Scientific Research Publishing

Journal of Power and Energy Engineering, 2025, 13(8), 307-320
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Investigation of Predictive Current Control and Hysterisis Current Control for Induction Motor

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How to cite this paper: Jamal, M.H.M., Talib, M.H.N., Rasin, Z., Lazi, J.M., Alias, A. and Muskhir, M. (2025) Investigation of Predictive Current Control and Hysterisis Current Control for Induction Motor. *Journal of Power and Energy Engineering*, **13**, 307-320.
https://doi.org/10.4236/jpee.2025.138017

Received: July 28, 2025
Accepted: August 26, 2025
Published: August 29, 2025

Abstract

Induction Motor (IM) drives are gaining substantial interest among researchers and industries due to their ability to deliver high-performance AC drives through vector control mechanisms. Advancements in power electronics and Digital Signal Processing (DSP) technologies have enabled the adoption of sophisticated motor drive control strategies, such as Model Predictive Control (MPC). This paper presents the design, analysis, and investigation of two alternative current control strategies: Model Predictive Current Control (MPCC) and Hysteresis Current Control (HCC) where HCC is implemented within a conventional Field-Oriented Control (FOC) scheme. The study focuses on the implementation of these control methods in IM drives particularly Model Predictive Current Control (MPCC). Furthermore, a comprehensive comparison is conducted between the MPCC and HCC methods using MATLAB/Simulink simulation studies with a Proportional-Integral (PI) speed controller. The findings reveal that the MPCC approach outperforms the HCC in terms of speed, torque, and current responses under both transient and steady-state situations. The results underscore the promising potential of MPCC strategies as viable alternatives for enhancing the performance of Induction Motor drives in practical applications.

Keywords

Induction Motors, Model Predictive Current Control, Hysteresis Current Control, Field Oriented Control, Electric Drives

1. Introduction

Induction motors (IM) have a place in various industries due to their simple structure and high cost effectiveness. Additionally, they require low maintenance and have high efficiency [1] [2]. Initially, IMs could only operate at constant speeds, but with power electronics progression, voltage and current source inverters, made the use of IMs more versatile through scalar drive control [3] [4]. The use of inverters has enabled variable speed drives, making them widely used in industrial electromechanical systems. Scalar control is also commonly applied in industry due to its simplicity and low cost. Scalar control gives an acceptable steady state performance but is objectionably poor in transient response as seen in this paper [5]. There are many restrictions with the method that make it undesirable for advanced users like roboticists or rolling mill users, who need fast V/f responses. They would instead use highly dynamical control methods like Field Oriented control (FOC) or Model Predictive Control (MPC) [6] [7].

Induction motors (IMs) are difficult to control at different speeds due to their multivariable and nonlinear characteristics. The varying electrical parameters make the issue worse, and as a consequence, there is a need for a higher-level topology including a Field-Oriented Control (FOC or vector control) [8]. FOC enhances the drive performance by reducing costs of the system through independent control of the torque and the flux, which are integral components of the motor control. The idea behind FOC is that the IM is controlled like a DC motor that is excited from a separate source. The armature current controls the torque, and the field current controls the flux. In an IM, this is done with special transformations that decouple the torque and flux components, which in vector control are d and q [9]. This performance is also achievable with a DC motor, but for an IM, this entails independent control of the components, which is made possible through the decoupling of torque and flux. Generally, control systems of IM consist of the outer loop responsible for speed control and the inner loop for current control.

The speed control loop utilizes an angle control technique based on constant torque and vector control that aims at isolating the motor's flux component to achieve desirable characteristics. So, FOC naturally separates torque and flux, which makes it possible to control IMs well. To improve torque and speed responses in a VSI-fed IM drive, it is important to choose an effective current controller. The main goal of a current controller is to guarantee that the load current closely adheres to the reference current path, thus reducing current discrepancies [10] [11]. Precision current control is required in high-performance drive systems to improve precision and power quality. The effectiveness of a current control strategy is judged by how quickly and steadily it can respond while also taking into account the system's nonlinearities, instabilities, and disturbances. A thorough review of various current control techniques for induction motor drives has been conducted in the existing literature. Hysteresis current control (HCC) is frequently used because of its simple implementation and ability to provide fast dynamic and transient responses [12] [13]. The HCC technique offers better speed tracking capabilities during transient conditions. Even though traditional HCC has many benefits, it might not be enough for situations with a lot of load because it often causes a lot of current ripple, which can lead to higher torque pulses and worse transient performance.

Because traditional hysteresis current control (HCC) has problems like high current ripple and poor transient responsiveness, it needs to be replaced with more advanced current control methods. Model Predictive Current Control (MPCC) has become prominent in induction motor (IM) drive applications due to its ability to forecast future current values and optimise voltage vector selection. MPCC identifies the best voltage vector by minimising a specified cost function, constructed using reference currents and anticipated stator currents [13] [14]. A thorough comparison of MPCC with diverse contemporary control systems is provided in [15], while an enhanced MPCC framework with a rapid dynamic reaction via an optimised mathematical plant model is proposed in [16] [17]. MPCC shows outstanding dynamic performance, drastically reducing current harmonics while maintaining precise control of torque and speed. By minimising the limitations of HCC, MPCC improves the precision and reliability of IM drive systems. This study explores the efficiency of IM drives using HCC and MPCC under various operating conditions. The performance of each controller is evaluated based on speed regulation, torque ripple, and current ripple characteristics during dynamic changes in speed and torque.

