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Comparative Analysis of DTC Based Switched Reluctance Motor Drive Using Torque Equation and FEA Models

P. Srinivas, P. V. N. Prasad

***Abstract*—**Since torque ripple is the main cause of noise and vibrations, the performance of Switched Reluctance Motor (SRM) can be improved by minimizing its torque ripple using a novel control technique called Direct Torque Control (DTC). In DTC technique, torque is controlled directly through control of magnitude of the flux and change in speed of the stator flux vector. The flux and torque are maintained within set hysteresis bands.

The DTC of SRM is analyzed by two methods. In one method, the actual torque is computed by conducting Finite Element Analysis (FEA) on the design specifications of the motor. In the other method, the torque is computed by Simplified Torque Equation. The variation of peak current, average current, torque ripple and speed settling time with Simplified Torque Equation model is compared with FEA based model.

***Keywords*—**Direct Toque Control, Simplified Torque Equation, Finite Element Analysis, Torque Ripple.

I. Introduction

SWITCHED Reluctance Motor (SRM) drive applications have increased in recent years because of advantages such as simple construction and low manufacturing cost [1]. Because of advancements in power electronic switches and fast computing controllers like Digital signal processors, the conventional variable AC/DC machines are now replaced by SRMs in applications like high speed trains, electric vehicles, compressors, washing machines, textile processing industry etc [2]. The main drawback of the motor is that it has highly non-linear torque-position characteristics and high torque ripple, which causes noise and vibrations [1], [2].

Different techniques have been proposed in the past to minimize torque ripple. An application of DTC technique to the SRM has been described in [3]. This scheme used the concept of a short flux pattern that links two separate poles of the stator. The major disadvantage of this scheme is that a new motor winding topology is required. Altering the motor winding configuration is both expensive and inconvenient. In [4], [5] a novel DTC technique is applied to 3-phase 6/4 SRM in which the difference between conventional DTC applied to ac machines and the new DTC proposed to SRM has been elaborately discussed. The DTC technique proposed in [4], [5] has been used in [6], [7] to study DTC technique in detail through simulations. The low speed and high speed operation of the DTC based 6/4 SRM drive is analyzed in [8]. DTC of 4 phases SRM is analyzed in [9]. DTC of 4 phase 8/6 SRM drive with constant torque load has been analyzed in [10].

In order to control the torque, DTC scheme requires torque feedback. One method of computing torque is by conducting FEA. To conduct FEA, the complete specifications of the SRM are required. The design specifications of SRM are not available or not disclosed by the manufacturer. Under such circumstances it is difficult to compute torque as a function of current and position. Alternately, the torque can be computed by Simplified Torque Equation [5].

This paper compares the performance of DTC based 4 phases 8/6 SRM in which torque is computed from Simplified Torque Equation and also using FEA.

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II. Principle of DTC

The approximate equation for torque developed by the SRM [5] is given by

$$T \approx i\frac{\partial \psi(\theta,i)}{\partial \theta} \tag{1}$$

where $\psi(\theta,i)$ is phase flux-linkage as a function of rotor position θ and stator current i

In SRM drives, as unipolar converters are normally used, the current flow in a motor phase winding is always positive. Hence, the sign of the torque is directly related to the sign of $\frac{\partial\psi}{\partial\theta}$. In other words a positive torque is developed when the change in stator flux increases with respect to the rotor position and to produce a negative torque the change in stator flux should decrease with respect to the rotor movement. When $\frac{\partial\psi}{\partial\theta}$ is positive it may be defined as "flux acceleration" and when it is negative it may be defined as "flux deceleration" [5].

The DTC technique [4], [5] for SRM is defined as follows.

(i). The stator flux-linkage vector of the motor is kept at constant amplitude (within set hysteresis band)

(ii). Torque is controlled by accelerating or decelerating the stator flux vector.

