Modeling &Torque Ripple Minimization of Switched Reluctance Motor for High Speed Applications

Joseph Peter

Abstract: This paper deals with the analysis, study and modeling of the torque ripple minimization setup for the closed loop control of Switched Reluctance Motor.SRM is becoming more and more popular for high speed industrial application environments due to its rugged and robust construction. For low cost, variable speed drives SRM are most widely used. But the torque pulsations in SRM are relatively higher compared to sinusoidal machines due to the doubly salient structure of the motor. Nonlinear inductance profile and pulse magnetizing make the torque ripple unavoidable. Both machine design and electronic control approaches have been used to minimize the torque ripples in SRM. This paper gives an extensive review of the origin of the torque ripple and approaches adopted to minimize the torque ripple.The mathematical modeling of three phase SRM is developed and integrated with different converter topologies in Matlab / Simulink environment along with control methods. The power spectrum density wave forms of torque are studied to verify the simulation results obtained.

Index Terms: Switched Reluctance Motor, mathematical modeling & simulation, converter topologies, torque ripple minimization, Power spectrum density

I. INTRODUCTION

With the advent of modern control technology and power electronics, switched reluctance motor drive are becoming increasingly popular. Because of high efficiency over wide operating range, the absence of rotor windings, and the maintenance free type of motor, SRMs have some advantages over other types of electrical machines

The primary disadvantages of SRMs are the torque ripple and acoustic noise. Torque production mechanism of SRM is basically successive excitation of each stator phases. Torque dip between two subsequent phases excitation dictates the existence of torque ripple. It has been agreed that the main source of the noise produced by SRM are the radial forces. The torque ripple and acoustic noise are not necessarily detrimental for the system in all cases, but it depends on the application. The torque ripple is particularly intolerable in servo or servo type systems, where its presence is painfully felt by the user or harmfully reflected on the load. While the drives designed in the early stages of SRM development were notoriously noisy with high torque ripples, significant progress have been made over the past decade to overcome the issues with decent success.

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There are primarily two approaches for reducing the torque ripple. One method is to improve the magnetic design of the motor, while the other is to use sophisticated electronic control techniques.

It is possible to separate the attraction force exerted on the rotor poles by the excited stator poles into two components as normal and tangential in an SRM. Tangential component of the force produces torque but radial component cause an attraction between stator and rotor poles and vibrations and acoustic noise occur in stator. The machine designers are able to reduce the torque pulsations by changing the stator and rotor pole structures, but only at the expense of some specific motor outputs. The electronic approach is based on optimizing the control parameters, which include the supply voltage, turn-on and turn-off angles, and current level. The minimization of torque ripple through electronic control may lead to a reduction in the average torque, since the motor capabilities are not being fully utilized at all power levels.

II. TORQUE RIPPLES

A. Origin of torque ripples

Torque pulsations are inherent in SRMs due to the doubly salient structure of the machine. The reluctance principle for torque production is utilized in these machines, where the phases operate independently and in succession. The machine torque is essentially defined by the nonlinear phase torque–angle–current characteristics and the magnetization of the phases. The magnetization pattern of the individual phases together with the characteristics of the motor dictate the amount of torque ripple during operation .[1]

B. Principle of operation

The switched reluctance motor is a rotating electric machine where both, stator and rotor have salient poles. The stator consists of simple concentric windings. There are neither windings or bar wires on the rotor. Stator windings on diametrically opposite poles are connected in series form to a single phase. When the stator pole pair is energized by the phase winding, the nearest rotor pole pair is attracted toward the position, where the magnetic path has the minimum reluctance. Thus, by energizing the consecutive stator phases in sequence, it is possible to develop a torque in either direction of rotation

III. INDUCTANCE PROFILE

The inductance of switched reluctance motor with various rotor positions has a non linear relationship as follows

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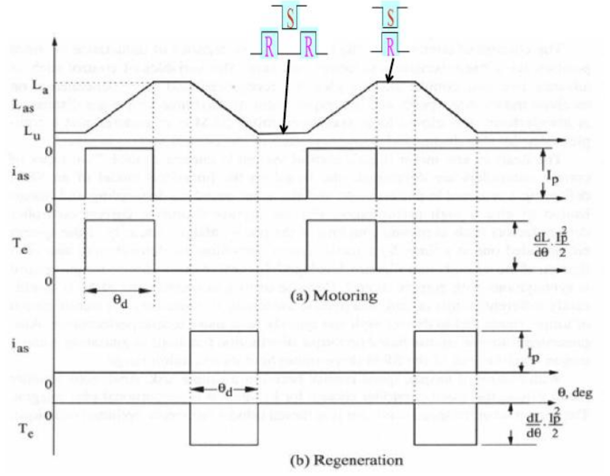

