DIRECT TORQUE CONTROL USING CASCADED H-BRIDGE MULTILEVEL INVERTER FOR INDUCTION MOTOR

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In the name of Allah, The Most Gracious and The Most Merciful.

To my beloved and supportive parents,

husband, Mohd Zaid Bin Puteh and daughter, Nurdiyana Farisha

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ABSTRACT

This thesis proposes methods to improve the performance of a Direct Torque Control (DTC) of induction motor drives. The basic principle and theoretical aspects of the DTC using a conventional inverter (DTC-Conv) and the DTC using a 5-level Cascaded H-Bridge Multilevel Inverter (DTC-CHMI) are reviewed with emphasis on two major problems: high torque and flux ripple and variable switching frequency. Based on the basic principle of the DTC, torque and flux are directly controlled by selecting appropriate voltage vectors. A DTC-Conv offers eight voltage vectors to increase (or decrease) both torque and flux. Regardless of the torque's demand, for the DTC-Conv, the application of voltage vector is limited to these eight voltage vectors. This will give a high torque and flux ripple because of the possible voltage vector selected is not optimal for the condition. Based on the investigation, by proposing the DTC-CHMI, a smaller torque and flux ripple can be achieved. Moreover this method offers a good torque response. This is due to the capability of the DTC-CHMI to offer 61 voltage vectors which give more options to choose the most optimum vector for any circumstances. In addition, less switching burden on the switching devices for the DTC-CHMI compared to DTC-Conv, which results in a lower power rating device to be used. It is well known that the implementation of the DTC-Conv consists of a hysteresis-based controller which results in a variable switching frequency in the switching devices. This undesirable condition will affect the inverter design since it is related to the rate of change of the torque which varies with various operating conditions. Therefore, this thesis proposes the proportional-integral controller constant switching frequency together with the DTC-CHMI to replace the DTC-Conv with a hysteresis-based controller. The proposed torque controller consists of three pairs of triangular carrier signals with three pairs of comparators. With this proposed controller, the variation of switching frequency can be narrowed and fixed at the carrier frequency. Furthermore, it minimizes the torque ripples. Design of the proposed controller is thoroughly discussed in this thesis. To verify the enhancement made by the proposed method, simulation and experiment, as well as the comparison with the DTC-Conv were carried out. Results prove that by using the proposed system, torque and flux ripple are reduced by 38.5% and 7.76% respectively. Apart from that, the switching frequency is fixed at 1.667 kHz and a less distorted sinusoidal phase current is obtained.

ABSTRAK

Tesis ini mencadangkan kaedah untuk meningkatkan prestasi bagi sebuah Kawalan Daya kilas Terus (DTC) untuk motor aruhan. Prinsip asas dan teori bagi DTC konvensional (DTC-Conv) dan DTC menggunakan penyongsang 5 aras berbilang tingkat terlata secara titian H (DTC-CHMI) diulangkaji dengan menekankan kepada dua masalah utama: riak daya kilas dan fluks yang tinggi dan frekuensi pensuisan yang berubah. Berdasarkan prinsip asas DTC, daya kilas dan fluks dikawal secara terus dengan memilih vektor voltan yang sesuai. DTC-Conv menawarkan lapan vektor voltan untuk menaikkan (atau menurunkan) daya kilas dan fluks. Tanpa mengira permintaan daya kilas, bagi DTC-Conv, penggunaan vektor voltan adalah terhad kepada lapan vektor voltan ini. Ini menghasilkan riak daya kilas dan fluks yang besar disebabkan kemungkinan vektor voltan yang dipilih tidak optimum bagi keadaan tersebut. Berdasarkan kajian ini, dengan mencadangkan DTC-CHMI, riak daya kilas dan fluks yang kecil dapat diperolehi. Tambahan pula kaedah ini menawarkan sambutan daya kilas yang pantas. Ini disebabkan oleh kemampuan DTC-CHMI menawarkan 61 vektor voltan yang memberi banyak pilihan vektor paling optimum dibuat bagi setiap keadaan. Ini ditambah dengan kurangnya bebanan ke atas peranti suis pada DTC-CHMI berbanding DTC-Conv, yang membolehkan penggunaan kadaran kuasa peranti yang rendah. Sudah diketahui bahawa perlaksanaan DTC-Conv menggunakan pengawal histeresis mengakibatkan frekuensi pensuisan yang berubah. Keadaan yang tidak diingini ini akan mempengaruhi reka bentuk penyongsang oleh kerana ia berkaitan dengan kadar perubahan daya kilas yang berubah mengikut keadaan operasi. Oleh itu, tesis ini mencadangkan pengawal kamiran berkadaran frekuensi pensuisan malar bersama dengan DTC-CHMI bagi menggantikan DTC-Conv dengan pengawal histeresis. Pengawal daya kilas yang dicadangkan ini mengandungi tiga pasang isyarat pembawa segitiga dan tiga pasang pembanding. Dengan pengawal ini, variasi frekuensi pensuisan akan malar pada frekuensi isyarat pembawa. Tambahan pula, ia meminimumkan riak daya kilas. Reka bentuk pengawal ini diterangkan secara mendalam di dalam tesis ini. Untuk menentusahkan peningkatan prestasi kaedah yang dicadangkan, simulasi dan ujikaji, dan juga perbandingan dengan DTC-Conv telah dijalankan. Keputusan membuktikan bahawa dengan menggunakan sistem yang dicadangkan, riak daya kilas dan fluks masing-masing berkurang sebanyak 38.5% dan 7.76%. Selain dari itu, frekuensi pensuisan malar pada 1.667kHz dan arus fasa sinus kurang herot diperolehi.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ASD	-	Adjustable Speed Drive
AI	-	Artificial Intelligence
CHMI	-	Cascaded H-Bridge Multilevel Inverter
DC	-	Direct Current
DCMI	-	Diode Clamped Multilevel Inverter
DTC	-	Direct Torque Control
FPGA	-	Field Programmable Gate Array
FCMI	-	Flying Capacitor Multilevel Inverter
FOC	-	Field Oriented Control
IM	-	Induction motor
DSP	-	Digital Signal Processing
m.m.f	-	Magnetomotive Force
NPC	-	Neutral Point Clamped
PI	-	Proportional-Integral
SFOC	-	Stator Field Oriented Controller
SVM	-	Space Vector Modulation
THD	-	Total Harmonic Distortion
VSI	-	Voltage Source Inverter
VHDL	-	VHSIC Hardware Description Language

