

Direct Torque Control of Brushless Doubly Fed Induction Machine

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Abstract

This article contributes a torque control based on hysteresis for Brushless Doubly Fed Induction Machine (BDFM) through machine analysis and extracting the d-q parameters that influence on the machine behavior. In this research, a Direct Torque Control (DTC) based on stator flux-oriented vectors and machine's relation and equations with voltage and current of both stators have been introduced. The control for the BDFM is implemented by a voltage source inverter connected to the second stator as a torque controller that uses the classical field-oriented control method widely used in voltage sector selection. Finally BDFM as a closed loop model with DTC is simulated and evaluated.

Keywords: BDFM, DTC, VSD

Nomenclature

V, I, λ	Voltage, current, and flux
ω_{s1}, ω_{s2}	Angular frequency of power winding (PW), and control winding (CW)
ω_r	Angular frequency of rotor
L_r	Self-inductance of rotor winding
L_{s1}, L_{s2}	Self-inductances of stator windings
L_{s1r}, L_{s2r}	Coupling inductances of PW and CW stators with rotor
R_r, R_{s1}, R_{s2}	Resistances of rotor, PW, and CW
P_1, P_2	Number of Pole pairs in PW and CW stators
T_e	Electrical torque output
J	Moment of inertia
B	Friction coefficient

1. Introduction

The Brushless Doubly-Fed Induction Machine (BDFM) is a special induction motor that similar to the cascade machines has 2 sets of three-phase stator windings with different pole numbers, but the preliminary doubly fed machine goes back to Siemens Brothers and F.Lydall in 1902 in the form of self-cascaded machine [10] that contained two induction machines together and allowed one to achieve three different speeds of efficient operation. Smith presented, for the first time, a model of the steady-state operation for the cascade mode of operation of the machine by a lower power frequency converter to extract slip power of the rotor by induction through the second winding [11]. Indisputably, major contribution was

contributed by Broadway and Burbridge [9] as the modern Brushless Doubly-Fed Reluctance Machine (BDFRM) [12], then Kusko and Somuah [13] presented their work on a BDFM with two sets of 3 phase windings on the rotor, and improved the Broadway/Burbridge machine. The 'BDFM' name originated by Wallace, Spée and Li; and their works developed a coupled-circuit dynamic model of BDFM [14, 15]. Li et al proposed a d-q dynamic model and represented the performance of a prototype BDFM machine in [7, 16, 17] and also Gorti et al considered steady state performance of the machine in the synchronous mode in [18]. On the other hand, Li also undertook open-loop analyses and stability of the BDFM in [17-20]. By the way, 'Direct Torque Control' method was the first algorithm for BDFM control, presented by Brassfield [21]. In this algorithm, the torque and control winding flux derivatives are regulated, and then the outer PI (Proportional plus Integral) loop is used to drive the controlled outputs to their reference set points [22]. In fact, this method is closely related to the application of feedback linearization to the BDFM. In the last mention of the 'Direct Torque Control' algorithm [23] authors noted that there were practical problems associated with it, and the problem mentioned was caused by computational complexity and associated hardware limitations; but there may have been more fundamental problems with the algorithm [1]. Nevertheless, this machine is known as an economic motor with rated frequency converter, and also as a stable generator without any brushes in wind-turbines [5]. Though, McMahan et al [2, 3] changed the design of the machine and improved it a great deal, but nowadays research on BDFM's control is still going on along with the design improvements seriously. As a motor, this machine can work in a wide range of desired speed with a smaller Variable Speed Drive (VSD) [4] compared with a simple induction machine. In this machine, both of stator fluxes influence on each other and this causes complex and nonlinear relations for machine terms such as electrical torque, so according to this fact and also the idea that a rated Variable Speed Drive can be used to control the required flux (speed), the direct torque control with hysteresis is proposed here; so the objective of this paper is to present a direct torque control (DTC) algorithm based on controlling the second stator flux and an optimized converter switching, and machine and its behavior is modeled in a simulation study. Parameters of a BDFM presented by Shao [5] are used in this simulation. Therefore, it is concluded that the DTC for BDFM can be considered as a rated power VSD; and DTC can also be used for regulating speed of BDFM motor as effective as a simple induction motor.

