Torque Ripple Minimization of 4 Phase 8/6 Switched Reluctance Motor Drive with Direct Instantaneous Torque Control

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Abstract: The switched reluctance motor drives has evolved as an alternative to conventional motors in variable speed drives because of advantages like simple and rugged structure, absence of rotor winding, adaptability to harsh environments like coal mining, high speed operation etc. Because of nonlinearity, torque ripple is high in the motor. This paper presents a high dynamic control technique called Direct Instantaneous Torque Control (DITC) where in the torque is maintained within a hysteresis band by changing the switching states of the phases. Thus torque ripple minimization and fast torque response is an inherent property of DITC. This paper analyses performance of the drive mainly in terms of the torque ripple during acceleration and steady state conditions with DITC in MATLAB/SIMULINK environment and results are discussed elaborately.

1. Introduction

The applications of SRM drive has increased in the recent past because of advantages such as simple mechanical structure, high torque/inertia ratio, adaptable to hazardous environment, high speed operation etc., [1,2]. The main drawback of the motor is that it has highly non linear torque characteristics and high torque ripple, which causes noise and vibrations. Different torque ripple reduction techniques have been proposed in the past. They can be classified as mechanical and electronic techniques. Both the above techniques can minimize the torque ripples considerably, but has the disadvantage of reduction in overall torque [3].To overcome the above problems a novel technique called Direct Instantaneous Torque Control (DITC) [4-6] is proposed. In this method the converter switches are controlled in such a manner as to ensure that the estimated shaft torque is held at the reference torque within a hysteresis band. During single phase conduction, the state of the phase changes between 1, 0 or -1 depending on the instantaneous torque. During the phase commutation when two phases conduct, the states of the outgoing phase changes between 1, 0 or -1. The states of the incoming changes between 1 and 0 only. A novel fixed frequency DITC which decreases the vibration and torque ripple has been presented in [7]. A 4 level converter based DITC which has fast magnetization and demagnetization is discussed in [8].

This paper presents a modified Direct Instantaneous Torque Control of 4 phase 8/6 SRM in which states of the outgoing and incoming phases changes between 1, 0 or -1 during the phase commutation. This is the contribution of the paper.

2. Principles of DITC

The priniciple of DITC controller can be explained as follows. First the controller identifies the incoming and the outgoing phases based on the information obtained from the position sensor and on the turn-on and turn-off angles of the converter. Based on the present states of the incoming and outgoing phases, instantaneous torque and reference torque the controller decides the next states of the incoming and outgoing phases to maintain the torque within a hysteresis band. The Asymmetrical converter used to excite the phases of the motor has three possible voltage states. Figure 1(a) shows that when both the switches are turned ON, currents flows through two switches and winding and a positive voltage is impressed across the motor phase winding. The voltage state for the given phase is defined as state 1. When one switch is turned ON and the other switch turned

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OFF, current freewheels through the diode and motor phase winding and a zero voltage loop occurs and the state is defined as state 0. This is shown in Figure 1(b). Figure 1(c) shows that when both the switches are turned OFF, the current flows through the diodes and motor phase winding. In this case negative voltage is impressed across the motor phase winding and the state is defined as state-1.

SRM normally operates in single phase conduction mode and during commutation two phases conduct simultaneously. In single phase conduction, only one phase will be excited. Thus, there are only three possible switching states i.e 1, 0,-1. In single phase conduction hysteresis torque controller regulates the developed torque of one phase. If the developed torque is less than the reference torque, the switching state of the phase is made equal to 1.If it is more than the reference torque it is made to 0 or -1.

During phase commutation, the torque of the two adjacent phases is controlled indirectly by controlling the total torque. The torque is maintained within the upper and lower hysteresis band, by changing the states of the outgoing and incoming coming phases between 1, 0 and -1 depending on the value of instantaneous torque. Also during phase commutation, if the incoming phase cannot produce the required torque, the outgoing state changes to 1.