The remaining content of the paper is organized as follows: the next section describes the mathematical model of IM and the vector control used in outer speed controller. The third section deals with the implementation of current control strategies. All the simulation results obtained from both the current control techniques and their comparison are presented in section four. At last, the conclusions drawn from the overall analysis are discussed in section five.

2. IM Drive System Description

2.1. Mathematical Model of Induction Motor

The mathematical model of an induction motor relies on its electrical and mechanical dynamics, articulated through nonlinear differential equations. These equations describe the interrelationships between the stator and rotor currents, the linkages of flux, the electromagnetic torque developed, and the rotor's speed. The relations are typically expressed in terms of a synchronous rotating reference frame d-q to facilitate the analysis and control, achieving time-invariant representation.

There are different reference frames, namely the stationary reference frame, the rotary reference frame, and the synchronous reference frame. All reference frame can be used to model the IM. Accurate models are quite important for analyzing the performance of the motor at different operating conditions such as speed changes, load changes, and voltage disturbances. These models help the application of advanced control strategies that increase motor performance, improve efficiency, and minimize harmonic distortion. The d-q axis representation offers significant advantages for modern control strategies, including Field-Oriented Control (FOC) and Model Predictive Control (MPC), which depend on accurate dynamic representations to ensure optimal performance.

Using phase transformation principle, the input three-phase voltages are converted into two-phase voltages and expressed in stationary reference frame with respect to the stator[18] as in the following Equations (1) - (8).

$$V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} \tag{1}$$

$$V_{sq} = R_s I_{sq} + \frac{d\varphi_{sq}}{dt} \tag{2}$$

$$V_{rd} = R_r I_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \tag{3}$$

$$V_{rq} = R_r I_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \tag{4}$$

And the flux equation can be expressed as:

$$\varphi_{sd} = L_s I_{sd} + L_m I_{rd} \tag{5}$$

$$\varphi_{sq} = L_s I_{sq} + L_m I_{rq} \tag{6}$$

$$\varphi_{rd} = L_m I_{sd} + L_r I_{rd} \tag{7}$$

$$\varphi_{rq} = L_m I_{sq} + L_r I_{rq} \tag{8}$$

The variables V_{sd}, V_{sq} represent the stator voltage, while V_{rd}, V_{rq} denote the rotor voltages. Additionally, I_{sd}, I_{sq}, I_{rd} and I_{rq}, are the corresponding d and q axis stator current and rotor currents. φ_{sd}, φ_{sq}, φ_{rd}, φ_{rq}, represent the components of flux for both the stator and rotor. R_s, R_r, represent the resistances of the stator and rotor, respectively. L_s, L_r, represent the inductances of the stator and rotor, while L_m signifies the mutual inductance, and ω_r indicates the rotor's rotational speed.

Furthermore, the machine's output torque can be stated mechanically and electrically in the following ways:

Mechanical torque:

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_L \tag{9}$$

Electrical torque:

$$T_e = \frac{3}{2} P L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq} \right) \tag{10}$$

where, J is the total moment of inertia, B is the viscous friction, T_L is the load torque. ω_r is the rotor electric angular speed in rad./s, ω_m is the motor speed in rad./s and P is the number of pole pair.

2.2. Two-Level VSI-Based Motor Drive

The two-level voltage source inverter (VSI) is a widely used power conversion topology in industrial motor drives and power electronics. It converts a DC-link voltage into a three-phase AC supply for driving electric machines. The topology consists of three inverter legs one for each phase where each leg includes two semiconductor switches (e.g., IGBTs or MOSFETs) and their corresponding anti-parallel diodes. The DC-link capacitor provides voltage stabilization and absorbs switching transients.

Each inverter leg operates with two switching states, resulting in a total of eight possible combinations across all three phases. These states generate a set of voltage vectors, including two zero vectors, which are essential in predictive and modulation-based control strategies. Although the two-level VSI introduces more harmonic distortion at lower switching frequencies, its structure remains simple, cost-effective, and highly reliable especially when combined with advanced control schemes. To generate a sinusoidal output at the desired fundamental frequency, pulse-width modulation (PWM) is typically applied. The line-to-neutral voltage of each phase can be expressed as:

$$V_{a0} = \frac{2}{3} V_{dc} \left(S_A - \frac{1}{2} \left(S_b + S_c \right) \right) \tag{11}$$

where S_A, S_B, and S_C represent the switching states of the three legs. *Due to these* features, the two-level VSI continues to be a preferred choice in IM and PMSM drive systems, as well as in renewable energy and UPS applications. Recent advancements have improved its performance through model predictive control (MPC) and space vector modulation (SVM) techniques [19] [20].

