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Design of Controller for Torque Ripple Minimization in Switched Reluctance Motor

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***Abstract*— Switched Reluctance Motor because of its intrinsic simplicity in structure, low cost, high reliability make them suitable for many application. However, due to double saliency structure of Switched Reluctance Motor, torque ripple is more severe than any other traditional motors. Torque ripple further leads to vibration and noise. In order to control the torque ripple, in this scheme torque and flux is regulated within hysteresis band by applying the method of DTC (Direct Torque Control). In this paper, Direct Torque Control of 6/4 SRM is simulated and performance is analysed at different load and speed conditions.**

***Keywords*— 6/4 Switched Reluctance Motor, Torque Ripple, Direct Torque Control, Switching Logic**

I. INTRODUCTION

Switched Reluctance Motor (SRM) has received significant importance in industrial applications because of its simple construction with non-winding construction on rotor side, low cost, high robustness and wide speed range. However, due to nonlinear torque characteristics and high torque ripple, acoustic noise and vibration are more severe in these motors than any other traditional motor.

Ripple in torque can be minimised by using proper torque control technique or through improvement in magnetic circuit design at motor design stage. Different methods have been obtained in past to minimize the torque ripple. The optimization of stator and rotor pole arc are presented in [1] [2]. Torque ripple minimization by changing turn off angle is presented in [3] [4], but this is effective only in commutation region. This paper presents DTC control of a 6/4 SRM. Here Torque is maintained within hysteresis by suitable selection of voltage space vector. The drive is simulated at different load conditions and the torque is maintained within the hysteresis band.

II. DTC BASED SRM DRIVE

A. DTC Principle

In case of switched reluctance motor the torque production depends upon the reluctance principle, where phases operate independently and in succession. Due to non-linear characteristics of the motor, the expression for the phase torque is given by,

$$T(\theta, i) = i\frac{\delta\psi(\theta, i)}{\delta\theta} \tag{1}$$

Where 'θ' is the rotor angular position; 'i' is the phase current; '$T(\theta, i)$' is phase torque which is directly proportional to $\frac{\delta\psi(\theta,i)}{\delta\theta}$. Therefore, in order to produce a positive torque the change in the stator flux amplitude must be increasing with respect to rotor position and in order to produce negative torque change in stator flux amplitude must be decreasing with respect to rotor position.

B. Stator Flux Calculation

For a phase k stator winding voltage equation of arbitrary phase switch reluctance motor can be expressed as

$$V_k = R_s I_k + \frac{\delta\psi(\theta,i)}{\delta\theta} \tag{2}$$

Where, V_k is the stator voltage vector of phase k; $\frac{\delta\psi(\theta,i)}{\delta\theta}$ is flux vector of phase k; R_s is the equivalent resistance of stator phase; I_k is phase current of phase *k*,

the stator winding flux linkage of phase *k* at a certain moment *t* can be computed using,

$$\psi_k(\theta, i) = \int_0^t (V_k - R_s I_k) + \psi_o \tag{3}$$

For three-phase SRM, the two axes components of the stator flux vector of the orthogonal frame can be calculated as,

