DIRECT TORQUE CONTROL OF INDUCTION MACHINES UTILIZING MULTILEVEL INVERTER AND ARTIFICIAL INTELLIGENT

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Special dedicated to my beloved father, mother & family

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ABSTRACT

This thesis presents 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 direct torque control of induction machines utilizing multilevel inverter and artificial intelligent. It proposes to use three, five and seven level cascaded and diode clamped inverter topology which results in further torque ripple minimization compare to the two level inverter-based conventional DTC. It also proposed a new Fuzzy DTC using Sugeno as the inference method to replace the hysteresis comparators in the conventional DTC, which results in reducing the flux ripples significantly as well as reducing the Total Harmonic Distortion (THD) of the phase current since a more sinusoidal current wave is achieved by solving the problem of variable switching frequency. The simulation of the multilevel inverter topology-based Conventional and Fuzzy DTC is presented. The simulation results prove that torque ripple reduction is obtained while the stator flux ripples also manage to achieve reduction. Furthermore, the switching frequency is fixed and a smoother sinusoidal phase current is obtained.

ABSTRAK

Tesis ini menyampaikan kaedah pelaksanaan pemacu Kawalan Daya Kilas Terus (DTC) dari mesin aruhan . Ringkasan tentang teori dan prinsip-prinsip DTC telah diberikan penekanan pada dua masalah utama, iaitu riak daya kilas yang besar dan frekuensi pensuisan yang berubah. Tesis ini telah memperkenalkan DTC dari mesin aruhan dengan menggunakan inverter yang mempunyai multi-tahap dan teknik (artificial intelligent). Ia menggunakan tiga, lima dan tujuh tahap inverter yang disambungkan secara bersiri dan (topologi inverter yang dijepit oleh diod). Ini akan mengurangkan riak tork yang selebihnya berbanding dengan inverter dua tahap yang berasakan konvensional konsep. Ia juga memperkenalkan Fuzzy DTC yang baru dengan menggunakan Sugeno sebagai kaedah inferensi untuk menggantikan pembanding histerisis bagi konvensional DTC. Ini akan mengurangkan riak flux secara berkesan, ia juga mengurangkan THD bagi arus fasa, kerana gelombang arus sinus dapat dicapai dengan mengatasi masalah frekuensi pensuisan yang berubah. (Simulasi) bagi inverter multi-tahap yang berasakan konvensional konsep dan Fuzzy DTC akan dipersembahkan. Keputusan simulasi telah mengesahkan bahawa pengurangan riak tork telah diperolehi dan riak fluks stator juga dapat dikurangkan. Di samping itu, frekuensi pensuisan telah ditetapkan dan fasa arus sinus yang lebih baik dapat diperolehi.

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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
L_m	---	Mutual inductance
L_s, L_r	---	Stator and Rotor self-inductance
Mmf	---	magneto-motive force
P	---	No. of poles
R_s, R_r	----	Stator and rotor resistance
r.m.s.	---	Root mean squared
Rpm	---	Revolutions per minute
S_a, S_b, S_c	----	Switching states of phase *a, b, c.*
SVM	---	Space Vector Modulation
T_e	----	Electromagnetic torque

Terror	--	Torque error
THD	--	Total Harmonic Distortion
V_a, Vb, V_c	---	line to neutral voltage of phase *a, b, c.*
Vdc	--	DC link voltage
VSI	--	Voltage Source Inverter

CHAPTER 1

INTRODUCTION

1.1 A Look Back On Electrical Machine Drives

DC machines have been 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. Whereas, 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.

