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Direct Instantaneous Torque Control of 4 Phase 8/6 Switched Reluctance Motor

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Abstract

The applications of Switched Reluctance Motor (SRM) Drives has increased in the recent past because of advantages like simple structure, no rotor winding, high torque to weight ratio, adaptability to harsh environments like coal mining etc. But the main disadvantage is that torque ripple is high because of the double saliency. 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 in magnetizing or freewheeling or demagnetizing.Thus torque ripple minimization is an inherent property of DITC. DITC based SRM drive is simulated in MATLAB/SIMULINK environment and results are discussed elaborately

Keywords*: Direct Instantaneous Torque Control, Switched Reluctance Motor, Torque Ripple*

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. The popularly used conventional control technique of SRM drives is hysteresis current control [3]. It has the disadvantage of high torque ripples. Hence different techniques have been proposed in the recent past to minimize torque ripple. Many mechanical techniques such rotor skewing and pole shaping, were suggested by the researchers to minimize the torque ripple, which unfortunately reduce the overall torque producing capability of the machine. Electronic methods which are basically concerned with profiling the phase current in such a manner as to minimize the torque ripple component. The most popular electronic method for torque ripple reduction is based on the optimization of control principles, which include the supply voltage, turn–on and turn–off angles of the converter and current levels. But this method has the disadvantage that it leads to reduction in the overall torque [4].

L. Venkatesha et al. [5] proposed the torque ripple minimization by suitably profiling the phase currents. But the method is quite involved and the computation time is high. The neuro-fuzzy control technique proposed in [6] adds a compensating signal to the PI controller. But the stability of this method depends on the selection of suitable value of the stopping time. P. Srinivas et al. [7] discussed the torque ripple minimization of 8/6 SRM using fuzzy logic controller for constant dwell angles. Torque ripple reduction is achieved by employing a torque controller for limiting the phase current, and the turn-on, turn-off angles are adjusted using fuzzy logic controller in [8]. But the method is limited to low speed region. The problem of the torque ripple is minimized by a novel technique called direct instantaneous torque control [9],[10].

This paper presents direct instantaneous torque control of 4 phase 8/6 SRM in which 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.

2. Priniciple of DITC

The DITC 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. Based on the present states of the incoming and outgoing phases the controller decides the next states of the incoming and outgoing based on the instantaneous torque i.e whether torque is greater than the upper hysteresis band or lesser than the lower hysteresis band. Asymmetrical converter is used to excite the phases of the motor. It has three possible voltage states. Fig. 1 shows the asymmetrical converter for one of the four phases. Fig. 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 'magnetizing' (state 1). When one switch is turned OFF, current freewheels through the diode and motor phase winding and a zero voltage loop occurs and the state is defined as 'freewheeling' (state 0). This is shown in Fig. 1 (b). Fig. 1 (c) shows that when both the switches are

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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 'demagnetizing'(state-1).

