“I hereby declare that I have read through this report entitled “Development of Direct Torque Control (DTC) Algorithm for Five-Phase Induction Machine” and found that it has complied with the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Power Electronics and Drive)”.

Signature : …………………………..

Supervisor’s Name : DR AUZANI BIN JIDIN

Date : 27 June 2012

DEVELOPMENT OF DIRECT TORQUE CONTROL (DTC) ALGORITHM FOR FIVE-PHASE INDUCTION MACHINE

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A thesis submitted in fulfillment of the
requirement for the award of the degree of
Bachelor of Electrical Engineering

Faculty of Electrical Engineering
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JUNE 2012

I declare that this thesis entitled “Development of Direct Torque Control (DTC) Algorithm for Five-Phase Induction Machine” is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : …………………

Name : GOH WEE YEN

Date : 27 June 2012

To my beloved family members

for their enduring love, motivation and support

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ABSTRACT

This thesis presents the development of direct torque control (DTC) algorithm for five-phase induction machine. In DTC, a de-coupled control of electromagnetic torque and stator flux was established so that a fast instantaneous torque and flux control can be achieved. Based on the look-up table, the suitable voltage vectors are selected according to the information of the flux sector and error status (output of hysteresis comparators) in order to control both of stator flux and torque. In comparison to three-phase DTC, five-phase DTC provides a higher number of switching states (i.e 32 voltage vectors) which can offer more options in selecting the most optimal voltage vectors to further improve the overall DTC performances. This thesis is served to develop mathematical modeling and simulation of DTC of five-phase induction machine. It consists of a look-up table for 32 voltage vectors selection, modeling of five-phase induction machine, transformation of five-to-two phase as well as flux and torque estimators. The feasibility of the modeling which is based on MATLAB SIMULINK was verified through simulation results.

ABSTRAK

Tesis ini memaparkan perkembangan algoritma untuk kawalan dayakilas terus (DTC) bagi mesin aruhan lima-fasa. Untuk DTC, satu kaedah bagi mengawal dayakilas dan fluks secara beasingan telah dicipta supaya pengawalan daya kilas dan fluks dapat dikawal dengan serta-merta. Merujuk kepada jadual pemilihan, pemilihan vektor voltan telah dibuat berdasarkan sektor fluks dan status ralat (keluaran histerisis comparator) untuk mengawal kedua-dua dayakilas dan fluks. Dalam pembandingan dengan DTC tiga-fasa, DTC lima-fasa mempunyai lima pensuisan voltan yang menyediakan lebih banyak pensuisan voltan (i.e 32 voltan vektor) di mana lebih banyak pemilihan dapat ditawarkan untuk memilih voltan vektor yang paling optimum supaya prestasi keseluruhan DTC dapat ditingkatkan lagi. Tesis ini berkhidmat untuk membangunkan pemodelan matematik dan simulasi DTC untuk mesin aruhan lima-fasa. Ini meliputi jadual pemilihan 32 vektor voltan, pemodelan mesin aruhan lima-fasa, transformasi lima-kepada-dua fasa, dan juga estimasi fluks serta dayakilas. Kesesuaian untuk pemodelan berdasarkan MATLAB SIMULINK telah disahkan melalui keputusan simulasi.

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LIST OF SYMBOLS AND ABBREVIATIONS

