



Optimum Switching Angle Prediction for Switched Reluctance Machine

Ramanathan, K.S.S.Prasad

Dept. of EEE, Bharath University, Chennai, Tamil Nadu, India

Assistant Professor, Dept. of EEE, Bharath University, Chennai, Tamil Nadu, India

ABSTRACT: - This paper presents the design and implementation of a control system for switched reluctance Machines applicable over the entire speed range, for generating operation. The proposed controller on-line determines the optimal firing angles for all operating modes. The suggested control system achieves high performance, single-pulse control modes. Simulation results under various operating conditions are presented to demonstrate the effectiveness of the proposed control scheme. SRG operation is presented by simulation on the 3-phase 6/4 SRG with asymmetric half-bridge power converter (APC) controlled by Microcontroller (PIC).

KEYWORDS: Reluctance motor drives, Reluctance generators, Variable speed drives, optimal control, Optimization methods. Asymmetric half-bridge power converter (APC), Equivalent circuit, mathematical model, Exciting mode.

1. INTRODUCTION

SWITCHED reluctance machine (SR) is a doubly salient machine with independent phase windings on the stator and a solid laminated rotor. The stator windings on diametrically opposite poles are connected in series to form one phase of the motor. Figure 1 (a) three phases 6/4 switched reluctance machine. When a stator phase is energized, the most adjacent rotor pole-pair is attracted towards the energized stator in order to minimize the reluctance of the magnetic path. Therefore, by energizing consecutive phases in succession it is possible to develop constant torque in either direction of rotation.[1-3]

The torque in a SRM is produced in pulses by the tendency of the rotor to move towards the position where the inductance of the excited stator pole winding is maximized.[4] At low speeds, the torque is limited by the current that is controlled by either voltage-PWM or current regulation and is called '*PWM-control mode*'. At high speeds, the machine back-EMF is increased and the available voltage is insufficient to regulate the current. This is called '*single-pulse control mode*' and the torque is controlled by the duration of the current pulses. (SRG)

The SRG has two phases (excitation and generation) in one electrifying period, with generation being the primary phase. When the two switches, Q1 and Q2, are turned on, the windings on the stator are excited by the outer circuit, and the electrical energy and mechanical energy provided by exterior circuit are converted into magnetic field energy. When the two switches are turned off and the two diodes, D1 and D2, are turned on, the magnetic field energy and mechanical energy are converted into electricity energy feeding back to the source or supplying power to the load. Because of the characteristics of time-sharing excitation, the control of SRG is very flexible. And there are several parameters for controlling SRG, such as turn-on angle, turn-off angle, and exciting voltage and controlling mode, all these will affect the generation greatly[5].

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 11, November 2014

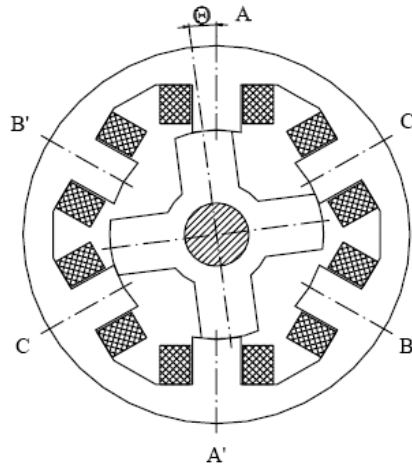


Figure 1. Stator and rotor configuration of SRM.

