AN ARTIFICIAL NEURAL NETWORK DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING MULTILEVEL INVERTER FOR TOTAL HARMONIC DISTORTION MINIMIZATION

CHIEN SIONG KAI

A thesis submitted in
fulfilment of the requirements for the award of the
Degree of Master of Engineering Technology

Faculty of Technology Engineering
Universiti Tun Hussein Onn Malaysia

SEPTEMBER 2023

"I dedicate this project to my beloved parents, my supervisor and all who involved directly and indirectly with thanks and grateful for supporting me all the time so that I can complete this report successfully."

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and gratitude to my supervisor, Ts. Dr. Sim Sy Yi for her supervision and professional guidance throughout the duration of my master project development. Appreciation also goes to everyone involved directly or indirectly towards the compilation of this project report, especially my parents who are willing to stand by my side and love me unconditionally. Without them, I am sure that I will be able to make it as the journey is not an easy one. I am very pleased to be able to deepen my knowledge and apply what I know to this project.

ABSTRACT

Direct Torque Control (DTC) is a method applied in Induction Motor (IM) drives to control the speed and torque of IM accurately and independently without a feedback signal. However, in Fast Fourier Transform (FFT) analysis, the Total Harmonic Distortion (THD) of the IM drives is high in the DTC method with a Conventional Inverter (CI). Therefore, a DTC IM drive with multilevel inverter (MLI) is proposed in this study with the aim of reducing THD without affecting the drive's performance, and preserve good speed and torque response of IM simultaneously. The proposed DTC IM drive with MLI based THD minimization has several advantages over the DTC IM drive with CI, including higher generated output voltage with low distortion, operation under low switching frequency, and working with renewable energy. In order to validate the effectiveness of the proposed MLI based THD minimization in DTC IM drive, MATLAB Simulink is used to investigate the response of the IM drive and THD under different operating conditions. Furthermore, the result from MATLAB Simulink is further verified by using real-time simulation of Typhoon HIL 402. From this study, the proposed MLI based THD minimization DTC IM drive is able to reduce THD with a maximum of 14% in low speed operation, 11% in medium speed operation and 2% in high speed operation as compared to DTC IM drive with CI. Therefore, the proposed MLI based THD reduction DTC IM drive shows the effectiveness of the proposed MLI in reducing the THD of the IM drive.

ABSTRAK

Kawalan tork terus (DTC) ialah kaedah yang digunakan dalam pemacu motor aruhan (IM) untuk mengawal kelajuan dan tork IM secara tepat dan bebas tanpa isyarat maklum balas. Walau bagaimanapun, dalam analisis transformasi *fast fourier* (FFT), jumlah herotan harmonik (THD) pemacu IM adalah tinggi dalam kaedah DTC dengan penyongsang konvensional (CI). Oleh itu, pemacu IM DTC dengan penyongsang berbilang peringkat (MLI) dicadangkan dalam kajian ini dengan tujuan untuk mengurangkan THD tanpa menjejaskan prestasi pemacu, dan mengekalkan kelajuan yang baik dan tindak balas tork IM secara serentak. Pemacu IM DTC yang dicadangkan dengan pengecilan THD berasaskan MLI mempunyai beberapa kelebihan berbanding pemacu IM DTC dengan CI, termasuk voltan keluaran terjana yang lebih tinggi dengan herotan rendah, operasi di bawah frekuensi pensuisan rendah dan berfungsi dengan tenaga boleh diperbaharui. Untuk mengesahkan keberkesanan pengecilan THD berasaskan MLI yang dicadangkan dalam pemacu IM DTC, *MATLAB Simulink* digunakan untuk menyiasat tindak balas pemacu IM dan THD di bawah keadaan operasi yang berbeza. Tambahan pula, hasil daripada *MATLAB Simulink* disahkan lagi dengan menggunakan simulasi masa nyata *Typhoon HIL 402*. Daripada kajian ini, cadangan pemacu DTC IM pengecilan THD berasaskan MLI mampu mengurangkan THD dengan maksimum 14% dalam operasi kelajuan rendah, 11 % dalam operasi kelajuan sederhana dan 2% dalam operasi kelajuan tinggi berbanding dengan pemacu IM DTC dengan CI. Oleh itu, pemacu IM DTC pengurangan THD berasaskan MLI yang dicadangkan menunjukkan keberkesanan MLI yang dicadangkan dalam mengurangkan THD pemacu IM.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

I_{ds} , I_{qs}	-	d and q axis of stator current
V_{ds} , V_{qs}	-	d and q axis of stator voltage
F_{ds} , F_{qs}	-	d and q axis of stator flux
ΔF	-	Flux error signal
ΔT	-	Torque error signal
R_s	-	Stator resistance
F_s	-	Flux magnitude
T_e	-	Torque
P	-	Number of poles
θ	-	Stator flux position angle
V_{dc}	-	DC voltage
ANN	-	Artificial Neural Network
CI	-	Conventional Inverter
DFOC	-	Direct Field-oriented Control
DFT	-	Discrete Fourier Transform
DSP	-	Digital Signal Processing
DTC	-	Direct Torque Control
FFT	-	Fast Fourier Transform
FOC	-	Field-oriented Control
HIL	-	Hardware-in-Loop
IFOC	-	Indirect Field-oriented Control
IM	-	Induction Motor

