"A Study of Response of Switched Reluctance Motor (SRM) In Sensor-Based and Sensor-Less Control Mode"

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***Abstract*: - This paper aims at implementing a Switched Reluctance Motor drive in sensor-based mode using dsPIC30F6010 motor control demo-board. For this purpose, initially the sensor-based and sensor-less control technique for the SRM drive have been studied. The simulation model in sensor-based operation has been developed in SIMULINK/MATLAB environment and the responses of the drive for different load torques and reference speeds have been obtained. The impact of varying firing angles, θ_{ON} and θ_{OFF}, of the control devices in each of the phases also has been analyzed. The sensor-less control technique that has been used here is Flux-current-theta method. This has also been simulated in the SIMULINK/MATLAB environment. Initially, the motor is run in stepper mode and later on it is run in open-loop with the help of rotor position signals. The sensor-based scheme also has been successfully implemented with outer speed loop and inner current loop.**

***Keywords* – Switched reluctance motor drives, sensor-based mode, sensor-less mode, control strategies, MATLAB/SIMULINK**

I. INTRODUCTION

The first acknowledged application of Switched Reluctance Motor (herein after referred to as "SRM") dates back to 19th century [1]; its development since then has been hampered by the non-availability of fast switching devices. However there have been some vast improvements of the power electronics drive technologies that have made a great success in achieving adjustable speed drives with Switched Reluctance Motor.Over the last two decades,continuous research and development efforts have led to evolution of SRM drive systems suitable for commercial production. Technological breakthrough in the field of power semiconductor devices, digital signal processing and solid-state control of electrical motors [2,3] has revolutionized variable/adjustable speed drive systems.

Recently, SRM drives have received considerable attention from the researchers and the drive industry due to their various attractive features. The SRM is a viable candidate for variable speed applications because of its high torque density, low inertia, quick response, low loses, wide speed range capability, simple control and low overall cost. The absence of permanent magnets or windings in the rotor makes switched reluctance (SR) machine a low-cost machine.Moreover, the SR machine stator windings are electively separated. Hence, the choice of converter topology and control strategy has more flexibility than any other drive system.

The robust brushless construction and good thermal features make the SRM drive attractive for mining and traction applications. Simplicity and low cost have implications for its applications in domestic sector. The excellent speed controllability is attractive in machine tool and robotics applications. Other application areas include electrical vehicle propulsion, aerospace industry and military. These motors have also potential applications as a variable speed drive in compressors, conveyors, extruders, pumps, paper feed rolls, refrigeration and air-conditioning, heating and ventilation, food processor drive, pallet truck drive, spindle and servo drive, packaging machines etc.

The advantages of SRM drive over other conventional drives are: (a) simple motor construction requiring very few manufacturing steps, (b) high torque to weight ratio means low moment of inertia and quick response, (c) stator windings are concentrated, so it is simple to wind and repair, (d) bulk of losses appear in stator which is relatively easier to cool, (e) the absence of rotor excitation allows its operation at higher operating temperature and speeds, (f) electromagnetic torque is independent of the polarity of current which leads to reduced number of power devices and control complexity, (g) stator winding is in series with semiconductor switch thereby eliminating the possibility of shoot through faults and (h) very high speeds are possible as rotor has no winding or no permanent magnets.

The main limitations of SRM drive are: (a) inherent torque ripple and acoustic noise is present due to doubly salient structure of SRM, (b) forcommutation and current control SRM drive requires an external or built in rotor position sensor, which is costly as it increases the size of motor drive and increases the complexity of the system and hence causes limitation for industrial application; also any error in the rotor position can lead to failure of control and (c) due to extremely high winding inductance energy is stored, which has to be removed after excitation, therefore, a long energy removal period is usually required, limiting the maximum current to a relatively lowrange.

Switched reluctance motors are gaining popularity because of its simple construction and high torque to inertia ratio. Demanding higher reliability and an equivalent performance to the DC and induction motor drives are very cost sensitive. The SRM drive system is quite promising to meet such demands in a cost effective fashion, hence the activities in this field are bound to grow.