LIST OF SYMBOLS

C_{p-p}	-	Peak-to-peak value of the triangular Carrier Signal
C_{Upper2}	-	Triangular number 3 of Upper Carrier Signal
C_{Upper1}	-	Triangular number 2 of Upper Carrier Signal
C_{Upper}	-	Triangular number 1 of Upper Carrier Signal
C_{Lower}	-	Triangular number 1 of Lower Carrier Signal
C_{Lower1}	-	Triangular number 2 of Lower Carrier Signal
C_{Lower2}	-	Triangular number 3 of Lower Carrier Signal
DT	-	Sampling Time
f_{tri}	-	Carrier Signal Frequency
$H_{\Psi,Upper1}$	-	Flux Hysteresis Upper Band 2
$H_{\Psi,Upper}$	-	Flux Hysteresis Upper Band 1
$H_{\Psi,Lower}$	-	Flux Hysteresis Lower Band 1
$H_{\Psi,Lower1}$	-	Flux Hysteresis Lower Band 2
$H_{T,Upper2}$	-	Torque Hysteresis Upper Band 3
$H_{T,Upper1}$	-	Torque Hysteresis Upper Band 2
$H_{T,Upper}$	-	Torque Hysteresis Upper Band 1
$H_{T,Lower2}$	-	Torque Hysteresis Lower Band 3
$H_{T,Lower1}$	-	Torque Hysteresis Lower Band 2
$H_{T,Lower}$	-	Torque Hysteresis Lower Band 1
$\bar{i_s}, \bar{i_r}$	-	Stator and rotor current space vector in stationary
	-	reference frame
i_{sd}, i_{sq}	-	d and q component of stator current in stationary reference
	-	frame
i_{rd}, i_{rq}	-	d and q component of rotor current in stationary reference
	-	frame
J	-	Moment of inertia
B	-	Viscous Friction
K_p	-	Proportional gain of the PI controller
K_i	-	Integral gain of the PI controller
L_m	-	Mutual inductance

L_s - Stator self-inductance

L_r - Rotor self-inductance

p - Number of pole

R_s, R_r - Stator and rotor resistance

Ψ^* - Stator flux reference

Ψ_{err} - Stator flux error

Ψ_{status} - Stator flux error status

Ψ_{est} - Estimated stator flux

T^* - Torque reference

T_{err} - Torque error

T_{status} - Torque error status

T_{est} - Estimated torque

T_c - PI controller output

$\bar{v_s}$ - Stator voltage space vector in stationary reference frame

V_{sd}, V_{sq} - d and q component of stator voltage in stationary reference frame

V_{aN}, V_{bN}, V_{cN} - Output phase voltage of CHMI for phase a, b and c

θ_{sr} - Difference angle between stator flux linkage and rotor flux linkage

$\bar{\Psi_s}, \bar{\Psi_r}$ - Stator and rotor flux linkage space vector in stationary reference frame

Ψ_{sd}, Ψ_{sq} - d and q component of stator flux linkage in stationary reference frame

ω_r - Rotor electrical speed in Rad/s

ω_m - Rotor mechanical speed in Rad/s

ω_e - Steady state synchronous frequency in Rad/s

ω_{slip} - Steady state slip frequency in Rad/s

σ - Total flux leakage factor

τ_r - Rotor time constant

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Electrical machines play an important role in the industry as well as in our daily life. It has been employed in almost every industrial and manufacturing process of various types and sizes. For example electrical machines can be used to provide electricity in a power plant or to provide mechanical work such as in steel mills, textiles mills, and similar industries.

There are three types of basic electrical machines; DC machines, induction machines and synchronous machines. These basic electrical machines can either be generators or motors. Owing to the fact that induction machines are maintenance free with a simple construction, reliable and rugged, they have been widely used in various industrial and manufacturing processes. This type of motor was initially constructed at the end of the 19^{th} century and improvements were made to its performance during the 20^{th} century, reaching maturity in the late 1930's [1]. In contrast to the DC machine, an induction machine can be used in an explosive, corrosive or any harsh environment since the latter has no problems with spark and corrosion due to the commutator and the brushes as experienced in the former.

Despite these advantages, the induction machines (IM) however, suffer from control problems when used in high-performance adjustable speed drive (ASD) applications. Controlling IM is considerably more complex than controlling DC machines. There are several ways to control an IM. It can be classified into two general control methods: scalar control and vector control. In scalar control, the variations in the control variables are only concerned with the magnitude and frequency of the voltage, current and flux linkage space vectors. Whereas, in the vector control, the variations in the control variables include the instantaneous position together with the magnitude and frequency of the voltage, current and flux linkage space vectors.