3. Current Control Methods

3.1. Hysteresis Based Current Control

According to the research conducted in [21], the hysteresis current controller offers a simple and rapid automated scheme in the oversight of IM drive systems. This design, a Proportional Integral (PI) controller is set as the speed controller of the system, while a Hysteresis Controller (HC) acts as the Current Controller. Currents flows in a three-phase motor (ia, ib, ic) are measured using current sensors and checked against set values (ia*, ib*, ic*). The difference between the reference current signal and the actual current signal is handled by comparators using a hysteresis band. hysteresis band in the HCC send signal to IGBT gate to generate pulse signals which control the inverter as shown in **Figure 1**.

3.2. Model Predictive Current Control

The Model Predictive Current Controller (MPCC), as discussed in [22], is a discrete controller for motor drives. There is an explicit prediction made for every sampling interval, which occurs at a fixed time. a prediction horizon is used to forecast future states (e.g., speed and current) over multiple time steps, such as at $(k+1)^{th}$, $(k+2)^{th}$, …, k^{th} time slice. Selecting an appropriate the right prediction horizon for an application makes it a function of the computational resources available and the performance objectives. A longer prediction horizon can improve performance, but it also increases computational effort significantly. However, the performance improvements decrease beyond a certain point, making it important to find the right balance (**Figure 2**).

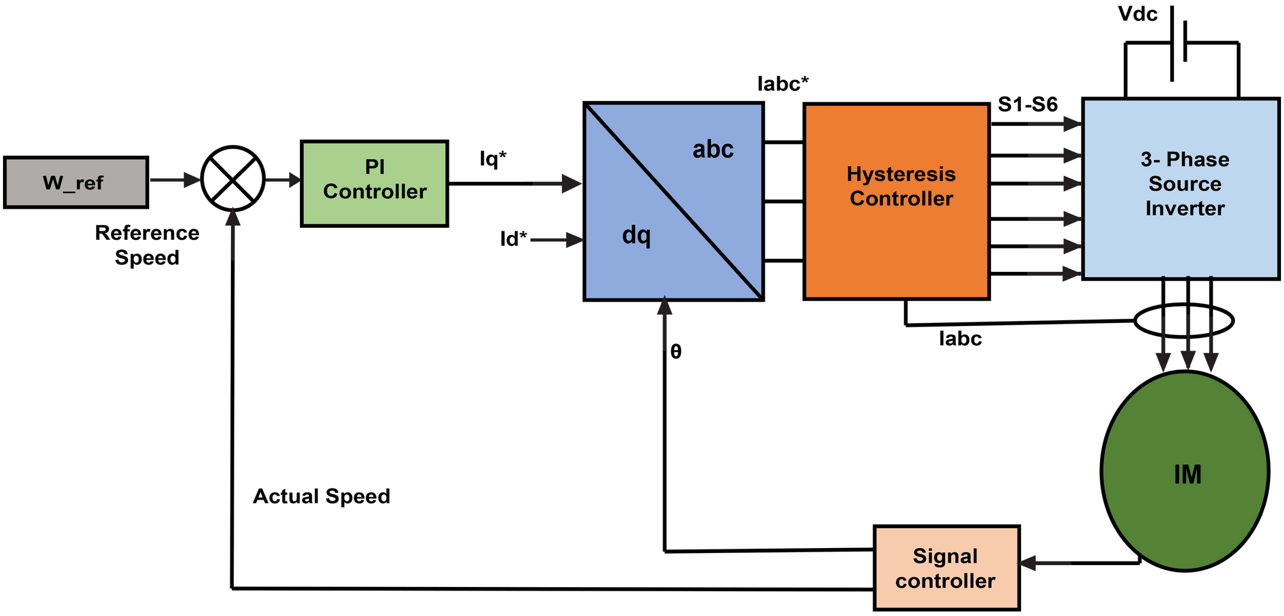


Figure 1. Block diagram of FOC based HCC of IM.