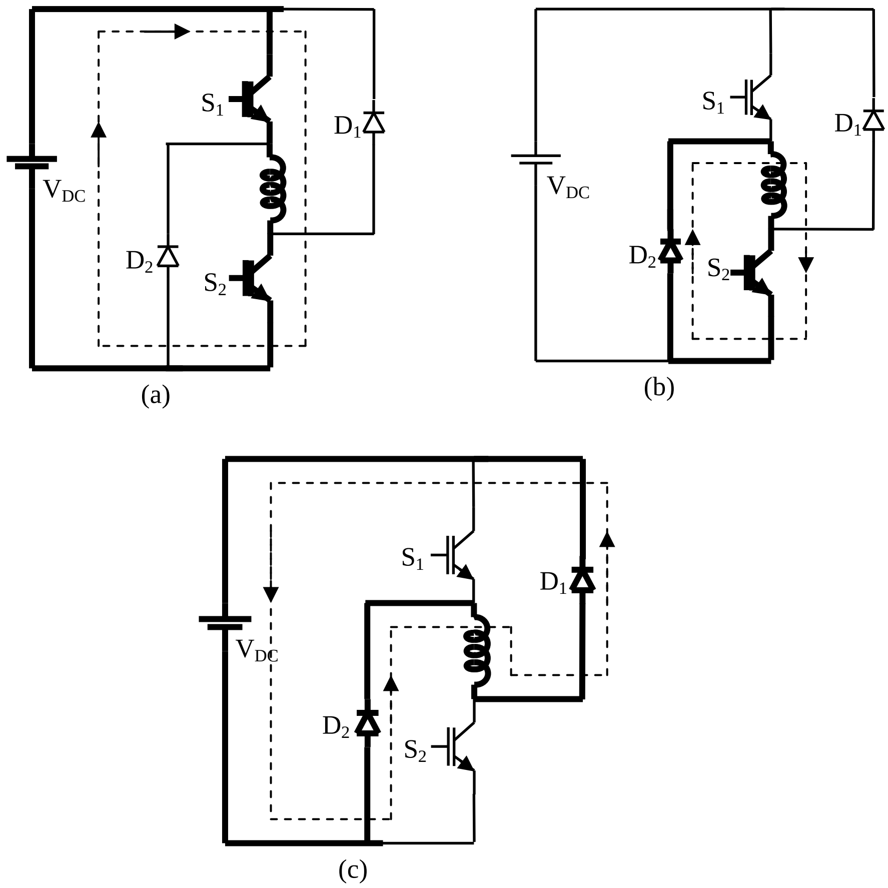


Figure 1. SRM voltage states (a) state 1 (b) state 0 (c) state -1

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 torque hysteresis 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.

3. Block Diagram of DITC

Fig. 2 shows the overall block diagram of DITC. The reference torque and the actual torque are given to a torque hysteresis controller which outputs increasing or decreasing torque signal. 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.