The following are the main advantages of an SR motor drive: Simple and low-cost machine construction due to the absence of rotor winding and permanent magnets. [6-7] No shoot-through faults between the dc buses in the SR motor drive converter since each stator winding is connected in series with converter switching elements. Unidirectional current required by the motor drive makes power electronics drive circuitry simple and reliable. Low rotor inertia and high torque/inertia ratio. Stator phases can be controlled independently. This makes SR drive more robust than other motor drives. Failure or loss of one of the stator phases does not prevent drive operation. SR motor can be operated in a harsh environment. [8-9]

The main disadvantages of SR motor drives are the following. High torque ripple. Higher acoustic noise level than other motors. However, advanced motor design techniques and high Performance algorithms are successfully addressing the above mentioned disadvantages and SR motor drives are becoming more and more suitable for a wide range of applications.[10]

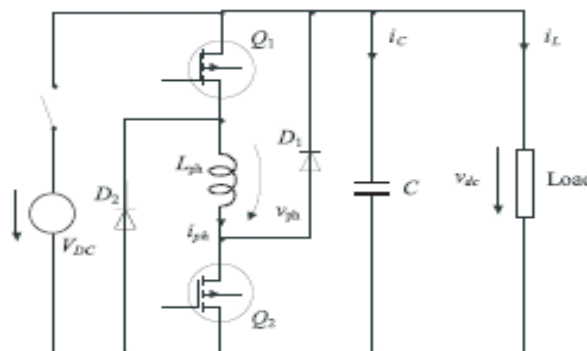


Fig. 2 Single-phase SRG equivalent circuit

III. EQUIVALENT CIRCUIT

A classical equivalent circuit of SRG with APC usually consists of phase windings, power switches and diodes, main DC bus capacitor, load resistor and mostly also a DC source with series connected diode or a switch for

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 11, November 2014

starting excitation, [1]. In the Fig. 2 there is such circuit for a single-phase winding. Phase winding with two switches (Q1,Q2) and diodes (D1,D2) form a phase leg and their number in complete circuit depends on the total SRG phase number. The basic voltage equation of one phase of SRG is following.[1]

$$R_a V_{DC} = R_a i_a + L_a \frac{di_a}{dt} + \frac{dL_a}{d\theta} \omega i_a \quad (1)$$

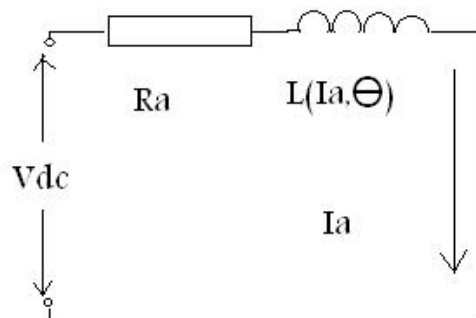


Fig. 3. Simple SRG equivalent circuit

The phase voltage equation in Switched reluctance motor can be written as:

$$V = iR + \frac{d\lambda}{dt} \quad (2)$$

Where, V is the dc bus voltage, 'i' is the instantaneous phase current, R is the phase winding resistance and λ is the flux linking the phase coil. Ignoring stator resistance, Equation 1 can also be written as:

$$V = L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{d\theta} \omega \quad (3)$$

Where, ω is the rotor speed, θ is the rotor angular position, and $L(\theta)$ is the instantaneous phase inductance. The rate of flow of energy can be obtained by multiplying the voltage with current and can be written as:

$$Vi = Li \frac{di}{dt} + i^2 \frac{dL}{d\theta} \omega \quad (4)$$

Or

$$P = \frac{d}{dt} \left(\frac{1}{2} Li^2 \right) + \frac{1}{2} i^2 \frac{dL}{d\theta} \omega \quad (5)$$

The first term of the above equation represents the rate of increase in the stored magnetic field energy while the second term is the mechanical output. Thus, the instantaneous torque can be written as:

$$T(\theta, i) = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (6)$$

The step angle of the rotor is given by

$$\theta_s = \frac{2\pi}{qR_n} \quad (7)$$

Where 'q' is the number of phases, and 'R_n' is the no of rotor poles, then for 6/4 SRM the step angle is 30 degrees.

