IMPROVEMENT OF MAXIMUM EFFICIENCY AND TORQUE DYNAMICS FOR DIRECT TORQUE CONTROL DRIVE SYSTEMS

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DEDICATION

This thesis is dedicated to my father, who taught me the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the most significant task could be accomplished one step at a time.

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ABSTRACT

In high-performance direct torque control (DTC) drive systems, the torque and flux components are always decoupled to establish a fast instantaneous torque response. Furthermore, the rated flux is always applied to ensure maximum torque capability during the torque dynamic even at full load conditions. However, most of the time, the drive normally operates at a lower than the full-load condition, and operating the drive at rated flux reduces its efficiency. To overcome this problem, an optimal efficiency DTC drive is normally employed whereby the flux is set to an optimal value that produces maximum efficiency whenever the drive is operated below its rated load conditions. However, to ensure fast dynamic torque, the rated flux will be set during transient states, and a new optimal flux has to be recalculated for the new operating condition once the steady-state speed is reached. Two problems are faced with this method: (i) it will take some time to calculate the new optimal flux after the transient states, and (ii) the dynamics torque will be sluggish due to the poor flux response during the step from the optimal value to the rated value. To overcome the first problem, a new method is introduced in this thesis that instantaneously calculates the reference flux to a value that is almost equal to the optimal flux, called the High-Efficiency Flux Reference (HEFR). The calculation of the HEFR is based on the load torque and is obtained almost immediately with no convergence time. The second problem is tackled by introducing a modified voltage vector constructed based on the initial and final values of the flux reference. The effectiveness of the proposed method is studied through simulation using MATLAB and verified experimentally. In the experiment, a 186 W induction motor is used, with the proposed algorithm implemented using dSPACE DS1104 controller board and Xilinx FPGA controller board. It is found that at steady-state, the drive efficiency using HEFR is almost similar to the conventional optimal efficiency DTC, which is 63% and 72% at the speed of 70 rad/s and 90 rad/s, respectively. However, with the HEFR, the drive efficiency during the transients is improved by 4%. The rise time of the torque with the modified voltage vectors was measured as 1.64 ms, and has improved to 1.2 ms when it is implemented with the HEFR.

ABSTRAK

Dalam sistem pemacu kawalan tork terus (KTT) yang berprestasi tinggi, komponen tork dan fluks sentiasa dipisahkan bagi mewujudkan tindak balas tork yang pantas. Tambahan pula, fluks terkadar sentiasa digunakan untuk memastikan keupayaan tork maksima dalam keadaan beban penuh. Walau bagaimanapun, dalam kebanyakan masa, pemacu biasanya beroperasi dalam keadaan yang lebih rendah daripada keadaan beban penuh, dan pengendalian pada fluks terkadar akan mengurangkan kecekapannya. Untuk mengatasi masalah ini, kecekapan optimum pemacu KTT biasanya digunakan untuk menetapkan nilai fluks optimum yang menghasilkan kecekapan maksimum apabila pemacu dikendalikan pada beban yang rendah. Walau bagaimanapun, untuk memastikan tork dinamik pantas, fluks terkadar akan digunakan semasa fana, dan fluks optimum baharu perlu dikira semula untuk keadaan operasi baharu sebaik sahaja keadaan kelajuan mantap dicapai. Dua masalah akan dihadapi dengan kaedah ini: (i) mengambil masa untuk mengira fluks optimum baharu selepas fana, dan (ii) dinamik tork akan menjadi lembap kerana tindak balas fluks yang lemah semasa perubahan langkah dari fluks optimum ke fluks terkadar. Untuk mengatasi masalah pertama, kaedah baru diperkenalkan dalam tesis ini bagi mengira fluks dengan serta-merta yang nilainya hampir sama dengan fluks optimum, dipanggil Fluks Rujukan Berkecekapan Tinggi (FRBT). Pengiraan FRBT adalah berdasarkan tork beban dan diperolehi hampir serta-merta. Masalah kedua ditangani dengan memperkenalkan vektor voltan yang diubah suai berdasarkan pada nilai awal dan akhir fluks. Keberkesanan kaedah yang dicadangkan dikaji melalui simulasi MATLAB dan disahkan melalui eksperimen. Dalam eksperimen, motor aruhan 186 W digunakan, dengan algoritma yang dilaksanakan mengguna papan pengawal dSPACE DS1104 dan papan pengawal Xilinx FPGA. Adalah didapati bahawa dalam keadaan mantap, kecekapan pemacu yang menggunakan FRBT hampir sama dengan kecekapan optimum konvensional KTT, iaitu 63% dan 72% pada kelajuan 70 rad/s dan 90 rad/s. Walau bagaimanapun, dengan FRBT, kecekapan pemacu semasa fana meningkat sebanyak 4%. Masa menaik untuk tork dengan vektor voltan yang diubah suai diukur sebanyak 1.64 ms, dan telah bertambah baik kepada 1.2 ms apabila ia dilaksanakan bersama FRBT.

