

OPEN LOOP AND CLOSED LOOP PERFORMANCE OF SRM DRIVE WITH A NEW CONVERTER TOPOLOGY

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ABSTRACT

Switched Reluctance Motor (SRM) has become a competitive selection for many applications of electric machine drive systems recently due to its relative simple construction and its robustness. It not only features a salient stator with concentrated coils, which allows earlier winding and shorter end returns than other types of motors, but also features a salient pole rotor, which has no conductors or magnets and is thus the simplest of all electric machines. In this paper, the design of new converter, consisting of Half-bridge IGBT modules and SCRs for open loop and closed loop control of switched reluctance motor drives are proposed. The proposed converter topology is the variation of asymmetric bridge converter. In order to verify the proposed converter topology for SRM drives, it is verified through open loop and closed loop control through MATLAB/SIMULINK environment.

Keywords: *Switched Reluctance Motor Drives, Asymmetric Bridge Converter, Converter Topology.*

I. INTRODUCTION

The Switched Reluctance Motor (SRM) drives have recently gained considerable attention among researchers due to several reasons. In construction, the SRM is simplest of all electric machines. Only the stator has windings. The rotor contains no conductors or permanent magnets. It consists simply of steel laminations stacked onto a shaft. It is because of this simple mechanical construction that SRMs carry the promise of low cost, which in turn has motivated a large amount of research on SRMs in the last decade. The mechanical simplicity of the device, however, comes with some limitations. Like the brushless DC motor, SRMs cannot run directly from a DC bus or an AC line, but must always be electronically commutated. Also the saliency of the stator and rotor is necessary for the machine to produce reluctance torque, causes strong non-linear magnetic characteristics, complicating the analysis and control of the SRM. Not surprisingly, industry acceptance of SRMs has been slow. This is due to combination of perceived difficulties with the SRM, the lack of commercially available electronics with which to operate them, and the entrenchment of traditional AC and DC machines in the market place.

Fig.1 shows the cross section of an 8/6 pole four phase basic switched reluctance motor. It has been realized [1], that the reluctance motor requires only unipolar or unidirectional currents and this gives rise to the possibility of operating with only one switching device in series per phase, instead of two in series in each phase leg of an AC or brushless DC drive.

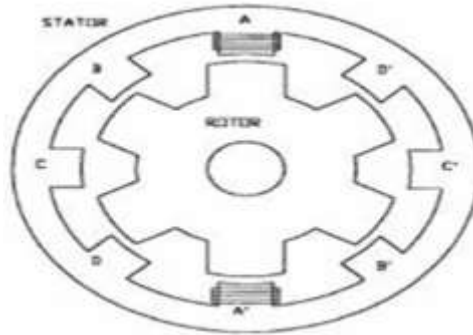


Fig.1: Basic Switched Reluctance Motor

True reluctance machine in the sense that both rotor and stator have variable reluctance magnetic circuits, or, more properly, it is a double salient machine. The concept of switched reluctance machine is very old, going back to the 19th century inventions called “electromagnetic engines” [3], which were the forerunners of modern stepper motors. The switched reluctance motor is basically a stepper motor and has had many applications as both rotary and linear steppers. The idea of using the SR configuration in a continuous mode (on contrast to a stepper mode) with semiconductor control is due primarily in 1960’s [4]. At that time only thyristor power semiconductors were available for the relatively high-current, high-voltage type of control needed for SR machines. These years, power transistors, GTOs, IGBTs and power MOSFETs have been developed in the power brushes required for SRM control [5]. SR motors eliminate permanent magnet (PMs), brushes and commutators. As the windings are electronically commutated, the torque ripple and acoustic noise are the two awkward issues which have to be tackled. All these make the control of SRM a tough challenging.

II. OPERATION AND MATHEMATICAL MODELLING OF SRM

The basic operating principle of the SRM is quite simple: as current passed through one of the stator winding, torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position which can be determined by the position sensor [7]. Generally increasing the number of SRM phases reduces the torque ripple, but at the expense of requiring more electronics with which to operate the SRM. At least two phases are required to guarantee starting, and at least three phases are required to ensure the starting direction. The number of rotor poles and stator poles must also differ to insure starting. Also, the torque of SRM drive is related to the rotor position and the inductance or flux linkage. The typical inductance characteristics in a four-phase SRM drive are shown in the Fig 2.

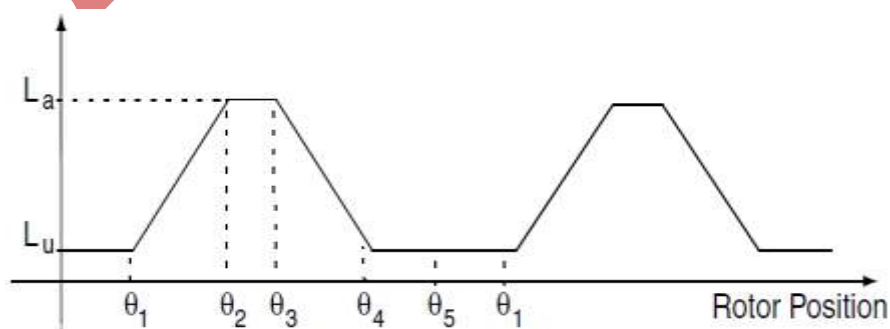


Fig.2: Inductance Characteristics

Another important feature of an SRM drive is that the mutual coupling between phases can be neglected. It makes the independent current control possible. Meanwhile, the lack of mutual coupling brings about the problem of dealing with the stored magnetic field energy. An additional path has to be provided for the magnetic field energy during phase commutation. Otherwise, it will result in excessive voltage across the windings and hence on the power switches leading to their failure. Neglecting the mutual coupling between phase windings and regarding all components as ideal ones, the operation of an SRM drive can be described as

