Performance analysis of Switched Reluctance Motor using Linear Model

M. Venkatesh, Rama Krishna Raghutu
Dept. of Electrical & Electronics Engineering, GMRIT, RAJAM
E-mail: venkateshmudadla@gmail.com , ramakrishnaree@gmail.com

Abstract- The switched reluctance motor (SRM) drive demands that the motor and converter to be considered as one unit. The SRM motor has double salient structure makes its magnetic characteristics highly nonlinear. This paper we consider linear characteristics for analysis of SRM. The motor flux linkage appears to be a nonlinear function of stator currents as well as rotor position. This paper deals we are using different control parameters and H-bridge asymmetric converter topology of switched reluctance motor for observing its performance. These Control parameters and its H-bridge asymmetric converter topology are obtained by using linear model and dynamic behaviour of SRM are observed. Simulations are done in MATLAB and results are analysed.

*****

[I]. INTRODUCTION

The switched reluctance motor is basically a stepper motor and has many applications as both rotary and linear steppers. In an SRM, only the stator presents windings, while the rotor is made of steel laminations without conductors or permanent magnets. Its simple structure greatly reduces its cost. Because of this mechanical simplicity together with the recent advances in the power electronics components, much research has being developed in the last decade. The SRM, when compared with the ac and dc machines, shows two main advantages. i)It is a very reliable machine since each phase is largely independent physically, magnetically, and electrically from the other machine phases. ii) It can achieve very high speeds (20000—50000 rev/m) because of the lack of conductors or magnets on the rotor.

The idea of using the SR configuration in a continuous mode with power semiconductor control is due primarily to Nasar[1] in the 1960. In those times, only thyristor power semiconductors were available for the relatively high-current, high-voltage type of control needed for SR machines, after the invention of power transistors, GTOs, IGBTs, and power MOSFETs the application SRM drives are popular in applications such as aerospace, automotive, domestic appliance. Manufacturing industries etc. The major advantages of SRMs are high torque output, wide range of operating speed, simple structure and fault tolerance. The SRM has very simple, cost effective construction, but determining its performances is difficult because of highly nonlinear relationship between the torque and excitation current. Because of its nonlinear magnetic characteristics and the doubly salient pole structure, the finite element analysis approach[2] is often adopted for obtaining its accurate magnetic characteristics.

The performances of SRM drive strongly depend on control topology. The total drive consists of signal processing, power converter and motor. These must be designed as a single unit for the specific application. Here, the model given in is used for the control of SRM. The emphasis of many researches has been on SRM control [3], converter topologies and ratings [4], design of motor[5]. The most significant problems encountered in the design of converters for SRMs are: i) The high level of energy involved in the commutation of the motor phase currents, ii) the difficulty of closed control of the motor phase currents. These problems are due to that motor inductances are high and their values are varying in a wide range with the rotor position.

In this paper we investigate the control of the switched reluctance motor with the motor's structure properties, model equations, operation principle, and power converter topology. The converters feeding of SRMs are usually simple than inverters feeding ac motors because only unidirectional currents are required. Most of the converters uses only one switch per phase and the power switches operate independently so that shoot-through fault can be avoided. In this paper we assumes that (i) linear model of the motor (ii)the magnetic field distribution is sinusoidal, rotor position θ, the saliency shape is such that no harmonics of the fundamental frequency are present (iii) neglects the mutual inductance due to coupling between phases.

[II]. SRM CHARACTERISTICS

In SRM, motion is produced because of the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, producing a single magnetic field, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. When a rotor pole is aligned with a stator pole, as shown in Fig. 1, there is no torque because field lines are orthogonal to the surfaces (considering a small gap). In this position, the inductance is maximal since reluctance is minimum. Once rotor displaces its position, there will be torque products that will trends to bring back the rotor toward the aligned position. If current is injected in the phase when in the unaligned position, as shown in Fig. 2, there will not be torque production. If the rotor displaces from the unaligned position, then a torque tends to displace the rotor toward the next aligned position.