For IM, vector control is the most suitable control method when it is used in high-performance ASD applications. Based on the early works of F. Blaschke [2] and K. Hasse [3, 4], the Field Oriented Control (FOC) has been proposed as a high-performance control method for IM. This type of control is based on the rotor-flux oriented which means that the rotor-flux vector is the orienting vector of the controller. This method enables induction machines to emulate the separately excited DC machines and gives the induction machines high dynamic performance. Other than that, FOC also can be controlled based on the stator-flux orientation which is known as Stator Flux Oriented Control (SFOC) [5, 6]. In contrast to the rotor-flux FOC, SFOC does not require the knowledge of rotor speed. Therefore it is more robust to parameter variations and easier to implement [7]. However there is literatures that has reported drawbacks of using FOC as a control method such as poor dynamic response, high torque and flux ripples and the complexity of the system configuration due to the employment of a position sensor for coordinate transformation of the IM parameters.

1.2 Background of Direct Torque Control

In the early 1980s, an innovation of FOC has been created by I. Takahashi and T. Noguchi [8] and M. Depenbrock [9] by omitting the coordinate transformation block and replacing it with the hysteresis controller for the developed torque and stator flux. In addition, the approach for the inverter control is clearly different from that FOC. This control strategy is referred to as Direct Torque Control (DTC). This controller has continuously been improved and developed by many researchers since it was proposed in the early 1980s. As a result, in 1996, the first speed-sensorless DTC induction motor drive was introduced by ABB [10, 11]. This simple control scheme which offers a better high-performance torque control for the induction machine and it has gained popularity and continue expanding as a main vector control drives in industry applications.

The basic DTC configuration that was proposed by I. Takahashi and T. Noguchi is illustrated in Figure 1.1. It consists of a pair of hysteresis comparators, voltage model torque and flux estimator, look-up table for voltage vector selection and 3-phase voltage source inverter (VSI).

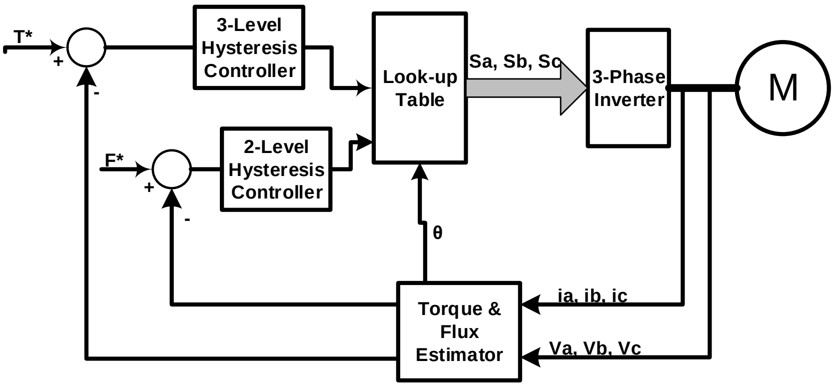

Figure 1.1: Basic DTC configuration

In the DTC scheme, the torque and stator flux are separately controlled using 3-level and 2-level hysteresis controllers, respectively. This control structure is also known as the decouple control. The main objective of this control method is to reduce the torque and stator flux errors to zero by using the hysteresis comparators. An appropriate voltage vector will be selected based on the stator flux orientation together with the torque and stator flux error status that is generated by the hysteresis controllers. In order to select an appropriate voltage vector, it is vital to have an accurate estimation of the flux and torque. Inaccurate estimation will result in irrelevant voltage vector selection.

Voltage model is the basic method for estimating the stator flux which does not require rotor speed parameter, i.e. only the stator resistance and terminal value (stator voltage and stator currents) are required. Hence, it provides a robust control of the DTC. However, this method is associated with noise in the voltage measurement, integration drift, and initial conditions' problem especially at low speed [12]. In the year 2002, an improvement in terms of the technique in the voltage model based on the stator flux estimation was introduced in [13]. This method has improved the stator flux estimation under steady state conditions which lead to a quite significant improvement in the DTC's performance. The current model is another method for the stator flux estimation which can solve the low speed problem. Nevertheless it needs an additional speed sensor or observer since this method requires the knowledge of rotor speed. In [8], a combination of voltage model and current model flux estimation using a simple first-order lag network have been applied in order to obtain an appropriate flux estimator for the entire speed range.

The device switching frequency in hysteresis-based DTC scheme is totally produced by the switching of the torque and flux hysteresis controller. According to the [14], it is clearly shown that the device switching frequency vary with the motor operating conditions (i.e. stator and rotor fluxes, rotor speed and DC link voltage). The variable device switching frequency is undesirable since it will create an unpredictable harmonics in the current flow. Furthermore the inverter maximum switching capability is not fully utilized since the selection of the hysteresis band's width is based on the system's extreme condition which is limited by the thermal ratings of the switching devices. As a result, the operation other than in extreme conditions is not optimized.

1.2.1 Variation of The DTC Implementation

Since DTC was introduced in mid 1986 [8], it has been experiencing continuous improvement and further development by many researchers throughout the years. Most of the research's major areas of concern on reducing the torque and flux ripple, achieving fast torque response and obtaining constant switching frequency. In order to achieve this, various methods have been proposed. The DTC with the Space Vector Modulation (SVM) [15, 16], the predictive control method [17, 18, 19] and the artificial intelligence (AI) control [20, 21, 22] are the popular non-hysteresis based techniques. It shows a great improvements to the DTC's performance and produce a constant switching frequency. However, these types of method will diminish the simple structure inherent in the DTC. In addition, these methods have increased the drive complexity which needs a faster processor to run it. Variable hysteresis band technique is another method that had been proposed to overcome the inherent drawbacks of the hysteresis-based DTC[14, 23, 24]. By adjusting the hysteresis controller's band-width according to the operating conditions, a constant switching frequency can be achieved. However this method does not guarantee the reduction of the flux and torque ripple, especially in discrete implementation due to the sample time selection [25].