Figure 1.Inductance and Torque profile

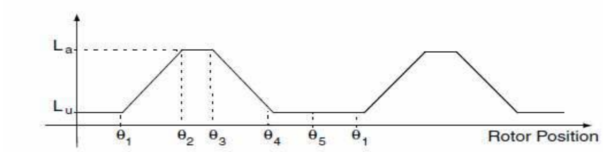

Figure 2.Variation of inductance with rotor positions

A. Modeling of SRM

This paper describes a Matlab / Simulink environment to simulate a 6/4-switched reluctance motor. From its linear model to the non-linear model, its dynamics is described and discussed in detail. All simulations are completely documented through the paper by their block diagrams and corresponding special Matlab functions and parameters to the reader quickly develop its model.[2] Based on the developed model, simulation studies are performed and compared. Motor phase currents for hysteresis control strategies, are measured and studied the steady-state motor operation to validate the model.

B. Equations

Applying KVL to SRM phase electromagnetic circuit,

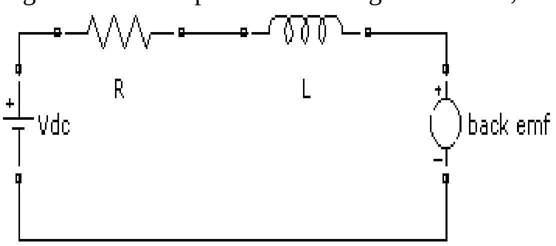

Figure 3 equivalent circuit

$$V = Rs * i + \frac{d\lambda}{dt} \quad (1)$$

$$\lambda = L(\theta, i) * i \quad (2)$$

$$V = Rs * i + \frac{dL(\theta, i)i}{dt} \quad (3)$$

$$V = Rs * i + L(\theta, i)\frac{di}{dt} + i\omega \frac{dL(\theta, i)}{d\theta} \quad (4)$$

$$\frac{di}{dt} = \frac{1}{L}\{V - iR - Eb\} \quad (5)$$

Where V is the DC link voltage, Rs is the electrical phase resistance, λ is the flux linkage related to inductance (L) and current (i) in the electromagnetic circuit, Eb is the back electromotive force developed.
The electromagnetic torque developed is

$$Te = \frac{1}{2} i^2 \frac{dl}{d\theta} \quad (6)$$

$$Te - Tl = J\frac{d\omega}{dt} + B\omega \quad (7)$$

Where Tl is the load torque, J is the inertia of the rotating part, B is the frictional coefficient, ω is the angular speed.

$$\frac{d\omega}{dt} = \frac{1}{J}(Te - Tl - B\omega) \quad (8)$$

$$\int \omega = \theta \quad (9)$$

C. Matlab simulink model

The plant model of SRM with position sensor is given below

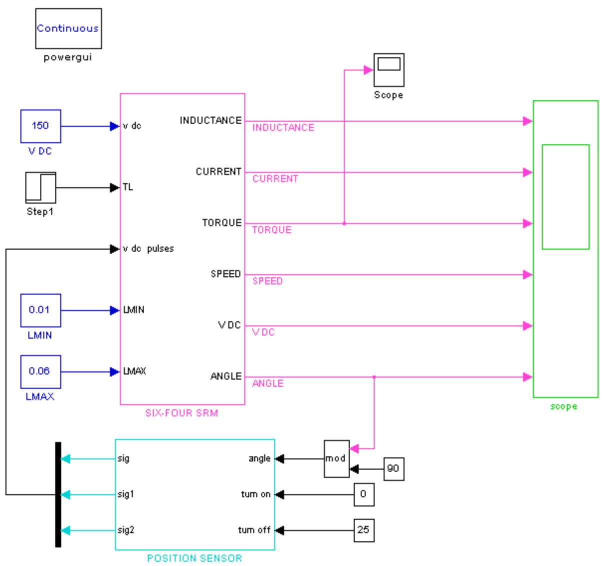

Figure 4.Open loop SRM Matlab model

The mathematical model of 6/4 SRM is developed in Matlab Simulink environment based on the mathematical equations given above.

