MINIMIZATION OF TORQUE RIPPLES IN DIRECT TORQUE CONTROL OF INDUCTION MOTOR AT LOW SPEEDS

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To the Almighty Allah, for bestowing me the guidance and blessings.
To my beloved parents for their unconditional love and unlimited support,
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ABSTRACT

Direct Torque Control (DTC) of induction motor has attracted a considerable attention in the motor drives industry. The key merits of DTC include fast torque dynamic response, simple structure, insensitivity to motor's parameters. Nevertheless, DTC inherently suffers from two major downsides namely: high torque ripples and variable switching frequency. This thesis presents a new technique to minimize the torque ripples inherited in the digital-based DTC of induction motor. The typical discrete-based DTC imposes a delay time which frequently allows the torque to overshoot beyond hysteresis bands. This triggers the selection of reverse voltage vectors which, in turn, cause large torque decrements. The torque ripples become of great significance at low speeds where torque overshoot is most likely to occur due to steep positive torque slope. A multi-level DC link voltage is proposed to vary the DC voltage of Voltage Source Inverter (VSI) according to motor's speed. By varying the DC link voltage, the torque slopes can be controlled and, hence, the torque overshoots are mostly avoided. Therefore, the torque ripples are significantly minimized. The viability of proposed technique has been validated using MATLAB/Simulink software. Results show the proposed technique may yield over 50% reduction in the RMS torque ripples while maintaining a low switching frequency. Also, the torque dynamic response is maintained as good as in the conventional DTC scheme.

ABSTRAK

Direct Torque Control (DTC) untuk motor aruhan telah menarik perhatian yang besar dalam industri pemacuan motor. Merit utama DTC termasuklah dinamik tork yang pantas, struktur binaan mudah dan tidak sensitif kepada parameter motor. Walaubagaimanapun, DTC masih mengalami dua kelemahan utama iaitu: riak tork yang tinggi dan pensuisan frekuensi yang tidak tetap. Tesis ini membentangkan teknik baru untuk mengurangkan riak tork dalam implementasi digital DTC. Kebiasaan implementasi DTC secara digital menghasilkan tork yang terlajak keluar dari jalur histerisis. Ini mencetuskan pemilihan vektor voltan terbalik yang, seterusnya, menyebabkan pengurangan tork yang besar. Kemungkinan berlakunya riak tork pada kelajuan yang rendah adalah besar kerana kecerunan positif tork adalah besar. Pelbagai peringkat voltan DC adalah dicadangkan untuk mengubah voltan DC untuk Voltan Source Inverter (VSI) mengikut kelajuan motor. Dengan mengubah voltan DC, kecerunan tork boleh dikawal dan, dengan itu, lanjakan tork kebanyakannya dapat dielakkan. Oleh itu, riak tork dengan ketara dapat dikurangkan. Teknik yang dicadangkan itu telah disahkan dengan menggunakan perisian MATLAB / Simulink. Keputusan menunjukkan teknik yang dicadangkan boleh menghasilkan pengurangan lebih 50% riak tork RMS disamping mengekalkan frekuensi penukaran yang rendah. Juga, dinamik tork dikekalkan seperti mana yang diperolehi dalam skim DTC konvensional.

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LIST OF SYMBOLS

d^r, q^r - Direct and quadrature axis of the rotor reference frame

$d\tau_{Te}$ - Torque error status

$d\tau_{\psi}$ - Stator flux error status

d, q - Direct and quadrature axis of the stationary reference frame

f - frequency

$\bar{i}_s^g$, $\bar{i}_r^g$ - 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_{rd} , i_{rq} - d and q components of the rotor current in stationary reference frame

i_{sd} , i_{sq} - d and q components of the stator current in stationary reference frame