Now, SRM drive requires a power converter and associated control system for its basic operation. Advancement in power semiconductor technology and high-speed digital signal controllers paved the way for renewed interest in SRM drives. A typical SRM drive system consists of the machine, the power converter and associated control system. The converter connected to a DC power supply, which is derived from the utility lines through a diode rectifier. The controller excites each phase of the SRM in a sequence and the excitation is synchronized with the rotor position in order to produce smooth unidirectional torque. This necessitates a mechanical position sensor, which usually is connected to the shaft of the SRM in order to provide rotor position feedback for the controller. However, the attractions of SRM drives will be significantly enhanced if the machine position sensor can be eliminated. This paper is an attempt to explore this possibility.

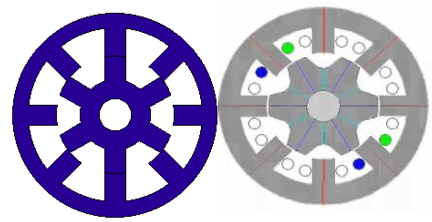
II. SCOPE OF THE PAPER

This paper envisages implementing sensor based control of an 8/6 Switched reluctance motor drive using dsPIC30F6010 motor control demo-board. The steps involved are as follows:

a) To model 4 phase Switched reluctance motor using MATLAB/SIMULINK platform in sensor-based mode.
b) To simulate motor model in closed loop using MATLAB/SIMULINK platform and to see the influence of variation in θ_{ON} and θ_{OFF}.
c) To simulate the motor model in sensor-less mode using MATLAB/SIMULINE platform.

III. CONSTRUCTION AND OPERATING PRINCIPLE OF SRM DRIVES

Switched reluctance motor (SRM) is a rotating electrical machine and falls under a special class of motor wherein both stator and rotor have salient poles. It is a type of a stepper motor, an electric motor that runs by reluctance torque.



(a) **(b)**

Fig.1. A typical 4 phase SRM with eight stator/ six rotor poles **(a) Pole configuration (b) Switching Pattern**

Stator winding comprises of a set of coils, each of which is wound on one pole. SRM is excited by a sequence of current pulses applied at each phase. The individual phases are consequently excited, forcing the motor to rotate. The rotor does not have any windings or magnets. It is made up of silicon steel, so the inertia of the rotor is very less.

The basic operating principle of the SRM is quite simple; as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator.

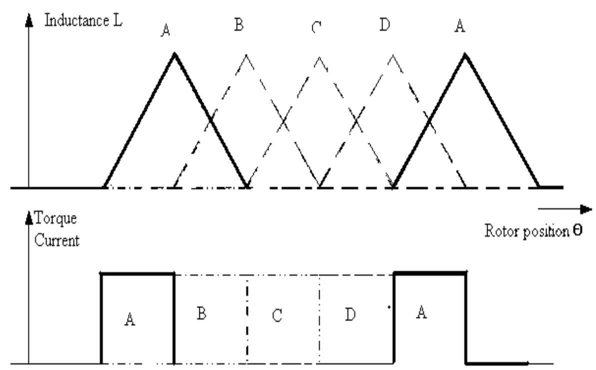


Fig. 2 Inductance Profile of 8/6 SR Machine

The direction of torque generated is a function of the rotor position with respect to the energized phase. The motor is excited by current pulse applied at each phase. Energization of a phase will lead to the rotor movement into alignment with the stator poles, minimizing the reluctance of the magnetic path. Reluctance of the magnetic circuit decreases as the rotor aligns with the stator pole. When the rotor is in line with the stator, the gap between the rotor and stator is very small. The rotor forms a magnetic circuit with the energized stator pole.

IV. SIMULATION OF SWITCHED RELUCTANCE MOTOR

4.1 Control Philosophy

The schematic of the closed loop drive system of a typical 4 phase SRM is shown in Fig. 3. It consists of outer speed loop comprising motor with rotor position sensor, speed controller and inverter. The inner current loop consists of current sensors, reference current generator, current controller and commutation logic. General working is that first set the value of reference speed. The output of encoder is fed to DSP that calculate the actual speed of SRM and compare with reference speed. If error occurs then feed to PI controller. The output of PI controller will be reference current and compared with actual current. The output of the PI controller will behave as duty ratio. According to the value of duty ratio respective phases will be excited.