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LIST OF ABBREVIATIONS

AC	-	Alternating-current
DC	-	Direct-current
DRM	-	Duty ratio modulation
DSC	-	Direct Self Control
DTC	-	Direct Torque Control
EV	-	Electric vehicle
FLC	-	Fuzzy logic controller
FOC	-	Field-Oriented Control
FPGA	-	Field-programmable gate array
GTO	-	Gate-turn-off thyristor
HEFR	-	High-Efficiency Flux Reference
IGBT	-	Insulated-gate bipolar transistor
IM	-	Induction machine
LMC	-	Loss model controller
NFC	-	Neuro-fuzzy controller
NNC	-	Neural-network controller
NPC	-	Neutral-point clamped
PI	-	Proportional-Integral controller
PSO	-	Particle Swarm Optimisation
MEPT	-	Maximum efficiency per torque
PWM	-	Pulse-width modulation
RMS	-	Root-mean-square
SC	-	Search controller
SVM	-	Space vector modulation
THD	-	Total harmonic distortion
VSI	-	Voltage source inverter
V/Hz	-	Volts-per-hertz

LIST OF SYMBOLS

D, Q	-	Real and imaginary axis of stator windings
d, q	-	Real and imaginary axis of rotor windings
D_{band}	-	Duty cycle hysteresis band
D_{status}	-	Duty cycle status
E	-	Speed encoder
$\vec{i}_s^g, \vec{i}_r^g$	-	Stator and rotor current space vectors in the general reference frame
$\vec{i}_s$	-	Stator current space vector in the stationary reference frame
i_{sd}, i_{sq}	-	*d* and *q* components of stator current in the stationary reference frame
i_{rd}, i_{rq}	-	*d* and *q* components of rotor current in the stationary reference frame
i_a, i_b, i_c	-	Stator currents of phases A, B, and C
J	-	Moment of inertia
k_m	-	Constant of high-efficiency flux reference
L_{ls}, L_{lr}	-	Stator and rotor self-leakage inductances
L_s, L_r	-	Stator and rotor inductances
L_m	-	Mutual inductance
P	-	Number of pole pairs
P_{in}	-	Input power
P_{out}	-	Output power
P_{losses}	-	Power losses
R_s, R_r	-	Stator and rotor resistances
s	-	Derivative of *d/dt*
S_a, S_b, S_c	-	Switching states of phases A, B, and C
T_e	-	Motor torque
$T_{e,ref}$	-	Motor torque reference
$T_{e,band}$	-	Torque hysteresis band
$T_{e,error}$	-	Torque error

