Faculty of Electrical Engineering

A CONSTANT SWITCHING FREQUENCY OF DIRECT TORQUE CONTROL OF BRUSHLESS DC MOTOR

Yusnida binti Ahmad Tarmizi

Master of Science in Electrical Engineering

2019

© Universiti Teknikal Malaysia Melaka

A CONSTANT SWITCHING FREQUENCY OF DIRECT TORQUE CONTROL OF BRUSHLESS DC MOTOR

YUSNIDA BINTI AHMAD TARMIZI

A thesis submitted in fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

© Universiti Teknikal Malaysia Melaka

DECLARATION

I declare that this thesis entitled “A Constant Switching Frequency of Direct Torque Control of Brushless DC Motor” 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 : Yusnida binti Ahmad Tarmizi
Date : ……………………………

© Universiti Teknikal Malaysia Melaka

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 Science in Electrical Engineering.

Signature : ……………………………..

Supervisor Name : PM Dr. Kasrul bin Abdul Karim

Date : ……………………………..

© Universiti Teknikal Malaysia Melaka

DEDICATION

To my beloved mother, father and family.

© Universiti Teknikal Malaysia Melaka

ABSTRACT

Direct torque control (DTC) for DC motor have extensively used in many applications because it provides the simple control structure, faster torque dynamic control and longer lifespan. However, the used of hysteresis comparator in DTC structure have provides two major drawbacks namely, larger torque ripple and variable switching frequency. These problems occur due to low sampling time which creates delay actions in minimization of torque error with appropriate voltage vectors and inappropriate voltage selection of voltage vectors which leads to larger torque ripple in DTC scheme and cause the torque error cannot restrict within the hysteresis bandwidth. Therefore, this thesis presents the optimal DTC switching strategy to reduce torque ripple and gain the constant switching frequency for BLDC motor. Next, to analyze and compare the switching frequency and torque control performance produced by other strategy schemes such as torque hysteresis control (THC), direct torque control (DTC) and constant switching frequency (CSF). The minor modification is made without changing the original structure of DTC scheme. The hysteresis controller is replaced with torque controller and look-up table is added where the selection of voltage vector is occurred. The most suitable voltage vector for different speed range can be defined as the vector that produces minimum torque slopes. The torque ripple and switching frequency can be reduced when the torque slope is minimized. Next, to obtain the constant switching frequency, PI controller and high injection frequency are proposed. The proper proportional – integral (PI) controller are determine by analyzing or insuring that the absolute torque shape does not exceed the absolute carrier slope. The results of improvements are obtained and were verified via simulation and experiment, as well as comparison with the conventional DTC and others schemes. The results obtained clearly show that the torque ripple is reduced and constant switching frequency is achieved.

© Universiti Teknikal Malaysia Melaka

ABSTRAK

Kawalan tork langsung (DTC) untuk motor DC telah digunakan secara meluas dalam banyak aplikasi kerana ia menyediakan struktur kawalan mudah, kawalan dinamik tork yang lebih cepat dan jangka hayat yang lebih lama. Walau bagaimanapun, penggunaan komparator histeresis dalam struktur DTC telah menyediakan dua kelemahan utama iaitu riak torak yang lebih besar dan kekerapan menukar suis. Masalah ini berlaku kerana masa pensampelan yang rendah yang menghasilkan tindakan kelewatan dalam mengurangkan kesilapan tork dengan vektor voltan yang sesuai dan pemilihan voltan yang tidak sesuai akan yang membawa kepada pengeluaran riak tork yang lebih besar dalam skema DTC. Masalahnya menyebabkan ralat tork tidak dapat disekat dalam lebar jalur histerisisnya. Oleh itu, tesis ini membentangkan strategi penukaran DTC yang optimum untuk mengurangkan riak tork dan mendapatkan kekerapan menukar suis berterusan untuk motor BLDC. Seterusnya, untuk menganalisis dan membandingkan prestasi kawalan frekuensi dan tork yang dihasilkan oleh skim strategi lain seperti kawalan histerisis tork (THC), kawalan tork langsung (DTC) dan kekerapan penukaran berterusan (CSF). Pengubahsuaian kecil dibuat tanpa mengubah struktur asal skema DTC. Pengawal histerisis digantikan dengan pengawal torsi dan jadual paparan ditambah di mana pemilihan vektor voltan berlaku. Vektor voltan yang paling sesuai untuk pelbagai kelajuan yang berbeza boleh ditakrifkan sebagai vektor yang menghasilkan cerun tork minimum. Rintangan tork dan kekerapan tukar boleh dikurangkan apabila cerun tork diminimumkan. Seterusnya, untuk mendapatkan kekerapan penukaran berterusan, pengawal PI dan kekerapan suntikan tinggi dicadangkan. Pengawal berkadar proporsional (PI) yang betul adalah menentukan dengan menganalisis atau menginsuranskan bahawa bentuk tork mutlak tidak melebihi cerun pembawa mutlak. Hasil penambahbaikan diperoleh dan disahkan melalui simulasi dan percubaan, serta perbandingan dengan skema DTC konvensional dan lain-lain. Keputusan diperoleh dengan jelas menunjukkan bahawa riak tork dikurangkan dan kekerapan beralih berterusan dihasilkan.