Linear inductance profile

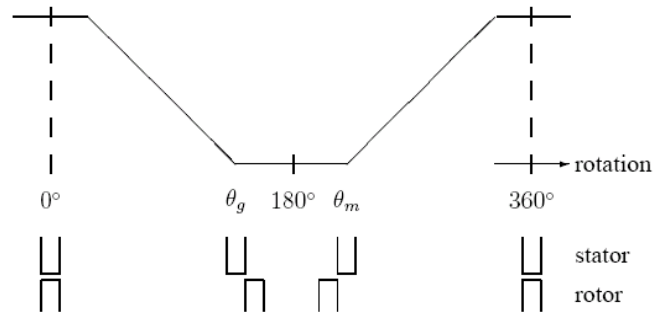


Fig 4. The linear inductance profile of the SRM showing θ_g and θ_m .

The minimum inductance region is defined by the angular interval over which the rotor poles do not overlap the stator poles. The maximum inductance region is defined by the angular interval over which there is complete overlap between the stator and rotor poles. The regions of increasing and decreasing inductance correspond to varying overlap between the stator and rotor poles.[3]

Control Algorithm

Control of the SRM is more complicated for generator operation than it is for motor operation. Operating as a motor, the turn-on angle can be used to directly control the peak phase current, thereby partitioning the responsibilities of the turn-on angle and conduction angle ($\theta_{cond} = \theta_{off} - \theta_{on}$). Operating as generator, the turn-on and turn-off angles control the peak phase current jointly and severally. However, we have no control over where the peak phase current occurs once the SRG has entered single pulse operation above base speed.[3]

In order to maximize switched-reluctance generator (SRG) efficiency, we seek to maximize the ratio of the average output power to given input average mechanical power, P_{out}/P_{mech} . This ratio captures our intended goal of providing the required electrical output with the minimum electromechanical input. [3]

For operation of the SRM as a generator, phase current must be present in the phase winding as the inductance is decreasing in the direction of rotation. The polarity of current is immaterial, so we assume that the phase current is always positive. As we operate the generator above base speed, the magnitude and shape of the phase current directly depends on the turn-on and turn-off angles. The amount of power generated is dictated by the phase current and its relative position with respect to inductance profile. In order to produce a map of power production for a given speed, turn-on and turn-off angles, the SRG is modeled using finite element magnetization data and the generator system is simulated for every 1000 rpm between 3000 rpm and 10,000rpm with turn-on and turn-off angles taking all combinations of θ_{on} and θ_{off} in increments of 2 electrical degrees. Among all simulated data, the optimum turn-on and turn-off angles are selected for a given speed and power level. The criteria are to find the excitation angles that produce the required power at a given speed with minimum mechanical power. So it requires look up table that generated by using finite element analysis method of flux calculations. (Magnet software). Here turn-on and turn-off angles are the controlling parameters for SRG. So we can get the efficiency-optimal by adjusting either turn-on or turn-off angles easily.[3]

III. DEFINING THE SRM OPTIMAL CONDITIONS

The average torque control is an easily implemented and cost-effective control method that is based on time-averaged analysis of machine operation and the control is developed on per-stroke basis [1]. The efficiency can be improved and torque ripple can be reduced by controlling the flux-linkage level of the machine, so that an appropriate balance between the contributions of each phase to the total flux is



International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 11, November 2014

accomplished. Therefore, high efficiency with reduced torque ripple is achieved by on-line controlling the SRM turn-on and turn-off angles.[2]

In PWM current controlled generating operation, the optimal turn-on angle at which the flux-linkages of two neighboring phases are equal on their intersection angle θ_i^G is defined by

$$\theta_{onopt}^G = \theta_{lu}^1 - [\theta_{01}^G + 2\theta_{sk} (1 - \frac{\theta_{01}^G}{\theta_{e1}^G})] \quad (8)$$