The objective (i) is achieved by selecting an appropriate Space voltage vector. The stator flux variation will have the same directional variation as the voltage vector and a change in amplitude is proportional to the magnitude of the voltage and the time interval of application. The objective (ii) is also achieved similarly to the conventional AC motor by DTC, because the torque is increased or decreased by acceleration or

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deceleration of the stator flux vector relative to the rotor movement [5].

Asymmetrical converter is popularly used for the SRM drives. As shown in Fig. 1, when both the switches are turned ON, the state is defined as 'magnetizing' (state 1). When one switch is turned ON and other is turned OFF, the state is defined as 'freewheeling' (state 0). When both the switches are turned OFF, the state is defined as 'demagnetizing' (state -1). The 4 phase Asymmetrical converter can have a total of 81 possible space voltage vectors. However, in order to apply DTC to SRM, eight equal amplitude voltage vectors that are separated by $\pi/4$ radians, are sufficient. The space voltage vector states are shown in Fig. 2. These voltage state vectors are defined to lie in the center of eight sectors or zones where each zone has a width of $\pi/4$ radians.

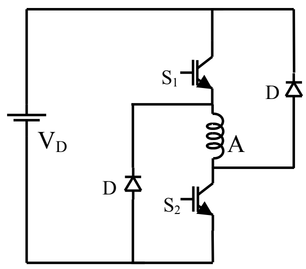


Fig. 1 Asymmetrical Converter

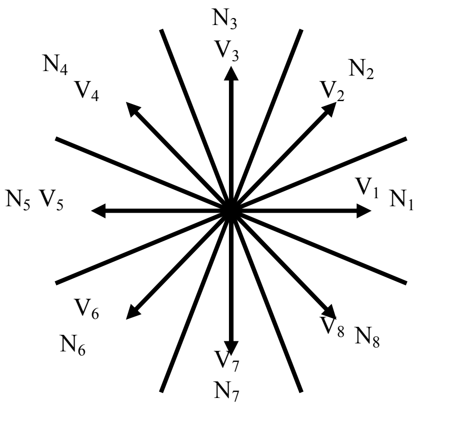


Fig. 2 Definition of SRM motor voltage vectors for DTC.

One of the eight possible states is chosen at any one time in order to keep the stator flux-linkage and the motor torque within hysteresis band. As in the conventional DTC scheme, if the stator flux linkage lies in the kth zone, where k = 1 to 8 , the magnitude of the flux can be increased by using the switching vectors V_{k+1} and V_{k-1} and can be decreased by using the vectors V_{k+2} and V_{k-2} [5]. Hence, whenever the stator flux-linkage reaches its upper limit in the hysteresis band, it is reduced by applying voltage vectors which are directed toward the center of the flux vector space and vice-versa. As detailed previously, the torque is controlled by an acceleration or deceleration of the stator flux relative to the rotor movement. Hence, if an increase in torque is required, voltage vectors that advance the stator flux-linkage in the direction of rotation are selected. This corresponds to selection of vectors V_{k+1} and V_{k+2} for a stator flux-linkage in the kth zone. If a decrease in torque is required, voltage vectors are applied which decelerate the stator flux-linkage vector. This corresponds to the vectors V_{k-1} and V_{k-2} in the kth zone [5]. Hence, a switching table for controlling the stator flux-linkage and motor torque can be defined as shown in Table I, where $\psi_Q = 1$ & $\psi_Q = 0$ indicate increase and decrease in the flux-linkages respectively and $T_Q = 1$ & $T_Q = 0$ indicate increase and decrease in torque respectively.

TABLE I
SWITCHING TABLE OF VOLTAGE VECTORS

k		1	2	3	4	5	6	7	8
$\psi_Q = 1$	$T_Q = 1$	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_1
	$T_Q = 0$	V_7	V_8	V_1	V_2	V_3	V_4	V_5	V_6
$\psi_Q = 0$	$T_Q = 1$	V_3	V_4	V_5	V_6	V_7	V_8	V_1	V_2
	$T_Q = 0$	V_6	V_7	V_8	V_1	V_2	V_3	V_4	V_5