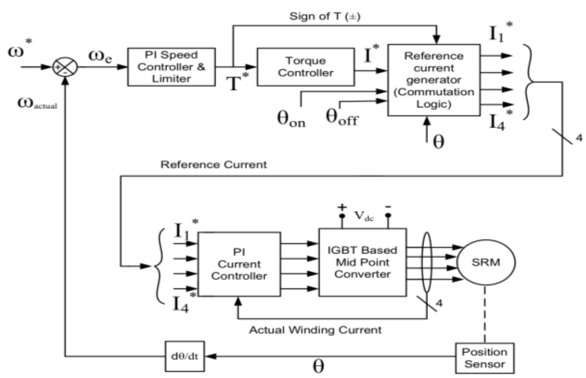


Fig. 3 Schematic block diagram of closed loop speed control of SRM

4.2 Simulation of SRM with Position Sensor

The dynamic performance of SRM is simulated in MATLAB/SIMULINK environment. MATLAB/SIMULINK is a powerful tool to simulate the system, having non-linear set of differential equations.

- SRM can be simulated in various controlled environments, like:

A. Simulation of SRM with position sensor – Sensor Mode

(a) Simulation of SRM with speed loop only

* Simulation results with outer speed loop

(b) Simulation of SRM with both speed and current loop

* Simulation results in closed loop

(c) Simulation of SRM with position sensor for theta on and theta off variation

* Inference from simulation results

B. Simulation of SRM without position sensor – Sensor-less mode

A. *Simulation of SRM with Position Sensor – Sensor Mode*

Here the two opposing simulation environments of Sensor Mode have been discussed with varying scenarios:

(a) Simulation of SRM with speed loop only - Outer speed loop

Initially the SRM with sensor is simulated with speed loop only. No current controller is incorporated here. The results for the sensor mode with speed loop only are presented in this section for torque, speed, current etc.

(1) For speed variation from 50 rad/s to 100 rad/s, with load torque = 5 N-m

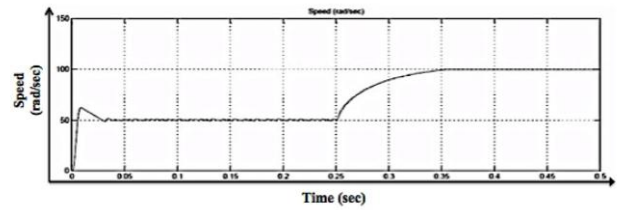


Fig. (a)(1)(i) speed variation with respect to time

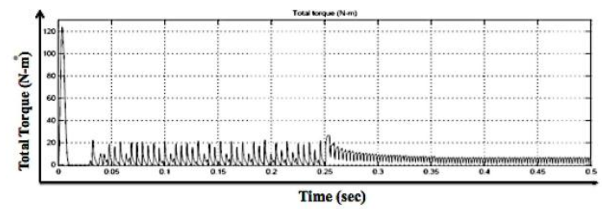


Fig. (a)(1)(ii) torque variation with respect to time

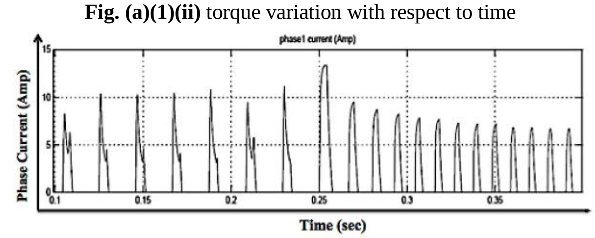


Fig. (a)(1)(iii) phase1 current variation with respect to time

(2) For load torque variation from 5 N-m to 10 N-m at reference speed of 50 rad/s