MLI	-	Multi-level Inverter
NN	-	Neural Network
NNDTC	-	Neural Network Direct Torque Control
PID	-	Proportional-Integral-Derivative
RDFT	-	Recursive Discrete Fourier Transform
SVPWM	-	Space Vector Pulse Width Modulation
THD	-	Total Harmonic Distortion
VFD	-	Variable Frequency Drive
VSI	-	Voltage Switching Inverter

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Electric motor drives have recently been recognized as one of the most promising motor systems due to their low energy consumption and reduced emissions. With some exceptions, the electric motor drive is the main source for the provision of mechanical energy in industry. Large energy efficiency potentials have been identified in electric motor drives with many saving options showing very short payback period and high-cost effectiveness.

An induction motor (IM) is an alternating current (AC) electric motor that is extensively used in industrial and household appliances that consume about 54% of the total consumed electrical energy [1]. IM consist of two parts which are the stator and rotor. The magnetic field of the stator winding induces the magnetic flux in the rotor to produce rotating torque on it. The rotor is connected to mechanical load devices by using the shaft [2]. The efficiency of IM is high when operated at rated speed and load torque [3]. However, for a variable load operation the application of the IM at rated flux will cause iron losses to increase excessively, thus total harmonic distortion (THD) will increase and efficiency will decrease dramatically. In order to reduce the iron losses, the flux level should be set lower than the rated flux, but this will increase the copper loss. Therefore, to optimize the efficiency of the IM drive system at partial load, it is essential to obtain the flux level that minimizes the total motor losses [1], [4].

IM drives that have speed control has enormous use in the industry sector. This IM drives occupy more than 75% of the load in the industry of any country [2]. High performance IM drives application needs high efficiency, low cost and simple control circuitry for the complete speed range [2]. There are two different approaches for IM drive efficiency optimization. The first approach uses analytical computation of motor losses to optimize the efficiency named as losses model controller method. This method has the main advantage that it does not require additional hardware but need accurate knowledge of motor parameters. The second approach will search the flux level gradually to obtain maximum efficiency that named as online or search efficiency optimization control method. This method has advantage that it is completely insensitive to motor parameters variation.

THD of IM drive is important since minimization of THD will increase the efficiency of the motor drive. THD variation analysis of current source inverter fed electric motor drive system during various fault conditions is carried out in [5] and it shows that THD increases during fault conditions. THD minimization can be done using various methods, out of which multi-level inverter (MLI) fed IM drive is preferably used to reduce THD in IM drive [6], [7]. This is because MLI are good power quality and higher voltage capability. MLI not only achieves a higher power rating but also enables the use of renewable energy sources [8].

1.2 Problem Statement

The reduction of energy consumption in IM through improvement in energy efficiency has become an important goal for energy saving. Basically, when an IM is operated at a rated condition, i.e. rated load torque and rated speed, the THD of the IM drive is minimum and efficiency of the motor is high and gives the best transient response. Unfortunately, when the motor operates at variable load, particularly at light load, the application of the motor at a rated operating point will cause the core loss to increase excessively, and this cause the THD to increase and efficiency to decrease dramatically due to the imbalance between iron and copper losses. Therefore, for a given operating point, the highest efficiency of IM can be achieved by minimizing losses by reducing magnetic flux or by programming the flux to obtain a balance between copper and iron losses. Direct torque control (DTC) is a control method that allows direct, accurate and independent control of the speed and torque of an induction motor without pulse encoder feedback from the motor shaft. Besides that, DTC control method also provides ease of implementation and control of IM at medium to high speed operation.

In addition, THD is one of the major power quality issues occurring in most of the IM drives. The significant effect of harmonics on IM that caused heating due to iron and copper losses and harmonic currents in the rotor leads to rotor heating and pulsating or reduced torque. THD variation analysis of inverter fed IM drive during various fault conditions has been carried out in some previous research shows that THD increases during fault conditions with the efficiency of IM drive decrease simultaneously [4]. Minimization THD of IM drive had proven a significant improvement in the performance and the efficiency of the motor drive. THD of the motor drive can be reduced by implementing MLI in the motor drive system. MLI is an inverter that operates by using multiple lower-level direct current (DC) voltages as an input to generate an alternating voltage at the output to feed as input of the IM. Besides that, MLI is an inverter that uses a series of semiconductors to generate higher output voltage with a better harmonic spectrum and achieves higher voltage with the stepped waveform in the maximum available device rating, which has recently increased interest in research and industry applications. Due to the low electromagnetic interference (EMI), high efficiency, and low switching losses, MLI is suitable for high power motor drive applications.