2. Equivalent BDFM dynamic model

Details of the operation of the BDFM in synchronous mode have been given by various authors [7], [8]. Under synchronous conditions, the shaft angular velocity is related to the supply frequencies in the first stator winding as "Power Winding" (PW) and the second stator winding as "Control Winding" (CW), Hence the angular speed of the rotor is given as

$$\omega_r = \frac{2\pi(f_1+f_2)}{P_1+P_2} \quad (1)$$

One can be convinced that the BDFM is two induction machines in the same frame [7], [9]. Therefore it is possible to show the BDFM as two connected induction machines, and develop an equivalent circuit using the standard per phase model. Figure 1 shows a standard equivalent circuit for a BDFM that N_i 's are the effective turn ratios; L_{mi} 's are the magnetizing

inductances of the fundamental fields. The space harmonics are also shown in series with the leakage terms in the stators and rotor as L_1 , L_2 and L_r respectively.

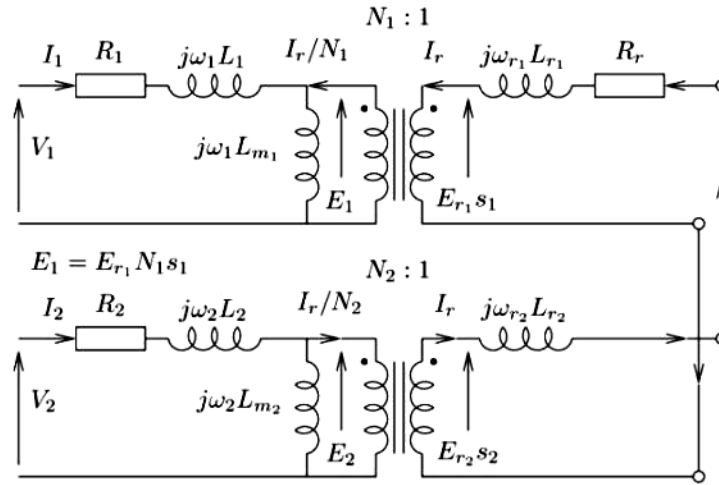


Figure 1.BDFM equivalent circuit

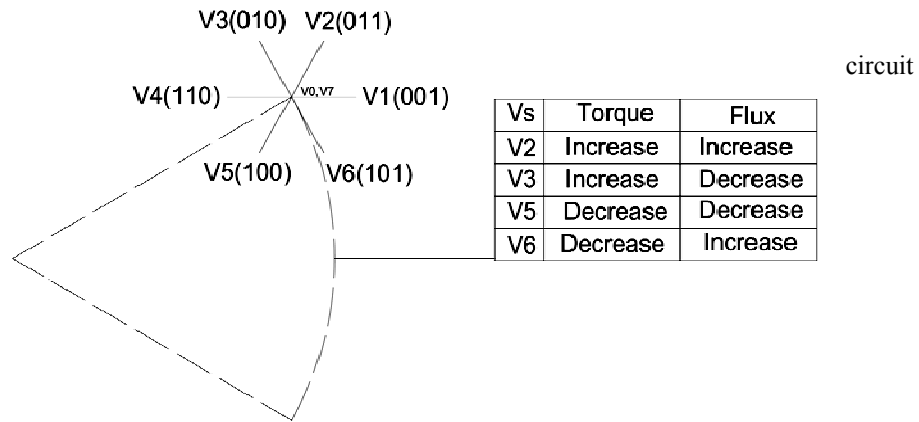


Figure 2.The Effect of Voltage Vectors on Torque and Flux

3. DTC Strategy

Direct Torque Control (DTC) or sensorless vector-control, first introduced by Takahashi [6] in Japan, is used for speed/flux control of induction machines. Nowadays, DTC of induction machine has been continuously becoming the best alternative to Field Orientation Control (FOC). There are two control strategies for FOC that have dissimilarity on the operation principle but their objectives are same.

