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Closed Loop Operation of Switched Reluctance Motor with Hysteresis Controller

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Abstract
The low cost, simple construction of switched reluctance motor, with its features of fault tolerance and the ability to withstand high temperature makes it very attractive for automotive applications. The switched reluctance motors cannot be run directly from a dc or ac source and hence a converter is used to drive the motor as per the desired direction of rotation. A current controller is used to track the rotor current with the reference current values. This paper presents the simulation of the closed loop control of a 6/4 switched reluctance motor driven with an asymmetric converter and a hysteresis controller. The excitation of the different phases of the converter are dependent on the rotor position and are derived from the speed output and the teta output of the motor.

Keywords— Switched Reluctance Motor, Asymmetric Converter, Hysteresis Controller, Speed Position Sensing, Teta Position Sensing

INTRODUCTION
The switched reluctance motor (SRM) have the attraction of simple and robust construction, high temperature and high speed performance, low cost and fault tolerant capabilities. It can achieve very high speeds due of the absence of conductors or magnets on the rotor. Being an electronically commutated drive, it cannot be directly run from an ac line or a dc bus. Its double salient structure causes strong nonlinear magnetic characteristics, complicating its analysis and control.
The conventional converter used to run the switched reluctance motor is the asymmetric converter. When power is applied to the stator phase windings, the rotor magnetic reluctance creates a force that tends to align the rotor pole with the nearest stator pole. In order to maintain rotation, a power electronic converter applies voltage to the windings of successive stator poles in sequence so that the magnetic field of the stator leads the rotor pole. The excitation of the phase windings of the machine are rotor position dependent. The rotor position is computed from the teta output or by integrating the speed output [1].
The hysteresis controller is used to control the current through the stator phase windings. The current error is computed and the gate signals for the switches are generated depending on its relationship to the hysteresis current window. The aim of this paper is to analyze the performance of the closed loop operation of the switched reluctance motor driven with the asymmetric converter and controlled by the hysteresis current controller. The excitation of the phases being dependent on the rotor position, the rotor position is derived from the speed signal and teta output of the machine. In this paper, the closed loop control of the switched reluctance motor is performed speed signal is used to generate the switching signal for the converter rather than the teta output.
The paper is organized as follows. Section II provides the basic features of the switched reluctance motor. Section III presents the principles of asymmetric converter and hysteresis controller used to control the machine. Section IV describes the simulation of the closed loop operation of switched reluctance motor. Section V explains the simulation results generated by SIMULINK with phase activation through speed position sensing and teta position sensing.

SWITCHED RELUCTANCE MOTOR
A. Basic Features of Switched Reluctance Motor
The Switched Reluctance motor consists of a salient-pole stator made of laminated steel and a salient-pole rotor which is usually made from normal electrical steel laminations. The laminations are thinner than those normally used for ac motors in high-efficiency applications and is to reduce the eddy current losses. The reason being that the switching frequency in SRM is higher than for an ac motor with comparable rating and speed. The rotor does not require any rotor conductors or permanent magnets. And hence higher speed of operation is possible for switched reluctance motors [2].
The SRM is an electric machine that converts the reluctance torque into mechanical power where the reluctance torque is produced by the alignment tendency of poles. The rotor will shift to a position of minimum reluctance thereby maximizing the inductance of the excited winding. The SRM is a reliable and a low cost variable-speed drive due to its inherent simplicity [3]. The stator houses a set of coils or windings per salient pole connected in series between the opposing poles. The concentrically wound coils without any phase overlap, results in little mutual inductance between them and ensures a greater portion of copper to be utilized as active length.
Fig. 1 shows the construction of switched reluctance motor with its stator core, windings and the rotor core [4]. The number of rotor and stator poles are generally different to ensure that the rotor is never in a position where the

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electromagnetic torque due to a stator current in any stator phase is zero. Switched reluctance motors with higher number of stator and rotor poles exhibit low torque ripple. By choosing a combination where the stator poles are two more than rotor poles, high average torque and low switching frequency of the converter is ensured.