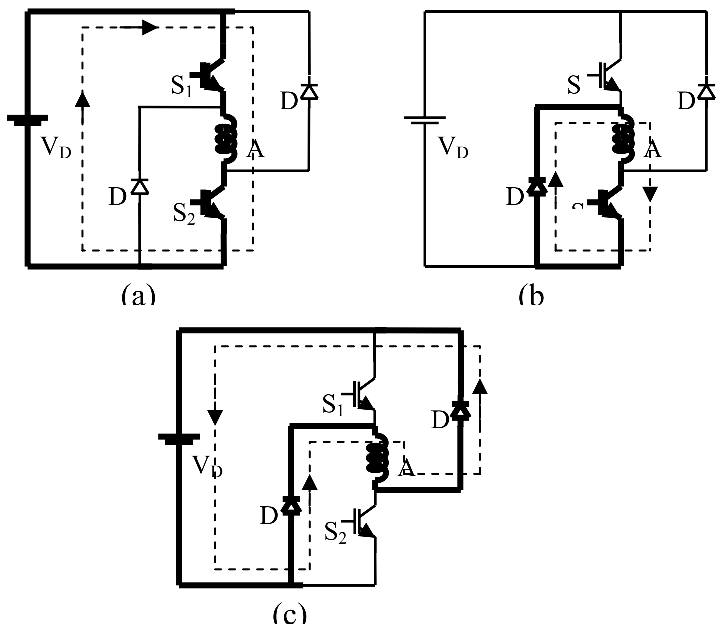


Figure 1 SRM voltage states (a) state 1 (b) state 0 (c) state-1

3. Block Diagram of DITC

Figure 3 shows the overall block diagram of DITC. The reference torque is compared with the actual generated torque and given to a hysteresis torque controller which outputs torque increase or decrease. If the torque generated by the motor is less than reference torque, the torque is increased by turning on the top and bottom switches of the converter to enter into state 1. If the torque developed is more than the reference, then it is reduced by turning off either top or bottom switch or both the switches to enter into state 0 or -1. Switching control unit does the following operations

[a] It detects the outgoing and incoming phases based on the position sensor signal, turn-on and turn-off angles.

[b] Torque is maintained between upper and lower hysteresis levels by hysteresis comparator. Based on the present states of the incoming and outgoing states, reference torque and the developed torque the next state of the incoming and outgoing phases is decided to maintain the torque within hysteresis band.

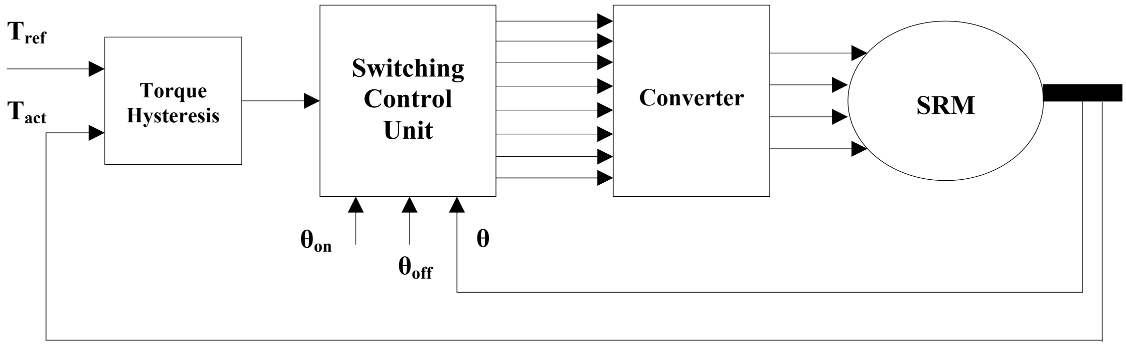


Figure 3 Block diagram of DITC

4. Modeling of SRM

To investigate the behavior of SRM, dynamic model is required. The dynamic mathematical model [1], [2], [9] of a SRM is composed of a set of electrical equations for each phase and equations of mechanical system [9]. In a typical m-phase SRM, the machine's voltage equation can be expressed as

$$v_j = R_j i_j + \frac{d\lambda_j(i_j,\theta)}{dt}, j=1,...,m \tag{1}$$

$$\frac{d\lambda_j(i_j,\theta_j)}{dt} = v_j - R_j i_j, j=1,...,m, \tag{2}$$

Where v_j is the terminal voltage of phase j in Volts, i_j is phase current in Amperes, R_j is phase winding resistance in Ohms, λ_j is the flux linkage in Weber-turns and θ_j is rotor position in degrees. The flux linkage is a function of current and rotor position.

