TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 12, No. 12, December 2014, pp. 8085 ~ 8091
DOI: 10.11591/telkomnika.v12i12.6718

Effect of Switching Frequency in DTC Based Switched Reluctance Motor Drive

P.Srinivas
Dept. of Electrical Engg., University College of Engg., Osmania University, Hyderabad, India
email: srinivasp.eedou@gmail.com

Abstract

Since the magnetizing characteristics are highly non-linear in nature, the torque ripple is high in the Switched Reluctance Motor (SRM). The torque ripple can be minimized by using a novel control technique called Direct Torque Control (DTC). In DTC technique, torque is controlled directly through control of magnitude of the flux-linkage and change in speed of the stator flux vector. The flux and torque are maintained within set hysteresis bands. This paper analyzes performance of the DTC based drive mainly in terms of the torque ripple in MATLAB/SIMULINK environment and results are discussed elaborately. The paper also analyzes the effect of these two bands on switching frequency of the converter.

Keywords: *switched reluctance motor, direct torque control, switching frequency, torque ripple*

1. Introduction

Switched Reluctance Motor drives are considered as an alternative to the conventional motor drives in variable speed applications because of advantages such as simple mechanical structure, no winding or magnet on rotor, high speed operation, wide speed operating range etc. Because of doubly salient structure and highly non-linear magnetic characteristics, the torque ripple is high [1, 2].

The torque ripple reduction of SRM drive using Direct Torque Control is proposed in [3]. But this method requires a new winding scheme which is expensive and inconvenient. To overcome the above disadvantages, a novel DTC technique is proposed in [4, 5]. This technique clearly describes the difference between DTC applied to Induction motor and DTC as applied to SRM. This also clearly analyses the performance of SRM drive using conventional Hystersis Current Control technique and the new DTC scheme. It also proves that using DTC technique torque ripples can be minimized to a greater extend than when compared to the Hysteresis Current Control method [6-8]. The novel DTC technique presented in [4, 5] is simulated in [9, 10].

The simulation and analysis of DTC based 4 phase 8/6 SRM drive for constant torque load is analyzed in [11]. This paper analyzes the performance of DTC based drive for Fan load. Performance analysis of DTC based SRM drive using simplified Torque Equation and FEA models is discussed in [12]. This paper presents the variation of switching frequency in DTC based drive for different combinations of Flux and Torque Hysteresis bands in MATLAB/SIMULINK environment.

2. Principle of DTC

The mathematical equations of DTC [4, 5] as applied to SRM are discussed here. The instantaneous voltage across the motor winding is given by:

$$v = Ri + \frac{d\psi(\theta, i)}{dt} \tag{1}$$

Where $\psi(\theta,i)$ is the phase flux linkages as a function of rotor position θ and stator current i.

Received August 19, 2014; Revised October 22, 2014; Accepted November 8, 2014

Expanding Equation (1) results in Equation (2)

$$v = Ri + \frac{\partial \psi(\theta, i)}{\partial i}\frac{di}{dt} + \frac{\partial \psi(\theta, i)}{\partial \theta}\frac{d\theta}{dt} \quad (2)$$

The differential mechanical energy obtained [5] is shown in Equation (3)

$$dW_m = i\frac{\partial \psi(\theta, i)}{\partial \theta}d\theta - \frac{\partial W_f}{\partial \theta}d\theta \quad (3)$$

The instantaneous torque equation is defined as:

$$T = \frac{dW_m}{d\theta} \quad (4)$$

Thus, by substituting (4) into (3) the expression for the instantaneous torque production of an SRM phase can be written as:

$$T = i\frac{\partial \psi(\theta, i)}{\partial \theta} - \frac{\partial W_f}{\partial \theta} \quad (5)$$

This is a rarely used variant of conventional torque equation. Due to saturation in the SRM, the influence of the second term in (5) is negligible. Therefore, by using this approximation, the following equation for torque production may be obtained as:

$$T \approx i\frac{\partial \psi(\theta, i)}{\partial \theta} \quad (6)$$

In SRM, unipolar drives are normally used and thus the current in a motor phase is always positive. Hence, from eq. (6) the sign of the torque is directly related to the sign of $\partial\psi/\partial\theta$. In other words to produce a positive torque, the stator flux amplitude must increase relative to the rotor position, whereas to produce a negative torque the change in stator flux should decrease with respect to the rotor movement. A positive value of $\partial\psi/\partial\theta$ may be defined as *flux acceleration*, whereas a negative value of $\partial\psi/\partial\theta$ may be defined as *flux deceleration.* The DTC technique is clearly explained in [4, 5].