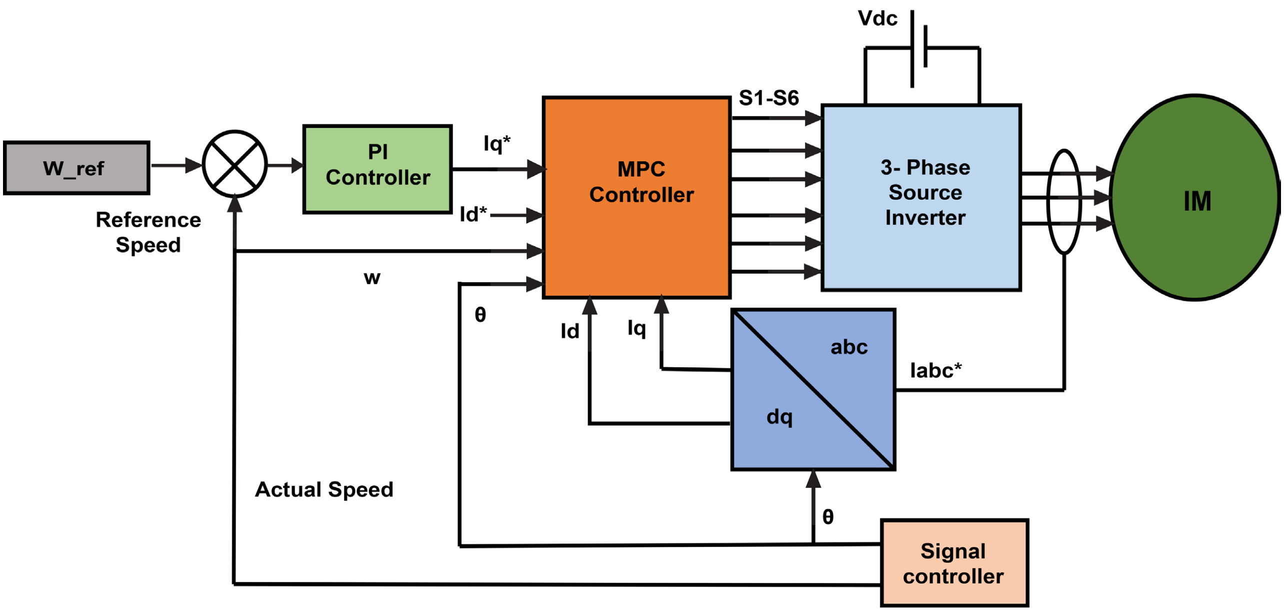


Figure 2. Block diagram of MPCC of IM.

3.2.1. Stator Current Prediction

The stator currents id and iq are predicted for (k + 1) instant [23]. Based on the IM plant model, these equations are derived for the anticipation of future values and these predicted currents and reference stator currents are used for modelling of cost function.

$$A=\left(1-\frac{T_s k_b}{K_a}\right),\ B=\frac{T_s}{k_a}$$

$$I_s(k+1)=AI_s(k)+B\left[\left(-j\omega_m L_m+k_c\right)F_r(k)+L_r\cdot v_i\right] \tag{12}$$

3.2.2. Cost Function

Cost function consists of direct and quadrature axis currents (id and iq) such that the weighting factor can be eliminated. The cost function is designed to evaluate the performance of predicted currents. In the implemented MPCC the cost function is represented in Equation (13). The reference currents are taken from outer speed control loop.

$$g(i) = \left| i_\alpha^* - i_\alpha (k+1)_i \right| + \left| i_\beta^* - i_\beta (k+1)_i \right| \tag{13}$$

This simplified form is suitable as both current components are handled equally [24]. Here there is no need any weighting factors which make the control design more simple. Additionally, it reduces computational burden making the controller more efficient and better for real-time implementation. In the overall controller, the cost function plays a vital role for the selection of optimized voltage vector to generate gate pulses for the inverter switching.

4. Simulation Results

In order to evaluate the effectiveness of the proposed MPCC, both the HCC and the proposed MPCC are simulated in a MATLAB/Simulink environment. The parameters of the IM are given in **Table 1**. To achieve a fair comparison between the two methods, the speed PI controllers are configured with the same parameters.

Table 1. Induction motor parameters.

Quantity	Value
Rated Speed	1400 rpm
Stator Resistance	3.45 Ω
Rotor Resistance	3.6141 Ω
Stator Inductance	0.3246 H
Rotor Inductance	0.3252 H
Magnetizing Inductance	0.3117 H
Inertia	0.02 kgm^2
Viscous Friction	0.001 Nm/(rad/s)
Quantity	Value
Rated Speed	1400 rpm

4.1. No-Load Operation

At no load the motor performance is investigated for sudden rated speed. The considered reference speed for the analysis is 1400 RPM. **Figure 3** illustrates the actual motor speed in comparison with the reference speed for both Hysteresis Current Control (HCC) and Model Predictive Current Control (MPCC). The time taken for the actual speed to reach the reference speed is analyzed to evaluate the dynamic response of both control strategies.