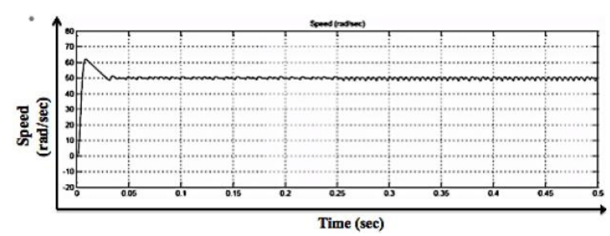


Fig. (a)(2)(i) Speed variation with respect to time

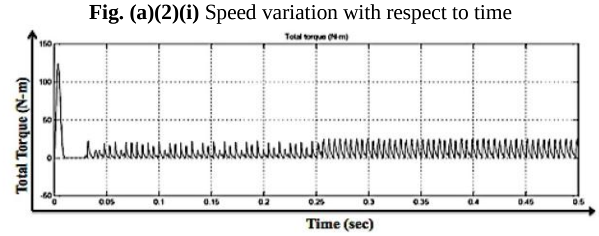


Fig. (a)(2)(ii) torque variation with respect to time

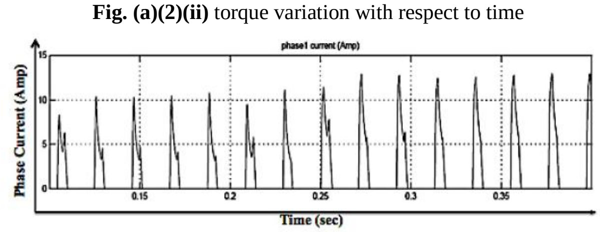


Fig. (a)(2)(iii)phase1 current variation with respect to time

Fig (a)(1)(i), Fig (a)(1)(ii) and Fig (a)(1)(iii) show variation of speed, torque and current with respect to time at a load torque of 5 N-m. Reference speed is changed at 0.25 sec.

Fig (a)(2)(i), Fig (a)(2)(ii) and Fig (a)(2)(iii) show variation of speed, torque and current with respect to time, at a reference speed of 50 rad/s. Torque is changed from 5 N-m to 10 N-m at 0.25 sec.

(b) Simulation of SRM with Both Speed and Current Loop - Closed loop

(1) For speed variation from 50 rad/s to 100 rad/s, with load torque = 5 N-m

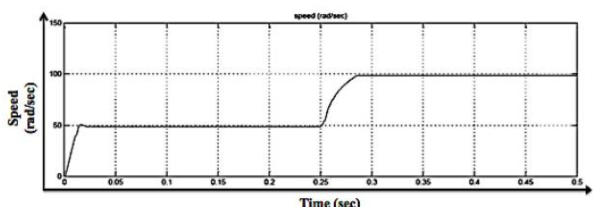


Fig. (b)(1)(i) speed variation with respect to time

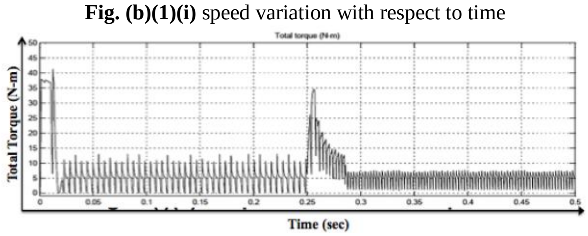


Fig. (b)(1)(ii) Torque variation with respect to time

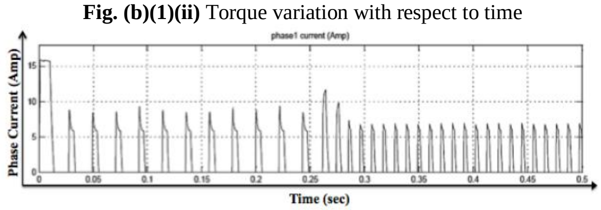


Fig. (b)(1)(iii) phase1 current variation with respect to time

(2) For load torque variation from 5 N-m to 10 N-m at reference speed of 50 rad/s

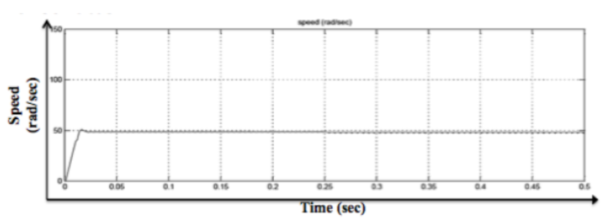


Fig. (b)(2)(i) speed variation with respect to time

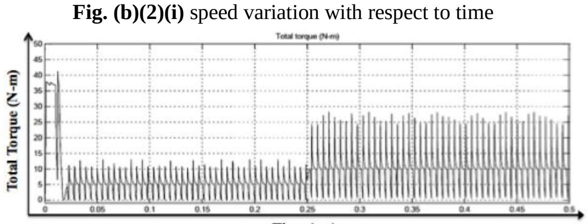


Fig. (b)(2)(ii) Torque variation with respect to time

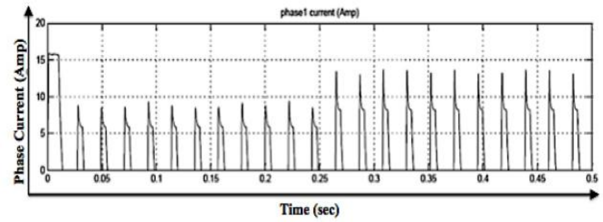


Fig. (b)(2)(iii) Phase1 current variation with respect to time

Fig (b)(1)(i), Fig (b)(1)(ii) and Fig (b)(1)(iii) show variation of speed, torque and current with respect to time at a load torque of 5 N-m. Reference speed is changed from 50 rad/sec to 100 rad/sec at 0.25 sec.

