IMPLEMENTATION OF DIRECT TORQUE CONTROL OF INDUCTION MACHINES UTILIZING DIGITAL SIGNAL PROCESSOR (DSP) AND FIELD PROGRAMMABLE GATE ARRAYS (FPGA)

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Special dedicated to my beloved Daddy, Mummy, Chuen Hauw & Chuen Jie

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ABSTRACT

This thesis presents the implementation of a high performance Direct Torque Control (DTC) of induction machine (IM) drives. A summary of the theoretical aspects and principles of DTC are given with emphasis on two major problems, i.e. high torque ripple and variable switching frequency. In order to solve these problems, this thesis proposed a pair of torque and flux controllers to replace the hysteresis-based controllers. The proposed torque controller consists of a PI controller, 2 triangular carrier generators and a pair of comparator. It produces three level output, namely –1, 0, and 1, which is similar to the three level hysteresis comparator. The proposed flux controller works similar to the torque controller and consists of a proportional controller, a single triangular carrier generator and a comparator. The output is switched between 1 and 0 similar to the two-level hysteresis comparator. The design of these controllers is thoroughly discussed and is applied to a ¼ HP squirrel cage IM. The simulation of the proposed controllers applied to the DTC drive is presented. The simulation results are then verified by experimental results. The main components of the hardware are implemented using DSP TMS320C31 and Altera FPGA devices. The DSP is used to estimate the torque and flux while the FPGA is responsible in generating the triangular carriers, selecting the appropriate voltage vectors and generating the blanking time for the 3-phase VSI. The results prove that 80% of torque ripple reduction is obtained while the stator flux ripples also manage to achieve 57% of reduction. Furthermore, the switching frequency is fixed at 10.4 kHz and a smoother sinusoidal phase current is obtained.

ABSTRAK

Tesis ini membentangkan kaedah pelaksanaan pemacu Kawalan Daya Kilas Terus (DTC) untuk mesin aruhan. Ringkasan teori-teori dan prinsip DTC telah diberi dengan penumpuan diberi terhadap dua masalah utama iaitu riak daya kilas yang besar dan frekuensi pensuisan yang berubah. Untuk menyelesaikan masalah-masalah ini, tesis ini memperkenalkan pengawal-pengawal dayakilas dan fluks stator untuk menggantikan pengawal histeresis. Pengawal dayakilas mengandungi sebuah pengawal kamiran berkadaran, dua buah penjana pembawa segitiga dan sepasang pembanding. Pengawal dayakilas ini menghasilkan tiga tahap pengeluaran, iaitu –1, 0 dan 1, sama seperti yang dihasilkan oleh pembanding histeresis tiga tahap. Pengawal fluks stator yang dicadangkan beroperasi sama dengan pengawal dayakilas, ia mengandungi sebuah pengawal berkadaran dan sebuah penjana pembawa segitiga dan sebuah pembanding. Keluaran pengawal ini hanya akan bertukar di antara 1 dan 0 seperti yang dihasilkan oleh pembanding histeresis dua tahap. Rekabentuk pengawal-pengawal tersebut dibincang dengan terperinci dan telah digunapakai ke atas sebuah motor aruhan sangkar tertupai yang berkadar ¼ kuasa kuda. Simulasi untuk pengawal dayakilas yang digunakan pada pemacu DTC telah dibentangkan. Keputusan-keputusan simulasi telah disahkan dengan keputusan-keputusan ujikaji. Perlaksanaan peralatan dibina dengan menggunakan DSP TMS320C31 dan Altera FPGA. DSP digunakan untuk menganggar nilai-nilai dayakilas dan fluks sementara FPGA bertanggungjawab untuk menjana pembawa segitiga, memilih vektor voltan yang sesuai serta menjana masa mati bagi penyongsang 3 fasa. Keputusan-keputusan yang diperolehi telah mengesahkan bahawa pengurangan riak dayakilas sebanyak 80% telah dicapai dan riak fluks stator juga dikurangkan sebanyak 57%. Di samping itu, frekuensi pensuisan telah ditetapkan pada 10.4 kHz dan arus fasa sinus yang lebih baik diperolehi.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADC	-	Analog to Digital Converters
C	-	Triangular carrier for flux loop
C_{upper}	-	Upper triangular carrier for torque loop
C_{lower}	-	Lower triangular carrier for torque loop
$C_{p\text{-}p}$	-	Peak to peak value of the triangular carrier
CPLD	-	Complex Programmable Logic Device
d	-	Continuous duty ratio
DAC	-	Digital to Analog Converter
DSP	-	Digital Signal Processor
DTC	-	Direct Torque Control
F_c	-	Compensated stator flux
f_{t_tri}	-	Frequency of C_{upper} or C_{lower}
f_{f_tri}	-	Frequency of C
FOC	-	Field Oriented Control
FPGA	-	Field Programmable Gate Array
HP	-	Horse Power
IE	-	Incremental Encoder
IM	-	Induction Machine
I/O	-	Input/Output
$\bar{i}_s^g, \bar{i}_r^g$	-	Stator and rotor current space vectors in general reference frame
$\bar{i}_s, \bar{i}_r$	-	Stator and rotor current space vectors in stationary reference frame
i_{ds}, i_{qs}	-	d and q components of the stator current in stationary reference frame
i_{dr}, i_{qr}	-	d and q components of the rotor current in stationary reference frame