The modeling of the switched reluctance motor is based on certain assumptions.

1. SRM is having 6 stator poles and 4 rotor poles
2. SRM is initially aligned with phase C
3. Stroke angle ,the angle at which rotor moves when we give stator excitation in SRM is 2π/ q Nr, where q is the number of phases and Nr is the number of rotor poles. So we have stroke angle =30°
4. Stator and rotor is having same pole arc, β s =β r
5. Magnetic saturation is neglected
6. Mutual inductance is neglected

The model subsystem for SRM is given below

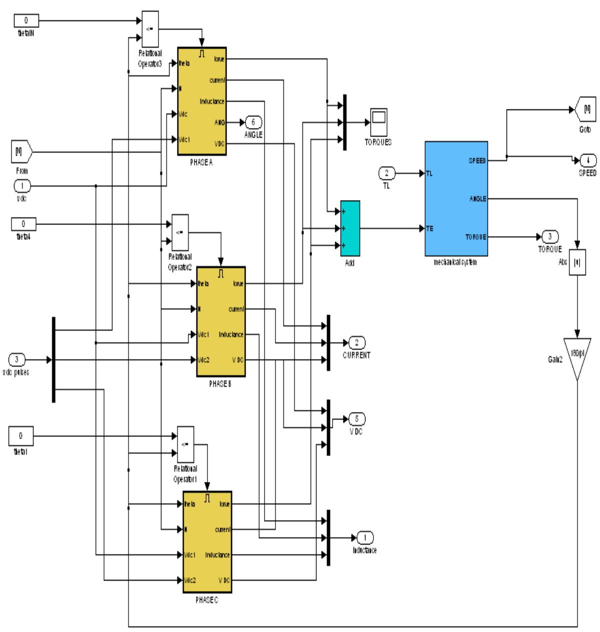

Figure 5 .Subsystem of SRM

SRM consists of three phases. Each phase in SRM is excited according to the rotor positions control signals and rotor moves to the minimum reluctance position. Inside the position sensor we produce signals for each stroke angle . In 90̊, each phase will be excited once. In 360̊, ie one revolution cycle ,each phase will be excited four times.

The main challenges faced in the mathematical modeling of SRM are

1. **The variation of inductance of SRM with rotor positions are non linear**
2. **The current and torque profiles of SRM are non linear .**

So for getting the inductance profile we can go for look up table method or linear algebraic equations for each stroke angle. [3]

From the basic electrical equations we will calculate the current and from current ,torque of each phases are calculated. Torque in a SRM is depending upon rate of change of inductance with rotor positions and is independent on the direction of phase currents.

The machine parameters are as follows:

Table 1. Ratings of SRM

Machine parameters	Values	Units
Rated power	1.8	K w
Dc link voltage	150	Volts
L max	60	mH
L min	10	mH
Frictional coefficient	.0183	Nm/rad/sec
Moment of inertia	.0013	Kgm^2

IV. SIMULATION RESULTS

The simulated results of open loop three phase SRM are given. A load torque of 3 Nm are applied after 2 seconds of simulation