The evolutions and improvements of the DTC scheme continue to emerge until now. Due to the rapid development on the high-power-medium-voltage in AC drive applications, the use of multilevel inverter in the AC drive has become more popular recently. As in the DTC scheme, a conventional 3-phase inverter has been replaced by a multilevel inverter. There are numerous technical papers that have shown the improved performance of the DTC using multilevel inverter.

By employing the multilevel inverter in the DTC scheme, it gives more options in choosing a voltage vector to control flux and torque. Several approaches of the torque and flux control and switching strategies have been proposed for the DTC using a multilevel inverter; hysteresis-based controller and non-hysteresis-based controller such as the space vector modulation (SVM) [26, 27, 28, 29, 30, 31, 32, 33], the predictive control strategy [34, 35, 36] and the fuzzy logic controller [37, 38, 39, 40]. The implementation of the hysteresis-based control strategy still faces a problem with the torque ripple especially in discrete implementation even with a small hysteresis band. This is due to the delay in the sampling time. On top of that, the variable switching frequency of the switching devices which leads to unpredictable harmonics current is also produced by implementing the hysteresis-based control strategy. As for the non-hysteresis-based control strategies, significant improvements in terms of flux and torque ripple and switching frequency are accomplished by using these control strategies. However, the use of complex mathematical equations and algorithms has led to the computational burden and complexity of the DTC using a multilevel inverter scheme especially when the level of voltage is increased. A detailed discussion of the DTC using a multilevel inverter will be given in Chapter 2.

1.3 Problem Statement

A major area of concern in the DTC scheme is reducing the torque and flux ripple, achieving faster torque response and obtaining constant switching frequency besides having a simpler control strategy. Traditionally, the DTC scheme is using a 3-phase inverter to supply the induction motor. In order to regulate the torque and flux value within its desired value, an appropriate voltage vector needs to be selected to correct the errors. However, this 3-phase inverter only can offer a limited voltage vector (8 voltage vectors) whereby these voltage vectors are used either to increase or decrease torque and/or flux regardless of the error size (large or small error). Hence, this produces a slow torque response and a high torque and flux ripple which causes an acoustic noise and vibration to the induction motor. Besides that, by having a high ripple of flux and torque, it will lead to a high ripple of the stator phase current which contains high harmonic components. This, in turn, causes high switching losses in the inverter and needs a higher rating for the switching devices due to the high peak current. Furthermore, the use of the hysteresis controller in the DTC using a 3-phase inverter will cause a variable device's switching frequency. This uncertain variations of switching frequency is undesirable since it will create an unpredictable harmonics in the current flow. Moreover, it will cause an inverter switching capability not to be fully utilized since the selection of the hysteresis band's width will be based on the system's extreme condition which is limited by the switching device's thermal ratings. As a results, the operation other than in the extreme conditions is not optimized.

1.4 Thesis Objective

The objective of this thesis is to study, implement and improve the performance of the DTC using a multilevel inverter for induction machines. The thesis proposes a method of improvements in terms of stator flux and torque ripple reduction, constant switching frequency, good dynamic response and less distortion in the stator phase current.

1.5 Thesis Contributions

While conducting the research, the thesis makes the following contributions:

- It proposes a multilevel hysteresis torque and flux controller for the DTC using a 5-level cascaded H-bridge multilevel inverter, which has further minimized the torque and flux ripple, faster torque response and smoother stator phase current compared to the conventional DTC scheme.
- It proposes a constant frequency torque controller to replace a multilevel hysteresis torque controller in [41], which results in constant torque switching frequency as well as the switching devices switching frequency, reduced torque ripple, enhanced torque and flux responses and smoother stator phase current.
- It develops a model for the proposed torque controller as a guide in selecting appropriate parameters for the controller. It includes averaging and linearizing the torque equations, and constructing the torque loop transfer function in the frequency domain.
- It develops a simulation and experimental set-up to verify the proposed controller schemes to DTC drive. The simulations are based on MATLAB and Simulink program from Mathworks, Inc. and the experimental set-up consist of dSpace DS1104 hardware platform as the main controller board and Altera DE2 FPGA. The main purpose of incorporating these DS1104 and DE2 FPGA board in the

experimental set-up is to minimize a sampling period of main controller board (DS1104) while operating the proposed controller schemes.

1.6 Scope of Research

This research focuses on implementing a 3-phase 5-level cascaded H-bridge multilevel inverter to a DTC scheme for a 3-phase induction motor. This study focuses on evaluating the enhancement of the DTC scheme with a 5-level cascaded H-bridge multilevel inverter performance in terms of reducing torque and flux ripple, achieving faster torque response and constant switching frequency compared to the DTC-conventional (DTC using 3-phase inverter). It will include a simulation study on the developed system through MATLAB/Simulink, followed by the experimental work to verify and evaluate the feasibility of the developed system. Both results are used to analyse the performance of the proposed system.

1.7 Organization of the Thesis

The thesis is organized as follows:

Chapter 2 describes the mathematical modelling of induction machines and the basic principles of DTC. Problems associated with the DTC in discrete implementation such as high torque ripple and flux ripple and variable switching frequency are discussed. This chapter also briefly reviews research development in DTC using a multilevel inverter for induction motors.