The mechanical dynamic equations can be expressed as

$$\frac{d\theta}{dt} = \omega \tag{3}$$

$$\sum_{j=1}^{m} T_j(i_j,\theta) - T_L = J.\frac{d\omega}{dt} + B.\omega \tag{4}$$

Where T_j is the phase torque in Nm, T_L is the load torque in Nm and ω is angular speed in radians per second. J and B represent the moment of Inertia in kg-m^2 and coefficient of friction in Nm/rad/s respectively.

The speed equation can be rearranged as

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\sum_{j=1}^{m} T_j(i_j,\theta) - T_L - B.\omega\right) \tag{5}$$

The dynamic model of drive is developed using (2), (3) and (5). The technique is to utilize a look-up table which approximates the flux and torque as a function of current and position. The specifications of motor are shown in Appendix. Two lookup tables namely Position-fluxlinkage-current (θ - λ- i) and Position-current-torque (θ- i-T) are obtained by conducting Finite Element Analysis (FEA). The look-up tables were formulated for 61 rotor positions from 0 to 60o and 31 different current values from 0 to 30A by using FEA [9,10]. Only three positions of the SRM are shown. Figure 4(a) shows the aligned position of the SRM and it is observed that the flux linkages and phase inductance is maximum in this position. Figure 4(b) shows the misaligned position.

Figure 4(c) shows the unaligned position where the flux linkages and phase inductance is minimum. Mesh plots of two lookup tables are shown in Figure 5(a) and Figure 5(b).

5. Simulation and Results

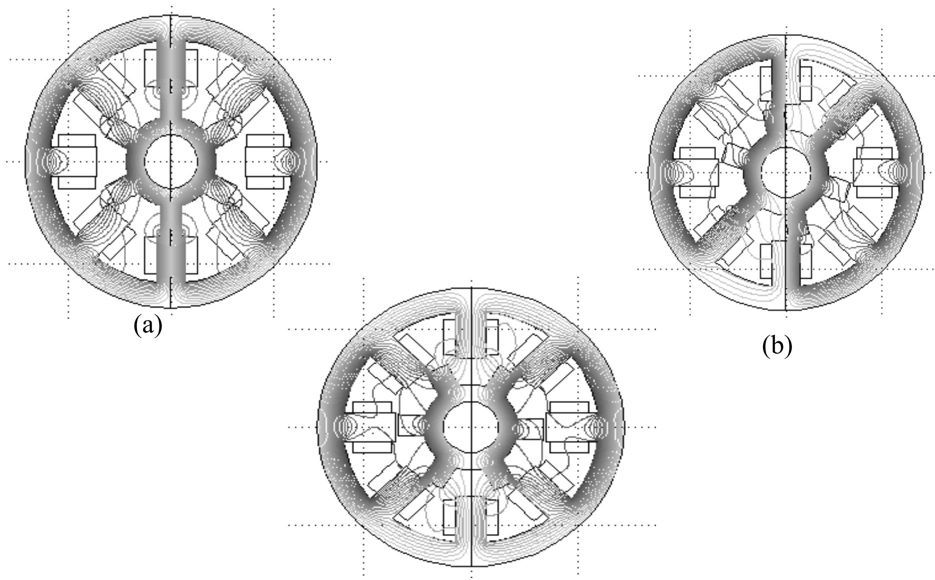
To analyze the performance of the drive, a near perfect model of the motor is required. Using the dynamic mathematical equations the model of 4 phase 8/6 SRM is constructed in the MATLAB/SIMULINK environment. The converter simulated is an asymmetrical bridge converter. The complete model of the 4-phase 8/6 SRM with DITC controller is shown in Figure 6(a). The model consists of electrical system, mechanical system, position sensing, asymmetrical converter and DITC controller blocks. DITC program is written in the embedded function block. Figure 6(b) shows the single phase model. The single phase model has two look up tables. ITBL is the flux-current-angle (λ- i - θ) look up table and TTBL is the torque – current –angle (T- i - θ) look up table. The same is repeated for the remaining phases but each phase is displaced from one other by the stroke angle. The stroke angle for 4 phase 8/6 SRM is 15^0.