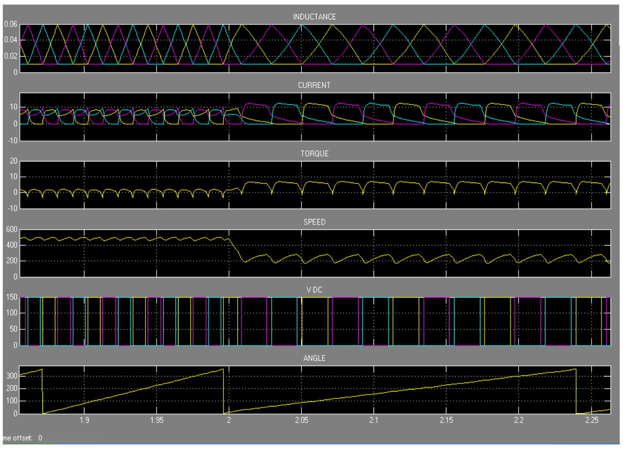

Figure 6.Simulation results of open loop SRM

V. CONVERTER TOPOLOGIES IN SRM

Asymmetric bridge converter

The asymmetric bridge converter considering only one phase of the SRM is shown.. The rest of the phases are similarly connected. Turning on transistors $T1$ and $T2$ will circulate a current in phase A of the SRM. If the current rises above the commanded value, $T1$ and$T2$are turned off. The energy stored in the motor winding of phase A will keep the current in the same direction until it is depleted. Hence, diodes $D1$and diodes D 2will become forward biased leading to recharging of the source. The classic converter is one in which two switch per phase are employed. The upper transistor is used to control the amount of current in the ending, while the lower transistor synchronizes the proper operation of that phase with the rotor position sensor

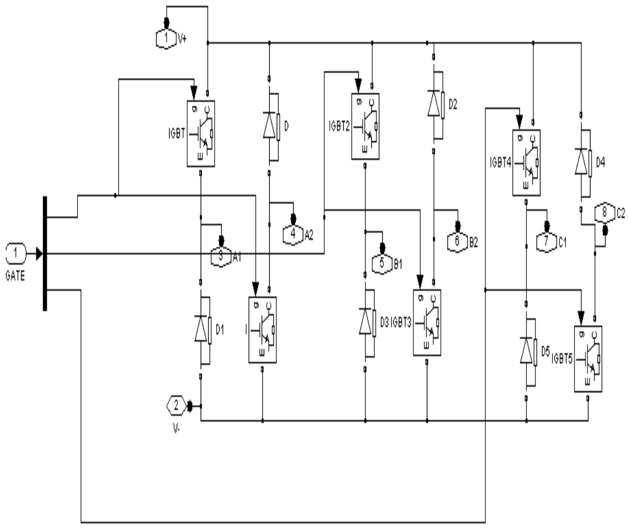

Figure 7Asymmetric bridge converter

Miller converter

In an Miller converter circuit for N phase motor one transistor is common to all the phases for the control of the current ,while the other transistor are used for the proper operation of the phases.

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This type of converter circuit directs the excess energy back to the source through a diode.[4]

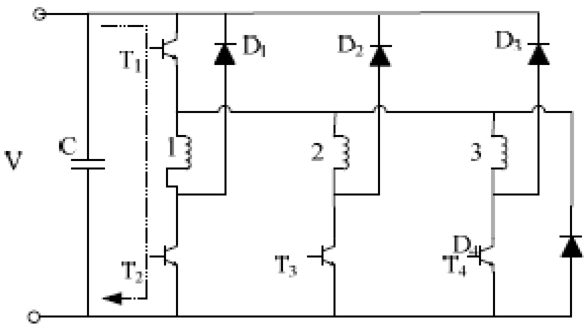

Figure 8.Miller converter

When transistor T1 and T2 are ON, current flows through phase 1. When transistor T2 is off and T1, T3 are switched ON, then current flows through phase 2 and phase 1 current do not reduces to zero as it freewheels through T1 and D1. Similarly when T2, T3 are OFF , AND T1,T4 are ON , current flows through phase 3.and phase 1 and phase 2 currents do not reduce to zero as it freewheels through T1,D1 and T1,D2 . Again when phase 1 is switched on then current in phase 2 and phase 3 has not reduced to zero. Hence at higher speeds the current start rising in each phase before reaching the zero value causing negative torque and excessive heat in the windings