The instantaneous voltage across the terminals of a phase of an SR motor winding is related to the flux linked in the winding by Faraday's law as

$$V = Ri + \frac{d\Psi}{dt}$$

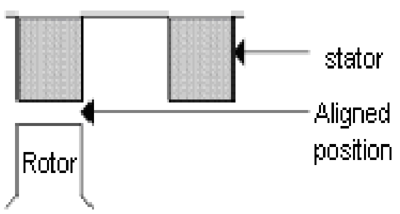


Fig.1 Aligned position

ISSN: 2321-8169
1841 – 1846

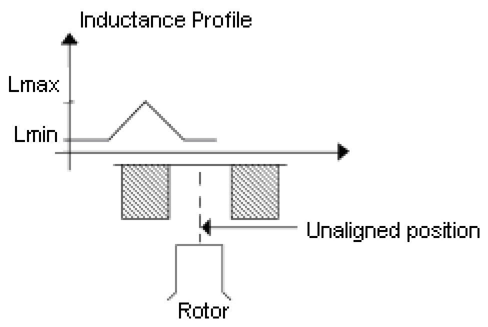


Fig.2 Unaligned position

Where V is the terminal voltage, I is the phase current, R is the phase winding resistance, and ψ is the flux linked by the winding. Because of the double salience construction of the SR motor and the magnetic saturation effects, the flux linked in an SRM phase varies as a function of rotor position θ and the phase current. Therefore above Equation can be written as

$$V = RI + \frac{\partial\Psi}{\partial I}\frac{dI}{dt} + \frac{\partial\Psi}{\partial\theta}\frac{d\theta}{dt}$$

where ∂ψ=∂I is defined as L(θ, I), the instantaneous inductance, and term (∂ψ=∂θ)(dθ=dt) is the instantaneous back electromotive force (EMF).

The SRM can be described by a convex function that only depends on rotor position and currents in the n phases

I = (I1, I2, : : : , In)'.

This function is the co-energy W(I,θ). In a similar manner, the function energy W(ψ,θ), whose variables are the fluxes of n phases ψ= (ψ_1,ψ_2, : : : ,ψ_n)' and the rotor position, also permits to describe the SRM. Whatever the vectors ψ and I are, the functions of co-energy and energy, verify the following inequality:

$$W(I,\theta) + W(\Psi,\theta) \geq \Psi^t I$$

Due to its double saliency, the SRM can have a variation of the magnetic energy and therefore torque production. The partial derivative of the energy function in relation to the rotor position gives the machine torque Γ:

$$\Gamma(\Psi_1, \dots, \Psi_n, \theta) = \frac{\partial W}{\partial\theta}(\Psi_1, \dots, \Psi_n, \theta)$$

Applying this relation to the 6/4 SRM, one has

$$\Gamma(\Psi_1, \Psi_2, \Psi_3, \theta) = \frac{\partial W}{\partial\theta}(\Psi_1, \Psi_2, \Psi_3, \theta)$$

When one phase is energizes, the torque appears so that the rotor evolves in the direction where the inductance increases. Therefore, the torque will be in the direction of the nearest aligned position.

Flux-Linkage Characteristics:

The double saliency structure of the SRM causes its highly nonlinear motor characteristics, which reflects completely on the flux-linkage characteristics of the motor. The relationship between the electrical torque and the stator currents of the SRM appears to be more complex, compared with the other types of motors. The generated electrical torque can be approximated by a high order polynomial of the stator currents with an order equal to or larger than two. In the linear flux region, the electrical torque is not a linear function of the stator current. For studying the motor's magnetic property it is essential for proper control of SRM.

Properties of the Flux-Linkage Characteristics of SRM:

If both the stator and rotor poles are symmetrically distributed, it is easy to find that the flux-linkage Ψ has following properties:

a) The flux-linkages Ψ of the SRM is a function of both the stator current i (phase A) and rotor position θ.
b) For fixed rotor position θ, the flux-linkage Ψ is purely a linear function of the stator current only under the case when there is no saturation effect. Generally, when the stator current is under certain value (in the linear flux region), the relationship between Ψ and i appears to be linear. As the stator current i increases, saturation occurs, which means Ψ is no longer a linear function of i. The larger i is, the heavier the saturating effect.
c) For fixed stator current i, Ψ is a periodic function of rotor position θ with periodic equals.
d) If the magnetic characteristics is plotted as shown in Fig. 6, the flux-linkage Ψ is always bounded between the aligned and unaligned positions. For the same i, Ψ is symmetric with respect to both the aligned and unaligned position.
e) For the same larger i, the saturation level differs considerably for distinct for position θ. The closer to the aligned position, the sharper the saturation effect becomes.

