

MODIFIED DIRECT TORQUE CONTROL FOR BLDC MOTOR DRIVES

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ABSTRACT

In this paper, a new adaptive reference based approach to direct torque control (DTC) method has been proposed for brushless direct current (BLDC) motor drives. Conventional DTC method uses two main reference parameters as: flux and torque. A main difference from the conventional method of it was that only one reference parameter (speed) was used to control the BLDC motor and the second control parameter (flux) was obtained from speed error through the proposed control algorithm. Thus, the DTC performance has been especially improved on systems which need variable speed and torque during operation, like electric vehicles. The dynamic models of the BLDC and the DTC method have been created on Matlab/Simulink. The proposed method has been confirmed and verified by the dynamic simulations on different working conditions. The simulation studies showed that the proposed method reduced remarkably the speed and the torque ripples when compared the conventional DTC method. Moreover, the proposed method has also very simple structure to apply the conventional DTC and its extra computational load to the controller is almost zero.

KEYWORDS

Brushless machines, Direct torque control, Vector control, Torque control

1. INTRODUCTION

The BLDC motors are in our life for many years in computers, robotics, aerospace applications etc. In recent years, the BLDC motors applications have become more popular in industrial and daily utilization, like CNC machine tools, servo systems, home appliances, and electric vehicles. The main reasons of the increasing on popularity of the BLDC motors, in other words, main advantages of the BLDC motors, can be listed as follows[1-4]:

- High efficiencies
- High power densities
- High starting torque
- Wide speed ranges
- Linear torque and speed characteristics
- Low maintenance and works in any condition

The BLDC motors not only have advantages of conventional DC motors but also have advantages of AC motors as can be seen from the list. Because, they have the AC motor mechanical structures –no brushes or collectors–while they have the DC motors electrical characteristic.[5]

The DTC method was developed by Takahashi in the middle of the 1980s, for three phase induction motors. The DTC method converts three phase parameters of the motor (three phase voltage and currents) to two phase independent vector components with Clarke transformation; thus, it proposes control of every component separately, like conventional DC motors. Although, it was developed for the induction motors, it has been applied many other motor types like permanent magnet AC motors, BLDC motors, switched reluctance motors, linear motors[6-7].

In literature, many kind of BLDC motor drive methods can be found. In [8], artificial neural networks based method was used in modeling of BLDC to get the maximum power consumption. Very simple and effective three-level neutral point clamped inverter was proposed to drive axial flux BLDC motors, in [9]. Field Programmable Gate Array (FPGA) based BLDC motor driver with using digital pulse-width modulation (PWM) is presented in [10]. In addition, several different methods, which based of the DTC, were studied in BLDC drivers. Reference [11] proposes the DTC method for matrix converter fed BLDC motor. The DTC of BLDC motor method using with four-switch inverter in constant torque region was proposed in [12].

In this paper, a new approach to the DTC method has been proposed for small scale electric vehicles that work in variable speed and torque conditions, naturally. In the proposed method, optimum stator flux reference value was obtained by PI controller with usage of the speed error. The dynamic model of the proposed method was developed with Matlab/Simulink. The dynamic simulations were performed and results were presented to illustrate the validity of the proposed method.

2. DIRECT TORQUE CONTROL OF BLDC

The BLDC motor has three phase stator windings with permanent magnet rotor and electrical model of the motor that connected with PWM inverter, is given in Fig. 1[13].

Voltage equations of the motor can be obtained by the following equation;

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where V_a, V_b, V_c are phase voltages, R is phase resistance, L is phase inductance, i_a, i_b, i_c are phase currents and e_a, e_b, e_c are back EMFs.

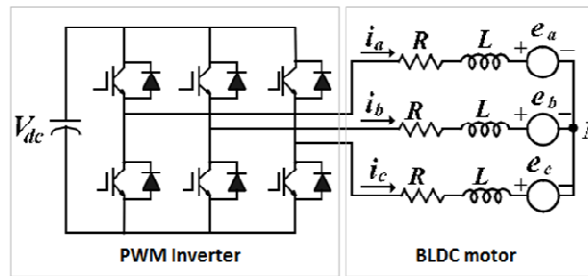


Figure 1. Electrical Model of the Motor that Connected with PWM Inverter

The mechanical moment equation of the motor given by the following equation;

$$T_e = T_L + B\omega_m + j \frac{d\omega_m}{dt} \quad (2)$$

T_e and T_L describes generated electromagnetic torque and load torque, respectively. B is the friction coefficient, j is the inertia and ω_m is the angular velocity of rotor[14].