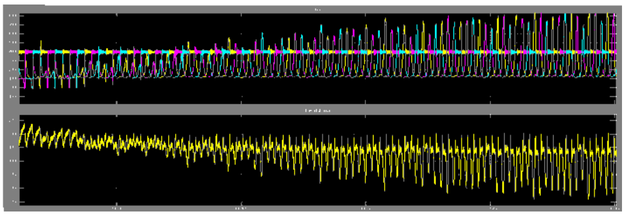

Figure 9.current and torque

The pulses of switching signals are as follows

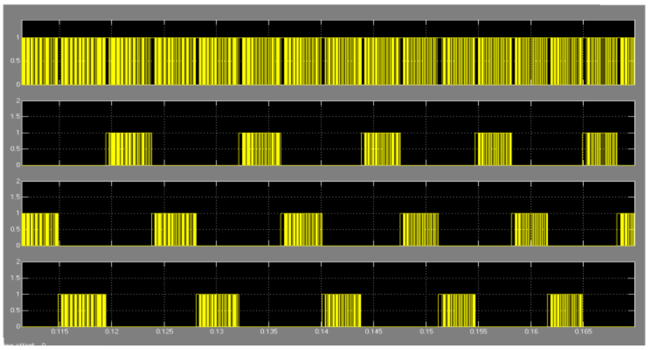

Figure 10.Switching pulses

Modified miller converter

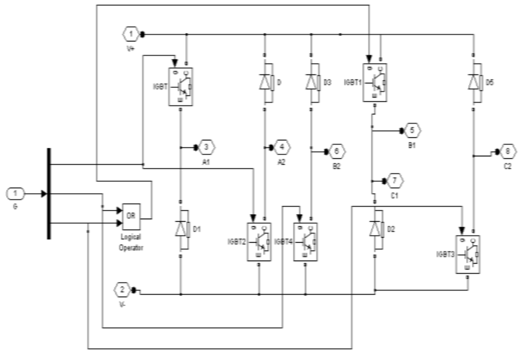

Figure 11 . Modified miller

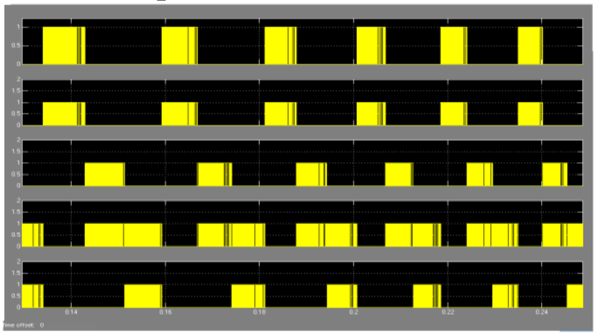

Figure 12 .Pulses of switching signals

T_1, T_{21} on-current flows through phase1 &T_1, T_{21} off, T_{22}, T_3 on current flows through phase2 & phase1 current reduced to zero through D_{21}, D_1 . T_{22}off and T_3, T_4 on current flows through phase3. Phase1 current reduced to zero & Phase2 current freewheels through T_3, D_{22} .Again when phase1 is on ,Current in phase3&2 reduced to zero &I_{ph2} take some time to reduced to zero & all phase currents reduced to zero

VI. CONTROL STRATEGIES OF SRM.

Current and speed control

In the control method the magnitude of the current flowing into windings is controlled using a control loop with a current feedback. The current in a motor phase winding is directly measured with a current/voltage converter or a current sense resistor connected in series with the phase. [5]The current is compared with a desired value of current, forming an error signal. The current error is compensated via a control law, such as a PID, and an appropriate control action is taken. The block diagram below shows that both current and position feedback are needed for controlling the SR motor. Position feedback is needed to synchronize the current flow, with respect to the rotor position, in order to generate the desired motoring torque.[6] Position feedback is also needed to compute the rotor mechanical speed, which is compared with the desired value of speed

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Block Diagram of SRM

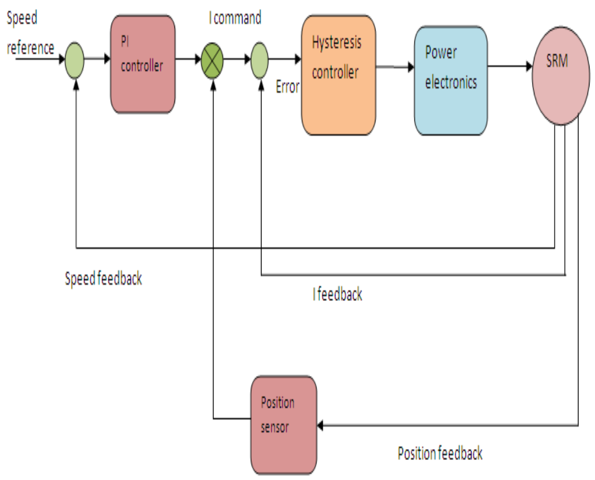

Figure13. Block diagram

SRM with asymmetric bridge converter

The Matlab Simulink diagram for the current control using asymmetric bridge converter is given as follows