© Universiti Teknikal Malaysia Melaka

ACKNOWLEDGEMENTS

First of all, alhamdulilah, with His blessings, finally I am able to complete this thesis. I am truly grateful to Allah for He has given me knowledge, patience and everything good in this life. Nevertheless, I could not make it through without the help of these special people (name them here). Their guidance and encouragement have helped me to go through the obstacles. First and foremost, my special thanks goes to my academic supervisor, PM Dr. Kasrul bin Abdul Karim and Dr. Auzani bin Jidin who have been very helpful in guiding and motivating me. I am also grateful for their advice, patience and willingness to spare most of their precious time helping me in completion of the thesis. I also would like to express my deep gratitude to my bosom friends: Miss Azura, Mr. Khairi, Miss Arifah and Miss Farah for their continuous encouragement, assistance and patience. A million thanks go to Mr Fadil, Mr. Rahim, who have been reaching out their hands helping me in the technical discussions throughout the hardware implementation which I have benefited a lot.

Finally, last but not least, my heartfelt gratitude for my parents: Ahmad Tarmizi bin Mad Yassin and Noormiah binti Razali, who have been supporting me with their love and patience, and mere words could not express my gratitude. Without you, I could not have gone any further than where I am now. Thank you all.

© Universiti Teknikal Malaysia Melaka

TABLE OF CONTENTS

© Universiti Teknikal Malaysia Melaka

© Universiti Teknikal Malaysia Melaka

LIST OF TABLES

© Universiti Teknikal Malaysia Melaka

LIST OF FIGURES

© Universiti Teknikal Malaysia Melaka

© Universiti Teknikal Malaysia Melaka

© Universiti Teknikal Malaysia Melaka

© Universiti Teknikal Malaysia Melaka

LIST OF APPENDICES

© Universiti Teknikal Malaysia Melaka

LIST OF ABBREVIATIONS

B	-	Viscous friction
d, q	-	Real and imaginary of the stationary reference frame
d_1, d_2, d_3	-	Duty ratio
H_a, H_b, H_c	-	Hall effect status (i.e. Hall effect a, b and c)
i_a, i_b, i_c	-	Three-phase stator current (i.e phase a, b and c)
i_{sd}, i_{sq}	-	Real and imaginary stator voltage in stationary reference
J	-	Inertia
L_m	-	Mutual self-inductance
L_r	-	Rotor self-inductance
L_s	-	Stator self-inductance
S_{a1}, S_{b1}, S_{c1}	-	Upper switching states of phase a, b and c
S_{a2}, S_{b2}, S_{c2}	-	Lower switching states of phase a, b and c
T_e	-	Electromagnetic torque
U_b	-	Upper hysteresis band
V_{DC}	-	DC voltage
δ_T	-	Torque error status
δ_φ	-	Flux error status
ε_T	-	Torque error
ε_φ	-	Stator flux error
φ_r	-	Rotor flux
φ_s	-	Estimated of stator flux
ω_e	-	Angular frequency
ω_m	-	Mechanical angular speed in rad/s
$\Delta {T_e}^-$	-	Torque slope decrease
$\Delta {T_e}^+$	-	Torque slope increase