III. Simulation and Analysis of Direct Torque Control using Simplified Torque Equation

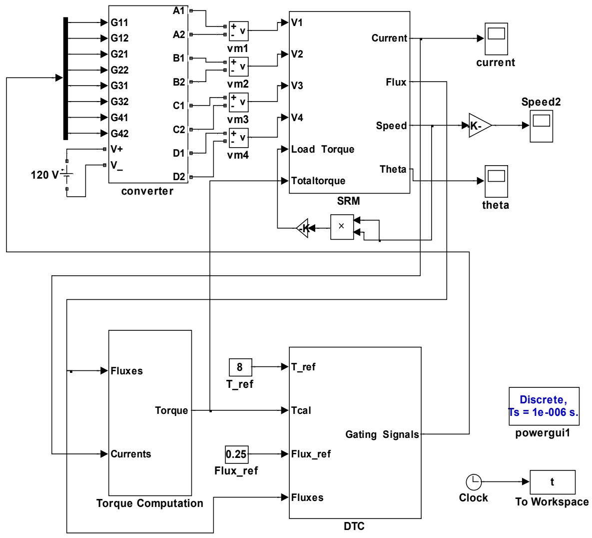
If the design specifications of the motor are not disclosed by the manufacturer, the instantaneous torque can be computed by simplified equation shown below [5]

$$T = p(\psi_\alpha i_\beta - \psi_\beta i_\alpha) \tag{2}$$

where p is the number of pole pairs, i_α & i_β are respective currents in α and β axes and ψ_α & ψ_β are respective α and β components of flux-linkages in the stationary reference frame.

The complete Non-linear model of the 4 phase 8/6 SRM with Direct Torque Controller is shown in Fig. 3. The specification of the SRM is given in Appendix. The model consists of electrical system, mechanical system, position sensing block, Asymmetrical converter, torque computation block and DTC block. In this model, the torque is computed using (2), which is realized by torque computation block shown in Fig. 3 (a). The reference flux is set at 0.25 Wb and flux hysteresis band is set at 0.02 Wb. The reference torque is set at 8 Nm and the torque hysteresis band is set at 0.40 Nm. The DTC scheme is simulated by selecting the following set of 8 space voltage vectors. V1 = (-1010), V2 = (-1-111), V3 = (0-101), V4 = (1-1-11), V5 = (10-10), V6 = (11-1-1), V7 = (010-1), V8 = (-111-1).

The performance of the DTC based SRM drive is analyzed for a Fan type load of 8 Nm and at a reference speed of 800rpm. Fig. 4 shows the simulation waveforms of the drive with DTC technique. Fig. 4 (a) shows the variation of stator current in all the four phases as a function of time. The maximum current and the average current in the each phase are 8.16 A and 3.86 A respectively. Fig. 4 (b) shows the magnitude of the stator flux vector. The flux is maintained at the reference value of 0.25 Wb by following a hysteresis band of 0.021 Wb as against the set band of 0.02 Wb. Fig. 4 (c) shows the total torque response. It is observed that the torque is maintained within the hysteresis band of 0.54 Nm as against the set band of 0.4 Nm. The calculated torque ripple is 6.75 %. Instantaneous torques of all the four phases is shown in Fig. 4 (d). Fig. 4 (e) shows the speed response. The settling time for steady state speed is 0.301 sec. Fig. 4 (f) shows the variation of ψ_α with ψ_β. It can be seen that the trajectory of fluxes between α and β axes is circular in nature.



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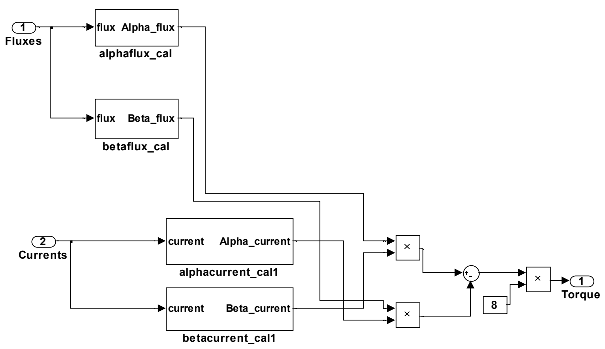