J - Moment of inertia

L_m - Mutual inductance

L_s - Stator inductance

L_r - Rotor inductance

p - No. of poles

R_s , R_r	-	Stator and rotor resistance
S_a, S_b, S_c	-	Switching states of phase a, b, c
T_s	-	Sampling time
T_e	-	Electromagnetic torque
T_e^*	-	Reference torque
T_L	-	Load torque
V_{dc}	-	DC link voltage
$\bar{v}_s^g$	-	Stator voltage space vector in general reference frame
$\bar{v}_s$	-	Stator voltage space vector in stationary reference frame
v_{sd} , v_{sq}	-	d and q components of the stator current in stationary reference frame
α	-	Angle between the rotor and stator axis
θ_r	-	Angle with respect to the rotor axis
θ_s	-	Angle with respect to the stator axis
$\overline{\psi}_s^g$, $\overline{\psi}_r^g$	-	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
$\overline{\psi}_{sd}$, $\overline{\psi}_{sq}$	-	d and q components of stator flux in stationary reference frame
$\overline{\psi}_{rd}$, $\overline{\psi}_{rq}$	-	d and q components of rotor flux in stationary reference frame
ω_g	-	Rotor speed in general reference speed
ω_r	-	Rotor electrical speed in rad/s
ω_e	-	Steady state synchronous frequency in rad/s

ω_m - Rotor mechanical speed in rad/s

σ - Total flux leakage factor

τ_{Te} - Torque error

τ_{ψ} - Stator flux error

τ_r - Rotor time constant

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CHAPTER 1

INTRODUCTION

1.1 Overview of Electrical Drives

Prior to the 1960s, DC machines were vastly employed for industrial applications that demand a variable-speed and four-quadrant operation. The key feature of DC machine is the high performance of torque control at low and near-zero speeds. However, DC machines have always suffered from some significant and intolerable drawbacks that limited their deployment in industry. These drawbacks may include unreliability issues which is mainly due to commutators and brushes; incapability to operate in a harsh, dusty or explosive environment; considerable maintenance required; and higher costs incurred.

The aforementioned disadvantages of DC machines could be overcome by employing Induction Machines (IMs) at the applications where reliability, efficiency and effectiveness are highly required. A principal feature of IMs is that they do not need commutators or brushes since the stator and rotor windings are magnetically connected. Hence, IMs are maintenance-free machines. Another attractive feature is the capability of IMs to operate in an explosive environment owing to the fact that IMs do not produce sparks. Other advantages of IMs may include the immunity to a high overloading case and high efficiency, leading to less failures at high speeds operation. Furthermore, IMs have low weight and inertia as well as a low cost due to their simple and robust structure. Considering all these features, the DC machines were tremendously superseded by IMs in the industrial market over the past decades.

As a result of the technological advances in power electronics and semiconductors fields, Adjustable Speed Drives (ASDs), a.k.a. Variable Frequency Drives (VFDs), are among the most efficient and reliable drive systems of IMs. ASDs have been known with attractive features such as a reliable transient response, control of a continuous range of speed and considerable energy saving [1]. Furthermore, the torque control performance of the ASDs are much superior to that of DC machines drives. This is because of the unprecedented technology evolution in digital microprocessors and DSPs that effectively help to handle complex control problems in the electrical drives schemes.

The control technologies of IMs can be principally classified into two main categories: scalar and vector controllers. The scalar controller is a basic drive scheme that uses a simple algorithm to control rotor speed based on applying a constant ratio between magnitude of the stator voltage and frequency, hence it is well-known as *voltage/frequency*, or *V/f*, controller. For speed and torque control, the accuracy of scalar controllers is typically low especially at transient state since the employed algorithm is solely based on the steady-state model of IMs so that the stator flux and torque are not well regulated. Nonetheless, the scalar controllers have witnessed noticeable improvements in the past decades that make them among the most widespread drive schemes used for basic applications in the industry [2-4].

On the other hand, vector controllers are considered as revolutionary drive systems that had a significant impact on the industrial applications. In vector controllers, the electromagnetic torque is controlled based on the phase angle and magnitude of the motor’s current. Similar to the DC motor drives, the stator flux and torque are independently controlled, leading to a high control performance of torque and speed in AC machines. Generally, vector controllers have two well-known schemes: Field Oriented Control (FOC) and Direct Torque Control (DTC). Each control scheme has its own features and downsides, but they share an ultimate objective of providing an effective and reliable flux and torque control regardless of any external variations or disturbances. Furthermore, both schemes got a considerable attention and a wide acceptance in most variable-speed industrial applications worldwide. A brief discussion of both schemes, FOC and DTC, is addressed in the following subsections.