[III]. SRM LINEAR MODEL

To establish a linear model of switched reluctance machine, L(θ) is defined first. As shown in Fig.1, L(θ) is even symmetric to θ = 0°. Fig. 3 shows L(θ) for phase A. Each phase inductance displaced by an angle θ_s given by

$$\theta_s = 2\pi\left(\frac{1}{N_r} - \frac{1}{N_s}\right) \qquad (1)$$

where N_r and N_s are the number of rotor and stator poles, respectively. When the motor has equal rotor and stator pole arcs, $\beta_r = \beta_s$, one has the following angle relations

$$\theta_x = \left(\frac{\pi}{N_r} - \beta_r\right), \qquad \theta_y = \frac{\pi}{N_r} \qquad (2)$$

The electrical equation of phase A is given by

$$\frac{d\Psi_i(\theta, I)}{dt} + RI = V \qquad (3)$$

While excluding saturation and mutual inductance effects, the flux in phase A is given by the linear equation

$$\Psi(\theta, I) = L(\theta)\, I \qquad (4)$$

The total energy associated with the three phases (n = 3) is given by

$$W_{total} = \frac{1}{2}\sum_{i=1}^{3} L(\theta + (n - i - 1)\theta_s)I_i^2 \quad (5)$$

and total torque by

$$\Gamma = \frac{1}{2}\sum_{i=1}^{3} \frac{dL(\theta + (n - i - 1)\theta_s}{d\theta} I_i^2 \quad (6)$$

The mechanical equations are

$$J\frac{d\omega}{dt} = \Gamma - \Gamma_l - f\omega \quad (7)$$

$$\frac{d\theta}{dt} = \omega \quad (8)$$

where Γ_l represents the torque load, and f the machine friction coefficient.

The basic circuit shown in Fig.4 is approximate equivalent circuit of the SRM. V(t) is the voltage source, R is the phase resistance, L(θ) is the instantaneous inductance, and e(t) is the instantaneous back emf.

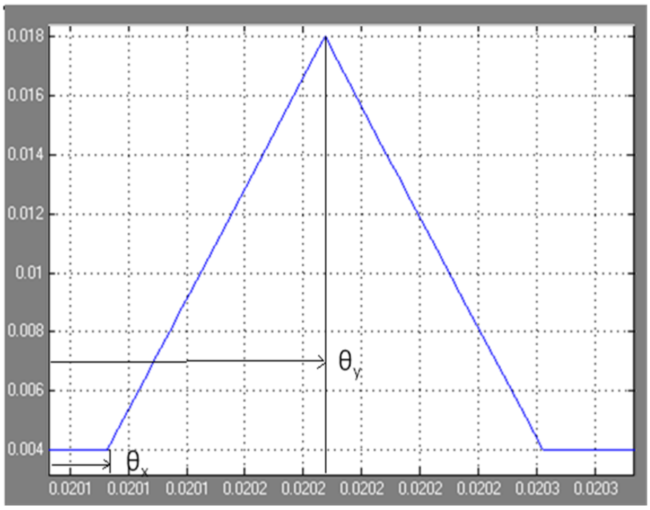


Fig3. SRM linear model inductance profile of phase A

The simulation is performed for three stages because of switching the SRM in three regions. All parameters of a function of rotor position is converted to parameters of a function time (from θ domain to t domain) by using the equation

$$t = \frac{\theta}{\omega}\left(\frac{rad}{rad/sec}\right) \quad (9)$$

Inductance profile for phase A is drawn with time domain. Also switching rotor position angles are converted into time domain by using follow equations.

$$\theta_x \rightarrow t_x \Rightarrow t_x = \frac{\theta_x}{\omega}$$

$$\theta_y \rightarrow t_y \Rightarrow t_y = \frac{\theta_y}{\omega} \quad (10)$$

$$\mathrm{K} = \omega\frac{\mathrm{dL}}{\mathrm{d\theta}} \quad (11)$$

After conversion, the new circuit model derived is shown in Fig. 5. In this circuit, e(t) is the e.m.f. of the SRM and it is modelled as a current-controlled voltage source.

The simulation is performed for three stages and explanation is given only for stage I, here (for region I of the switching SRM).

Stage 1. The control takes place by applying the voltage source V(t) to a phase coil at turn-on angle θ_{on} (turn-on time t_{on}) until a turn-off angle θ_{off} (turn-off time t_{off}). All initial values are zero.

