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. The primary disadvantage of an SRM is the higher torque ripple with conventional machines, which contribute to acoustic noise and vibrations. The torque ripple can be reduced by improving the magnetic design of the motor and by using sophisticated electronic control techniques. This paper presents a comparative performance of an SRM for various parameters such as torque, current, and speed using asymmetric bridge converter, miller converter and modified miller converter topologies. Performance is simulated in Matlab environment considering three phase 6/4 SRM at no load.

Index Terms— Switched Reluctance Motor, Asymmetric Bridge Converter, Miller Converter, Modified Miller Converter, Hysteresis Current Control.

I. INTRODUCTION

The industrial requirements give more focus on speed and torque variation in various applications from transportation to robotics which can vary with cost, size, user comfort and efficiency. SRM comes under various applications requiring high performance of the drive. This is due to their various advantages such as simple, high speed and fault tolerance control capabilities.[1,4,5].

The conventional way to operate a SRM consists in supplying unidirectional current pulses sequentially to each of the SRM phase coils. The current pulse could be controlled by its amplitude and on and off timing. The current pulse form depends largely on the SRM speed, i.e., the voltage drop equivalent to a back electromagnetic force (back emf). Due to its special construction, i.e., the lack of a clear magnetic excitation current and nearly zero mutual inductance between the SRM phases, the equivalent back emf is due to the change of the self-inductance of the excited phase, during the rotor movement. At low and intermediate rotor speeds, due to a low back emf, the source voltage is sufficient to impose a rather rectangular current pulse though the excited phase coils. At high speeds, the back emf becomes quite large. As a result, the current pulse is no longer rectangular but becomes rather triangular.[14-18].

Because of the wide variety of switched reluctance motors it is desirable either to have a general model of SRM, in which the phase number is one of the parameters, or to be able to build models of SR motors with specified number of phases using standard modeling elements for one phase. The latter approach has been chosen. As it was stated earlier, for a well-designed SRM mutual interaction between phases is negligible. Therefore, having a model of one phase, a complete model of the motor can be created for any phase number. Using such a model of SRM, its electromagnetic characteristics are calculated individually for each phase, whereas its torque is established by combining the individual torque contributions of the phases.[2]

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.[3]

Torque ripple is inversely related to the smoothness of current transfer between phases, and it is possible to minimize the ripple during transition by controlling currents in the overlapping phases.[3]

The use of power electronic simulation software together with a circuit-oriented model of SRM makes possible the analysis of the complete SR drive system. Therefore, analysis of new converter supply topologies and control methods are possible.[3]

A new practical and simple approach to model and simulate a SRM on the assumption that the SRM phase inductance profiles have triangular shapes whose peak values depend on the electrical current through the phase windings due to magnetic saturation. A SRM inverter with a single high-side IGBT and a low-side IGBT per phase was designed and constructed for a three-phase 6/4 SRM. The control system strategy consisted of two simultaneous actions: adjusting the motor speed using voltage pulse width modulation (PWM) and regulating the advanced firing angles as a function of the desired motor speed.[6]

This paper deals with comparative performance of SRM for torque, current and speed using asymmetric bridge converter, miller converter and modified miller converter under Hysteresis Current Control i.e. open loop control of SRM at no load condition.
II. MATHEMATICAL MODELLING

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

\[ V = R_s i + \frac{d\lambda(\theta, t)}{dt} \]  

(1)

Where,

\( R_s \) is the resistance per phase, and \( \lambda \) is the flux linkage per phase given by,

\[ \lambda = \lambda(\theta, t) \]  

(2)

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

The phase voltage is given by,

\[ V = R_s i + \frac{d\lambda(\theta, t)}{dt} \]  

\[ V = R_s i + L\frac{d\lambda(\theta, t)}{dt} + i \frac{d\phi(\theta, t)}{dt} \]  

(3)

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,

\[ e = i \frac{d\lambda(\theta, t)}{dt} \]  

(5)

The electromagnetic torque developed is,

\[ T_e = \frac{1}{2} i^2 \frac{d\phi}{d\theta} \]  

(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.

\[ T_e - T_i = J \frac{d\omega}{dt} + B\omega \]  

(7)

Where,

\( T_i \) is the load torque (N/m)
\( J \) is the inertia of the rotating torque (Kg.m^2)
\( B \) is the frictional coefficient (Nms)
\( \omega \) 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]

Where, \( \psi \) denotes the flux linkage.

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 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 3600 rotation for the motor with six stator poles and four rotor poles is as shown by the truth table 1.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Phase</th>
<th>Switches in Asymmetric Bridge Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>ON</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>OFF</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>OFF</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>OFF</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>OFF</td>
</tr>
</tbody>
</table>

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

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.

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.

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]

The Circuit requires (n+1) switches for an n-phase motor. When T1, T2 are turned on, current flows through T1, T2 and phase 1 winding. When T2 is turned off, the current in phase A goes through T1 and D1. When T1 is turned off current in phase A goes through D4 and 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 T1 and T2 are ON, current flows through phase A. When T2 is off and T1, T3 are switched ON then current flows through phase B and phase A 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 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]

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:

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.

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 ($\theta_{on}$) and shuff off angle ($\theta_{off}$).[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).

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

![Figure 5: Block diagram of Switched Reluctance Motor](image)

![Figure 6: Phase current waveform for Asymmetric Bridge Converter](image)

![Figure 7: Torque waveform for Asymmetric Bridge Converter](image)

Table 2: Parameters for three phase 6/4 SRM

<table>
<thead>
<tr>
<th>Machine Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2</td>
<td>hp</td>
</tr>
<tr>
<td>DC link voltage, $V_{dc}$</td>
<td>150</td>
<td>Volts</td>
</tr>
<tr>
<td>Stator Resistance, $R_s$</td>
<td>1.3</td>
<td>Ohm</td>
</tr>
<tr>
<td>Frictional coefficient, f</td>
<td>0.0183</td>
<td>Nm/rad/sec</td>
</tr>
<tr>
<td>Moment of inertia, $J$</td>
<td>0.0013</td>
<td>Kgm$^2$</td>
</tr>
<tr>
<td>Aligned Inductance, $L_{max}$</td>
<td>60</td>
<td>mH</td>
</tr>
<tr>
<td>Unaligned Inductance, $L_{min}$</td>
<td>8</td>
<td>mH</td>
</tr>
<tr>
<td>Reference Current, $I_{ref}$</td>
<td>10</td>
<td>Amphere</td>
</tr>
<tr>
<td>Speed</td>
<td>2600</td>
<td>rpm</td>
</tr>
</tbody>
</table>

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.

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.
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:

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 8: Speed waveform of Asymmetric Bridge Converter

B. Miller Converter:

Figure 9: Phase current for Miller Converter

Figure 10: Torque waveform for Miller Converter

Figure 11: Speed waveform of Miller Converter

Figure 12: Phase current for Modified Miller
Comparative Performance Analysis Of Switched Reluctance Motor Using Converter Topology

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.

CONCLUSION

Performance analysis of three phase 6/4 SRM is determined by using asymmetric bridge converter, miller converter and modified miller converter in the Matlab environment. Reduction in torque ripples and phase current overlapping is comparatively less in modified miller converter as compare to asymmetric bridge converter and miller converter which results in the smooth and torque free operation of Switched Reluctance Motor (SRM).

REFERENCES

[14] H. E. Akhtar, V. K. Sharma, —Modelling simulation and performance analysis of SRM operating with optimum...
value of fixed turn-on and turn-off switching angles, IEEE 2003, pp.392-402.


***

Comparative Performance Analysis Of Switched Reluctance Motor Using Converter Topology