Chapter 3 discusses a methodology of the proposed DTC drives using a 5-level cascaded multilevel inverter for induction motors. There are two methods of DTC drives using 5-level cascaded multilevel inverter; a multilevel hysteresis torque and flux controller and a constant frequency torque controller. The procedure in developing both methods are discussed in this chapter.

Chapter 4 discusses a simulation and experimental set-up for a DTC using a 5-level cascaded multilevel inverter with a multilevel hysteresis torque and flux controller and DTC using 5-level cascaded multilevel inverter with constant frequency torque

REFERENCES

1. Amin, B. *Induction Motors : Analysis and Torque Control*. Springer - Verlag Berlin Heidelberg New York. 2001.
2. Blaschke, F. The principle of field orientation as applied to the new transvektor closed-loop control system for rotating-field machines. *Adjustable Speed AC Drive Systems*, 1972. 34: 201–220.
3. Hasse, K. On the dynamic behavior of induction machines driven by variable frequency and variable voltage sources. *ETZ Arch, Bd*, 1968. 89: 77–81.
4. Hasse, K. Control of cycloconverters for feeding asynchronous machines. *IFAC Conference on Control in Power Electronics and Drives, Dusseldorf*. 1977. 537–546.
5. Xu, X., De Doncker, R. and Novotny, D. W. A stator flux oriented induction machine drive. *19th Annual IEEE Power Electronics Specialists Conference (PESC'88)*. 1988. 870–876. Power Electronics Specialists Conference, 1988. PESC'88 Record., 19th Annual IEEE.
6. Xu, X. and Novotny, D. W. Implementation of direct stator flux orientation control on a versatile DSP based system. *IEEE Transactions on Industry Applications*, 1991. 27(4): 694–700.
7. Habetler, T. G., Profumo, F., Griva, G., Pastorelli, M. and Bettini, A. Stator resistance tuning in a stator-flux field-oriented drive using an instantaneous hybrid flux estimator. *IEEE Transaction on Power Electronics*, 1998. 13(1): 125–133.
8. Takahashi, I. and Noguchi, T. A new quick-response and high-efficiency control strategy of an induction motor. *IEEE Transactions on Industry Applications*, 1986. 22: 820–827.
9. Depenbrock, M. Direct self-control (DSC) of inverter-fed induction machine. *IEEE Transactions on Power Electronics*, 1988. 3(4): 420–429.
10. Tiitinen, P. and Surandra, M. The next generation motor control method, DTC direct torque control. *Proceedings of the 1996 International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*. IEEE.

1996, vol. 1. 37–43.

11. ABB. *Direct Torque Control - Technical Guide No. 1.* Technical report. ABB Industry Oy, Findland. 1999.

12. Hurst, K. D., Habetler, T. G., Griva, G. and Profumo, F. Zero-speed tacholess IM torque control: simply a matter of stator voltage integration. *IEEE Transactions on Industry Applications,*, 1998. 34(4): 790–795.

13. Idris, N. R. N. and Yatim, A. H. M. An improved stator flux estimation in steady-state operation for direct torque control of induction machines. *IEEE Transactions on Industry Applications*, 2002. 38(1): 110–116.

14. Casadei, D., Grandi, G., Serra, G. and Tani, A. Effects of flux and torque hysteresis band amplitude in direct torque control of induction machines. *20th International Conference on Industrial Electronics, Control and Instrumentation (IECON'94).* IEEE. 1994, vol. 1. 299–304. 20th International Conference on Industrial Electronics, Control and Instrumentation, 1994. IECON'94.

15. Rodriguez, J., Pontt, J., Silva, C., Kouro, S. and Miranda, H. A novel direct torque control scheme for induction machines with space vector modulation. *IEEE 35th Annual Power Electronics Specialists Conference (PESC).* 2004, vol. 2. 2004 IEEE 35th Annual Power Electronics Specialists Conference, 2004. PESC 04.

16. Lai, Y.-S. and Chen, J.-H. A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripple reduction. *IEEE Transactions on Energy Conversion*, 2001. 16(3): 220–227.

17. Kennel, R. and Linder, A. Predictive control of inverter supplied electrical drives. *IEEE 31st Annual Power Electronics Specialists Conference (PESC '00).* 2000, vol. 2. 2000 IEEE 31st Annual Power Electronics Specialists Conference, 2000. PESC 00.

18. Kennel, R., El-kholy, E. E., Mahmoud, S., El-refaei, A. and Elkady, F. Improved direct torque control for induction motor drives with rapid prototyping system. *Energy Conversion and Management*, 2006. 47(13): 1999–2010.

19. Casadei, D., Serra, G., Tani, A., Zarri, L. and Profumo, F. Performance analysis of a speed-sensorless induction motor drivebased on a constant-switching-frequency DTC scheme. *IEEE Transactions on Industry Applications*, 2003. 39(2): 476–484.

20. Cruz, P. P. and Paredes, J. P. S. Artificial intelligence applications in direct torque control. *The Fifth International Conference on Power Electronics and Drive Systems (PEDS)*. IEEE. 2003, vol. 2. 1208–1212.

21. Atas, M. and Okumus, H. I. Stator resistance estimation using ANN in DTC IM drives. *Turkish Journal of Electrical Engineering & Computer Sciences*, 2010. 18(2): 197–210.

22. Alagappan, P. and Dhanasekaran, R. Implementation Of Fuzzy Logic Based Direct Torque Control Of Induction Motor. *International Journal of Electrical and Electronics Engineering Advance Research*, 2014. 2: 183–187.