Stage 2. and Stage 3. (for region II and III): For the stage 2, voltage source's value is changed. Its value is equal – V. For the stage 3, voltage source's value is equal zero. Similar equations are derived for regions II and III by using the same circuit.

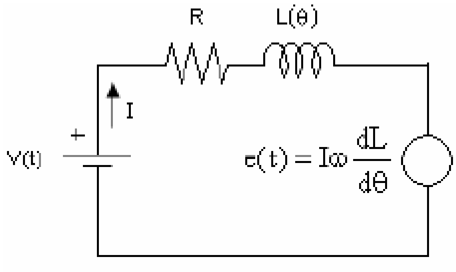


Fig.4 The basic circuit of SRM

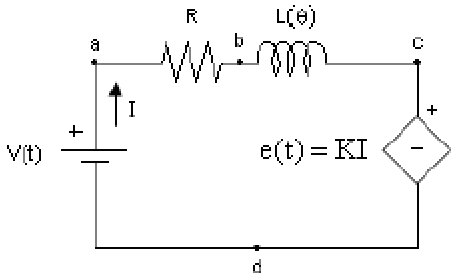


Fig.5 The equivalent circuit model of SRM

[IV]. CONTROL OF THE SWITCHED RELUCTANCE

It's quite convenient if the SRM is operated completely in the linear region of its flux-linkage characteristics chart. According to the flux-linkage chart of the SRM shown in Fig. 6, if the stator currents are small enough, this linear region operation can be guaranteed.

This work will focus on a four phase 8/6 SRM which is operated completely in its linear flux region.

A. Model in the Linear Flux Region

In this paper, the control of SRM will be done under the following assumptions:

1. No Saturation Effect

This assumption implies two cases. The first one is an ideal case. Means the SRM is designed to be free from saturation effect. Another case is that the motor is running completely in the linear flux region, where the stator currents are not large enough to cause saturation. This assumption

 ISSN: 2321-8169
1841 – 1846

makes the flux a linear function of the stator current for any fixed rotor position.

2. Mutual inductances are ideally zero due to symmetric stator excitation. The torque equation will be greatly simplified if the mutual inductances are zero, for the contribution of the mutual inductances to the system energy exchange will be zero too.

3. The magnetic field distribution is sinusoidal with the rotor position θ.

4. The saliency shape is such that no harmonics of the fundamental frequency are present for the inductance per phase. This assumption simplifies the torque equation. At the same time, it makes the controller much simple for real-time implement.

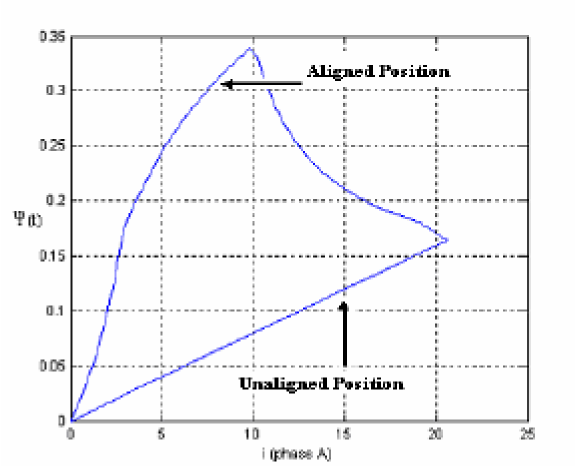


Fig.6 Flux-linkage characteristics of SRM

B. Power Converter Topology

Phase-to-phase switching in the SRM drive must be precisely timed with rotor position to obtain smooth rotation and the optimal torque output. Rotor position feedback, so-called "sensorless" feedback method, is needed for proper control. This phase-to phase switching is realized by power semiconductors. The power converter topology refers to different circuit structures by power semiconductors, which can meet the SRM's switching operation mode requirement. The power converter topology has great influence on the SRMs performance. There are two main classes: independent and dependent structure, according to the criterion whether it makes the control between the successive excited phases independent or not. In most cases, the dependent structure topology needs less power semiconductors than the independent structures. Also, another key difference between them is that they have different dwell angle requirements. particularly for the dependent structures, there are certain limitations on the dwell angles for proper motor control. These limitations directly affect the commutation strategy, which is the main reason why the converter topology has considerable influence on the SRMs performance. SRM converters differ from each other by the feeding scheme and by the energy recovery technique used during commutation from one phase to the next.