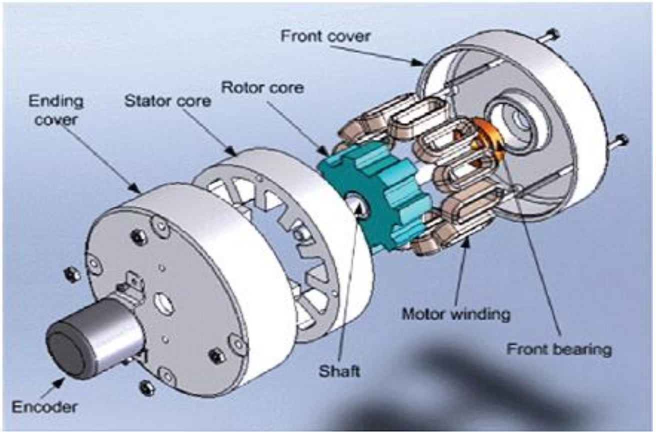

Fig. 1. Construction of switched reluctance motor

A minimum rotor losses and low switching losses in the controller enable high overall system efficiency over wide control range. Hence, SR motors are not designed and optimized to a fixed synchronous speed. Also this produces a higher power (torque) to weight ratio as standard ac or dc motors. Very high starting torque is realizable in SRM permitting prolonged operation in the stall condition because of its low rotor losses. The simple construction of the magnet-free, brushless SR Motor enables integration with the driven machine easier than with more conventional motor [5].

CONTROL OF SWITCHED RELUCTANCE MOTOR

The power converter is a power supply unit used to apply current in each phase in coordination with the rotor position to achieve the desired operating mode and torque output. It is required to activate and commutate the motor phases. Therefore, it does not only deliver energy to an electronic device from an electrical outlet, it also regulates the current to meet specific device requirements. The position detector detects the rotor position as the phase excitation pulses need to be properly synchronized to the rising region of the inductance profile for motoring operation. The controller regulates the motor performance. It derives the gate signals from the rotor position signal which may be realized by a rotor position sensor or a sensor less control procedure [6].

The SRM requires only unidirectional current to operate in all four quadrants, enabling fewer semiconductor switches to be used in the converter design and widens the range of drive circuit options as compared to other motor types requiring bi-directional or sinusoidal current. Because of the inductive nature of each phase winding, the switches must be protected from transients due to the induced voltages after commutation occurs and current must always be provided a conduction path, so freewheeling diodes, so named because they allow current to circulate or freewheel within the circuit after turn-off or some other type of clamping mechanism will also be required.

A. Asymmetric Converter

The Asymmetrical converters are the most commonly converter configuration used with switched reluctance drives. There are two semiconductor switches and two flywheel diodes for each phase winding as shown in Fig. 2. During the period of chopping, one switch is turned on and the other is turned off. The phase current flows through the turned on main switch and the flywheel diode. During the period of commutation, the main switches are turned off and the stored magnetic energy in the motor is fed back to the source with the flywheel diodes by the continuing current [1]. The three states, modes of operation are magnetization, freewheeling mode and demagnetization mode.

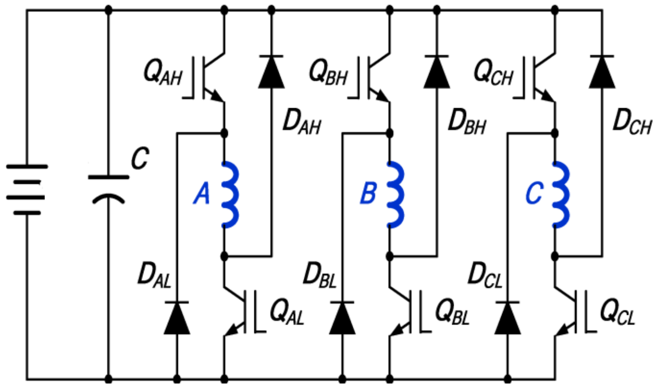

Fig. 2. Asymmetrical converter

During the energization or magnetization mode, both switches of the corresponding phase are on and the current rises rapidly in the phase winding. During the second mode, the freewheeling state, only one switch and one diode are on. Voltage is not applied across the phase winding and the current continues to flow through one switch and one diode, although it is gradually decaying. No energy is transferred to or from the supply. The third mode, demagnetization, occurs when both switches are off and the energy in the phase winding is returned to the supply via the freewheeling diodes. The voltage is reversed across the phase winding which forces the current to rapidly decay to zero [7, 8].

