International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 15, No. 4, December 2024, pp. 2049~2057
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v15.i4.pp2049-2057

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

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Article Info

Article history:

Received Nov 14, 2023
Revised Mar 21, 2024
Accepted Apr 24, 2024

Keywords:

Induction motor
Model predictive control
Model predictive current control
Model predictive torque control
Vector control

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.

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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).

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

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

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

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

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

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (13)$$

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (14)$$

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).

$$K_r = \frac{L_m}{L_r} \quad (15)$$

$$R = K_r^2.R_r \quad (16)$$

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

$$\tau_\sigma = \frac{L_\sigma}{R_\sigma}\tau_\sigma = \frac{L_\sigma}{R_\sigma} \quad (18)$$

$$\tau_r = \frac{L_r}{R_r} \quad (19)$$

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

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

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

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

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

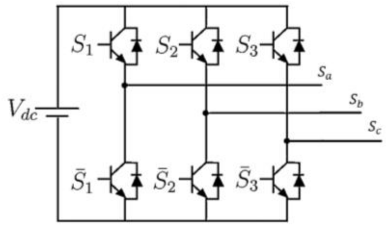
$$\frac{d\theta}{dt} = \omega \quad (24)$$

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.

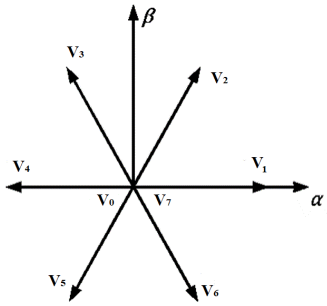
3. INVERTER MODEL

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

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

These output voltage vectors ($\mathrm{v_a}, \mathrm{v_b}$ and $\mathrm{v_c}$) 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).

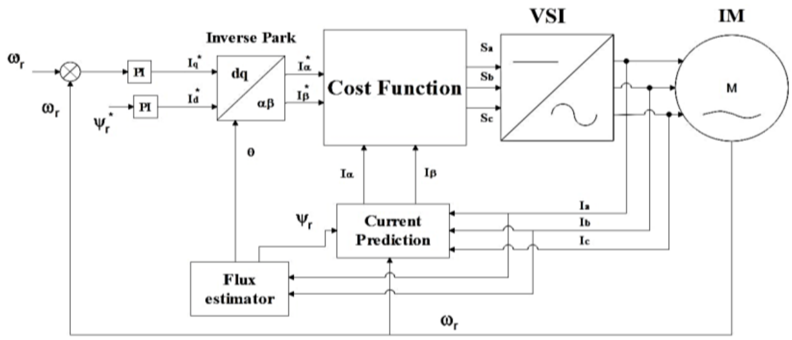


Figure 2. The block diagram of the MPCC technique

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).

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

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

The stator current is predicted based on (32).

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

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).

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

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.

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

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.

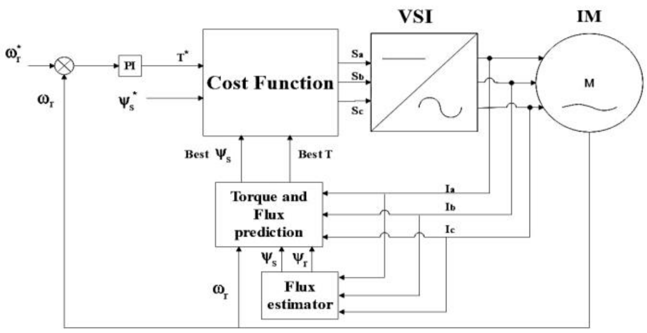


Figure 3. The block diagram of the MPTC technique

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].

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

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.

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

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.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding support provided by the Universiti Teknikal Malaysia Melaka (UTeM) and the Ministry of Higher Education Malaysia under the research grant No: FRGS/1/2020/FKE-CERIA/F00419.

REFERENCES

[1] E. Agamloh, A. von Jouanne, and A. Yokochi, "An overview of electric machine trends in modern electric vehicles," *Machines*, vol. 8, no. 2, p. 20, Apr. 2020, doi: 10.3390/machines8020020.

