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Torque Ripple Minimization in Switched Reluctance Motor Drives by Using Converter Topology

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ABSTRACT

Switched Reluctance motor (SRM) is gaining prominence due to its simple and rugged construction, absence of permanent magnets, low cost, fault tolerant capability and development in power electronics. Non-linear inductance profile and pulse magnetizing make the torque ripple unavoidable. But machine design and electronic control approaches have been used to minimize the torque ripple. The torque ripple can be reduced by improving the magnetic design of the motor and by using sophisticated electronic control techniques. The mathematical modeling of three phase 6/4 switched reluctance motor (SRM) is developed and integrated with different power converter topologies i.e. asymmetric bridge converter, miller converter and modified miller converter in Matlab/ Simulink environment along with hysteresis current control method.
Keywords: Switched Reluctance Motor, Asymmetric Bridge Converter, Miller Converter, Modified Miller Converter, Hysteresis Current Control.

I. INTRODUCTION

With the advent of modern control technology and power electronics, switched reluctance motor drive is 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 phase 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 systems, where its presence is 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 [1],[3].

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 [4], [5].

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 increase in the average torque, since the motor capabilities are not being fully utilized at all power levels [4].

II. MATHEMATICAL MODELLING

An equivalent circuit neglecting the mutual inductance between the phases as follows. [1, 4, 7]

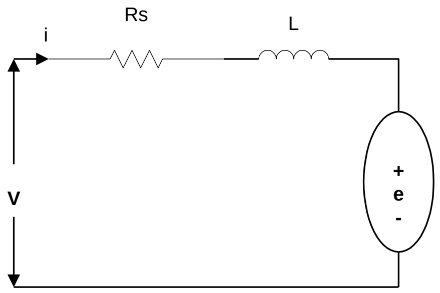

Figure 1. Equivalent circuit of SRM

The applied voltage to a phase is equal to the sum of the resistive voltage drop and the rate of the flux linkages as,

$$V = Rsi + \frac{d\lambda(\theta, i)}{dt} \quad (1)$$

Where,

Rs is the resistance per phase, and λ is the flux linkage per phase given by,

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

Where, L is the inductance dependent on the rotor position and phase current.

The phase voltage is given by,

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

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

The right hand side represents the resistive voltage drop, inductive voltage drop and induced emf respectively and the result is similar to the series excited dc motor voltage equation.

The induced emf e is obtained as,

$$e = i * \omega \frac{dL(\theta, i)}{d\theta} \quad (5)$$

The electromagnetic torque developed is,

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

This completes development of the equivalent circuit and equations for evaluating electromagnetic torque, air gap power and input power to the SRM both for dynamic and steady state operations.

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

Where,

TL is the load torque (N/m)

J is the inertia of the rotating torque (Kg.m2)

B is the frictional coefficient (Nms)

w is the angular speed (rad/s)

III. TORQUE EXPRESSIONS

The instantaneous torque per phase is expressed as the rate of change of co-energy with respect to position at constant current. [8]

$$\mathrm{T_{phase}} = \frac{\partial W'(i, \theta)}{\partial \theta} \quad (8)$$

Where, $W'(i,\theta)$ is the co-energy and is given by

$$W'(i, \theta) = \int_0^i (\psi) \quad di \quad (9)$$

Where, ψ denotes the flux linkage.

The total instantaneous torque of motor is given by sum of all the individual phase torques.

$$\mathrm{T_{total}} = \sum_{phases} \mathrm{T_{phase}}(i, \theta) \quad (10)$$

The average torque expression is obtained by integrating equation (10) over a time interval T.

$$\mathrm{T_{Average}} = \frac{1}{T}\int_0^T \mathrm{T_{total}} \quad dt \quad (11)$$

Torque ripple is defined as the difference between maximum and minimum total instantaneous torques expressed as percentage of average torque.

$$Torque \quad ripple = \frac{\mathrm{T_{total}(max)} - \mathrm{T_{total}(min)}}{\mathrm{T_{Average}}} * 100\% \quad (12)$$

IV. CONVERTER TOPOLOGIES

The mutual coupling between the phases is negligible in SRMs. This gives complete independence to each winding for control and torque generations. This unique feature of the SRM, together with the fact that the stator phases are electrically isolated from one another, has generated a wide variety of power circuit configuration.