The DTC method needs to transformation of the three phase motor parameters to two phases. In this transformation, electrical parameters of the motor (voltages, currents, back emf) should be transformed to stationary reference frame and it can also be named as $\alpha - \beta$ transformation or Clarke transformation in many sources. The Clarke transformation matrix is given (3).

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (3)$$

Where, f_α, f_β are $\alpha - \beta$ components of motor parameters, and f_a, f_b, f_c are the abc frame components [15].

With the transforming of the three phase parameters of the motor, $\alpha - \beta$ components of the phase voltages can be written as:

$$v_{s\alpha} = R_s i_{s\alpha} + L_s \frac{di_{s\alpha}}{dt} + e_\alpha \quad (4)$$

$$v_{s\beta} = R_s i_{s\beta} + L_s \frac{di_{s\beta}}{dt} + e_\beta \quad (5)$$

Where $v_{s\alpha}, v_{s\beta}$ are the stator voltages, $i_{s\alpha}, i_{s\beta}$ are the stator currents and e_α, e_β are back emf in the $\alpha - \beta$ reference frame.

In the DTC scheme, stator flux components are obtained from $\alpha - \beta$ components of the measured stator voltages and currents as given below [16]:

$$\lambda_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha}) dt \quad (6)$$

$$\lambda_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt \quad (7)$$

The magnitude of the flux can be calculated with;

$$\lambda = \sqrt{\lambda_{s\alpha}^2 + \lambda_{s\beta}^2} \quad (8)$$

and position of the stator flux vector can be calculated with;

$$\theta = \arctan \frac{\lambda_{s\beta}}{\lambda_{s\alpha}} \quad (9)$$

The calculation of the electromagnetic torque of the BLDC motor in $\alpha - \beta$ reference frame is given below;

$$T_e = \frac{3p}{4} \left[\frac{d\lambda_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\lambda_{r\beta}}{d\theta_e} i_{s\beta} \right] \quad (10)$$

Where $\lambda_{r\alpha}$ and $\lambda_{r\beta}$ are the $\alpha - \beta$ components of the rotor flux vector, p is the number of the poles and θ_e is electrical angle of the rotor.

The $\alpha - \beta$ components of the rotor flux vector can be obtained as:

$$\lambda_{r\alpha} = \lambda_{s\alpha} - L_s i_{s\alpha} \quad (11)$$

$$\lambda_{r\beta} = \lambda_{s\beta} - L_s i_{s\beta} \quad (12)$$

The different forms of the rotor flux $\alpha - \beta$ components can also be obtained from the following equations;

$$\frac{d\lambda_{r\alpha}}{d\theta_e} = \frac{d\lambda_{r\alpha}}{dt} \frac{dt}{d\theta_e} = \frac{1}{\omega_e} \frac{d\lambda_{r\alpha}}{dt} = \frac{e_\alpha}{\omega_e} \quad (13)$$

$$\frac{d\lambda_{r\beta}}{d\theta_e} = \frac{d\lambda_{r\beta}}{dt} \frac{dt}{d\theta_e} = \frac{1}{\omega_e} \frac{d\lambda_{r\beta}}{dt} = \frac{e_\beta}{\omega_e} \quad (14)$$

It means, electromagnetic torque can be written with in another form as:

$$T_e = \frac{3p}{4} \left[\frac{e_\alpha}{\omega_e} i_{s\alpha} + \frac{e_\beta}{\omega_e} i_{s\beta} \right] \quad (15)$$

The six active voltage vector, PWM inverter switching states and stator voltage vector sectors are shown in Figure 2. Inverter switching look-up table is also given in Table 1.

