Overview: Model predictive control techniques for controlling induction motor based on vector control

Moataz M. A. Alakkad[1], Md. Hairul Nizam Talib[1], Zulhani Rasin[1], Jurifa Mat Lazi[1], Muhammad Haziq Md. Jamal[1], Zainuddin Mat Isa[2]
[1]Faculty of Electrical Technology and Engineering (FTKE), Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis, Arau, Malaysia

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ABSTRACT

This paper presents a comprehensive review of electric induction motor (IM) drive systems. It conducts an evaluation and critical analysis of modern control techniques aimed at enhancing induction motors or IM drive performance, drawing insights from a systematic literature survey. This review paper introduces the mathematical and dynamic models of induction motors and control via two-level inverter drives. Furthermore, the paper offers an extensive review of model predictive control (MPC) for induction motors which is considered a vector control (VC) technique. The MPC are subdivision based on control parameters into two modes, model predictive current control (MPCC) and model predictive torque control (MPTC). The paper thoroughly examines each control technique, providing insights into mathematical control analysis, block diagrams, and operational mechanisms, as well as the advantages and disadvantages associated with the method. The model predictive control (MPC) stands out due to its distinct advantages, particularly in terms of simplicity, accuracy, and efficiency.

Corresponding Author:

Md Hairul Nizam Talib
Faculty of Electrical Technology and Engineering (FTKE), Universiti Teknikal Malaysia Melaka
Melaka,76100 Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia
Email: hairulnizam@utem.edu.my

1. INTRODUCTION

The induction motors (IMs) stand out as the most prevalent choice for electric drive systems due to their affordability in manufacturing and maintenance. IMs exhibit robustness under diverse operational and environmental conditions, making them suitable for hazardous environments [1]. However, IMs are known for their nonlinear mechanical characteristics and historical challenges in speed control, limiting their use to industries without stringent speed control requirements. Advancements in power electronics and microprocessor technologies have ushered in various speed control techniques for IMs [2]. The model predictive control (MPC) represents a highly advanced and evolving technique for electric motor control. Over the past few decades, MPC has undergone significant advancements and gained prominence [3]. In the context of MPC, it is important to note that there are two distinct topologies: Model predictive torque control (MPTC) and model predictive current control (MPCC). MPC stands out for its ability to optimize control actions over a finite prediction horizon. It leverages a mathematical model of the system to predict the future behavior of the motor and utilizes this information to compute optimal control inputs [4]. MPC considers various constraints and objectives, allowing for precise tuning of motor performance while ensuring that operational limits are not exceeded. It is particularly valuable in applications where dynamic and constrained motor control is essential, adapting to varying operating conditions and providing precise control of motor behavior [4]-[8].

MPTC and MPCC are two subcategories of MPC, each tailored to specific control objectives. MPTC primarily focuses on optimizing the torque production of the motor, ensuring that it operates at peak efficiency while adhering to operational limits [9]. On the other hand, MPCC centers on controlling the stator currents of the motor, enabling fine-grained control over the motor's electrical characteristics [10]. Both MPTC and MPCC offer unique advantages and are suited to various motor control applications, further expanding the capabilities of MPC in the field of electric drives and motors. This paper contributes and congregates the advantages and disadvantages of vector control strategies, especially MPC techniques. The main challenges of the motor drive techniques centered on the time response and the resultant torque ripple as well as the total harmonic distortion of output current. The previous work of induction motor drives was focused on proposed several models in order to minimize both time response and the resultant torque ripple.

In this paper: i) section 2 discusses the mathematical model and dynamic model for the induction motor, ii) section 3 declares the mathematical model for two-level three-phase inverters for induction motor drives, and iii) section 4 focuses on classifying the MPC technique for the induction motor and they advantage and disadvantages.