Fig (b)(2)(i), Fig (b)(2)(ii) and Fig (b)(2)(iii) show variation of speed, torque and current with respect to time, at a reference speed of 50 rad/s. Torque is changed from 5 N-m to 10 N-m at 0.25 sec.

B. Simulation of SRM without Position Sensor

SRM model is simulated in MATLAB/SIMULINK environment in Sensor-less mode. Flux-current method is used for simulating the model. The SRM flux-current characteristics are stored in the form of look-up table.

Voltage and current are used for calculating flux; this calculated flux along with current is fed to ψ-*i*-θ look-up table, which gives rotor position θ as output. This rotor position along with current is fed to look-up table, which gives torque as output. Rotor position information is obtained from this look up table ψ-*i*-θ, which is accordingly used for carrying out the commutation of different phases.

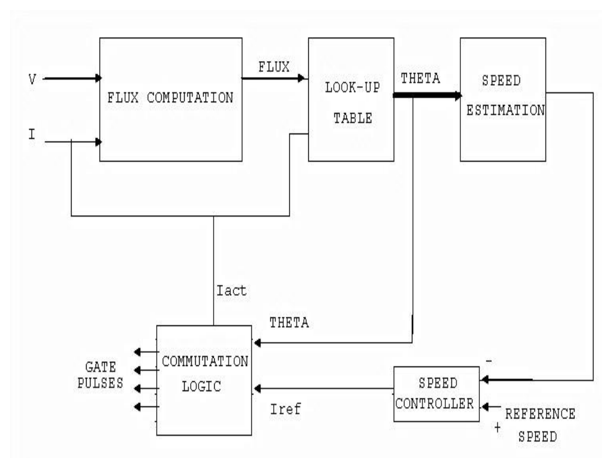


Fig. 4 Block diagram for Sensorless control

The results for the sensorless mode are presented in this section for torque, speed, current etc.

(1) For speed = 82 rad/s and load torque = 2 N-m

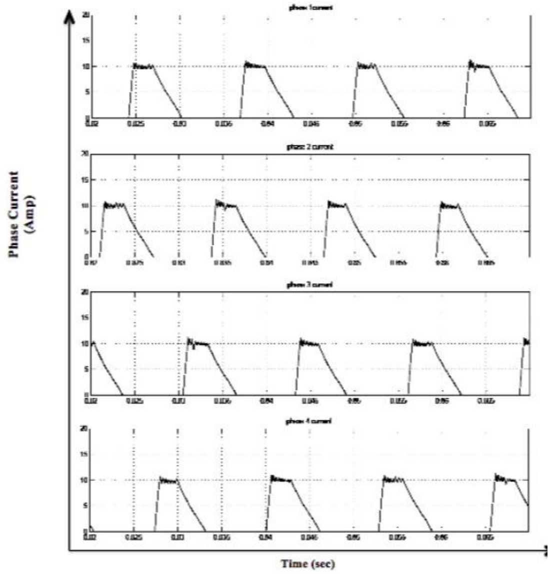


Fig. 5 (a) Phase current variation with respect to time

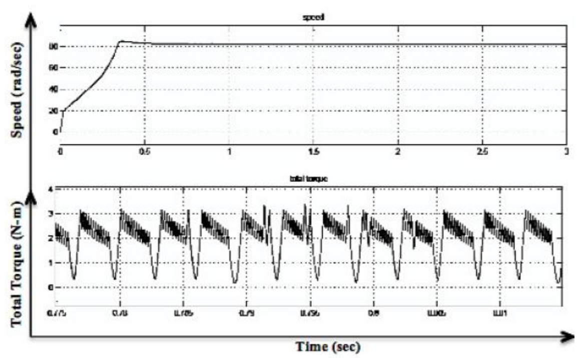


Fig 5(b) Speed and torque variation with respect to time

Fig 5 (a) shows the variation of four phase currents with respect to time for speed = 82 rad/s and load torque = 2 N-m and Fig 5 (b) shows speed and torque response.