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

Where R_s is the resistance per phase and λ the flux linkage per phase given by

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

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

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

The induced emf 'e' is expressed as

$$e = \frac{dL(\theta, i)}{d\theta} \omega_m i = K_p \omega_m i \quad (4)$$

Multiplying both sides of the equation (3) with the current gives the instantaneous power.

$$P_i = Vi = R_s i^2 + L(\theta, i) i \frac{di}{dt} + \frac{dL(\theta, i)}{d\theta} \omega_m i^2 \quad (5)$$

The energy stored in an inductor is given by

$$W = \frac{1}{2} L i^2 \quad (6)$$

Power in an inductor is given as the change in energy over time. The product rule gives

$$P_L = \frac{d}{dt} \left(\frac{1}{2} L i^2 \right) = \frac{1}{2} i^2 \frac{dL}{dt} + L i \frac{di}{dt} = \frac{1}{2} i^2 \omega \frac{dL}{d\theta} + L i \frac{di}{dt} \quad (7)$$

Subtracting Equation (7) and $R i^2$ from equation (5) will give

$$P_i = \frac{1}{2} \frac{dL(\theta, i)}{d\theta} \omega_m i^2 \quad (8)$$

Hence, the induced voltage contains information about the rotor position. With constant current, (4) is linked to both increase in magnetic field energy and produced mechanical power. In unsaturated conditions, both terms equal each other, and torque can be expressed as:

$$T = \frac{i^2}{2} \frac{dL(\theta, i)}{d\theta} \quad (9)$$

When $\frac{dL}{d\theta} > 0$ the torque is positive and electrical power is converted into mechanical output (motoring), while $\frac{dL}{d\theta} < 0$ the torque is negative and mechanical power is converted into electrical power (generating). Note that the produced torque is independent of the direction of the current, since i^2 is always positive. With the machine driven in saturation, although equation (9) being no longer valid, these conclusions remain true.

III. EXISTING TOPOLOGY-ASYMMETRIC BRIDGE CONVERTER

For switched reluctance motors, the converter is not fixed till now also, the research is still going on and various topologies viz. resonant, bifilar, split dc supply, r-dump, c-dump, asymmetric bridge converter [8]. In this paper, a new effective converter topology, which can be regarded as a variation of asymmetric bridge topology, is developed. The proposed converter topology overcomes with the disadvantages of the asymmetric bridge

converter topology. Furthermore, it has higher utilization of switching devices. Thus the proposed converter circuit can be designed with more compact configuration, smaller size and lower cost. Among those converters, the asymmetric bridge converter is the most popular and best performed one, in which each phase branch consists of two discrete switching components and two freewheeling diodes, as shown in Fig 3. It is efficient for fault tolerant and independent current control can be accomplished. However, the high switching component counts and the poor utilization are the main disadvantages of this topology. The major disadvantages of asymmetric bridge converter configuration are there are high switching losses and the presence of larger heat sinks [6]. Also, the asymmetric bridge converters are not suitable for high power applications. The major application of asymmetric bridge converter is in low power levels inverters fed from a voltage source.

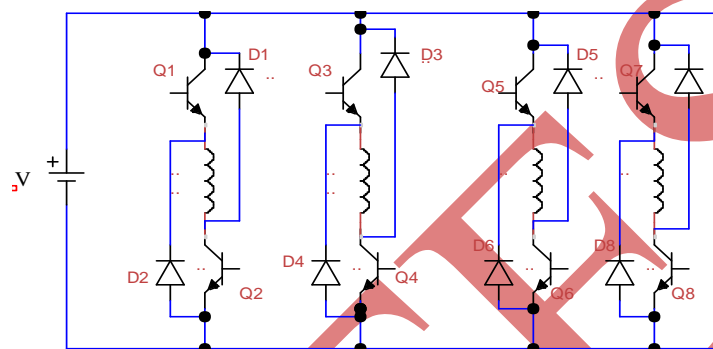


Fig.3: Asymmetric Bridge Converter for Four-Phase SRM Drives

IV. PROPOSED CONVERTER TOPOLOGY

Half-bridge IGBT modules are the popular choice to build asymmetric bridge converters and many other converters in industrial applications, instead of discrete IGBT modules. Because the diodes for freewheeling are necessary even there are build-in diodes in the discrete IGBT modules [4]. It makes the circuit less trustworthy and more complicated. Fig 4 illustrates the phase branch with half-bridge modules for typical SRM converters. It can be seen that each phase branch needs two half-bridge switch modules. Consequently, a four phase SRM drive requires eight half-bridge switch modules. Therefore, the use of half-bridge switch modules in asymmetric bridge converter brings low utilization and high count of switching devices.

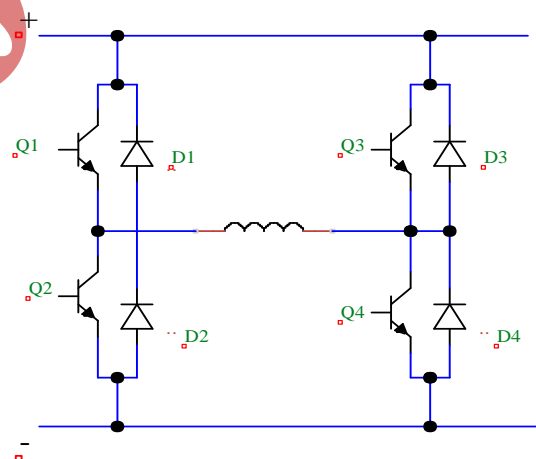


Fig.4: Phase Branch Using Half-Bridge Switch Modules

To figure out the problem, a new converter for SRM drives is developed in this paper. Fig 5 illustrates the proposed converter circuit for four phase SRM drives. It can be observed that the proposed converter needs four half-bridge IGBT modules and four SCRs, in comparative to the eight discrete IGBT modules in asymmetric bridge converters. On the other hand, each phase is controlled by different switching devices. It is helpful to reduce the temperature rise and extend the lifetime of IGBT components.

