Switched Reluctance Motor/Generator with Optimum Turn-on and Turn-off Controller for Hybrid Electric Vehicle Application

V.Vasan Prabhu[1], Dr.V.Rajini[2]
[1]Research Scholar, Anand Institute of Higher Technology, Anna University, Chennai
[2] professor SSN college of Engineering, Anna University, Chennai
vasanprabhu@gmail.com, rajiniv@ssn.edu.in

Abstract— ***The problem of performance optimization in current controlled switched reluctance motor (SRM) and voltage controlled switched reluctance generator are investigated. A mathematical model has been developed for a Switched Reluctance Machine using Matlab/Simulink environment for both motoring and generating mode with an asymmetrical half-bridge converter. An optimal performance of the machine is targeted for improving the motor efficiency. The effects of rotational speed and current are taken into account for performance optimization of this machine. Two controllers are proposed to determine the optimal turn-on and turn-off angles as per the speed variations due to loading requirements. The simulation results for SRM/Gs are also presented.***

Index Terms— **SRM, SRG, SRM/G, Current control, Optimization methods, Reluctance motors**

1. Introduction

Switched Reluctance Machine (SRM) has been used in many commercially adjustable speed applications due to its unique mechanical structure and simple power electronic drive requirements. The intrinsic simplicity and ruggedness make it superior to other electric machines. Its high speed capability, high torque to inertia ratio, reliability and high robustness has attracted many researchers' interest all over the world. However, the SRM suffers noticeable torque ripple and acoustic noise that prevent it from use in high performance drives. The torque ripple in the switched reluctance machine is induced due to highly nonlinear and discrete nature of the torque production mechanism, which is significant at the commutation instant. Hysteresis current controller, as a traditional open-loop current control scheme for SRM brings large acoustic noise due to the varying switching frequency [1].

In the past, several control schemes have been suggested for the torque ripple and noise reduction. The most prior arts have been focused on motor design, converter topology and modulation strategy. Soft computing techniques such as fuzzy logic, neural network are most widely used to reduce ripples in the torque [10]-[13]. The modified asymmetrical half-bridge converter provides a full four quadrant operation with independent energization and commutation of each phase winding. By the comparison provided in [2], it is clear that from [4] most of the SRM works effectively well with an asymmetrical power converter (APC). In [3][5][15] the simulation of linear and nonlinear model of SRM using Matlab/Simulink environment are provided. The proper selection of turn-on and turn-off angle in rising and falling inductance profile of the SRM/G provides better performance in both the mode of operation [6].

A mathematical model with optimum tuning controller has been developed for 6/4 SRM/G [6]-[9]. In the present work, the simulation studies are performed for both motoring and generating operation of a 6/4 SRM using a modified converter. The complete model can be used in application of Hybrid Electric Vehicle with proper turning on/off the operating mode region of SRM/Gs

2 Dynamic Characteristics

Switched reluctance machine is a doubly salient electric machine. The rotor is aligned whenever diametrically opposite stator poles are excited. In a magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation; the basic model is shown in **fig.1**

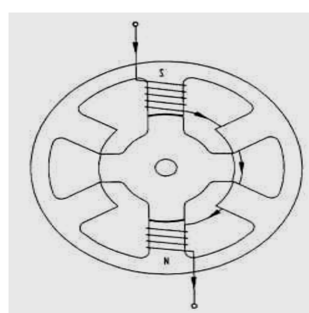

Figure 1. SRM/G Basic Model

The electromagnetic equation of SRM phase can be derived by neglecting the mutual inductance between the phases, which is given by

$$V_j = R_j I_j + d\varphi_j/dt \qquad (1)$$

Where j=1, 2...., m number of phases, V_j, R_j, I_j and φ_j are the phase voltage, phase winding resistance, phase current and phase flux linkage. Because of the double saliency of SRM and the magnetic saturation effects, the flux linked in an SRM phase varies as function of rotor position and phase current and thereby (1) can be expanded as

$$V_j = R_j I_j + L_j \left(\frac{dI_j}{dt}\right) + \omega \left(\frac{dL_j}{d\theta}\right) \qquad (2)$$

In (2), the three terms on the right hand side represent the resistive voltage drop, inductive voltage drop and the induced back electromotive force (EMF) which depends on the speed of the rotor. The ω and θ denote rotor speed and its position angle.

