OVERMODULATION AND FIELD WEAKENING IN DIRECT TORQUE CONTROL OF INDUCTION MOTOR DRIVES

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ABSTRACT

During transient conditions, for instance during acceleration and deceleration, the inverter used in an induction motor drive normally operates in overmodulation in order to efficiently utilize the DC-link voltage. Beyond the based-speed, the flux is normally reduced proportionally with speed to extend the speed range of the drive system. The capability of the induction motor drive under overmodulation and field weakening modes are important, especially in electric vehicle applications, where the available power is limited and the speed range needs to be increased to avoid use of the mechanical gear. In order to fully utilize the dc link voltage, it is important to understand the characteristics and performance of the drive system under these conditions. The project will perform a simulation study on the performance of direct torque control (DTC) induction motor drive under overmodulation and field weakening conditions. In this project the study on overmodulation and field weakening modes will be concentrated mainly on constant frequency torque controller-based DTC drive. The potential of the constant frequency torque controller in overmodulation and field weakening regions will be analyzed through simulation using Matlab/Simulink package. The results obtained from the simulation is evaluated.

ABSTRAK

Semasa keadaan fana, misalnya semasa dalam keadaan memecut dan nyah-pecutan, elemen penyongsang yang digunakan di dalam kawalan motor aruhan biasanya beroperasi dalam keadaan pemodulatan lebih bagi memastikan penggunaan voltan rangkai arus terus (a.t.) adalah efisien. Fluks juga biasanya akan berkurangan secara berkadaran terhadap halaju apabila motor beroperasi melebihi halaju dasar. Dari itu, keupayaan kawalan motor aruhan beropearsi di bawah pemodulatan lebih dan penyusutan medan adalah penting terutamanya untuk aplikasi kenderaan berkuasa elektrik. Ini adalah disebabkan kuasa yang dibekalkan kepadanya adalah terhad dan pada masa yang sama halaju kenderaan perlu ditambah dengan segera bagi mengelakkan penggunaan gear mekanikal. Bagi memastikan penggunaan voltan rangkai arus terus yang optimum, ciri-ciri dan prestasi sistem pemacuan semasa dalam keadaan tersebut perlulah difahami terlebih dahulu. Oleh itu, malalui projek ini, kajian simulasi terhadap prestasi sistem kawalan dayakilas (DTC) secara terus bagi motor aruhan di dalam keadaan pemodulatan lebih dan penyusutan medan akan dilakukan. Kajian yang dilakukan adalah tertumpu kepada pengawal dayakilas berfrekuensi tetap yang digunakan pada sistem kawalan dayakilas secara terus. Kebolehan pengawal dayakilas berfrekuensi tetap beroperasi dalam keadaan modulasi lebih dan susutan medan akan dianalisa mengunakan simulasi perisian Matlab/Simulink. Kemudian, keputusan yang diperolehi daripada simulasi dinilaikan.

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LIST OF SYMBOLS

a - Complex spatial operator $(e^{j2\pi/3})$

$C_{p\text{-}p}$ - Peak-to-peak of carrier signal

$\overline{i_r}$ - Space phasor of rotor current expressed in rotor reference frame

$\overline{i_r}'$ - Space phasor of rotor current expressed in stationary reference frame

$\bar{i}'_{rd}$ - d-axis rotor current expressed in stationary reference frame

$\bar{i}'_{rq}$ - q-axis rotor current expressed in stationary reference frame

$\overline{i_s}$ - Space phasor of stator current expressed in stationary reference frame

$\overline{i_s}'$ - Space phasor of stator current expressed in rotor reference frame

i_{ra}, i_{rb}, i_{rc} - Instantaneous values of rotor current in rotor phases

i_{rd}, i_{rq} - Instantaneous values of direct and quadrature-axis rotor current components in stator reference frame

$i_{r\alpha}, i_{r\beta}$ - Instantaneous values of direct and quadrature-axis rotor current components in rotor reference frame

i_{sA}, i_{sB}, i_{sC} - Instantaneous values of stator current in stator phases

i_{sD}, i_{sQ} - Instantaneous values of direct and quadrature-axis stator current components

$\overline{i}_r^{\,g}$ - Space phasor of rotor current expressed in general reference frame

$\overline{i}_s^{\,g}$ - Space phasor of stator current expressed in general reference frame