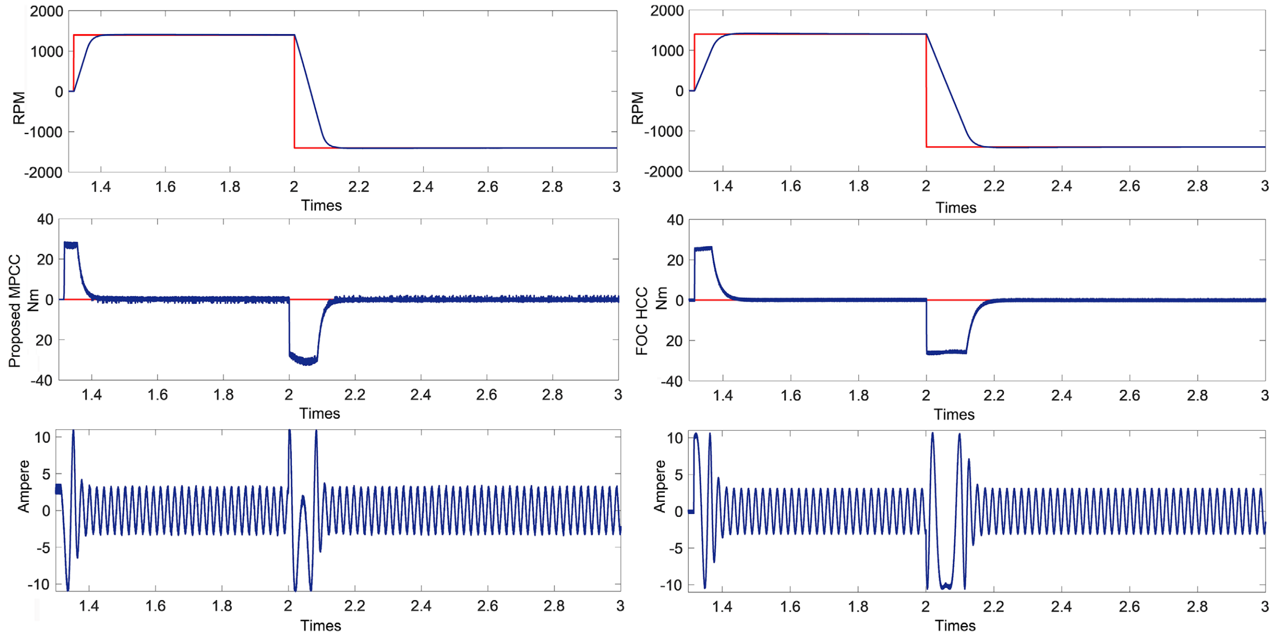


Figure 3. Show the simulation results of MPCC, and HCC when performing variable speed control.

Further closed up view of the speed performance of the IM drives at rated forward and reversal speed condition with MPCC and HCC methods is presented in Figure 4. Based on speed performance, it can be seen that the MPCC has better dynamic response than HCC. MPCC shows a fast rise time 0.029 s and settles time 0.049 quickly without any overshoot. HCC, on the other hand, exhibits a slower response rise time at 0.058 with a clear overshoot before settling at 0.108. During the reversal speed, MPCC again responds faster and settles earlier compared to HCC, which takes longer to reach steady state.

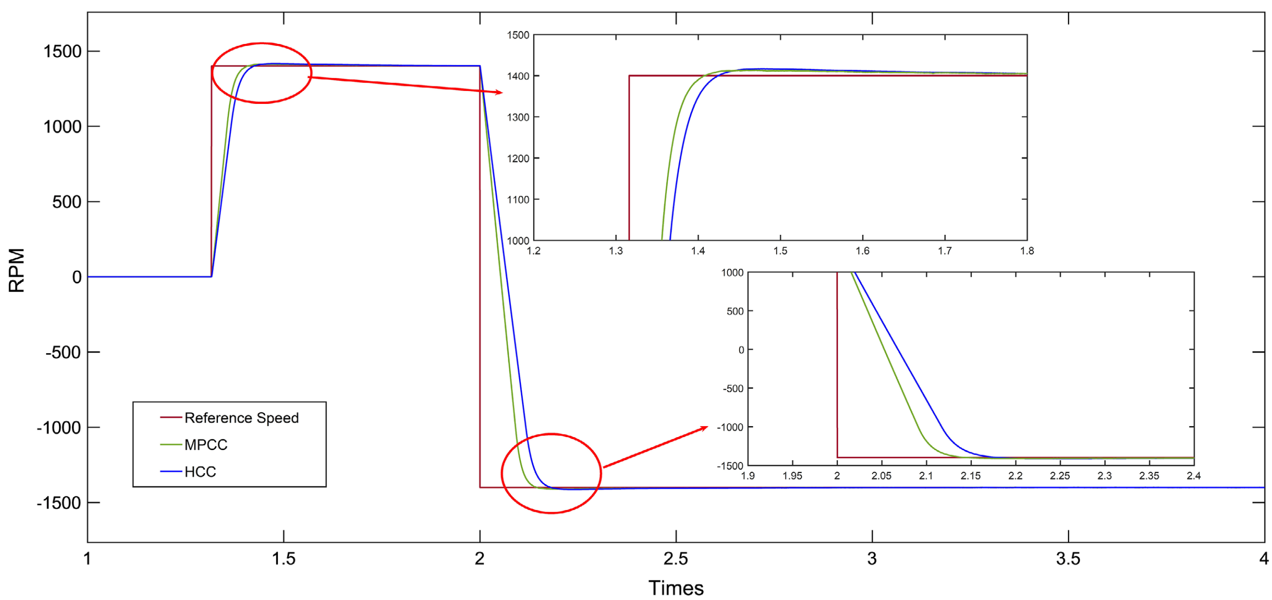


Figure 4. Speed performance comparison of MPCC, and HCC.

4.2. Variable Load Operation

The robust controlling of motor involves variable load torque application. In this section variable load torque is given to the motor and corresponding motor characteristics are analyzed. The load torque 10 Nm is applied to the motor at 3 to 5.5 sec of time for HCC and MPCC as shown in Figure 5. The torque characteristics are evaluated based on the magnitude of the ripples observed. As illustrated in Figure 5 shows MPCC method exhibits a greater torque ripple of 16.6%, with a maximum torque of 11.47 Nm and minimum of 8.15 Nm. Compared to the HCC method which shows a significantly lower torque ripple of 7.5%, with a maximum of 10.80 Nm and minimum of 9.30 Nm. This indicates that the HCC method provides smoother torque performance under the same operating conditions. However, during load disturbance it provides a faster dynamic response with recovery time at 0.402 and least speed drop with only 118 rpm compared to HCC.