The performance of the DITC based SRM drive is analyzed for a constant load torque of 1 Nm and a reference speed of 400 RPM. Actual speed is compared with the reference speed and error is given to a PI controller. The output of PI controller is the reference torque. The PI controller output is 2 Nm whenever the speed is less than the reference speed. When the speed reaches the reference value the PI controller output equals the load torque.

The Table 1 shows the variation of switching frequency of the switching device with the torque hysteresis band. It is observed that as the hysteresis band decreases, the switching frequency of the device increases. The normal operating frequency range of the device is 5 kHz - 20 kHz. Thus 8% torque hysteresis band can be selected for this drive. At lower hysteresis bands switching frequencies are higher resulting in higher switching losses and reduced efficiency.

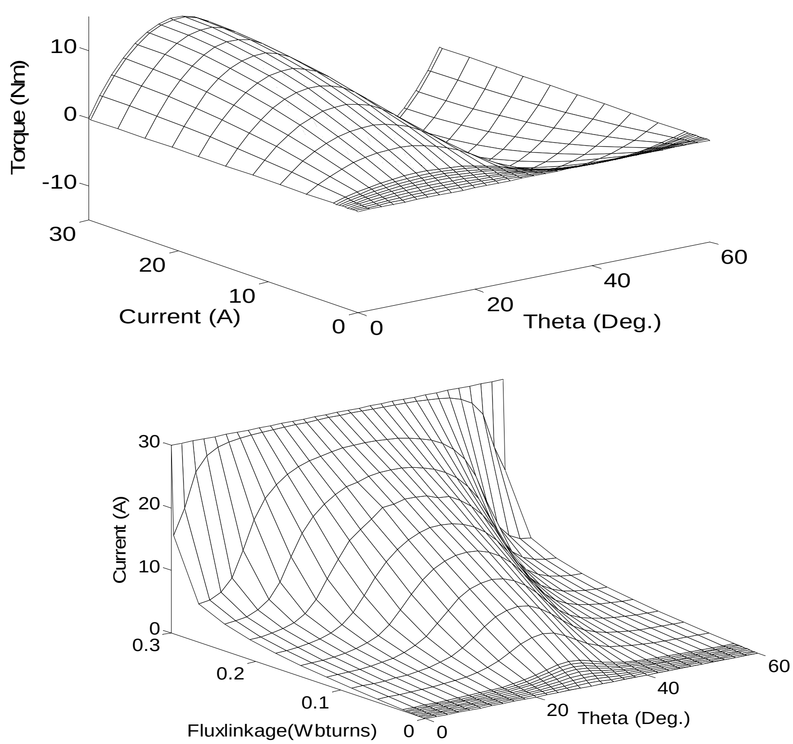
Figure 7(a) shows the total torque waveform developed by the motor under steady state. It is observed that the torque is maintained within a band of 0.084 Nm as against the set band of 0.08 Nm. Thus torque ripple is less in the steady state. The torque ripple is only 8%. Figure 7(b) & (c) shows the voltage applied across two consecutive phases respectively. Ph1 is the outgoing phase and Ph2 is the incoming phase. The voltage in each phase changes between +120V, 0V or -120V depending on the torque error to maintain the torque equal to the load torque. Figure 7(d) shows the torque sharing between two successive phases, while maintaining the total torque constant at 1Nm in steady state. It is observed that during phase commutation torque of the outgoing phase is decreasing and the torque of the incoming is increasing but the total torque is maintained constant by DITC controller by changing the states between 1,0 or -1. Figure 8 shows the enlarged view of the Figure 7.

Figure 9(a) shows the instantaneous torque responses of the four phases in the steady state. The maximum values of instantaneous torque and torque band in each phase are 1 Nm and 0.085 Nm respectively. The instantaneous current waveforms of all the four phases in the steady state are shown in Figure 9(b). The maximum current and average current in each phase are 2.646 A and 0.912 A respectively. The maximum value of the current band in each phase is 0.365 A. Figure 9(c) shows the total torque response of the motor. The torque is maintained at 2 Nm within a hysteresis band of 0.084 Nm till the steady state is reached. When the steady state is reached it is maintained at the load torque value by maintaining within hysteresis band of 0.084 Nm. Thus the torque ripple is minimized in the steady state and during acceleration period**.** Figure 9(d) shows speed response. The steady state speed is maintained constant at 401 rpm. The motor accelerates linearly with a slope of 1138 rad/s^2 .The settling time of the speed is 0.34 Sec.



