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PERFORMANCE ANALYSIS OF DIRECT TORQUE CONTROL OF INDUCTION MACHINES

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PERFORMANCE ANALYSIS OF DIRECT TORQUE CONTROL

OF INDUCTION MACHINES

RAJA NOR AZRIN BIN RAJA YUNUS

A thesis submitted

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DECLARATION

I declare that this thesis entitle "Performance Analysis of Direct Torque Control of Induction Machines" 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 candidate of any other degree.

Signature : ....

Name : RAJA NOR AZRIN BIN RAJA YUNUS

Date : 15 MEI 2014

APPROVAL

I hereby declare that I have read this dissertation and in my opinion this dissertation is sufficient in terms of scope and quality as a partial fulfillment of Master of Electrical Engineering (Industrial Power).

Signature : ....

Supervisor Name : DR AUZANI BIN JIDIN

Date : 02/12/2014..

DEDICATION

A special dedication to my beloved wife, Mrs. Nurul Asmaa' Binti Ismail, My beloved mother Mrs. Siti Asah Binti Awang, My Beloved father Mr. Raja Yunus Bin Raja Musa, My beloved son Raja Amjad Ajwad Bin Raja Nor Azrin.

For taking care of me and educating me all these while. Also thank for their continuous prayers until I became what I'm now.

Also for my supervisor

Dr. Auzani Bin Jidin

Thank you very much

May God bless all of us.....Amin

ABSTRACT

This thesis presents the analysis of the effects of hysteresis controllers on performance of direct torque control (DTC) of induction machines. The motivation of this research is that to provide the consideration for the designer in choosing appropriate bandwidth to have high performance of DTC drives. It should be noted that the DTC drive has gained widely acceptance for many industrial applications due to its simplicity. However, the DTC which is based on hysteresis comparators has two major drawbacks, namely variable switching frequency and larger torque ripple. It can be shown that the DTC performance may deteriorate if the inappropriate flux or/and torque band width are chosen. This research is aimed to analyze DTC performances in terms of total harmonic distortion (THD), torque ripple and switching frequency for variations of torque and flux hysteresis bandwidths. At first, the modeling of induction machine and study of principle of DTC were carried out, before they were being simulated using MATLAB-Simulink. The problems which are mainly associated in hysteresis controllers were identified by simulating the DTC of induction machine at different applications of hysteresis bandwidth, sampling frequency and operating condition (e.g. different of load torque and speed levels). By analyzing the DTC performances through simulations, it can provide useful information for the designer to identify the root of problem and hence chooses the appropriate hysteresis bandwidths at different operating conditions to achieve high DTC performance.

ABSTRAK

Tesis ini membentangkan kajian kesan-kesan kawalan histeresis terhadap prestasi kawalan langsung dayakilas (DTC) bagi motor aruhan. Motivasi bagi pembelajaran ini adalah untuk menyediakan pertimbangan bagi pereka dalam memilih jalur lebar yang sesuai untuk mempunyai pemacu kawalan langsung dayakilas berprestasi tinggi. Adalah perlu untuk diambil kira bahawa pemacu DTC telah mencapai penerimaan luas dalam aplikasi industri disebabkan oleh kawalan strukturnya yang ringkas. Walaubagaimanapun, DTC yang berpandukan kepada pembanding histeresis mempunyai dua masalah besar iaitu frequensi pensuisan yang berubah-ubah dan riak dayakilas yang besar. Adalah boleh ditunjukkan bahawa prestasi DTC boleh merosot jika jalur lebar bagi fluks dan dayakilas yang tidak sesuai dipilih. Kajian ini mensasarkan untuk menganalisa prestasi DTC berkaitan dengan jumlah herotan harmonik (THD), riak dayakilas dan frekuensi pensuisan terhadap perubahan lebar jalur hysteresis bagi dayakilas dan flux. Pada mulanya, pemodelan bagi motor aruhan dan pembelajaran bagi prinsip kawalan DTC telah dilaksanakan, sebelum kesemuanya disimulasikan menggunakan MATLAB-Simulink. Masalah-masalah tersebut yang berkaitan dengan kawalan histeresis telah dikenalpasti dengan simulasi terhadap DTC bagi motor aruhan pada aplikasi yang berbeza untuk jalur lebar histeresis, frequensi pensampelan dan keadaan operasi (contoh perubahan bagi dayakilas beban dan peringkat kelajuan). Dengan menganalisis prestasi DTC melalui simulasi, ia boleh menyediakan maklumat berguna kepada pereka untuk mengenalpasti punca masalah dan seterusnya memilih jalur lebas histeresis yang sesuai pada setiap keadaan operasi berbeza untuk mencapai DTC berprestasi tinggi.