Asymmetrical converter is popularly used for the SRM drives. The converter for one phase is shown in Figure 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. But in order to apply DTC to SRM, eight Space Voltage Vectors that are separated by 45^0 are sufficient. The eight Space Voltage Vectors that lie in the center of eight sectors N = 1, 2…8, are shown in Figure 2.

As in the conventional DTC scheme, if the stator flux linkage lies in the k^{th} 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} . 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 [5].

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 k^{th} 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 k^{th} zone [5]. Based on the output of the torque and flux hysteresis blocks, appropriate Space Voltage Vectors are selected.

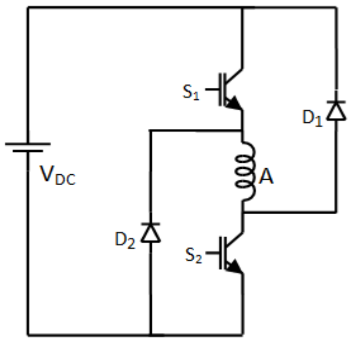


Figure 1. Asymmetrical Converter

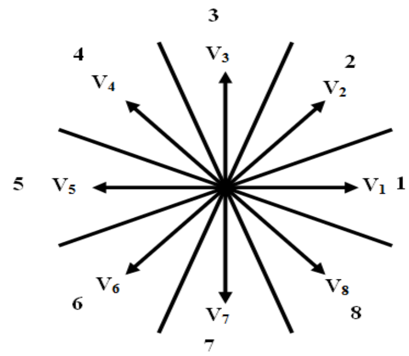


Figure 2. Definition of SRM motor voltage vectors for DTC

3. Simulation and Analysis of Direct Torque Control of SRM

The complete Non-linear model of the 4-phase 8/6 SRM with Direct Torque Controller is shown in Figure 3(a). The specification of the SRM is given in Appendix A. The model consists of electrical system, mechanical system, position sensing block, Asymmetrical converter and DTC block. Figure 3(b) shows the internal block of SRM. Figure 3(c) shows the one phase model.