A. Asymmetric Bridge Converter

The most versatile and most flexible SRM converter is the bridge converter as shown in figure 2 which requires two switches and two diodes per phase.

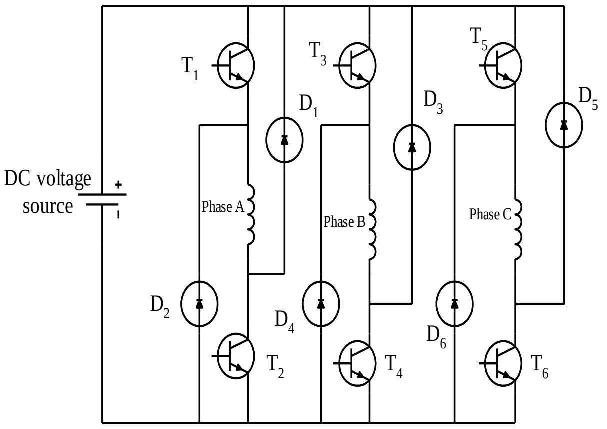

Figure 2. Asymmetric Bridge Converter

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 D1and diodes D2 will 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. [4]

The switching sequence to complete a full 360 rotation for the motor with six stator poles and four rotor poles is as shown by the truth table 1.

Table 1. Switching sequences of Switches in Asymmetric Bridge Converter. [13]

Cycle	**Phase**			**Position**
	A	**B**	**C**	
1	ON	OFF	OFF	0
	OFF	ON	OFF	30
	OFF	OFF	ON	60
2	ON	OFF	OFF	90
	OFF	ON	OFF	120
	OFF	OFF	ON	150
3	ON	OFF	OFF	180
	OFF	ON	OFF	210
	OFF	OFF	ON	240
4	ON	OFF	OFF	270
	OFF	ON	OFF	300
	OFF	OFF	ON	330

5	ON	OFF	OFF	360

B. Miller Converter:

The Miller converter for a three phase drive is as shown in figure 3. In this converter, chopping is performed by one switch common to all phases.

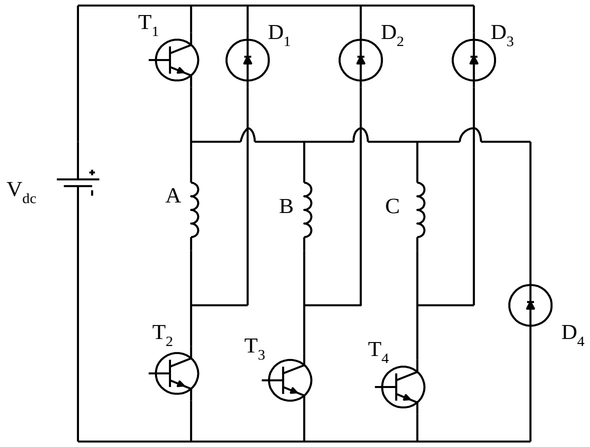

Figure 3. Miller Converter

The Circuit requires (n+1) switches for an n-phase motor. When T1, T2are turned on, current flows through T1, T2 and phase 1 winding, When T2is turned off, the current in phase A goes through T1and D1. When T1is turned off current in phase A goes through D4and D1. A similar procedure occurs when phase B and C are excited. During normal operation the conducting phase shifts between the adjacent legs, however, the current in the phases do not drop to zero before next Turn-ON and therefore current in windings go on rising. When transistor T1and T2 are ON, current flows through phase A. When T2 is off and T1, T3are switched ON then current flows through phase B and phase A current do not reduces to zero as it freewheels through T1and D1. Similarly when T2, T3 are off and T1, T4 are ON current flows through phase C and phase1 and phase B current do not reduces to zero as it freewheels through T1, D1 and T1, D2. Again when phase A is switched on then current in phase B and phase C has not reduced to zero. Hence the current start rising in each phase before reaching the zero value causing negative torque and excessive heat in windings. [9]