- Vector Control (VC): based on stator current control in the field rotating reference frame using Pulse-Width-Modulation (PWM) inverter control.

- Direct Torque Control (DTC): based on stator flux control in the stator fixed reference frame using direct control of inverter switching.

The DTC scheme is very simple in its basic configuration. It consists of hysteresis (or On-Off) controllers, torque and flux estimators and a switching table. The DTC-based drives are controlled in the form of an FOC closed loop system without using the current regulation loop [6]. DTC scheme is a stationary d-q reference frame having its d-axis aligned with the CW-stator q-axis. Torque and flux are controlled by the CW stator voltage space vector defined in this reference frame. In other words, the basic concept of DTC is to control both the CW-stator flux linkage and electromagnetic torque of the machine directly and simultaneously by the selection of optimum inverter switching modes. So depending on the machine operation and the rotating angle of the CW-stator flux, the voltage vectors can be used. The influence of selected voltage vectors on electromagnetic torque and CW flux in first sector could be seen in figure 2.

Basically, there are four principles with respect to DTC:

- From the measured CW and PW stator voltages and currents, the stator flux linkage space vector (λ_s) can be calculated as follows:

$$V_{s1} = R_{s1}I_{s1} + \frac{d\lambda_{s1}}{dt} + j\omega_{s1}\lambda_{s1} \quad (2)$$

$$V_{s2} = R_{s2}I_{s2} + \frac{d\lambda_{s2}}{dt} + j\omega_{s2}\lambda_{s2} \quad (3)$$

$$\lambda_{s1} = \int (V_{s1} - R_{s1}I_{s1} - j\omega_{s1}\lambda_{s1}) \quad (4)$$

$$\lambda_{s2} = \int (V_{s2} - R_{s2}I_{s2} - j\omega_{s2}\lambda_{s2}) \quad (5)$$

So the d-q derivatives of (4) and (5) using (1) are

$$\lambda_{s1d} = \int (V_{s1d} - R_{s1}I_{s1d} + \omega_{s1}\lambda_{s1q}) \quad (6)$$

$$\lambda_{s1q} = \int (V_{s1q} - R_{s1}I_{s1q} - \omega_{s1}\lambda_{s1d}) \quad (7)$$

$$\lambda_{s2d} = \int (V_{s2d} - R_{s2}I_{s2d} + (\omega_{s1} - (p_1 + p_2)\omega_r)\lambda_{s2q}) \quad (8)$$

$$\lambda_{s2q} = \int (V_{s2q} - R_{s2}I_{s2q} - (\omega_{s1} - (p_1 + p_2)\omega_r)\lambda_{s2d}) \quad (9)$$

- The flux space-vector, λ_r , of the rotor, hence the speed of the rotor flux-linkage vector can be determined from the stator fluxes λ_s .

Note that the rotor winding is nested and thus is short circuit; therefore, the rotor voltage is zero:

$$0 = R_r I_r + \frac{d\lambda_r}{dt} + j(\omega_{s1} - p_1 \omega_r) \lambda_r \quad (10)$$

On the other hand, λ_r can be shown as follows [1]

$$\lambda_{s1} = L_{s1r} I_{s1} + L_{s1r} I_r \quad (11)$$

$$\lambda_{s2} = L_{s2r} I_{s2} + L_{s2r} I_r \quad (12)$$

$$\lambda_r = L_r I_r + L_{s1r} I_{s1} + L_{s2r} I_{s2} \quad (13)$$

and based on d-q frame, the d-q derivatives can be formulated as follows [5]

$$\lambda_{s1d} = L_{s1r} I_{s1d} + L_{s1r} I_{rd} \quad (14)$$

$$\lambda_{s1q} = L_{s1r} I_{s1q} + L_{s1r} I_{rq} \quad (15)$$

$$\lambda_{s2d} = L_{s2r} I_{s2d} + L_{s2r} I_{rd} \quad (16)$$

$$\lambda_{s2q} = L_{s2r} I_{s2q} + L_{s2r} I_{rq} \quad (17)$$

$$\lambda_{rd} = L_r I_{rd} + L_{s1r} I_{s1d} + L_{s2r} I_{s2d} \quad (18)$$

$$\lambda_{rq} = L_r I_{rq} + L_{s1r} I_{s1q} + L_{s2r} I_{s2q} \quad (19)$$

iii. The machine torque can be calculated from these vector quantities:

$$T_e = \left[\frac{3}{2} p_1 L_{m1} (I_{s1q} I_{rd} - I_{s1d} I_{rq}) + \frac{3}{2} p_2 L_{m2} (I_{s2q} I_{rd} + I_{s2d} I_{rq}) \right] \quad (20)$$

The mechanical differential equation (21) shows that ω_r can be regulated by controlling T_e

$$T_e = (Js + B)\omega_r + T_l \quad (21)$$

where J is the mass moment of inertia and B is the viscous friction.

iv. Switching sectors are chosen based on torque and second stator (CW) flux hysteresis, and also based on the angle of CW stator flux, α , presented by (22). There are three possible output states with a total of 3^3 or 27 possible switch combinations for the three phases. DTC algorithm selects the inverter voltage sectors to be applied to the CW stator of BDFM according to the Table 1.

$$\alpha = \tan^{-1} \frac{\lambda_{s2q}}{\lambda_{s2d}} \quad (22)$$

To get the d-q frame, the phase-voltage of the inverter output, V_a , V_b and V_c are changed to phase-to-phase voltage, presented in Table 2; where S_a , S_b and S_c are commands to thyristors.

The phase-to-phase voltages $V_{p-p} = [V_{ab} \ V_{bc} \ V_{ca}]_{2 \times 3}$, are transformed to d-q format using (23) and the vector summation law. The d-q coordination of voltage sectors are shown

	-1	V6	V1	V2	V3	V4	V5
	1	V3	V4	V5	V6	V1	V2
0	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

Table2:algorithm of inverter switching

Voltage Sector	S_a	S_b	S_c	V_a	V_b	V_c	V_{ab}	V_{bc}	V_{ca}
V1	1	0	0	V_{dc}	0	0	V_{dc}	0	$-V_{dc}$
V2	1	0	1	V_{dc}	0	V_{dc}	V_{dc}	$-V_{dc}$	0
V3	0	0	1	0	0	V_{dc}	0	$-V_{dc}$	V_{dc}
V4	0	1	1	0	V_{dc}	V_{dc}	$-V_{dc}$	0	V_{dc}
V5	0	1	0	0	V_{dc}	0	$-V_{dc}$	V_{dc}	0
V6	1	1	0	V_{dc}	V_{dc}	0	0	V_{dc}	$-V_{dc}$
V7	1	1	1	V_{dc}	V_{dc}	V_{dc}	0	0	0
V0	0	0	0	0	0	0	0	0	0

4. SIMULATION RESULTS

The DTC of BDFM system has been developed in a simulation program in three subsystems (Figure 4):

- 1) BDFM model
- 2) DTC controller that implements the sector selection
- 3) VSD Model with three phase inverter and d-q Coordination

The prototype machine parameters are taken from an experimental machine presented by Shao et al [5]. PW stator is fed by a constant 220 AC voltage and 50Hz frequency in each phase and CW stator is fed by VSD. A list of parameters and their values can be found in the Table 4.

The DTC controller consists of three feedback signals:

- 1- The rotor's angular speed, which is fed back to the speed reference, passes through a PI controller to make the reference for the electrical torque.
- 2- The estimated torque computed by (20) is fed back and compared with the torque from part (i) and goes to a hysteresis switch(see Figure 5).
- 3- The flux of CW stator that is fed back to the flux reference also goes to the other hysteresis switch (see Figure 5).

The VSD system is considered as a three phase inverter fed by a 700 VDC as a DC link; and also a 3 to 2 converter is simulated using equation (23), Table 2 and Table

3. Figure 6 shows that in a fraction of a second the BDFM torque reaches 40 N.m and the BDFM is responsive to the DTC very well; though there is a slight deviation caused by selection sequence of VSD's voltage sectors. As seen in Figure 7, the speed reaches 480 rpm after about 7.5 seconds.