23. Kang, J. K., Chung, D. W. and Sul, S. K. Direct torque control of induction machine with variable amplitude control of flux and torque hysteresis bands. *International Conference on Electric Machines and Drives (IEMD'99)*. IEEE. 1999. 640–642. Electric Machines and Drives, 1999. International Conference IEMD'99.

24. Kaboli, S., Zolghadri, M. R. and Emadi, A. Hysteresis band determination of direct torque controlled induction motor drives with torque ripple and motor-inverter loss considerations. *IEEE 34th Annual Power Electronics Specialist Conference (PESC'03)*. IEEE. 2003, vol. 3. 1107–1111. Power Electronics Specialist Conference, 2003. PESC'03. 2003 IEEE 34th Annual.

25. Kaboli, S., Zolghadri, M. R. and Homaifar, A. Effects of sampling time on the performance of direct torque controlled induction motor drive. *IEEE International Symposium on Industrial Electronics (ISIE'03)*. IEEE. 2003, vol. 2. 1049–1052. Industrial Electronics, 2003. ISIE'03. 2003 IEEE International Symposium on.

26. Zhang, Y., Zhu, J., Zhao, Z., Xu, W. and Dorrell, D. G. An improved direct torque control for three-level inverter-fed induction motor sensorless drive. *IEEE Transactions on Power Electronics*, 2012. 27(3): 1502–1513.

27. Alloui, H., Berkani, A. and Rezine, H. A three level NPC inverter with neutral point voltage balancing for induction motors Direct Torque Control. *XIX International Conference on Electrical Machines (ICEM)*. IEEE. 2010. 1–6. Electrical Machines (ICEM), 2010 XIX International Conference on.

28. Wang, Y., Li, H. and Shi, X. Direct Torque Control with Space Vector Modulation for Induction Motors Fed by Cascaded Multilevel Inverters. *32nd Annual Conference on IEEE Industrial Electronics, (IECON)*. 2006. 1575–1579. IEEE Industrial Electronics, IECON 2006-32nd Annual Conference on.

29. del Toro Garcia, X., Arias, A., Jayne, M. G., Witting, P. A., Sala, V. M. and

Romeral, J. L. New DTC control scheme for induction motors fed with a three-level inverter. *Automatika-Zagreb-*, 2005. 46(1/2): 73.

30. Patil, U., Suryawanshi, H. and Renge, M. Torque Ripple Minimization in Direct Torque Control Induction Motor Drive Using Space Vector Controlled Diode-clamped Multi-level Inverter. *Electric Power Components and Systems*, 2012. 40(7): 792–806.

31. Sheng-wei, G. and Yan, C. Research on torque ripple minimization strategy for direct torque control of induction motors. *International Conference on Computer Application and System Modeling (ICCASM)*. IEEE. 2010, vol. 1. V1. Computer Application and System Modeling (ICCASM), 2010 International Conference on.

32. Kouro, S., Bernal, R., Miranda, H., Silva, C. A. and Rodriguez, J. High-performance torque and flux control for multilevel inverter fed induction motors. *IEEE Transactions on Power Electronics*, 2007. 22(6): 2116–2123.

33. Khoucha, F., Lagoun, M. S., Kheloui, A. and El Hachemi Benbouzid, M. A comparison of symmetrical and asymmetrical three-phase H-bridge multilevel inverter for DTC induction motor drives. *IEEE Transactions on Energy Conversion,*, 2011. 26(1): 64–72.

34. Urrejola, P., Perez, M., Rodriguez, J. and Trincado, M. Direct torque control of an 3L-NPC inverter-fed induction machine: A model predictive approach. *36th Annual Conference on IEEE Industrial Electronics Society (IECON)*. IEEE. 2010. 2947–2952. IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society.

35. Khoucha, F., Lagoun, S. M., Marouani, K., Kheloui, A. and El Hachemi Benbouzid, M. Hybrid Cascaded H-Bridge Multilevel-Inverter Induction-Motor-Drive Direct Torque Control for Automotive Applications. *IEEE Transactions on Industrial Electronics*, 2010. 57(3): 892–899.

36. Obermann, T. R., Hurst, Z. D. and Lorenz, R. D. Deadbeat-direct torque & flux control motor drive over a wide speed, torque and flux operating space using a single control law. *IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE. 2010. 215–222. Energy Conversion Congress and Exposition (ECCE), 2010 IEEE.

37. Mortezaei, A., Azli, N. A., Idris, N. R. N., Mahmoodi, S. and Nordin, N. M. Direct torque control of induction machines utilizing 3-level cascaded H-Bridge Multilevel Inverter and fuzzy logic. *IEEE Applied Power Electronics Colloquium (IAPEC)*. IEEE. 2011. 116–121.

38. Youb, L., Craciunescu, A. and Ciumbulea, G. A new fuzzy logic direct torque control scheme of induction motor for electrical vehicles application. *XIX International Conference on Electrical Machines (ICEM)*. IEEE. 2010. 1–6. Electrical Machines (ICEM), 2010 XIX International Conference on.

39. del Toro, X., Calls, S., Jayne, M. G., Witting, P. A., Arias, A. and Romeral, J. L. Direct torque control of an induction motor using a three-level inverter and fuzzy logic. *IEEE International Symposium on Industrial Electronics*. 2004, vol. 2. 923–927 vol. 2.

40. Liu, S.-X., Wang, M.-Y., Chen, Y.-G. and Li, S. A novel fuzzy direct torque control system for three-level inverter-fed induction machine. *International Journal of Automation and Computing*, 2010. 7(1): 78–85.

41. Nordin, N., Idris, N. and Azli, N. Direct Torque Control with 5-level cascaded H-bridge multilevel inverter for induction machines. *37th Annual Conference on IEEE Industrial Electronics Society (IECON)*. IEEE. 2011. 4691–4697.

