International Journal of Advancements in Electronics and Electrical Engineering – IJAEEE
Volume 3: Issue 2 [ISSN 2319 – 7498]
Publication Date : 25 June 2014

Steady-State Analysis of 6/4 Switched Reluctance Motor using Matlab/Simulink Environment

Mohamed A. Aboungem [1] , Salem Ali[2], Daw M. ALZENTANI [3]

[1] *(Department, Electric and Electronic, ZAWIA University, Zawia, Libya)*

[3] *(Department, Electric and Electronic, ZAWIA University, Zawia, Libya)*

***Abstract*—This work reports on the steady-state analysis and control strategies of switched reluctance motors (SRMs). For this purpose, a theoretical background is introduced and a mathematical model is derived. A Matlab code has been written to determine the motor magnetic characteristics. The inductance profile has also been determined and from which the induced voltage constant, which is used to find the electromagnetic torque, is obtained. A low-performance voltage control strategy is applied to the motor. Simulation results are given to evaluate the overall system performance.**

***Index Terms*—switched reluctance motor, voltage control strategy.**

I. Introduction

DURING the last few years, switched reluctance motor (SRM) has been one of the active research areas in the field of electrical machines [1]. The importance of the SRM is emerged from its capability of providing a high performance level over a wide range of specifications in a reliable form. The motor has salient poles on both its stator and rotor sides. The number of pole pairs for the stator and rotor usually are unequal. The stator is assembled from silicon steel laminations with the saliencies being wound with concentric coils. Each two diametrically opposite poles are connected in series to form a phase. The rotor is built from a stack of salient pole laminations. The motor is fed via a power converter, which acts as an electronic commutator for the different phase windings. The control pulses of the power converter must be locked with the rotor position. A shaft encoder is essential for this purpose. Torque is produced by the rotor tendency to align up along a minimum reluctance position established by the alignment of a particular stator and rotor saliencies. Continuous rotation is produced by sequentially switching the stator current from one phase to the next as the rotor pole moves into alignment with each successive stator pole. The high operating performance of the SRM introduced it to find its way to the market of electrical motor drives and to become a challenge competitive for certain industrial applications. Due to its controllability, it has been employed in plotter drives, air-handler motor drives, train-air conditioning drives, and general purpose drives [2]. The high starting torque is suitable for traction and hoist applications [3]. The robust brushless construction and the good thermal features made the motor attractive for hazardous areas such as mining and petrochemical industries [4]. The main challenge of the motor performance analysis and control is the nonlinear nature of the relationships between the flux linkage and the current of each phase winding at different rotor positions. This nonlinearity makes the motor noisily with torque pulsations [5]. Several different numerical approaches have been reported in the literature for obtaining the relationship between the phase current, flux linkage and angular rotor position [6, 7], but the finite element approach was popular [8, 9, 10]. To control the SRM two common methods (voltage control and current control) are widely used [11]. With both methods, the goal is a square voltage waveform in voltage control or a square current waveform in current control. In [12] a linearized PI-current controller has been proposed. In [13] a nonlinear IMC- based current controller has also been proposed.

This work is to give a background about the switched reluctance motors SRMs and their control. For this purpose, a theoretical background is introduced and a mathematical model is derived. A Matlab code has been written to determine the motor magnetic characteristics. The inductance profile has also been determined and from which the induced voltage constant, which is used to find the electromagnetic torque, is obtained. A low-performance voltage control strategy is applied to the motor. Simulation results are given to evaluate the overall system performance.

II. Machine model

An equivalent circuit for the SRM can be derived neglecting the mutual inductance between the phases as follows. The general equation governing the flow of the stator current of one phase of an SRM can be
Written as

$$v_{ph} = iR + \frac{d\lambda}{dt} \qquad (1)$$

Where Vph is the DC bus voltage, *i* is the instantaneous phase current, R is the phase winding resistance, and λ is the flux linking the coil. The SRM is always driven into saturation to maximize the utilization of the magnetic circuit [3, 13], and hence, the flux linkage λ is a nonlinear function of stator current and rotor position.

$$\lambda = \lambda\,(i,\theta) \tag{2}$$

The stator phase voltage can be expressed as:

$$v_{ph} = iR + \frac{\partial\lambda\,(\theta,i)}{\partial i}\frac{di}{dt} + \frac{\partial\lambda\,(\theta,i)}{\partial\theta}\frac{d\theta}{dt} \tag{3}$$