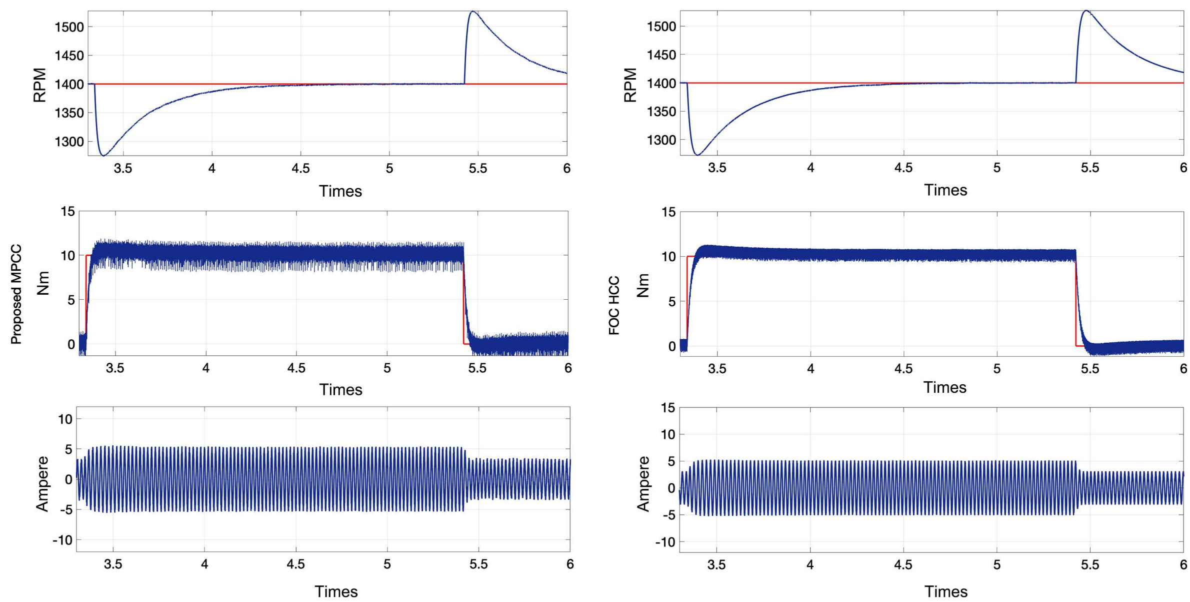


Figure 5. The simulation results of proposed MPCC, and FOC HCC when performing variable torque control.

These results highlight the superior dynamic performance and tracking accuracy of MPCC over HCC. When a load is applied to the motor a temporary drop in speed occurs as the system responds to the sudden increase in demand. The controller quickly acts to restore the speed to its reference value which is gradually regained within a short period. Figure 6 shows the full simulation run under rated load conditions whereas Figure 5 provides a detailed zoomed in view of the speed, torque, and current waveforms for closer analysis (Table 2).

Table 2. Measured maximum and minimum torque value.

Methods	Torque Max (Nm)	Torque Min (Nm)	Torque Ripple (%)
MPCC	11.47	8.15	16.6
HCC	10.80	9.30	7.5

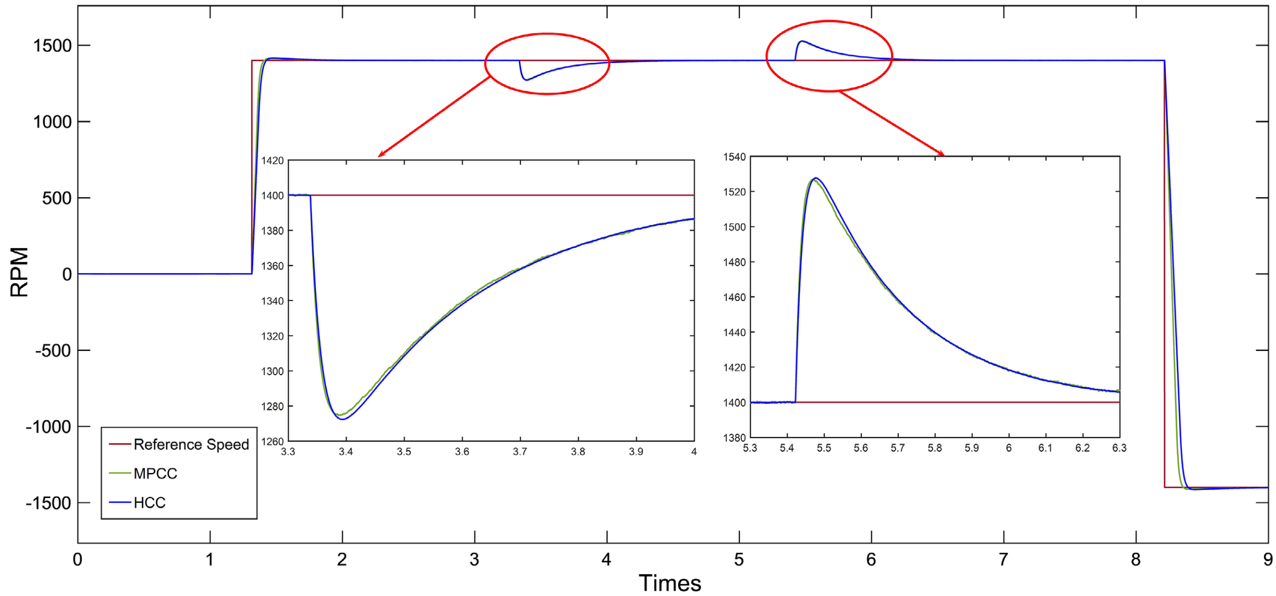


Figure 6. Load performance comparison of MPCC, and HCC.