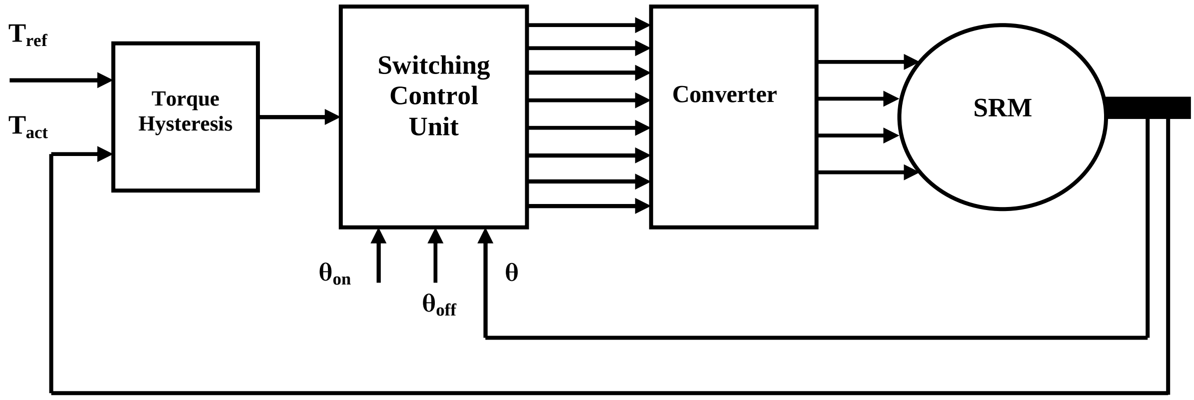
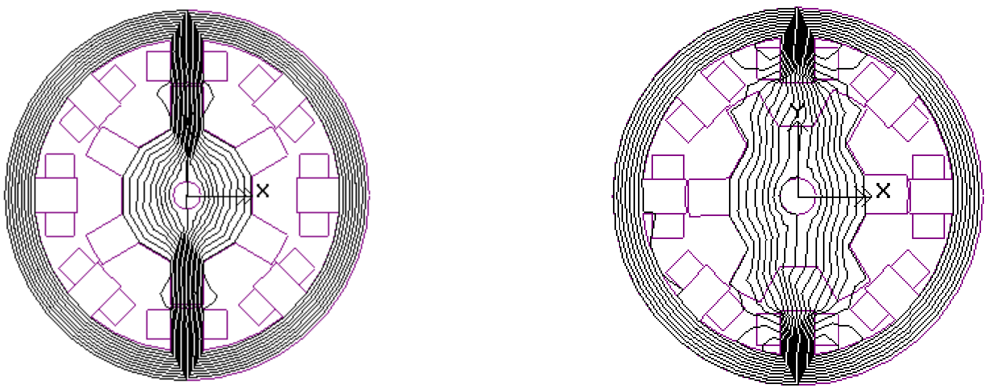
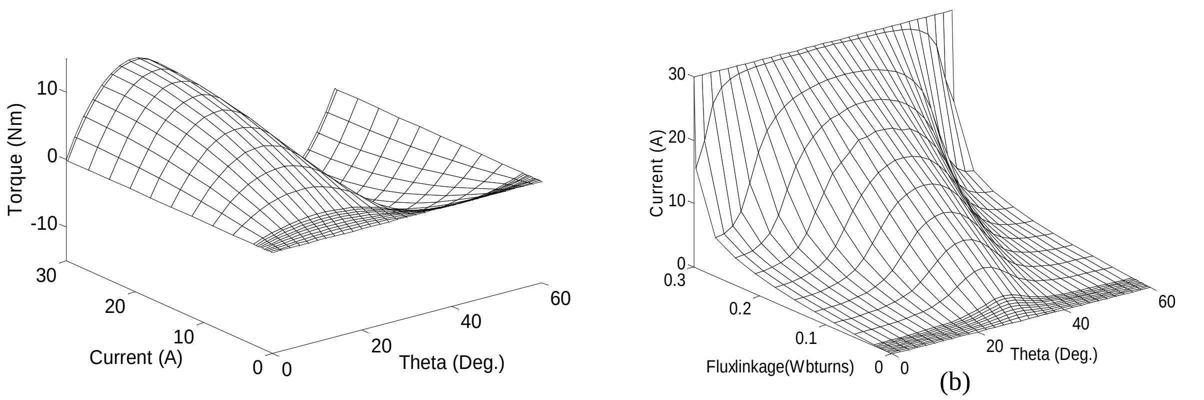


Figure 2. Block diagram of DITC



(a) (b)

Figure 3. Flux plots of FEA (a) Aligned position (b) Unaligned position



(a) (b)

Figure.4. Mesh plots (a) position-current-torque (b) position-flux linkage-current

4. Modeling of SRM

To investigate the behavior of SRM, dynamic model is required. The dynamic mathematical model [1], [2], [11] of a SRM is composed of a set of electrical equations for each phase and equations of mechanical system [11]. 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 4 phase 8/6 SRM drive is developed using (2), (3) and (5). 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 60^o and 31 different current values from 0 to 30A by using FEA [3],[12]. The FEA diagrams for the aligned and unaligned positions are shown in Fig. 3(a) and Fig. 3(b). Mesh plots of two lookup tables are shown in Fig. 4(a) and Fig. 4(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 complete model of the 4-phase 8/6 SRM with DITC controller is shown in Fig. 5 (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. Fig. 5 (b) shows the single phase model. The single phase model has two look up tables. ITBL is the Position-fluxlinkage-current (θ – λ - *i*) look up table and TTBL is the Position-current-torque (θ - *i* - *T*) look up table. The same is repeated for the remaining three 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 Fan load of 4 Nm at a speed of 800 rpm with dwell angle of 29^o. Fig. 6 (a) shows the total torque developed by the motor. Total torque is maintained at 4 Nm by setting a hysteresis band of 5% of rated torque. The torque is found to be between 3.895 Nm and 4.105 Nm which gives a torque ripple of 5.25%. Fig.6 (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 can take any of the three discrete voltages i.e. +120V, 0V or -120V depending on the torque error to maintain the torque equal to the load torque. Fig. 6(d) shows the torque sharing between two successive phases, while maintaining the average constant torque of 4 Nm 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 switching of the phases in three states. Fig. 6 (e) shows the current in two phases. The maximum current in each phase is 6.41A. Fig. 7 shows the zoomed version of the Fig. 6. Fig. 8(a) shows the torque response of the four phases. The current waveforms of all the four phases are shown in Fig.8 (b). Fig.8 (c) shows the total torque response over the entire simulation time. Fig. 8 (d) shows speed response.