1.1.1 Field Oriented Control (FOC)

Field Oriented Control (FOC) was first introduced by Hasse [5] and Blaschke [6] in 1972. In FOC of IMs, stator current is transformed to a rotor-flux reference frame (i.e. d^r-q^r coordinates), mostly, using Park's transformation theory. Similar to a separately excited DC machine, the coordinate transformation made possible the decoupling process by which stator flux and torque are independently controlled through d^r- and q^r- components, respectively. Furthermore, FOC of IMs can be broadly categorized into two main types: Direct FOC (DFOC) and Indirect FOC (IFOC). In DFOC, rotor flux angle (θ_r) is estimated directly by either using a flux-sensor attached inside the machine or manipulating measured stator's parameters (voltages and currents). On the contrary, IFOC estimates the angle by using the measured rotor speed and slip speed where the latter is estimated through motor's parameters [7]. Despite its high sensitivity to motor's parameters, IFOC is highly preferred in the industry, compared with DFOC, in order to avoid structure complexity, high thermal requirement and extra expenses associated with the latter [8].

A great deal of research attention has been devoted for the performance improvements of FOC control scheme at several perspectives. For instance, authors in [9, 10] have improved functionality of FOC scheme in terms of parameter sensitivity; [11-13] introduced new techniques for flux estimation and [14-16] developed sensorless FOC schemes. Among the variety of proposed FOC schemes, Stator FOC (SFOC) [13, 17] is the most attractive scheme due to its high immunity to motor's parameters. In fact, SFOC does not require knowledge of rotor speed as the estimation of stator flux is accomplished using stator parameters i.e. its voltage, current and resistance [13].

With the intense research and impressive improvements, FOC-based control systems were the most reliable and dominant drive schemes that effectively can control the torque of AC machines for a wide range of speeds. However, the necessity for position encoder, current controllers and coordinates transformation are major shortcomings that significantly degrade the overall system performance.

1.1.2 Direct Torque Control (DTC)

After nearly a decade of remarkable technological advancements, a superior motor’s control technique was proposed by Isao Takahashi as Direct Torque Control (DTC) [18], and Depenbrock as Direct Self Control (DSC) in 1980s [19]. The first industrialized DTC scheme was developed by ABB in the late 1990s [20]. Since its invention, intense research studies have widely devoted to DTC, or DSC, due to its quick dynamic response, simple structure and insensitivity to motor’s parameters. The basic block diagram of DTC, as initially proposed in [18], is shown in Figure 1.1. In its basic configuration, DTC consists of four main blocks which are: Voltage Source Inverter (VSI), parameters (i.e. stator flux and torque) estimator, Switching Table (ST) and a pair of hysteresis controllers.

The fundamental principle of DTC is to select a voltage vector (i.e. inverter switching states), from a predetermined lookup table, to compensate the errors of stator flux and electromagnetic torque. These errors are basically obtained by comparing the reference and estimated values of both parameters. The decoupling process is established through the hysteresis controllers where stator flux and torque are independently controlled. Two- and three- level hysteresis controllers are used to digitize the errors of stator flux and torque, respectively. The outputs of hysteresis comparators along with flux position are used to choose a proper voltage vector that simultaneously regulate both stator flux and torque. In contrast to FOC-based controllers, DTC allows a quick and instantaneous dynamic torque response without the need for coordinate's transformation.