B. Hysteresis Controller

Hysteresis or chopping current control is a control strategy used with SRM for controlling the phase current to be within a band around a reference value. This strategy is preferable over wide speed range for SRM operation as the desired current can be easily reached. The switches of the converter are turned on when the phase current is lower than a lower band limit and turned off when the current is above an upper band limit [9]. The lower limit and the upper limit can be obtained according to the control requirements and the switching frequency of the power converter of SRM.

The hysteresis controller is the most classical and easily implemented controller with the hysteresis band Δi as the only controlling parameter as shown in Fig. 3. The current ripple is equal to Δi and the current controller output takes only two distinct values $\pm V_{dc}$. The current error is computed from which the switching is generated depending on its relationship to the hysteresis current window. The on time of the switches corresponds to the phase winding energisation and off time corresponds to demagnetization of the winding.

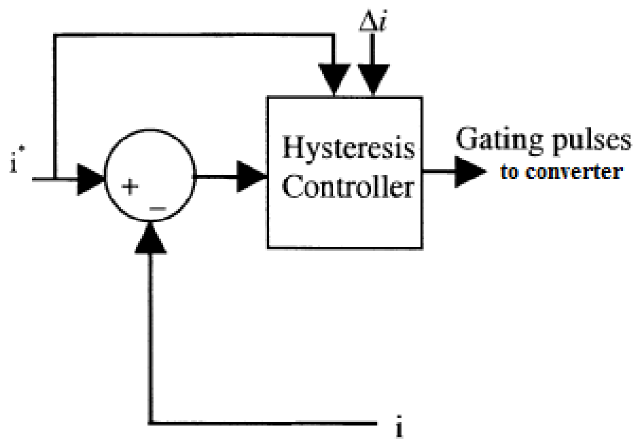

Fig. 3. Hysteresis current controller

The freewheeling corresponding to the interim off times during which the phase conduction time have to be discriminated and coordinated with the current command and outputs of the hysteresis current controller. The modeling is as follows: The current command will be compared to the motor phase current, i_a. The switching logic of the hysteresis controller is summarized as:

If $(i_a^* - i_a) \geq \Delta i$ then $V_a = V_{dc}$

If $(i_a^* - i_a) \leq -\Delta i$ and $i_a^* > 0$ then $V_a = 0$

If $(i_a^* - i_a) \leq -\Delta i$ and $i_a^* \leq 0$ then $V_a = -V_{dc}$

where Δi is the hysteresis window and V_{dc} is the link voltage. It is assumed that the power devices in the converter are ideal, hence their voltage drops and switching times are neglected. The applied voltage is 0 or $-V_{dc}$, depending on the converter configuration and switching strategy for negative current error. When the current error is less than the negative of the hysteresis current window, the applied voltage to the machine phase is zero when the current command is positive, and the applied voltage to the machine phase is negative when the current command is negative.

CLOSED LOOP CONTROL OF SWITCHED RELUCTANCE MOTOR

As the switched reluctance motor is an electronically commutated machine, it need to be driven with a power electronic converter. The conventional asymmetric converter drives the motor as per the required direction of rotation dependent on the sequence of excitation. The gate signals are generated from the hysteresis controller in order to track the current reference signal. The DC supply can be used to excite the phase windings. The closed loop control of a 6/4 three phase switched reluctance motor is performed with the help of computer simulation in SIMULINK.

Fig. 4 shows the SIMULINK model of the closed loop control of switched reluctance motor. The excitation of the windings is dependent on the rotor position. The speed output and the teta output from the motor is used to sense the position of the rotor [10].

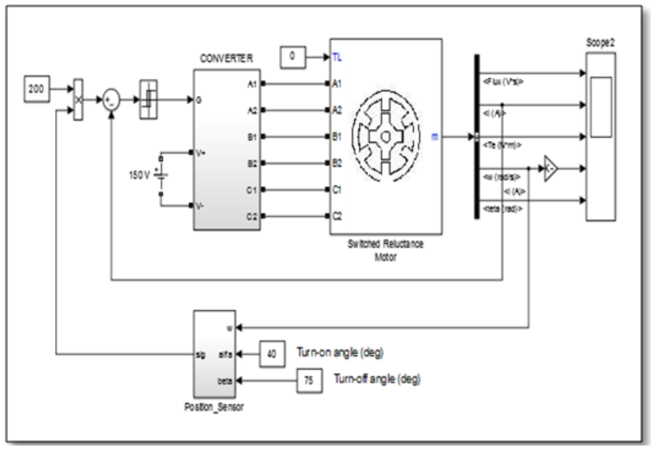

Fig. 4. Simulink model of closed loop control of SRM

The switched reluctance motor used for simulation is a 6/4 configuration SRM taken from MATLAB software with the block parameter specification given in Table 1 [11].