J	-	Moment of inertia
K_{ti}	-	Integral gain of the PI controller
K_{tp}	-	Proportional gain of the PI controller
K_{ψ}	-	Proportional gain of the Proportional controller
L_m	-	Mutual inductance
L_s, L_r	-	Stator and Rotor self-inductance
L_{ls}, L_{lr}	-	Stator amd Rotor leakage-inductance
LSB	-	Least Significant Bit
MSB	-	Most Significant Bit
mmf	-	magneto-motive force
p	-	No. of poles
P	-	Proportional
PC	-	Personal Computer
PI	-	Proportional – Integral
p.p.r.	-	Pulse per revolution
PWM	-	Pulse Width Modulation
q_t(t)	-	Torque error status
q_f(t)	-	Flux error status
R_s , R_r	-	Stator and rotor resistance
r.m.s.	-	Root mean squared
rpm	-	Revolutions per minute
RQFP	-	Power quad flat pack
ROM	-	Read Only Memories
S_a, S_b, S_c	-	Switching states of phase *a, b, c*.
SVM	-	Space Vector Modulation
T_c	-	Compensated torque
T_e	-	Electromagnetic torque
T_{error}	-	Torque error
T_{ref}	-	Torque reference
T_{load}	-	Load torque
THD	-	Total Harmonic Distortion
T_{DSP}	-	DSP's sampling time
T_s	-	Sampling time
T_{t_tri}	-	Period of C_{upper} or C_{lower}

T_{f_tri}	-	Period of C
VHDL	-	Very high-speed integrated circuits, Hardware Description Language
v_a, v_b, v_c	-	line to neutral voltage of phase *a, b, c.*
V_{dc}	-	DC link voltage
$\overline{v}_s^g, \overline{v}_r^g$	-	Stator and rotor voltage space vector in general reference frame
$\overline{v}_s, \overline{v}_r$	-	Stator and rotor voltage space vector in stationary reference frame
v_{ds}, v_{qs}	-	*d* and *q* components of the stator voltage in stationary reference frame
v_{dr}, v_{qr}	-	*d* and *q* components of the rotor voltage in stationary reference frame
$v_s^{\psi_s}$	-	The stator voltage in stator flux rotating reference frame
VSI	-	Voltage Source Inverter
θ_f	-	Angle of each sector in the stator flux plane
θ_r	-	Rotor angle
ω_{cutoff}	-	Cut off frequency in rad/s
ω_e	-	Steady state synchronous frequency in rad/s
ω_m	-	Rotor mechanical speed in rad/s
ω_r	-	Rotor electrical speed in rad/s
ω_{slip}	-	Steady state slip frequency in rad/s
ω_{ψ_s}	-	Instantaneous stator flux frequency in rad/s
$\overline{\psi}_s^g, \overline{\psi}_r^g$	-	Stator and rotor flux linkage space vectors in general reference frame
$\overline{\psi}_s, \overline{\psi}_r$	-	Stator and rotor flux linkage space vectors in stationary reference frame
ψ_{ds}, ψ_{qs}	-	*d* and *q* components of the stator flux in stationary reference frame
ψ_{dr}, ψ_{qr}	-	*d* and *q* components of the rotor flux in stationary reference frame
ψ_{ref}	-	Stator flux reference
σ	-	Total flux leakage factor
τ_r	-	Rotor time constant

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CHAPTER 1

INTRODUCTION

1.1 A Look Back On Electrical Machine Drives

DC machines were used extensively in variable speed drive over the past decades mainly because of the decoupled control of flux and torque that could be achieved by the field and armature current control respectively. They are mostly used in variable speed applications to give a fast and good dynamic torque response because the commutator maintains a fixed (and nearly ideal) torque angle at all times. However, DC machines have two major weaknesses, the mechanical commutator and brush assembly. These make periodical maintenance a must and limit the use of DC machines in explosive environment.