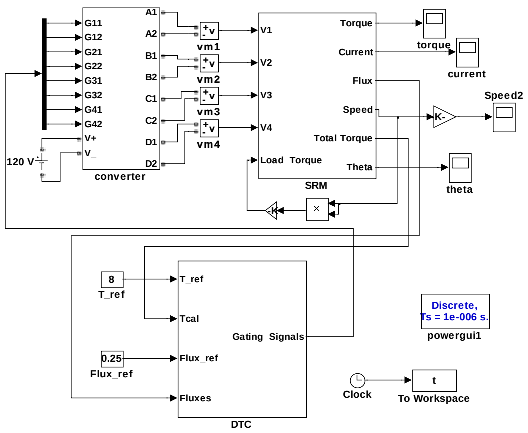


Figure 3(a). Simulation model of DTC based drive

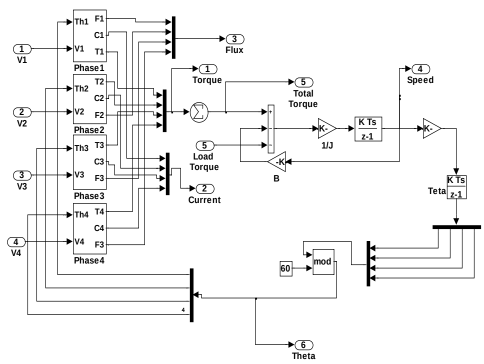


Figure 3(b). Internal block

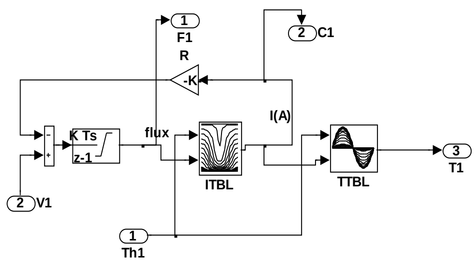


Figure 3(c). One phase model

Mesh plots of two Lookup tables are shown in Figure 4(a) and Figure 4(b). Figure 5(a) shows the four phase Asymmetrical converter using IGBT switches. One leg of the converter is shown in Figure 5(b). IGBT switches are used as the controllable switches in the converter.
The torque computation block is shown in Figure 6. It contains Flux transformation block, Sector selection block and Flux magnitude and computation block. The function of Flux transformation block is to convert fluxes in four phases into two phases [8]. The Sector selection block has information about the eight sectors. Based on the angle, the Sector selection block outputs the present sector number of the stator flux vector. The MATLAB program takes sector number, flux increase or decrease signal and torque increase or decrease signal as the inputs and generates the required gate signals to the IGBTs of the converter to apply appropriate Space voltage vectorThe DTC scheme is simulated by selecting the following set of 8 Space voltage vectors. V_1 = (-1010), V_2 = (-1-111), V_3 = (0-101), V_4 = (1-1-11), V_5 = (10-10), V_6 = (11-1-1), V_7 = (010-1), V_8 = (-111-1).

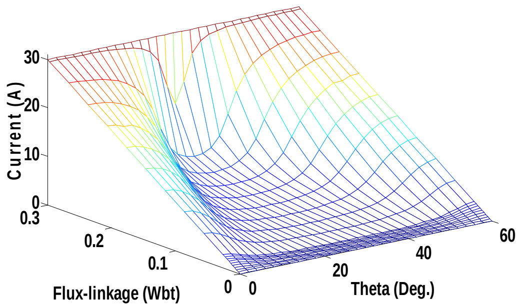


Figure 4(a). Mesh plot of flux-current-angle

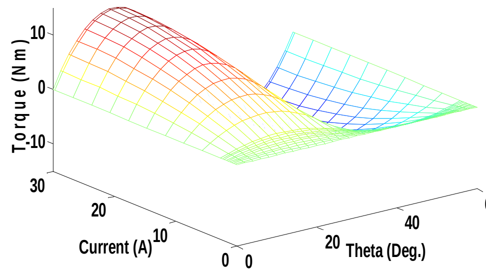


Figure 4(b). Mesh plot of Torque-current-angle

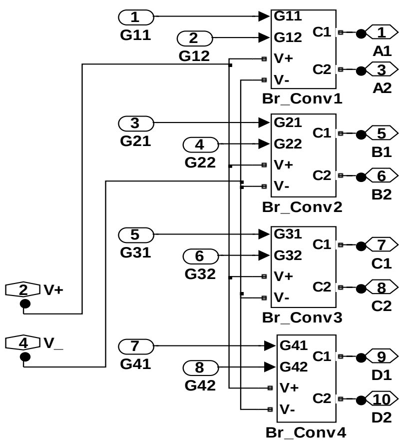


Figure 5(a). Asymmetrical converter

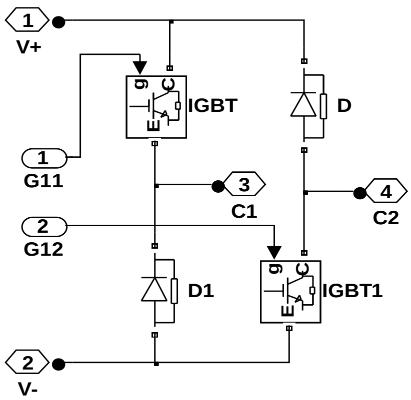


Figure 5(b). One leg of the converter

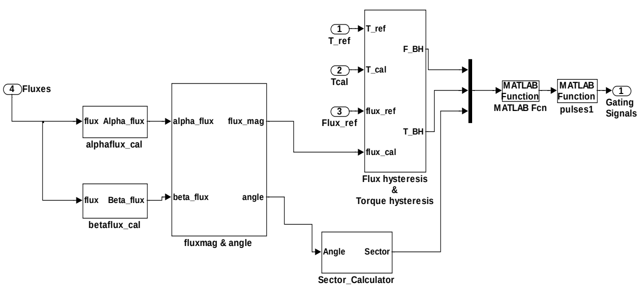


Figure 6. Torque computation block

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. These Lookup tables are formulated by conducting Finite Element Analysis (FEA) which is discussed clearly in [13]. 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.