2. INDUCTION MOTOR

The mathematical model of an induction motor can be simplified using space-vector theory, converting three-phase variables into vector quantities [11]. Following the magnitude invariant principle, the equations for a squirrel-cage induction motor are as (1)-(5) [12]. Where V_s are stator voltage. ψ_s and ψ_r are stator flux and rotor flux, respectively. I_s and I_r are stator current and rotor current, respectively. R_s and R_r are stator resistance and rotor resistance, respectively. L_s, L_r and L_m are stator inductance and rotor Inductance, mutual Inductance, respectively. ω are electrical speed. p are a number of pole pairs. T are electromagnetic torque.

$$V_s = R_s.I_s + \frac{d\psi_s}{dt} \tag{1}$$

$$0 = R_s.I_s + \frac{d\psi_r}{dt} - j.\omega.\psi_r \tag{2}$$

$$\psi_s = L_s.L_s + L_m.I_r \tag{3}$$

$$\psi_r = L_r.L_r + L_m.I_s \tag{4}$$

$$T = \frac{3}{2}.p.|\psi_s.I_s| \tag{5}$$

The dynamic model of an induction motor can be expressed differently depending on the reference frame selected. Using the stator reference frame and considering the direct and quadrature components (dq-axis) for stator current (i_s) and rotor flux ψ_r as state variables. The dynamic equations can be formulated in state-space representation using complex vector notation as in (6) and (7) [13]. These equations provide an accurate description of the electromagnetic behavior of the induction machine and involve four state variables, two inputs, and two outputs [14]. Where X are the components of state variables, u are the components of input stator voltage and y are the components of the output stator current.

$$X(t) = A.x(t) + B.u(t) \tag{6}$$

$$Y(t) = C.x(t) + D.u(t) \tag{7}$$

Matrices A, B, C, and D can be determined as (8)-(14).

$$X = [i_{sd} \quad i_{sq} \quad \psi_{sd} \quad \psi_{sq}] \tag{8}$$

$$u = [V_{sd} \quad V_{sq}]^T \tag{9}$$

$$Y = [i_{sd} \quad i_{sq}]^T \tag{10}$$

$$A = \begin{bmatrix} \frac{-1}{\tau_\sigma} & 0 & \frac{K_r}{R_\sigma.\tau_\sigma.\tau_r} & \frac{K_r}{R_\sigma.\tau_\sigma}.\omega_r \\ 0 & \frac{-1}{\tau_\sigma} & \frac{-K_r}{R_\sigma.\tau_\sigma}.\omega_r & \frac{K_r}{R_\sigma.\tau_\sigma.\tau_r} \\ \frac{L_m}{\tau_r} & 0 & \frac{-1}{\tau_r} & \omega_r \\ 0 & \frac{L_m}{\tau_r} & \omega_r & \frac{-1}{\tau_r} \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} \frac{1}{R_\sigma.\tau_\sigma} & 0 \\ 0 & \frac{1}{R_\sigma.\tau_\sigma} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{12}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{13}$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{14}$$

In which k_r is the rotor coupling factor that can be defined as in (15), R_σ represents the equivalent resistance that can be defined as in (16), L_σ is the leakage inductance of the machine that can be defined as in (17), τ_σ is the stator transient time constant that can be defined as in (18), and τ_r is the rotor time constant that can be defined as in (19).

$$K_r = \frac{L_m}{L_r} \tag{15}$$

$$R = K_r^2.R_r \tag{16}$$

$$L_\sigma = L_r\left(1 - \frac{L_m^2}{L_r}\right) \tag{17}$$

$$\tau_\sigma = \frac{L_\sigma}{R_\sigma}\tau_\sigma = \frac{L_\sigma}{R_\sigma} \tag{18}$$

$$\tau_r = \frac{L_r}{R_r} \tag{19}$$

Hence, the physical-mathematical model of an induction motor is described as (20)-(24) [15].

$$\frac{di_{sd}}{d\tau} = -\frac{1}{\tau_\sigma}.i_{sd} + \omega_s.i_{sq} + \frac{K_r.\psi_{rd}}{R_\sigma.\tau_\sigma.\tau_r} + \frac{u_{sd}}{R_\sigma.\tau_\sigma} \tag{20}$$

$$\frac{di_{sq}}{d\tau} = -\omega_s.i_{sq} - \frac{1}{\tau_\sigma}.i_{sq} - \frac{\omega K_r.\psi_{rd}}{R_\sigma.\tau_\sigma} + \frac{u_{sq}}{R_\sigma.\tau_\sigma} \tag{21}$$

$$\frac{d\psi_{rd}}{d\tau} = -\frac{1}{\tau_\sigma}.\psi_{rd} + \frac{L_m}{\tau_r}.i_{sd} \tag{22}$$

$$\frac{d\omega}{dt} = \frac{f_d}{J_e}.\omega + \frac{3p}{2L_r.J_e}.\psi_{rd}.i_{sq} - T_L \tag{23}$$