$$\psi_\alpha = \psi_a - \psi_b \cos 60° - \psi_c \cos 60° \tag{4}$$

$$\psi_\beta = \psi_b \sin 60° - \psi_c \sin 60° \tag{5}$$

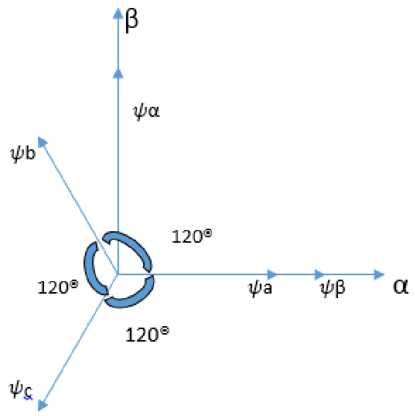


Fig. 1 Two frame reference axis for 6/4 motor voltage

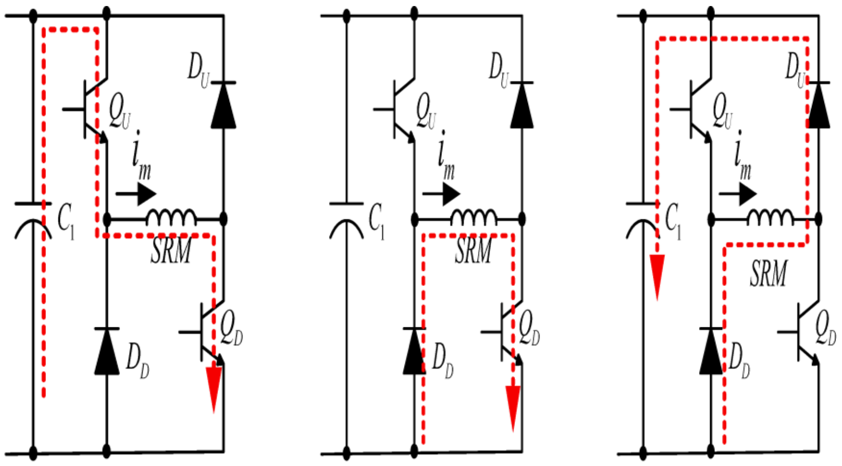
The stator flux amplitude and space angle can be obtained using ψ_α and ψ_β,

$$\psi_{S}=\sqrt{\psi\alpha^2 + \psi\beta^2} \quad (6)$$

$$\delta = \arctan\frac{\psi\alpha}{\psi\beta} \quad (7)$$

C. Space Voltage Vector And Switching Logic

Asymmetrical power converter is used to carry out the work. Each phase winding has three possible state as shown in Fig.2. In positive/ magnetising state, Q_{11} and Q_{12} are turned ON simultaneously, as a result, winding is excited, magnetic field is established and phase torque starts increasing. In zero/ freewheeling state, Q_{11} or Q_{12} is solely turned ON and total torque is maintained constant. In negative/ demagnetising state, Q_{11} and Q_{12} are turned OFF simultaneously, phase torque decreases as energy stored in winding is fed back to source.



(A) Magnetising Mode '1' (B) Freewheeling Mode '0' (C) Demagnetising Mode '-1'

Fig. 2 Voltage state in asymmetric power converter

For a three-phase SRM, with three possible voltage states, only six voltage vectors { (1 0 -1) (0 1 -1)} (-1 1 0) (-1 0 1) (0 -1 1) (1 -1 0)} are selected. One of the six states is chosen at a time, depending on the sector which stator flux linkage lies in order to control stator flux and torque within hysteresis limit. If suppose the stator flux vector lies in kth sector then flux can be increased by switching to vector V_{k+1} and V_{k-1}, and can be decreased by V_{k+2} and V_{k-2}.

Since torque is controlled by acceleration or deceleration of stator flux relative to rotor position, therefore, in order to increase the torque, voltage vector is selected that advances the stator flux in the direction of rotation, which corresponds to vector V_{k+1} and V_{k+2}. If a decrease in torque is required, vector V_{k-1} and V_{k-2} is chosen for a stator flux linkage in kth zone.

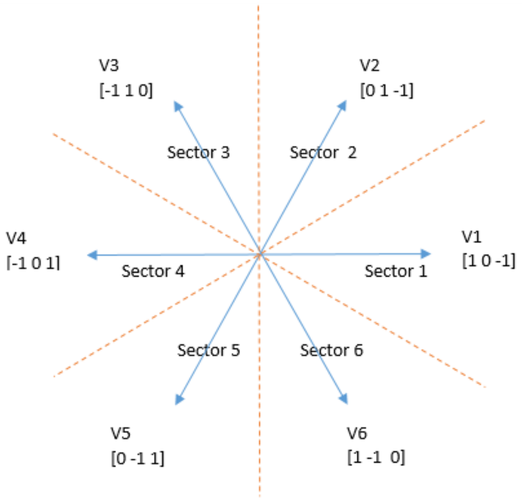


Fig. 3 Voltage space vector of 6/4 SRM

. Switching table for controlling the flux and motor torque is shown in TABLE I. ↑ and ↓ are increase and decrease command respectively and = signifies within hysteresis band.