Each phase torque is given by the slope of the inductance versus rotor position characteristics ($dL_j/d\theta$). It is understood in (3) that the inductance of a stator winding is a function of both the rotor position and current, thus making it nonlinear by their resistive magnetic co-energy variation

$$T_j = 1/2\, I_j^2 (dL_j/d\theta) = (dW_c/d\theta) \qquad (3)$$

The torque is directly proportional to the square of the current thereby the machine has good starting torque. The total torque is expressed in (4) as the sum of the m individual phase torques when the magnetic coupling between the phases is not taken into account.

$$T_e = \sum_j T_j (I_j, \theta) \qquad (4)$$

The mechanical equation of the switched reluctance machine using the phase torque expression (5) is

$$T_e - T_l = J(\partial\omega/\partial t) + F\omega \qquad (5)$$

where T_l, J, F and ω are the load torque, moment of inertia, frictional coefficient and speed of the rotor

Mathematical Model

In this paper, the mathematical model of three phases SRM is considered for linear model simulation. The phase shift for each phase inductance (6) is given as

$$\theta_s = 2 * pi * ((1/N_r) - (1/N_s)) \qquad (6)$$

Initially, assume that the stator and rotor poles are not overlapped and the inductance is in minimum or constant. The overlap occurs(7) at the angle

$$\theta_x = 0.5 * ((2 * pi)/N_r) - (\beta_r + \beta_s) \qquad (7)$$

Increase in inductance with the rotor position gives a positive slope. The current in this region produces positive torque (i.e., motoring). The stator and rotor poles gets aligned at the angle (8)

$$\theta_y = \theta_x + \beta_s \qquad (8)$$

Inductance remains constant for some period based on the selection of rotor pole arcs which is (9)

$$\theta_w = \theta_y + (\beta_r - \beta_s) \qquad (9)$$

In (9) there is no change in inductance, and so the torque generation is zero even though there is a presence of current in this interval. It serves as a useful function by providing time for the stator current to come to zero or lower levels when it is commutated, thus preventing negative torque generation for part of the time if the current has been decaying in the negative slope region of the inductance

The rotor pole is moving away from overlapping the stator pole with decreasing inductance and increasing rotor position

$$\theta_{xy} = \theta_w + \beta_s \qquad (10)$$

Equation (10) gives negative slope of inductance from the angle (9), hence the operation of machine has negative torque (i.e., generating region). Fig.2 shows the overall block diagram of SRM/G. It can be used in both motoring and generating mode as desired by the control signal. If the control signal is given as "1", the converter works in motoring mode where the speed is controlled as per the desired value and the speed error is given to the PI Controller and the current reference is tuned.

If the control signal is given as "0", the converter works in generating mode and the load gets connected to the converter. The IC Engine acts as the prime mover. Here, similar to the motoring mode voltage error is given to the PI controller and the flux-linkage is varied. SRM model consists of two controllers which determine the turn ON and turn OFF angles for motoring mode and generating mode as per the control signal given.

Optimum Controller

Optimum controller gives the optimum value of turn On and turn Off value in the rising and falling inductance profile of the SRM/G. optimum controller block diagram is shown in **fig.2** for the verification purpose optimum value is compared with the various operating points that will be greater and lesser than the optimum values.