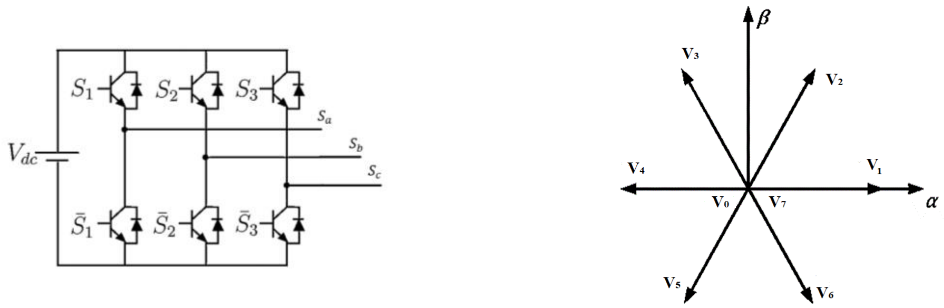
$$\frac{d\theta}{dt} = \omega \tag{24}$$

For model parameter notation, ω are motor shaft velocity; θ are motor shaft angle; ω_s are synchronous speed; J_e and f_d are inertia and friction coefficient, respectively; p are number of pole pairs; T_L are load torque.

3. INVERTER MODEL

In general, the inverter model is classified into two main types based on the waveform power output. These types are centered in two-level output voltage source inverters (2L-VSI) and multilevel output voltage source inverters (ML-VSI) [16]. The 2L-VSI has fixed structure topology which can change only based on the number of output phases. On other hand the ML-VSI have several topologies that can classified based on structure topology and the number of output levels [17]. The inverter converts the DC power into a variable-frequency AC output, allowing precise control of the motor's speed and torque [18]. The Inverters provide the ability to control the speed of the motor by varying the frequency and voltage of the AC output. This is crucial in applications where the motor needs to operate at different speeds or ramp up and down smoothly, such as in industrial processes, heating, ventilating, and air-conditioning (HVAC) systems, or electric vehicles [19], [20]. It enables energy-efficient operation by adjusting the motor's speed and power output according to the load requirements. By running the motor at the optimal speed for the task, energy consumption is minimized, resulting in energy and cost savings. This allows for precise control of motor parameters, including speed, torque, and direction [21]. This level of control is valuable in applications where accuracy and consistency are paramount, such as robotics and conveyor systems. Moreover, the inverters can gradually start and stop the motor, reducing mechanical stress and wear and tear. This soft-start capability extends the motor's lifespan and reduces maintenance costs [22], [23].

The 2L-VSI is widely used in drive applications for inverting electrical power into AC form due to the simplicity of producing the signal control, high dynamic performance, and extensive availability [24]. In a typical drive configuration of this inverter type is utilized to provide power to an induction machine are shown in Figure 1(a) that consists of two switches per phase resulting in a total of eight possible switching states for a three-phase system, as outlined in Table 1. These switching states are determined by the gating signals S_a, S_b, and S_c [25]. This inverter configuration can generate eight distinct voltage vectors, as depicted in Figure 1(b).



(a) (b)

Figure 1. Two levels voltage source inverter where (a) is the two-level three-phase inverter circuit diagram and (b) is the vector control diagram

Table 1. Two levels voltage source inverter switching state

Phase switches	Voltage vector							
	V_0	V_1	V_2	V_3	V_4	V_5	V_6	V_7
S_a	0	1	1	0	0	0	1	1
S_b	0	0	1	1	1	0	0	1
S_c	0	0	0	0	1	1	1	1

The system allows for the identification of six active voltage vectors (V_1, V_2, V_3, V_4, V_5, and V_6) and two zero vectors (V_0 and V_7) within this system. The different switching states can be represented using a vector notation, as (25).

$$S = \frac{2}{3}(S_a + S_b.\alpha + S_c.\alpha^2) \tag{25}$$

Where $\alpha = e^{j2\pi/3}$. Therefore, the output voltage space vectors that can be generated by the two-level voltage source inverter are defined as (26).

$$V = \frac{2}{3}(v_a + v_b.\alpha + v_c.\alpha^2) \tag{26}$$

Where v_a, v_b, and v_c are the phase voltages of the inverter. These can be computed in relation to the switching states $S_{a,b,c}$ as (27) [26].