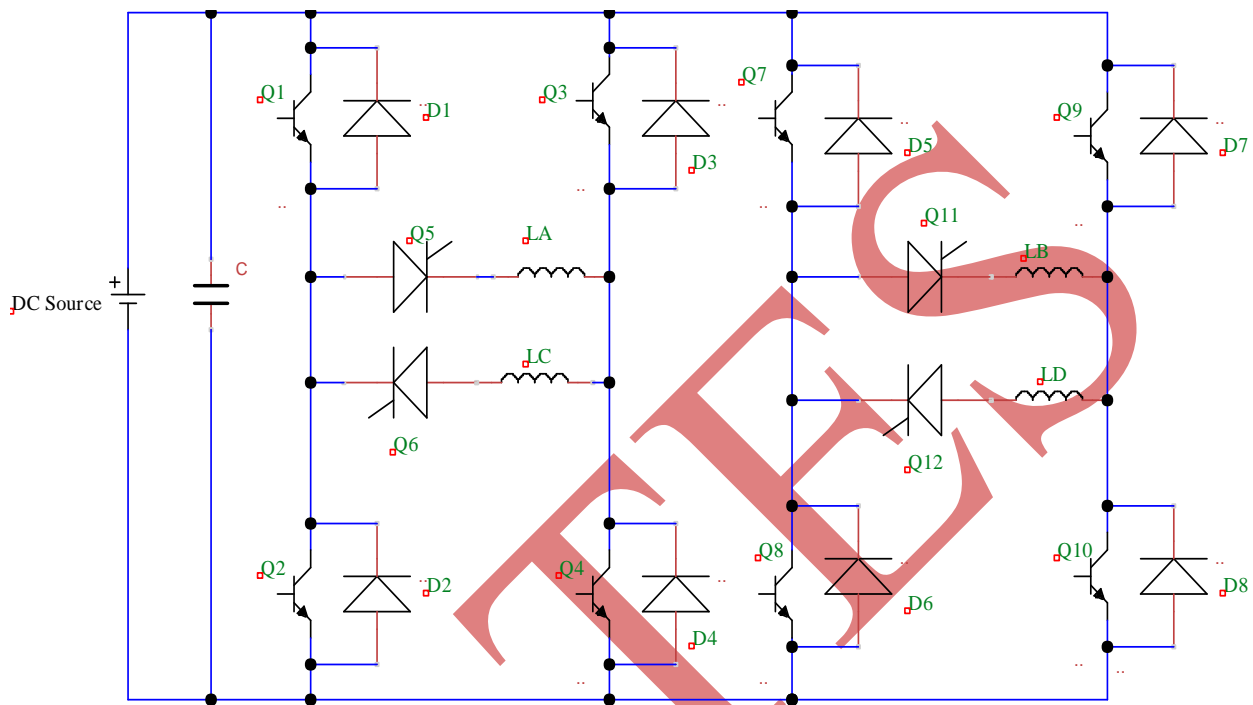


Fig.5: Proposed Converter Topology For Four-Phase SRM Drives

According to the principle of operation of SRM drives, the energy conversion process may occur simultaneously in two adjacent phase, in order to acquire high starting torque and low torque ripple. This mode of operation may cause a current overlap [9]. In the developed converter, therefore alternate phase are grouped together, such as Phase A and Phase C or Phase B and Phase D can be operated at a time.

4.1operation of Proposed Converter

As for the developed converter, the operation of each phase includes three modes, which are named as charging, freewheeling and discharging respectively. For the sake of simplicity, the operations of two phases in a group are analyzed. Fig 6and Fig 7 depict the operations of Phase A and Phase C in a group respectively. The typical gate signals and corresponding current profile are shown in the figures below respectively.

Mode 1: Charging

Referring to figure 6(a) if the switching devices Q1,Q4,Q5 are turned ON, then the DC link voltage is applied to Phase A and then the current rises rapidly in the phase winding. Referring to Fig 7(a) if the switching devices Q2, Q3, Q6 are switched ON, the phase C is charged through the switches Q2,Q3,Q6. This mode is called as charging mode or Energizing mode.

