2013 International Conference on Electrical Machines and Systems, Oct. 26-29, 2013, Busan, Korea

High Performance Torque Control of BLDC Motor

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***Abstract*— This paper presents a simulation study using Matlab introducing Direct Torque Control (DTC) method which is implemented on BLDC motor. BLDC motor is well known and has been widely used in the industrial area due to the high speed and power density. Electronic commutation is by far more favourable compare to the conventional DC motor which uses brushes and commutators that wears and tears by time. However, a precise controller is required in order to control the switches prior to commutation process. DTC of BLDC combines a simple control method and a demanding motor to complete a better drives system. Based on in depth analysis of BLDC mathematical model and the operation of DTC system, a simulation model is developed using Matlab/Simulink. The capability and performance of torque and flux control of the drive system is verified.**

Keywords-components; Brushless DC motor, Hall Effect, Direct Torque Control (DTC)

I. INTRODUCTION

Brushless DC (BLDC) motor is one the more popular choices for applications which demands great reliability and high efficiency. BLDC motor has advantage of longer lifespan, faster torque response and capability of high speed drive in comparison with DC motor [1]. The motor provide lots of torque over a wide speed range and share similar torque and speed performance curve characteristics with brushed motor even though brushed motor provides more torque from standstill. A higher reliability offered by BLDC motor is due to the elimination of the brushes for commutation in classical DC motor. By having mechanical commutator and brushes, frequent maintenance for this wear and tear item is a major concern to avoid severe limitations for its voltage, current ratings and power output capability. Sparking and dust that produced by DC motor makes it undesirable in industries like semiconductor, food and beverages and industries with explosive atmosphere. Current arcing translates to losses which results in problems such as losses generating due to arcing which raise the temperature of the brushes commutator system resulting in increased wear rate. Secondly it may also increase the machine resistance which can decrease the performance characteristics of the drive system.

BLDC motor is a type of synchronous motor which means the magnetic field generated by the rotor rotates at the same frequency thus eliminates slip which normally seen from induction motor. The characteristics of a BLDC motor are essentially the same as a separately excited dc motor, though the motor construction is different but the operating principles is the same. The fundamental difference is that current commutation is done by solid state switches such as IGBT/Mosfet rather than mechanically via rotor contacts. BLDC motor are generally design as surface mounted motors with concentrated windings on the stator and with appropriate placement of permanent magnet on the rotor, a trapezoidal back-emf shape can be obtained. In order to achieve smooth torque production, quassi-square wave currents need to be applied to the stator phases when the corresponding back-emf having a flat constant portion of approximately 120 degrees with the currents.

Vector control and direct torque control (DTC) drives are the two types of instantaneous electronic torque controlled AC drives used for high performance applications. The first vector control which is called Field Oriented Control (FOC) was introduced more than 25 years ago in Germany by Hasse, Blaske [2] and Leonhard. FOC transforms the motor equations into a coordinate system that rotates in synchronism with the rotor flux vector. There is a linear relationship between the control variables and the torque when operating under constant rotor flux amplitude. FOC drives achieved a high degree of maturity and established in worldwide market.

DTC was introduced in Japan by Takahashi and Nagochi [3] and also in Germany by Depenbrock [4]. DTC is a method that uses a bang-bang / hysteresis control instead of a decoupling control which symbolizes the characteristic of a vector control. The hysteresis control technique works well with the on-off operation of the switches (i.e Mosfet and IGBT). DTC controls the electromagnetic torque and flux linkage directly and independently by the use of six or eight voltage space vectors as defined in the lookup table. Lookup table is constructed to choose appropriate switching state of the inverter which the selection is based on the output of the bang-bang controller and the sector of the stator flux vector in the circular trajectory.

DTC technique was first introduced in the late 1980's to drive the induction machine; however the method has been absorbed to the other types of AC drives to improve the existing results. Now researcher in focusing on combining the DTC techniques with PMSM / BLDC machines, as reported in [5-16]. DTC scheme for induction machines still has a few drawbacks which are the high torque and stator flux linkage ripples, switching frequency that varies with load torque, rotor speed and the bandwidth of the hysteresis controllers. Researchers have been working to reduce the torque and flux ripple and fix the switching frequency of the DTC system as reported in [17-23]. A modified DTC schemes with fixed switching frequency and low torque and flux ripple were introduces in [24].