TABLE I
SWITCHING TABLE

		V1	V2	V3	V4	V5	V6
Ψ↑	T ↑	V2	V3	V4	V5	V6	V1
	T =	V0	V7	V0	V7	V0	V7
	T ↓	V6	V1	V2	V3	V4	V5
Ψ↓	T ↑	V3	V4	V5	V6	V1	V2
	T =	V0	V7	V0	V7	V0	V7
	T ↓	V5	V6	V1	V2	V3	V4

III. SIMULATION AND RESULTS

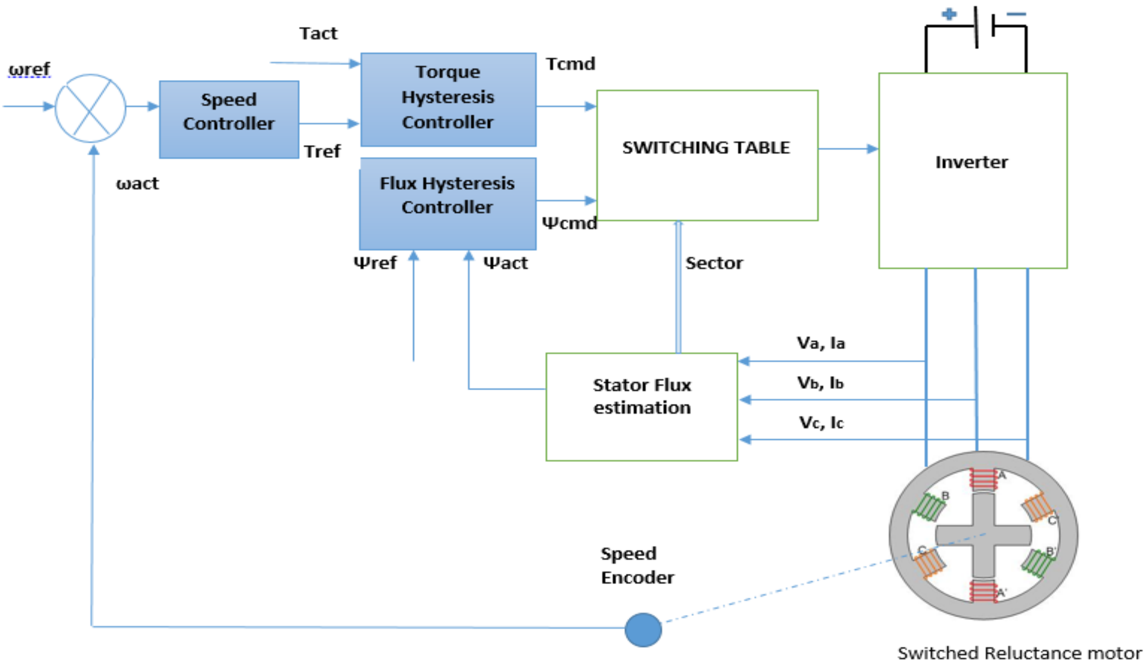


Fig. 4 Block diagram of DTC

The schematic of DTC based speed control of SRM is shown in Fig.4. Here the instantaneous speed is compared with speed reference and reference torque is obtained. Stator flux linkage is obtained using phase current and phase voltage. Output torque and flux linkage are compared with reference value in hysteresis comparator. The hysteresis bands were defined to be ± 0.02 Wb and ± 0.2 Nm for Stator flux linkage and torque respectively. Command from Hysteresis controllers and the sector then decides the next vector state.

A. Simulink Model

To analyse the performance of the proposed drive, the drive is simulated using MATLAB/SIMULINK software. The simulation parameters of 6/4 SRM used are: Rated power: 60KW; rated voltage: 220V; max flux linkage: 0.45Wb; torque: 25N.m. Fig. 5 shows the Simulink model of DTC.