By using the relation:

$$L(\theta,i)\,i = \lambda\,(\theta,i) \tag{4}$$

The voltage equation is then written as:

$$v_{ph} = iR + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{dt}\omega \tag{5}$$

In Eq. (5), the three terms in the right-hand side represent the resistive voltage drop, inductive voltage drop, and back-EMF respectively.
The general expression for instantaneous torque for the SRM can be calculated by using the co-energy as follows:

$$T_{ph}(\theta,i) = \frac{\partial W'(\theta,i)}{\partial\theta},\; i = const. \tag{6}$$

Where W' is the co-energy defined as:

$$W' = \int_0^i \lambda(\theta,i)\,di \tag{7}$$

The instantaneous torque is not constant, the total instantaneous torque of the machine is given by the sum of the individual phase torques i.e.:

$$T_{inst}(\theta,i) = \sum_{phases} T_{ph}(\theta,i) \tag{8}$$

The electromagnetic torque assuming that the inductance is varies as a function of rotor position for an assumed current is known to be:

$$T_{em} = \frac{1}{2}i^2\frac{dL(\theta,i)}{d\theta} \tag{9}$$

The average torque can be derived mathematically by integrating Eq. (8) as:

$$T_{av} = \frac{1}{T}\int_0^T T_{inst}\,dt \tag{10}$$

The average air gap power is given by:

$$P_a = T_{av} * \omega \tag{11}$$

The relationship between the electromagnetic develop torque *Tem* and the shaft torque *Tshaft* is given by (12) ,that is,

$$T_{shaft} = T_{em} - J_{motor}\frac{d\omega}{dt} - T_{fri} \tag{12}$$

where *Jmotor* is the motor inertia, ω is the angular mechanical speed, and *Tfri* is the frictional losses.
The simple general load model used in this paper is given by (13), that is,

$$T_{load} = J_{load}\frac{d\omega}{dt} + c\omega^2 + b\omega + \tau_{static} \tag{13}$$

where b and c are constants.
By equating (12) and (13) a mechanical model of the SRM is derived,

$$T_{em} = J_{total}\frac{d\omega}{dt} + c\omega^2 + b\omega + T_{fri} + \tau_{static} \tag{14}$$

Where J_{total} is the load and motor inertias.

III. ASYMMETRICAL H-BRIDGE CONVERTER

Since the torque produced in the SRM is independent of the direction of current flow in each motor phase. This means the inverter is only required to supply unidirectional currents into the stator windings. One of the major circuit topologies that have been widely used for SRM drives, known as two-switch per phase inverter type [1], or asymmetric half-bridge (H-bridge), is shown in Figure (1) [2, 3, 4, 5,11]. This circuit is used successfully in SRM drives and has the advantage of allowing full reverse voltage across the windings.
As indicated in the Figure, this inverter type uses two switches devices and two fast recovery diodes per phase, hence three modes of operation are possible in this circuit.

A. Mode 1, Positive Phase Voltage

A positive phase voltage can be applied by turning both switching devices on (S11 and S12 in Figure (1.1)). This will cause the current to increase in the phase winding.

B. Mode 2, Zero Phase Voltage

A zero voltage loop can be imposed on the motor phases when either of the switches is turned-off while current is flowing through the phase winding. This results in current flow through a freewheeling loop consisting of one switching device and one diode (S12 and D12 in Figure (1.2), with no energy being supplied by, or returned to, the DC supply. The current will decay slowly due to the small resistance of the semiconductors and connections.

C. Mode 3, Negative Phase Voltage

When both switching devices in a motor phase leg are turned-off, the third mode of operation occurs. In this mode, the motor phase current will transfer to both of the freewheeling diodes (D11 and D12 in Figure (1.3)) and return energy to the supply. When both of the diodes in the circuit are conducting, a negative voltage with amplitude equal to the DC supply voltage level is imposed on the phase windings