TABLE 1: Block parameters of switched reluctance motor

Parameter	Value
Stator resistance (ohm)	0.05
Inertia (kg.m^2)	0.05
Friction (Nm.s)	0.02
Initial speed and position (rad/s and rad)	0,0
Unaligned inductance (H)	0.67e-3
Aligned inductance (H)	23.6e-3
Maximum current (A)	450
Maximum flux linkage (V-s)	0.486

The SRM block input is the mechanical load torque in Nm which is positive for motoring and negative for generating operation. The block output of SRM is a vector containing stator voltage in V, Flux linkage in Vs, Stator current in A, Electromagnetic torque in Nm, Rotor speed in rad/s and rotor position in rad respectively. Simulation is run in discrete mode and the turn on and turn off angles are kept constant at 40 and 75 respectively [12-13].

RESULTS AND DISCUSSION

The asymmetric converter consists of two diodes and two IGBT switch for each phase. Each phase is excited according to the gate pulses generated depending upon the rotor position such that each phase is excited in every 90 degree rotation of the rotor as there are 4 rotor poles. Same gate pulse is given to both the switches of the corresponding phase. When the gate pulse are high the switch of the corresponding phase is turned on and the supply voltage appears across the supply. An input voltage of 150 V is given to excite the phase windings.

The gate signals for the switches of the corresponding phases are produced depending upon the rotor position. Fig. 5 shows the gate signals for the individual phases. When the gate pulses are high the applied voltage appears across the phase windings of the corresponding phases. Fig. 6 shows the position sensor block using the speed position sensing and Fig. 7 shows the waveforms at different stages of the sensing.