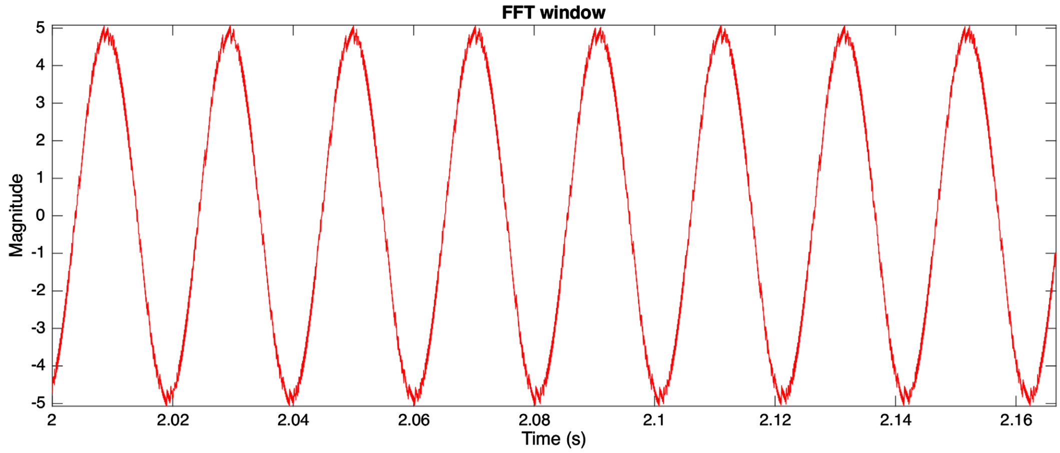
4.3. THD Comparison Test

The sampling frequency is set at 20 kHz. At the beginning of the simulation, the motor runs at 1400 RPM with rated load 10 Nm. Figure 7 is the phase current waveform of ia. Figure 8 is the a-phase current THD waveform of the motor under two different control methods. From Figure 7 and Figure 8, it can be seen that the waveform of HCC and MPCC are similar in same conditions. However, MPCC shows little improvement with THD value of 21.31% compared to HCC with 21.36%. Steady-state response for HCC and the proposed MPCC are presented in Figure 7 and Figure 8, respectively.

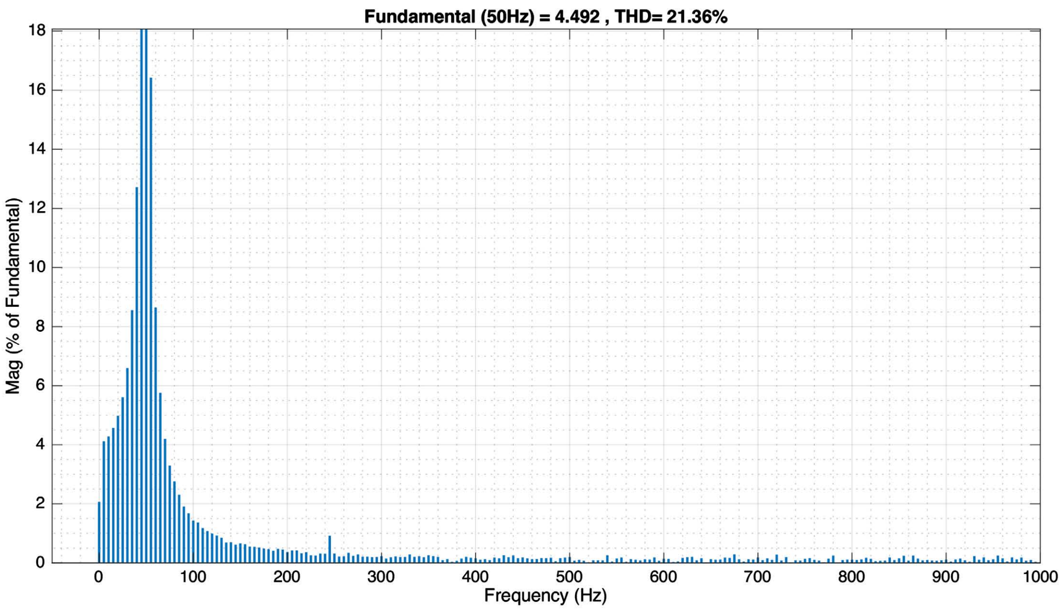
To verify the performance analysis of the proposed MPC methods, the IM drive response at the rated speed of 1400 rpm is analyzed. The evaluation includes overshoot, rise time, settling time, speed drop during load application, and the time taken to recover. Table 3 presents the results, showing that MPCC performs better overall, with no overshoot, faster rise and settling times, and quicker recovery after the load is applied.

Table 3. Numerical comparison of MPCC and HCC.