3. Results and Analysis

The performance of the DTC based SRM drive is analyzed in Matlab/Simulink environment. The effect of variation of flux and torque hysteresis bands on switching frequency of the converter is analyzed.

Table 1 shows the variation of switching frequency of the switching device with the flux hysteresis band and torque hysteresis band. It is observed that for certain combinations where the flux and torque hysteresis bands are higher the switching frequency is low. This combination cannot be selected as the switch is underutilized. For the combinations in which either flux or toque hysteresis is high cannot be selected as the switching frequency is high. It is observed that as the hysteresis bands decreases, the switching frequency of the device increases. The normal operating frequency range of the device is 5 kHz - 15 kHz. Thus, 8 % flux hysteresis band and 5 % 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.

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. The analysis is performed for 8% flux hysteresis band and 5% torque hysteresis band. Figure 7 shows the simulation waveforms of the drive with DTC technique.

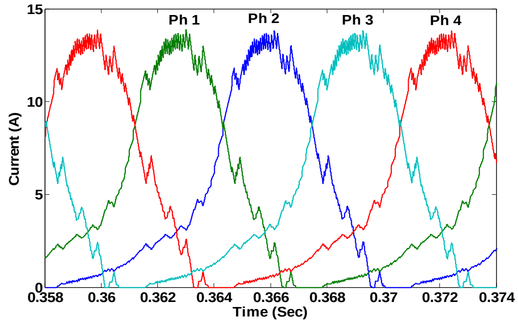
Figure 7(a) shows the variation of stator current in all the four phases as a function of time. It is observed that DTC leads to regularly spaced and periodic currents in all the phases. It is observed the current is not directly controlled and thus due to the nonlinear motor characteristics, the phase currents are nonlinear in nature. The maximum current and the average current of each phase are 13.87 A and 4.85 A respectively.

Figure 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. Figure 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 %. It is observed that the actual or calculated torque and flux has higher error. This can be attributed to finite iteration time of the simulation. Figure 7(d) shows the load torque and it varies as the square of the speed.

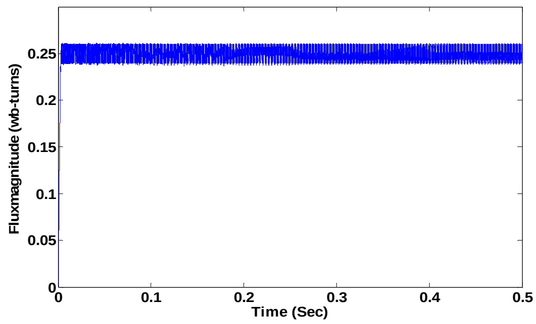
The instantaneous torques of all the four phases is shown in Figure 7(e). Figure 7(f) shows the speed response. The settling time for steady state speed is 0.310 sec. Figure 7(g) shows the variation of ψ_α with ψ_β. It can be seen that the trajectory of fluxes between α and β axes is circular in nature. Figure 7(h) shows the delta angle, which varies between -180^0 and $+180^0$.