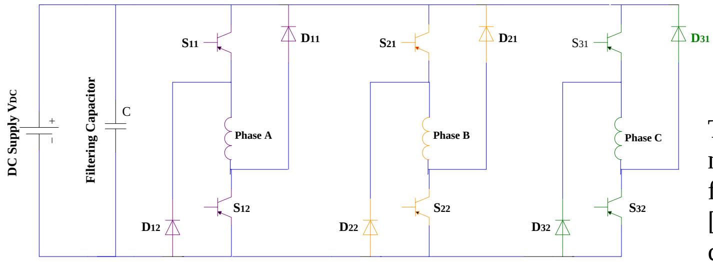

Figure (1) Half-bridge inverter topology for three-phase SRM

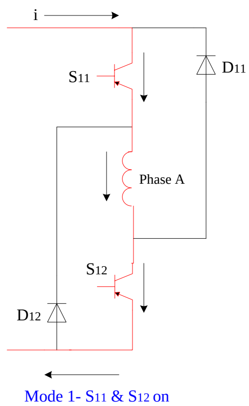

Figure (1.1) Half-bridge first mode (Fluxing)

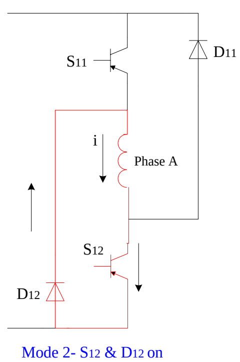

Figure (1.2) Half-bridge inverter second mode

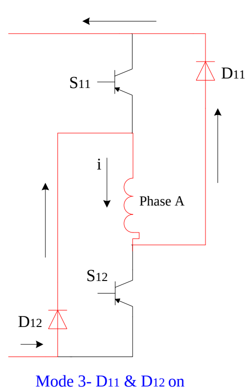

Figure (1.3) Half-bridge inverter third mode

IV. MAGNETIC CHARACTERISTICS

To control the motor, it is always important to study its magnetic characteristic. In the presented work, the motor's flux linkages are studied in a similar way to that of reference [2]. A matlab file has been developed to find the flux linkage curves versus current versus rotor position. The inductance profile for the aligned, intermediate and fully aligned positions has also been determined using another algorithm.