$T_{e,status}$	-	Torque error status
T_{load}	-	Load torque
T_{sp}	-	Sampling period
$T_{v,m}$	-	Sampling period of voltage vector *m*
$T_{v,m+1}$	-	Sampling period of voltage vector *m+1*
$\vec{v}_s^g$	-	Stator voltage space vector in the general reference frame
$\vec{v}_s$	-	Stator voltage space vector in the stationary reference frame
v_{sd}, v_{sq}	-	*d* and *q* components of stator voltage in the stationary reference frame
v_{rd}, v_{rq}	-	*d* and *q* components of rotor voltage in the stationary reference frame
$\vec{v}_k$	-	Active or conventional voltage vectors
$\vec{v}_m, \vec{v}_{m+1}$	-	Proposed voltage vectors
$\vec{v}_0, \vec{v}_7$	-	Zero voltage vectors
V_{DC}	-	DC link voltage
$v_{s,rated}$	-	Rated stator voltage
$\omega_{cut-off}$	-	Cut-off frequency of low-pass filter
ω_e	-	Synchronous angular frequency
ω_m	-	Rotor mechanical speed
$\omega_{m,ref}$	-	Motor speed reference
$\omega_{m,ref(step)}$	-	Step of motor speed reference
ω_r	-	Rotor electrical speed
x_0	-	Zero sequence component
x_d, x_q	-	*d* and *q* components of the space vector
x_a, x_b, x_c	-	Space vectors of phases A, B, and C
$\vec{\Psi}_s^g, \vec{\Psi}_r^g$	-	Stator and rotor flux linkage space vectors in the general reference frame
$\vec{\Psi}_s, \vec{\Psi}_r$	-	Stator and rotor flux linkage space vectors in the stationary reference frame
Ψ_{sd}, Ψ_{sq}	-	*d* and *q* components of stator flux in the stationary reference frame
Ψ_{rd}, Ψ_{rq}	-	*d* and *q* components of rotor flux in the stationary reference

		frame
$\vec{\Psi}_s^r, \vec{\Psi}_r^r$	-	Stator and rotor flux linkage space vectors in the rotor flux reference frame
Ψ_s	-	Stator flux
$\Psi_{s,ref}$	-	Stator flux reference
$\Psi_{s,rated}$	-	Rated stator flux
$\Psi_{s,opt}$	-	Optimal stator flux
$\Psi_{s,band}$	-	Stator flux hysteresis band
$\Psi_{s,error}$	-	Stator flux error
$\Psi_{s,status}$	-	Stator flux error status
$\Psi_{s,HEFR}$	-	New high-efficiency flux reference
$\Psi_{s,ramp}$	-	Ramped flux reference
$\Psi_{s,threshold}$	-	Threshold value of ramped flux reference
$\Delta\Psi$	-	Flux step size
θ_r	-	Rotor angle
θ_{sr}	-	Angle between stator and rotor flux linkages
θ_{Ψ_s}	-	Stator flux sector
σ	-	Total flux leakage factor
τ_r	-	Rotor time constant
η	-	Efficiency

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CHAPTER 1

INTRODUCTION

1.1 Development of Vector-Based Control Drive System

Initially, the direct-current (DC) motor has been used widely in the variable speed operation due to its mechanical construction that is able to produce the orthogonal flux and torque. In this simple control structure, the decoupled flux and torque control can be controlled directly using the respective field and armature current. In other words, the instantaneous torque response can be achieved by varying the armature current and keeping the field current constant. However, the presence of brushes and commutator introduces several disadvantages. The DC motor requires regular maintenance, has limited speed due to the commutator capability, is expensive, and cannot be operated under an explosive or corrosive environment. These problems can be solved by using the alternating-current (AC) motor, which has a simple and rugged construction, robust to heavy loads, is cheaper, does not require regular maintenance and can operate at a higher speed.

There are two broad categories of control techniques in AC motors: scalar and vector controls. The scalar control regulates the magnitude and frequency of the stator voltage or stator current, whereas in vector control, the instantaneous position, magnitude and frequency of the voltage vector, current vector and flux vector are controlled. For scalar control, the most commonly used method is the constant volts per hertz (V/Hz), which maintains the motor-rated magnetic flux by controlling the ratio of the voltage magnitude (V) and the frequency (Hz). Meanwhile, two widely adopted techniques used in vector control are Field-Oriented Control (FOC) and Direct Torque Control (DTC). In FOC, the flux and torque are controlled via the stator currents, whereas in DTC, the flux and torque are controlled directly by selecting the suitable voltage vectors of the voltage source inverter.