[V]. CONVERTER TOPOLOGIES

There are several possible configurations to energize a switched reluctance machine and these different energizing structures distinguish themselves by their number of semiconductors and passive components. They also depend on the number of phases and the way of which the stator coils are connected. The maximum control and flexibility is obtained, with the H-bridge asymmetric type converter shown in Fig. 7. Each phase has two IGBTS and two diodes. The number of semiconductors is the same that for an inverter of a Synchronous machine. However, the structure is completely different. One can also notice that it is not possible to short-circuit the source because the resistance of the coils limits the current. For switched-reluctance motors, two feeding schemes are possible: voltage-source feeding and current-source feeding (Fig. 8). Each scheme has its own advantages and drawbacks. Current-source feeding is particularly suitable for low speed operation when the motor torque must be closely controlled with minimum ripple. On the other hand, voltage-source feeding is suitable for high-speed operation when the counter emf is high and it is difficult to maintain constant currents. It has been pointed out that a current-controlled voltage-source converter is a good compromise for the problem of SRM feeding. Current control operation provides effective torque control and inherent protection. However, current regulation is no longer effective at very high speeds so that the converter operates in the voltage-source mode. Voltage-source is used in this work

In this, voltage source is modeled as a variable voltage source and its period is defined by using switching period which is shown in Fig.9.The switching period is divided into three regions:

Region I: The control takes place applying the voltage source to a phase coil at turn-on angle θ_{on} until a turn-off angle θ_{off}.

Region II: The applied voltage is reversed until a certain demagnetizing angle θ_d, which must allow the return of the magnetic flux toward zero.

Region III: After region II, the applied voltage's value is zero.

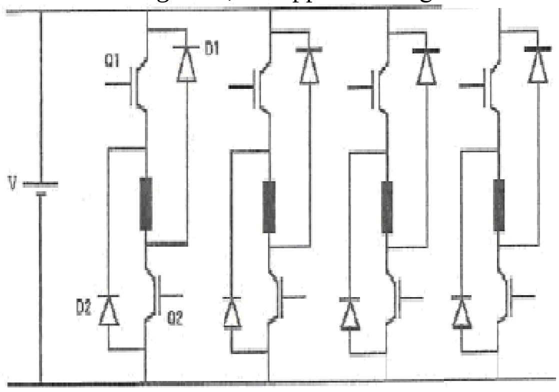


Fig. 7 H-bridge asymmetric converter

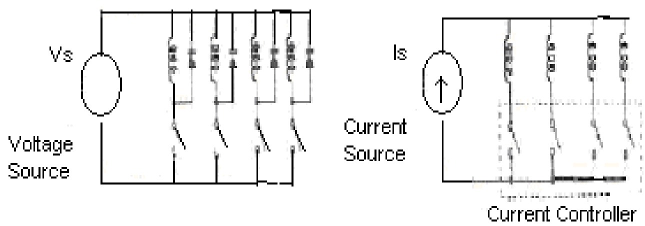


Fig. 8 SRM feeding schemes, (a) Voltage-source feeding, (b) Currentsource feeding

ISSN: 2321-8169
1841 – 1846

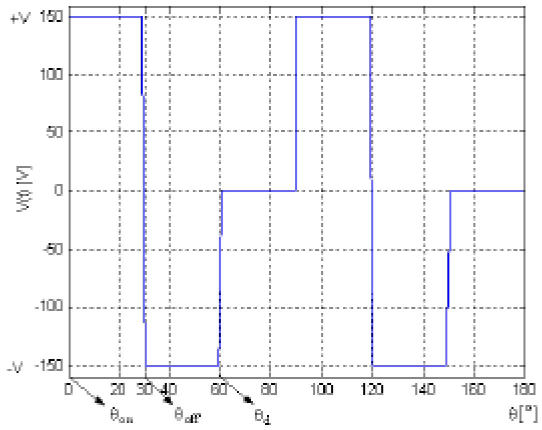


Fig. 9 SRM linear model phase voltage

To apply voltage V in one phase, the two IGBTs Q1 and Q2 in Fig.7 must be ON. On the contrary, to apply –V voltage and assure the current continuity, the two diodes D1 and D2 are used.