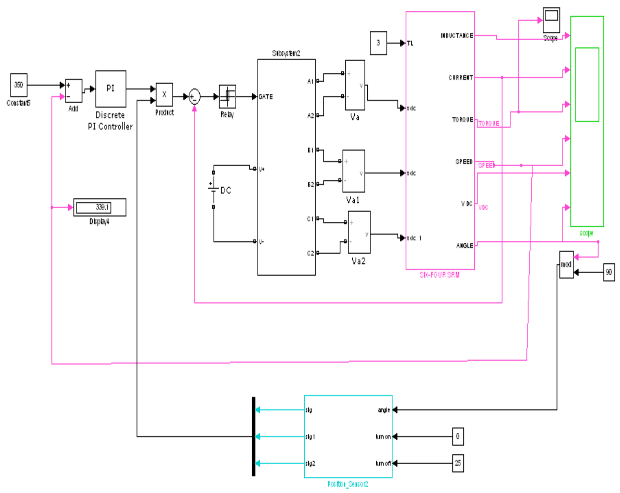

Figure 14 Closed loop SRM model

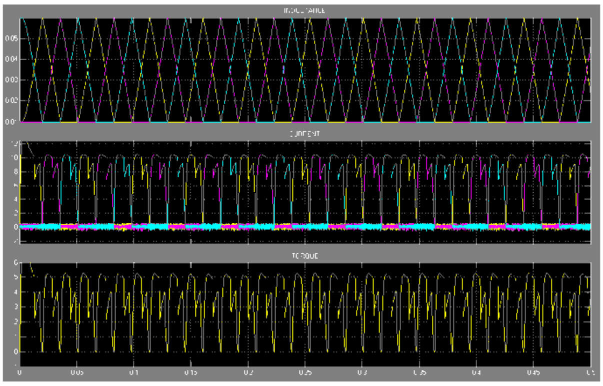

Figure 15. Simulation result with asymmetric converter

SRM with Miller converter

Miller converter is having (n+1) switches for n phases. Although it reduces the number of switches, the problem of overlapping of phase currents at higher speeds creates a problem of negative torque.The Matlab Simulink diagram for the current control using miller converter topology is done The simulation results are as follows

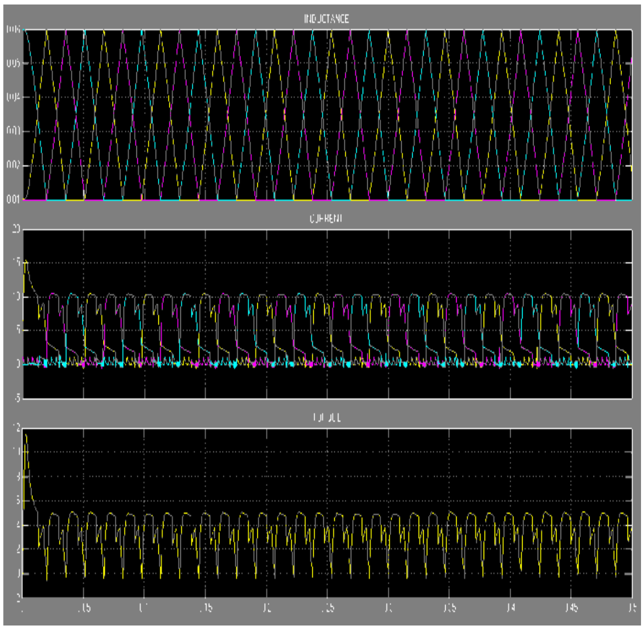

Figure 16. Simulation result with miller converter

SRM with modified Miller

Modified miller topology have (2n-1) switches for n phase SRM. The converter topology help to improve the problem of overlapping of phase currents.

The simulation results of modified miller using Matlab Simulink are as follows

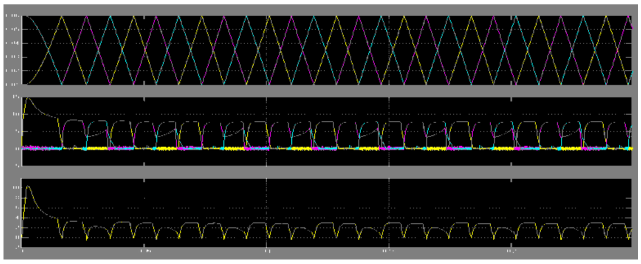

Figure 17. Simulation results with modified miller converter

VII. POWER SPECRUM DENSITY (PSD)

Power spectral density function (PSD) shows the strength of the variations(energy) as a function of frequency. In other words, it shows at which frequencies variations are strong and at which frequencies variations are weak.Computation of PSD of torque wave form in each cases is done directly by the method called FFT or computing autocorrelation function and then transforming it. In open loop SRM, PSD gives different frequencies corresponding to variable power levels. This means there are higher ripple content in the open loop SRM