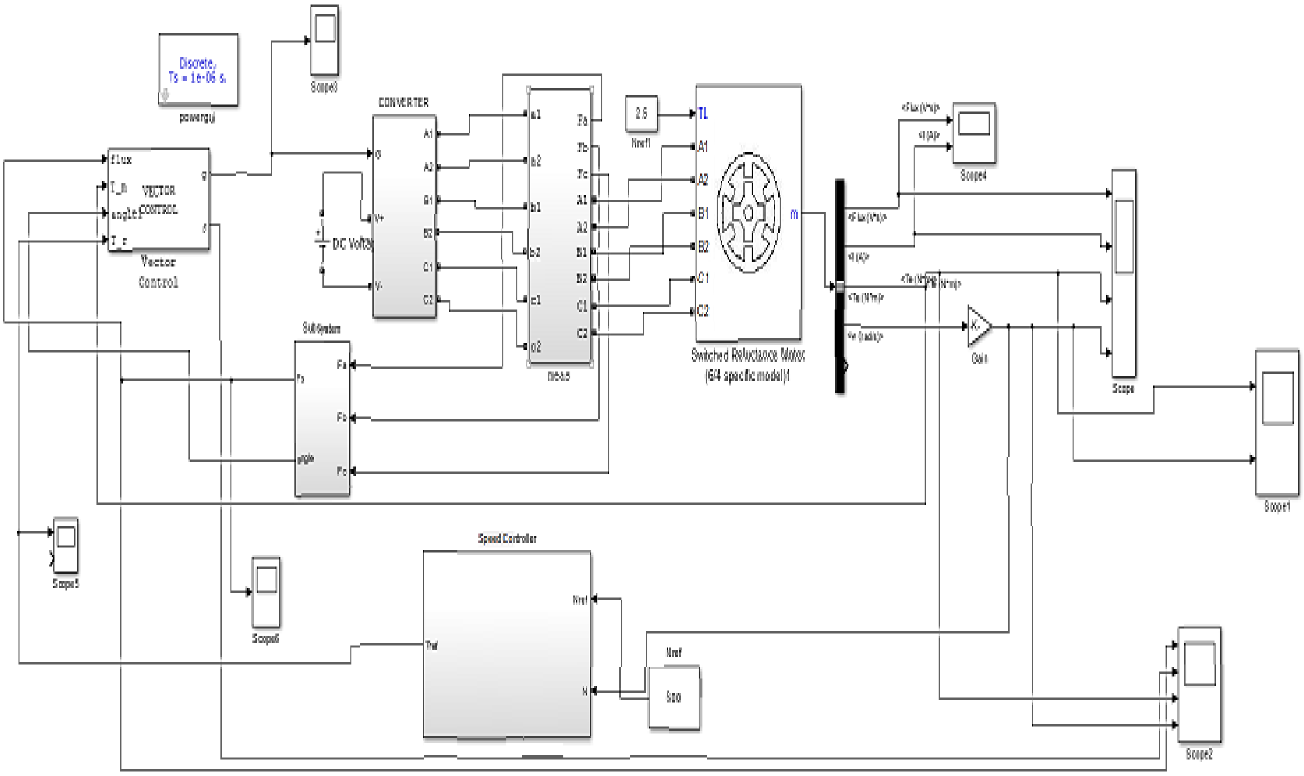


Fig. 5 Simulink model of SRM with DTC

Phase current and flux linkage response are shown in Fig. 6(a). Stator flux linkage is maintained within hysteresis band of ±0.02 as shown in Fig. 6(b) for reference flux of 0.3Wb.