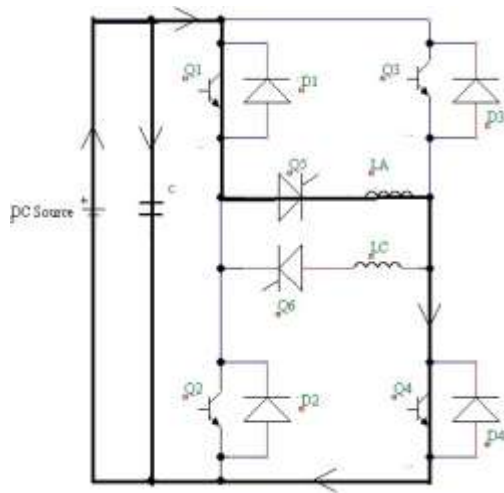


Fig.6 (a): Charging mode for Phase A

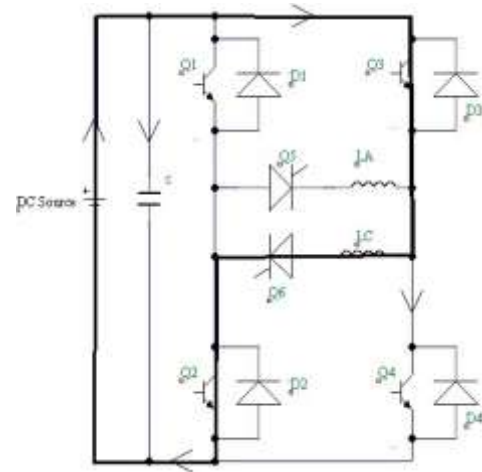


Fig.7(a): Charging mode for Phase C

Mode 2: Freewheeling

Referring to Fig 6(b), it can be seen that if the switch Q1 is turned off and Q4, Q5 are still ON, then current circulates through the switches Q4, Q5 and forward biased diode D2. In the case of Fig7(b), it can be seen that Phase C freewheels through switches Q2, Q6 and diode D4 when the switch Q3 is turned OFF and the switches Q2 and Q6 are still ON. In this mode, there is no energy will be transferred between phase winding and Dc source. This mode is called as Freewheeling mode or unenergized mode.

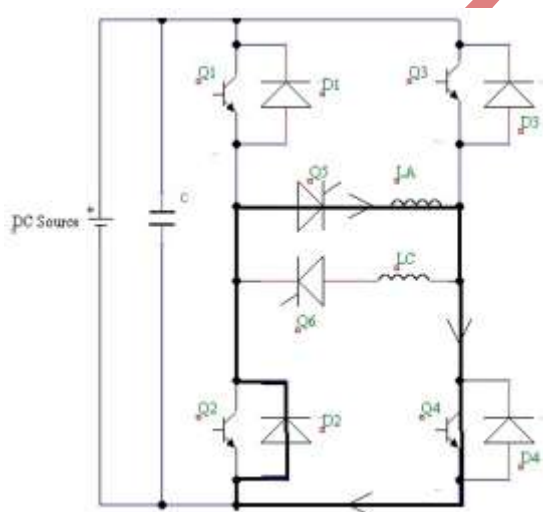


Fig.6 (b): Freewheeling mode for Phase A

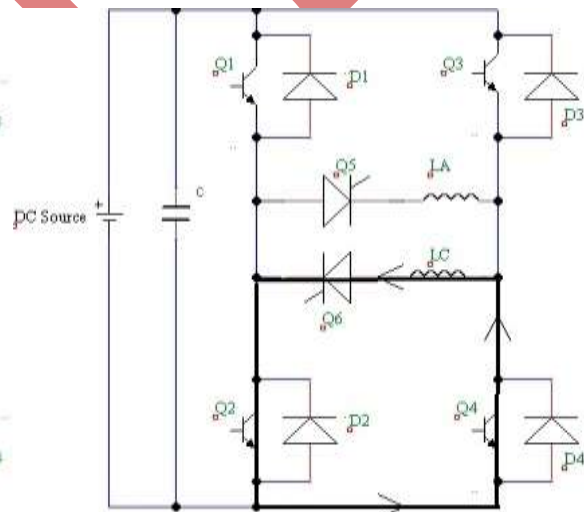


Fig.7 (b): Freewheeling mode for Phase C

Mode 3: Discharging

As shown in Fig 6(c) the switches Q1 and Q4 are turned OFF and the switch Q5 is still turned ON in this mode. Hence Phase A discharges to the DC link capacitor through the diodes D2, D3 and switch Q5. Referring to Fig 7(c) Phase C discharges to the Dc link capacitor through the switch Q6 and the diodes D1 and D4 if the switches Q2 and Q3 are switched OFF and the switch Q^ is still ON. This mode is called as Discharging mode or De-energized mode.

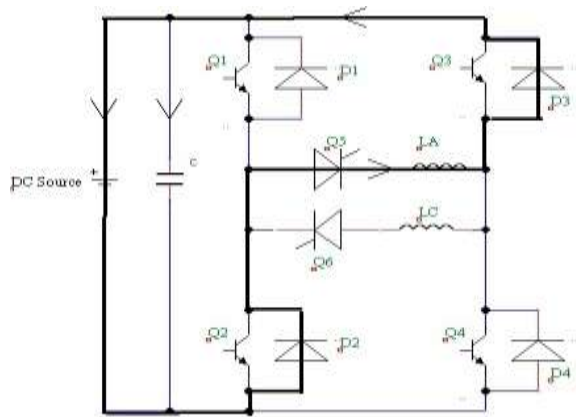


Fig.6(c) Discharge mode for Phase A

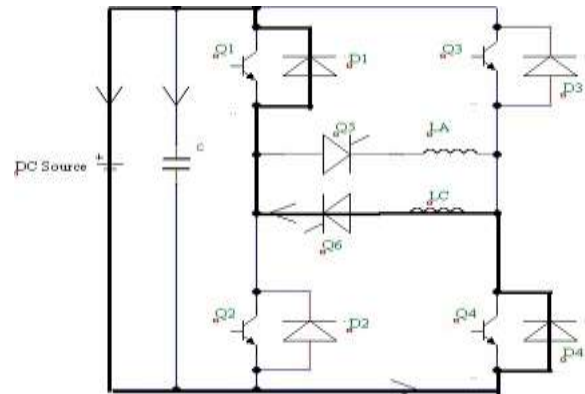


Fig.7(c) Discharge mode for phase C

4.2 Control Methods

From the above analysis and discussion, it can be seen that three conventional control methods for typical asymmetric bridge converters of SRM drives can be realized in the proposed converter. They are the voltage switching method, Speed control method and hysteresis current control method. The voltage switching state includes the charging and discharging modes. The speed control method and hysteresis current control method is composed of the charging, freewheeling and discharging modes respectively.

V. MATLAB/SIMULINK MODELLING AND SIMULATION RESULTS

In order to verify the proposed converter topology for switched reluctance motor drives, the simulation is based on MATLAB/SIMULINK was carried out. The simulation was carried out in both open loop and closed loop configuration. Along with the proposed converter, the SRM drive with the basic converter circuit is also carried out.