During the de-fluxing interval θ_{o1}^G , the stored field energy is returned to the dc-link and the flux and phase current are extinguished. If the de-fluxing interval exploits the unaligned region, the stored field energy is released without extracting mechanical energy from the prime mover. Then, the optimal turn-off angle is selected at the rotor position that stator and rotor pole corners complete overlap

$$\theta_{offopt}^G = \theta_{lu}^1 \quad (9)$$

in single pulse controlled SRM generating operation the θ_{o1}^G interval should be proportional to the de-fluxing period θ_{e2}^G .

$$\theta_{01}^G = C_{\lambda}^G \theta_{e2}^G \quad (10)$$

$$\theta_{01}^G = C_{\lambda}^G \frac{\lambda_c \omega_r}{V_{dc}} \quad (11)$$

Where C_{λ}^G the optimization parameter that could be is determined experimentally ($C_{\lambda}^G \leq 1$). Since in single pulse mode, the dwell period is almost equal to the de-fluxing period ($\theta_{e1}^G \approx \theta_{e2}^G$), the optimal turn-on angle in generating operation is given by

$$\theta_{onopt}^G = \theta_{lu}^1 - 2\theta_{e1}^G + \theta_{01}^G \quad (12)$$

$$\theta_{onopt}^G = \theta_{lu}^1 - (2 - C_{\lambda}^G)\theta_{e1}^G \quad (13)$$

and consequently the optimal turn-off angle condition is defined by

$$\theta_{offopt}^G = \theta_{onopt}^G + \theta_{e1}^G \quad (14)$$

$$\theta_{offopt}^G = \theta_{lu}^1 - (1 - C_{\lambda}^G)\theta_{e1}^G \quad (15)$$

Experimental Results

The performance of the controller is experimentally verified through a 6/4 three-phase SRG designed for a 1.2kW 160V automotive application. The control algorithm that we have developed is implemented using programmable interrupt controller 16F877A (PIC). The SRG is coupled to DC Shunt motor, which acts as constant speed mechanical power source using an adjustable speed drive [3]. For generator operation the DC motor driven SRG bring above rated speed by adjusting its flux through field winding. Then the converter operation begins with PWM input from Programmable Interrupt Controller (PIC).It gives gate drive signal to the MOSFETS at appropriate timings. From the electrical time constant of SRG we allowing little time to discharging stored energy, before going to next phase excitation. According to the inductance profile, need to switch the phase in the negative torque region, this can be achieved by using PIC generated PWM signal to the MOSFETs gates. This can be done by the simple C code program, PCW compiler which converts to HEX code.

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 11, November 2014

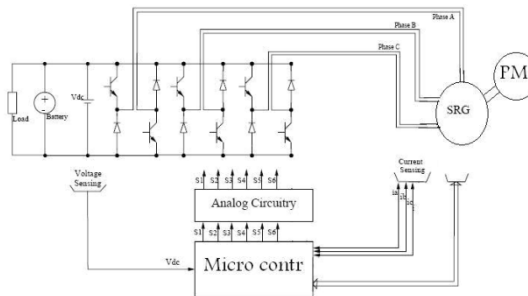


Fig 5.The block diagram of the experimental setup

In this simulation, a DC supply voltage of 160 V is used. The converter turn-on and turn-off angles are taken from 2D lookup table, for over the speed range. The reference current is 16 A and the hysteresis band is chosen as ± 4 A. The SRG is started by using DC shunt motor and applying the step reference to the regulator input (SRG).[2]

The SRG torque characteristic can be optimized by applying appropriated pre-calculated turn-on and turn-off angles in function of the machine current and speed. The optimum values of optimum angles can be stored in a 2-D lookup table.

The SRG waveforms (phase voltages, magnetic flux, windings currents, torque, and speed) are displayed on the scopes.