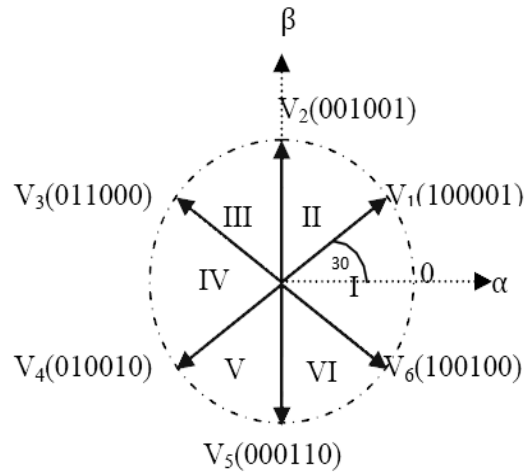


Figure 2. PWM Inverter Switching States and Stator Voltage Vector Sectors

Table 1. Inverter Switching Look-Up Table

Flux hys	Torq. hys	Sector (Θ)					
		1	2	3	4	5	6
1	1	V ₁	V ₂	V ₃	V ₄	V ₅	V ₆
	0	V ₆	V ₁	V ₂	V ₃	V ₄	V ₅
0	1	V ₃	V ₄	V ₅	V ₆	V ₁	V ₂
	0	V ₄	V ₅	V ₆	V ₁	V ₂	V ₃

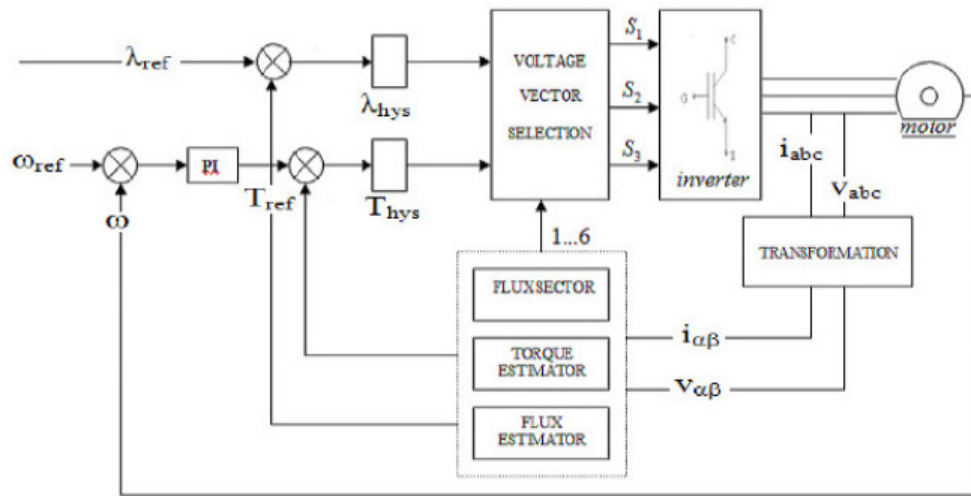


Figure 3. The Conventional DTC Block Diagram

In the conventional DTC (C-DTC) method, control algorithms works with two separate reference values as torque (or speed) and flux references. Because, in idea of the DTC, stator flux vector has two components ($\alpha - \beta$ components) and they can be controlled independently from each other. One of them controls flux, while the other one controls torque. In generally, flux reference is kept constant and the speed control of the motor can be achieved by setting up the torque reference value. This approach is very appropriate for constant torque-variable speed applications. The conventional DTC block diagram is given in Figure 3.

3. ADAPTIVE FLUX BASED METHOD

In variable torque and variable speed applications, like small electric vehicles, keeping the flux constant causes high torque and speed ripples. A new approach was designed and investigated in this paper to overcome this problem. In the proposed approach, a new PI controller was used to determine optimum flux reference value according the motor speed. So, two different PI controllers were used in proposed DTC (P-DTC) method. One of the PI controllers calculates reference torque and the other one calculates reference flux with use of the speed error. The proposed DTC Simulink block diagram was given in Figure 4.

In dynamic simulations, the BLDC motor was performed under two different working conditions. The parameters of the blocks and the motor that used in dynamic simulations were given in appendix. Total simulation time was 1 sec. for all conditions. The sampling time was 10 μ s. The motor load constant (5Nm) and the speed reference was changed 500 rpm to 1500 rpm at 1. sec. in first working condition. The speed and the torque responses of the motor were given in Fig. 5 and Fig. 6, respectively.