[2] J. A. Melkebeek, *Electrical machines and drives*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-72730-1.

[3] M. M. M. S. El Shormbably, "Model predictive control of induction motor drives," King Fahd University of Petroleum and Minerals (Saudi Arabia), 2018. [Online]. Available: https://www.proquest.com/openview/525a16fc2771596334ffefccf2fcdfd6/1?pq-origsite=gscholar&cbl=2026366&diss=y

[4] H. Wang, X. Chen, Y. Liu, M. Su, W. Feng, and W. Yu, "Model predictive control of three-phase voltage-source converters with improved tracking performance," *ISA Transactions*, vol. 133, pp. 424–434, Feb. 2023, doi: 10.1016/j.isatra.2022.07.012.

[5] M. Hassan *et al.*, "A look-up table-based model predictive torque control of IPMSM drives with duty cycle optimization," *ISA Transactions*, vol. 138, pp. 670–686, Jul. 2023, doi: 10.1016/j.isatra.2023.02.007.

[6] S. U. Ali, A. Waqar, M. Aamir, S. M. Qaisar, and J. Iqbal, "Model predictive control of consensus-based energy management system for DC microgrid," *PLOS ONE*, vol. 18, no. 1, p. e0278110, Jan. 2023, doi: 10.1371/journal.pone.0278110.

[7] I. Hammoud *et al.*, "On continuous-set model predictive control of permanent magnet synchronous machines," *IEEE Transactions on Power Electronics*, vol. 37, no. 9, pp. 10360–10371, Sep. 2022, doi: 10.1109/TPEL.2022.3164968.

[8] N. Kumar, B. Singh, and B. K. Panigrahi, "Voltage sensorless based model predictive control with battery management system: for solar PV powered on-board EV charging," *IEEE Transactions on Transportation Electrification*, vol. 9, no. 2, pp. 2583–2592, Jun. 2023, doi: 10.1109/TTE.2022.3213253.

[9] A. Boyar, E. Kabalcı, and Y. Kabalcı, "Model predictive torque control-based induction motor drive with remote control and monitoring interface for electric vehicles," *Electric Power Components and Systems*, vol. 51, no. 18, pp. 2159–2170, Nov. 2023, doi: 10.1080/15325008.2023.2211581.

[10] P. G. Carlet, A. Favato, S. Bolognani, and F. Dorfler, "Data-driven continuous-set predictive current control for synchronous motor drives," *IEEE Transactions on Power Electronics*, vol. 37, no. 6, pp. 6637–6646, Jun. 2022, doi: 10.1109/TPEL.2022.3142244.

[11] T. Asikainen, "Parameter estimation of induction machines," 2020. [Online]. Available: https://urn.fi/URN:NBN:fi:tuni-202009136979

[12] K. Sundareswaran, "Induction motor fundamentals," in *Elementary concepts of power electronic drives*, CRC Press, 2019, p. 14. [Online]. Available: https://www.taylorfrancis.com/chapters/mono/10.1201/9780429423284-9/induction-motor-fundamentals-sundareswaran

[13] N. Farah, M. H. N. Talib, Z. Ibrahim, J. M. Lazi, and M. Azri, "Self-tuning fuzzy logic controller based on Takagi-Sugeno applied to induction motor drives," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 9, no. 4, pp. 1967–1975, Dec. 2018, doi: 10.11591/ijpeds.v9.i4.pp1967-1975.

[14] N. F. Djagarov, H. A. Milushev, M. B. Bonev, Z. G. Grozdev, and J. V. Djagarova, "Adaptive vector control of induction motor drives," in *2019 8th International Conference on Power Science and Engineering (ICPSE)*, Dec. 2019, pp. 29–34. doi: 10.1109/ICPSE49633.2019.9041180.

[15] A. Gholipour, M. Ghanbari, E. Alibeiki, and M. Jannati, "Sensorless FOC strategy for current sensor faults in three-phase induction motor drives," *Journal of Operation and Automation in Power Engineering*, vol. 11, no. 1, pp. 1–10, 2023, doi: 10.22098/JOAPE.2022.9274.1648.