For DTC of BLDC, the back EMF integration for the stator flux linkage calculation requires the knowledge of stator flux position during start up. In order to find its position in the circular trajectory it need to be sensed by position sensor but it is not desired due to its cost and bulky characteristics, therefore some initial position sensing methods are required for DTC of BLDC applications. In [25] proposed a method for detecting the initial rotor position estimation at standstill for PM motors. A better solution was introduced for the rotor position estimation by applying high frequency voltage to the motor; this method is adopted in the DTC of BLDC motor for initial position estimation in [8].

II. MODELLING OF BLDC MACHINES

Mathematical modeling of a BLDC motor can be derived similar to DC machines as in [26] where there are two equivalent circuits, i.e electrical and mechanical equations. Figure 1 show the basic blocks of BLDC motor that contains three phase stator circuit and mechanical part. The main difference compare to DC machines is the construction of the machine where it has three phase windings at the stator (with n number of poles) and the rotor equipped with permanent magnet which is positioned at the center of the motor by the bearing. The rotor is not electrically connected to the stator thus preventing arcing phenomena which cause carbon to be produce hence making insulation failure.

For simplification, the electrical model is expressed for one phase of stator winding, e.g. phase k ($k = a$,b or c) as given by (1).

$$v_{kn}(t) = i_k \mathrm{R_k} + \mathrm{L_k}\frac{di_k}{dt}(t) + e_k(\mathrm{t}) \qquad (1)$$

where,

$v_{kn}(t)$	= instantaneous of k-phase voltage
$i_k\,(t)$	= instantaneous of k-phase current
$e_k\,(t)$	= instantaneous of k-phase back-emf voltage
$\mathrm{R_k}$	= k-phase resistance
$\mathrm{L_k}$	= k-phase inductance

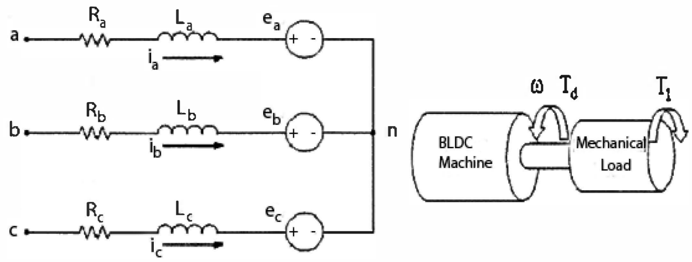


Fig 1. Three phase Brushless DC machine equivalent circuit and mechanical model.

On the other hand, the mechanical model of BLDC machine actually represents the production of torque as given by (2).

$$T_{em}(t) = \mathrm{J}\frac{d\omega(t)}{dt} + \mathrm{b}\omega(t) + T_L(t) \qquad (2)$$

where,

$\omega(t)$	= rotor angular velocity
B	= viscous friction
J	= moment of inertia
$\mathrm{T_L}$	= load torque

It should be noted that the production of torque is the summation of the torque produced for each phase

$$T_{em}(t) = \sum_{k=a,b \text{ and } c} T_{em,k}(t) \qquad (3)$$

The productions of torque and back-emf voltage for each phase are calculated as;

$$T_{em,k}(t) = i_k(t).\,k_{T,k}(\theta) \qquad (4)$$

$$e_k(t) = k_{v,k}(\theta).\,\omega_e(t) \qquad (5)$$

where, the torque factor $k_{T,k}(\Theta)$ can be assumed equivalent to the back-emf voltage factor $k_{V,k}(\Theta)$. The angular velocity (ω_e) is multiplication of rotor angular velocity and number of poles of the machine, i.e. ω x number of poles. For trapezoidal operated in BLDC motor, the $k_{T,k}(\Theta)$ and $k_{V,k}(\Theta)$ are not constant as opposed to the constant field operated in brushes DC motor. Given the rotor position (Θ), these factors can be simply obtained using piece-wise normalized trapezoidal function as illustrated in Fig. 2.