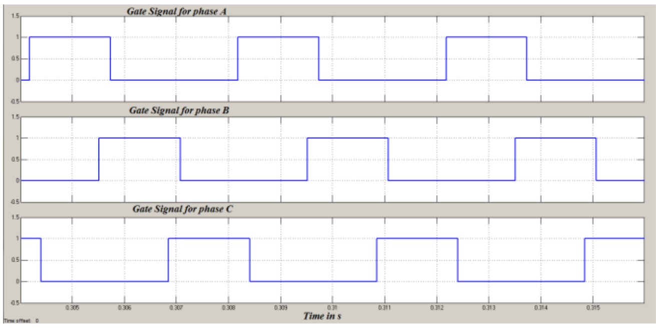

Fig. 5. Gate signals generated for asymmetric converter

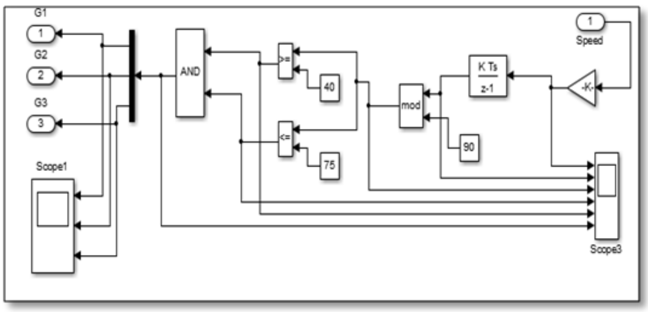

Fig. 6. Simulink model of speed position sensing

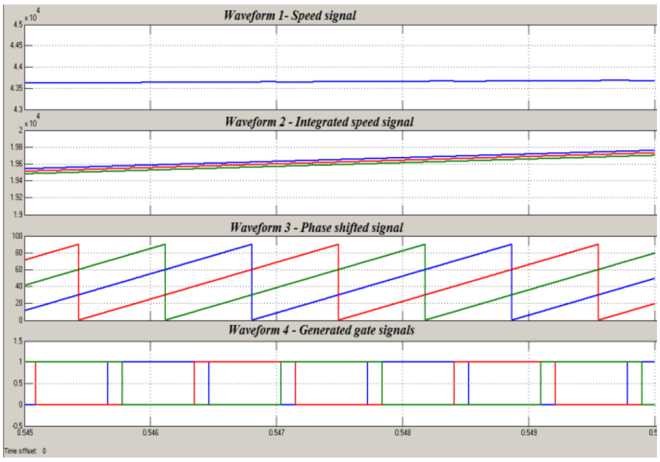

Fig. 7. Different stages of speed position sensing

The speed output from motor in rad/s is initially converted into rpm as in waveform 1 as shown in Fig. 7. The speed signal continuously increases with time. It is integrated to obtain the teta signal shown in waveform 2 and is distributed for the individual phases. The angle position is reset from 0° to 90° using modulus operator and dividing with 90 as shown in waveform 3 and is done to relate the absolute rotor position to position relative to the stroke. The cycle repeats after each 90 degrees.

The angle position signal for each phase are phase shifted by 30° as shown in waveform 3. These signals are compared with the turn on and turn off angles to generate the gate signals for different phases. When teta is between the turn on and turn off angle the gate signal is high triggering the IGBT switches of the particular phase. Waveform 4 shows the generated gate signal for the three phases with phase shift. The signals are high for rotor positions between turn on, 40° and turn off angle, 75°.

Fig. 8 shows the motor performance parameters of the closed loop control of switched reluctance motor with phase activation through speed position sensing. The output voltage has three states coinciding with the output of the asymmetric dump converter which is fed to the phase windings. The current waveform shows a peak while the phase rotor position is between the turn on and turn off angle. Fig. 9 shows the speed and teta output from the motor with speed position sensing.

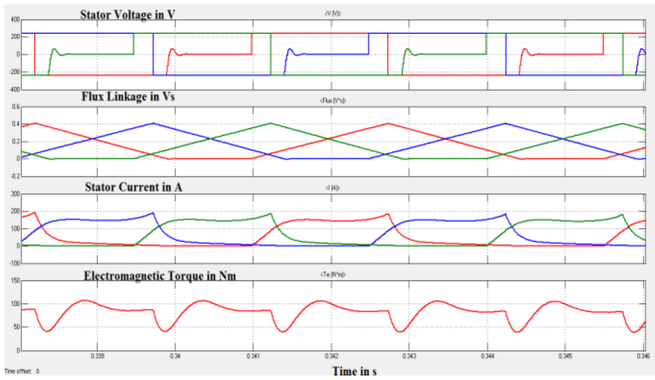

Fig. 8. Motor output waveforms of closed loop control (enlarged view)

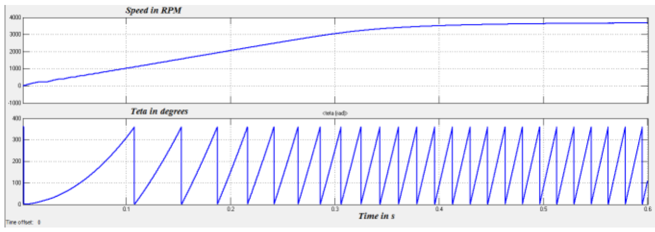

Fig. 9. Motor torque, speed and teta waveforms of closed loop control

Fig. 10 shows the position sensor block using the teta position sensing and Fig. 11 shows the waveforms at different stages of the sensing.

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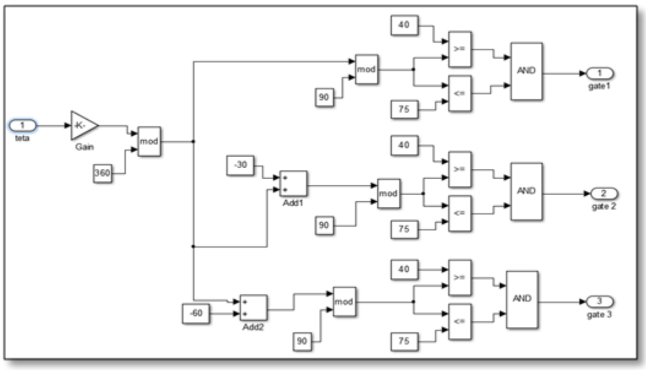

