Faculty of Electrical Engineering

IMPLEMENTATION OF DIRECT TORQUE CONTROL OF BRUSHLESS DC MOTOR UTILIZING DIGITAL SIGNAL PROCESSOR

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IMPLEMENTATION OF DIRECT TORQUE CONTROL OF BRUSHLESS DC MOTOR UTILIZING DIGITAL SIGNAL PROCESSOR

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DECLARATION

I declare that this thesis entitle “Implementation of Direct Torque Control (DTC) of Brushless DC Motor Utilizing Digital Signal Processor” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	…………………………………
Name	:	…………………………………
Date	:	…………………………………

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Electrical Engineering (Industrial Power) .

Signature : ………………………………….

Supervisor Name : ………………………………….

Date : ………………………………….

DEDICATION

To my beloved mother, father, wife, daughter, son and other family members.

ABSTRACT

This thesis presents the implementation of Direct Torque Control (DTC) of Brushless DC (BLDC) motor drive using a dSPACE DSP DS1104. BLDC motor is well-known and has been widely used in the industrial area due to its high speed and power density capabilities. Electronic commutation is by far more favourable compared to the conventional method, which uses brushes and commutators, that wear and tear by time. However, a precise controller is required in order to control the switches prior to commutation process. Over the past years, DTC method for induction motor drives received lots of attention from researchers, and motor drive industries. Its simple control structure uses a pair of hysteresis controller, torque and flux estimator, switching table and a three phase voltage source inverter. In DTC, torque and flux are controlled independently to satisfy the demands using optimum voltage vectors. The conventional Field Oriented Control (FOC) drive controls the torque and flux from the current components which being produced, and more machine parameters and current regulated Pulse Width Modulation are required. DTC of BLDC combines a simple control method and a demanding motor to complete a better drives system. DTC method is known to have a simple structure without having complex calculations thus offers a fast response and a good dynamic performance. The drawbacks of the conventional DTC are having high-torque ripple and variable switching frequency. A mathematical modeling which is created using MATLAB simulation on the motor drive for BLDC Motor is presented along with a complete model of the DTC system for BLDC motor with trapezoidal back EMF waveform using SIMULINK block. The model is described briefly to give a better understanding on the whole system. FPGA is used to perform blanking time generation which the main priority in performing this task is to avoid short circuit within the legs of VSI and a blanking time about 2μs is implemented for each leg. The usage of dSPACE is fully utilized which is used to minimize the system sampling time up to 50μs. Finally, the simulation and experimental results are shown to validate the performance of DTC of BLDC motor.