Fig 8 shows the matlab/simulink model of basic converter circuit fed SRM drive.

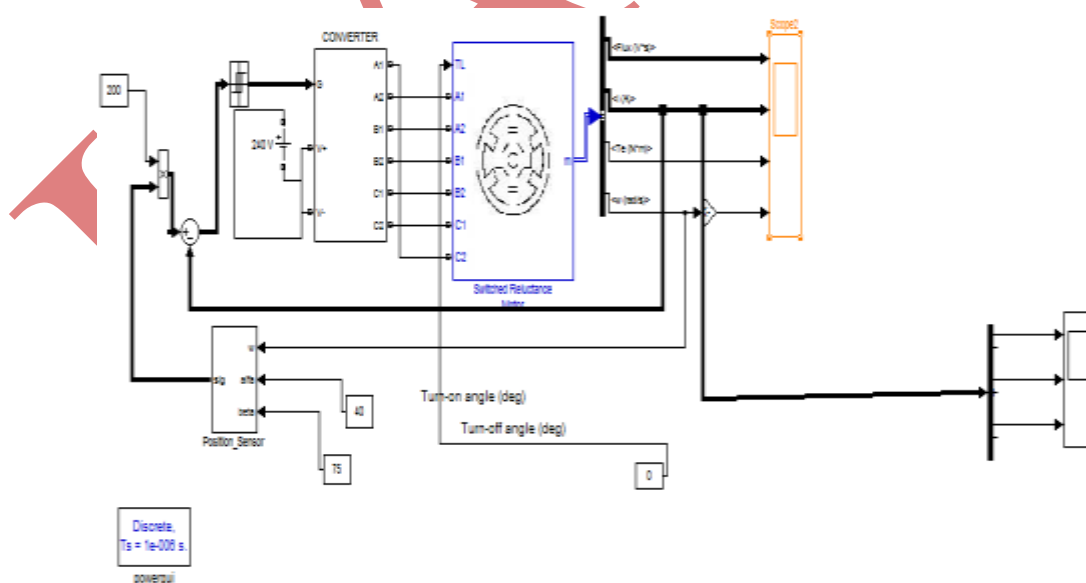


Fig.8: Matlab/Simulink Model of SRM Drive with Basic Converter Circuit

Figure 8(a), 8(b), 8(c), 8(d) shows the resultant waveforms of electromagnetic torque, Current, Flux, Speed of the switched reluctance motor drive when fed through the basic converter circuit.