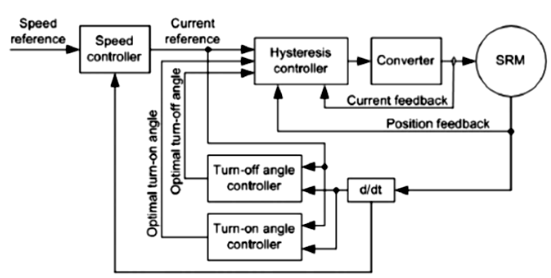

Figure 2. SRM/ optimim controller Block diagram

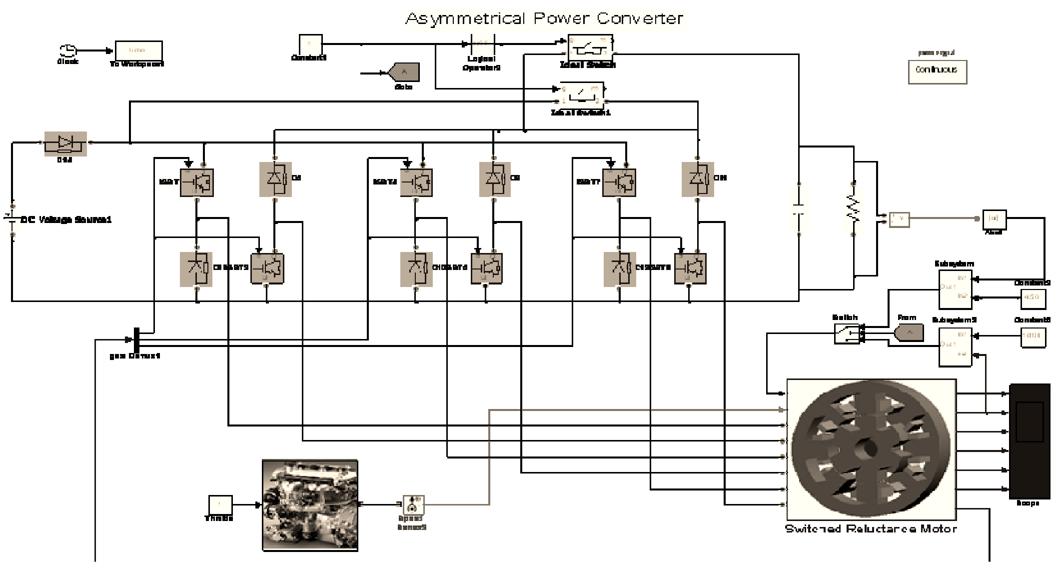

Figure 3. SRM/G Model with Optimum Controller

The optimum turn-on angle (11)condition for motoring mode is derived as,

$$\theta_{on}^{M} - \theta_{x} - \frac{L_u i_{rm} \omega_r}{V_{dc}} \qquad (11)$$

In motoring operation, the turn-on angle is selected such that the phase current acquires its reference value on an angle , that the stator and rotor poles start to overlap and the inductance rises. The demagnetization in a SRM takes significantly longer time than magnetization. The choice of turn-on angle is less important than the turn-off angle. The optimum value of turn-off angle depends on the turn-on angle. **Fig.3** shows the entire simulation of SRM/G with optimum controller.

The optimum turn-off angle (12) for motoring mode is derived as

$$\theta_{off}^{M} = \theta_x + (2\theta_s - \theta_{e1})\left[1 - \frac{\theta_{o1}}{\theta_{e1}}\right] \qquad (12)$$

For calculating the turn-off angle, the rotor angle intervals θ_{o1} and θ_{e1} are required.

The rotor angle interval over which phase is excited is given as,

$$\theta_{e1} - \frac{\lambda_c \omega_r}{V_{dc}} \qquad (13)$$

$$\theta_{o1} = \frac{L_u i_{rm} \omega_r}{V_{dc}} \qquad (14)$$

the optimum turn-on angle condition for generating mode is derived as (15)(16),

$$\theta_{on}^{G} = \theta_{xy} - \theta_{e1}(2 - C_\lambda) \qquad (15)$$

$$C_\lambda = \frac{(2\theta_{e1} + \theta_{on}) - \theta_{xy}}{\theta_{e1}} \qquad (16)$$

The optimum turn-off angle for generating mode is derived as(17),

$$\theta_{off}^{G} = \theta_{on}^{G} + \theta_{e1} \qquad (17)$$

As the SRM considered is 6/4, it consists of 3 phases. If 8/6 SRM is considered, the number of phases is increased to 4 by adding another phase block. The mode of operation, generating or motoring is selected by the control switch. While in operating in motoring mode, turn on value is less than optimum means copper loss increases, greater than optimum means the average torque is reduced due to insufficient switching period to reach the actual phase current magnitude. Turn off value is less than optimum average torque is reduced, if it is greater than optimum (falling slope) negative torque will be produced it will also reduce the total torque value.