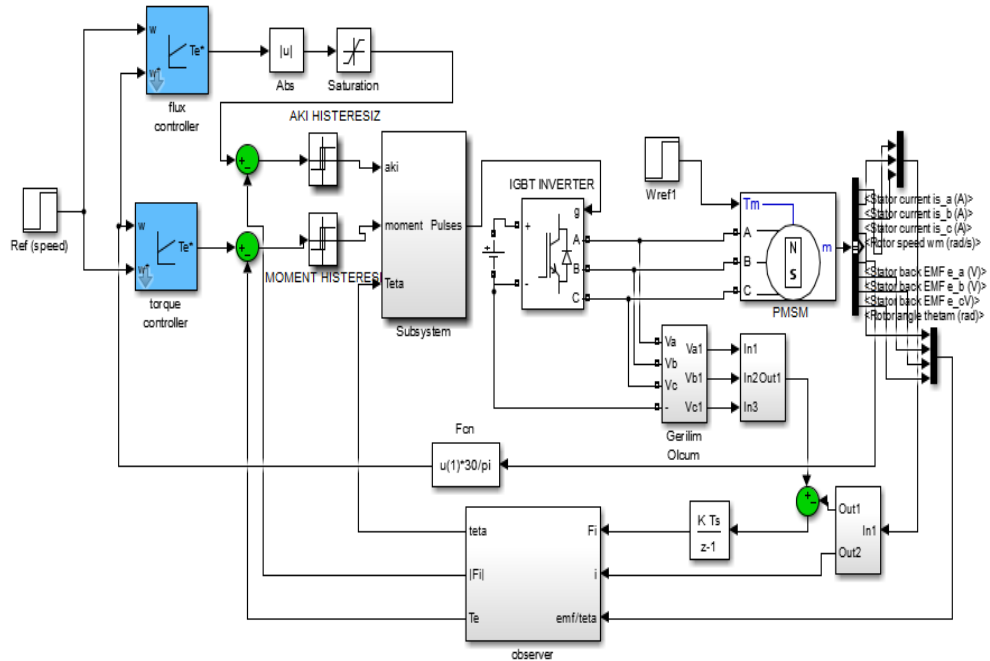


Figure 4. The Proposed DTC Simulink Block Diagram

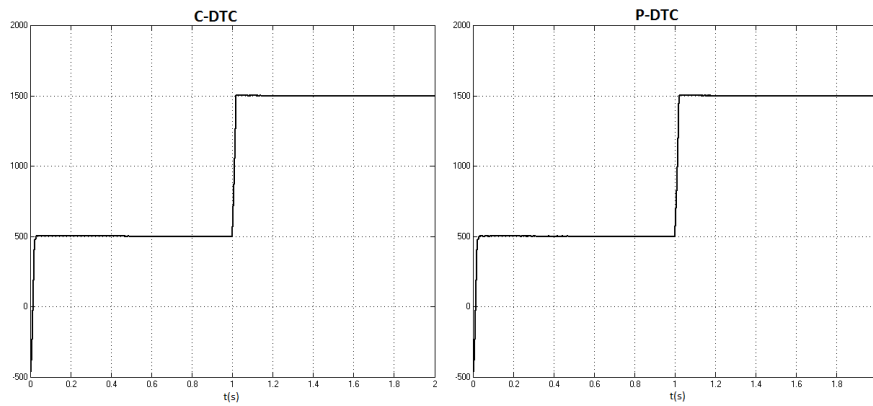


Figure 5. Overview to Speed Responses of the BLDC in Variable Speed-Constant Load

