)$$

for an input sequence of length of N, the DFT of a continues time signal is given by:

$$X(k) = \sum_{n=1}^{N} x(n)e^{-j2\pi(k-1)\frac{(n-1)}{N}} \quad 1 \le n \le N \qquad (9)$$

and its inverse DFT is given by:

$$x(n) = \frac{1}{N}\sum_{n=1}^{N} X(k)e^{j2\pi(k-1)\frac{(n-1)}{N}} \quad 1 \le n \le N \qquad (10)$$

If x (n) is real, we can rewrite the above equation in terms of a summation of sine and cosine functions with real coefficients:

$$x(n) = \frac{1}{N}\sum_{k=1}^{N} a(k)\cos\left(\frac{2\pi(k-1)(n-1)}{N}\right) + b(k)\sin\left(\frac{2\pi(k-1)(n-1)}{N}\right)$$

Where:

$$a(k) = \mathrm{real}(X(k)), b(k) = -\mathrm{imag}(X(k)), 1 \le n \le N$$

Modeling of FT Block: The FT block available in Simulink is used to analysis the EM torque. The FT block can accept only frame data, which is implemented through the delay line block.

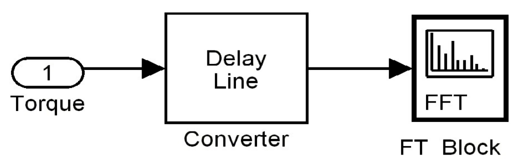

Fig. 14: FT Conversion Block

RESULTS

The vibration frequency analysis is done for the different conduction periods (θ_{ON} and θ_{OFF} period) and different loads and the results of the simulation are presented in Table 1. The vibration frequency of the SRM for the single pulse voltage setup with 1N-m load is tabulated in Table 1. The Table 2 presents the same for the PWM control of the input voltage.

This analysis is repeated for different load conditions and loop currents. The results are proportional table formed. This analysis shows that vibration of the motor is very less for the conduction period from 12-44 degrees.

Table 1: Simulation Results of Frequency Vibration Analysis of SRM for the Single Pulse Voltage Setup with 1 Nm Load

θ_{ON}-θ_{OFF} in degrees	3^{rd} order frequency magnitude in dB	5^{th} order frequency magnitude in dB	Speed in radians/ses
14-44	16	9	97
13-44	14	9	96
12-44	10	8	94
11-44	15	10	94
10-44	20	15	93
9-44 24	17	93	
5-44 26	20	97	
2-44 26	20	98	
0-44 27	20	99	
0-34 24	20	102	
0-32 24	20	106	
0-30 24	20	108	

Table 2: Simulation Results of Frequency Vibration Analysis for PWM Control of the Input Voltage

θ_{ON}-θ_{OFF} in degrees	3^{rd} order frequency magnitude in dB	5^{th} order frequency magnitude in dB	Speed in radians/ses
14-44	12	4	70
13-44	10	4	69
12-44	7	3	68
11-44	19	13	65
10-44	20	14	62
9-44 21	12	58	
5-44 22	14	60	
2-44 22	14	60	
0-44 24	16	61	
0-34 21	15	65	
0-32 19	14	68	
0-30 19	14	70	

CONCLUSION

In this study, the electromagnetic analysis of 6/4-SRM is done using MAGNET 6.12 software to obtain the current- flux linkage- rotor position characteristics. The current-flux linkage-rotor position characteristic obtained from the FEA software MAGNET6.1 is used for the SRM model using MATLAB/SIMULINK. In this study single pulse and PWM controlled operation are simulated and validated through experimentation. The comparison proves that the developed model can be universally applied to any kind of SRM. Most importantly, this study utilizes the back emf in the flux linkage equation, which was not discussed in earlier papers. From the vibration analysis of the SRM, it's understood that most optimum conduction period for reduced vibration could be achieved for single pulse and PWM control. This simple algorithm has implemented practically in DSP processor and the simulated results are verified. From this analysis the toque ripple and vibration frequency of SRM are estimated, so it is possible to get enhanced control of the motor.

REFERENCES

1. Miller, T.J.E., 1989. Brushless Permanent Magnet and Reluctance Motor Drives. Oxford University Press.
2. Krishnan, R., 2001. Switched Reluctance Motor Drives: Modelling, Simulation, Analysis, Design and Applications. CRC Press, Hardcover ISBN: 0849308380
3. Pragasen Pillay and William (Wei) Cai, 1999. An investigation into vibration in switched reluctance motor. IEEE Transactions on Industry Applications, 35: 3.
4. Cameron, D.E., J.H. Lang and S.D. Umans, 1992. The origin and reduction of acoustic noise in doubly salient variable reluctance motor. IEEE Transactions on Industry Applications, 28: 1250-1255.
5. Pragasen Pillay, R.M. Samudio Mothahar Ahmed and T.T. Patel, 1995. A chopper-controlled SRM drive for reduced acoustic noise and improved ride-through capability using super capacitors. IEEE Transactions on Industry Applications, 31: 1029-1038.
6. Chi-Yao Wu and C. Pollock, 1995. Analysis and reduction of vibration and acoustic noise in the switched reluctance motor. IEEE Transactions on Industry Applications, 31: 91-98.
7. Pragasen Pillay and William (Wei) Cai, 2001. Resonant frequencies and mode shapes of switched reluctance motors. IEEE Transactions on Energy Conversion, 16: 43-48.
8. Watanabe, S., S. Kenjo, K. Ide, F. Sato and M. Yamamoto, 1983. Natural frequencies and vibration behavior of motor stator. IEEE Transactions on Power Apparatus and Systems, PAS-102: 949-956.
9. Picod, C., M. Besbes, F. Camus and M. Gasbi, 1997. Influence of stator geometry upon vibratory behavior and electromagnetic performances of switched reluctance motors. EMD97, IEE Conf. Publi. No. 444.
10. Colby, R.S., F.M. Mottier and T.J.E. Miller, 1996. Vibration modes and acoustic noise in a four-phase switched reluctance motor. IEEE Transactions on Industry Applications, 32: 1357-1364.
11. Soares, F. and P.J. Costa Branco, 2001. Simulation of a 6/4 switched reluctance motor based on Matlab/Simulink environment. Aerospace and Electronic Systems, IEEE Transactions on, 37: 3.