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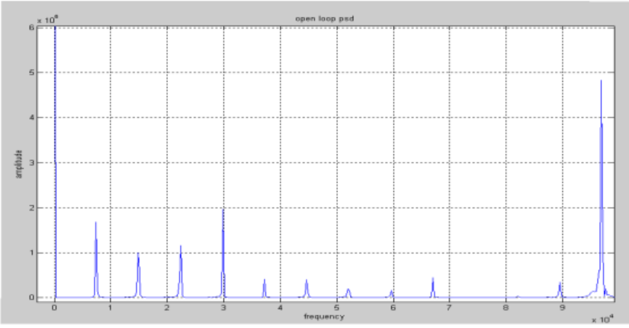

Figure 18. Power spectrum of torque in open loop SRM

The closed loop operation of SRM gives ripple less torque waveforms. when we do the PSD of the corresponding torque waveforms using asymmetric, miller ,modified miller converter topologies less number of variable frequencies with different energy levels compared to open loop SRM are obtained which proves the control of SRM with converters helps to minimize the torque ripples in switched reluctance motor.

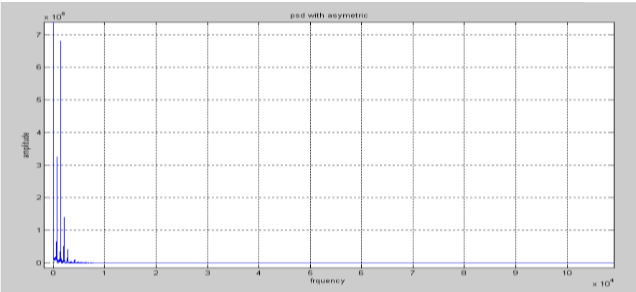

Figure 19 .Power spectrum of torque with asymmetric converter

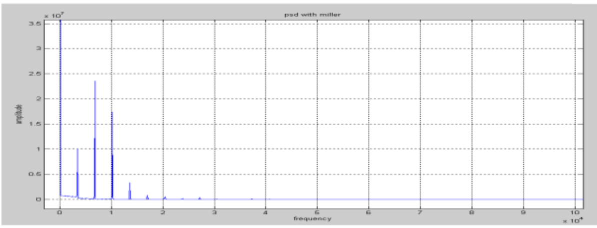

Figure 20.Power spectrum of torque with Miller converter

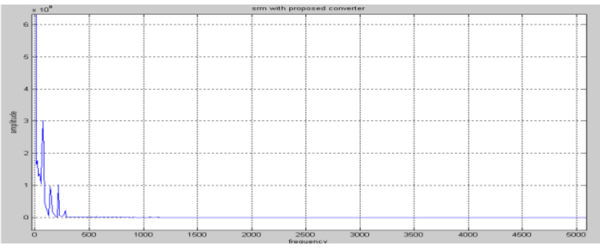

Figure 21. Power spectrum of torque with modified miller

IX. CONCLUSION

In this paper, mathematical modelling of SRM and advanced PI and hysteresis controllers for SRM position control have been presented. The parameters of the speed PI controller are adjusted according to the load torque and rotor speed. The control scheme is based on the various converter topologies and it is capable for maintaining the torque ripple at an acceptable level over a wide speed range. Thus, it provides quick response and high-precision position control of the SRM drive. The proposed control scheme has been applied on a three-phase 6/4 SRM, with asymmetric, miller and modified miller converter topologies and several simulation results have been presented. Power spectrum density of the torque waveforms has been studied. Asymmetric converter is having six switches topology for three phases. Miller topology is having four switches but there is a problem of overlapping of phase currents and less utilisation of the devices at higher speeds. Modified miller converter topologies have number of switches greater than miller converter and lesser than asymmetric bridge converter. Also the problem of overlapping of phase currents has been reduced resulting in lesser torque ripples and can be used for closed loop operation of switched reluctance motor

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