J - Moment of inertia

K_i - Integral gain of PI controller

K_p - Proportional gain of PI controller

L_m - Mutual self inductance

L_r - Rotor self inductance

L_s - Stator self inductance

$\overline{M}_r$ - Mutual inductance between rotor phases

$\overline{M}_s$ - Mutual inductance between stator phases

$\overline{M}_{sr}$ - Maximal value of the stator-rotor mutual inductance

$P = \frac{d}{dt}$ - Differential operator

P - Number of pole-pairs

P_e - Electrical power

P_{mech} - Mechanical power

R_r - Rotor resistance

R_s - Stator resistance

$\mathrm{T_c}$ - Compensated torque error signal

T_e - Electromagnetic torque

$\mathrm{T_{tri}}$ - Period of triangular carrier waveform

V_{dc} - DC-link voltage

$\overline{v}_r$ - Rotor voltage space phasor expressed in rotor reference frame

v_{ra}, v_{rb}, v_{rc} - Instantaneous values of rotor voltage for every phases

$\overline{v}_s$ - Stator voltage space phasor expressed in stator reference frame

v_{sA}, v_{sB}, v_{sC} - Instantaneous values of stator voltage for every phases

$\overline{v}_{sD}, \overline{v}_{sQ}$ - Instantaneous values of direct and quadrature-axis stator voltage components in stationary reference frame

σ - Leakage factor

θ_r - Rotor angle

θ_s - Stator angle

τ_r - Rotor time constant

τ_s - Stator time constant

$\overline{\psi}_r$ - Space phasor of rotor flux expressed in rotor reference frame

$\overline{\psi}'_r$ - Space phasor of rotor flux linkage expressed in stator reference frame

$\psi_{ra}, \psi_{rb}, \psi_{rc}$ - Instantaneous values of flux linkage in rotor phases

$\overline{\psi}_s$ - Space phasor of stator flux expressed in stator reference frame

$\overline{\psi}'_s$ - Space phasor of stator flux expressed in rotor reference frame

$\overline{\psi}_{sD}, \overline{\psi}_{sQ}$ - Instantaneous values of direct and quadrature-axis stator flux linkage component in stationary reference frame

$\psi_{sA}, \psi_{sB}, \psi_{sC}$ - Instantaneous values of flux linkage in stator phases

ψ^+ - Flux error status

ψ^- - Modified flux error status

Δt - Change in time

ω_r - Rotor speed

ω_{slip} - Slip frequency

LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DSC	Direct Self-Control
DTC	Direct Torque Control
DTC-SVM	Direct Torque Control Space Vector Modulation
FOC	Field Oriented Control
IM	Induction Motor/Machine
PI	Proportional Integral
PWM	Pulsewidth Modulation
VSI	Voltage Source Inverter

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CHAPTER 1

INTRODUCTION

1.1 Overview

The induction motors (IM) are so common and widely use in industry rather than the other type of electric machine. This is due to their simplicity in construction and excellent scheme of electromechanical energy conversion. The rotor is inaccessible especially in the squirrel cage motors. There is no moving contact, such as commutator and brushes as in dc machine or slip rings and brushes in ac synchronous motors. These arrangements greatly increase the reliability of induction motors, less maintenance and eliminate the danger of sparking and corrosion. Therefore, the motors are safely used in explosive environment.

An additional degree of ruggedness, the induction motors is provided by less wiring in the rotor, where the winding consist of uninsulated metal bars. It is also light in weight and has low inertia. A robust rotor has the capability to run at high speed and withstand heavy mechanical and electrical overload. Typically, the induction motors have a significant torque reserve and low dependence of speed on the load torque.

Although the induction motor is superior to the d.c. motor with respect to the advantages as described above, due to its highly non-linear dynamic structure with strong dynamic interactions, it is necessary for complex control schemes compared to the d.c. motor. However, with the gain in power electronics technology, the complex control technique becomes easy and reduces the uses of expensive hardware because of powerful semiconductor devices are available.

The induction motor control can be divided into two schemes; the scalar control and vector control. In general, the genealogy of the variable frequency control methods is illustrated in Figure 1.1. In the scalar control, it is only valid on the steady state operations where only magnitude and frequency of voltage, current and flux linkage space vector are controlled. Whereas uses of vector control, it is possible to control in steady state and during transient operations. According to Figure 1.1, there are many techniques can be implemented under vector control scheme. The most popular technique is called field-oriented control (FOC) that has been proposed over 30 years ago by Blaschke as discussed in [1]. Then, in the middle of 1980's, a new technique for the torque control of induction motors was proposed and presented by I. Takahashi and T. Noguchi which is known as direct torque control (DTC) [2] and by M. Depenbrock named as direct-self control (DSC) [3],[4] also categorized under DTC drives. These techniques are simpler, more robust, gives better performance, and possible to obtain good dynamic response of torque compared to the FOC scheme.