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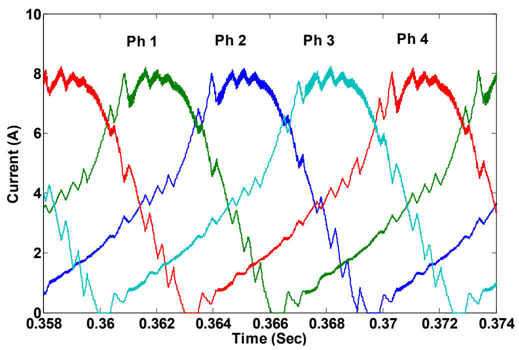
Fig. 3 Simulation diagram of SRM drive with Direct Torque Controller (Simplified Torque Equation) (a) Complete diagram (b) Torque computation block



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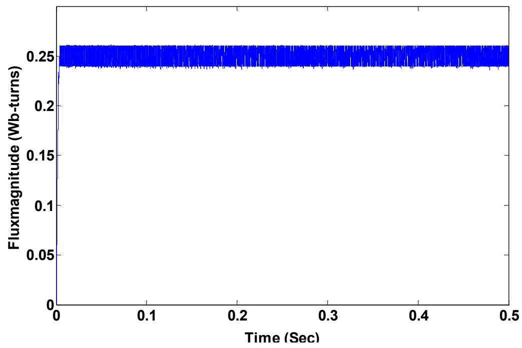

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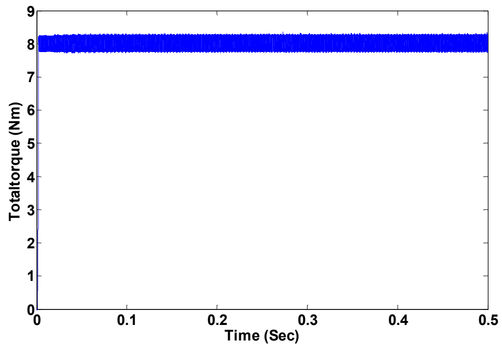

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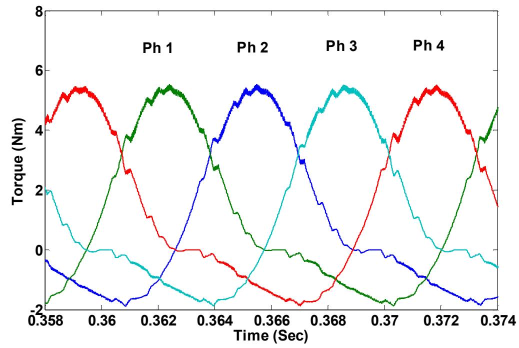

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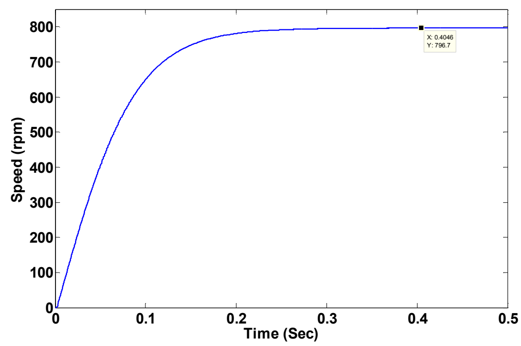

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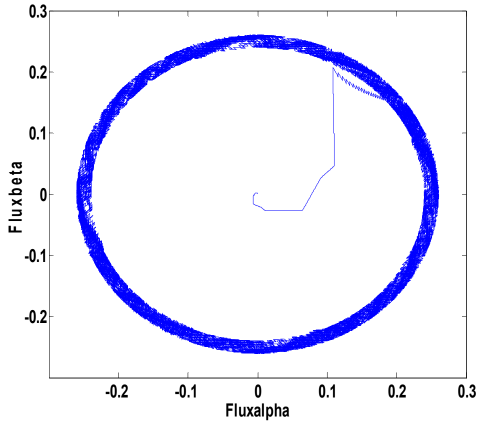