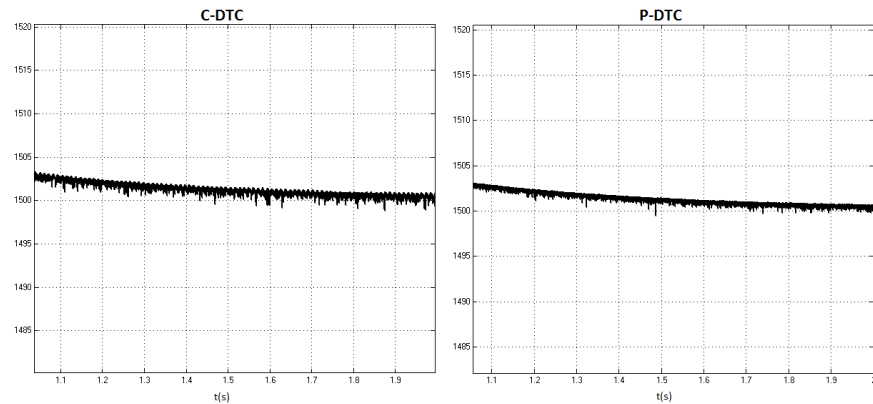


Figure 6. Zoomed-View to Speed Responses of the BLDC in Variable Speed-Constant Load

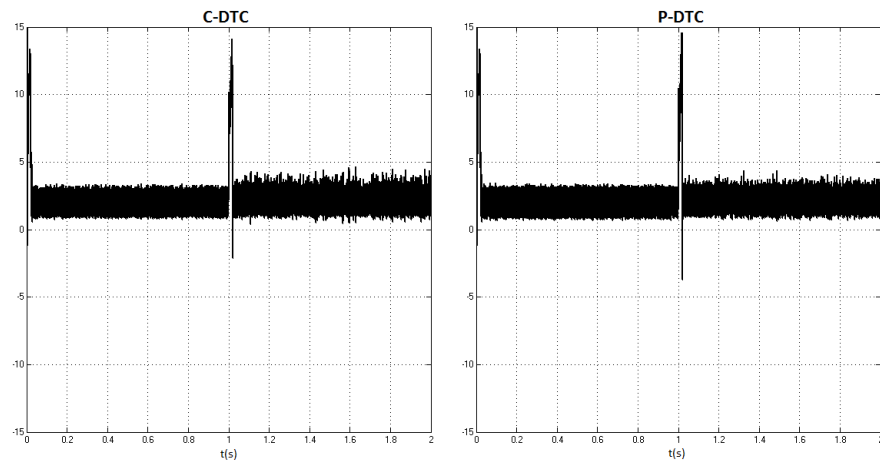


Figure 7. Torque Responses of the BLDC in Variable Speed-Constant Load

It can be seen in Figure 5–7. that, the BLDC motor speed and torque responses were improved with the P-DTC method. The torque and speed ripples reduced remarkably with the P-DTC method especially in high speed reference values. In 500 rpm speed reference, the motor dynamic behaviors were almost same with both methods.

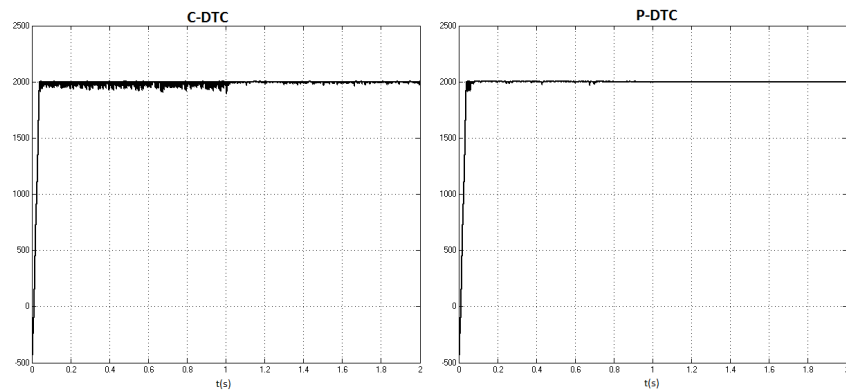


Figure 8. Overview to Speed Responses of the BLDC in Variable Torque-Constant Speed