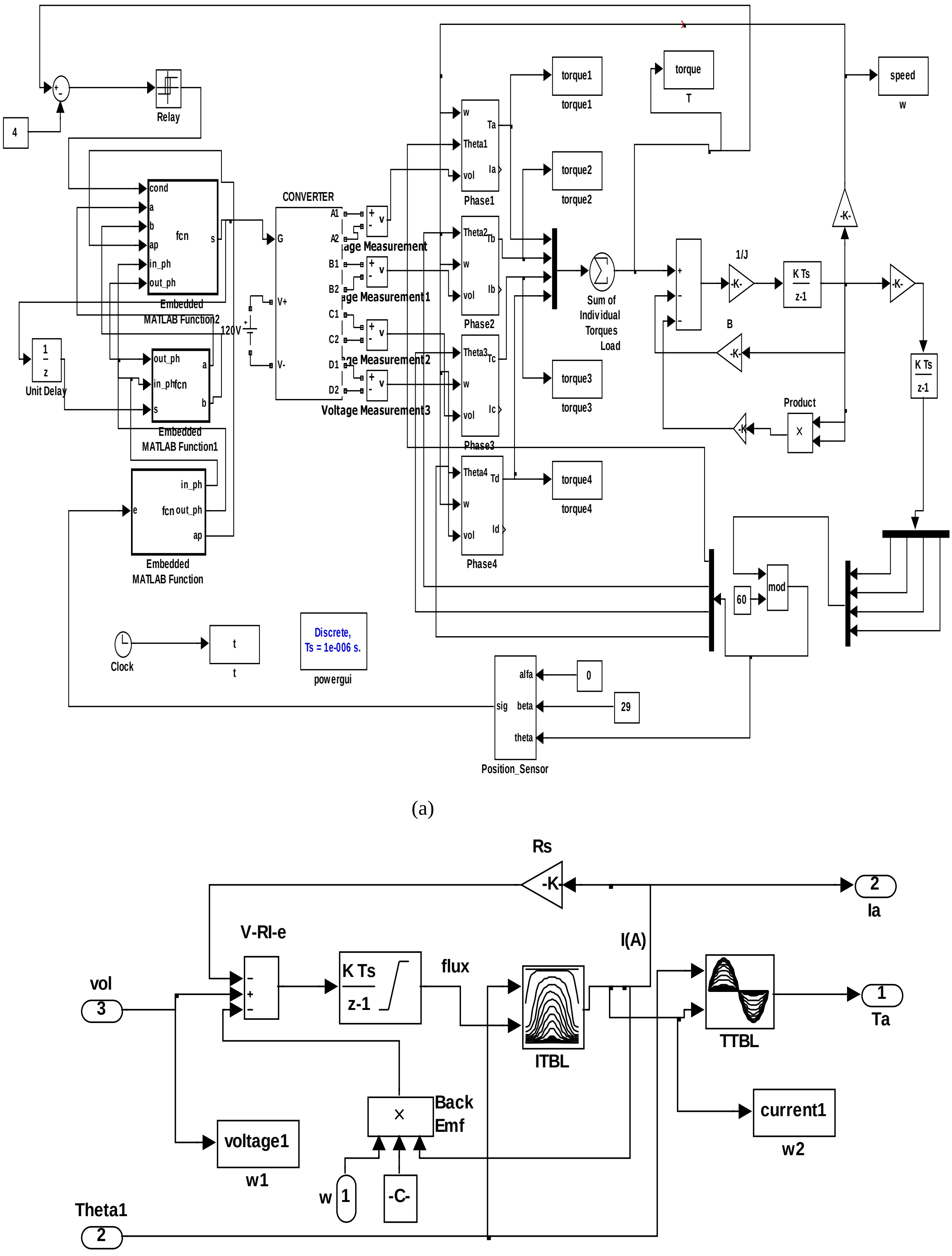


Figure 5. (a) Simulation model of 8/6 SRM with DITC (b) Single phase model