5. CONCLUSION

As it can be seen, the possibility of DTC for BDFM using hysteresis controller and based on field oriented is stated. Several simulation studies show that the machine works in a wide range of speed, arriving at the desired torque instantly. Furthermore, in comparison with a simple induction machine in the same range of power as BDFM, we can reach to the same results in speed and torque by use of a smaller rated VSD. To eliminate nonlinear behavior of CW stator, however, it seems that a better control strategy than a simple PI is required for utilizing estimation of desired change of flux and torque for a given set points .

TABLE3: TRANSFORMATION OF V_{abc} INTO V_{dq}

<i>Voltage Sector</i>	V_{as}	V_{bs}	V_{cs}	V_{ds}	V_{qs}
V_1	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	0
V_2	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{V_{dc}}{\sqrt{3}}$
V_3	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{V_{dc}}{\sqrt{3}}$
V_4	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	0
V_5	$-\frac{1}{3}V_{dc}$	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{V_{dc}}{\sqrt{3}}$
V_6	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{V_{dc}}{\sqrt{3}}$
V_7	0	0	0	0	0
V_0	0	0	0	0	0

TABLE4: BDFM SPECIFICATION

Parameter	Value	Parameter	Value
$R_{s1}(\Omega)$	2.3	$L_{s1r} (H)$	0.0031
$R_{s2}(\Omega)$	4	$L_{s2r} (H)$	0.0022
$R_r(\Omega)$	1.2967×10^{-4}	P_l	2

$L_{s1}(H)$	0.3498	P_2	4
$L_{s2}(H)$	0.3637	$J(kgm^2)$	0.53
$L_r(H)$	4.4521×10^{-5}	$B(N.s/m)$	0.036