While in operating in generating mode turn on value is less than optimum charging period decreases so when conduction period is decreased then flux linkage get decreased which cause reduction of torque/phase and output power. **Fig.4** shows the linear model of the SRM's single phase winding model.

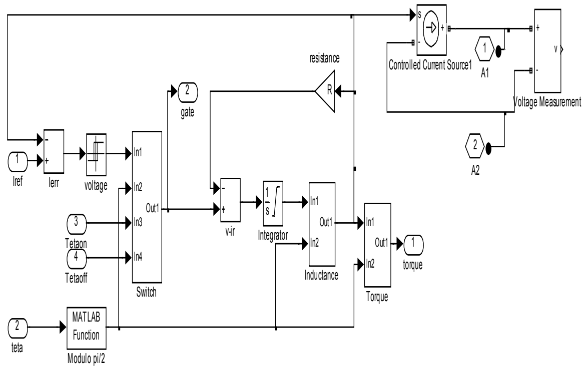

Figure 4. Single Phase Linear Model

Motoring mode

In motoring mode when an excitation voltage of 150 V and current 5 A is given, speed of 65 rad/sec is obtained. The Fig.5 shows inductance variation in SRM. The speed characteristic in motoring mode is shown in Fig 6. Fig.7 gives the flux-linkage and gate signal with respect to time. Here, the ripples are due to the current chopping control. The phase current is given in Fig 8. It can be seen that the current flows only in the inductance rising slope as it is in motoring mode. Fig.9 shows the total torque of all the three phases with respect to time, the total electromagnetic torque is around 1.35 Nm

Generating mode

For the generating mode, the prime mover speed is taken as 1500 rpm and the excitation voltage is 150 V. The generated output voltage of is obtained as170 V and is shown in Fig.10. Fig.11 shows that the excitation is given during the falling inductance for SRG operation. The total electromagnetic torque is around -0.91 Nm.

In Hybrid Electric Vehicles, dual mode of operation is essential for driving as well as charging the batteries. In the Motoring mode, the SRM operates as a Driving source whereas in Generating mode the driving force is obtained from Internal Combustion Engine From the energy management system (EMS) of the vehicle , the control signal for the motoring mode or generating mode can be obtained. This shifts from motoring mode to IC engine with generating mode. It's possible to switch the operating mode smoothly by using the optimal controller. The torque variation from motoring mode to generating mode is shown in fig.12.

The selection of the turn-off angle (θ_{off}) is critical for the optimum SRM/G performance. The variations of torque ripple factor, average torque and power loss versus turn-off angle (θ_{off}) for SRM/G values are illustrated in tabulation 1.

$$T_{rip} = \frac{T_{max} - T_{min}}{|T_{avg}|} \qquad (18)$$

$$\text{Power loss} = 1 \qquad (19)$$

Table 1 gives the average torque, torque ripple, power loss (18)(19)for SRM/ G for various values of turnoff angles. The optimum turnoff angle gives better efficiency in SRM by reducing torque ripples and gives better efficiency in SRG by reducing the power loss. For motoring mode of operation, when θoff is less than opt θoff, conduction loss is reduced. When θoff is greater than opt θoff then it torque ripple is minimized. But under optimal condition total electrical loss is reduced and maximum efficiency is obtained. Similarly same condition in generator shows that power loss is much reduced in optimum condition.

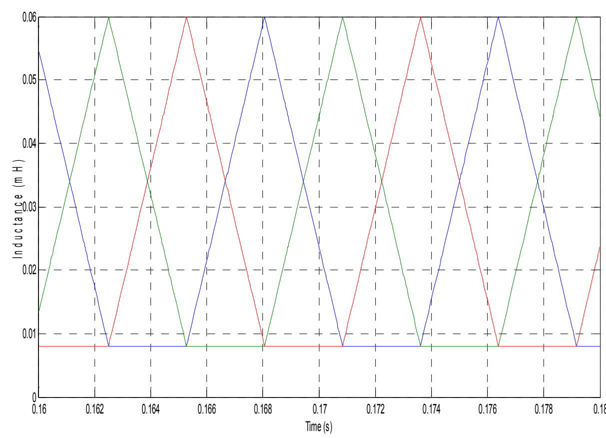

Figure 5. Inductance profile

Simulation Results (Motoring Mode)