Induction machines have several advantages over DC machines. They are robust, require less maintenance, cheaper, and operate at higher speed. Basically, induction machines control methods can be classified into scalar and vector control. In scalar control, only magnitude and frequency of voltage, current, and flux linkage space vectors are controlled. Where as, in vector control, the instantaneous positions as well as the magnitude and frequency of voltage, current, and flux linkage space vectors are controlled. A chart showing the hierarchy of variable frequency control of induction machine is given in Figure 1.1. Constant volt per hertz is a well-known scalar control method while Field Oriented Control (FOC) and Direct Torque Control (DTC) are the two most popular vector control methods.

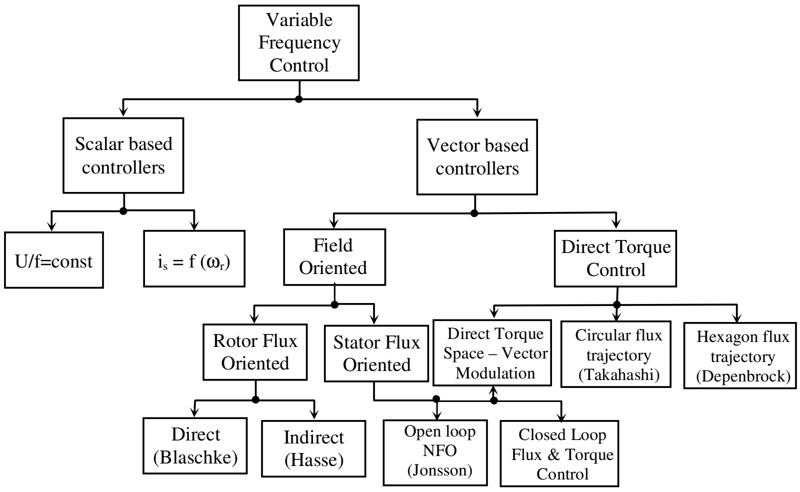

Figure 1.1 : Classification of induction machines control methods

The invention of Field-Oriented Control (FOC) in early 1970 by F.Blaschke enables rugged induction machines to be controlled similar to that of DC machines [1]. The advent of fast microprocessors and DSPs make the vector control popular in the 1980's. It is believed that the AC machines are supplanting the DC machines in the near future [2].

FOC provides similar decoupled control of torque and flux, which is inherently possible in the DC machines. The motor input currents are adjusted to set a specific angle between fluxes produced in the rotor and stator windings. The rotor flux position angle with respect to the stator must be known in this control method. Once the flux angle is known, an algorithm performs the transformation by changing three-phase stator currents into the orthogonal torque and flux producing components [2]. These components are controlled in their d-q axis and an inverse transformation is used to determine the necessary three-phase currents or voltages.

Although the FOC enables an induction machine to attain fast torque response, some problems still exist. An accurate flux estimator had to be employed to ensure the estimated value used in calculation does not deviate from the actual value. Besides, the coordinate transformation had increased the complexity of this control method. In [3], it is highlighted that the inverter switching frequency, torque ripple, and harmonic losses of the machine increase in the steady-state operation if the hysteresis-based current-controlled inverter is used.

1.2 Direct Torque Control (DTC)

Direct Torque Control was first introduced by Takahashi in 1986. The principle is based on limit cycle control and it enables both quick torque response and efficiency operation [3]. DTC control the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [4]. It has many advantages compare to FOC, such as less machine parameter dependence, simpler implementation and quicker dynamic torque response [5]. It only needs to know the stator resistance and terminal quantities (v and i) in order to perform the stator flux and torque estimations. The configuration of DTC is simpler than the FOC system due to the absence of frame transformer, current controlled inverter and position encoder, which introduces delays and requires mechanical transducer [6]. In [3], Takahashi had proved the feasibility of DTC compared to FOC.

In 1996, ABB has introduced the first industrial, speed-sensorless DTC induction motor drive. This simple control scheme has gained popularity and it is believed that they will soon replace the vector control drives commonly found in industry applications [7].

1.2.1 The Conventional DTC

The basic configuration of the conventional DTC drive proposed by Takahashi is as shown in Figure 1.2. It consists of a pair of hysteresis comparator, torque and flux estimators, voltage vector selector and a Voltage Source Inverter (VSI) [3].