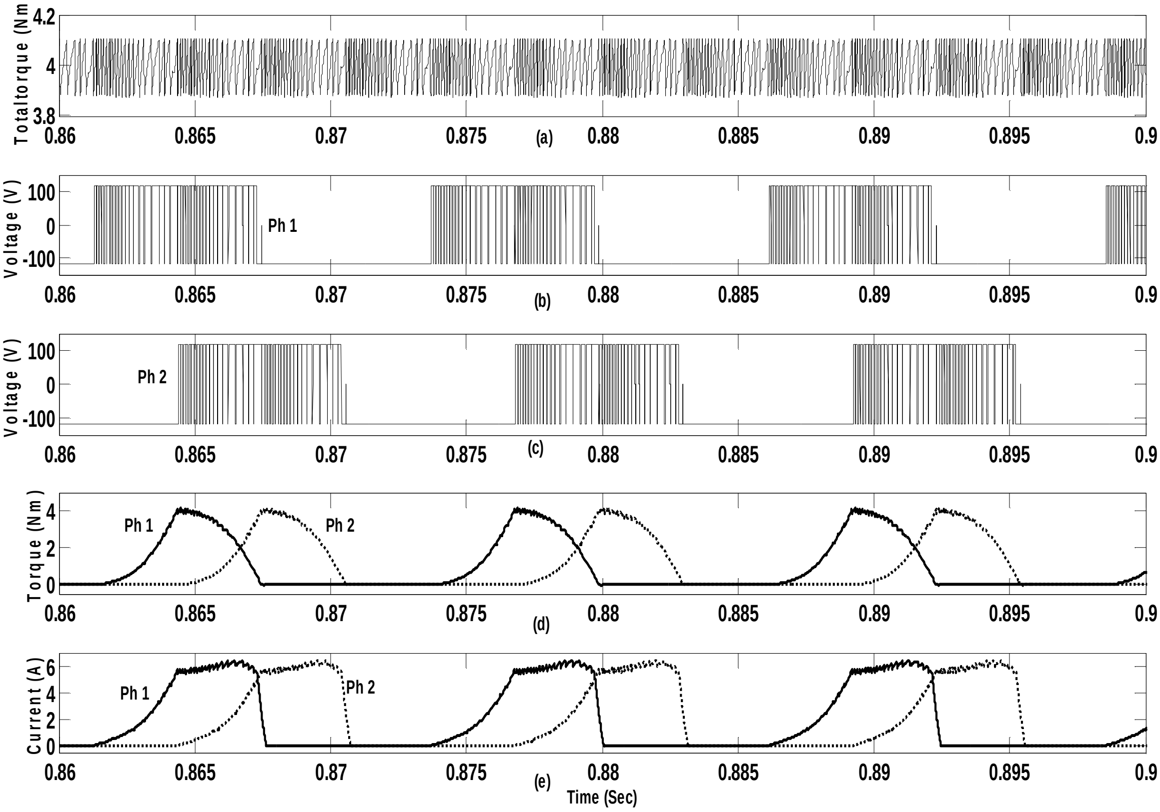


Figure 6. (a) Total torque (b) & (c) Phase voltages (d) Phase torques (e) Phase currents