Measure	MPCC	HCC
Overshoot (rpm)	0	1426
Overshoot (%)	0%	1.79%
Rise Time (S)	0.029	0.058
Settling Time (S)	0.049	0.108
Speed drop (rpm)	118	128
Recovery Time (S)	0.402	0.448

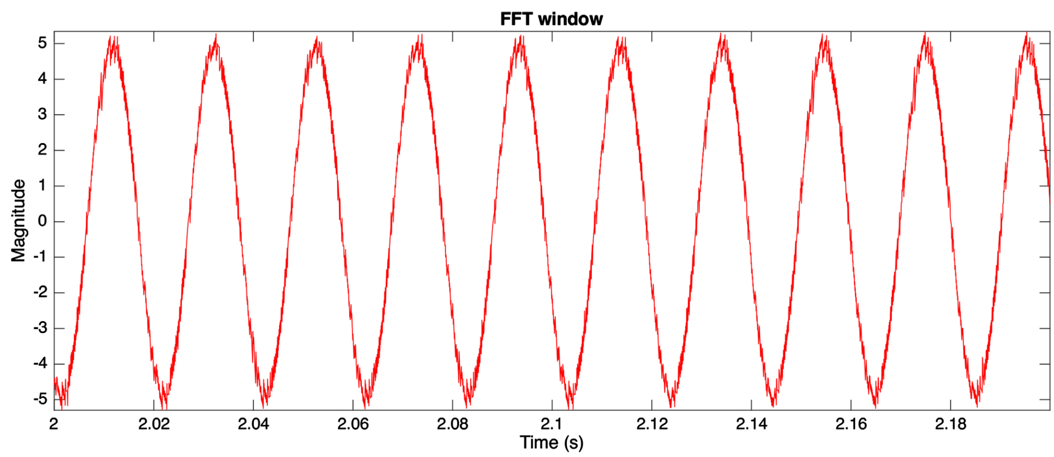


(a)

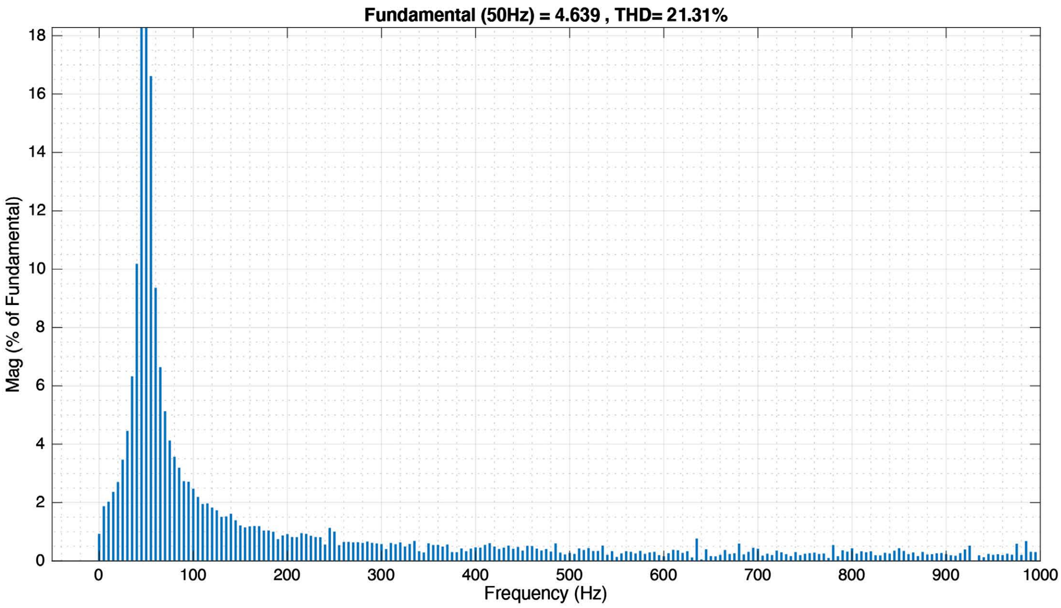


(b)

Figure 7. A-phase stator current at rated speed 1400 rpm. (a) FOC HCC; (b) Proposed MPCC.



(a)



(b)

Figure 8. Harmonic spectrum of the a-phase stator current under the three methods at a rated speed of 1400 rpm and a rated load of 10 Nm. (a) FOC HCC; (b) Proposed MPCC.

From the comparison between HCC and MPCC, it is observed that MPCC delivers better performance in both no-load and loaded conditions with faster tracking of the reference speed. However, the ripples in torque are noticeably higher compared to HCC. Overall, the transient response of MPCC under both operating conditions is clearly superior compared to HCC.

5. Conclusion

In this work, HCC and MPCC strategies were applied for efficient control of an Induction Motor using MATLAB/Simulink. A detailed comparison was carried out under different operating conditions to evaluate both methods. The results show that MPCC provides faster tracking, smoother transients in speed and current while HCC offers lower torque ripple. MPCC also handles dynamic changes better with minimal overshoot and quicker recovery. However, MPCC demands higher computational effort because it involves model-based prediction and evaluates multiple switching state candidates during every control cycle. This increased complexity may limit its adaptation in a low cost system. Despite this, MPCC is well-suited for applications where high performance, fast dynamics, and precise current control are critical such as in high-speed drives, robotics, and electric vehicles. Overall, MPCC offers more reliable and consistent performance than HCC, making it a better option for advanced IM control.

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.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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