The FOC was invented in the early 1970's by F. Blaschke, who was an engineer at Siemens. In FOC, the DC motor theory was applied in controlling the induction machine. This method decouples the flux and torque by controlling the orthogonal flux-producing and torque-producing currents in order to produce a similar performance as the DC motor [5]. The FOC can be further classified as either direct or indirect, depending on how the flux position is obtained. The orientation of the rotating frame can either be fixed to the stator flux, rotor flux or magnetising flux [2, 3, 5, 6]. In direct FOC (invented by F. Blaschke), the position of the flux which is used for the frame transformation, is obtained from the estimated flux using the terminal variables (voltage and current), as shown in Figure 1.1 (a). This method requires the knowledge of the rotor current vector that relies on the sensing devices (i.e., Hall-Effect current sensors). The deviation in estimated angular position may occur due to the error in the current measurement and the parameter mismatch in the flux model, which will affect the system's performance. To overcome this, the indirect FOC was introduced by K. Hasse. By using this method, the knowledge of flux vectors is not required. As shown in Figure 1.1 (b), the angular position is calculated by adding the measured motor speed and slip speed, which are obtained from the reference values (torque and flux references). Due to the relatively simpler implementation compared to direct FOC, this method is more popular in industrial applications [2]. Over the past few decades since it was introduced, there have been tremendous improvements introduced to FOC, which can be seen from the huge number of published papers related to FOC.

One aspect of the improvements in FOC which is related to the work in this thesis, is the torque dynamic. Instead of maintaining the flux-producing current at its rated value to improve the torque response, the current shifting between the flux-producing and torque-producing currents has been proposed in [7, 8]. Initially, the current of converters in [7] is all shifted to the flux-producing current. When the rotor flux increases to a high value, all currents are then shifted to the torque-producing current. Although the flux-producing current reference is removed, the rotor flux is still sustained due to the slow decaying of the rotor current. On the contrary, in [8], the flux-producing current is initially increased to twice of current limit in order to build up the rotor flux. At the same time, the torque-producing current is increased too before the flux-producing current is reduced after a few milliseconds. The research work in [7] and [8] indicate that field flux control plays an important part in order to improve the torque dynamic. Even when the system is in the field-weakening region, the torque capability can be maximised by introducing a current regulation algorithm [9] to control the torque. In [9], the flux-producing current command is determined by controlling the zero time of space vector modulation (SVM) to the desired value, whereas the torque-producing current is determined from the torque command and flux-producing current. But when the maximum voltage angle is reached, the controller maximises both the applied voltage and slip frequency to provide the maximum torque capability to the motor.

The frame transformation, pulse-width modulator (PWM), and current-control loop that are required to control the torque and flux in the FOC drive can be eliminated in the DTC drive, which was introduced by Depenbrock [10] and Takahashi-Noguchi [11]. Due to its instantaneous torque response, high-efficiency operation, and relatively more straightforward implementation than FOC [11], its popularity has tremendously increased in industrial motor drive applications since ABB Industry first commercialised it in 1996 [12]. This system is less dependent on the motor’s parameters and produces a simpler control structure and better transient performance compared to the FOC system [11, 13, 14]. In DTC, the motor torque and stator flux are controlled directly by applying the voltage vector to satisfy their demands. In contrast, the FOC drive regulates the torque and flux based on respective current components and thus requires a current-control loop. Since the torque and flux are directly controlled using selected voltage vectors, the delay associated with the current-control loop and PWM in FOC is removed, resulting in faster torque dynamics.