C. Modified Miller Converter:

The Modified Miller converter for a three phase drive is as shown in figure 4. When the transistor T1 and T2 are switched on the current flows through phase A. When T1, T2 are off and T3, T4 are switched on then current flows through phase B and phase A current reduces to zero through D2 and D1.

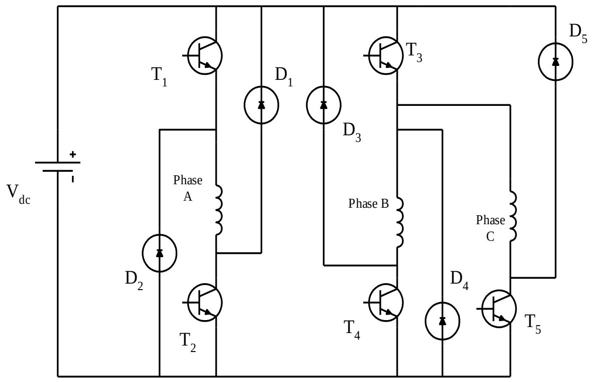

Figure 4. Modified Miller Converter

Similarly when T4, is off and T3, T5 are switched on current flows through phase C then phase A current reduces to zero and phase B current do not reduces to zero as it freewheels through T3, D3. Again when phase A is switched on then current in phase C and phase B reduces to zero. Here only phase current B takes time to reduce to zero. But all the phase currents reduce to zero. [10].

V. CONTROL STRATEGY

In this paper two control strategies is discussed under open loop control of Switched Reluctance motor.

A. Open Loop Control of SRM:
The combination of hysteresis current control and angle position control comes under open loop control of SRM.

a. Hysteresis Current Control:
Turning ON Switches will circulate a current in phase of the SRM. If the current rises above the commanded value, the switches are turned OFF. The current command or reference current value is enforced with a current feedback loop where it is compared with the phase current. The current error is proceeding through a hysteresis current controller with the current window. When the current error exceeds current window, the switches are turned OFF simultaneously. At that time freewheeling diodes take over the current and complete the path through the dc source. [4]

b. Angle Position Control:
When the phase current changes slowly, so select angle position control to control phase current i.e. phase current is controlled by controlling conduction angle (θon) and shuff off angle (θoff).[3]

From above analysis, the control strategy that combines Current Chopping Control and Angle Position Control can improve operating performance of SRM. In specific operating area, we adopt voltage Pulse-Width Modulation (PWM) control strategy which can adjust speed by adjusting duty ratio to get optimal controlling result.[11,14]

VI. PROPOSED SYSTEM AND SIMULATIONS

System considered for the comparative analysis by simulation in Matlab using asymmetric bridge converter, miller converter and modified miller converter is as shown in figure.5.1

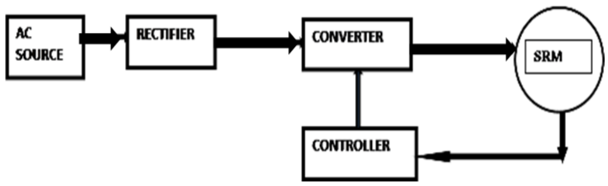

Figure 5.1. Block diagram of Switched Reluctance Motor

Parameter for three phase 6/4 SRM which is considered for analysis and simulation is reported in table 2. [1]

Table 2. Parameters for three phase 6/4 SRM

Machine Parameters	Values	Units
Power	2	hp
DC link voltage, Vdc	150	Volts
Stator Resistance, Rs	1.3	Ohm
Frictional coefficient, f	0.0183	Nm/rad/sec
Moment of inertia, J	0.0013	Kgm2
Aligned Inductance, Lmax	60	mH
Unaligned Inductance, Lmin	8	mH
Reference Current, Iref	10	Amphere
Speed	2600	rpm

In the scheme the input ac mains is converted into DC supply by means of rectifier or can be directly obtain from batteries in order to provide a dc input source to the SRM converters. An analysis is made by using all three converters with hysteresis current control. Comparative analysis for current, torque and speed have been made for all three converters.