42. Vas, P. *Vector Control of AC Machines*. Oxford University Press, New York. 1990.

43. Leonhard, W. *Control of Electrical Drives*. 3rd ed. Springer-Verlag Berlin Heidelberg New York. 2001.

44. Novotny, D. W. and Lipo, T. A. *Vector Control And Dynamics of AC Drives*. Oxford University Press Inc., New York. 1996.

45. Bose, B. K. *Power Electronics and AC Drives*. Prentice-Hall. 1986.

46. Casadei, D., Grandi, G., Serra, G. and Tani, A. Switching strategies in direct torque control of induction machine. *International Conference on Electrical Machines (ICEM)*. 1994. 204–209.

47. Elbuluk, M., Langovsky, N. and Kankam, M. D. Design and implementation of a closed-loop observer and adaptive controller for induction motor drives. *IEEE Transactions on Industry Applications*, 1998. 34(3): 435–443.

48. Jansen, P. L. and Lorenz, R. D. A physically insightful approach to the design and accuracy assessment of flux observers for field oriented induction machine drives. *IEEE Transactions on Industry Applications*, 1994. 30(1): 101–110.

49. Salem, F. B. and Derbel, N. Direct torque control of induction motors based on discrete space vector modulation using adaptive sliding mode control. *Electric Power Components and Systems*, 2014. 42(14): 1598–1610.

50. Karamanakos, P., Stolze, P., Kennel, R. M., Manias, S. and du Toit Mouton, H. Variable switching point predictive torque control of induction machines.

IEEE journal of emerging and selected topics in power electronics, 2014. 2(2): 285–295.

51. Adel, E. A. H., Salama Abo-Zaid, D. and Refky, A. Improvement Of Direct Torque Control Of Induction Motor Drives Using Neuro-Fuzzy Controller. *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, 2015. Vol. 2 Issue 10: 2913 – 2918.

52. Gawade, K. and Panchade, V. Simulation & Modelling of Direct Torque Control of Induction Motor Using Fuzzy Logic Controller. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering (IJIREEICE)*, 2016. 4(5): 60–64.

53. Venkataramana Naik, N. and Singh, S. Improved torque and flux performance of type-2 fuzzy-based direct torque control induction motor using space vector pulse-width modulation. *Electric Power Components and Systems*, 2014. 42(6): 658–669.

54. Haseeb, E. M. Torque ripple reduction in Direct Torque Control of induction motor using double fuzzy logic control. *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, 2016. Vol. 3 Issue 3: 4329–4334.

55. Singh, B., Jain, S. and Dwivedi, S. Torque ripple reduction technique with improved flux response for a direct torque control induction motor drive. *IET Power Electronics*, 2013. 6(2): 326–342.

56. Liu, X. and Zheng, A. New direct torque control of asynchronous motor with low ripple in torque and current, and quick response. *IEEE Transportation Electrification Conference and Expo Asia-Pacific (ITEC Asia-Pacific)*. IEEE. 2016. 100–105.

57. Kiran, T. V. and Amarnath, J. A sliding mode controller based DTC of 3 level NPC inverter fed induction motor employing space vector modulation technique. *International Conference on Advances in Engineering, Science and Management (ICAESM)*. IEEE. 2012. 372–377.

58. Gholinezhad, J. and Noroozian, R. Analysis of cascaded H-bridge multilevel inverter in DTC-SVM induction motor drive for FCEV. *Journal of Electrical Engineering and Technology*, 2013. 8(2): 304–315.

59. Boulouiha, H. M., Allali, A., Laouer, M., Tahri, A., Denai, M. and Draou, A. Direct torque control of multilevel SVPWM inverter in variable speed SCIG-based wind energy conversion system. *Renewable Energy*, 2015. 80: 140–152.

60. Khoucha, F., Marouani, K., Benbouzid, M., Kheloui, A. and Mamoune,

A. A 7-Level Single DC Source Cascaded H-Bridge Multilevel Inverter with a Modified DTC Scheme for Induction Motor-Based Electric Vehicle Propulsion. *International Journal of Vehicular Technology*, 2013. 2013: 1–9.

61. Wang, Y., Niimura, N. and Lorenz, R. D. Active braking schemes for low and high power induction machines using loss manipulation deadbeat-direct torque and flux control. *17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*. IEEE. 2015. 1–10.

62. Martins, C. A., Roboam, X., Thierry, A. M. and Carvalho, A. S. Switching frequency imposition and ripple reduction in DTC drives by using a multilevel converter. *IEEE Transactions on Power Electronics*, 2002. 12(2): 286 –297.

63. Rodríguez, J., Pontt, J., Kouro, S. and Correa, P. Direct torque control with imposed switching frequency in an 11-level cascaded inverter. *IEEE Transactions on Industrial Electronics*, 2004. 51(4): 827–833.

64. Prats, M. A. M., Escobar, G., Galvan, E., Carrasco, J. M. and Portillo, R. A switching control strategy based on output regulation subspaces for the control of induction motors using a three-level inverter. *IEEE Power Electronics Letters*, 2003. 1(2): 29–32.

65. Stolze, P., Karamanakos, P., Kennel, R., Manias, S. and Mouton, T. Variable switching point predictive torque control for the three-level neutral point clamped inverter. *15th European Conference on Power Electronics and Applications (EPE)*. IEEE. 2013. 1–10.

66. Oikonomou, N., Gutscher, C., Karamanakos, P., Kieferndorf, F. D. and Geyer, T. Model predictive pulse pattern control for the five-level active neutral-point-clamped inverter. *IEEE Transactions on Industry Applications*, 2013. 49(6): 2583–2592.