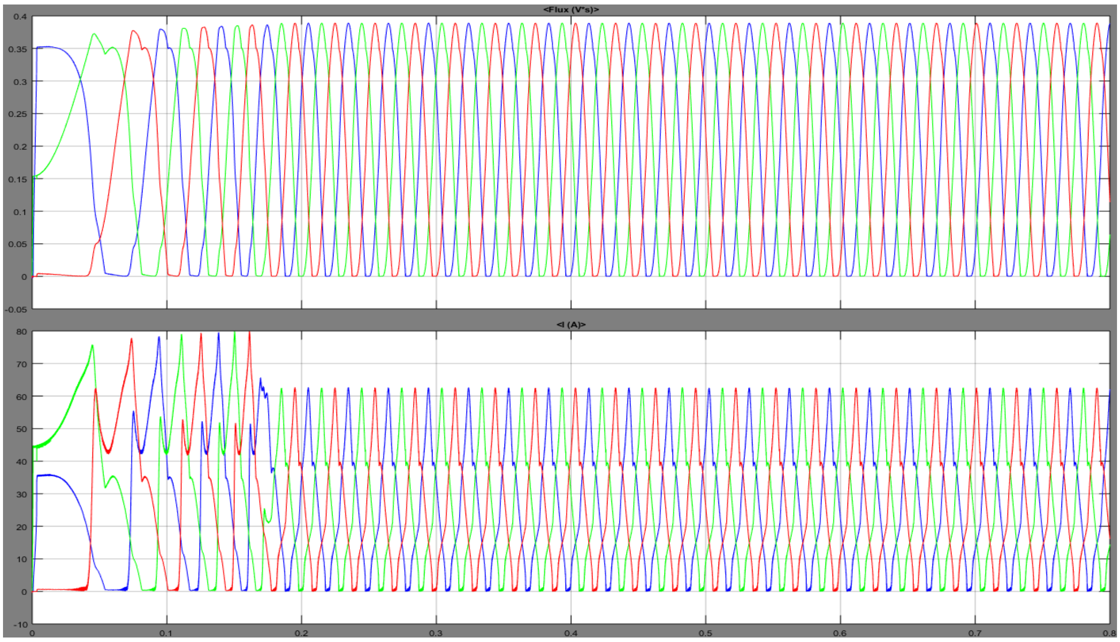


Fig. 6(a) Current and flux response of the proposed drive

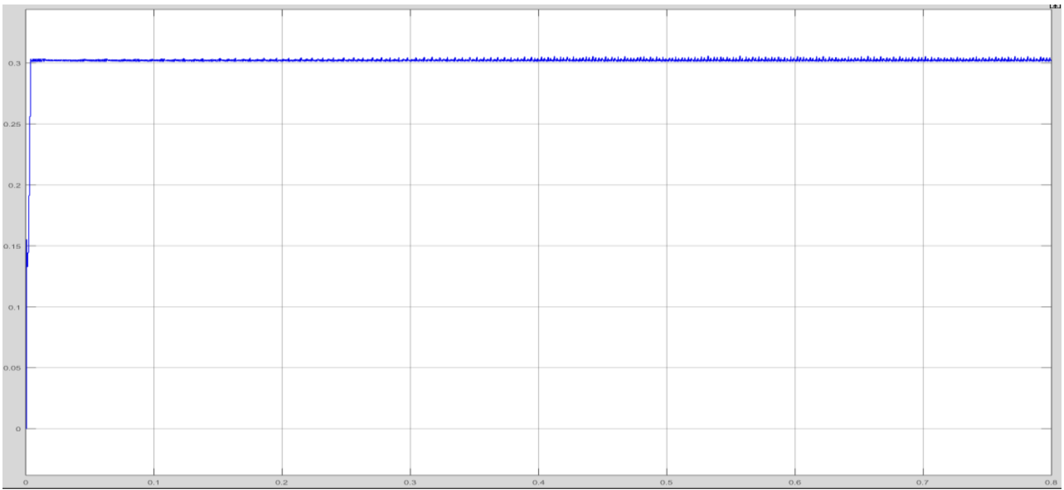


Fig. 6(b) Stator flux response of the proposed drive

Total torque and speed response of the drive for different speed reference and at different load conditions are shown in Fig.7 to Fig.9.