From Fig. 2, it can be noticed that each phase winding is conducted in sequence for 120^0 per one cycle of period to carry either positive or negative constant current. The conduction of each phase winding is determined by the rotor position where the position can be known from hall effect sensors that provides three digitized output. The generation of three digitized outputs (i.e. $\mathrm{H_1}$,$\mathrm{H_2}$ and $\mathrm{H_3}$)

from the sensor according to the rotor position can be also described in Fig. 2.

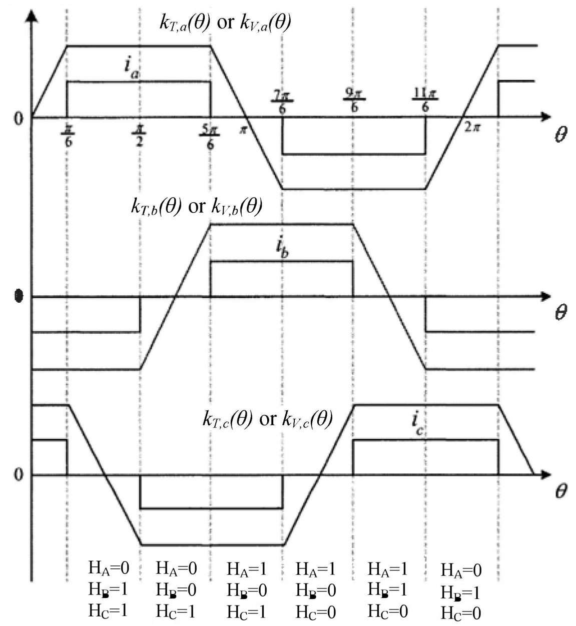


Fig 2. Ideal torque or back-emf voltage factor and current waveform for each phase (The output of Hall Effect sensors according to the rotor position are also given in the figure).

III. DTC OF BLDC

DTC of Brushless DC Machine is chosen as the method of the drive system as it has the potential to further improve the drawbacks of the basic DTC and cope with the demanding application from the industry. The basic concept of DTC will still remain and apply to the drive system such that the uses of two hysteresis comparator (i.e one for torque and one for flux), a switching table for voltage vectors selection and a three phase Voltage Source Inverter (VSI). The flux in DTC is to keep its amplitude within the predefined hysteresis band and by applying the required voltage vector, the amplitude of the stator flux can be controlled.

In the DTC of BLDC, the selection or situation of applying the zero voltage vectors is not the same as in the induction machines because the stator flux linkage will change even when the zero voltage vectors are selected since the magnets rotate with the rotor. Hence, zero voltage vectors are not considered in controlling the stator flux linkage in a BLDC system. Stator flux linkage should always be in motion with respect to the rotor flux linkage vector and the higher the stator vector rotation speed the faster the torque response is achieved.

The three phases BLDC motor is operated in a two phase on fashion which means the two phases that produce highest torque are energized based on rotor position while the third phase is off. The three phases VSI for DTC BLDC is represented by six individual solid state semiconductor switches i.e IGBT/MOSFET and the output contains six signals (i.e S_1-S_6) which is either 1 or 0. Unlike VSI for DTC induction machine which requires 3 input (S_a, S_b and S_c) gate signal that can be represented by either 1 (upper leg switch is ON) or 0 (lower leg switch is ON).