Furthermore, conventional PI torque controller used in classic DTC IM drive is regularly indicated with poor load disturbance rejection and longer rise-time during start-up response. This is due to the PI controller gain cannot be set to a desired value. Neural network torque controller has been proposed to replace the conventional PI torque controller to overcome the poor performance of the PI torque controller. Neural network was inspired from the successful function of human brain and can be defined as a data processing system that consists of a large number of simple and highly interconnected processing elements named artificial neurons which compute values from input to solve wide variety of complicated problems. Neural network is chosen to proposed in this study due to the advantages of neural network has the ability to categorize data patterns, the capabilities to imitate approximate function and potentially parallel to complex hardware implementation.

1.3 Objectives

This research embarks on the following objectives:

i. To proposed MLI DTC IM drive to minimize and analyse the THD of IM drive systems for different operating condition.
ii. To proposed an artificial neural network (ANN) torque controller to further minimize and analyse THD of IM drive for different operating condition.
iii. To evaluate the effectiveness and robustness of the proposed MLI based THD minimization towards the drive system's improvements and the system performances by Matlab Simulink and Typhoon HIL 402 verification.

1.4 Project Scopes

The scopes of this research project are as follows:

i. Minimize the THD with the implementation of cascaded H-bridge MLI to improve the performance and power quality for DTC IM drive system by reducing rotor heating and improving the torque of IM in three different conditions which are the constant speed with a constant load, step speed with a constant load, and constant speed with step load.
ii. Analyse THD of IM drive system with ANN torque controller to ensure the effectiveness of NN torque controller in reducing THD at any operating point over the entire torque and speed range as compared to proportional-integral (PI) torque controller.
iii. Matlab Simulink and experiment with Typhoon HIL 402 is conducted to evaluate the effectiveness and robustness of the proposed THD minimization towards the drive system efficiency and system performance.

1.5 Project Contribution

In this master research project, the aim is to reduce the THD of DTC IM drive with a conventional inverter (CI) since THD minimization can increase the drive efficiency. To overcome the THD of the IM drive with CI, cascaded H-bridge MLI is choose to use in this project to reduce the THD of the IM drive at three different condition including the constant speed with a constant load, step speed with a constant load, and constant speed with step load. The effectiveness and robustness of MLI in reducing the THD of IM drive are observed and analyze by using software simulation with Matlab Simulink and experiment with Typhoon HIL 402 and a comparison is made between DTC IM drive with CI and proposed MLI based THD reduction DTC IM drive. Besides that, the project is further conducted by changing PI torque controller of the proposed MLI based THD reduction DTC IM drive to NN torque controller to observe and analyze the torque performance and THD minimization of the DTC IM drive.

1.6 Report Outlines

This project is divided into five main chapters. Firstly, chapter 1 is the introduction of this project that include the introduction, problem statement, objectives, project contribution and project scope. Secondly, chapter 2 presents of literature review that discusses and reviews the previous studies and theories related to this project. This chapter also describe the fundamental of IM, variable frequency drive (VFD) with scalar control and vector control, THD and ANN. Thirdly, chapter 3 discusses the details of the methodology which consists of the problem formulation as well as the proposed MLI based DTC IM drive. This chapter also describes the hardware development of the proposed MLI based DTC IM drive with the use of Typhoon HIL 402. Fourthly, chapter 4 presents the result and analysis of the DTC IM in terms of THD minimization at different speed operation done in Matlab Simulink and Typhoon HIL 402. Lastly, chapter 5 concludes the whole project in summary and a recommendation is written for the purpose of improvement and suggestion for the upcoming research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Basically, motor can be classified into two types, namely AC motor that powered by alternating current and DC motor that powered by direct current. Both AC and DC motor used electrical current to generate rotating magnetic field, in turn, generate rotational mechanical force in the armature. However, AC motors are generally more powerful than DC motors because they can generate higher torque by using more powerful current.

Figure 2.1 shows the overall IM control system that generally consists of four main parts: IM, inverter, control system and load. IM works by converting electrical energy to mechanical energy, which is widely used in numerous applications such as industrial sectors, electric home appliances, electric vehicles, etc., accounting for approximately 60% of the total industrial electricity [9], [10]. Furthermore, IM has several advantages, including being easy to maintain due to its simple structure, reliability, efficiency maximization, and cost minimization [11], [12]. Therefore, IM has been used to replace DC motors due to DC motors are difficult to maintain, corrode and spark when rotating [12]–[14]. However, there is difficulty in controlling the speed, torque and flux of IM due to the complex design of IM and the nonlinear model [15], [16]. Therefore, scalar and vector control are two major methods developed to control the IM [17], [18].