DC - Direct current

AC - Alternating current

FOC - Field-Oriented Control

$\mathrm{T_e}$ - Electromagnetic torque

$\mathrm{T_{e,\,ref}}$ - Torque reference

Ψ_s - Estimated stator flux linkage

$\Psi_\mathrm{s,\,ref}$ - Flux reference

DTC - Direct torque control

VSI - Voltage source inverter

S_a, S_b, S_c - Switching states of phase A, B and C

i_a, i_b, i_c - Stator current of phase A, B and C

v_a, v_b, v_c - Stator voltage of phase A, B and C

SVM - Space Vector Modulation

$v_{s,\,ref}$ - Reference voltage vector

S_a, S_b, S_c, S_d, S_e - Switching states of phase A, B, C, D and E

THD - Total harmonic distortion

mmf - Magnetomotive force

$\mathrm{d^s}$, $\mathrm{q^s}$ - Real and imaginary axis of the stator

$\mathrm{d^r}$, $\mathrm{q^r}$ - Real and imaginary axis of the rotor

α - Angle between real axis of stator and rotor

θ_s - Angle with respect to stator axis

θ_r - Angle with respect to rotor axis

v_s^g - Stator voltage in general reference frame

i_s^g, i_r^g - Stator and rotor current in general reference frame

Ψ_s^g, Ψ_r^g - Stator and rotor flux in general reference frame

ω_r - Rotor electric angular speed

ω_m - Motor speed

R_s, R_r - Stator and rotor resistances

L_s, L_r, L_m - Stator, rotor and mutual inductances

P - Pole pairs

J - Total inertia in the motor

v_{sd}, v_{sq} - Stator voltage in terms of d-q axis components

v_{rd}, v_{rq} - Rotor voltage in terms of d-q axis components

i_{sd}, i_{sq} - Stator current in terms of d-q axis components

i_{rd}, i_{rq} - Rotor current in terms of d-q axis components

Ψ_{sd}, Ψ_{sq} - Stator flux in terms of d-q axis components

Ψ_{md}, Ψ_{mq} - Mutual flux in terms of d-q axis components

δ_{sr} - Angle difference between stator and rotor flux vectors

Ψ^+ - Flux error status

T_{stat} - Torque error status

T_{load} - Load torque

ω_e - Steady-state synchronous frequency

ω_c - Cut-off frequency

i_a, i_b, i_c, i_d, i_e - Stator current of phase A, B, C, D and E

V_{DC} - DC voltage

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CHAPTER 1

INTRODUCTION

1.1 Vector Control of Induction Machine Drives

Due to its simplicity and high performance torque control, DC machines have been used widely in many applications. Their commutation movement produces orthogonal torque and flux, which constructs high performance control under optimal conditions. Nonetheless, the DC machines are expensive, required regular maintenance, limited speed and unable to operate in dirty or explosive environment. Thus, the induction machines became popular and gradually replacing DC machine drives in many industrial applications due to the Field-Oriented Control (FOC) introduced by F. Blaschke in 1970's. FOC can produce comparable performance that obtained in DC machines [1]. Furthermore, their popularity is also assisted by the rapid development in power semiconductor devices and the emergence of high speed microprocessor and digital signal processors [2].

Vector control in AC drives is used to control the flux and torque independently. The torque dynamic control is improved in order to obtain the results which are comparable to that DC machines. Under optimal circumstances, the orthogonal (90°) of torque and flux will produce high performance control of AC machines due to:

$$T_e = \Psi \, I_{qs} \, \sin\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.1)$$

In view of their respective producing current components, FOC provides a decoupled control of torque and flux which is equivalent to the DC machine control method. This is because of the stator current vector (in the rotating reference frame) that produces orthogonal stator torque and flux current components to develop as DC quantities. The rotating reference frame refers either to the rotor or stator flux. Based on rotor flux, the Rotor Flux-Oriented Control is sensitive to the parameter variations and it also requires the knowledge of rotor speed and position using absolute encoder. Therefore, Stator Flux-Oriented Control is more frequently in used for induction machine as it does not require the information of the rotor speed and position.

1.2 Direct Torque Control of Induction Machine

In the past decades, the Direct Torque Control (DTC) scheme for induction motor drives [3] has gained its popularity in industrial motor drive applications. It was also used as the main platform for the ABB inverter technology, and the first DTC drive was marketed by ABB in 1996 [4-5]. Its popularity increases since it offers a faster instantaneous dynamic control and its control structure is simpler compared to the FOC scheme [3, 6-7]. In FOC, the torque and flux are controlled based on their producing current components. As for the DTC, the torque and flux are controlled independently.

The simple control structure of DTC proposed by Takahashi [3] is illustrated in Figure 1.1. This control structure consists of three-phase voltage source inverter (VSI), hysteresis comparator, flux and torque estimators as well as switching table. The stator flux and electromagnetic torque can be controlled independently using a two-level and three-level hysteresis comparators respectively. Then, an appropriate voltage vector is chosen to satisfy the flux and torque requirement. A combination of the voltage model and current model using a first order lag network was implemented in [3]. To achieve a proper flux estimator for entire speed range operations, the voltage model produces better flux estimation for high speed range operations. They require only stator resistance and terminal quantities such as stator voltages and currents, which in turn leads to the robust control of DTC.