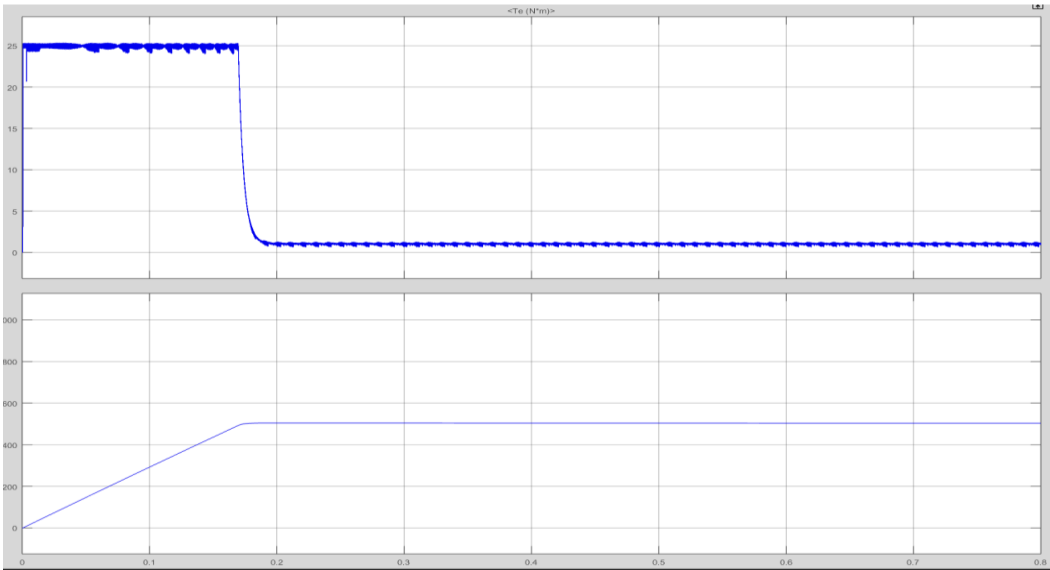


Fig. 7 Total torque and speed response at no load and speed reference equal to 500 RPM

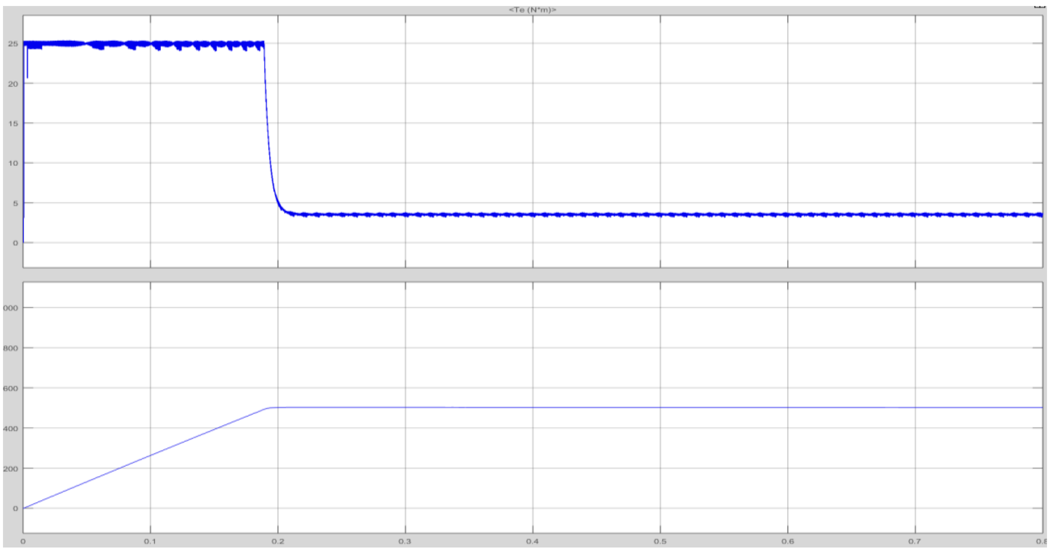


Fig. 8 Total torque and speed response at 2.5N.m load and speed reference equal to 500 RPM