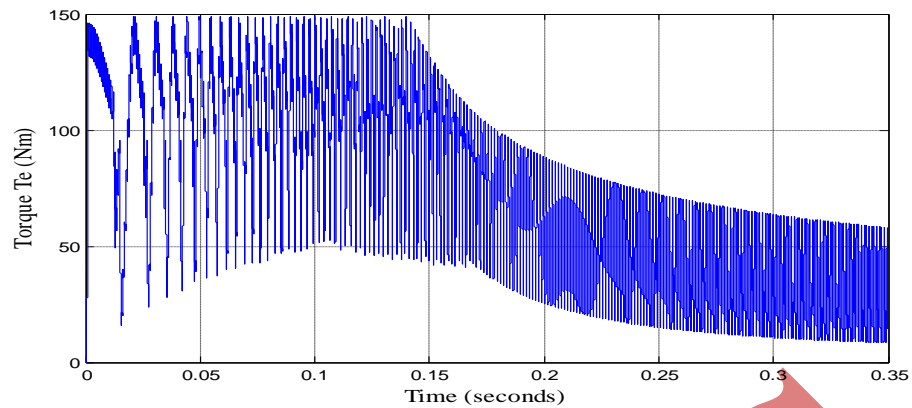


Fig.8 (a) Electromagnetic torque for basic converter circuit of SRM drive

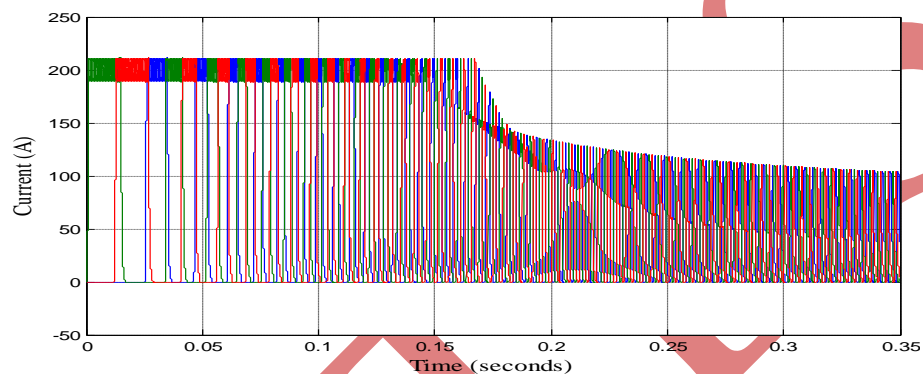


Fig.8 (b) Current for basic converter circuit of SRM drive

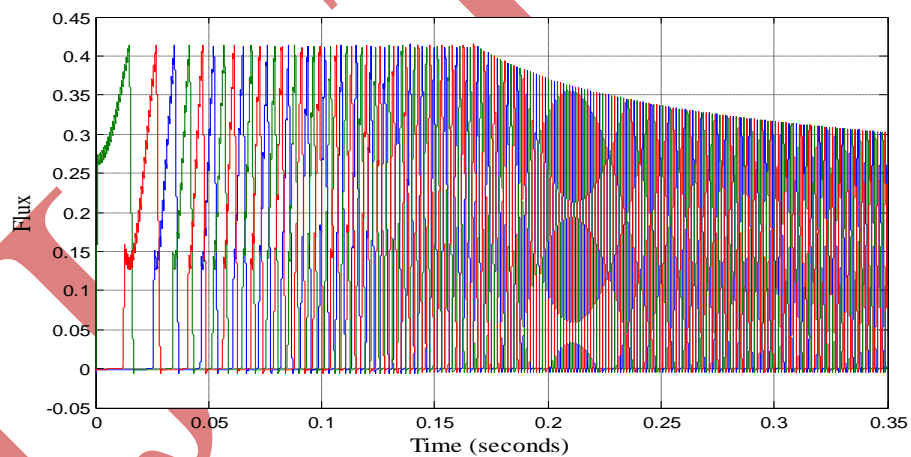


Fig. 8(c) Flux waveforms for basic converter circuit of SRM drive

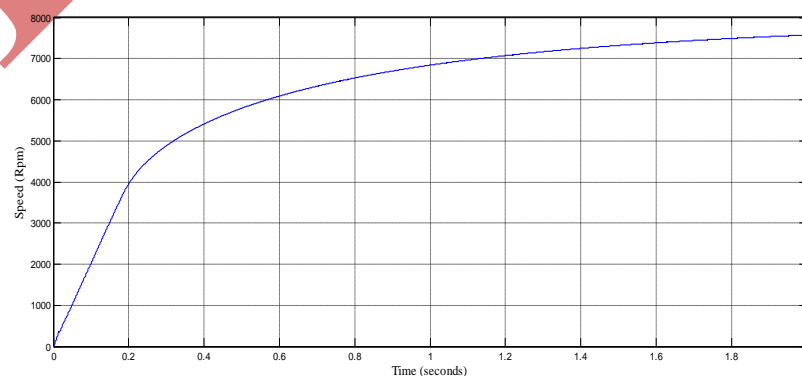


Fig.8 (d) Speed characteristics for basic converter circuit of SRM drive

Fig 9 shows the simulink model of the proposed converter in open loop configuration. The actual speed of the motor is compared with the reference speed. This gives the speed error in the circuit. The speed error is applied to the controller which generates the reference current which generates the required gate pulses for driving the motor. In the open loop system, the controlling cannot be done automatically i.e., the open loop control can only counteract against disturbances for which it has been designed; the other disturbances cannot be removed.

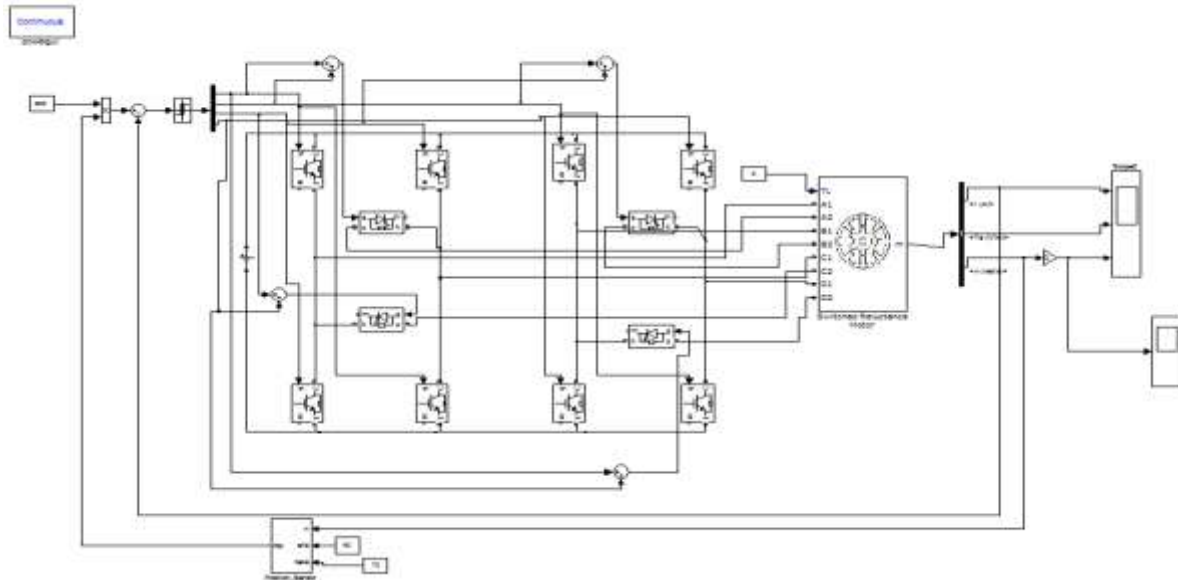


Fig.9: Matlab/Simulink Model of Proposed Converter in Open Loop Configuration

Fig 9(a), 9(b), 9(c) shows the simulation results of electromagnetic torque, current, speed characteristics of the proposed converter in open loop configuration.

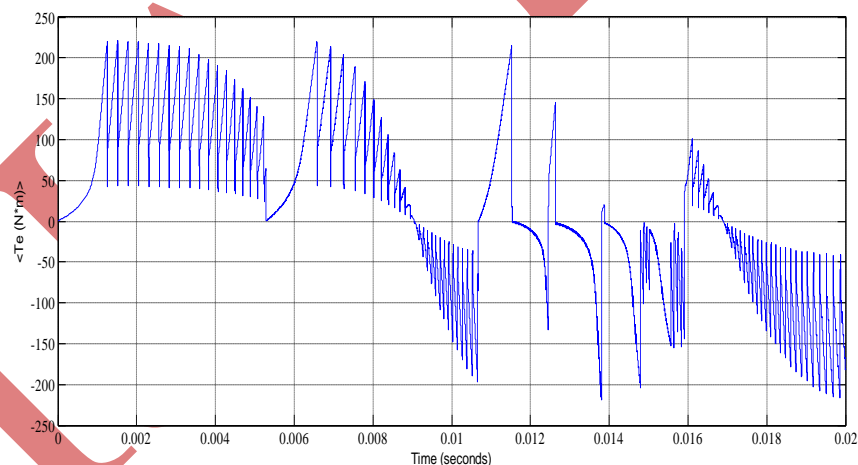


Fig.9 (a) Torque characteristics in Open loop configuration

As the torque is directly proportional to square of the current, the current waveforms vary according to the electromagnetic torque. The speed in the open loop is varying through each phase and it is not maintained constant. Also there will be a slight delay in order to achieve the steady state position i.e. the steady state error will be high. These are the certain disadvantages in the open loop model, which can be easily overcome by the closed loop configuration of the proposed converter.

