

Robust Simplified Predictive Torque Control of IM Using Hybrid Fuzzy Logic Anti-Windup PI and Sliding Mode Regulation Loops

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Abstract: Predictive Torque Control (PTC) is an effective strategy for high-performance induction motor (IM) drives, that provides a rapid dynamic response and allows an intuitive implementation. The conventional PTC selects the optimal inverter switching state by minimizing a cost function based on torque and flux errors, but this requires all voltage vectors, resulting in a high computational demand. As such, this work proposes a simplified PTC-based approach named Predictive Direct Torque Control (PDTC) which is based on a fuzzy logic anti-windup PI controller and sliding mode speed regulators and employs a reduced switching table with only three voltage vectors, maintaining the prediction accuracy while lowering the computational complexity. Furthermore, the conventional speed loop regulation using a standard PI controller is sensitive to load variations and parameter uncertainties, limiting the performance of the analysed motor. Hence, a robust speed controller is required in order to withstand such unpredictable disturbances. The suggested approach improves the steady-state accuracy and reduces the overshoot under varying operating conditions. The MATLAB/Simulink simulations which were carried out validate the proposed PDTC-based approach, showing notable improvements in torque regulation, reduced torque and flux ripples, and an enhanced robustness in comparison with the traditional torque control algorithms, making it suitable for advanced motor drive applications.

Keywords: Predictive Direct Torque Control, IM, Fuzzy logic, Anti-windup, Load torque change, Sliding mode.

1. Introduction

Induction motors (IM) have been broadly used in diverse industrial applications due to their simple structure, low cost, high efficiency, and low maintenance (Jnayah and Khedher, 2019; Jnayah and Khedher, 2022). Thus, recently, many strategies have been put forth to control the asynchronous machine and ensure a speed dynamic response. Conventional Direct Torque Control (CDTC) and Field Oriented Control (FOC) are assumed to be the most stipulated approaches for AC motors. For the FOC strategy, three Proportional Integral (PI) regulators are usually employed to control speed, torque, and flux. Then, six internal parameters needed to be tuned properly to guarantee an accurate control scheme. Nonetheless, this may rise the realization time in practical implementation (Zhang, et al., 2021). Likewise, for the CDTC strategy, despite its simple structure and fast torque response, there are significant torque and flux ripples due to the variable switching frequency caused by hysteresis comparators (Massoum et al., 2021). To overcome these problems, several methods have been introduced in the last decades.

Nowadays, Model Predictive Control (MPC) is attracting the interest of many researchers since it can be deployed to control different variable speed drives accounted to induction motors. In fact, MPC has the ability to directly predict the future values

of the control variables such as stator flux and torque by optimizing their errors via a predefined cost function (Ahmed, et al., 2023). Furthermore, unlike FOC strategy, the MPC can ascertain a faster dynamic response and a simpler architecture (Gao et al., 2021). Additionally, in comparison with CDTC, the voltage vector selection in PTC is more precise and efficient through the online optimization of the cost function (Zhang et al., 2020). Accordingly, the implementation of PTC in motor drives has been widely explored and attempts to further improve its dynamics were exhibited in many research works (Praveen Kumar & Kumar, 2019; Himabindu et al., 2019; Ha & Giang, 2022). In the field of electric drive systems, the MPC strategy can be classified into two primary categories: 1) Continuous Control Set MPC (CCS-MPC), where the converter is linearized using a modulation scheme, such as pulse width modulation (PWM) and 2) Finite Control Set MPC (FCS-MPC) (Elmorshedy et al., 2021). It directly computes all the potential switching states and selects the optimal one by minimizing the cost function. In the existing literature, MPC has been applied in two primary forms: Predictive Torque Control (PTC) or Predictive Current Control (PCC) (Elmorshedy et al., 2021). Recently, PTC has emerged in high-performance adjustable-speed drives since it

exhibits lower torque ripples compared with the PCC method.