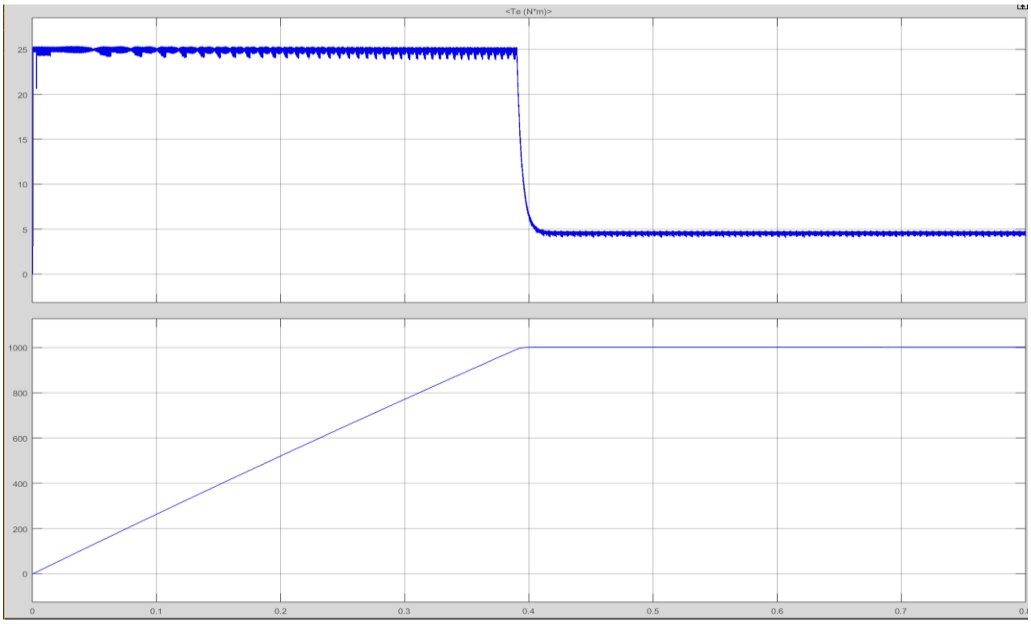


Fig. 9 Total torque and speed response at 2.5N.m load and speed reference equal to 1000 RPM

It is observed from above figures that the acceleration is smooth till speed reaches steady state value i.e. till it reaches reference speed. The maximum flux is maintained at 0.3Wb both during acceleration and steady state condition. The total torque is maintained at 25Nm within hysteresis band until reference speed is obtained.