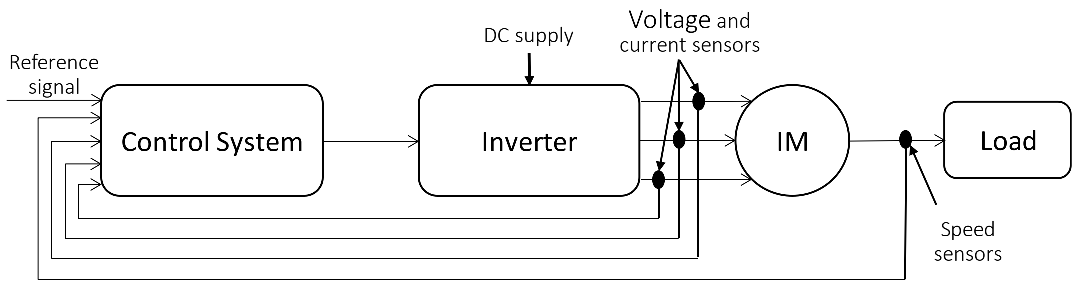

Figure 2.1: Architecture of the IM control system [19]

From several research studies of the scalar control method by researchers, the scalar control method has the advantages of its simple structure, cost minimization, simple and easy design, and low steady-state error [8], [12], [15], [17], [20]. Moreover, scalar control method performs well in controlling medium to high speed without IM parameters [21]. Research studies claim that many researchers used scalar control method in controlling IM (using digital-signal-processing (DSP)) [20], single-phase IM [22], five-phase IM [23] and permanent magnet synchronous motors (using DSP) [24], [25].

Conversely, vector control method with high capability in controlling IM over scalar control method is a frequently used control scheme in previous research studies [23], [26]. The working principle of vector control method in controlling IM is obtaining the magnitude of amplitudes and frequency voltages. Thus, the vector control method controlled the position of flux, voltage and current vector. However, IM controller increase in difficulty and complexity with vector control method due to the coupling between electromagnetic torque and flux, and it also affected by the sensitivity of IM parameter. The coupling between the electromagnetic torque and flux can be solved by field-oriented control (FOC) and DTC [23], [25]. Blaschke proposes two control techniques in FOC namely direct field-oriented control (DFOC) in 1972 [27], and indirect field-oriented control (IFOC) proposed by Hasse in 1968 [27]. The main objective of both direct and indirect FOC is to obtain the torque and flux decoupling even with their complex mathematical equation for IM.

2.2 Variable Frequency Drives (VFDs)

Several control method has been focused on the control of IM before the invention of variable frequency drive. In 1946, the performance of a transient IM was investigated using analog computer is done by Charp and Weygandt during a survey of IM control development [19]. Further in 1956, silicon-controlled rectifier was invented by Bell Laboratories for motor control [19]. Following in 1959, new analysis in a study the transient IM of rotating frames was performed by Kovacs and Racz [19]. During 1960s, semiconductor revolution was happening with the development of power electronic devices to support the design of several power electronic converters and switching techniques used to control IM drive. Accordingly, the design and development of VFD methods in numerous research bodies for control purposes. IM was investigated in terms of speed control improvement, strategy implementation for motor control, and energy efficiency maximization. The challenging issues of IM control for nonlinear dynamic systems such as changes in resistance value due to heating of rotor resistance, and difficulties in measuring rotor flux and currents should be addressed. VFD can be divided into two main methods, which are scalar control and vector control methods as shown in Figure 2.2, according to IM speed, torque, flux, voltage, and current control [28], [29].

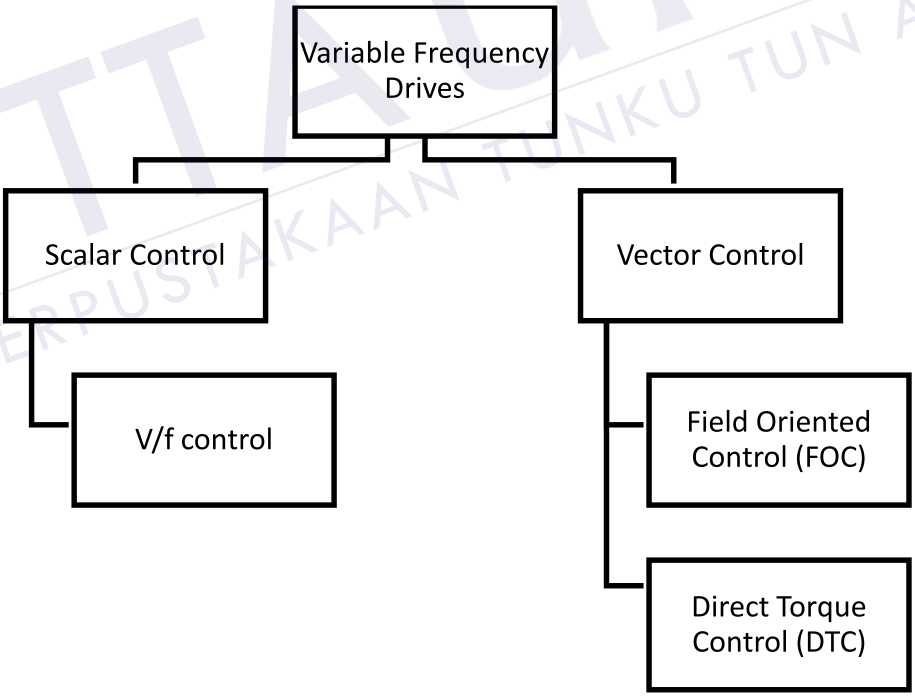

Figure 2.2: Categorization of variable frequency drive methods

2.2.1 Scalar Control

V/f control is a type of scalar control that was introduced in 1960 for IM control which