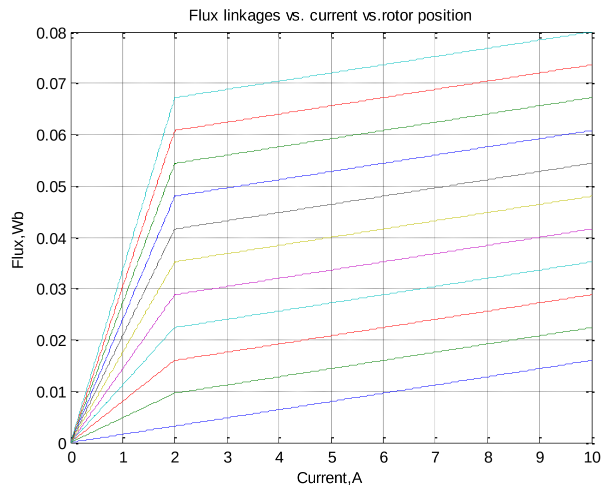

Figure (2) flux linkage vs current vs rotor position

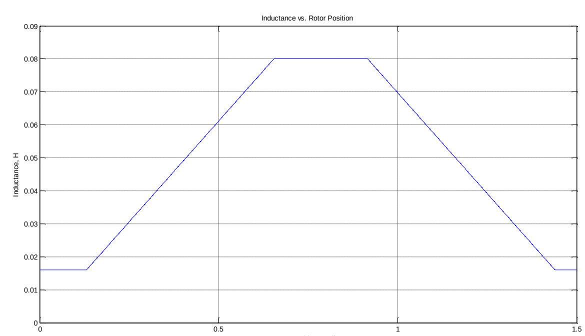

Figure (3) inductance profile vs rotor position

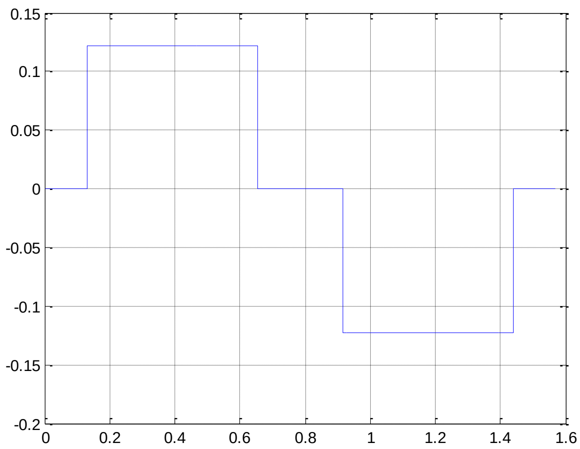

Figure (4) the emf constant, kb

V. VOLTAGE CONTROL STRATEGY

In voltage control strategy, the amplitude is simply controlled by a fixed duty cycle d, having a number larger than zero in the magnetization period. The duty cycle is kept constant during the magnetization period until the turn-off angle is reached, after which the phase is rapidly demagnetized by the application of full negative voltage. If the duty cycle is unity in the whole conduction period, a special case is entered, which is called single-pulse mode of operation [3, 5, 15, 16]. Thus, three parameters, turn-on angle, turn-off angle, and duty cycle characterize voltage control waveform.

VI. SYSTEM DESCRIPTION AND OPERATION

Figure (5) shows the basic control structure for the system under study. The input to the control structure is a speed reference ωref, which is the desired speed. The speed error is then the difference between the actual speed and the reference speed. The speed error signal is used in the speed controller, which is for instance is PI-controller. The constants for this controller are found in a similar manner to the homework assignments. i.e. by try and error. After some playing, kp has found to be 10 while Ki is found to be 100.

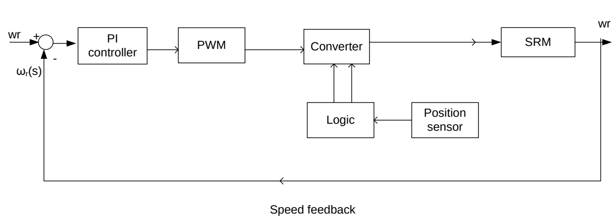

Figure (5) SRM basic control structure

At the begging the inductance pattern is found. Figure (3) shows that profile. As shown, from zero to pi/2, we have five regions, which are 0.1309, 0.6545; 0.9163; 1.4398; and pi/2. As I have not used position sensor in my simulations, those figures are of great importance. Then, after getting the inductance profile, this pattern has been differentiated to get the back emf constant (equation 5), which is the differentiation of the inductance with respect to the rotor position. This constant will be utilized later to find the developed torque and also the current feedback. Absolutely, look up tables have been used for both the inductance profile and the back emf constant for the three phases. Now, for motoring operation the voltage pulses should be applied in the rising inductance period and the application of the negative voltage should be in the period when the slope becomes negative. This is done to forbid any negative or (generating) torque. In this simulation, for instance, the rising inductance period starts at 0.6545 and ends at 0.9163 radians. After playing with some figures, I started applying the voltage at 0.2 and stopped at 0.5. An algorithm has been developed to do this. By knowing the voltage, the inductance profile, and the back emf constant, equation 5 can be used to determine the phase current. By knowing the phase current and the emf constant, the developed torque can also be found, equation 9.

For high speeds of operation, the PWM chopping is no longer possible since the back emf reaches the dc bus voltage in very short time. Hence, the single pulse mode is widely used. In this mode we apply full voltage in the rising inductance period and sometimes even in advance to the rising inductance period. Moreover, the dwell angle (the difference between on and off periods) has to be reduced to forbid the induced voltage from exceeding the bus voltage. For this part I only generated the single pulse voltage waveform and hopefully I could do this as a future work.