ABSTRAK

Tesis ini membentangkan pelaksanaan Kawalan Terus Daya Kilas (DTC) bersama Brushless DC (BLDC) motor memacu menggunakan DSpace DSP DS1104. BLDC motor terkenal dan telah digunakan secara meluas di kawasan perindustrian berikutan keupayaan memacu pada kelajuan tinggi dan mempunyai ketumpatan kuasa yang tinggi. Pergantian elektronik adalah jauh lebih ekonomik dan menjimatkan jika dibandingkan dengan kaedah konvensional yang menggunakan 'brush' dan komutator yang akan memerlukan penggantian dan servis yang kerap. Bagaimanapun, satu sistem pengawal yang tepat diperlukan untuk mengawal suis sebelum proses pergantian. Selama bertahun-tahun yang lalu, kaedah kawalan Terus Daya Kilas (DTC) untuk pemacu motor aruhan menerima banyak perhatian dari penyelidik dan industri pemacu motor. Difahamkan struktur kawalan system itu menggunakan sepasang pengawal histerisis, tork dan penganggar fluks, jadual pensuisan dan 3 fasa penyongsang sumber voltan . Di dalam sistem DTC, daya kilas dan fluks dikendalikan secara bebas untuk memenuhi tuntutan menggunakan vektor voltan yang optimum. Cara konvensional iaitu menggunakan 'Field Oriented Control (FOC) memacu dan mengawal daya kilas dan fluks dari komponen arus yang dihasilkan dan bergantung pada parameter mesin dan arus Pulse Width Modulation yang teratur diperlukan. DTC BLDC menggabungkan kaedah kawalan yang mudah dan motor yang menjadi pemintaan ramai untuk membuat satu sistem pemacu yang lebih baik. Kaedah DTC diketahui mempunyai struktur yang mudah tanpa perhitungan yang kompleks dengan demikian menawarkan tindak balas yang cepat dan prestasi dinamik yang baik. Kelemahan dari DTC konvensional mengalami riak tork yang tinggi dan frekuensi pensuisan berubah-ubah. Sebuah model matematik dibuat menggunakan simulasi MATLAB pada pemacu motor untuk BLDC motor dibentangkan bersama-sama dengan model yang lengkap untuk sistem DTC menggunakan BLDC motor dengan bentuk gelombang trapezoid EMF menggunakan SIMULINK blok. Model ini diterangkan secara menyeluruh untuk memberi pemahaman yang lebih baik pada seluruh sistem. FPGA digunakan untuk melaksanakan generasi masa blanking di mana keutamaan utama dalam melaksanakan tugas ini adalah untuk mengelakkan litar pintas pada kaki VSI dan masa untuk blanking yang digunakan ialah 2μs untuk dilakasanakan pada setiap rangkaian VSI. Penggunaan DSpace digunakan sepenuhnya dimana ianya digunakan untuk mengurangkan masa sistem pensampelan sehingga 50μs . Akhir sekali, simulasi dan keputusan eksperimen ditunjukkan untuk mengesahkan prestasi DTC daripada BLDC motor .

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LIST OF SYMBOLS AND ABBREVIATIONS

ADC	-	Analogue to Digital Converter
B	-	Viscous friction
B	-	Flux density of the field in which the conductors are placed
BLDC	-	Brushless DC Motor
CPLD	-	Complex Programmable Logic Device
DAC	-	Digital to Analogue Converter
DSC	-	Direct Self Control
DSP	-	Digital Signal Processor
DTC	-	Direct Torque Control
e_α , e_β	-	Motor back EMF in stationary reference frame
EMF	-	Electromotive Force
FOC	-	Field Oriented Control
FPGA	-	Field Programmable Gate Array
i_{ds} & i_{qs}	-	d and q components of the stator current in stationary reference frame
IE	-	Incremental Encoder
IM	-	Induction Machine
J	-	Moment of Inertia
k_α , k_β	-	Stationary reference frame back EMF constant according to electrical rotor position

K_{E_I}	-	Back EMF constant of one phase
l	-	Length of the conductor, m
L_m	-	Mutual Inductance
L_s , L_r	-	Stator and Rotor self-inductance
N	-	Number of conductors in series per phase
p	-	No. of poles
PC	-	Personal Computer
PM	-	Permanent Magnet
PMSM	-	Permanent Magnet Synchronous Motor
PWM	-	Pulse Width Modulation
r	-	Radius of the rotor bore, m
R_s	-	Stator Resistance
T_{em}	-	Electromagnetic Torque
T_L	-	Load torque
v	-	Velocity, m/s
V_a, V_b and V_c	-	Line to Neutral Voltage
V_{dc}	-	DC Link Voltage
VHDL	-	Very high speed integrated circuit, Hardware Description Language
VSI	-	Voltage Source Inverter
δ_{sr}	-	Rotor angle
$\varphi_s^g \varphi_r^g$	-	Stator and rotor flux linkage space vectors in general reference frame.
φ_s, φ_r	-	Stator and rotor flux linkage space vectors in stationary reference frame.
σ	-	Total flux leakage factor

θ_e	-	Electrical rotor angle
θ_m	-	Mechanical rotor angle
ω	-	Rotor speed
ω_e	-	Electrical rotor speed
ω_m	-	Rotor angular velocity, rad/s