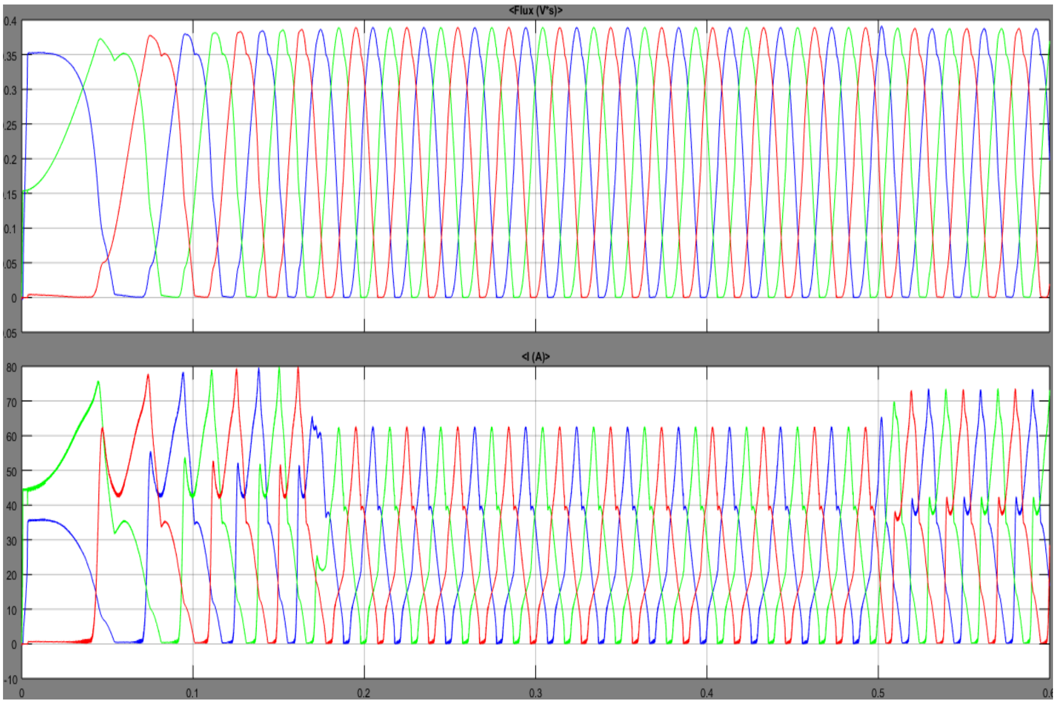


Fig. 10(a) Flux response and current response for speed reference equal to 500 RPM and load torque of 20N.m applied at t=5sec

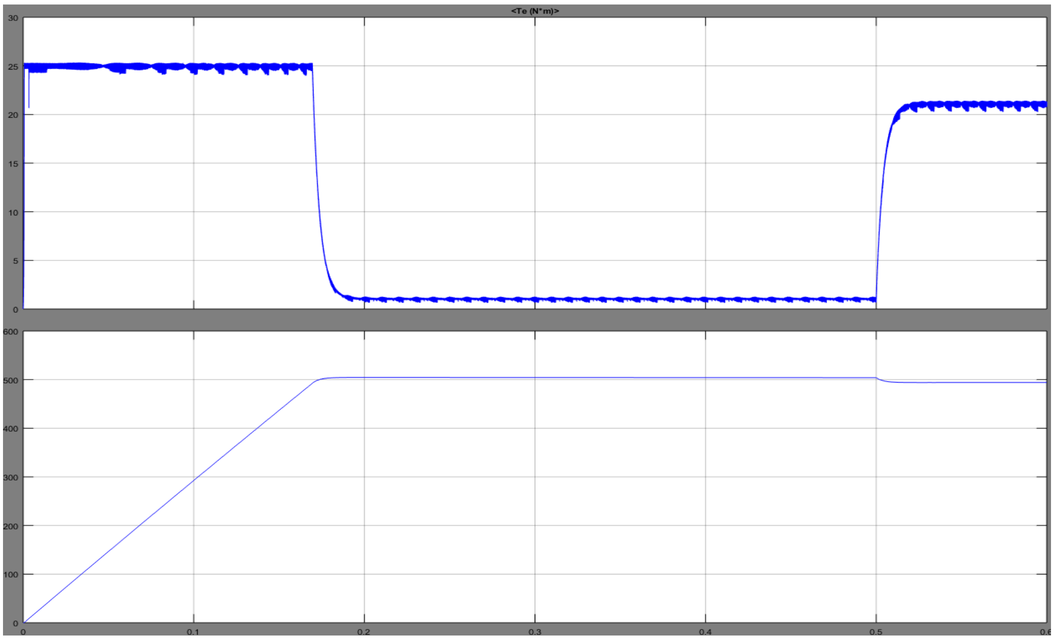


Fig. 10(b) Total torque and speed response for speed reference equal to 500 RPM and load torque of 20N.m applied at t=5sec

In Fig.10 (a) and Fig.10 (b), the load torque of 20Nm is applied at t=0.5 sec, motor torque increases gradually and there is small increase in current. However, with this application of load, motor torque remains within the hysteresis limit thus torque ripple remains within acceptable limit irrespective of load applied.

IV. Conclusions

This paper proposes a torque controller for minimizing the torque ripple in Switched Reluctance motor. The Drive with DTC Controller is simulated using MATLAB/SIMULINK for stator flux reference equal to 0.3 Wb. In this method, torque and torque ripple is directly controlled through the control of the magnitude of the flux linkage and the change in speed of the stator flux vector. From simulation result it is observed that the flux and torque are maintained within set hysteresis band both during acceleration and steady state conditions.

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