Since DTC was introduced, many researchers working on this area in order to overcome the drawbacks have been encountered. Most of the contributions proposed have improved the performance of DTC drive, but they lead to more complex approaches and at the same time the simple structure of DTC drive is lost. One of the techniques proposed to improve the conventional DTC (hysteresis-based) is utilizing a constant frequency torque controller as presented in [5]-[8]. Utilizing this control technique, it is managed to overcome the drawbacks and at the time retain the basic structure of DTC drive as proposed by Takahashi and Noguchi. According to this advantage of the constant frequency torque controller implemented in DTC scheme, this project will gain the capability of the technique to be able to operate in overmodulation and field weakening regions. The operation of DTC drive under overmodulation and field weakening modes is extremely important especially in traction and electric vehicle implementation. The operation under both conditions is to ensure the dc-link voltage of the inverter use in DTC will be fully utilized. For that reason, this thesis will delve into the operation of constant frequency torque controller in DTC under the overmodulation and field weakening regions.

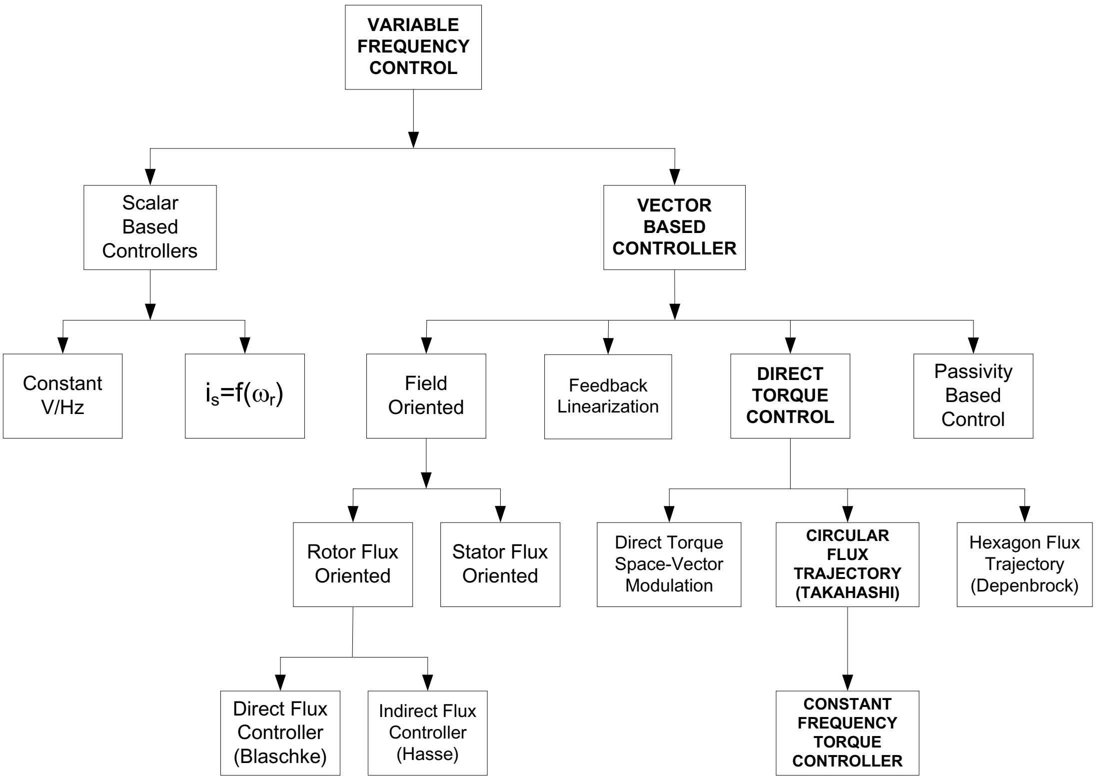

Figure 1.1: Genealogy of induction motor control techniques [9].

1.2 Objective of The Research Project

The main objective of this project is to study and analyse the potentials of the constant frequency torque controller implemented in the direct torque control (DTC) of induction motor drive under overmodulation and field weakening modes. The study will be carried out using Matlab/Simulink simulation package.

1.3 Scope of Project

The works undertaken in this project are limited to the following aspects:

1. Study the working principles of DTC motor drives utilizing constant frequency torque controller.
2. Proposing a new switching strategy to achieve overmodulation and field weakening operations of constant frequency torque controller-based.
3. Simulation work using Matlab/Simulink as a platform.

1.4 Research Methodology

The research work is undertaken in the following developmental stages:

1. Conceptual study on overmodulation and field weakening regions from the previous finding in various techniques of direct torque control space vector modulation (DTC-SVM) based.
2. Study the inverter switching sequences of DTC that utilize constant frequency torque controller.
3. Establish a control technique to determine an appropriate switching of voltage vectors.
4. Perform simulation using Matlab/Simulink.
5. Analyze and evaluate the results obtained from simulation.

1.5 Literature Review

The research on DTC has gained rapidly over the last decade to improve its performance. This is due to the hysteresis-based DTC drive proposed by Takahashi and Noguchi, which present some disadvantages. The major disadvantages are high current and torque ripples, variable switching frequency behavior, difficulty to control torque and flux in low speed and unable to operate in high speed applications. Some of the techniques developed to solve the problems encountered are based on the following contributions [10]:

a) Use of improved switching tables.
b) Introduce constant switching frequency operation with PWM or space vector modulation (SVM) techniques.
c) Use of fuzzy or neuro-fuzzy techniques.
d) Use of sophisticated flux estimators to improve the low speed behavior.