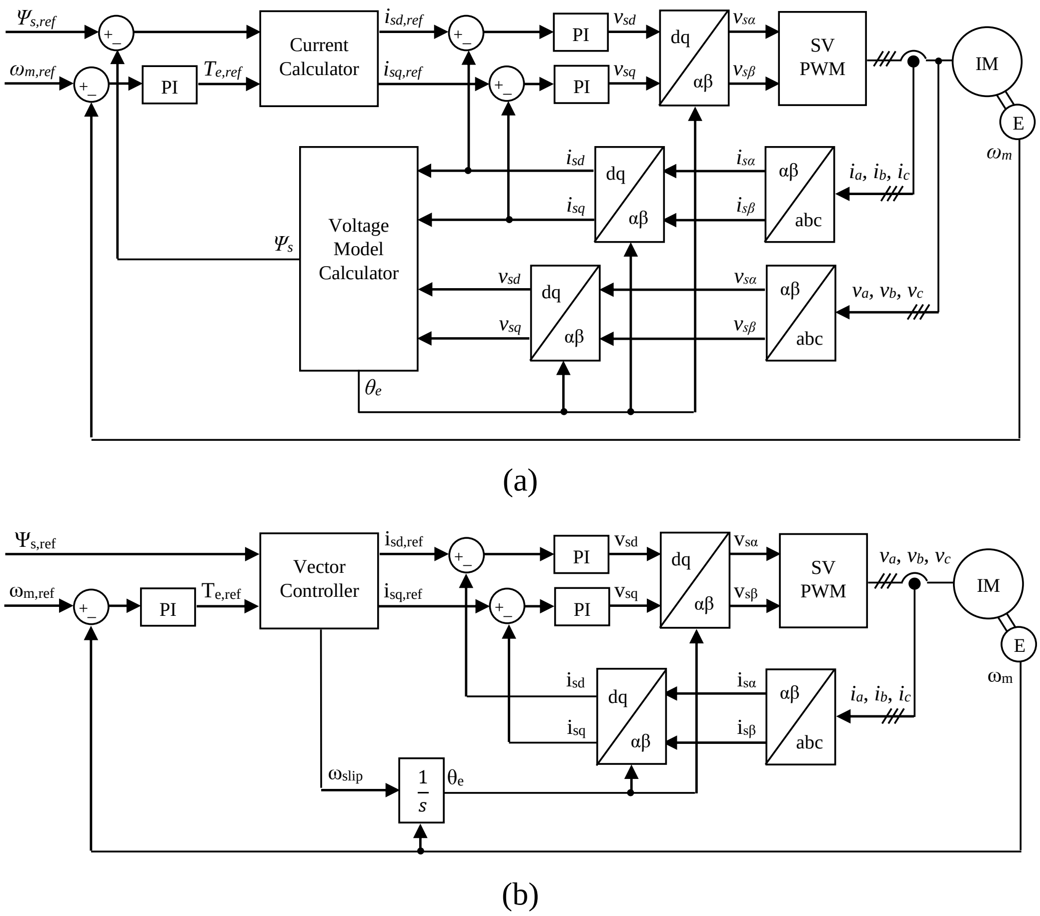


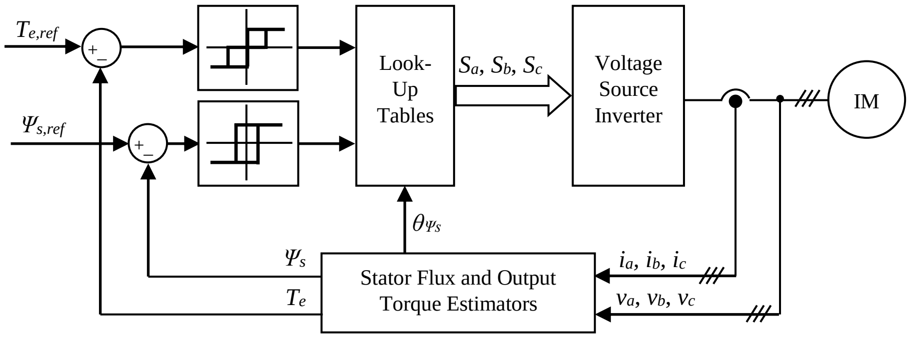
Figure 1.1 Control structures of (a) Direct FOC, and (b) Indirect FOC

In recent decades, the implementation of DTC using a permanent magnet synchronous machine (PMSM), which was introduced by Zhong *et al.* [15], is competing with the induction machine-based DTC. Since the field winding produced by the rotor circuit is substituted with the permanent magnet, the rotor copper loss is eliminated, leading to higher efficiency and more compact than the induction machine [2]. However, using a permanent magnet will increase the cost and might produce the demagnetisation effect that reduces the air-gap flux density in the machine. Even though it has higher efficiency compared to induction machines, recycling the devastated magnet material will cause another problem [16, 17] (e.g., global pollution and climate change), especially when it is used in large demand. In this work, the DTC for the induction machine is chosen; the focus is to improve the efficiency and dynamic torque of the basic DTC drive system by introducing some modifications to the existing control strategy.