[16] M. M. A. Alakkad, Z. Rasin, M. Rasheed, and R. Omar, "Harmonic minimization using artificial neural network technique for CHB-ML inverter," in *2021 IEEE International Conference in Power Engineering Application (ICPEA)*, Mar. 2021, pp. 12–17. doi: 10.1109/ICPEA51500.2021.9417759.

[17] M. M. A. Alakkad, Z. Rasin, and W. A. Halim, “Investigation on total harmonics distortion for transistor clamped cascaded H-Bridge multilevel inverter using newton-raphson method,” in *2022 IEEE International Conference in Power Engineering Application (ICPEA)*, Mar. 2022, pp. 1–6. doi: 10.1109/ICPEA53519.2022.9744670.
[18] H. Matsumori, T. Kosaka, N. Matsui, and S. Saha, “Alternative PWM switching strategy implementation for a dual inverter fed open winding motor drive system for an electric vehicle application,” *IEEE Transactions on Industry Applications*, vol. 59, no. 5, pp. 5957–5970, Sep. 2023, doi: 10.1109/TIA.2023.3291340.
[19] M. S. Choudhary *et al.*, “Solar powered space vector pulse width modulation based induction motor drive for industry applications,” *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 4, pp. 1828–1836, Aug. 2022, doi: 10.11591/eei.v11i4.3023.
[20] T. Li, J. Gudex, R. Olson, H. Abdallah, R. M. Cuzner, and J. Katcha, “Modeling and validation of common-mode emissions of SiC MOSFET-based voltage source inverter motor drive,” in *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Mar. 2023, pp. 56–63. doi: 10.1109/APEC43580.2023.10131302.
[21] W. Wang, Y. Liu, Y. Chen, and C. Liu, “Optimization-based duty cycle allocation for a five-leg inverter to drive two electric motors,” *IEEE Transactions on Power Electronics*, vol. 38, no. 9, pp. 11327–11337, Sep. 2023, doi: 10.1109/TPEL.2023.3287469.
[22] A. Alahmad and F. Kacar, “Simulation of induction motor driving by bridge inverter at 120°, 150°, and 180° operation,” in *2021 8th International Conference on Electrical and Electronics Engineering (ICEEE)*, Apr. 2021, pp. 121–125. doi: 10.1109/ICEEE52452.2021.9415930.
[23] S. M. El-koliel, H. Eleissawi, and A. S. Nada, “Speed control of electrical submersible pumps using fuzzy logic control,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 4, pp. 2515–2528, Dec. 2022, doi: 10.11591/ijpeds.v13.i4.pp2515-2528.
[24] Z. Dong, H. Wen, T. Wang, B. Zhang, Z. Song, and C. Liu, “Common-mode voltage reduction-based space vector modulation strategy for three-phase two-level inverter with delta-connected loads,” in *2023 IEEE 32nd International Symposium on Industrial Electronics (ISIE)*, Jun. 2023, pp. 1–6. doi: 10.1109/ISIE51358.2023.10228124.
[25] T.-D. Duong, M.-K. Nguyen, T.-T. Tran, D.-V. Vo, Y.-C. Lim, and J.-H. Choi, “Topology review of three-phase two-level transformerless photovoltaic inverters for common-mode voltage reduction,” *Energies*, vol. 15, no. 9, p. 3106, Apr. 2022, doi: 10.3390/en15093106.
[26] T. Qanbari, B. Tousi, and M. Farhadi-Kangarlu, “A novel vector-based pulse-width modulation for three-phase two-level voltage source inverters,” *Journal of Operation and Automation in Power Engineering (JOAPE)*, vol. 11, no. 1, pp. 50–60, 2023, doi: https://doi.org/10.22098/joape.2023.9997.1708.
[27] F. Ahmed, L. Sobiesiak, and J. R. Forbes, “Cascaded model predictive control of a tandem-rotor helicopter,” *IEEE Control Systems Letters*, vol. 7, pp. 1345–1350, 2023, doi: 10.1109/LCSYS.2023.3237954.
[28] Z. Cui, Z. Zhang, T. Dragicevic, and J. Rodriguez, “Dynamic sequential model predictive control of three-level NPC back-to-back power converter PMSG wind turbine systems,” in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2020, pp. 3206–3211. doi: 10.1109/IECON43393.2020.9255096.