8/6 SRM model simulation results on Matlab: The SR motor has following parameters:
W(speed) = 300 rev/sec, V(t) = (150 & -150 & 0) volt
R = 1.30 Ω, Lmin = 4e-3 H, Lmax = 18e-3 H,
$\beta_r = \beta_s = (15^0)*(\pi/180)$ rad/sec, $\theta_x = (15^0) * (\pi/180)$rad/sec
$\theta_y = (30^0) * (\pi/180)$ rad/sec, $\theta_{on} = (0^0) * (\pi/180)$ rad/sec
$\theta_{off} = (20^0) * (\pi/180)$ rad/sec, $\theta_d = (40^0) * (\pi/180)$ rad/sec

The speed is assumed to be constant and the initial condition is set to be zero. For N_r = 6, the rotor is at aligned 30^0. The commutation angle θ_{off} is chosen 20^0. Fig. 10 shows the simulation block diagram. Fig.11 shows some results for $\theta_{on} = 0^0$ and $\theta_{off} = 20^0$, with the machine parameters without load.

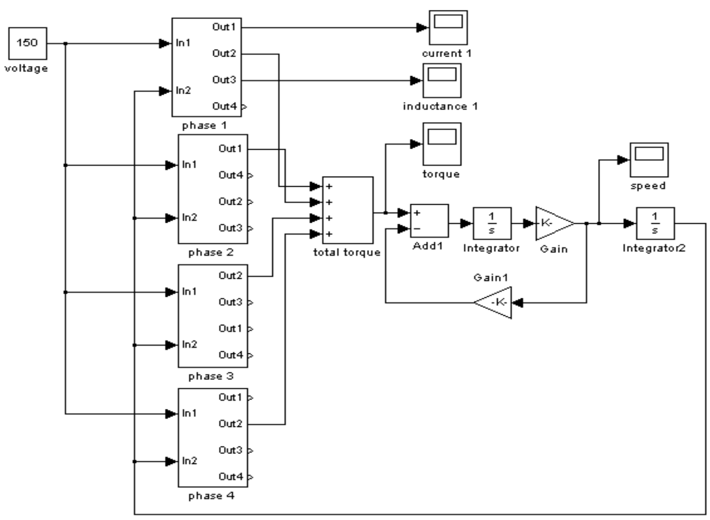
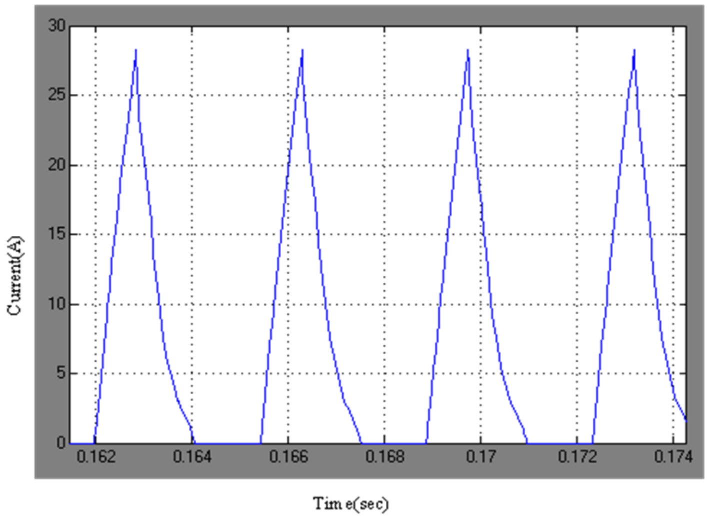
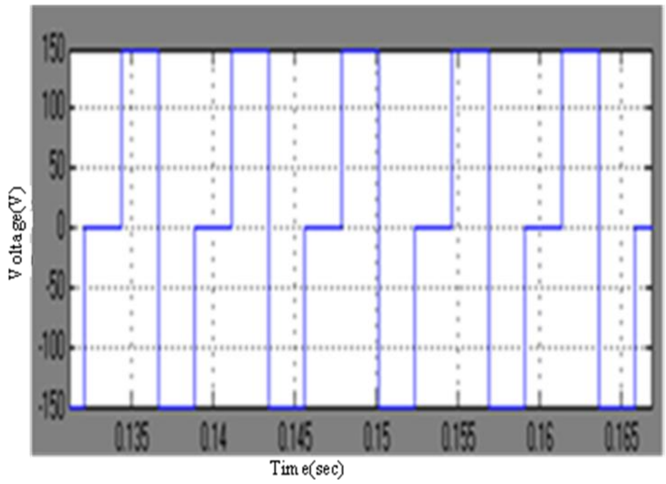