LIST OF PUBLICATIONS

NO.	TITLE
1	AHMAD FAIZ BIN NOOR AZAM , M. B. M., AUZANI BIN JIDIN , NORHAZILINA BINTI BAHARI, , HATTA BIN JOPRI, ABDUL RAHIM BIN ABDULLAH 2012. Torque Hysteresis Controller for Brusless DC Motor Drives. *Power and Energy Conversion Symposium (PECS 2012)*.
2	AZAM, A. F. N., JIDIN, A., NGATIMAN, N. A., JOPRI, M. H., MANAP, M., HERLINO, A. L. & ALIAS, N. F. 2013 Current control of BLDC drives for EV application. Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International, 3-4 June 2013. 411-416.
3	NOOR AZAM, A. F., JIDIN, A., SAID, M. A., JOPRI, H. & MANAP, M. 2013. High performance torque control of BLDC motor. Electrical Machines and Systems (ICEMS), 2013 International Conference on, 26-29 Oct. 2013. 1093-1098.

CHAPTER 1

INTRODUCTION

1.0 Research Background

Conventional dc motors are highly efficient and their characteristic makes it reliable for use in many applications. However, the only drawback is that it uses commutator and brushes that require frequent maintenance and cannot be performed at dirty and explosive environment and at very high speed operating conditions. Maintenance-free motor can be developed by replacing the functions of commutator and brushes by solid-state switches, and these types of motors are now known as Brushless DC (BLDC) motors. BLDC motors are, in fact, a type of permanent magnet synchronous motors (PMSM). It is driven by dc voltage, and the current commutations are done by solid-state switches.

BLDC motor has advantages of longer lifespan, faster torque response and capability of high speeds drive in comparison with DC motor (Jeon et al., 2000). BLDC motor implements the basic operating principles of DC motor operation but with a difference by placing the permanent magnet in the rotor and coils in the stator. The coil windings are electrically separate from each other, which allow it to be turn on and off in a sequence that creates a rotating magnetic field. The rotor position needs to be determined so that excitation of the stator field always leads the permanent magnet field to produce torque. The commutation instants are determined by the rotor position, and the position of the rotor is detected either by position sensors or by sensorless techniques. The signals from Hall Effect sensors that usually used in BLDC motor need to be decoded to determine the shaft position and appropriate excitation of stator windings.

The three phase power electronic converter is necessary to operate the BLDC machine. The converter converts DC to AC via six solid-state semiconductor switches. MOSFET and IGBT are the most common types of switches being used. In lower power application, MOSFET are preferred over IGBT. The power electronic inverter must be capable of applying positive, negative and zero voltage across the motor phase terminals. Each drive phase consists of one motor terminal driven high, one motor terminal driven low, and one motor terminal floating.

1.1 Significance of Research

This research is based on the popularity of BLDC motor drives as mentioned above, i.e. high-torque density, high-speed operations, free-maintenance, etc. The BLDC motor drives require precise and robust control of torque, as well as current limiter to avoid inrush current due to sudden large torque demand especially during acceleration modes. Traditionally, the method of hysteresis torque/current controller was used to meet the above requirements. However, this conventional method operates the inverter at three phase conduction mode, in which produces high switching frequency as well as switching losses. In addition, the three phase conduction mode in this method may degrade the inverter switching reliability. The significance of the research is to minimize the problems, i.e. switching frequency/losses by applying DTC method with two-phase conduction mode as proposed in (Ozturk and Toliyat, 2007) for a BLDC motor. The DTC operation of two-phase conduction mode is verified via simulation and experimental results.

1.2 Overview of Modern BLDC Motor Drives

Vector control and 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, Blaschke (Blaschke, 1972). 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 markets.

DTC was introduced in Japan by Takahashi and Nagochi (Takahashi and Noguchi, 1986) and also in Germany by Depenbrock (Depenbrock, 1988). 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 using six or eight voltage space vectors as defined in the lookup table. Lookup table is constructed to choose appropriate switching states of the inverter which the selection is based on the output of the hysteresis 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 researchers are focusing on combining the DTC techniques with PMSM / BLDC machines, as reported in (Ozturk et al., 2010, Ozturk and Toliyat, 2007, Ozturk and Toliyat, 2011, Rahman et al., 2004, Yong et al., 2005, Yong et al., 2007, French and Acarnley, 1996, Lixin et al., 2003, Seog-Joo and Seung-Ki, 1995, Sung Jun et al., 2000, Zhong et al., 1997, Zhu et al., 2005). 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 (Buja et al., 1997b, Buja et al., 1997a, Casadei et al., 1995, Jidin et al., 2011a, Jidin et al., 2011b, Jidin et al., 2012, Takahashi and Noguchi, 1997). A modified DTC scheme with fixed switching frequency and low torque and flux ripple was introduced in (Jidin et al., 2010).