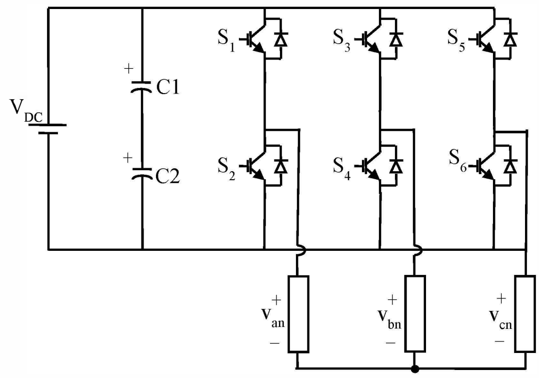


Fig 3. Switching states of the voltage source inverter for DTC of BLDC motor

A simulation model is created using Matlab/Simulink block based on Fig. 4 which shows the overall block diagram of the DTC of a BLDC drive system which operates in the two-phase conduction mode. Torque and flux control is implemented for this drive system. The main differences between the conventional DTC and DTC BLDC are in the voltage vector selection which is using the lookup table from [6] as shown in Table 1, and the formula for torque estimation (8). Flux estimation and current formula which is used is shown below.

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\frac{d\varphi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e} i_{s\beta}\right] \quad (6)$$

$$\frac{d\varphi_{r\alpha}}{d\theta_e} = \frac{e_\alpha}{\omega_e} \; and \; \frac{d\varphi_{r\beta}}{d\theta_e} = \frac{e_\beta}{\omega_e} \quad (7)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[\frac{e_\alpha}{\omega_e} i_{s\alpha} + \frac{e_\beta}{\omega_e} i_{s\beta}\right] \quad (8)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\left[k_\alpha(\theta_e) i_{s\alpha} + k_\beta(\theta_e) i_{s\beta}\right] \quad (9)$$

$$\varphi_{r\alpha} = \varphi_{rd}\cos\theta_e - \varphi_{rq}\sin\theta_e \quad (10)$$

$$\varphi_{r\beta} = \varphi_{rd}\sin\theta_e + \varphi_{rq}\cos\theta_e \quad (11)$$