[29] T. Wang, Y. Wang, Z. Zhang, Z. Li, C. Hu, and F. Wang, “Comparison and analysis of predictive control of induction motor without weighting factors,” *Energy Reports*, vol. 9, no. 2, pp. 558–568, Apr. 2023, doi: 10.1016/j.egyr.2023.03.046.
[30] M. Costin and C. Lazar, “Field-oriented predictive control structure for synchronous reluctance motors,” *Machines*, vol. 11, no. 7, p. 682, Jun. 2023, doi: 10.3390/machines11070682.
[31] Y. Zhang, J. Jin, and L. Huang, “Model-free predictive current control of PMSM drives based on extended state observer using ultralocal model,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 2, pp. 993–1003, Feb. 2021, doi: 10.1109/TIE.2020.2970660.
[32] S. Jaman *et al.*, “Comparative performance assessment of predictive torque control strategy for motor drive applications,” in *IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2022, pp. 1–6. doi: 10.1109/IECON49645.2022.9968403.
[33] R. Alik, N. R. N. Idris, N. M. Nordin, and S. M. Ayob, “Online tuning weighting factor for a predictive torque control of induction motor drive,” in *2022 IEEE International Conference on Power and Energy (PECon)*, Dec. 2022, pp. 225–229. doi: 10.1109/PECon54459.2022.9988878.
[34] J. Rodas *et al.*, “Weighting-factorless sequential model predictive torque control of a six-phase AC machine,” in *2023 IEEE Conference on Power Electronics and Renewable Energy (CPERE)*, Feb. 2023, pp. 1–5. doi: 10.1109/CPERE56564.2023.10119622.
[35] Y. Zhang, Z. Yin, W. Li, J. Liu, and Y. Zhang, “Adaptive sliding-mode-based speed control in finite control set model predictive torque control for induction motors,” *IEEE Transactions on Power Electronics*, vol. 36, no. 7, pp. 8076–8087, Jul. 2021, doi: 10.1109/TPEL.2020.3042181.
[36] M. S. Mousavi *et al.*, “Predictive torque control of induction motor based on a robust integral sliding mode observer,” *IEEE Transactions on Industrial Electronics*, vol. 70, no. 3, pp. 2339–2350, Mar. 2023, doi: 10.1109/TIE.2022.3169831.
[37] M. Khosravi, D. Arab Khaburi, M. Alikhani, and M. Yousefzade, “Two-stage deadbeat-based predictive torque control strategy for modular multilevel converter-fed three-phase induction motors,” *IET Electric Power Applications*, vol. 18, no. 1, pp. 20–41, Jan. 2024, doi: 10.1049/elp2.12363.
[38] S. T. Ramsham and S. Lakhimsetty, “Fuzzy-logic speed controller for 3-level open-end winding induction motor drive with predictive torque control technique,” in *2022 Second International Conference on Power, Control and Computing Technologies (ICPC2T)*, Mar. 2022, pp. 1–5. doi: 10.1109/ICPC2T53885.2022.9776783.
[39] M. F. Elmorshedy, W. Xu, F. F. M. El-Sousy, M. R. Islam, and A. A. Ahmed, “Recent achievements in model predictive control techniques for industrial motor: a comprehensive state-of-the-art,” *IEEE Access*, vol. 9, pp. 58170–58191, 2021, doi: 10.1109/ACCESS.2021.3073020.
[40] H. A. G. Al-Kaf and K.-B. Lee, “Fast dynamic field-oriented control using direct large voltage vector and hysteresis switch,” in *2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia)*, May 2023, pp. 3057–3062. doi: 10.23919/ICPE2023-ECCEAsia54778.2023.10213539.
[41] G. Bai, Y. Meng, L. Liu, W. Luo, Q. Gu, and L. Liu, “Review and comparison of path tracking based on model predictive control,” *Electronics*, vol. 8, no. 10, p. 1077, Sep. 2019, doi: 10.3390/electronics8101077.

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