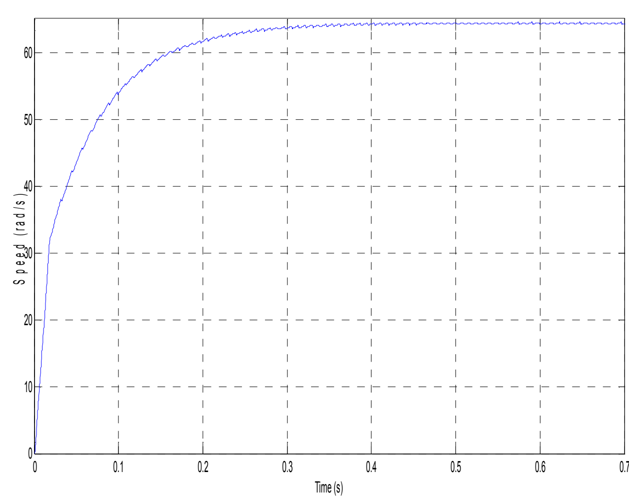

Figure 6. Speed Characteristics

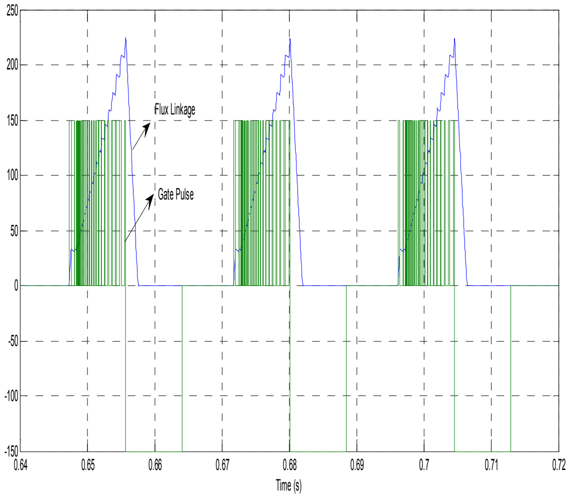

Figure 7. Gate Pulse and Flux-Linkage

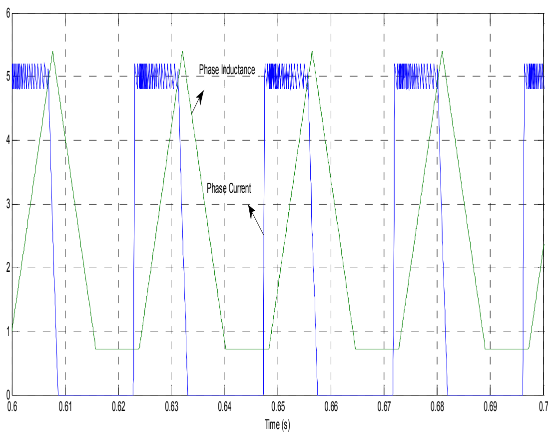

Figure 8. Current and Inductance

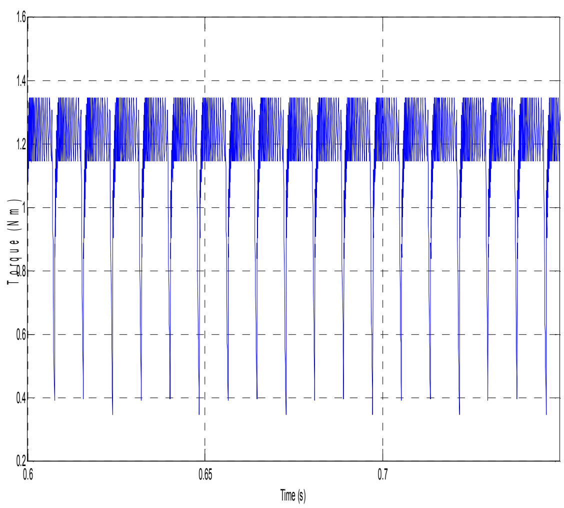

Figure 9. Total torque

Simulation Results (Generating Mode)