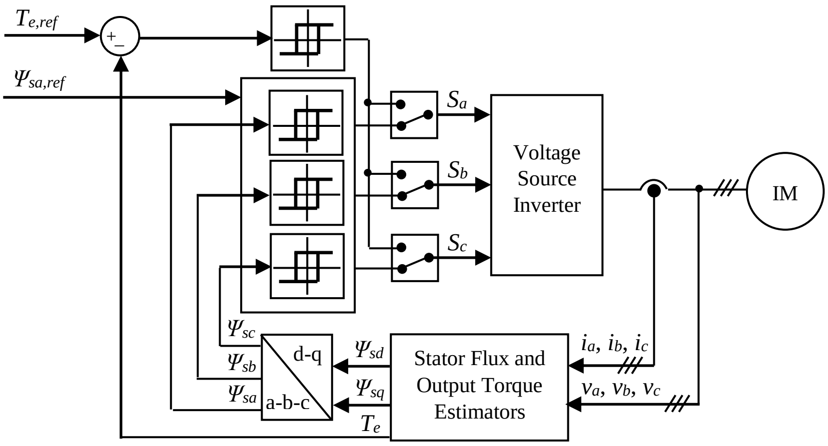
1.2 Overview of Direct Torque Controlled Induction Machine

DTC was introduced by Takahashi and Noguchi [11] as an alternative to the popular FOC for high-performance induction motor drive applications. As shown by Figure 1.2 (a), the main components of DTC for induction motor drive are a pair of hysteresis comparators (one for each torque and flux), a look-up table, a three-phase voltage source inverter (VSI), and a stator flux and motor torque estimators. The stator flux and motor torque are controlled directly and independently using the respective two-level and three-level hysteresis comparators. The outputs of the hysteresis comparators and stator flux position are used to select the voltage vectors from the look-up table. With a constant flux reference, the stator flux's locus is circular and bounded within its hysteresis band. DTC is typically used for low and medium-power applications with high switching frequencies.

An almost similar control strategy to DTC is known as Direct Self Control (DSC), which was invented by Depenbrock [10], is illustrated in Figure 1.2 (b). In DSC, the main components required are four hysteresis controllers (three for the flux and one for the torque), electronic signal selectors, a three-phase VSI, and the stator flux and motor torque estimators. The switching states are regulated based on the errors between the reference and the estimated stator flux for each phase. In order to produce the active voltage vectors, the switching states in each phase are monitored and triggered individually by a hysteresis comparator. The torque is controlled by another hysteresis comparator which is used to switch between an active voltage vector and a zero-voltage using the electronic signal selector. In the DSC scheme, the locus of the stator flux is hexagonal since the flux reference is compared with the instantaneous flux for each phase. DSC is more suitable for high-power applications where the switching frequency needs to be reduced. It is interesting to note that the switching pattern of DSC can be generated from DTC by increasing the width of the stator flux hysteresis (for DTC) so that the stator locus becomes hexagonal.



(a)



(b)

Figure 1.2 Control structures of (a) basic DTC, and (b) DSC

1.2.1 Direct Torque Control Drive System with Optimum Flux

Typically, for speed operation below base speed in high-performance induction motor drives, the flux reference is always set to the rated flux to produce a fast dynamics torque response. However, in most applications (such as traction applications, elevators, and machine tools) and at most of the time, the motor is operated at light load and operating at rated flux is unnecessary. In fact, operating the motor at rated flux under light load or unloaded conditions will reduce the efficiency of the drive system, and in the long term, the lifespan of the induction machine will shorten [18]. To maximise the DTC drive system's efficiency at light load or unloaded conditions, the motor is operated with optimal flux (lower than the rated flux) to reduce the power losses. However, when the flux is set to the optimal value, a fast instantaneous torque response cannot be achieved when a rated torque is suddenly needed; the degraded torque dynamic in some applications is unacceptable. Therefore, operating at optimum flux is not a good choice.

Based on the previous publications, the optimised stator flux can be attained by introducing the torque regulation controller [19-22], loss model controller (LMC) [11, 23-35], search controller (SC) [16, 18, 36-53] or a combination of them [4, 17, 54, 55]. In the torque regulation controller, the optimal flux is calculated according to the torque value, while in LMC, it is derived by considering the losses of the motor. At the light-loaded conditions, the rated flux in LMC must be reduced to balance the copper and iron losses. But decreasing the flux will decrease the iron loss and increase the copper loss. Therefore, the drive system's efficiency is maximised when the iron loss is approximately equal to the copper loss. By applying the SC method, the objective function is decreased by regulating the flux value in consecutive steps. The selected objective function can either be the input power or stator current. When the selected objective function is at its minimum, the optimised flux in SC is achieved. This method reduces the flux value from its rated to an optimal value by using a step flux. These controllers will be discussed in detail in Chapter 2 (section 2.4).