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DC	-	Direct current
FOC	-	Field-Oriented Control
i_q^{Ψ}	-	Torque Producing Current Component
i_d^{Ψ}	-	Flux Producing Current Component
SFOC	-	Stator Flux Oriented Control
RFOC	-	Rotor Flux-Oriented Control
DTC	-	Direct Torque Control
VSI	-	Voltage Source Inverter
S_T, S_{Ψ}	-	Error Status
T_e	-	Electromagnetic torque
$T_{e,\ ref}$	-	Torque reference
Ψ_s	-	Estimated stator flux linkage
$\Psi_{s.\ ref}$	-	Flux reference
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
DSP	-	Digital Signal Processor
LB	-	Lower Band

MB	-	Middle Band
UB	-	Upper Band
Ψ_r	-	Rotor Flux
ω_r	-	Rotor Speed
v_s	-	Stator Voltage
THD	-	Total harmonic distortion
SVM	-	Space Vector Modulation
mmf	-	Magenetomotive Force
d^s, q^s	-	Real And Imaginary Axis Of the Stator
d^r, q^r	-	Real And Imaginary Axis of the Rotor
θ_s	-	Angle with respect to Stator Axis
θ_r	-	Angle with respect to Rotor Axis
α	-	Angle between Real Axis of Stator and Rotor
$\boldsymbol{x}$	-	Space Vector
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
V_{DC}	-	DC voltage

LIST OF PUBLICATIONS

The following paper has been published in ICEMS Conference.

1. Raja Nor Azrin Bin Raja Yunus, Auzani Jidin, Adeline Lukar Herlino, Nor Faezah Binti Alias, "Performance Analysis of Direct Torque Control of Induction Machines", (this paper has been presented at International Conference on Electrical Machines and Systems 2013 (ICEMS), Busan, Korea on October 26-29,2013).

CHAPTER 1

INTRODUCTION

1.1. Research Background

A direct torque control (DTC) was introduced to give fast and good dynamic torque response. DTC can be considered as an alternative to the field-oriented control (FOC) technique. Since it was introduced in 1986, a large number of technical papers have appeared in the literature, mainly seeking to improve the performance of DTC of induction machine drives. Two of the major issues which are normally addressed in DTC drives are the variation of the switching frequency of the inverter used in the DTC drives with operating conditions and the high torque ripple.

1.2. Motivation of the Research

The importance of analyzing the performance of DTC due to the effects of torque or flux hysteresis bands variations is necessary to identify the roots of problem in order to prevent deterioration of DTC performance. It will be shown that by selecting inappropriate bandwidth, this will affect the restriction of torque ripple within the hysteresis band and hence causes larger torque ripple. Moreover, the larger bandwidth of flux comparator chosen may cause current distortion (i.e. high total harmonic distortion) and degrades the DTC performance. Based on this research, it will provide useful analysis on different behaviours or operating conditions of the DTC performance for the designer to select the appropriate bandwidth. It should also be noted that the inappropriate bandwidth (i.e. too small level of bandwidth), may result switching frequency increases beyond the switching device's limitation, particularly at the worst conditions. This will degrade the switching performance and as a consequence damages the DTC drive systems.

1.3. Problem Statements of the Research

Despite its simplicity and high-torque performance control, the DTC which is based on hysteresis controller has two major drawbacks namely variable switching frequencies and larger torque ripple [1][2]. It should be noted that the torque and flux variations within the hysteresis bands are mainly affected by the operating conditions such as speed, load torque, DC input voltage, torque and flux demands [3][4][5].

For clearer picture, the problems in DTC associated with hysteresis controller can be described by simulation result as shown in Fig.1.1. The simulation of control of torque based on the hysteresis comparator with a sampling period of DT is considered as performed in Digital Signal Processor (DSP). In digital implementation, the output torque is calculated, and the appropriate switching states are determined at fixed sampling time (which is DT). However, it causes a delay between the instant the variables are sampled (i.e. the instant torque is calculated) and the instant the corresponded switching status pass to the inverter. Because of that, the torque ripple cannot be restricted, exactly, within the hysteresis band (between lower band (LB) and middle band (MB)). If the band is set too small, it does not minimize the torque ripple. This is because, the incidents of overshoot in the estimated torque above the torque hysteresis band may occur (i.e. torque touches the upper band (UB)) and hence causes the reverse voltage vector is selected. The selection of the reverse voltage vector which is indicated by the torque error status (S_T) that produces -1 cause the torque decreases rapidly and as a result the torque ripple increases.