(f)

Fig. 4 DTC with Simplified Torque Equation (a) Phase currents (b) Flux magnitude (c) Total torque (d) Phase torques (e) Speed (f) Flux vector trajectory

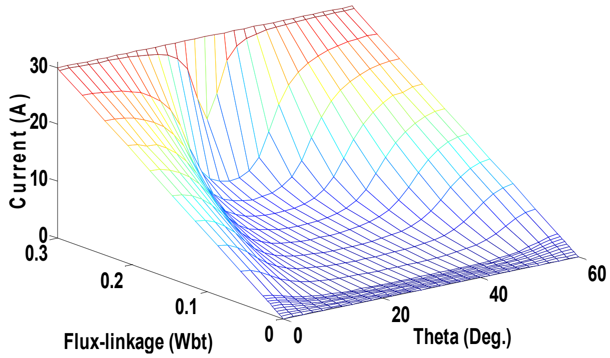
IV. Simulation and Analysis of Direct Torque Control using FEA

In another method torque is computed by performing FEA on the SRM whose specifications are given in the Appendix. In this method the motor is modeled by formulating two Look-up tables namely Position-flux-linkage-current and Position-current-torque. These Look-up tables are formulated for 16 rotor positions from 0^0 to 30^0 and 16 different current values from 0 to 30 A by using FEA. Fig. 5 (a) shows the 3D mesh plot of flux-linkage as a function of position and current. Fig. 5 (b) shows the 3D mesh plot of total torque as a function of position and current.

The complete Non-linear model of the 4-phase 8/6 SRM with Direct Torque Controller is shown in Fig. 6. The model consists of electrical system, mechanical system, position sensing block, Asymmetrical converter and DTC block. Fig. 6 (a) shows the model for one phase. The reference flux is set at 0.25 Wb and flux hysteresis band is set at 0.02 Wb. The reference torque is set at 8 Nm and the torque hysteresis band is set at 0.40 Nm. The DTC scheme is simulated by selecting the following set of 8 space voltage vectors. V1 = (-1010), V2 = (-1-111), V3 = (0-101), V4 = (1-1-11), V5 = (10-10), V6 = (11-1-1), V7 = (010-1), V8 = (-111-1).

The performance of the DTC based SRM drive is analyzed for a Fan type load of 8 Nm and at a reference speed of 800 rpm. Fig. 7 shows the simulation waveforms of the drive with DTC technique. Fig. 7 (a) shows the variation of stator current in all the four phases as a function of time. The maximum current and the average current of each phase are 13.87 A and 4.85 A respectively. Fig. 7 (b) shows the magnitude of the stator flux vector. The flux magnitude is maintained at the reference value of 0.25 Wb by following a hysteresis band of 0.021 Wb, as against the set band of 0.020 Wb. Fig. 7 (c) shows the total torque response. It is observed that the torque is maintained within the hysteresis band of 0.48 Nm as against the set band of 0.40 Nm. The calculated torque ripple is 6.00 %. The instantaneous torques of all the four phases is shown in Fig. 7 (d). Fig. 7(e) shows the speed response. The settling time for steady state speed is 0.310 sec. Fig. 7 (f) shows the variation of ψ_α with ψ_β. It can be seen that the trajectory of fluxes between α and β axes is circular in nature.

The variation of peak current, average current, torque ripple and speed settling time for DTC of drive with two methods is given in the Table II.