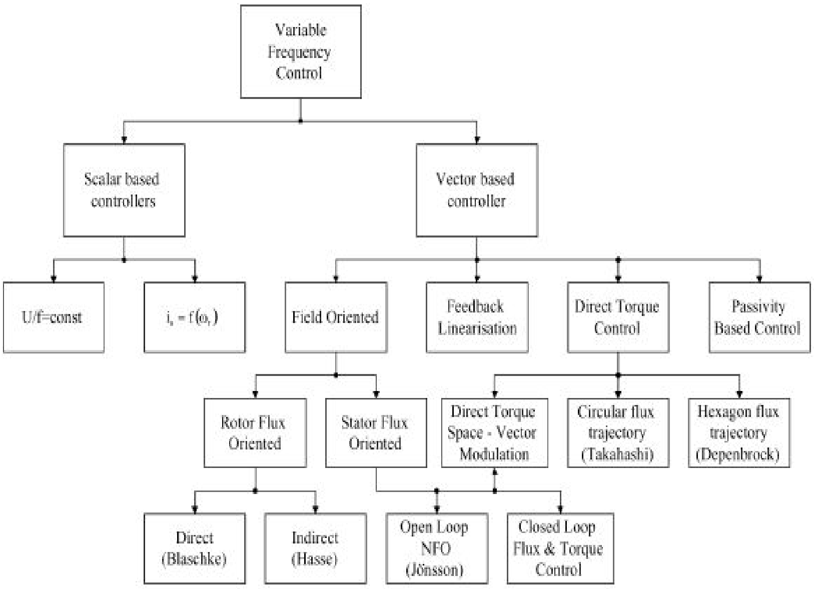

Figure 1.1: Classification of induction machines control methods

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 has to be employed to ensure the estimated value used in calculation does not deviate from the actual value. Besides, the coordinate transformation has 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 controls the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [4]. It has many advantages compared 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 has 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].

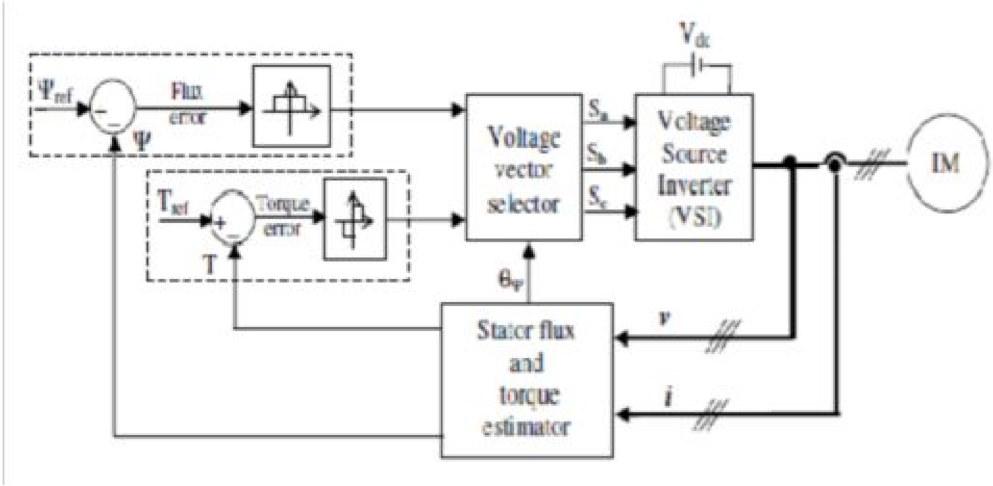

Figure 1.2: Conventional DTC drive configuration

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 has 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 have 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 has 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 detail 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 and improve the performance of the DTC of induction machines. The thesis proposes multilevel inverter topology-based DTC for torque and stator flux ripple reduction. Meanwhile, artificial intelligent in selecting voltage vectors of the multilevel inverter applied in DTC of induction machine is considered. The simple control structure of the DTC drive is preserved. The contributions of this thesis are as follow:

It proposes to use three, five and seven level cascaded and diode clamped inverter topology which results in further torque ripple minimization compare to the two level inverter-based conventional DTC.

It introduces a new Fuzzy DTC using Sugeno as the inference method to replace the hysteresis comparators in the conventional DTC, which results in reducing the flux ripples significantly as well as reducing the Total Harmonic Distortion (THD) of the phase current since a more sinusoidal current wave is achieved by solving the problem of variable switching frequency.

It performs simulations to verify and analyze the performance of the multilevel inverter topology-based Conventional and Fuzzy DTC using MATLAB/SIMULINK simulation package.

1.4 Methodology of Research

A simulation on the two level inverter-based conventional DTC drive is performed for better understanding by using MATLAB/SIMULINK. With the understanding and knowledge of the 2-level inverter based conventional DTC, multilevel inverter-based conventional DTC is proposed and then simulated to study on their effectiveness. Finally, fuzzy DTC is introduced to solve the problem of variable switching frequency by replacing the hysteresis comparators. The simulation on fuzzy DTC shows significant reduction in flux ripples and a sinusoidal phase current is provided meaning that the THD of the phase current is reduced.

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 presents the principles of multilevel inverter-based conventional and fuzzy DTC via simulation using MATLAB/SIMULINK simulation package. The descriptions on modeling of the conventional and fuzzy DTC drive using SIMULINK block are given.

Chapter 4 gives all the simulation results and discussions.

Lastly, **Chapter 5** gives the conclusions of the thesis and possible directions of further research.