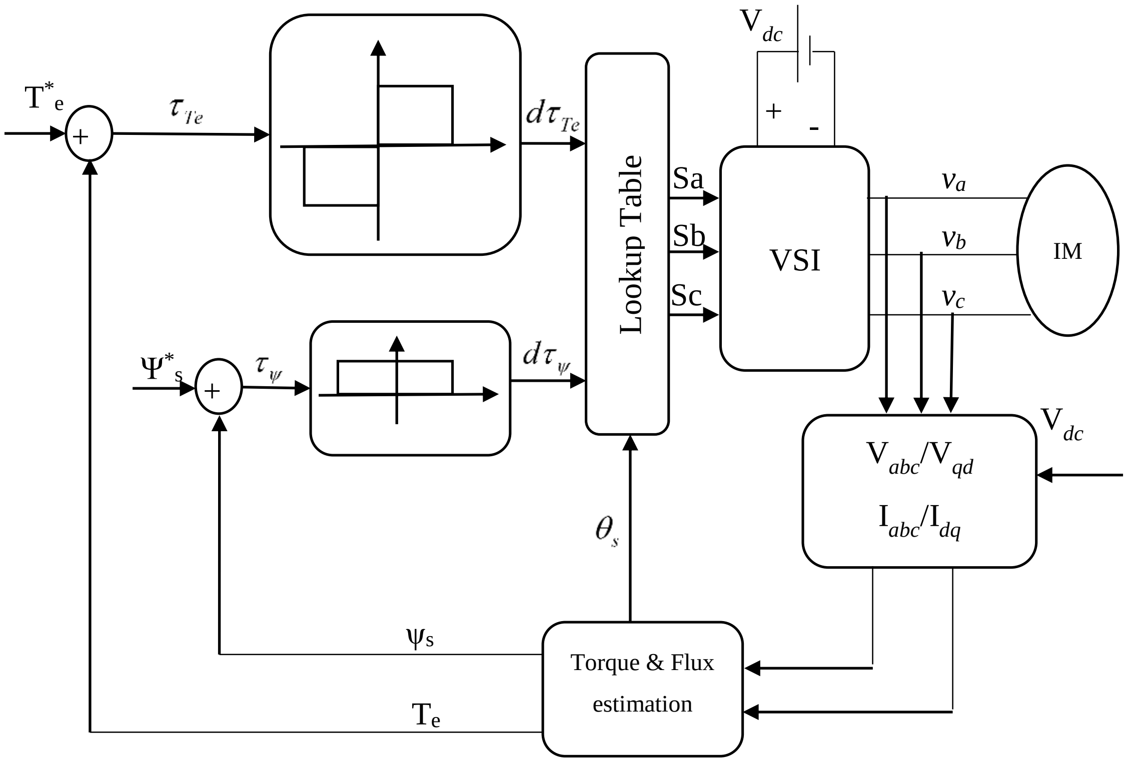

Figure 1.1: The typical configuration of Direct Torque Control proposed by [18].

Furthermore, the parameters estimation (stator flux and torque) technique of DTC is much simpler and straightforward than that of FOC. Generally, the estimation is based on manipulation of the stator voltages and currents, expressed in a stationary reference frame, as well as the stator's resistance only. Nevertheless, the accuracy of parameters' estimation is of significant importance as it may lead to selection of an improper voltage vector and hence highly degrades the control performance of DTC. The stator flux and torque can be estimated using voltage-, current- based estimators or combination of both. The conventional DTC scheme, proposed in [18], was based on a combination (voltage and current) estimator. On the one hand, the current-based estimator requires the knowledge of rotor speed. Sequentially, a further speed sensor is mandatory which, in turn, increases system's complexity. On the other hand, a speed-sensorless DTC scheme can be only implemented using a voltage-based estimator. Nonetheless, the voltage-based estimator may introduce a few critical concerns such as integration drift and initial condition issues especially at low and near-zero speed operations [21, 22].

1.2 Major DTC Problems

Despite its prominent merits over other drive schemes, the conventional DTC experiences two major shortcomings that have to be addressed and rectified. These are: high torque ripples and variable switching frequency. They are briefly discussed in the following subsections.

1.2.1 High Torque Ripples

In the digital implementation of DTC, a finite time should be allowed for data acquisition (measuring stator voltages and currents along with DC link voltage), manipulation (determining a proper voltage vector for certain torque and flux errors) and transmission (passing the selected vector to the inverter side) [23]. Due to this delay, the effect the selected voltage vector takes place in the next sampling period so that torque excursions cannot be precisely confined within its hysteresis bands. The torque overshoots, beyond hysteresis band, lead to the selection of reverse voltage vectors (instead of zero voltage vectors) which in turn causes the torque to steeply decrease. Therefore, high torque ripples are produced [24-26].