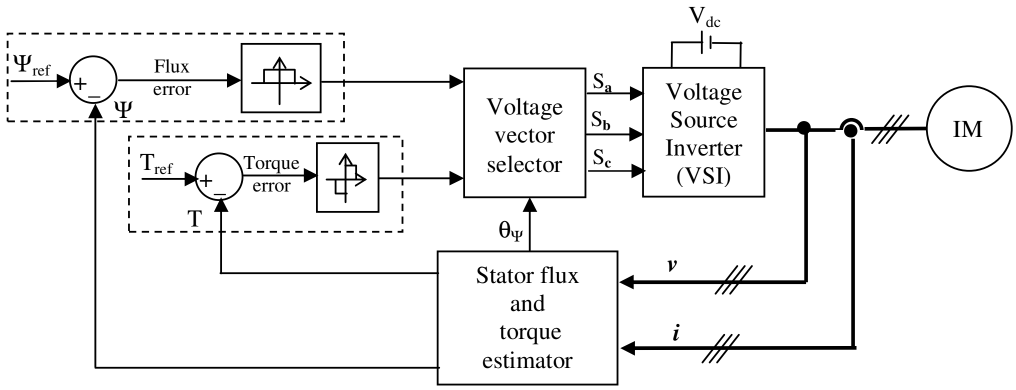

Figure 1.2 : Conventional DTC drive configuration

DTC performs separate control of the stator flux and torque, which is also known as decouple control. The core of this control method is to minimize the torque and flux errors to zero by using a pair of hysteresis comparators. The hysteresis comparators lie at the heart of DTC scheme not only to determine the appropriate voltage vector selection but also the period of the voltage vector selected. The performance of the system is directly dependent on the estimation of stator flux and torque. Inaccurate estimations will result in an incorrect voltage vector selection.

The basic method for estimating the stator flux is by using the stator voltage model. This model does not require rotor speed and only need a single machine parameter, i.e. the stator resistance. However, noise in voltage measurement and integration drift can pose significant problems at low speed [8]. Another method for estimating the stator flux is named current model. It solves the low speed problem but it needs to monitor the rotor speed. In other words, it requires additional speed sensor or observer. In [3], a combination of these 2 models had been proposed by using a simple lag network.

1.2.2 The Evolution Of DTC

Although DTC is gaining its popularity, there are some drawbacks, which need to be rectified. Variable switching frequency and high torque and flux ripples are the two major problems, which draw full attention of most researchers. To overcome these problems, extensive research and development had been carried out.

In order to maintain the flux and torque error within the fixed hysteresis bands, the switching frequency becomes unpredictable. It is highlighted in [9] and [10] that the switching frequency varies with the operating speed, load condition and parameters of the induction machine. Hence, in order to ensure that the switching frequency does not exceed the limit, we have to calculate the extreme cases corresponding to the maximum switching frequency. Nevertheless the drive does not operate at these extreme cases in most of the time; therefore the maximum switching frequency capability is not fully utilized.

In order to overcome this problem, a number of methods had been proposed in the literature. Basically these can be divided into hysteresis based and non-hysteresis based solutions. In [11] variable hysteresis band comparators had been designed where the band can be adjusted to maintain constant switching frequency. For non-hysteresis based solutions, a few techniques have been proposed, including the use of space vector modulation, predictive control schemes and intelligent control techniques, which had been published in [12-17].

Another problem normally associated with DTC drive is the high torque ripple. Ideally, small torque hysteresis band will produce small torque ripple. However, for microprocessor-based implementation, if the hysteresis band is too small, the possibility for the torque to touch the upper band is increased. As a result, the possibility of selecting a reversed voltage vector instead of zero voltage vector will also increase. Incorrect voltage vector selection will result in high torque ripple. In [19], it is proved that by reducing the sampling time, the torque ripple can be reduced significantly. In addition, there are numerous techniques proposed to reduce the torque ripple such as dithering technique [20], fuzzy logic control [15], [16] and SVM [12]. A more details discussion is given in Chapter 2 on fixed switching frequency and torque ripple reduction.

1.3 Thesis Objective and Contributions

The objective of this thesis is to study, implement and improve the performance of the DTC of induction machines. The thesis proposes a simple method for torque and stator flux ripple reduction. Meanwhile, the constant switching frequency is increased to 10kHz. The simple control structure of the DTC drive is preserved. The contributions of this thesis are as follow:

- It proposes a torque controller, which had further minimized the torque ripple (80% of ripple reduction had been achieved compare to the hysteresis-based torque controller) and maintained a constant switching frequency at around 10 kHz.