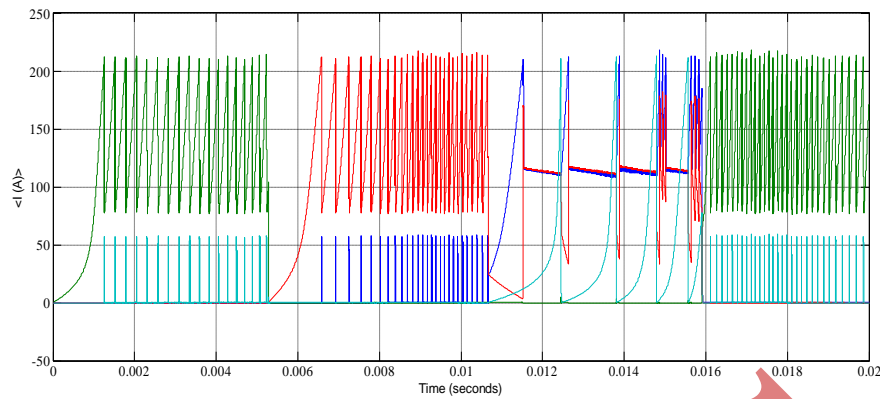


Fig.9 (b) Current characteristics in Open loop configuration

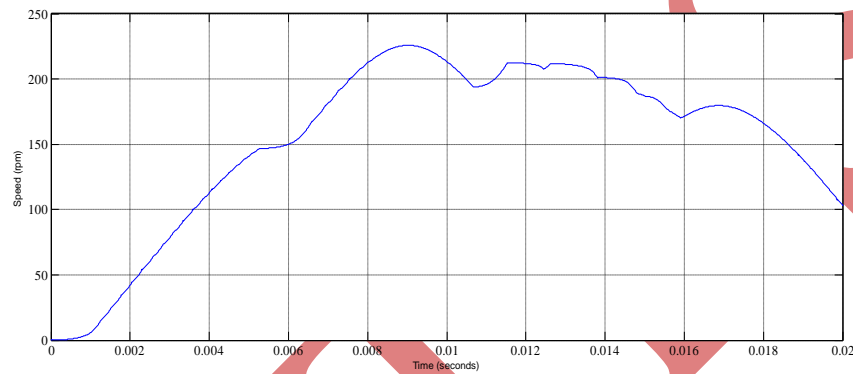


Fig.9 (c) Speed characteristics in Open loop configuration

Fig 10 shows the simulink model of proposed converter in closed loop configuration. In this case, the speed error is passed through a PI controller and a limiter to yield the torque command. From this torque command, the current command is obtained using the torque constant. This torque constant is for the linearized inductance vs rotor position characteristics for a particular value of current. The current command is added and subtracted from the hysteresis window, to determine the switching of the phase and main switches of any converter. The main advantage of closed loop is that this can counteract to any kind of disturbances. The speed is maintained constant. Steady state error can be much reduced compared to the open loop configuration.

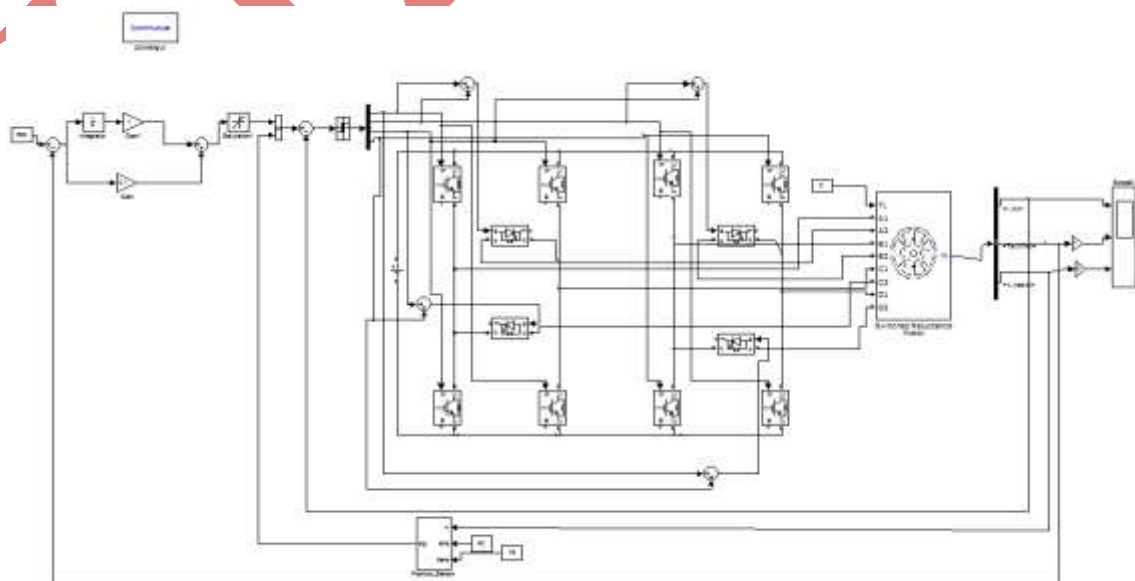


Fig.10: Matlab/Simulink Model of Proposed Converter in Closed Loop Configuration

Fig 10(a), 10(b), 10(c) shows the resultant waveforms of Electromagnetic torque, current, speed of SRM drive of proposed converter in closed loop configuration. Due to the fact that that torque is proportional to square of current the current varies as per the torque induced in the motor. By using closed loop analysis, the speed can be maintained constant; the system can achieve fast response compared to open loop model. The torque ripples are minimized in the case of closed loop compared to that of open loop configuration.