Table 1. Variation of Switching Frequency with Flux Hysteresis Band and Torque Hysteresis Band

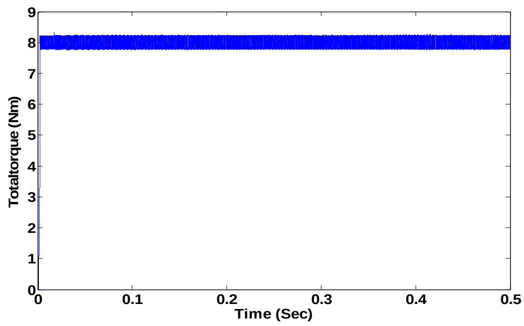
S.No.	% Flux-linkage Hysteresis Band	% Torque Hysteresis Band	Switching Frequency (kHz)
1	10	10	6.99
2	10	5	14.08
3	8	8	8.69
4	8	5	13.69
5	5	10	7.29
6	5	5	14.49



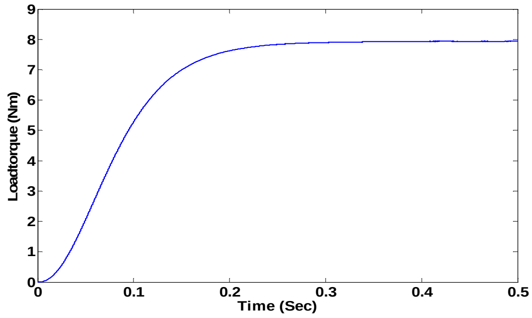
(a) Stator current



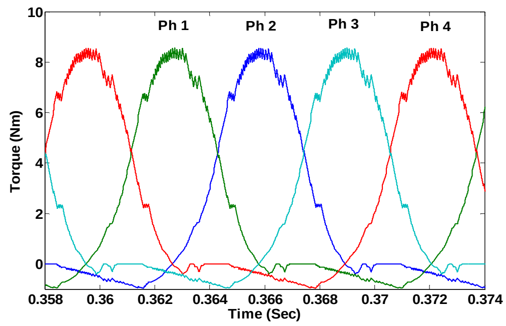
(b) Flux magnitude



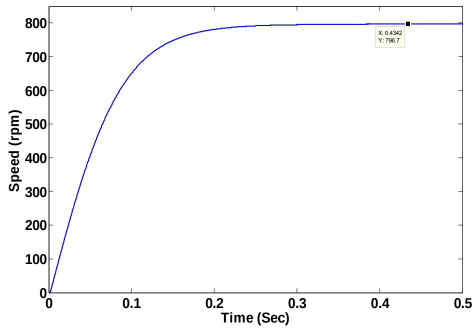
(c) TotalTorque response



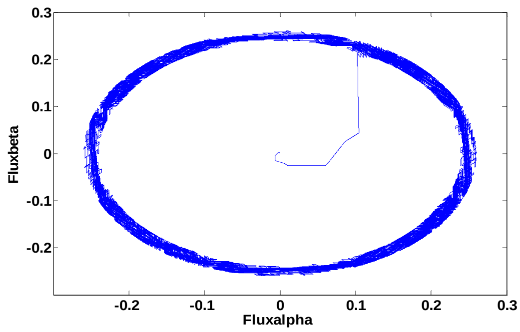
(d) Load torque



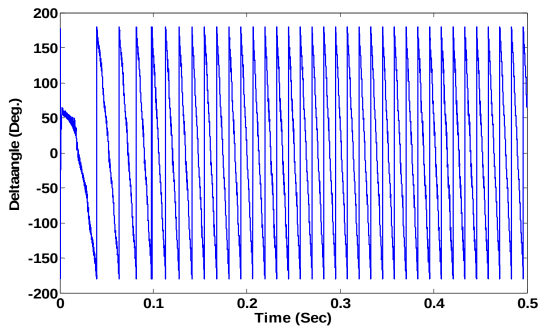
(e) Torque in all phases



(f) Speed



(g) Flux trajectory



(h) Delta angle

Figure 7. Simulation waveforms of SRM drive with Direct Torque Controller

4. 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 4 phase 8/6 SRM drive is analyzed. The variation of flux and torque hysteresis bands on switching frequency of the converter is analyzed. It is observed that as the hysteresis bands decreases, the switching frequency of the device increases. Finally, a combination a flux hysteresis band and torque hysteresis band is selected based on the normal operating frequency range of the device, which is 5 kHz - 15 kHz. Thus, 8 % flux hysteresis band and 5 % torque hysteresis band is selected for this drive

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