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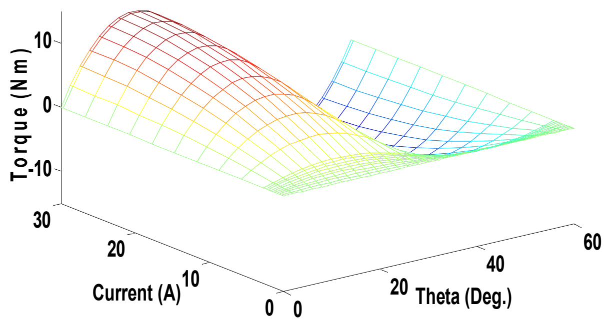
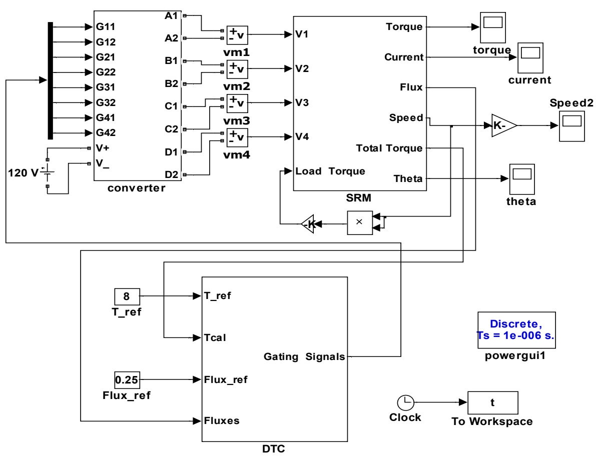


(b)

Fig. 5 Mesh plots (a) Position-flux-linkage-current (b) Position-current-torque



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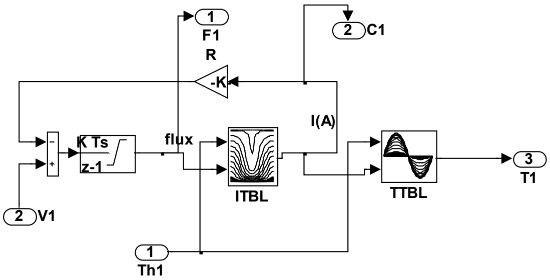

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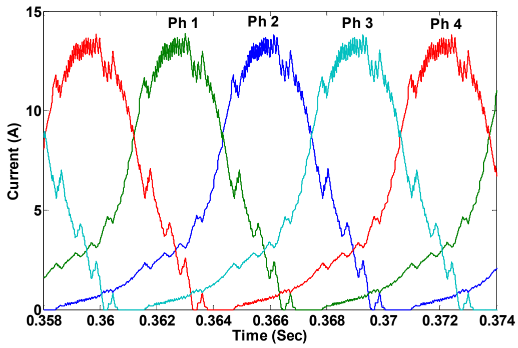
Fig. 6 Simulation diagram of SRM drive with Direct Torque Controller with FEA (a) Complete diagram (b) Internal block of one phase



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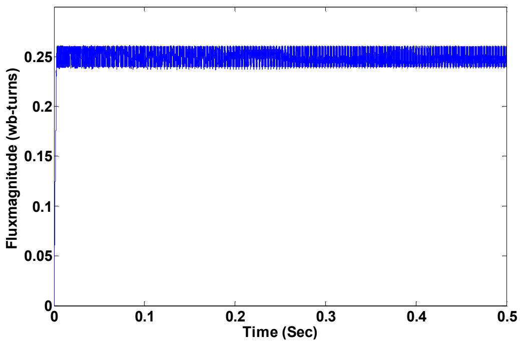

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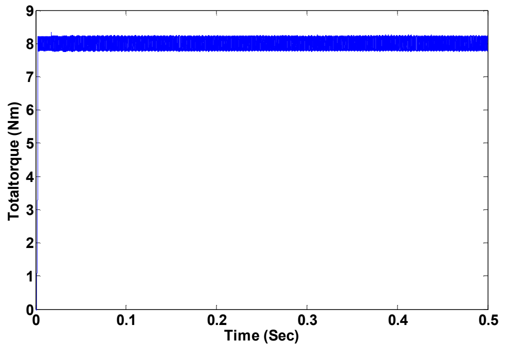