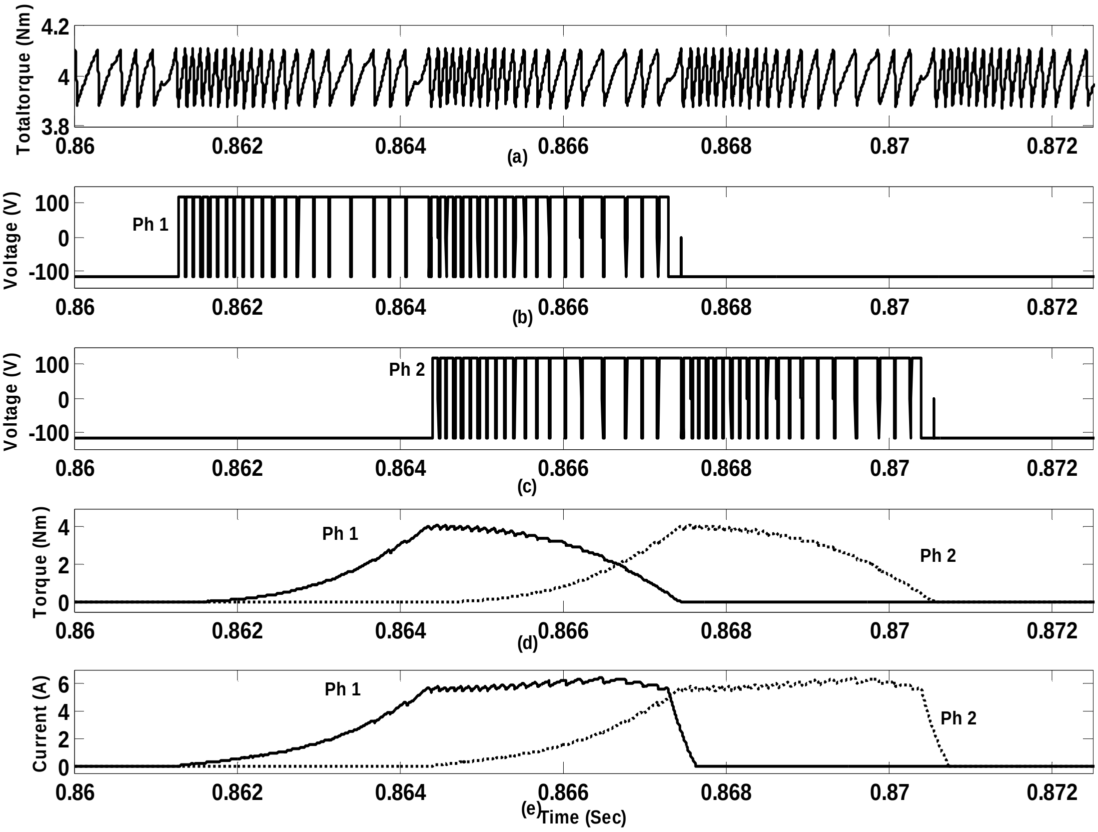


Figure 7. (a) Enlarged view of Figure 6

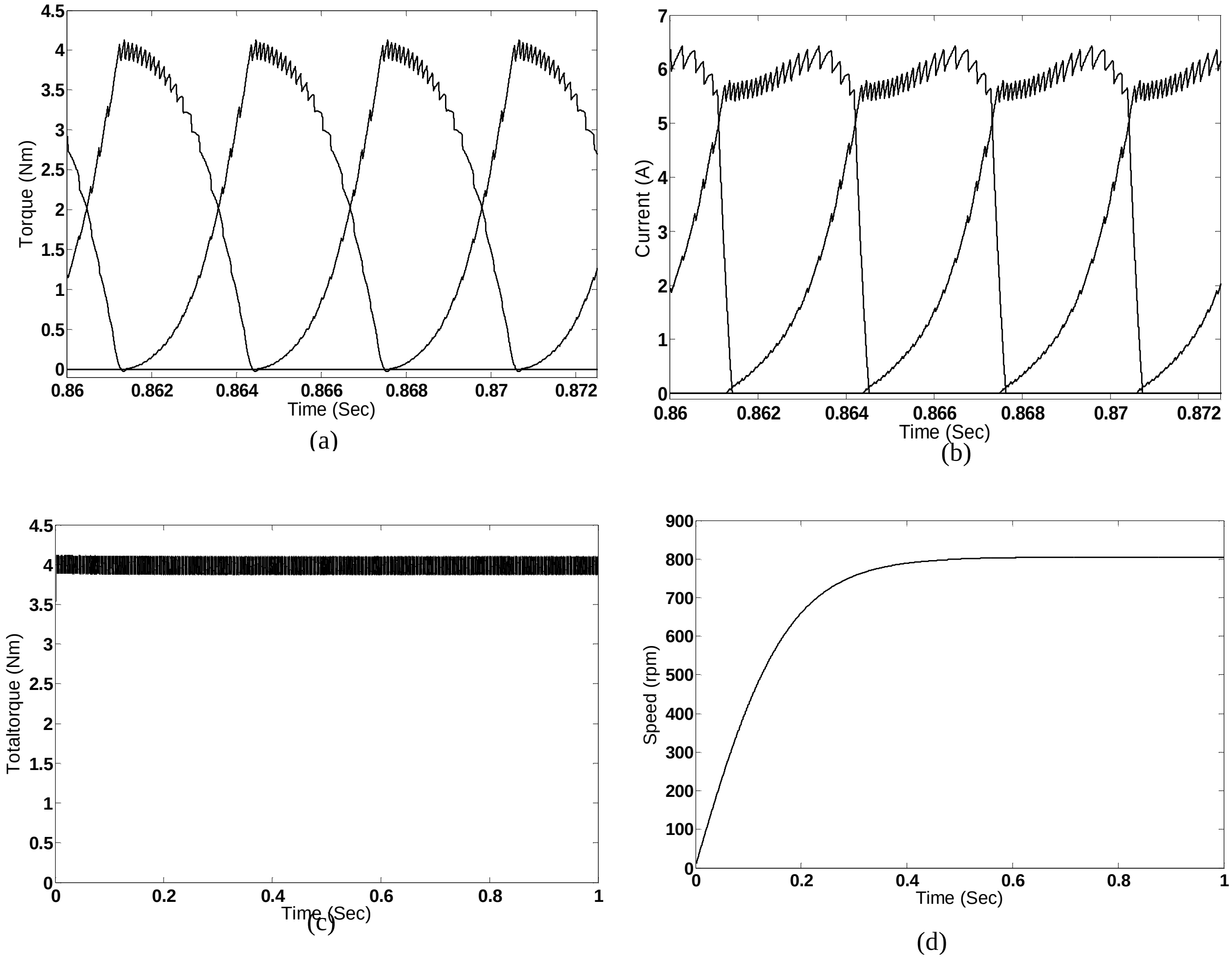


Figure 8. (a) Phase torques (b) Phase currents (c) Total torque (d) Speed

6. Conclusions

The performance of the SRM drive is analyzed with DITC controller. The SRM is modeled by developing two lookup tables namely Position-fluxlinkage-current and Position-current-torque using FEA. The drive with DITC controller is simulated for a Fan load of 4 Nm with a hysteresis band of 5% and maximum speed is set at 800 rpm. The dwell angle is set at 29^0 based on the value of load. It is observed that the average motor torque is maintained at 4 Nm with a hysteresis band of 0.21 Nm. The calculated torque ripple is 5.25%. Thus, it can be concluded that the torque ripple reduction is the inherent property of DITC and does not require any torque sharing functions or current shaping techniques as used in conventional methodologies.

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Appendix

Specifications of SRM

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

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