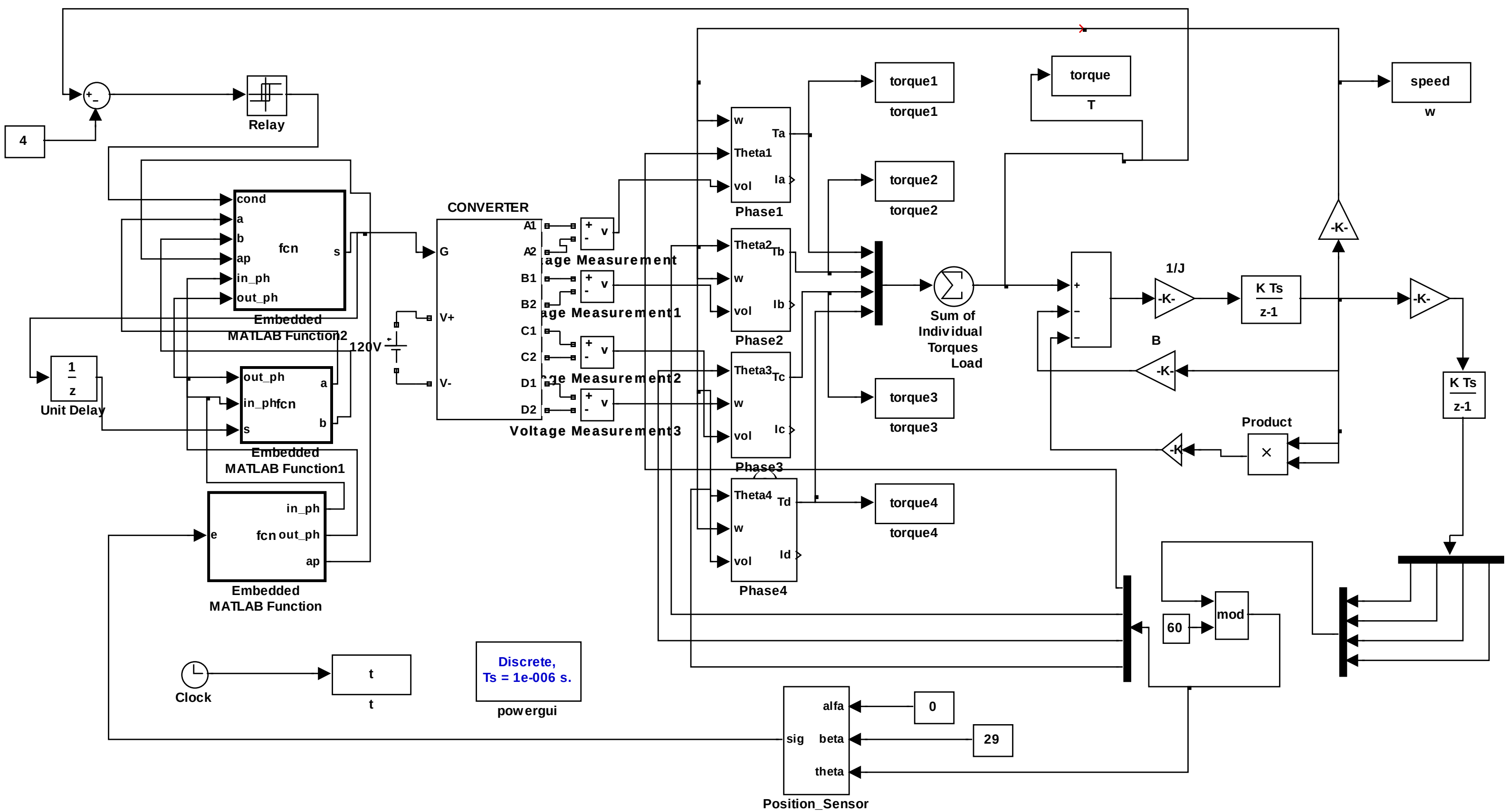
(a) (b) (c)