1.2.2 Variable Switching Frequency

In the conventional DTC, switching frequency of VSI highly depends on the switching frequency of the hysteresis controllers [18]. The latter is significantly affected by the respective slopes of stator flux and torque which vary with operating conditions such as speed, fluxes and DC link voltage. As a result, the switching frequency of VSI varies as well [18, 26]. It is worth mentioning that the switching capability of the switching device cannot be totally used because the switching of the hysteresis comparator is designed according to the worst condition [26].

1.3 Problem Statement

This thesis mainly addresses the problem of inherent torque ripples associated with the conventional DTC scheme. As discussed earlier, the root cause of torque ripples is the delay time associated with the digital implementation of DTC. To illustrate this, a simulation study of both digital-based and analog-based DTC was conducted with the same simulation settings (speed of *10 rad/sec*, load of *1 Nm*) to investigate further the torque ripples. Figure 1.2 shows the torque ripples and the torque error status of both cases. The latter indicates the selection of voltage vectors: “1” stands for selection of forward voltage vector, “0” stands for selection of zero voltage vectors and “-1” stands for selection of reverse voltage vectors.

On the one hand, the analog-based DTC does not suffer from high torque ripples since the delay time has no impact on it at all, as shown in Figure 1.2. Additionally, the torque error status is kept swinging between “1” and “0” which implies there is no torque overshoots have occurred. On the other hand, the digital-based DTC exhibits a significant deal of torque ripples as shown in Figure 1.2. That is because of the frequent occurrence of torque overshoots which trigger the selection the reverse voltage vectors (indicated by the torque error status “-1”).

Furthermore, the prospects of torque overshoots much depend on the torque slopes which are primarily influenced by rotor speed. At low speed, torque overshoots are very likely to occur. This is because the torque positive slope is relatively steep such that it rapidly escalates torque to exceed hysteresis band. This process produces considerable torque ripples that need to be rectified especially at low speed operations.

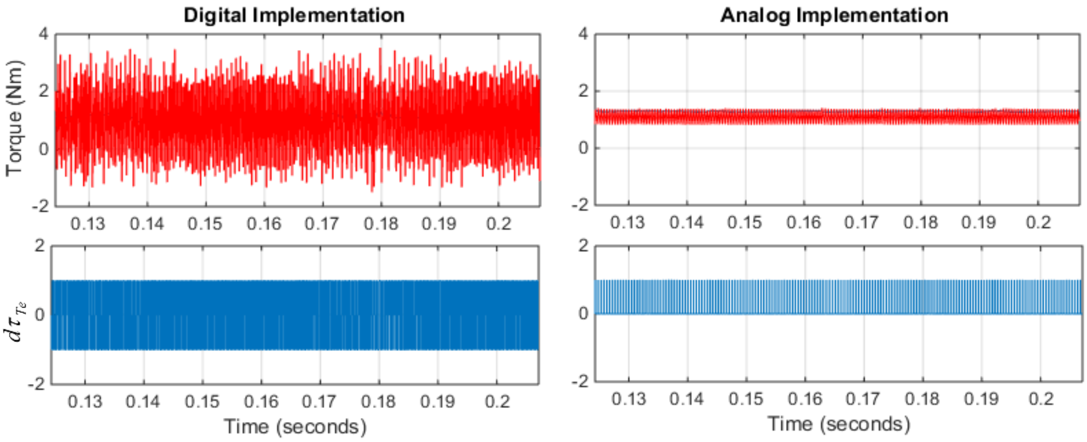

Figure 1.2: Torque ripples in digital-based and analog-based DTC schemes

1.4 Objectives

This research project mainly aims to study and improve the performance of Direct Torque Control (DTC) drive scheme of induction machines in term of reducing the torque ripple at low speed operations.

The objectives of project are:

1. To propose a new DTC scheme based on Multilevel DC Link Voltage (MDLV-based) to minimize torque ripples.
2. To develop a simulation model of the proposed MDLV-based DTC.

3. To validate the effectiveness of MDLV-based DTC against the conventional DTC scheme using MATLAB/Simulink.

1.5 Scope

This research project primarily focuses on improve performance of DTC drive scheme by minimizing current and torque ripples.

Limitations of the project include:

1. Utilization of three phase Induction motor only.
2. Focus on low speed operation.
3. Simulation validation only due to time constraints

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