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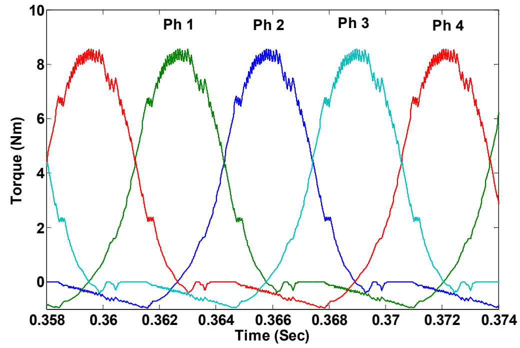

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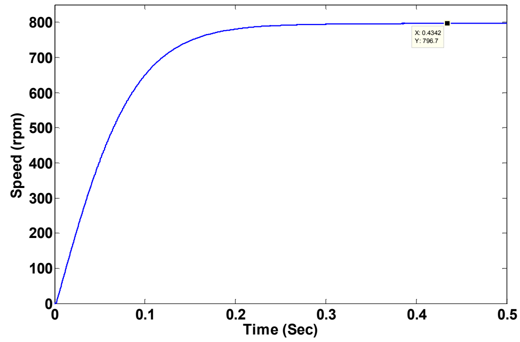

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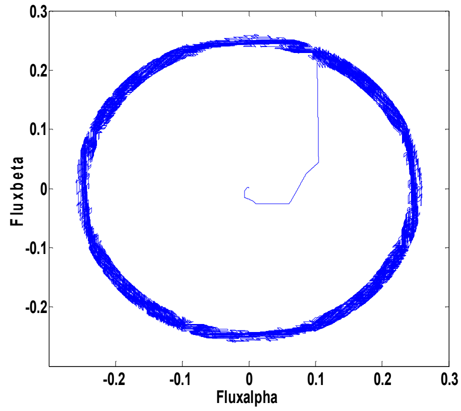

(f)

Fig. 7 DTC with FEA (a) Phase currents (b) Flux magnitude (c) Total torque (d) Phase torques (e) Speed (f) Flux vector trajectory

TABLE II
COMPARATIVE ANALYSIS OF DTC WITH SIMPLIFIED TORQUE EQUATION & FEA

Torque Computation	Maximum Current (A)	Average Current (A)	% Torque Ripple	Settling time (Sec)
Simplified Toque Equation	8.16	3.86	6.75	0.301
FEA	13.87	4.85	6.00	0.310

From the above table it is clear that the speed settling times are almost same in both the methods. The calculated torque ripple is slightly higher in Simplified Torque Equation method. The values of peak current and average current are lesser and optimistic in this method, because the inherent nonlinearity is not taken into consideration. The results obtained with FEA model are realistic in nature since, the nonlinear magnetic nature of the motor is automatically considered.

V. CONCLUSION

In DTC, the torque is controlled directly through the control of magnitude of the flux-linkage and the change in speed of the stator flux vector. The DTC based SRM drive is analyzed for two methods. In one method, the torque is computed by Simplified Torque Equation and in other method torque is computed by FEA. It is observed that the values of maximum current and average current are less by Simplified Torque Equation method when compared to FEA method. The speed settling times are almost same in both the methods. The calculated torque ripple is slightly higher in Simplified Torque Equation method. These wide variations in the results using Simplified Torque Equation model compared to FEA model can be attributed to the linear magnetic characteristics of SRM.

APPENDIX

Voltage	:	120 V DC
Maximum Current	:	30 A
Rated Speed	:	1500 rpm
Maximum Flux	:	0.3 Wb
Aligned Inductance	:	110 mH
Unaligned Inductance	:	10 mH
Resistance	:	0.3 Ω
Stator diameter	:	143 mm
Stator tooth height	:	24.5 mm
Stator poles	:	8
Stator tooth arc	:	0.416 radians
Stator yoke thickness	:	12.1 mm
Stack length	:	143 mm
Air gap	:	0.4 mm
Rotor diameter	:	69 mm
Rotor poles	:	6
Rotor tooth height	:	12.5 mm
Rotor yoke thickness	:	9 mm
Rotor tooth arc	:	0.492 radians
Shaft diameter	:	26 mm
Coil turns	:	180

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