© Universiti Teknikal Malaysia Melaka

AC - Alternating current
ADC - Analogue to digital converter
BDC - Brush Direct current
BLDC - Brushless Direct Current
CHMI - Cascaded H-Bridge Multilevel inverter
CSF - Constant switching frequency
DAC - Digital to analogue converter
DTC - Direct torque control
DTC-SVM - Direct torque control using space vector modulation
FCMI - Flying capacitor multilevel inverter
FOC - Field oriented control
FPGA - Field Programmable Gate Array
IGBT - Insulated-gate bipolar transistor
IM - Induction motor
NPCMI - Neutral-point clamped multilevel inverter
PI - Proportional integral
PWM - Pulse width modulation
SVM - Space vector modulation
THC - Torque hysteresis control
VSI - Voltage source inverter

© Universiti Teknikal Malaysia Melaka

LIST OF PUBLICATIONS

Journal Paper

Yusnida Tarmizi, Auzani Jidin, Kasrul Abdul Karim, and Tole Sutikno, 2018. A Simple Constant Switching Frequency of Direct Torque Control of Brushless DC motor. *International Journal of Power Electronics and Drive Systems (IJPEDS),* Vol. 10, No. 1, pp. 10-18.

Yusnida Tarmizi, Kasrul Abdul Karim, S. Azura Ahmad Tarusan and Auzani Jidin, 2017. Review and Comparison of Sensorless Techniques to Estimate the Position and Speed of PMSM. *International Journal of Power Electronics and Drive Systems (IJPEDS),* Vol. 8, No. 3, pp. 1062-1069.

Published Conference Proceeding

Yusnida Tarmizi, Auzani Jidin, Kasrul Abdul Karim, Siti Azura Ahmad Tarusan, 2015. Investigation of Torque and Flux-Current Producing Components in Indirect Rotor Flux Oriented Control (IRFOC) of Induction Machines, *IEEE Student Conference on Research and Development (SCOReD),* pp. 539-544.

Siti Azura Ahmad Tarusan, Yusnida Tarmizi, Auzani Jidin and Kasrul Abdul Karim, 2015. Constant Switching Frequency for Direct Torque Control of Induction Motor, *IEEE Student Conference on Research and Development (SCOReD),* pp. 228-233.

Huzainirah Ismail, Fazlli Pakar, Auzani Jidin, R. Sundram, M. Khairi Rahin, Yusnida Tarmizi, Atikah Razi, 2015. Direct Torque Control of Induction Machine Using 3-Level Neutral Point Clamped Inverter. *IEEE Student Conference on Research and Development (SCOReD),* pp. 571-576.

M. Khairi Rahim, Auzani Jidin, Fazlli Patkar, R. Sundram, Yusnida Tarmizi, Huzainirah Ismail, S. Azura Tarusan, 2015. Minimization of Torque Ripple and Switching Frequency Utilizing Optimal DTC Switching Strategy for Dual-Inverter. *IEEE Student Conference on Research and Development (SCOReD),* pp. 49-54.

© Universiti Teknikal Malaysia Melaka

CHAPTER 1

INTRODUCTION

1.1 Research background

Over the years, conventional DC motors have been highly efficient and extensively been used in many applications due to its reliable characteristics. DC motor drive has been attracting researcher's attention as it rigs the simple control structure and fast torque dynamic control. By controlling the armature current that is always perpendicular to the magnetic flux, the fast torque dynamic control can be gained. Due to several drawbacks in development of DC motor such that its construction is costly, its maintenance has to be performed regularly and at clean and non-explosive areas with a very high speed operating conditions.

Due to such limitation, the DC motor had been replaced with AC motor drive which has widely being used in many industrial applications since AC motor has longer lifespan, robust, faster torque response and able to operate with higher speed (Jeon at al., 2000). In fact, brushless DC motor (BLDC) can be categorized as AC family although it is powered by DC source. Its inverter is connected which allows itself to convert to AC power. The BLDC motor has becoming popular and gradually increased in industrial usage slowly to replace DC motor drives in many industrial applications as it negates the mechanical commutator used in traditional motors. In favor of improving the dependability, the BLDC motor replaces the mechanical commutator with electronic devices.