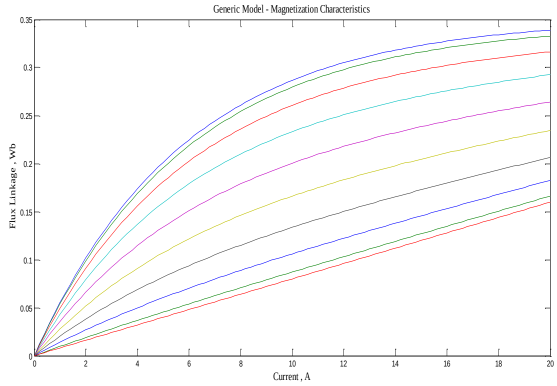

Figure 5.2. Magnetization Characteristics of SRM

Figure 5.2 shows the magnetic characteristics of three phase 6/4 SRM for different values of phase current and rotor position revealing the saturation effects. The inductance is minimum when the rotor and the stator are unaligned position. On the other hand it reaches its maximum value for the aligned position, where the saturation regime is reached more easily. The curve is not linear and shows that for large currents there are large saturation effects. The lowest curve corresponds to the unaligned position and the curve of the top corresponds to the aligned position.

A. Asymmetric Bridge Converter

The simulation results of current, torque and speed for current control using asymmetric bridge converter is as shown in figure 6, 7 and 8 respectively. This converter contains constant and non-overlapping phase winding current which results in torque ripple.