Meanwhile, the torque performance can be improved either by improving the dynamic torque response during the transient state [13, 42, 56-69] or reducing the torque ripple during the steady-state [13, 19, 39, 58, 59, 61-64, 67, 69-101]. To achieve this, the selection of voltage vectors (i.e., switching strategy) is modified since in DTC, the voltage vectors determine how fast the torque changes. In most of the methods proposed in the literature, the voltage vector is selected either by implementing the SVM, duty ratio modulation (DRM), fuzzy logic controller (FLC), neuro-fuzzy controller (NFC), or operating using two VSIs. The switching strategy of these methods in improving the torque response is further reviewed in Chapter 2 (section 2.5).

1.3 Problem Statement

DTC enables excellent stator flux and motor torque control without requiring a complex control algorithm. In optimum flux DTC, under light-load or unloaded conditions, the flux is set to an optimum value (lower than the rated) that minimises losses. When a step change in torque is suddenly needed (for instance, during acceleration), the flux reference will be increased to the rated value to ensure maximum torque capability. However, by doing so, the torque dynamic will be degraded due to the slow flux response, which is unacceptable in some applications, such as electric vehicles, traction drives, elevators, and high-performance machine tools. Furthermore, when the new steady-sate condition is reached after the transient, a new optimum flux has to be searched; typically, it will take some time before the new optimal flux is found. Therefore, the drive system's efficiency during the searching state is compromised. In DTC, unlike FOC, the torque and flux are not controlled via stator current components. Instead, torque and flux are controlled based on the selection of the voltage vectors. For this reason, the look-up table of the voltage vectors needs to be modified to improve the torque dynamic. Also, to eliminate the slow convergence problem, a new method that instantaneously generates the flux reference needs to be developed.

1.4 Objectives and Contributions of Thesis

The conventional method of determining the optimal flux value is non-instantaneous and is highly dependent on motor parameters. Thus, the efficiency of the drive during the searching state is compromised. Therefore, the first objective of this thesis is to develop a system that can generate flux reference instantaneously based on torque reference. This flux reference has to ensure the maximum efficiency operation of the DTC drive and is suitable for the proposed modified voltage vectors during the transient. Due to the step change in the flux reference, for example, when acceleration is needed, the dynamic torque response is degraded. Hence, the second objective of this thesis is to improve the torque dynamic of a maximum efficiency DTC of induction motor drive systems. To achieve this, the algorithm in selecting the voltage vectors needs to be modified and improved. To summarise, the objectives of the thesis are as follows:

i. To develop a system that produces instantaneous flux reference and can be used in the maximum efficiency DTC drive system.

ii. To improve the transient torque response of a maximum efficiency DTC of induction motor drive system.

Several aspects of these general objectives were explored and reported in this thesis. These include:

- Performing simulation and analysis on the efficiency of the DTC drive system under various operating conditions and subsequently proposing a technique to generate a High-Efficiency Flux Reference (HEFR). The flux reference can be instantaneously calculated and is almost similar to the optimal flux that minimises losses when the drive system is operated below its rated value.

- Performing simulation and analysis for the effect of different voltage vectors on the torque response. Based on the analysis, additional voltage vectors are proposed to satisfy the demands of stator flux and motor torque.

- Improving the torque response of maximum efficiency DTC drive system during transient states by modifying the selection of the voltage vectors. The proposed method generates the desired voltage vector based on the initial and final value of flux reference which is obtained from the HEFR generator.

- Developing a model of the maximum efficiency DTC drive system using MATLAB's Simulink, which is used to study the root cause of the problems. The simulation model is also used to verify the effectiveness of the proposed methods in improving the torque dynamic and efficiency of the DTC drive system.

- Constructing the hardware for DTC drive implementation. The main tasks of the DTC algorithm are implemented using the dSPACE DS1104 and Xilinx field-programmable gate array (FPGA) controller boards. The FPGA board is used primarily to implement conventional and the proposed look-up tables so that the execution time of the dSPACE controller can be reduced.