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 needs 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. (Noguchi et al., 1998) proposed a method for detecting the initial rotor position estimation at the 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 (Rahman et al., 2004).

1.3 Overview of Basic DTC

A simple control structure of basic DTC was introduced by Takahashi. The structure consist a pair of hysteresis controllers, switching table / lookup table for voltage vectors selection, a three phase voltage source inverter (VSI) and lastly flux and torque estimators as shown in Figure 1.1. In DTC, torque and flux are controlled by satisfying their demands simultaneously using appropriate voltage vector selection. Then the voltage vector is used either to increase or decrease the torque and stator flux based on the criteria of torque error status, flux error status and flux orientation.

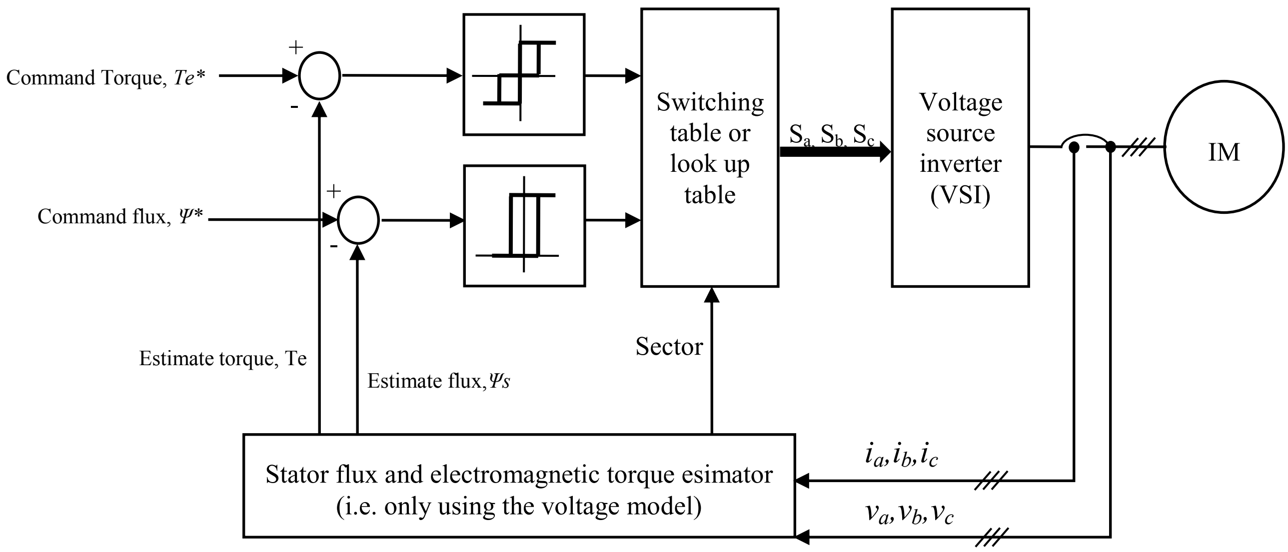

Figure 1.1 Control structure of basic DTC hysteresis based induction machine.

The motor operating condition which includes the rotor speed, stator and rotor fluxes and DC link voltage influence the torque and flux slope criteria hence affecting the switching pattern of the hysteresis comparators. Furthermore, the switching frequency of the VSI also gets affected by the operating conditions. A three phase VSI consists of six switching devices (i.e IGBT, MOSFET, GTO, etc.) which transform the DC link voltage to the AC voltage source. From Figure 1.2, it can be seen that the VSI is connected to a wye