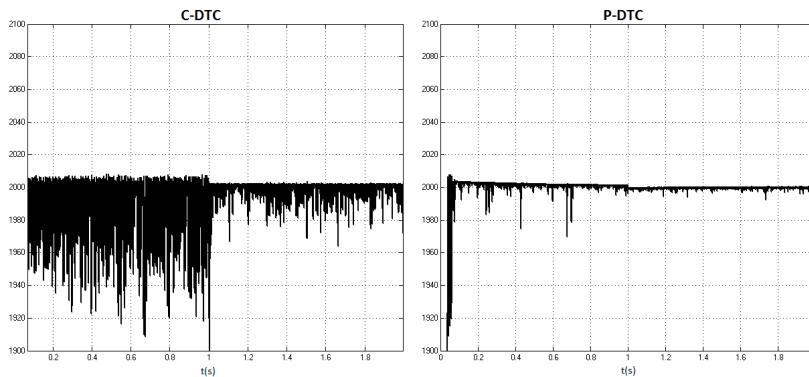


Figure 9. Zoomed- View to Speed Responses of the BLDC in Variable Torque-Constant Speed

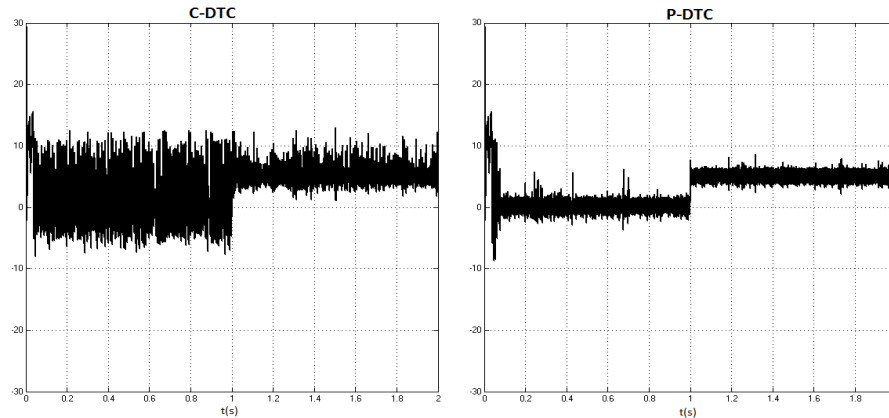


Figure 10. Torque Responses of the BLDC in Variable Torque-Constant Speed

In the second test, the motor was simulated at constant speed reference (2000 rpm) and the torque reference was changed to 0 Nm to 5 Nm at 1. sec. The speed and the torque responses of the motor were given in Figure 8–10, respectively.

After the second test studies, which the torque reference value was changed, the speed and the torque curves were showed that the motor performance was also improved in constant speed - variable torque conditions. The C-DTC method had much torque peaks especially in 0 Nm torque reference. But with the P-DTC method, the motor had very small peaks for both torque references. The dynamic simulations proved that the P-DTC method can be a good alternative to the C-DTC method. Moreover, the computational times of the both system were compared during the tests and it must be pointed out that the P-DTC method had almost same computational time with the C-DTC. So, it can be said that, the proposed method has not extra load on controller structure and it can applicable on BLDC motor driven electric vehicles.

4. CONCLUSIONS

In recent years, BLDC motors have been used many industrial applications and it has gain great popularity between electric motors. On the other hand, the DTC is well-known high performance control method not only for induction motors but also many other motor types. This paper presents a new perspective to the conventional DTC method. The proposed DTC method applied to the BLDC motors which considered drives small size electric vehicles. These vehicles works in variable speed and torque conditions with single reference input: speed. The conventional DTC method was modified with the adding of second PI controller that produces optimum flux reference. In order to test the validity and applicability of the proposed method, dynamic simulations were been performed under different working conditions and results were presented. The simulations results showed that the proposed method reduced remarkably the speed and the torque ripples when compared conventional DTC method. The proposed method had also very simple structure to apply the conventional DTC and its extra computational load to the controller was almost zero.

APPENDIX

The parameters of the blocks and the motor that used in dynamic simulations are, DC bus voltage 400V, stator phase resistance, R_s (ohm) = 0.45, stator phase inductance L_s (H) = $8.5e-3$, flux hysteresis band limits = ± 0.005 , torque hysteresis band limits = ± 0.02 , stator flux reference = 0.32 weber, sampling time 10 μ sec.

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