The function of the electronic devices is to allow torque control and achieving speed accuracy. Furthermore, it ensures the motor runs at peak efficiency. Moreover, they have

© Universiti Teknikal Malaysia Melaka

been gaining popularity due to its cost efficiency along with its extra functions. Such benefits are due to BLDC's brushless structure and its size which is comparatively smaller and lighter but provides the same magnitude of power output which is suitable to use for application in limited space.

1.2 Direct Torque Control of BLDC Motor Drives

Over the past several decades Takahashi and Noguchi proposed Direct Torque Control (DTC) in 1986 and Depenbrock in 1988 for induction motor drives and had received vast recognition in applications of industrial motor drive. Recently in line with that, many researchers are moving towards precise torque control and starting to work on DTC of BLDC motor for specified applications. As its name implies, the electromagnetic torque estimation is the main aspect in the DTC of a BLDC motor drives within constant torque region (Sajana Kunjumon and Johnson Mathew, 2013). In contrast to conventional three-phase DTC drives, the proposed DTC method comes with two-phase conduction mode. The concept outlines for DTC of AC drive is to regulate the electromagnetic torque and stator flux linkage directly and non-dependently under two-phase conduction mode by the use of six voltage vectors in lookup table. Unlike the DTC drives, Field Oriented Control (FOC) drives have complicated schemes which calls for frame transformation, comprehension of machine parameters and current regulated Pulse Width Modulation (PWM) in order to produce current components (i.e. d and q axis components of stator current) to regulate the torque and flux respectively.

Initially, the scheme of Direct Torque Control (DTC) for induction motor drives was proposed by (Takahashi and Noguchi, 1986) which turned out later to be popular in industrial motor drive applications due to its simplicity and superior torque dynamic control. Unlike

© Universiti Teknikal Malaysia Melaka

FOC scheme, the DTC scheme has more simple structure; frameless transformer and a positioned sensor. The simple control structure consists of a pair of hysteresis regulators, switching table/ lookup table for voltage vectors selections, a three-phase voltage source inverter (VSI) and lastly flux and torque estimators as shown Figure 1.1. The figure shows that, stator flux and electromagnetic torque can be regulated independently using 2-level and 3-level hysteresis comparators respectively. To make the flux and torque within the band, corresponding voltage vectors have to choose an option either to increase or decrease the torque or simultaneously increases or decreases the stator flux, which relative to the output from torque error status, flux error status and flux orientation. In fact, if the flux and torque are able to estimate precisely, high performance control in DTC drive are eventually structured with suitable selection of voltage vectors.

In hysteresis-based DTC, the hysteresis comparators are used to obtain the switching frequency for Voltage Sources Inverter (VSI). It was emphasized in (Li, Y., Shao, J. and Si, B., 1997) and (Jun-Koo, K. and Seung-Ki, S., 1998) that in general, the slopes of flux and torque affecting the switching in their hysteresis comparators and differ with operating conditions. This causes the switching frequency also differs with the operating conditions. As a result, the unpredictable harmonic current flow emerges due to variation in the switching frequency.

© Universiti Teknikal Malaysia Melaka

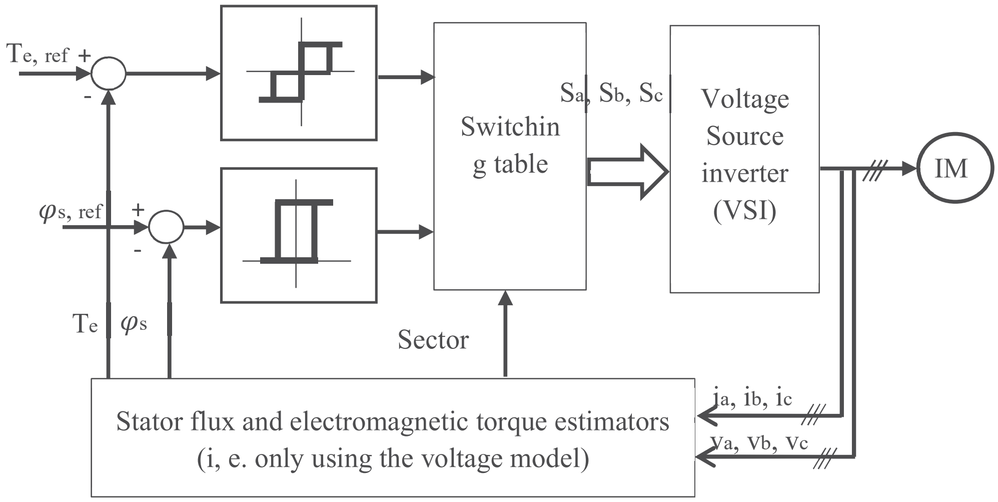


Figure 1.1: Control structure of basic DTC-hysteresis based induction machine (Takahashi and Noguichi, 1986)