67. Rahmani, R., Langeroudi, N. M., Yousefi, R., Mahdian, M. and Seyedmahmoudian, M. Fuzzy logic controller and cascade inverter for direct torque control of IM. *Neural Computing and Applications*, 2014. 25(3-4): 879–888.

68. Islam, M. D., Reza, C. and Mekhilef, S. Modeling and Experimental Validation of 5-level Hybrid H-bridge Multilevel Inverter Fed DTC-IM Drive. *Journal of Electrical Engineering & Technology*, 2015. 10(2): 574–585.

69. Zhao, J., Zhang, Z., Ren, Y. and Li, X. A direct torque intelligent control strategy for induction motor based on matrix converter. *Australian Journal of Electrical and Electronics Engineering*, 2015. 12: 1–8.

70. Babu, K. R. and Khan, S. A. Reduction of Torque Ripple in Direct Torque Control of Induction Machines by Use of all Voltage Vectors of Matrix Converters. *International Journal of Science Engineering and Advance Technology (IJSEAT)*, 2014. 2(1): 001–007.

71. Kouro, S., Bernal, R., Miranda, H., Rodriguez, J. and Pontt, J. Direct Torque Control With Reduced Switching Losses for Asymmetric Multilevel Inverter Fed Induction Motor Drives. *41st IAS Annual Meeting Conference Record of the 2006 IEEE Industry Applications Conference*. 2006, vol. 5. Industry Applications Conference, 2006. 41st IAS Annual Meeting. Conference Record of the 2006 IEEE.

72. Bendyk, M., Hartman, M. and Jayne, M. Investigation of direct torque control system fed by modified cascade of multilevel voltage source inverter. *IEEE Compatibility in Power Electronics*, 2005. 2: 265–272.

73. Tan, Z., Li, Y. and Li, M. A direct torque control of induction motor based on three-level NPC inverter. *IEEE 32nd Annual Power Electronics Specialists Conference (PESC)*. 2001, vol. 3. 2001 IEEE 32nd Annual Power Electronics Specialists Conference, 2001. PESC.

74. Zaimeddine, R., Refoufi, L. and Berkouk, E. M. An Improved Direct Torque Control Strategy for Induction Motor Drive. *International Journal of Electrical and Power Engineering, Medwell Journals*, 2007. 1(1): 21 – 27.

75. Escalante, M. F., Vannier, J. C. and Arzande, A. Flying capacitor multilevel inverters and DTC motor drive applications. *IEEE Transactions on Industrial Electronics*, 2002. 49(4): 809–815.

76. Dharmaprakash, R. and Henry, J. Direct torque control of induction motor using three level diode clamped multilevel inverter. *International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC)*. IEEE. 2014. 206–212.

77. Dharmaprakash, R. and Henry, J. 3-Level Inverter Fed Direct Torque Control of Induction Motor Without Using Medium Vectors. *Applied Mechanics and Materials*. Trans Tech Publ. 2014, vol. 573. 150–154.

78. Brando, G., Dannier, A., Del Pizzo, A., Rizzo, R. and Spina, I. Generalised look-up table concept for direct torque control in induction drives with multilevel inverters. *Institution of Engineering and Technology (IET) Electric Power Applications*, 2015. 9(8): 556–567.

79. Priya, S., Suresh, A. and Rashmi, M. GCMT-249 Investigation and Performance Analysis of Direct Torque Control of 3Φ Induction Motor using

7 Level Neutral Point Clamped Multilevel Inverter. *Indian Journal of Science and Technology*, 2016. 9(24): 1–7.

80. Ahmadi, M. Z. R. Z., Jidin, A., Othman, M. N., Jopri, H. and Manap, M. Improved performance of Direct Torque Control of induction machine utilizing 3-level Cascade H-Bridge Multilevel Inverter. *International Conference on Electrical Machines and Systems (ICEMS)*. IEEE. 2013. 2089–2093.

81. Casadei, D., Serra, G. and Tani, A. Analytical investigation of torque and flux ripple in DTC schemes for induction motors. *23rd International Conference on Industrial Electronics, Control and Instrumentation (IECON 97)*. IEEE. 1997, vol. 2. 552–556.

82. Idris, N. and Yatim, A. Reduced torque ripple and constant torque switching frequency strategy for direct torque control of induction machine. *Fifteenth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE. 2000, vol. 1. 154–161.

83. Kang, J.-K. and Sul, S.-K. Analysis and prediction of inverter switching frequency in direct torque control of induction machine based on hysteresis bands and machine parameters. *IEEE Transactions on Industrial Electronics*, 2001. 48(3): 545–553.

84. Idris, N., Yatim, A., Muhamad, N. and Ling, T. Constant frequency torque and flux controllers for direct torque control of induction machines. *34th Annual IEEE Power Electronics Specialist Conference (PESC'03)*. IEEE. 2003, vol. 3. 1095–1100.

85. Sen, P. C. *Principles of electric machines and power electronics*. John Wiley & Sons. 2007.

86. Krause, P. C., Wasynczuk, O., Sudhoff, S. D. and Pekarek, S. *Analysis of electric machinery and drive systems*. vol. 75. John Wiley & Sons. 2013.

87. dSPACE GmbH. *DS1104 R&D Controller Board Hardware Installation and Configuration*. dSPACE GmbH. 2011. URL `http://www.dspace.com`.

88. Jamil, Y. *Laporan Kursus Pendek CHICHE Projek 629*. Technical report. Universiti Teknologi Malaysia. 1995.