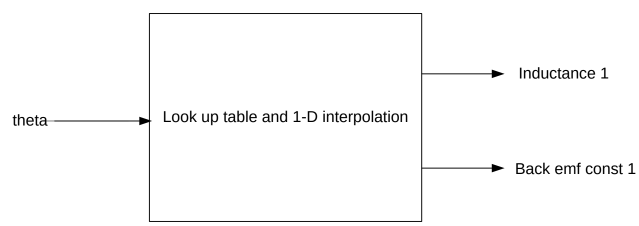

Figure (6) subsystem 1

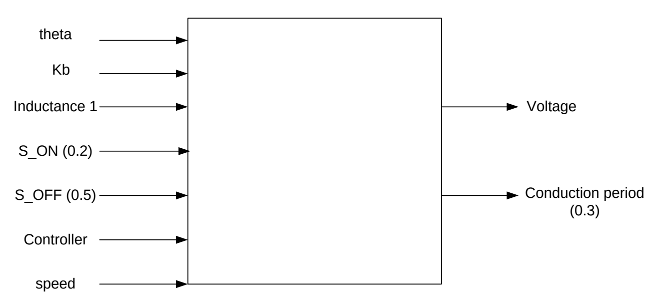

Figure (7) subsystem 2

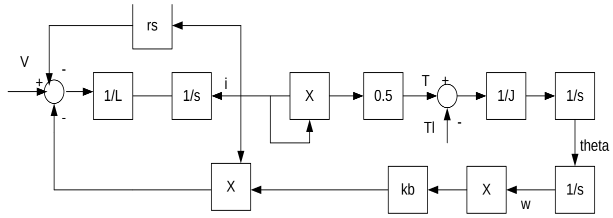

Figure (8) subsystem 3

VII. DISCUSSION OF RESULTS

Figures 9 and 10 show the phase A current and torque. As can be seen the ripple in torque is high and this is one of the major disadvantages of the SRMs. This ripple leads to acoustic noise, which is the other drawback of such machines. Many algorithms have been proposed in the literature to trim down the torque ripple and most of them are mainly dealt with the switching strategies. As can be seen from the current waveforms, the current is maintained constant due to the chopping strategy, so that it is kept constant by controlling the hysteresis band. Figures 11 and 12 showed the chopped voltage applied to the motor phase A. The continuous inductance pattern as well as the rotor position versus time is given in figures 13 and 14, respectively.

VIII. CONCLUDING REMARKS

This paper has discussed the performance analysis of switched reluctance motors. It started with a background about that subject. Voltage control strategy has been shortly discussed in section V. A 6/4 three phase SRM with rotor pole arc of 45 and stator pole arc of 30 degrees has been used in the presented work. The inductance pattern as well as the flux linkage family curves, both for different rotor positions, is determined. Motor performance under voltage control strategy has been studied. Some basic ideas about switching strategies has also been introduced and discussed.

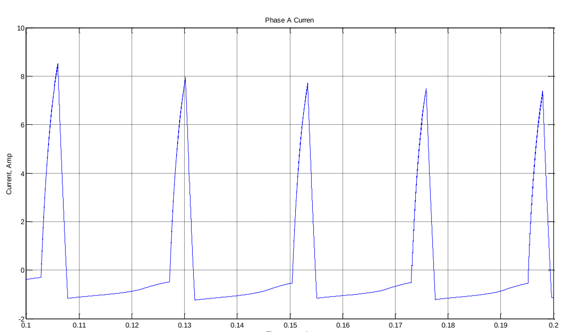

Figure (9) Phase A current

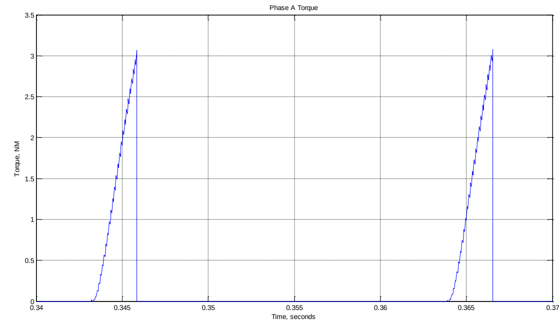

Figure (10) Phase A torque

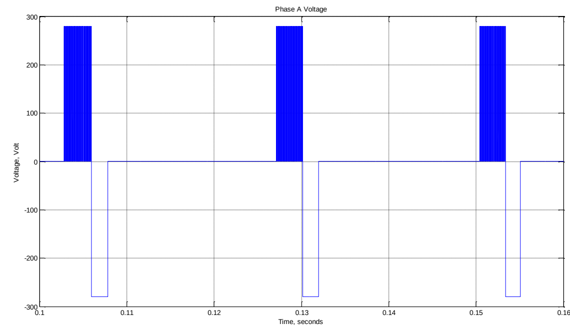

Figure (11) Phase A voltage

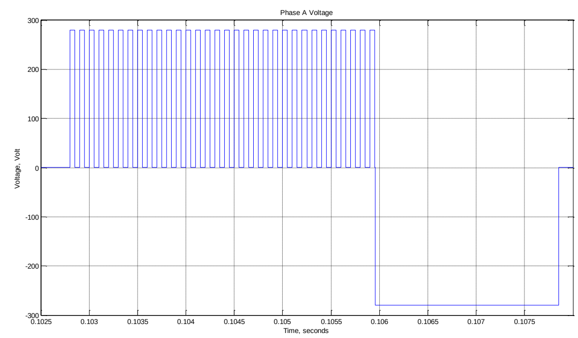

Figure (12) Phase A voltage (zoomed)