REFERENCES

1. A. H. M. Yatim and W. M. Utomo, “Efficiency Optimization of Variable Speed Induction Motor Drive Using Online Backpropagation,” in *2006 IEEE International Power and Energy Conference*, 2006, pp. 441–446.
2. J. Wadibhasme, S. Zaday, and R. Somalwar, “Review of various methods in improvement in speed, power & efficiency of induction motor,” in *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, 2017, pp. 3293–3296.
3. W. M. Utomo *et al.*, “An improved DTC of an induction motor drive with neural network controller,” *Int. J. Mech. Mechatronics Eng.*, vol. 14, no. 2, pp. 54–59, 2014.
4. W. M. Utomo, S. Y. Sim, Z. A. Haron, A. A. Bohari, and N. M. Zin, “Online adaptive flux control for space vector PWM-DTC IM drives towards optimum efficiency design,” *ARPN J. Eng. Appl. Sci.*, vol. 10, no. 19, pp. 9099–9105, 2015.
5. V. Sharma and G. Mendiratta, “Harmonic analysis of CSI-fed induction motor drive,” in *2014 International Conference on Computing for Sustainable Global Development (INDIACom)*, 2014, pp. 321–325.
6. S. Y. Sim *et al.*, “Enhance cascaded H-bridge multilevel inverter with artificial intelligence control,” *Indones. J. Electr. Eng. Comput. Sci.*, vol. 11, no. 1, pp. 105–112, 2018.
7. W. M. W. M. Utomo *et al.*, “Modeling of A Single Phase 7-Level Cascaded H-Bridge Multilevel Inverter,” *Int. J. Eng. Technol.*, vol. 7, no. 2, pp. 327–330, 2018.
8. P. Kant and B. Singh, “Power Quality Improvement in Sensorless Direct Torque Controlled Induction Motor Drive,” *2018 5th IEEE Uttar Pradesh Sect. Int. Conf. Electr. Electron. Comput. Eng. UPCON 2018*, Dec. 2018.

9. A. Liyanage, M. Nagrial, A. Hellany, and J. Rizk, “Speed Control of Induction Motors Using V/f Control Method,” *2022 Int. Conf. Electr. Comput. Technol. Appl. ICECTA 2022*, pp. 424–429, 2022.

10. R. Marino, P. Tomei, and C. M. Verrelli, “An adaptive tracking control from current measurements for induction motors with uncertain load torque and rotor resistance,” *Automatica*, vol. 44, no. 10, pp. 2593–2599, 2008.

11. A. Pugachev and A. Kosmodamianskiy, “Induction motor scalar control system with power losses minimization,” *2019 Int. Conf. Ind. Eng. Appl. Manuf. ICIEAM 2019*, Mar. 2019.

12. A. M. A. Abbas and A. A. H. Khamis, “Direct Torque Control of a Series-Connected Induction Motor,” *2021 IEEE 1st Int. Maghreb Meet. Conf. Sci. Tech. Autom. Control Comput. Eng. MI-STA 2021 - Proc.*, pp. 41–46, May 2021.

13. N. Wang, H. Yu, and X. Liu, “DTC of induction motor based on adaptive sliding mode control,” *Proc. 30th Chinese Control Decis. Conf. CCDC 2018*, pp. 4030–4034, Jul. 2018.

14. R. J. Wai and K. M. Lin, “Robust decoupled control of direct field-oriented induction motor drive,” *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 837–854, 2005.

15. M. Sreejeth, M. Singh, and P. Kumar, “Efficiency optimization of vector controlled induction motor drive,” *IECON Proc. (Industrial Electron. Conf.*, pp. 1758–1763, 2012.

16. S. Rafa, A. Larabi, L. Barazane, M. Manceur, N. Essounbouli, and A. Hamzaoui, “Implementation of a new fuzzy vector control of induction motor,” *ISA Trans.*, vol. 53, no. 3, pp. 744–754, 2014.

17. M. Suetake, I. N. Da Silva, and A. Goedtel, “Embedded DSP-based compact fuzzy system and its application for induction-motor V/f speed control,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 3, pp. 750–760, 2011.

18. G. Satyanarayana, M. Karthikeyan, R. Mahalakshmi, and T. Vandarkuzhali, “Vector Control of an Induction Motor for Speed Regulation,” *Proc. - 7th Int. Conf. Comput. Methodol. Commun. ICCMC 2023*, pp. 1621–1625, 2023.