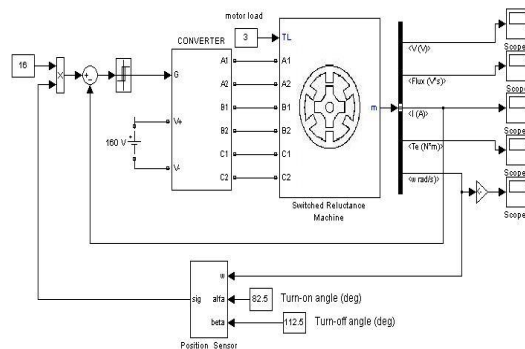


Fig. 6. Simulation model of SRM

Simulation Results

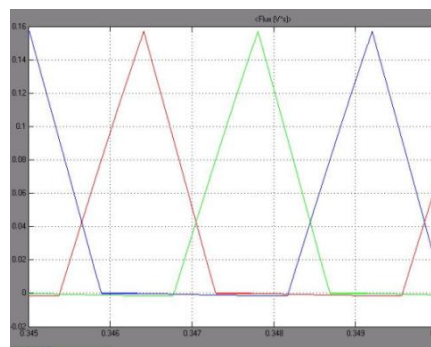


Fig. 7. Flux under each phases

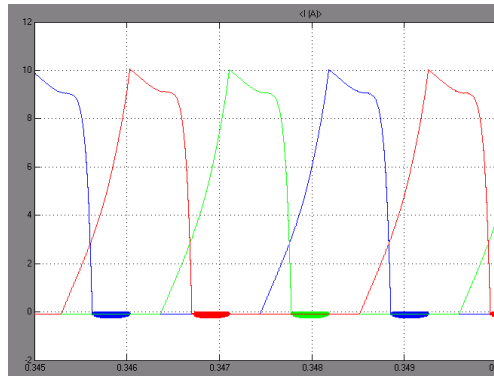


Fig. 8. Phase Current under each phase

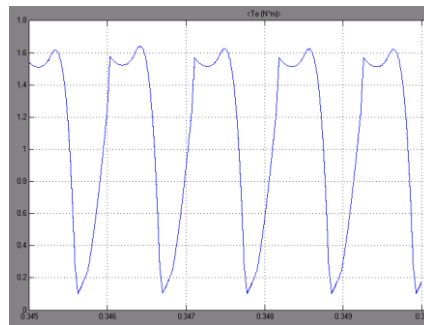


Fig. 9. Torque of the SRM

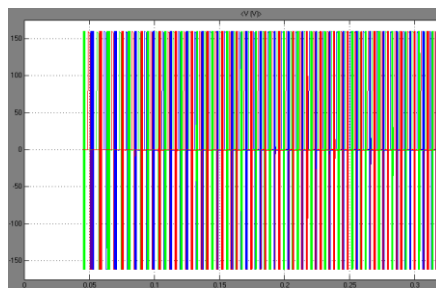


Fig. 10. Voltage of each phase

Fig. 11. Speed of the SRM

VI. CONCLUSION

This Paper suggested the linear and nonlinear Math model of SRG. The SRG linear math model was used to simulate and analyze the phase characteristic of SRG. Simulation model as well as corresponding experimental set-up of 3-phase 6/4 SRG controlled by means of hysteresis current control has been established and Simulation and measured results of phase current and voltage values and DC bus voltage have been presented and compared. Measured and simulated results are in a good agreement and the reasons of differences are in not precise mechanical configuration of Rotor position sensors, and in neglecting of magnetic circuit saturation.

NOMENCLATURE



International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 11, November 2014

- θ_{01}^G Rotor angle interval from a position at which stator and rotor pole corners complete overlap to an angle at which phase current extinguishes.
- θ_{e1}^G Rotor angle interval over which phase is excited.
- θ_{e2}^G Rotor angle interval over which phase flux-linkage decays to zero (de-fluxing period).
- λ Phase flux-linkage.
- ω_r Angular speed
- $\theta_{lu}, \theta_{lu}^1$ Rotor position at which stator and rotor pole corners start and complete overlap, respectively.
- C_λ Optimization parameter. (0.91)
- ω Base speed.
- R_a Resistance per phase in ohms.
- L_a Inductance per phase in Henry.
- i (or) i_{ph} Current/phase.
- θ_{sk} Stroke angle.
- P Rate of flow of Energy.
- T Instantaneous Torque.
- $L(\theta)$ Instantaneous inductance.