1.3 Problem statement

DTC offers a simple control structure and fast torque dynamic control. However, it has major problems during operation which causes larger torque ripple and variable inverter switching frequency. The problems can be indicated by the aid of a simulation result shown in Figure 1.2. Referring to a larger torque ripple problem, it is susceptible in DTC scheme which it is associated with the hysteresis controllers. Specifically, the problem is due to two factors as listed out below;

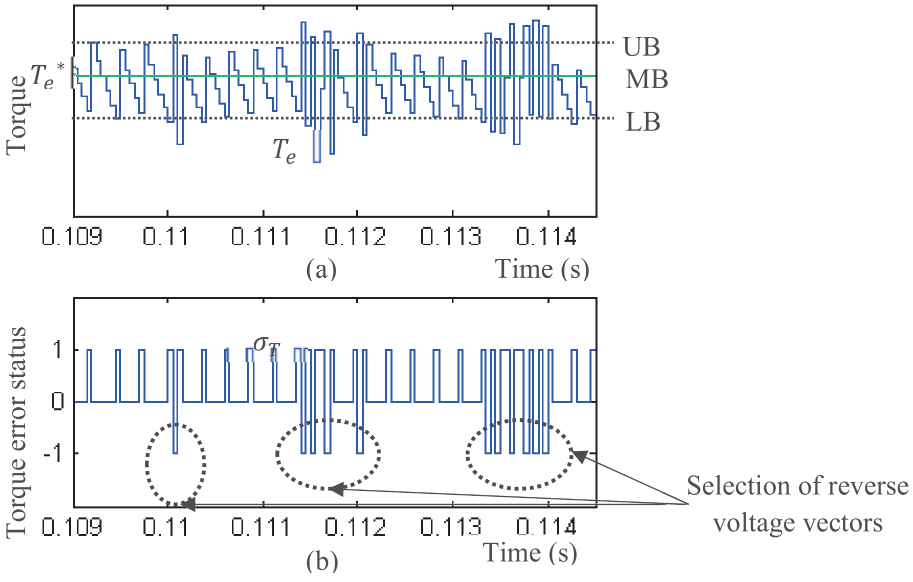
i) Note that, the digital implementation of hysteresis controllers produces a low sampling time, which creates delay actions in minimization of torque error with appropriate voltage vectors. The delay actions cause the torque error unable to specifically restrict within the hysteresis bandwidth where torque error will overshoot (or undershoot) and exceeds beyond (or below) the upper band (or the lower band). Due to that, larger torque ripple is caused by the torque changing

© Universiti Teknikal Malaysia Melaka

drastically and the execution of control algorithm at a lower sampling time. Figure 1.2 (a) shows the overshoot and undershoot of the torque due to delay actions and lower sampling time of the controller.

ii) Besides that, the unsuitable voltage vectors selection leads to larger torque ripple due to decreasing of sharp torque. When the torque touches the upper band (UB) or lower band (LB) of the hysteresis comparator, the mismatched voltage vector is selected as shown in Figure 1.2 (b). When the torque error status at σ_T = -1, the mismatched voltage vector (or reverse) is selected.

Hence, the two factors i.e. delay actions of hysteresis controllers and inappropriate selection of reverse voltage vectors lead to larger torque ripple production in DTC scheme (Takahashi and Noguochi, 1986). While the problems for variable switching frequency are caused by torque variations due to unpredictable and operating conditions that varies nonlinearly i.e. speed, load and etc. (Casedei et al., 1997, Kang and Sul, 2001)



(a)

(b)

Figure 1.2: Problem of larger torque ripple and variable switching frequency in hysteresis-based DTC

© Universiti Teknikal Malaysia Melaka