19. M. A. Hannan, J. A. Ali, A. Mohamed, and A. Hussain, “Optimization techniques to enhance the performance of induction motor drives: A review,”

Renew. Sustain. Energy Rev., vol. 81, no. September 2016, pp. 1611–1626, 2018.

20. T. H. Dos Santos, A. Goedtel, S. A. O. Da Silva, and M. Suetake, “Scalar control of an induction motor using a neural sensorless technique,” *Electr. Power Syst. Res.*, vol. 108, pp. 322–330, 2014.
21. B. S. Winslet, K. Preethi, K. S. Krishna, and J. S. V. Prasad, “Performance of Induction Motor using V/F Control Technique,” *MysuruCon 2022 - 2022 IEEE 2nd Mysore Sub Sect. Int. Conf.*, 2022.
22. G. S. Ilango and N. Rajasekar, “An improved energy saving v/f control technique for solar powered single-phase induction motor,” *Energy Convers. Manag.*, vol. 50, no. 12, pp. 2913–2918, 2009.
23. R. Hedjar, P. Boucher, and D. Dumur, “Robust nonlinear receding-horizon control of induction motors,” *Int. J. Electr. Power Energy Syst.*, vol. 46, no. 1, pp. 353–365, 2013.
24. G.-D. Andreescu, C.-E. Coman, S.-C. Agarlita, and I. Boldea, “Stable V/f control system with controlled power factor angle for permanent magnet synchronous motor drives,” *IET Electr. Power Appl.*, vol. 7, no. 4, pp. 278–286, 2013.
25. C. E. Coman, S. C. Agarlita, and G. D. Andreescu, “V/f control strategy with constant power factor for SPMSM drives, with experiments,” *SACI 2013 - 8th IEEE Int. Symp. Appl. Comput. Intell. Informatics, Proc.*, no. 4, pp. 147–151, 2013.
26. A. Ammar, A. Kheldoun, B. Metidji, B. Talbi, T. Ameid, and Y. Azzoug, “An Experimental Assessment of Direct Torque Control and Model Predictive Control Methods for Induction Machine Drive,” *Proc. 2018 3rd Int. Conf. Electr. Sci. Technol. Maghreb, Cist. 2018*, Jan. 2019.
27. T. Sawa, “History and Visions for the Future ---,” 2004.
28. M. A. Aazmi, M. I. Fahmi, M. Z. Aihsan, H. F. Liew, and M. Saifizi, “A review on VFD Control and Energy Management System of Induction Motor for Electric Vehicle,” *19th IEEE Student Conf. Res. Dev. Sustain. Eng. Technol. Towar. Ind. Revolution, SCOReD 2021*, pp. 36–41, 2021.
29. C. M. F. S. Reza, M. D. Islam, and S. Mekhilef, “A review of reliable and energy efficient direct torque controlled induction motor drives,” *Renew. Sustain.*

Energy Rev., vol. 37, pp. 919–932, 2014.

30. I. M. Alsofyani and N. R. N. Idris, “A review on sensorless techniques for sustainable reliablity and efficient variable frequency drives of induction motors,” *Renew. Sustain. Energy Rev.*, vol. 24, pp. 111–121, 2013.
31. M. Demirtas, “DSP-based sliding mode speed control of induction motor using neuro-genetic structure,” *Expert Syst. Appl.*, vol. 36, no. 3 PART 1, pp. 5533–5540, 2009.
32. Z. Yin, J. Luo, C. Du, X. Lei, and C. Bai, “Research on Finite-Time Control Strategy for Induction Motor Drives Based on Vector Control,” *2020 IEEE 9th Int. Power Electron. Motion Control Conf. IPEMC 2020 ECCE Asia*, pp. 2287–2291, Nov. 2020.
33. M. Ahmad, “Vector Control of Induction Motor Drives,” vol. 3, no. 2, pp. 47–75, 2010.
34. M. N. Uddin and M. M. Rahman, “Online Torque-Flux Estimation-Based Nonlinear Torque and Flux Control Scheme of IPMSM Drive for Reduced Torque Ripples,” *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 636–645, Jan. 2019.
35. T. I and N. T., “A new quick-response and high-efficiency control strategy of an induction motor,” *IEEE Trans. Ind. Appl.*, vol. 22, no. 5, pp. 820–827, 1986.
36. S. Gudhe and B. B. Pimple, “Improved torque response of induction motor drive using direct torque control technique applying Fuzzy Logic Control,” *1st IEEE Int. Conf. Power Electron. Intell. Control Energy Syst. ICPEICES 2016*, pp. 1–6, 2017.
37. P. J. Koratkar and A. Sabnis, “Comparative analysis of different control approaches of direct torque control induction motor drive,” *2017 Int. Conf. Intell. Comput. Instrum. Control Technol. ICICICT 2017*, vol. 2018–Janua, no. 3, pp. 831–835, 2018.
38. C. Fahassa, M. Akherraz, M. Jamma, A. Bennassar, and Y. Zahraoui, “Intelligent Hybrid Controller and Artificial,” 2017.
39. M. R. Pawar and P. A. Jhala, “Direct Torque Control of Induction Motor Drives,” *Ijireeice*, vol. 4, no. 1, pp. 108–111, 2016.
40. K. H. Nam, “Dynamic Modeling of Induction Motors,” *AC Mot. Control Electr. Veh. Appl.*, pp. 85–107, 2018.