- It introduces a simple flux controller to replace the two-level hysteresis comparator, which results in an almost circular stator flux locus with small ripple (achieve 57% of ripple reduction compare to the hysteresis-based flux controller).

- It reduces the Total Harmonic Distortion (THD) of the phase current since a more sinusoidal current wave is achieved by implementing the proposed flux controller.

- It performs simulations to verify and analyze the performance of the proposed torque and flux controllers using MATLAB/SIMULINK simulation package.

- It develops an experimental set-up to verify the proposed DTC drive. A combination of TMS320C31 DSP and FPGA device reduces the execution time.

However there are some constraints in this research:

- The feasibility of the proposed controllers is evaluated only in low speed region and low voltage due to laboratory equipment limitations.

- Equipment in laboratory is limited. The power supply can only support up to 120 V.

- The speed of the TMS320C31 DSP is limited to 60MHz.

- The duration and funding of this research are limited.

1.4 Methodology of Research

A simulation on the conventional DTC drive is performed for better understanding by using MATLAB/SIMULINK. With the understanding and knowledge of the conventional DTC, a new torque and flux controllers are proposed. The proposed controllers are then simulated to study on their effectiveness. Based on the simulation results, proper planning and prototype design are made.

Once the satisfactory simulation results are obtained, the hardware prototype are built and implemented. Hardware implementation is used to verify the feasibility of the proposed drive. It consists of three main components, a digital signal processor board DS1102 from dSPACE (TM320C31 at 60MHz), an Altera University Program (UP) Educational Board and the power circuit. The DSP is responsible for estimating the torque and stator flux. The proposed controllers are implemented using FPGA with Very high-speed integrated circuits, Hardware Description Language (VHDL). The power circuit consists of a 3-phase Voltage Source Inverter (VSI) connected to a ¼ HP induction machine. A friction load is coupled to the induction machine as a mechanical load.

Several tests are performed on the prototype of the DTC drive. Trouble-shoot, modifications, debug and improvements are carried out on the prototype until satisfactory tests results are obtained.

1.5 Thesis Organizations

A brief review of the contents of this thesis is given as follows:

Chapter 2 presents the principle of DTC and modeling of induction machines in space vector form. Problems associated with DTC such as stator flux estimation, fixed switching frequency techniques and torque ripple reduction are also discussed.

Chapter 3 proposes new flux and torque controllers, which reduce torque and flux ripples and produce constant switching frequency at around 10 kHz. The principles and design of the new controllers are discussed and implemented to a small induction machine.

Chapter 4 evaluates the performance of the proposed controllers via simulation using MATLAB/SIMULINK simulation package. The descriptions on modeling of the proposed DTC drive using SIMULINK block are given.

Chapter 5 describes the experiment set-up in this research. Detailed information of each hardware components is given.

Chapter 6 gives all the simulation results, experimental results and discussions.

Lastly, **Chapter 7** gives the conclusions of the thesis and possible directions of further research.

LIST OF PUBLICATIONS

Some of the published and accepted technical papers:

1. C. L. Toh, N. R. N. Idris and A. H. M. Yatim, N. D. Muhamad, M. Elbuluk, (2005) "Implementation of a new torque and flux controllers for Direct Torque Control (DTC) of induction machines utilizing Digital Signal Processor (DSP) and Field Programmable Gate Arrays (FPGA)", The 36th IEEE Power Electronics Specialist Conference, PESC05, Recife, Brazil.

2. C. L. Toh, N. R. N. Idris, A. H. M. Yatim, and M. Elbuluk, (2005) "A New Torque and Flux Controllers for Direct Torque Control of Induction Machines", IEEE Industry Application Society, 40th Annual Meeting, IAS 2005, Hong Kong.

3. C. L. Toh, N. R. N. Idris and A. H. M. Yatim, (2003) "New torque and flux controllers for Direct Torque Control of induction machines", The 5th International Conference on Power Electronics and Drive Systems 2003 (PEDS 2003), Singapore, Vol. 1, pp. 216-221.

4. C. L. Toh, N. R. N. Idris and A. H. M. Yatim, (2003) "Torque ripple reduction in Direct Torque Control of induction motor drives", National Power and Energy Conference (PECon) 2003, Bangi, Malaysia.

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