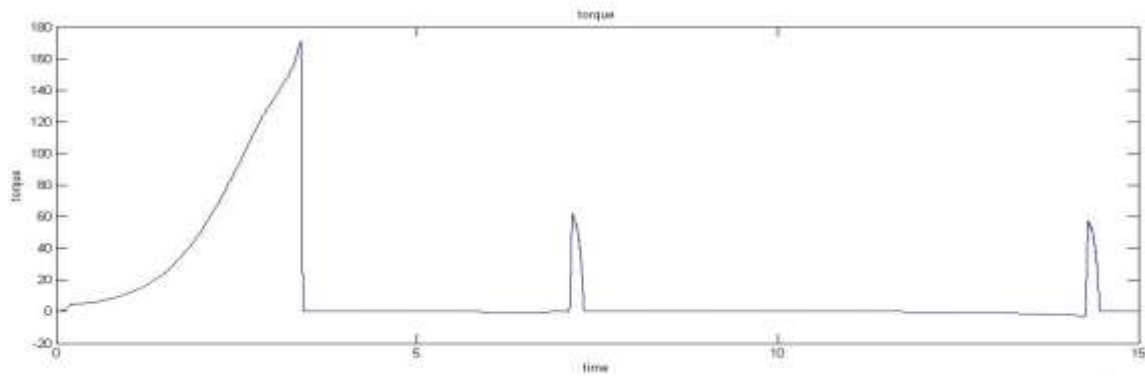


Fig.10 (a) Electromagnetic torque characteristics in closed loop configuration

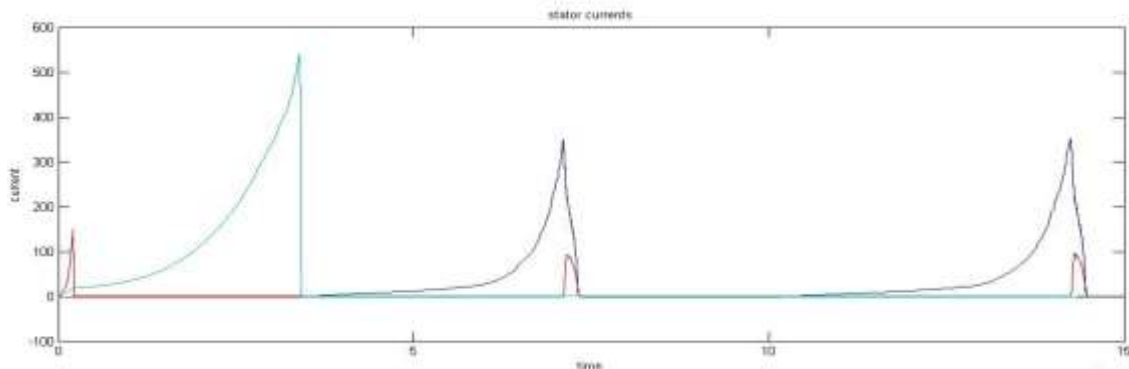


Fig.10 (b) Current characteristics in closed loop configuration

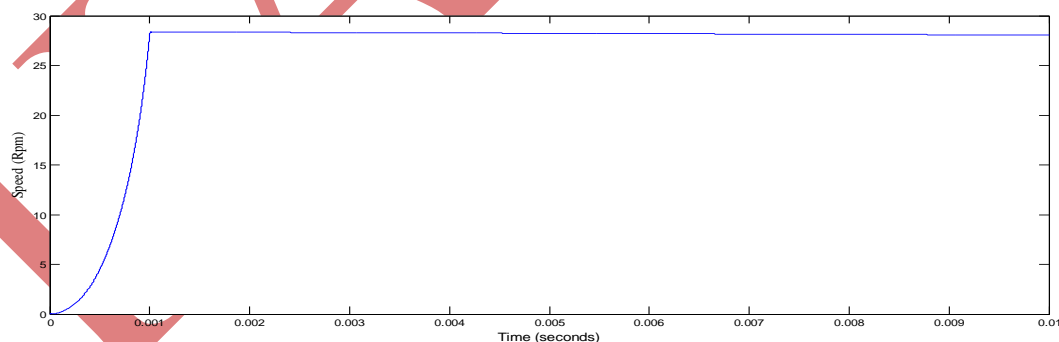


Fig.10 (c) Speed characteristics in closed loop configuration

VI. CONCLUSION



This paper presented the open loop and closed loop control of four phase 8/6 pole switched reluctance motor (SRM) drive. When compared to the asymmetric bridge converter, the proposed converter topology consisting of half-bridge switch modules is more compact and has higher utilization of power switches with lower cost, without degrading their performance. The control schemes enhanced with the SRM drives are presented. The simulation in Matlab/Simulink has demonstrated the proposed converter topology. This new converter topology allows reduction in switching components and thus the performance of the drive can be improved. Now a days,

closed loop control is enhanced all over in order to achieve fast transient response, constant speed of the machine. This method can be applied for all even numbers of phases of the switched reluctance motor drive.

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