REFERENCES

- [1] Martin Lipt'ak, Val'eria Hrabovcov'a, Pavol Rafajdus, Equivalent circuit of switched reluctance generator based on dc series generator. Journal of electrical engineering, vol. 59, no. 1, 2008.
- [2] Subha Palaneeswari M., Abraham Sam Rajan P.M., Silambanan S., Jothimalar, "Blood lead in end-stage renal disease (ESRD) patients who were on maintenance haemodialysis", Journal of Clinical and Diagnostic Research, ISSN : 0973 - 709X, 6(10) (2012) pp.1633-1635.
- [3] Sharmila S., Rebecca L.J., Saduzzaman M., "Effect of plant extracts on the treatment of paint industry effluent", International Journal of Pharma and Bio Sciences, ISSN : 0975-6299, 4(3) (2013) pp.B678-B686.
- [4] Jeyanthi Rebecca L., Dhanalakshmi V., Sharmila S., "Effect of the extract of Ulva sp on pathogenic microorganisms", Journal of Chemical and Pharmaceutical Research, ISSN : 0975 – 7384 , 4(11) (2012) pp.4875-4878.
- [5] Sharmila D., Saravanan S., "Efficacy of lead on germination growth and morphological studies of Horse Gram (Dolichos biflorus Linn)", Journal of Chemical and Pharmaceutical Research, ISSN : 0975 – 7384 , 4(11) (2012) pp.4894-4896.
- [6] Saduzaman M., Sharmila S., Jeyanthi Rebecca L., 'Efficacy of leaf extract of Moringa oleifera in treating domestic effluent', Journal of Chemical and Pharmaceutical Research, ISSN : 0975 – 7384, 5(2) (2013) pp.139-143.[7] Christos Mademlis and Iordanis Kioskeridis
- [7] Smooth Transition between Optimal Control Modes in Switched Reluctance Motoring and Generating Operation.
- [8] Yilmaz Sozer, David A. Torrey--Closed Loop Control of Excitation Parameters for High Speed Switched-Reluctance Generators.
- [9] Ing. Martin Mana, Doctoral Degree Programme, Mathematical model switched reluctance motor.
- [10] Pan Zai-ping, Jin Ying, zhang Hui, Study on switched reluctance generator. Journal of Zhejiang University science, 2004.
- [11] Premkumar, S., Ramu, G., Gunasekaran, S., Baskar, D., "Solar industrial process heating associated with thermal energy storage for feed water heating", Middle - East Journal of Scientific Research, v-20, i-11, pp:1686-1688, 2014.
- [12] Premkumar, S., Prabhakar, S., Lingeswaran, K., Ramnathan, P., "Development of direct methanol fuel cell and improving the efficiency", Middle - East Journal of Scientific Research, v-20, i-10, pp:1277-1280, 2014.
- [13] B.Vamsi Krishna, Significance of TSC on Reactive power Compensation, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, ISSN (Online): 2278 – 8875, pp 7067-7078, Vol. 3, Issue 2, February 2014
- [14] Mr D.Sridhar raja, Wireless Transmission of Real Time Electrocardiogram (ECG) Signals through Radio Frequency (RF) Waves, International Journal of P2P Network Trends and Technology (IJPTT), ISSN: 2278 – 8875 , pp 793-798, Vol. 2, Issue 2, February 2013.
- [15] E.Kanniga, N. Imocha Singh, K.Selva Rama Rathnam, Gated-Demultiplexer Tree Buffer for Low Power Using Clock Tree Based Gated Driver, International Journal of P2P Network Trends and Technology (IJPTT), ISSN (Print) : 2320 – 3765, pp 4652-4659, Vol. 2, Issue 10, October 2013