Figure 4 shows the flux lines (a) Aligned position (b) Misaligned position (C) Unaligned position



(b)

Figure 5 Mesh plots (a) position-current-torque (b) position-flux linkage-current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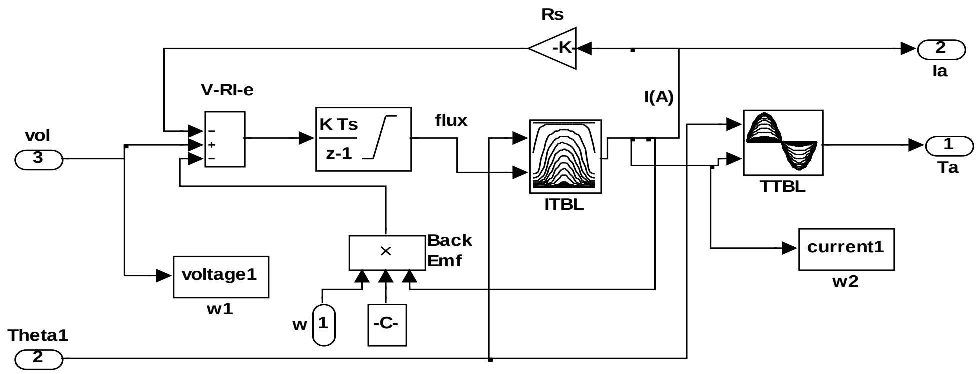
(a)



(b)