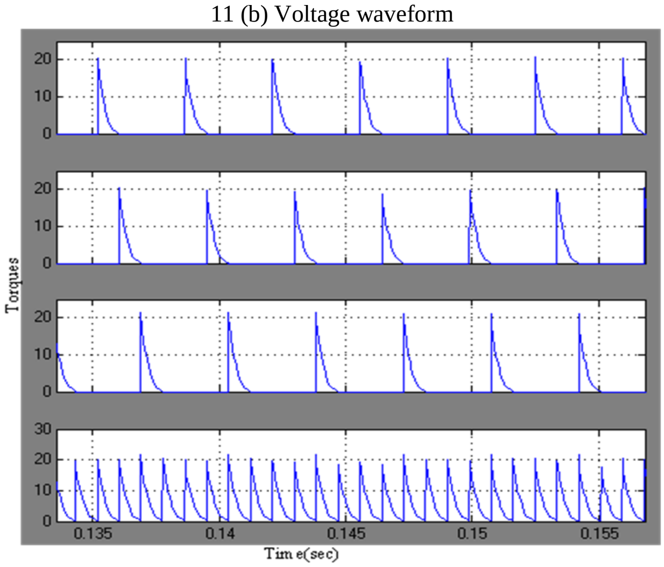
Fig.10 Simulation block diagram of 8/6 SRM



11 (a) Current waveform

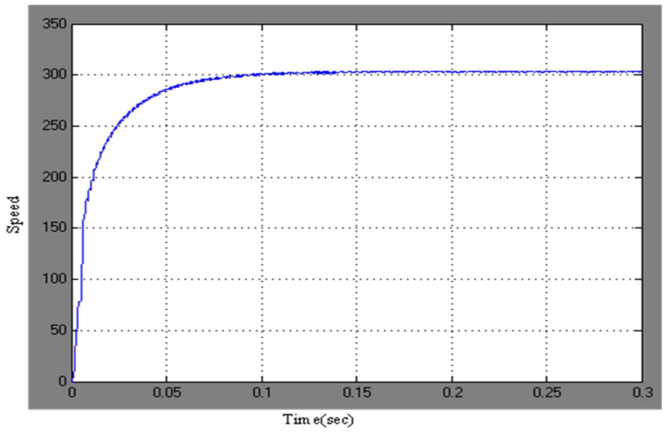


11 (b) Voltage waveform



11 (c) Torque waveforms in four phases

ISSN: 2321-8169
1841 – 1846



11 (d) Speed

Fig.11. simulation results for $\theta_{on}=0^0$ and $\theta off=20^0$,with the machine parameters without load.

[VI]. CONCLUSION

This paper presents control parameters, power converter topology, commutating strategy and simulation of a 8/6-switched reluctance motor (SRM) by using a linear model. Moreover, the energizing strategies, which affect on the control of the SRM are also discussed.

REFERENCES

[1] S.A. Nasar ''DC Switched Reluctance Motor '' *Proceeding of the Institution of Elec. Engineers, Vol*. 166, no 6, June 1996

[2] Y. Tang "Characterization, numerical analysis and design optimization of switched reluctance motors", *IEEE Trans. on Ind. Appl.*,Vol.33, no.6, Nov. 1997.

[3] G.Gao, "Speed Control of Switched Reluctance Motors", M.Sc. thesis, Department of Electrical and Electronic Engineering, The Hong Kong University of Science and Technology.

[4] M.R. Haris, A. Hughas, and P.J. Lawrenson, "Static torque production in saturated doubly-salient and machines," *Proc. Inst. Elec. Eng.*, Vol. 122, no. 10, pp. 1121-1127, 1975.

[5] R. Krishnan, R. Arumugam, and J.F. Lindsay, "Design procedure for Switched reluctance motors," *Conf. Record, IEEE-IAS Ann.* Mtg. (Denver, CO), Oct. 1986.

[6] H.Huy, K. Slimani, and P. Viarouge, "A Current-controlled Quasi-Resonant Converter for Switched-Reluctance Motor", IEEE *Transactions on Ind. Electronics*, Vol. 38, No. 5, October 1991.

[7] A. Radun, "Design considerations for the switched reluctance motor", *IEEE Transactions on Ind. Appl.*,Vol.31, no.5, Sep. 1995.

[8] A. Radun, "Analytical calculation of the switched reluctance motor's Unaligned inductance", *IEEE Trans. on Magn.*, Vol.35, no.6, Nov.1999.