It can also be observed from the Fig. 1.1, the slopes of torque which mainly affect the switching frequency are not consistent. Note that, the torque slope depends on the stator flux (Ψ_s), rotor flux (Ψ_r), the speed (ω_r) and the stator voltage (v_s) as proven in equation (1.1) derived by [21].

$$\frac{T_{e,n+1}-T_{e,n}}{DT} = -T_{e,n}\left(\frac{1}{\sigma\tau_s}+\frac{1}{\sigma\tau_r}\right)+\frac{3}{2}P\frac{L_m}{\sigma L_s L_r}\left[\left(\mathbf{v}_{s,n}-j\omega_r\Psi_{s,n}\right)\cdot j\Psi_{r,n}\right] \tag{1.1}$$

Thus, the variation of torque slope will be significant for different operating conditions, which causes the switching frequency becomes unpredictable. The unpredictable switching frequency somehow complicates the improvements of DTC in terms of current THD and optimization of switching devices.

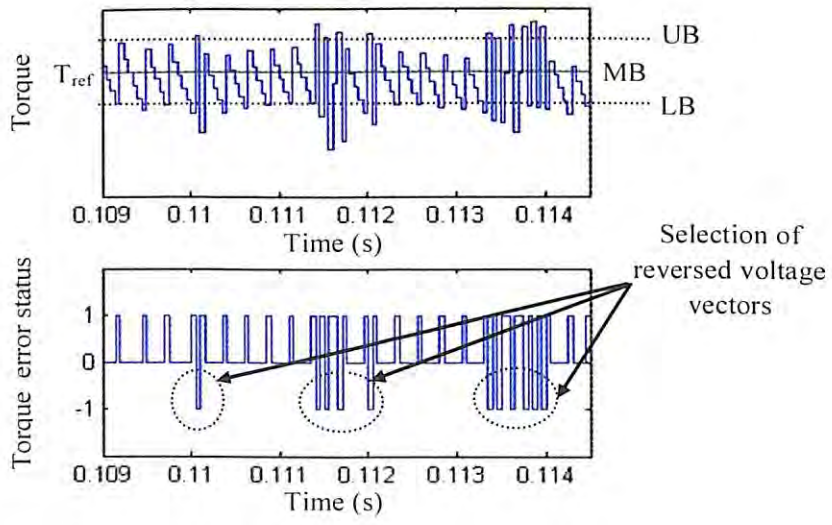

Figure 1.1: Simulation result to highlight major problems associated in hysteresis-based DTC

1.4. Objective of the Research

The main objective of this study is to identify the major problems in hysteresis based DTC of induction machines by analyzing the effects of DTC performance due to the variation of bandwidth of hysteresis controllers. In general, there are two objectives of the thesis which are as follows;

1. To analyze the root of problems (i.e. larger torque ripple and variable switching frequency) by studying the effects of hysteresis bands on DTC performances.
2. To verify the effects of hysteresis bands on DTC performance via simulation results.

1.5. Scope of the Research

The scopes of the research are listed as follows;

1. To study the principle of DTC operation and the variations of DT improvement through literature or technical papers.
2. To simulate and construct DTC using simulink block from Matlab Software (R2011a).
3. The performance of DTC of induction machines are analyzed based on the simulation results.

1.6. Thesis Organizations

The thesis is organized as follows:

Chapter 2 discusses the evolution of motor control technology, the various improvements of DTC drives, the mathematical modeling of three-phase induction machine and basic principles of three-phase DTC. In this chapter the explanation on how to control the flux and torque has been described. Then, an overview of the conventional control structure of three-phase DTC has been performed.

Chapter 3 describes the development of DTC algorithms for three phase induction machine. All simulation block of control structure of DTC is constructed by using MATLAB's SIMULINK. The equation of each block is shown and its respective waveform is presented in Chapter 4. The conclusion has been presented in the of this chapter.

Chapter 4 presents the simulation results the effect of hysteresis band on DTC performance in terms of switching frequency, torque ripple and total harmonic distortion. Then the discussion and analysis on the results has been done to prove the theory as presented in chapter 2.

Chapter 5conclude the study and provide some recommendations or future works to make further improvements or analysis related to the DTC of induction machines.