41. M. Malinowski, K. Gopakumar, J. Rodriguez, and M. A. Perez, "A survey on cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197–2206, Jul. 2010.

42. M. Keddar, M. L. Doumbia, M. Della Krachai, K. Belmokhtar, and A. Midoun, "Interconnection Performance Analysis of Single Phase Neural Network Based NPC and CHB Multilevel Inverters for Grid-Connected PV Systems," vol. 9, no. 3, 2019.

43. A. A. Hossam-Eldin, E. Negm, M. S. Elgamal, and K. M. AboRas, "Operation of grid-connected DFIG using SPWM- and THIPWM-based diode-clamped multilevel inverters," *IET Gener. Transm. Distrib.*, vol. 14, no. 8, pp. 1412–1419, Apr. 2020.

44. S. Choudhury, S. Nayak, T. P. Dash, and P. K. Rout, "A comparative analysis of five level diode clamped and cascaded H-bridge multilevel inverter for harmonics reduction," *Int. Conf. Technol. Smart City Energy Secur. Power Smart Solut. Smart Cities, ICSESP 2018 - Proc.*, vol. 2018–January, pp. 1–6, Jun. 2018.

45. S. Shi, X. Wang, S. Zheng, Y. Zhang, and D. Lu, "A new diode-clamped multilevel inverter with balance voltages of DC capacitors," *IEEE Trans. Energy Convers.*, vol. 33, no. 4, pp. 2220–2228, Dec. 2018.

46. M. F. Escalante, J. C. Vannier, and A. Arzandé, "Flying capacitor multilevel inverters and DTC motor drive applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 809–815, 2002.

47. M. Humayun, M. M. Khan, M. U. Hassan, and W. Zhang, "Analysis of hybrid switches symmetric flying capacitor multilevel inverter based STATCOM," *Int. J. Electr. Power Energy Syst.*, vol. 131, no. March, p. 107054, 2021.

48. S. Coday, A. Barchowsky, and R. C. N. Pilawa-Podgurski, "A 10-level gan-based flying capacitor multilevel boost converter for radiation-hardened operation in space applications," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, pp. 2798–2803, 2021.

49. M. Humayun, M. M. Khan, A. Muhammad, J. Xu, and W. Zhang, "Evaluation of symmetric flying capacitor multilevel inverter for grid-connected application," *Int. J. Electr. Power Energy Syst.*, vol. 115, no. August 2019, 2020.

50. C. B. Barth *et al.*, “Design and Control of a GaN-Based, 13-Level, Flying Capacitor Multilevel Inverter,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 8, no. 3, pp. 2179–2191, 2020.

51. T. Abhilash, K. Annamalai, and S. V. Tirumala, “A Seven-Level VSI with a Front-End Cascaded Three-Level Inverter and Flying-Capacitor-Fed H-Bridge,” *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 6073–6088, Nov. 2019.

52. M. Chithra and S. G. B. Dasan, “Analysis of cascaded H bridge multilevel inverters with photovoltaic arrays,” *2011 Int. Conf. Emerg. Trends Electr. Comput. Technol. ICETECT 2011*, pp. 442–447, 2011.

53. C. I. Odeh, A. Lewicki, and M. Morawiec, “A Single-Carrier-Based Pulse-Width Modulation Template for Cascaded H-Bridge Multilevel Inverters,” *IEEE Access*, vol. 9, pp. 42182–42191, 2021.

54. M. A. Memon, M. D. Siddique, M. Saad, and M. Mubin, “Asynchronous Particle Swarm Optimization-Genetic Algorithm (APSO-GA) based Selective Harmonic Elimination in a Cascaded H-Bridge Multilevel Inverter,” *IEEE Trans. Ind. Electron.*, 2021.

55. E. J. Lee, S. M. Kim, and K. B. Lee, “Modified phase-shifted PWM scheme for reliability improvement in cascaded H-bridge multilevel inverters,” *IEEE Access*, vol. 8, pp. 78130–78139, 2020.

56. S. Maurya, D. Mishra, K. Singh, A. K. Mishra, and Y. Pandey, “An Efficient Technique to reduce Total Harmonics Distortion in Cascaded H- Bridge Multilevel Inverter,” *Proc. 2019 3rd IEEE Int. Conf. Electr. Comput. Commun. Technol. ICECCT 2019*, Feb. 2019.