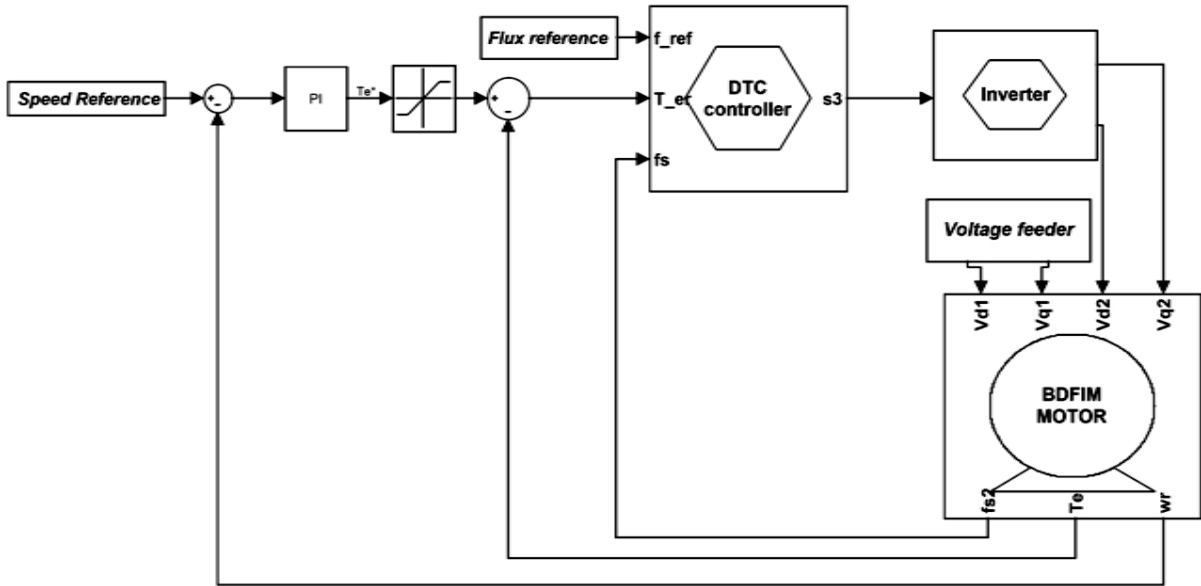


Figure 4. Simulink model of the BDFM with VSD and DTC controller

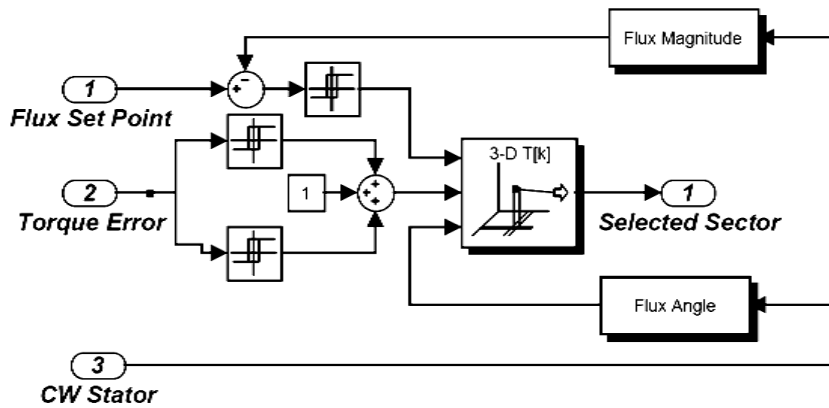


Figure 5. Hysteresis controller for Torque and Flux error

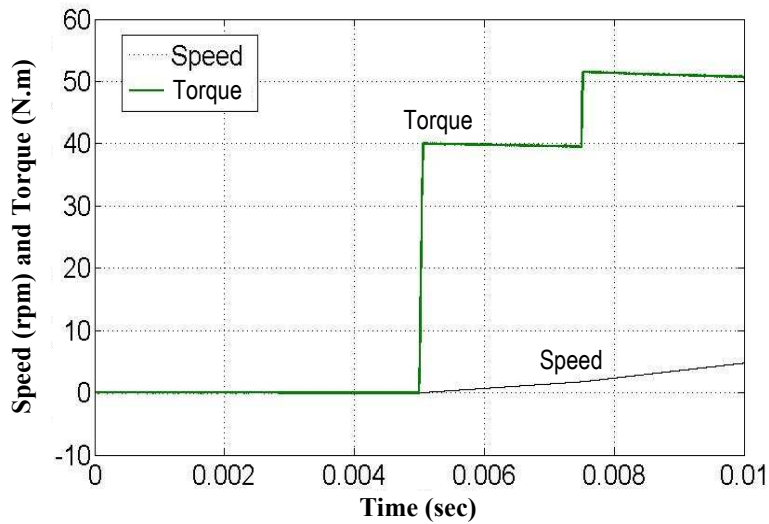


Figure 6. Torque of closed loop BDFM with DTC

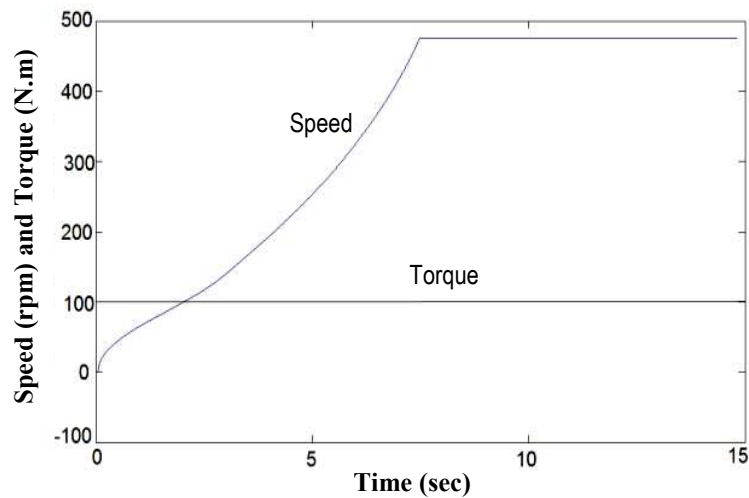


Figure 7. Speed of closed loop BDFM with DTC

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