$$V_{a,b,c} = V_{dc}.S_{a,b,c} \tag{27}$$

These output voltage vectors (v_a, v_b and v_c) are expressed in a stationary αβ-frame. To convert this voltage into a synchronous dq-frame aligned with the rotor flux, the Clarke transformation method is utilized. This method facilitates the calculation of the applied stator voltage, which can be expressed as (28). Where the Clarke transformation coefficient can be expressed as (29).

$$V_{a,b,c} = V_{dc}.S_{abc}.T_{clarke} \tag{28}$$

$$T_{clarke} = \frac{2}{3}\begin{bmatrix} 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \end{bmatrix} \tag{29}$$

4. MODEL PREDICTIVE CONTROL (MPC)

The MPC is a highly efficient strategy for controlling a wide range of industrial applications. It has proven to be effective in managing processes with various characteristics, including those with long delay times, nonminimum phase behavior, instability, multivariable interactions, constraints, and even complex and hybrid systems [27]. The fundamental concept behind predictive control is to utilize a plant model to predict future system outputs. Based on these predictions, an online optimization process is used at each sampling interval to compute a sequence of future control inputs. This sequence is designed to optimize tracking performance while adhering to any imposed constraints. However, only the first control input from this sequence is applied to the plant. This process is repeated in a receding horizon fashion at each subsequent sampling interval [28].

MPC has gained widespread adoption in the industry as an effective approach for addressing complex multivariable control problems with constraints. The MPC algorithm relies primarily on three key elements: the internal dynamic model of the process, a history of past control moves, and the optimization cost function applied over the prediction horizon [3]. In practice, there are two primary types of MPC controllers, which are categorized based on the reference parameters used for control prediction: model predictive torque control (MPTC) and model predictive current control (MPCC) [29].

4.1. Model predictive current control (MPCC)

In this type of MPC, the cost function substituted the inner current of PI controller based on the current error. It also called predictive field-oriented controller (PFOC) due to the controlling of the motor parameters is based on the stator current as like the FOC controller [30]. Figure 2 shows the block diagram of the MPCC technique that consists of two PI controllers that are used to control the torque and flux of current components, Park to Clarke angle transformation that is used to convert the current form d-q components reference frame into α-β component to use as input parameter of cost function [31]. The cost function predicates the optimum voltage vector and generates the best pulse width modulation signal [29]. The pulse width modulation signal is used to control the voltage source inverter (VSI).

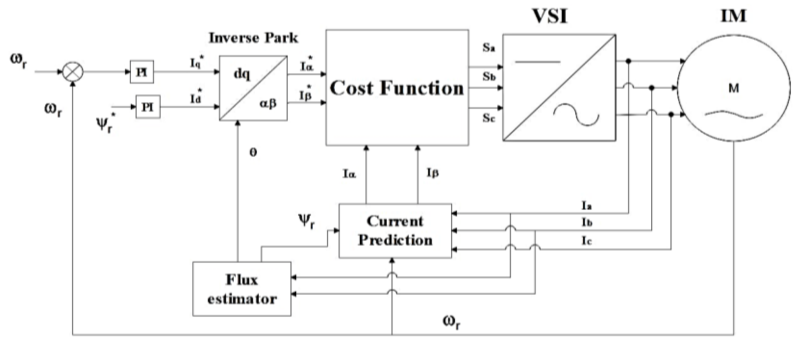


Figure 2. The block diagram of the MPCC technique

The reference stator current can be calculated from both of torque reference and rotor flux reference in which the i_d are purely depends on the rotor flux reference which can be calculated as (30)-(34) [10]. While i_q are depends on both of rotor flux reference and torque reference which can be calculated as (30)-(34).

$$i_d^{ref} = \frac{\left|\psi_r^{ref}\right|}{L_m} \tag{30}$$

$$i_q^{ref} = \frac{2L_r}{3L_m} \cdot \frac{T^{ref}}{\left|\psi_r^{ref}\right|} \tag{31}$$

The stator current is predicted based on (32).

$$i_s{}^{n+1} = (1 - \frac{T_s}{\tau_\sigma}).\, i_s{}^{n} + \frac{T_s}{\tau_\sigma.R_\sigma} \cdot (\frac{1}{T_s} - J.\, \omega^n).\, \psi_r^n + v_s^n \tag{32}$$