57. P. Bhatnagar, R. Agrawal, and K. K. Gupta, “Reduced device count version of single-stage switched-capacitor module for cascaded multilevel inverters,” *IET Power Electron.*, vol. 12, no. 5, pp. 1079–1086, May 2019.

58. R. Kumar Bindal and I. Kaur, “Comparative analysis of different controlling techniques using direct torque control on induction motor,” *Proc. 2016 2nd Int. Conf. Next Gener. Comput. Technol. NGCT 2016*, no. October, pp. 191–196, 2017.

59. H. Khan, S. Hussain, and M. A. Bazaz, “Neural network modulation for a Direct Torque controlled Induction Motor Drive,” *2015 IEEE Student Conf. Res. Dev. SCOReD 2015*, pp. 461–466, 2015.

60. K. Bouhoune, K. Yazid, M. S. Boucherit, and B. Nahid-Mobarakeh, “Simple and Efficient Direct Torque Control of Induction Motor Based on Artificial Neural Networks,” *2018 IEEE Int. Conf. Electr. Syst. Aircraft, Railw. Sh. Propuls. Road Veh. Int. Transp. Electrif. Conf. ESARS-ITEC 2018*, pp. 1–7, 2019.

61. S. Y. Sim, W. M. Utomo, Z. A. Haron, A. A. Bohari, N. M. Zin, and R. M. Ariff, “Neural network SVPWM-DTC of induction motor for EV load model,” *Proc. - 2014 Electr. Power, Electron. Commun. Control Informatics Semin. EECCIS 2014. conjunction with 1st Jt. Conf. UB-UTHM* , vol. 00, no. c, pp. 23–28, 2014.

62. Z. Mekrini and S. Bri, “High - Performance using neural networks in direct torque control for asynchronous machine,” *Int. J. Electr. Comput. Eng.*, vol. 8, no. 2, pp. 1010–1017, 2018.

63. S. Hussain, H. Khan, and M. A. Bazaz, “Neural Network Observer for Sensorless Direct Torque Controlled Induction Motor Drive,” *2018 Int. Conf. Power Energy, Environ. Intell. Control. PEEIC 2018*, pp. 835–840, 2019.

64. P. Ponce, A. Molina, and A. Tellez, “Neural network and fuzzy logic in a speed close loop for DTC induction motors,” *2014 Int. Caribb. Conf. Devices, Circuits Syst. ICCDCS 2014 - Conf. Proc.*, pp. 1–7, 2014.

65. “THD Analysis of Output Voltage for VSI fed Induction Motor Drives,” no. 4, pp. 130–133, 2014.

66. J. Ahmad *et al.*, “Performance Analysis and Hardware-in-the-Loop (HIL) Validation of Single Switch High Voltage Gain DC-DC Converters for MPP Tracking in Solar PV System,” *IEEE Access*, vol. 9, pp. 48811–48830, 2021.

67. Q. B. Dang, N. Di. Ngoc, V. H. Phuong, and M. C. Ta, “Implementation of frequency-approach-based energy management for EVs using typhoon HIL402,” *2019 IEEE Veh. Power Propuls. Conf. VPPC 2019 - Proc.*, Oct. 2019.

68. A. Brandis, D. Pelin, Z. Šimić, and I. Vidošić, “ATmega2560 MCU Space Vector Modulation Implementation on Three-phase Inverter and Validation via Typhoon HIL 402,” *Proc. Int. Conf. Smart Syst. Technol. SST 2022*, pp. 285–290, 2022.

69. V. P. Chandran, S. Kumar, and P. S. Bhakar, “Comparative Study for Steady-State Operation of IAG in Stand-Alone mode using MATLAB and Typhoon

HIL," *Proc. - 2018 3rd Int. Conf. Internet Things Smart Innov. Usages, IoT-SIU 2018*, Nov. 2018.

70. R. Collin, M. Stephens, and A. Von Jouanne, "Development of SiC-Based Motor Drive Using Typhoon HIL 402 as System-Level Controller," *ECCE 2020 - IEEE Energy Convers. Congr. Expo.*, pp. 2689–2695, Oct. 2020.

71. S. L. Kaila and H. B. . Jani, "Direct Torque Control for Induction Motor Using SVPWM Technique," *Natl. Conf. Recent Trends Eng. Technol. Direct*, no. May, 2011.

VITA

The author was born in June 29, 1994, in Sarawak, Malaysia. He went to Sekolah Menengah Kebangsaan Bandar Bintulu, Sarawak, Malaysia for his secondary school. He pursued his degree at the University Tun Hussein Onn Malaysia, and graduated with the B.Eng. (Hons) in Electronic Engineering (Mechatronic) in 2019. Upon graduation, he then enrolled at the University Tun Hussein Onn Malaysia, in 2019, where he was awarded the Master in Engineering of Technology in 2023. During this time, he was a research assistant with the research gap about minimize harmonic distortion of induction motor drive.