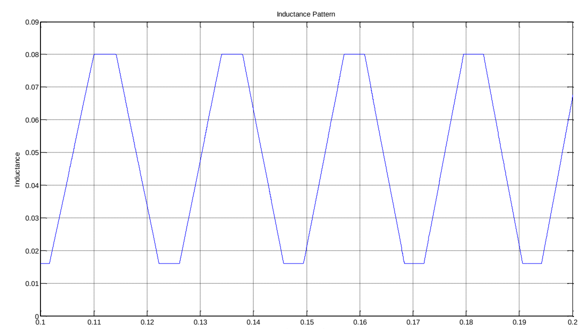

Figure (13) Phase A inductance

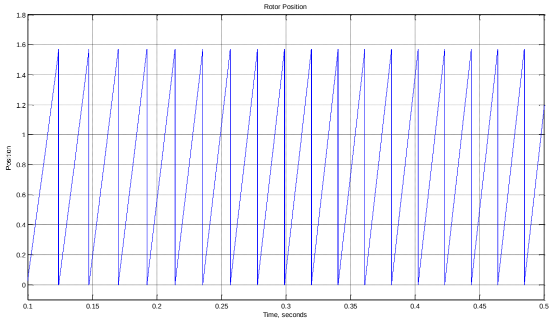

Figure (14) rotor position

IX. REFERENCE

[1] M. Mansour "On the control of SRMs" MSc. Thesis submitted to the Univesity of Manoufiya, Egypt, 2006.

[2] Ramu Krishnan "Switched Reluctance Motor Drives-Modeling, Simulation, Analysis, and Applications" Industrial Electronic Series, Library of Congress, ISBN 0-8493-0838-0, 2001.

[3] M.M. Khater et al "Dynamic Performance of Four pole/phase 12/8 SRM" Engineering Research Bulletin, Vol. 23, No. 1, pp. 213-228, ISSN 1110-1180 Minufiya University, Faculty of Engineering, Egypt.

[4] Shaker et al. " Characteristics Study of Switched Reluctance Motor Using Different Controllers" Engineering Research Journal ERJ, Vol. 29, No. 3, pp. 189-197, July 2006, Minufiya University, Faculty of Engineering, Egypt.

[5] Shaker et al. "Performance Study of Switched Reluctance Motor Using Different Modes of Control" proceedings of 5th International Engineering Conference, 5th IEC, Vol. 3, pp. 19-27, Al-Mansoura-Sharm-El_sheikh, Egypt, March 2006.

[6] A. Omekanda, and M. Renglet " Calculation of the Electromagnetic Parameters of a Switched Reluctance Motor using an Improved FEA-BIEM- Application to Different Models for the Torque Calculation" IEEE trans. on Indus. Applications, Vol. 33, No. 4, July/Aug. 1997.

[7] P.Shin, P. Otaduy, J. Mckeever, and D. Adams "Interactive Design and Analysis Program for Switched Reluctance Motor using an Analytical Method" Korean Research Foundation 2000.

[8] J. Rizk, M. Nagrial, and A. Hellany "Design Optimization of Switched Reluctance Motors" technical paper, Institution of Engineers, Australia 2003.

[9] R. Arumugam et al "Magnetic Field Analysis of a Switched Reluctance Motor Using a 2D Finite Element Method" IEEE trans. on magn., Vol. 21, Sep 1985.

[10] J. Lindsay, R. Arumugam, and R. Krishnan "Finite Element Analysis Characterization of a Switched Reluctance Motor with Multitooth per Stator Pole" IEE, proc., Vol. 133, Nov. 1986.

[11] P. Omand "Design and Advanced Control of Switched Reluctance Motors" PhD dissertation, Aalborg University, 2001.

[12] C. Roux. et al. " on the Use of a Simplified Model foe SRM's" IEEE trans. on Energy Conversion, Vol. 17, No. 3, Sep. 2002.

[13] S. K. Shaoo et al. " Iterative Learning-Based High-Performance Current Controller for SRM's" IEEE trans. on Energy Conversion, Vol. 19, No. 3, Sep. 2004.