In addition, to gain the capability of DTC in high speed applications, some techniques have been proposed to be able to operate in overmodulation and field weakening regions. All the techniques proposed are based on DTC-SVM scheme [11]-[16]. Below are several researches on DTC scheme that have been done by researches.

I. Takahashi and T. Noguchi (1986) [2], developed a new technique for the torque control of induction motors which is called DTC scheme (hysteresis-based). The technique proposed departs from the idea of coordinates transformation and the analogy of dc motor control. In addition, there are no current control loops and no separate voltage pulsewidth modulator. These features are not for the FOC scheme. It was also characterized by simplicity, robustness and good performance. Using DTC scheme, it is possible to obtain a good dynamic control of the torque in steady state and transient operating condition without need for mechanical transducers on the motor shaft. The scheme uses torque and flux hysteresis comparators to restrict the torque and flux error respectively and fed the signal to the voltage vector selection table. The torque and flux are calculated from the primary variable, hence its can be controlled directly and independently.

Thomas G. Habetler et. al. (1992) [17], proposed a scheme to improve the performance of DTC drive based on the stator flux-field oriented method. In this scheme, a voltage reference in generated based upon the errors of torque and flux by estimation of back emf. The voltage reference is determined using quadratic equations and the voltage components in direct and quadrature-axis are calculated for every sampling period. The principle of space vector modulation PWM is used to compute the inverter switching states in order to realize the voltage reference that has been generated. The proposed scheme has managed to achieve constant switching frequency operation, however the simple DTC algorithm and good dynamic torque response as in conventional DTC scheme are lost. This is due to the increased of computational burden for complex calculation of reference voltage.

J. Holtz et. al. (1993) [12] proposed a technique using common pulsewidth modulation in the basis of space vectors PWM for the operation of DTC drive under overmodulation to six-step regions. In PWM technique, the performance of the modulation is characterized by the modulation index, m that is in the range of $0 \leq m \leq 1$. In this scheme the operation under overmodulation to six-step region can be achieved only if the modulation index can be increased beyond 0.907 up to 1 (unity). Two different modes have been proposed and known as overmodulation mode I and mode II. Thereby, a pre-processor is employed to regenerate a new reference voltage vector and finally the switching times are calculated for space vector modulation of the inverter.

G. Griva et. al. (1995) [13] have developed a simplified method of torque and flux control in the transient and field weakening region based on DTC scheme. The proposed method limits the magnitude of the stator voltage reference to the maximum instantaneous value allowable with space vector PWM. The magnitude of the voltage input to the space vector PWM is limited to the maximum inverter voltage when the resultant of voltage reference from the dead beat DTC algorithm is lies outside the hexagonal boundary. The simplified method was verified that is satisfactory in transient and overmodulation operation without need for additional computational burden on the circuitry has been used.

A. Tripathi, A. M. Khambadkone, and SK. Panda (2002) [16] proposed a simple switching strategy of the inverter to achieve good dynamic torque and predictive deadbeat stator flux control. This method allows for smooth transition in overmodulation and six-step operations. The error in flux is used to compute the on-times of the inverter switching states. In this scheme, the use of flux error based SVM mitigates the problem of current controller saturation encountered in conventional vector control. In addition, it achieves fast torque dynamic at constant switching frequency, which is difficult in the conventional of DTC scheme.

The performance of DTC drive under overmodulation and field weakening regions is still undergoing research and thus works are still being carried-out to improve the DTC scheme performance.

1.6 Layout of Thesis

This section outlines the structure of the thesis.

Chapter 2 deals with the mathematical model of a squirrel cage induction motor. The space phasors representations in various quantities of the motor are discussed utilizing the physical and mathematical considerations. The compact and simplified space phasor notation of the motor also introduced and will be used in the simulation.

Chapter 3 will discuss the principles of direct torque control (DTC) of induction motor drives in detail. The working principle, pros and cons of DTC are described within this chapter. Afterwards, the DTC of induction motor drive that utilizes a constant frequency torque controller and the design algorithm will be demonstrated too.

Chapter 4 touches about overmodulation and field weakening regions in DTC drives. Various techniques from the previous finding on overmodulation and field weakening modes that is focus on DTC-SVM will be discussed briefly at the beginning of this chapter. Subsequently, a new strategy for overmodulation and field weakening modes of DTC drives will be presented.

Chapter 5 discusses the simulation results. The performance of DTC in overmodulation and field weakening modes is evaluated by simulation study using Matlab/Simulink.

Chapter 6 concludes the topics and suggests recommendation for future works.

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