(2) For speed variation from 50 rad/s to 100 rad/s and load torque = 2 N-m

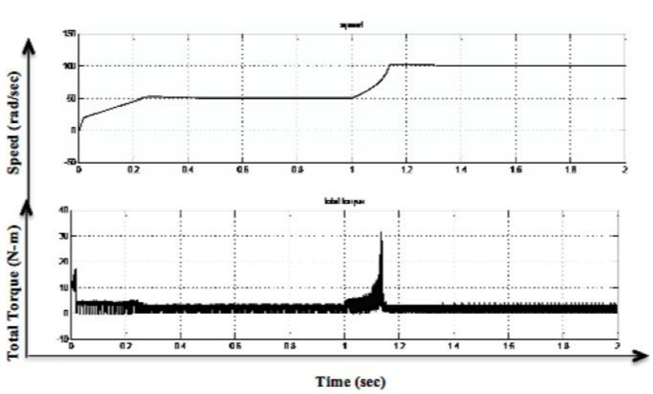


Fig 5(c) Speed and torque variation for step speed change

Fig 5 (c) shows variation of speed, and torque with respect to time at a load torque of 2 N-m. Reference speed is changed from 50 rad/sec to 100 rad/sec at 0.25 sec.

(3) For torque variation from 1 N-m to 2 N-m and speed reference = 50 rad/s

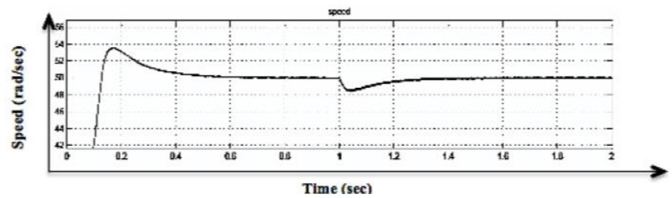


Fig 5 (d) Speed variation for step load change

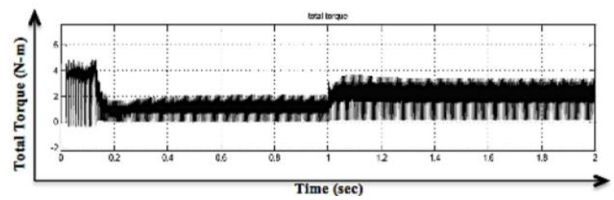


Fig 5 (e) Torque variation for step load change

Fig 5 (d), Fig5 (e) shows variation of speed and torque with respect to time, at a reference speed of 50 rad/s. Torque is changed from 1 N-m to 2 N-m at 1 sec.

From the above results we can infer that when speed is changed suddenly then it takes time to settle down to the new value. To accelerate or decelerate the drive, there is excess torque or less torque developed. But once the speed settles to the required value, the torque gets back to the original value.

Similarly, when step load change is applied to motor, speed is disturbed but settles down to its initial value as soon as motor torque settles to its new value.

V. CONCLUSION

From the above discussion it is concluded thatthe doubly salient structure of SRM makes its magnetic characteristics more nonlinear. Secondly, in comparison to other AC or DC motors the switched reluctancemotor is very simple in construction from the design point of view. Even at higher speed this switched reluctance motor provides very good result. This system is more compact, low cost, less prone to vibration and temperature changes and it does not require any frequent maintenance.

With decrease in switching ‘on’ time the switching frequency increases and as theswitching frequency increases the speed of the motor increases.The torque is developed during change of inductance. For constant inductance(unaligned position) torque developed is zero. To get positive torque, voltage shouldbe applied during positive (+ve) region and to get negative torque, voltage should be applied during negative (-ve) region.Therefore exact switching of (turn on and turn off angles) is required. Simulationhelps to get exact switching angles.

PID controller is used in order to track the reference speed at various load conditions.But in this method the torque produced in switched reluctance motor contains highamount of noise which needs to be controlled.By applying the direct torque control technique in the switched reluctance motor the ripple in the torque can be reduced andalso directly regulatethe torque output of the switched reluctance motor with in a hysteresis band.The torque and flux output can be simply controlled with in a hysteresis band byvarying the space vector output.

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