$$i_{s\alpha} = i_{sd}\cos\theta_e - i_{sq}\sin\theta_e \quad (12)$$

$$i_{s\beta} = i_{sd}\sin\theta_e + i_{sq}\cos\theta_e \quad (13)$$

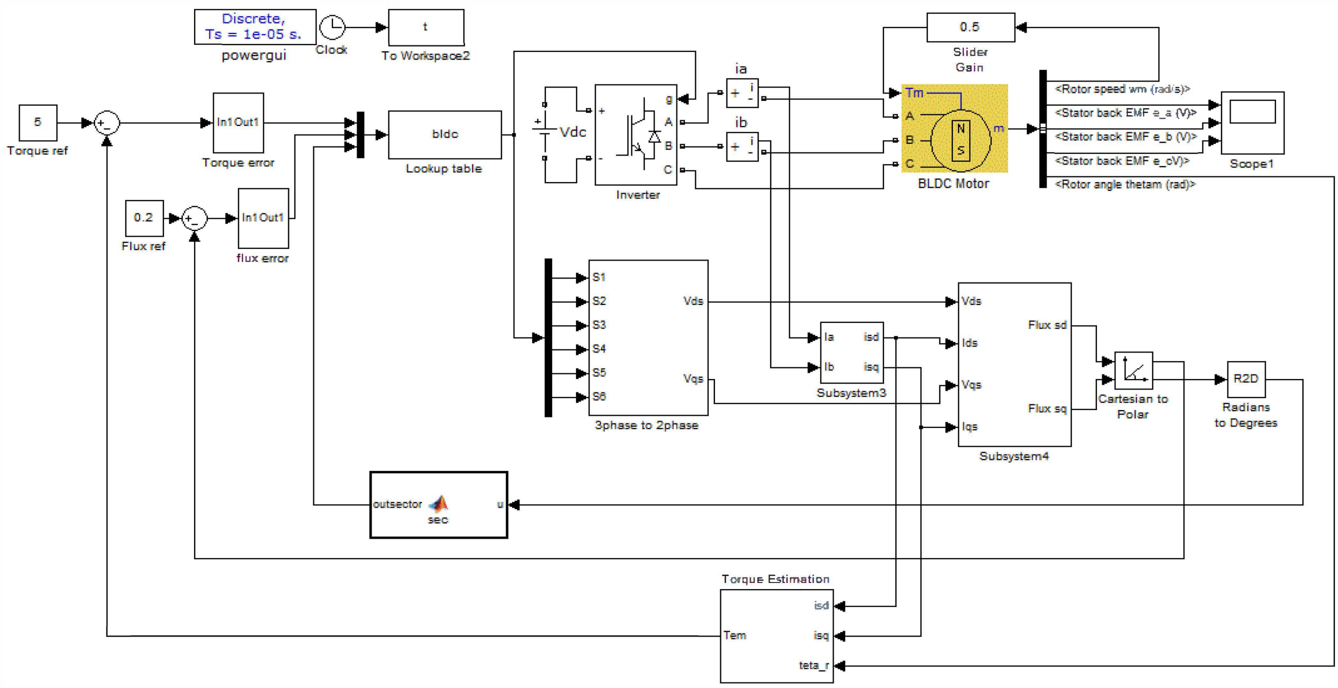


Fig 4. Block diagram of DTC of BLDC using Matlab/Simulink

TABLE I VOLTAGE VECTOR SELECTION TABLE AS PROPOSED IN [6]

Flux, φ	Torque, τ	Sector, θ					
		1	2	3	4	5	6
1	1	V_1	V_2	V_3	V_4	V_5	V_6
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_5	V_6	V_1	V_2	V_3	V_4
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	-1	V_4	V_5	V_6	V_1	V_2	V_3

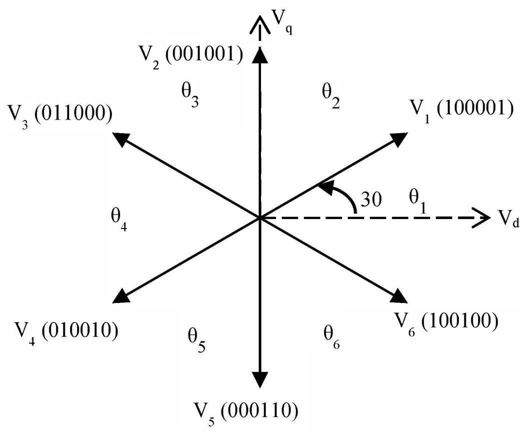


Fig 3. Definition of voltage vector

IV. SIMULATION RESULTS

The simulations of the closed loop DTC BLDC were performed using MATLAB/Simulink. The sampling time used for this system is 10μs and the simulation time is 1.5 sec. The hysteresis band for torque is set at 0.1 N.m and flux is set at 0.001 N.m /W.b. Meanwhile V_{dc} is set at 36V, torque reference is set at -5, 5 and 2 N.m and flux reference is set at 0.2 W.b. The motor parameter values used are shown in Table 2.

TABLE 2 Control and Motor Parameters Values

Control System	
Torque Hysteresis band	0.1 Nm
Flux Hysteresis band	0.001 Wb
Sampling time	10 μs
BLDC Motor	
Stator resistance	0.35 Ω
Stator inductance	4.64 mH
Flux linkage established by magnets	0.0794 V.s
Torque constant	1.4 Nm/A
Moment of inertia	$0.04 Kg.m^2$
Friction factor	0.005 Nms
Pole pairs	10

Fig. 5 shows the result of torque (N.m), phase current (A) and phase back emf (V), it can be observed that the torque stays within its reference value. Torque control during negative and positive value are shown thus proving the system capabilities. It also shown that the dynamic torque response is achieved based on the torque reference which are set at -5 N.m during the start up of the simulation and a step change of 5 N.m is applied at the simulation time of 1 second, finally the reference value is change to 2 N.m at the simulation time of 2 second. For the phase current [Ia, Ib, Ic] and back EMF voltage [Ea, Eb, Ec] it can be observed that during the first segment of the waveform with negative torque being applied, the phase sequence starts with phase A, phase C and followed by phase B. During the second segment with positive torque being applied, the phase sequence starts with phase A, phase B and followed by phase C. Finally during the third segment of the simulation process with the torque reference value changed to 2 N.m, the amplitude of the current and back EMF is also reduced propotional to the torque applied.