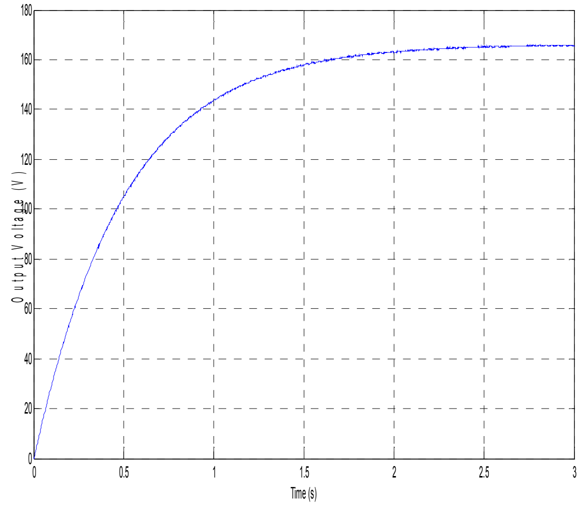

Figure 10. Output Voltage

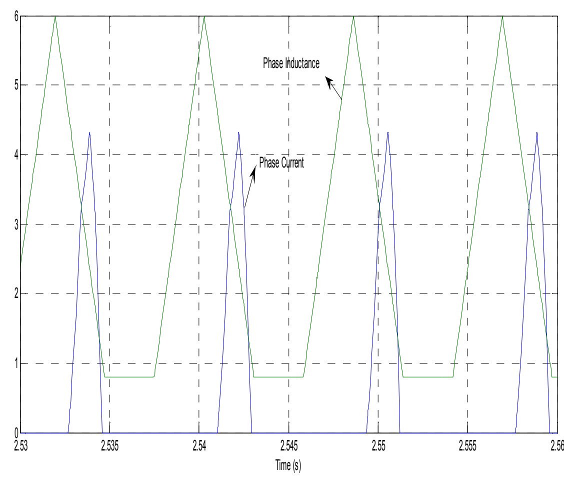

Figure 11. Current and Inductance

Dual mode operation of SRM/G

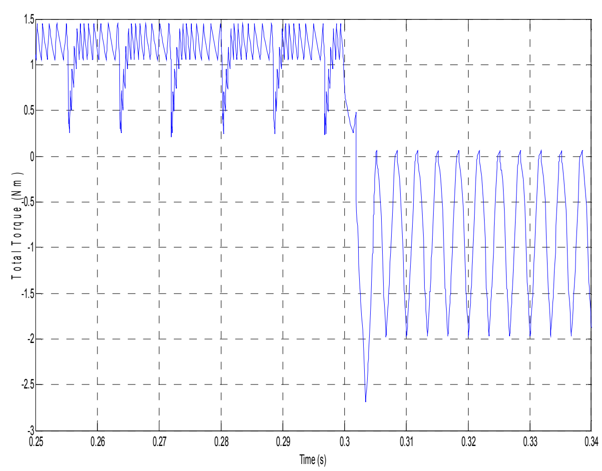

Figure 12. Change of mode from motor to generator

S.No	Rotor Angle rad/sec	SRM		SRG	
		Tavg (Nm)	Trip (Nm)	Tavg (Nm)	PL (w)
1	**Opt θoff**	**0.855**	**1.41**	**-0.45**	**24**
2	**θoff < Opt θoff**	**0.725**	**2**	**-0.17**	**51**
3	**θoff > Opt θoff**	**0.905**	**1.988**	**-0.62**	**42**

Table01. Average Torque and power loss

Conclusion

This paper, gives simulation results of Switched Reluctance Machine operating in both motoring and generating mode using a modified asymmetrical half-bridge converter. This is achieved by either connecting or disconnecting the load in modified converter. An IC Engine acts as a Prime mover while operating in generating mode. Therefore the output voltage from mechanical energy conversion is used in load or stored in battery for energy consumption in HEV. A mathematical model of switched reluctance machine for the application of Hybrid Electric Vehicles is presented with optimum turn on/off controllers.

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