While the cost function is applied to the system only to consider the stator current error in the form of α-β component frame as (33).

$$g_j = \sum_{h=1}^{n}\left[\left|i_\alpha{}^{ref} - i_\alpha{}^{(h+n)}\right| + \left|i_\beta{}^{ref} - i_\beta{}^{(h+n)}\right|\right] \tag{33}$$

Where h is the predictive horizon. Finally, the optimal vectors are selected based on the minimum value of the cost function, in which the best switching signal can be generated for the vectors that generate a lower cost value [4]. The (34) represented the formula of optimal vector selection for MPCC.

$$v_{opt} = arg\, M\, in_{\{v_0,v_1,....,v_7\}} g({v_s}^{k+1}) \quad (34)$$

4.2. Model predictive torque control (MPTC)

In this type of MPC, the cost function is formed based on both torque reference and flux directly without calculating the stator current components [32]. Figure 3 shows the block diagram of the MPTC technique that consists of one PI controller that is used to calculate the torque reference form the speed reference while the reference flux of stator is delivered directly to the cost function [33]. The actual flux for stator and rotor needs to be estimated from the generated current of VSI to predict the stator flux, while the actual torque is predicted using stator current and rotor speed [34]. The cost function predicates the optimum voltage vector and generates the best pulse width modulation signal [35]. The pulse width modulation signal is used to control the VSI. Observer that no need to use Park to Clarke angle transformation to convert the current form d-q components reference frame into α-β component which is not considered on the cost function formula.

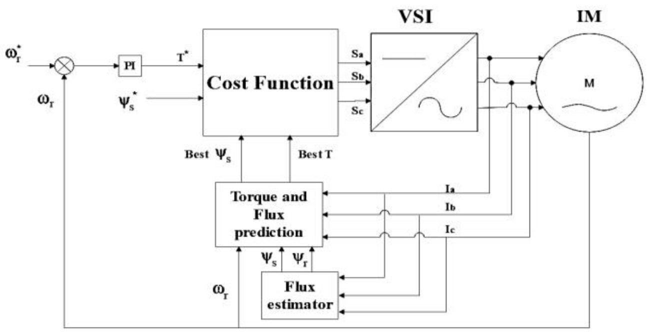


Figure 3. The block diagram of the MPTC technique

Basically, the designing of MPTC techniques has three main steps: i) Estimate the variable that can normally be measured directly such as the actual flux of stator and rotor [36]; ii) Predict the stator flux and torques in which the prediction can be figured out using discretization methods such as forwarded Euler approximation method or another method as reviews on discretization methods section [37]; and iii) Design the cost function that is used to predict the optimal space vector.

The cost function on the MPTC method is formed based on the error of toque and the error of stator flux which can be represented as (35) [32].

$$g_j = \sum_{h=1}^{n} \left[\left| T^{ref} - T^{(h+n)} \right| + W_f \left| {\psi_s}^{ref} - {\psi_s}^{(h+n)} \right| \right] \quad (35)$$

Where h is the predictive horizon and W_f are the weighting factor. Finally, the optimal vectors are selected based on the minimum value of the cost function, in which the best switching signal can be generated for the vectors that generate a lower cost value [38]. The (36) represented the formula of optimal vector selection for MPTC.

$$v_{opt} = arg\, M\, in_{\{v_0,v_1,....,v_7\}} g({v_s}^{n+1}) \quad (36)$$

MPC is a control technique with both merits and limitations. Understanding these aspects is crucial for its effective application [29], [39]-[41]. The advantages of MPC for driving the induction motor centered on offering a comprehensive approach to efficiently control parameters for multiple variables, making it a valuable tool for complex processes. One of its key strengths is the ability to consider actuator constraints, ensuring safe and optimal control while maximizing profits by operating near system limits. MPC excels in swift online computations and is particularly effective in controlling non-minimal phase and unstable processes. Its advantage lies in its relative ease of tuning for desired performance and adaptability to handle structural changes or system variations. This versatility makes MPC a powerful choice for advanced control applications. While the MPC offers significant advantages, also comes with its share of disadvantages. One notable drawback is its inherent complexity, often requiring more time for intricate online calculations, particularly when constraints need to be considered. Moreover, the effectiveness of MPC is heavily dependent on having a highly accurate process model. Any disparities between the model and the real process can significantly affect the quality of control, making the reliance on precise modeling a potential limitation.