Based on the objectives and work performed in this thesis, the original contributions of the thesis are summarised as follows:

- A method to generate an instantaneous flux reference – called HEFR generator, was developed and specifically used during a step change in the torque reference of a maximum efficiency DTC drive system. The HEFR produces the flux reference based on the torque reference.

- A novel modification to the applied voltage vectors during the torque transient was developed. It consists of adjacent voltage vectors with a specific duty cycle.

- A simulation model specifically used to study the effectiveness of the proposed system was fully developed in MATLAB's Simulink environment. The simulation model can also be used to study the conventional maximum efficiency DTC drive system.

- An experimental setup for the DTC of induction motor drive was developed. The conventional and proposed control algorithms were implemented using a dSPACE DS1104 board and Basys 2 FPGA development board containing a Xilinx FPGA device. Verifications of the proposed techniques were performed using this experimental setup.

1.5 Scopes of Thesis

To ensure the smoothness and achievement of the objectives, this research work is executed in three stages. The limitations and scope of conducting the work are as follows:

First stage

An extensive simulation of the various flux searching algorithms and their performances is conducted and studied. Subsequently, based on this study, a HEFR system is proposed that can instantly compute a flux reference to maximise the efficiency of the DTC drive at light load. The HEFR is calculated based on the load torque of the induction machine. Due to the limited memory of dSPACE, the calculation of the drive's efficiency is unable to be conducted online (i.e., task overrun); instead, it is calculated based on the simulation results.

Second stage

In the second stage, a thorough study of the problem of sluggish torque response is conducted using the MATLAB. A detailed Simulink-based model is developed to identify the root cause of the problem. Subsequently, a modification to the voltage vectors is proposed to overcome the problem of the sluggish torque response during the transient-state. The application of the modified voltage vector is only performed for the transient-state and does not include the steady-state. Next, the HEFR and the proposed modified voltage vector are combined. Comprehensive simulations are conducted using MATLAB/Simulink to study the effectiveness of the proposed system.

Third stage

The verification of the proposed methods is implemented by using a laboratory-scale DTC drive setup. The experimental setup is constructed using a standard squirrel cage induction machine, a three-phase voltage source inverter (IGBT), gate drivers, current sensors and an incremental speed encoder. The control algorithm is implemented using a dSPACE DS1104 controller and Basys 2 Xilinx FPGA board. For safety purposes, the power supply is limited to a nominal value that is lower than the rated voltage. Fine-tuning on the DTC control algorithm and experimental setup are conducted to achieve the expected performance of the DTC drive system.

1.6 Organisation of Thesis

This thesis is arranged into six chapters. In the first chapter, the DTC drive system's background and development, as well as the problem statement, are presented. The previous works by other researchers to improve the two problems stated are briefly discussed and studied. The purposes for implementing this research work are also discussed in this chapter. For the rest of this thesis, it is classified as follows:

Chapter 2 presents the mathematical modelling of induction machines in space vector theory. It is implemented to overcome the complex analysis of a dynamic three-phase model, which is caused by the continuous rotation of the rotor windings. In this chapter, the principles of basic DTC are also discussed in detail. The two problems encountered during the optimisation of efficiency are highlighted and reviewed thoroughly in this chapter.

Chapter 3 proposes the HEFR and modified voltage vector methods in order to improve the two problems stated. The HEFR is computed based on the load applied to the induction motor. Instead of using motor torque, the torque reference is used in the HEFR calculation to reduce the flux ripples in HEFR. Meanwhile, the modified voltage vector is obtained by adding two adjacent conventional voltage vectors. To produce the modified voltage vector, the activation time of each conventional voltage vector is estimated according to the initial and final value of the flux reference.

Chapter 4 describes the implementation of the proposed DTC in MATLAB's simulation package. In the real-time experimental setup, the main tasks of DTC are compiled and executed in the dSPACE DS1104 and Xilinx FPGA controller boards.

Chapter 5 provides the simulation and real-time results for both basic and proposed DTC. The improvements in the proposed DTC are evaluated by comparing them to the basic DTC.

Chapter 6 concludes the proposed methods and provides the potential guidance for further research regarding this work.

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