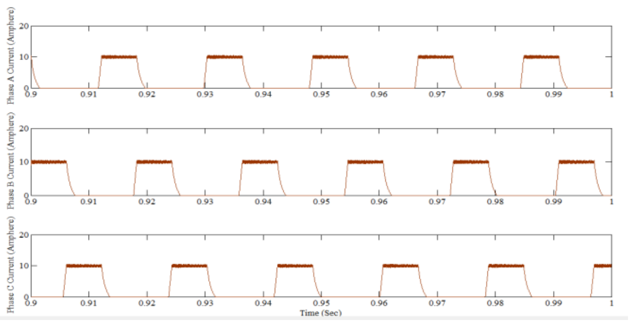

Figure 6. Phase current waveform for Asymmetric Bridge Converter

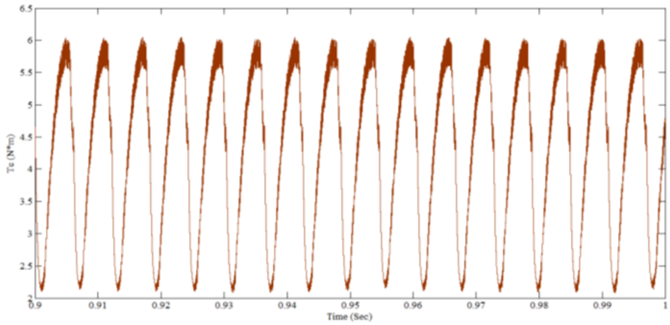

Figure 7. Torque waveform for Asymmetric Bridge Converter

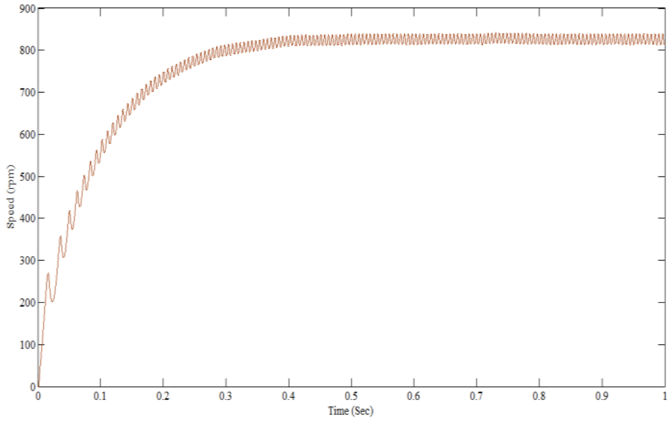

Figure 8. Speed waveform of Asymmetric Bridge Converter

B. Miller Converter:

The simulation results of current, torque and speed waveform for hysteresis current control using Miller Converter are shown in figure 9, 10 and 11.

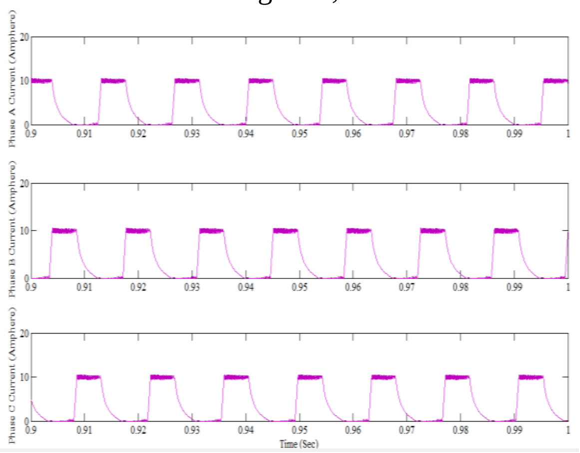

Figure 9. Phase current for Miller Converter

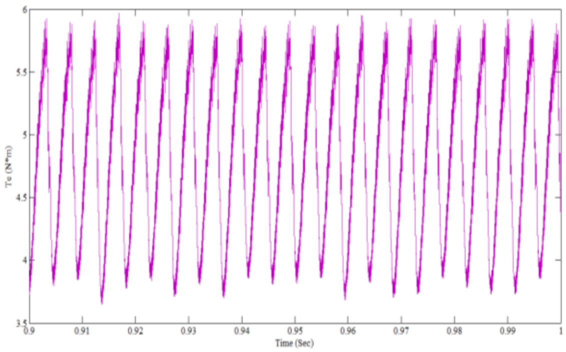

Figure 10. Torque waveform for Miller Converter

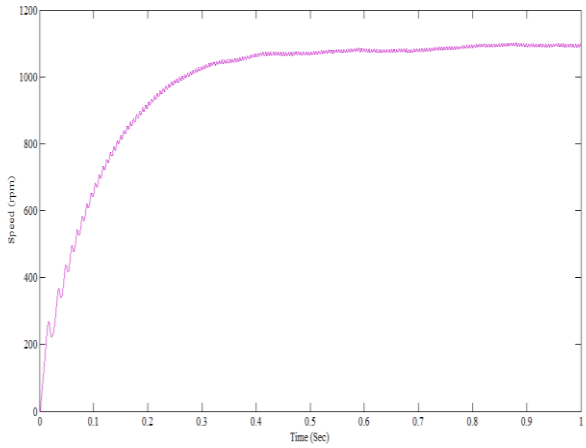

Figure 11. Speed waveform of Miller Converter

In this converter the current in each phase do not drop to zero before next turn on and therefore current in windings go on rising. Hence, as the current start rising in each phase before reaching the zero value which causing negative torque and excessive heat in the winding. As one switch is common for all phases, the problem of continuous current overlapping takes place which in result reduces the average torque ripple.