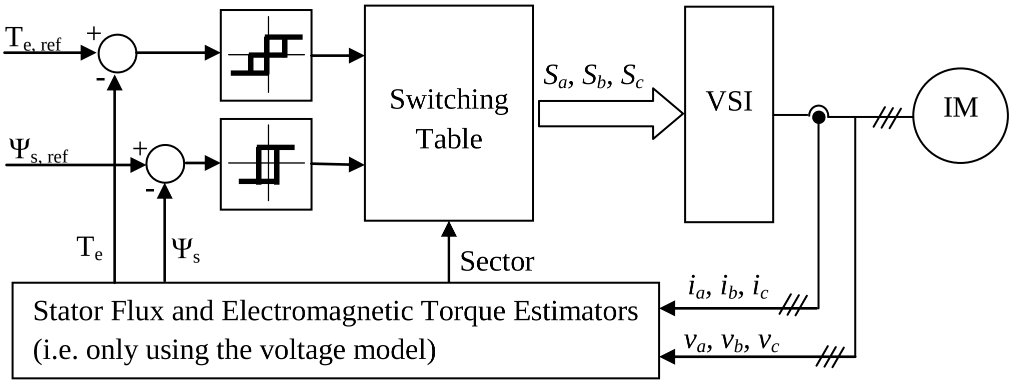

Figure 1.1 Simple Control Structure of DTC

1.3 Improvements of Direct Torque Control Performances

Since DTC was first introduced in 1986 [3], several modifications to its original structure (DTC hysteresis-based) were proposed to improve the performance of DTC. Recently, researchers are surveyed on the DTC overmodulation strategy in which it will enhance the dynamic performance and the output power of DTC. The improvements of DTC are categorized in three categories as follows:

- *Torque Ripple Reduction and Constant Switching Frequency*

  To reduce the output torque, the bandwidth of hysteresis comparator is reduced to an appropriate value. The selection of the appropriate bandwidth is based on the worst operating conditions [8] for ensuring the switching frequency does not exceed its limit. Besides that, it is advantageous for the usage of high speed processor to keep the ripple within the band.

  Furthermore, the ripple can be minimized by injecting high frequency triangular waveforms to the torque and flux errors [9]. This method is known as dithering technique. The purpose of this technique is to minimize the torque ripple even in performing the DTC at limited sampling frequency. Nevertheless, it still produces unpredictable switching frequency since the torque and flux slopes which are related to the switching frequency; do vary with operating conditions [10-11].

  To provide a constant switching frequency and reduced output torque ripple, a constant switching frequency is established in the DTC hysteresis-based by adjusting the bandwidth of the hysteresis comparators according to the changes in operating conditions [12]. This method increases the complexity of the DTC drive but it does not promise for a reduction of torque ripple.

  As proposed by [13], the principle operation of torque controller using the hysteresis-based is replaced with a triangular carrier-based. The most common approach to solve the problems is by using the space vector modulation (SVM) [14-15]. To synthesis the desired voltage vector, the switching period is divided into three or more states. This approach will produce the minimum torque ripple.

- *Fast Torque Dynamic Control via Overmodulation Strategy*

  The torque dynamic performance can be improved by employing the existed DC link voltage through overmodulation. To perform the DTC under overmodulation mode, it is preferable to use the SVM [14] rather than other techniques due to its flexibility to be implemented for advanced motor control. This technique requires a single reference voltage vector, $v_{s,ref}$, to define the mode of overmodulation. It is predictable that the $v_{s,ref}$ will surpase the voltage vector limits enclosed by a hexagonal boundary during large torque demand. Under this circumstances, the SVM has to be activated by modifying the $v_{s,ref}$ so that it will be positioned within the hexagonal boundary.

- *Improved Torque Capability via Flux Weakening and Overmodulation Strategy*

  In practice, a flux weakening strategy is developed to lengthen the motor speed beyond the base speed. This in turn will enhance the capability of torque. To achieve maximum torque capability in field weakening region, the optimal flux of the motor is estimated based on the maximum voltage and current of inverter. Basically, the algorithms require frame transformer, information of machine parameters and SVM. Moreover, a robust field weakening strategy is provided so that any variations of machine parameters used in calculating the optimal flux can be compensated [16-17]. The DTC must have the ability to operate in sixstep mode for the achievement of the fastest dynamic torque response and high torque capability in the flux weakening region.

1.4 Three-Phase versus Five-Phase Direct Torque Control

In three-phase DTC, it only has three switching states [S_a S_b S_c] that can compose eight space voltage vectors and are equally divided into six sectors. In comparison with the three-phase DTC, five-phase DTC has five switching states [S_a S_b S_c S_d S_e] which consists of 32 space voltage vectors in which it is evenly divided into 10 sectors. A more precise control of stator flux and electromagnetic torque can be achieved because this system provides greater flexibility in selecting the inverter switching states [18-20]. Due to the high phase number of drives, a fast torque response with low ripple in the stator flux and torque can be attained. An application of zero voltage vectors and those voltage vectors with the smaller amplitudes are applied to minimize the ripple in the stator flux and torque and thus, obtaining a better control schemes for DTC with 32 space voltage vectors [18].

Besides that, high phase number of drives possesses several advantages over conventional three-phase drives. The advantages are the torque pulsations have reduced amplitude and increased frequency, rotor harmonic currents are reduced, current per phase are reduced without enlarging the voltage per phase, DC link current harmonics are lowered as well as higher reliability [18-19, 21-25]. For the same volume machine, the torque per rms is increased by increasing the number of phases [18-19, 21, 26-27]. Therefore, the performance of DTC control system can be influenced by the number of space voltage vectors and switching frequency.