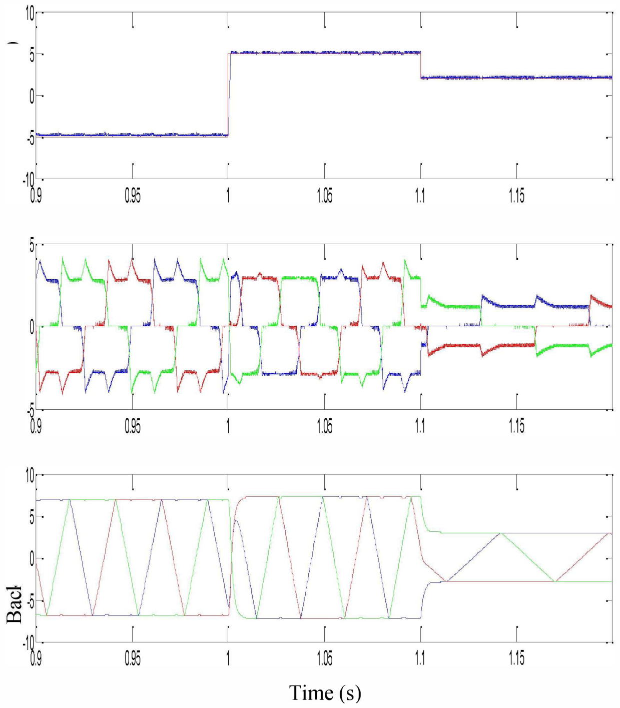
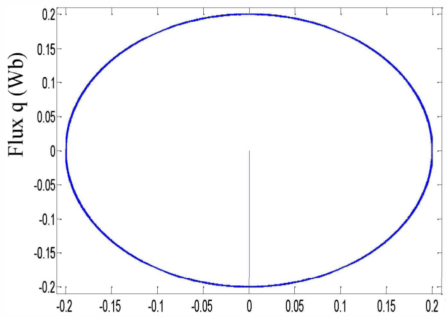
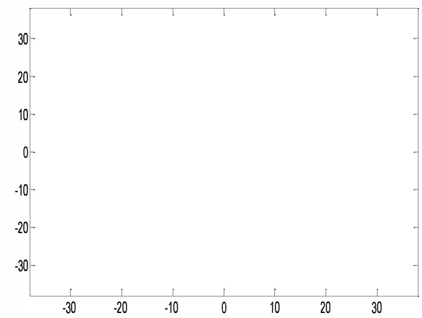


Fig 5. Simulation results for Torque Estimation (Tref=red Tactual=blue), Phase Current (Ia=blue, Ib=red, Ic=green) and Back EMF Voltage (Ea=blue, Eb=red, Ec=green)

Fig. 6 show the result of flux linkage locus with the flux reference value is set at 0.2 Wb and the flux stays within its hystersis band value. In DTC, the magnitude of flux space vector is controlled at its reference by limiting its error within the hysteresis band. Flux and torque control being implemented in the closed looped DTC of BLDC motor drive.

Fig. 7 show the result of voltage vector for the system. There are six non zero voltage vector space phasor that each has the same magnitude (i.e $\frac{\sqrt{3}\,Vdc}{2}$) but with differenct phase angle and the other two zero voltage vector is not implement for this system. The dc link voltage is set at 36V.





V. CONCLUSIONS

Based on the simulation model, results and literature review, it is expected that from DTC of BLDC motor drive system to have low frequency torque ripples and minimized torque response. It is achieved by proper selection of the inverter voltage space vectors of the two phase conduction mode from a simple lookup table at a predefined sampling time. It is expected that the system would have a higher dynamic response because it does not rely on tedious calculations and is simpler to implement. The proposed method is aimed to be used in application where fast torque response, minimum low-frequency torque oscillations, simple hardware, simple software, and a reasonably reduced inverter cost are desired.

ACKNOWLEDGMENT

The authors would like to Ministry of Higher Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant ERGS/2012/FKE/TK02/02/3/E00011 for this research.

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