C. Modified Miller Converter:

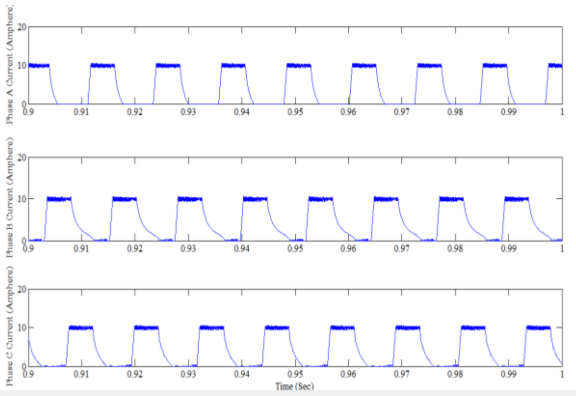

Figure 12. Phase current for Modified Miller Converter

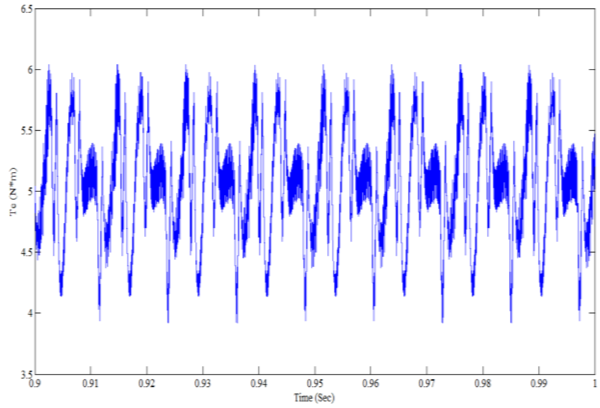

Figure 13. Torque waveform for Modified Miller Converter

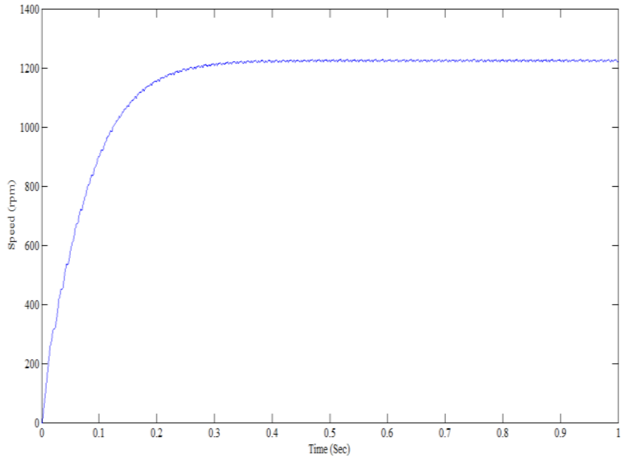

Figure 14. Speed waveform for Modified Miller Converter

The simulation results of current, torque and speed waveform for hysteresis current control using Modified Miller Converter are shown in figure 12, 13 and 14. After one phase conduction, only one phase winding current do not decays to zero. Thus, modified miller converter reduces the phase winding constant current overlapping and excessive heat in the winding.

The torque ripples and overlapping of current is less in Modified miller converter as compared to Asymmetric Bridge Converter and Miller Converter as reported in figure (6-14). This results in improvement in overall performance of SRM using Modified Miller Converter.

VII. CONCLUSION

Performance analysis of the three phase 6/4 Switched Reluctance Motor is determined by using asymmetric bridge converter, miller converter and modified miller converter in the Matlab environment. An overview of three different converter topologies i.e. asymmetric bridge converter, miller converter and modified miller converter are analyzed. In asymmetric bridge converter the overall torque ripple is 93.29% and that of miller converter is 48.35%. There is decrease in torque ripple by 49.94%. The overall torque ripple of modified miller converter is 42% this means torque ripple gets reduces by 51.29%. Although most of the converters achieve satisfactory minimization of torque ripple each converter has its limitations and therefore, choice of the converter depends upon application requirement.

Reduction in torque ripples and phase current distortion is comparatively less in modified miller converter as compared to asymmetric bridge converter and miller converter which results in smooth operation of Switched Reluctance Motor (SRM). It has been analyzed that the proposed modified miller converter is capable of simulating the performance of the given model operating over a wide speed range.

VIII. ACKNOWLEDGMENT

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