Fig. 10. Simulink model of teta position sensing

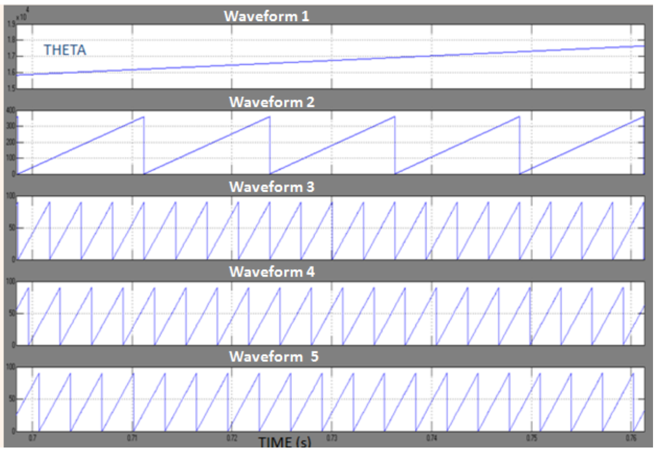

Fig 11. Different stages of teta position sensing

The teta output from motor is continuously increasing with time shown in waveform 1 as shown in Fig. 11. It is initially converted into degrees and then the angle position is reset to 0° to 360° using modulus operator and dividing with 360 as shown in waveform 2 and is done to relate the absolute rotor position to position relative to the stroke. This signal is again divided by 90 using the modulus operator as the cycle repeats after each 90 degrees and is distributed for the individual phases.

The signal for the first phase is phase shifted by 0° shown in waveform 3, for the second by -30° shown in waveform 4 and for the third phase by -60° shown in waveform 5 of Fig. 11 respectively. These signals are compared with the turn on and turn off angles to generate the gate signals for different phases. When teta is between the turn on and turn off angle the gate signal is high triggering the IGBT switches of the particular phase.

Fig. 12 shows the motor performance parameters of the closed loop control of switched reluctance motor with phase activation through teta position sensing.

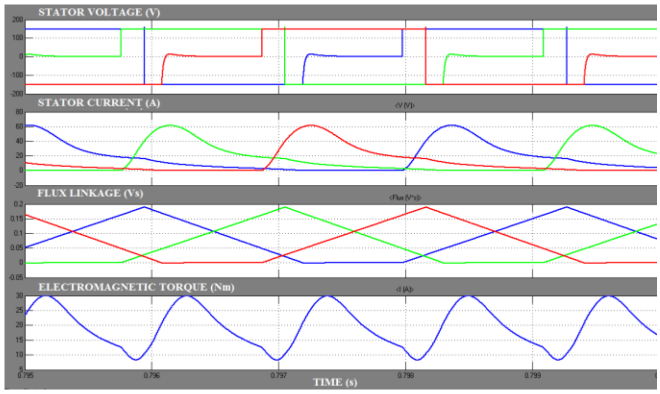

Fig. 12. Motor output waveforms of closed loop control

. The output voltage has three states coinciding with the output of the asymmetric converter which is fed to the phase windings. The current waveform shows a peak while the phase rotor position is between the turn on and turn off angle. Speed increases continuously with time to settle down at the base speed as shown in Fig. 13.

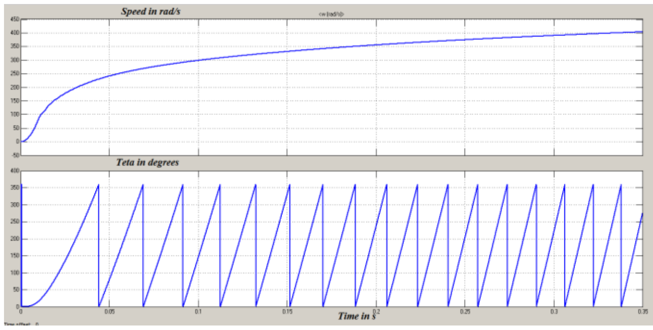

Fig. 13 Speed and teta waveforms using teta position sensing.

CONCLUSIONS

Asymmetrical converters and hysteresis controller are the classical converter configuration and the control strategy implemented with the switched reluctance motor. The closed loop operation of the switched reluctance motor driven with the asymmetric converter and the hysteresis controller is simulated using SIMULINK. The rotor position is derived from both teta and speed output of the machine. The torque ripple is found to be reduced for the operation with theta position sensing compared to speed position sensing.

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