5. CONCLUSION

The mathematical representation of an induction motor model using space vector quantities offers a simplified approach and effectively describes the motor's behavior under both transient and steady-state conditions. The dynamic representation of an induction motor can take different forms based on the selected reference frame. Control techniques for induction motors can be categorized into scalar control principles and vector control principles. Vector control techniques encompass control methods that utilize vector transformations for the variables of the induction motor. The MPC is considered a vector control technique.

The MPC can be classified in both MPTC and MPCC. variants offer notable advantages in terms of simplicity, accuracy, and efficiency. MPC operates by predicting future switching signals for inverter switches using a cost function formula. This prediction is based either on current vectors in both stationary and rotational frames (as in MPCC) or on reference values and actual values for torque and stator flux (as in MPTC). While MPTC requires careful weighting factor adjustments to achieve better optimization and control of the relative importance of torque and flux error minimization objectives, MPCC eliminates the need for weighting factors.

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BIOGRAPHIES OF AUTHORS

Moataz M. A. Alakkad was born in Khan Yunis, Gaza strip, Palestine in 1995. He received the B.E. degree in power electrical engineering from Quaid-e-Awam University of Engineering, Sciences & Technology, Nawabshah, Pakistan in 2019 and the M.E. from the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia in 2022. Currently, he is a Ph.D. scholar in the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia. His research interests include multilevel inverters, power electronic converters, AI, power control, and renewable energy. His research interests are on the electric drive application and induction motor. He can be contacted at email: moatazmoneer77@gmail.com.

Md. Hairul Nizam Talib is a senior lecturer at Universiti Teknikal Malaysia Melaka (UTeM). He received his B.S. in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Johor, Malaysia, in 1999, his M.S. in Electrical Engineering from the University of Nottingham, Nottingham, UK, in 2005, and his Ph.D. from Malaysia in 2016. His main research interests include power electronics, fuzzy logic control, and electrical motor drives. He can be contacted at email: hairulnizam@utem.edu.my.

Zulhani Rasin joined Universiti Teknikal Malaysia Melaka (UTeM) in 2006 and obtained his Ph.D. from University of New South Wales, Australia in 2006. Currently, he is a senior lecturer in the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM). His research interest is mainly in the field of power electronics and drives, focusing on photovoltaic inverter systems, and energy storage management for electrical drive systems. In teaching, he is in charge of the Power Electronics and Electrical Drive courses. Apart from that he is currently the editor of the International Journal of Electrical Engineering and Applied Sciences (IJEEAS) since 2017. He can be contacted at email: zulhani@utem.edu.my.

Jurifa Mat Lazi received her bachelor's and master's degrees in Electrical Engineering from Universiti Teknologi Malaysia in 2001 and 2003 respectively. She received his Ph.D. degree from University Universiti Teknikal Malaysia Melaka in 2016. She has served as an academic staff at Universiti Teknikal Malaysia Melaka (UTeM) since 2001 and she is currently a senior lecturer and head of Industrial Training Coordinator in the Faculty of Electrical Engineering, UTeM. Her research interests include machine drives, sensorless and PMSM drives, and power electronics. She can be contacted at email: jurifa@utem.edu.my.

Muhammad Haziq Md. Jamal was born in 1997, and received a bachelor’s degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka in Melaka, Malaysia. Currently, he is doing a master’s degree in Electrical Engineering at the Universiti Teknikal Malaysia Melaka. His research interests in power electronics, vehicle drive, and control. He can be contacted at email: hazziq097@gmail.com.

Zainuddin Mat Isa is a senior lecturer at Universiti Malaysia Perlis, specializing in Electrical Engineering. He holds a Master of Science (M.Sc.) degree in Electrical Engineering from Universiti Teknikal Malaysia Melaka (2006) and a Bachelor of Electrical Engineering degree from Universiti Teknologi Malaysia (2001). With over 15 years of teaching experience, Zainuddin has been actively involved in shaping the minds of aspiring engineers. His research interests encompass power electronics, optimization, and renewable energy. Zainuddin's dedication to his field and passion for sustainable solutions drive his contributions to academia and the development of efficient and clean power generation methods. He can be contacted at email: zainuddin@unimap.edu.my.