Figure 6(a) Simulation model of 8/6 SRM with DITC (b) Single phase model

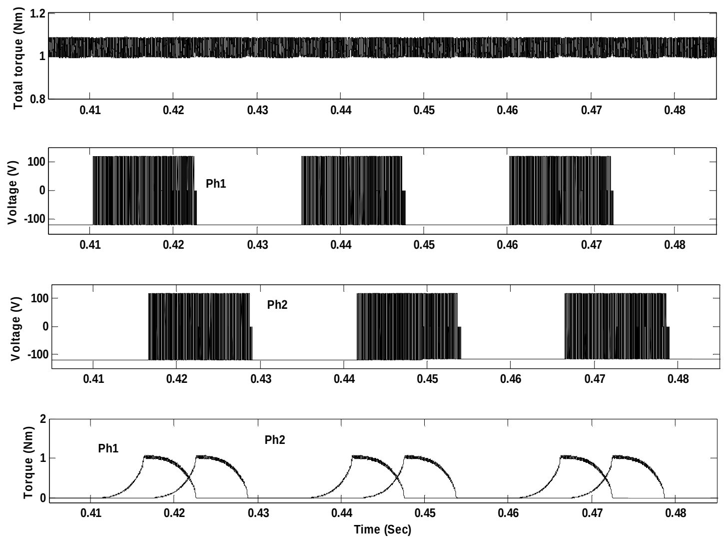


Figure 7 (a) Total torque (b) & (c) Phase voltages (d) Phase torques

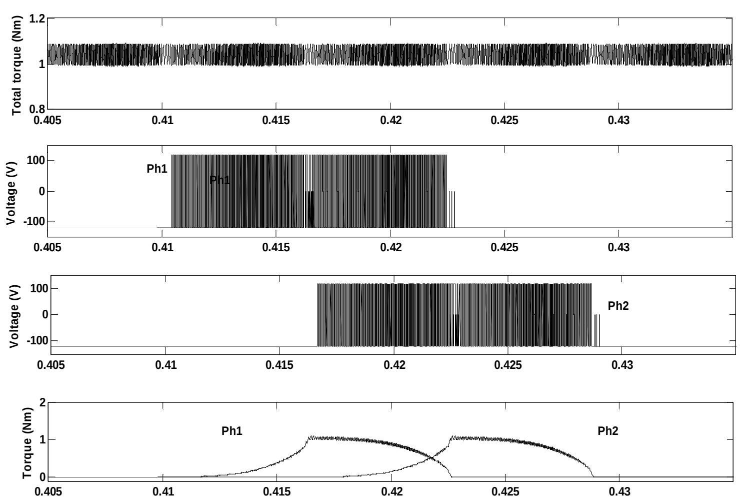
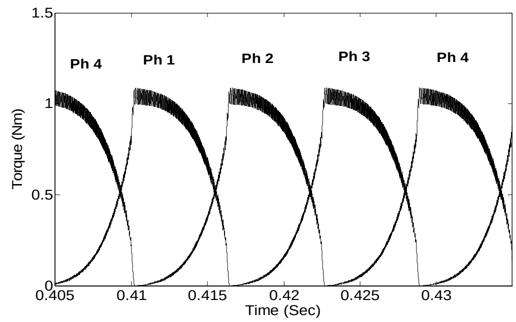
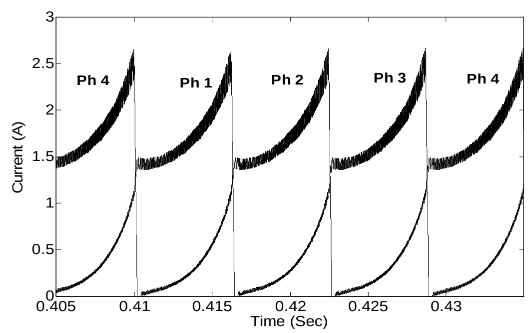


Figure 8 Enlarged view of Figure 7



(a)



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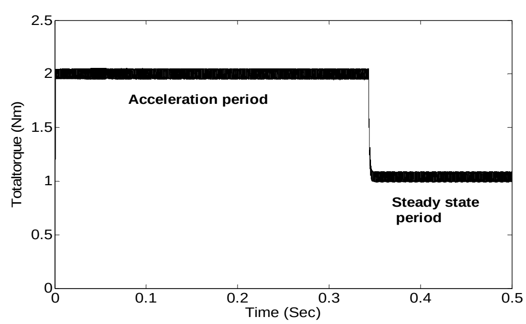
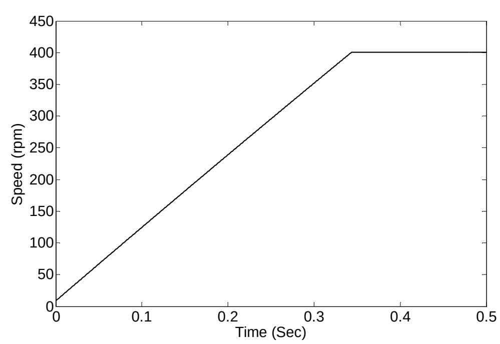


(c)



(d)

Figure 9(a) Instantaneous phase torques (b) Instantaneous phase currents (c) Total torque (d) Speed

Table 1

Torque Hysteresis band	**Switching Frequency (f_s) (kHz)**
10%	14.28
8%	20.00
5%	33.33
1%	50.00

Conclusion

The performance of the SRM drive is analyzed mainly in terms of torque ripple during acceleration and steady state conditions with DITC controller. The drive with DITC controller is simulated for a constant load torque of 1 Nm and for a reference speed of 400 rpm. It is observed that the maximum band of instantaneous phase current is 0.365 A and the maximum band of the instantaneous phase torque is 0.085 Nm. It is observed that the total torque is maintained within set hysteresis band of 0.08 Nm both during acceleration and steady state conditions at a switching frequency of 20 kHz. The DITC does not require any current profiles or torque sharing functions during single phase conduction or two phase conduction intervals unlike conventional techniques.

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Appendix
Specifications of SRM

Voltage:	120 V DC	Stator tooth arc:	0.416 radians
Maximum Current	30A	Rotor tooth arc:	0.492 radians
Maximum Flux	0.3 Wb	Stator yoke thickness:	12.1 mm
Stator poles:	8	Rotor yoke thickness:	9 mm
Rotor poles:	6	Stator tooth height:	24.5 mm
Stator diameter:	143 mm	Rotor tooth height:	12.5 mm
Rotor diameter:	69 mm	Shaft diameter:	26 mm
Air gap:	0.4 mm	Coil turns:	180
Stack length:	143 mm		

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