The proposed Predictive Direct Torque Control (PDTC) demonstrates clear advantages over the conventional DTC and PTC methods. It significantly reduces torque and flux ripples through optimized three-vector selection (Ghibeche et al., 2025), ensures a better or comparable dynamic response (Kasri et al., 2024), and operates at a reduced switching frequency with a smaller set of candidate vectors (Bonardo et al., 2025). In terms of steady-state accuracy, PDTC achieves a competitive performance due to the optimized vector choice (Karlovsky & Lettl, 2018), while maintaining a moderate computational complexity, lower than that of the conventional PTC (Li et al., 2025), and easier implementation on standard DSP hardware (Shahid et al., 2024).

Despite the revolutionary development in the field of PTC, speed regulation in the outer loop is still frequently ensured by a proportional-integral (PI) controller. Nevertheless, due to its sensitivity to the mathematical model of the machine and low control reliability, the PI regulator is afflicted by external disturbances and parameter variation. Indeed, in the presence of torque disturbances, it may not operate properly and hence, the dynamic behavior of the controlled machine will be affected (Tian et al., 2023). To address this issue, multiple speed regulation methods have been advocated in the literature to enhance the robustness of the control system and meet the high performance of the PTC strategy. Among them, Fuzzy Logic Controller (FLC) can provide a fast response and an accurate speed tracking without the knowledge of the system mathematical model (Ammar et al., 2019). During the quick change in load torque, the IM would stabilize well with FLC. In this contingency, the speed profile has the proficiency to follow the reference trajectory with a minimum error under external disturbance. Another reliable strategy for implementing a robust speed regulation is Sliding Mode Control (SMC). Using the SMC resolves not only the dependency of the PI regulator on motor parameters but also its sensitivity to load torque variations. In fact, this controller has been successfully used to improve the control performance of the drive system as it features an invariance property against uncertainties. It has been proven that the suggested speed controller ensures a high global

stability and a very good tracking performance with disturbance rejection. However, its concept is challenging which makes the design of the control strategy complex. Therefore, this paper aims to improve the steady-state performance of the IM for all speed ranges and ensure its robustness against external disturbances by combining the predictive control strategy with two different speed controllers, the FLC-anti-windup PI controller and the SMC instead of the conventional PI regulator.

The remainder of this paper is structured as follows: Section 2 introduces the principle of the simplified PDTC approach. Section 3 is devoted to improving the performance of the IM and ensuring the robustness of the control strategy against load torque variation by using different speed regulators. Section 4 presents the simulation results for the enhanced PDTC, while the experimental test bench is presented in Section 5. Finally, the conclusions of this paper are outlined in Section 6.

2. Design of the Simplified PDTC of IM Drive

2.1 IM Modelling

First, for implementing the PDTC control strategy, the dynamic model of the IM, based on the electrical and the mechanical equations, is written as:

$$\begin{cases} V_s = R_s i_s + \frac{d\psi_s}{dt} \\ 0 = R_r i_r + \frac{d\psi_r}{dt} - j\omega_m \psi_r \\ \psi_s = L_s i_s + M_{sr} i_r \\ \psi_r = L_r i_r + M_{sr} i_s \end{cases} \quad (1)$$

$$T_e = 1.5p(\varphi_s i_s) \quad (2)$$

Here, V_s , i_s , i_r , ψ_s , ψ_r , R_s , R_r , L_s , L_r , M_{sr} , T_e and p denote respectively the stator voltage vector, stator current vector, rotor current vector, stator flux vector, rotor flux vector, stator resistance, rotor resistance, stator inductance, rotor inductance, mutual inductance, electromagnetic torque and the number of pair poles, respectively.

The motor parameters with their respective values are mentioned in Appendix A.

$$\bar{\psi}_s(k) = \frac{L_m}{L_r} \bar{\psi}_r(k) + \sigma L_s \bar{i}_s(k) \quad (7)$$

Hence, the estimation of the electromagnetic torque can be easily calculated based on the following expression:

$$\bar{T}_e(k) = \frac{3}{2} \text{Im}(\bar{\psi}_s(k) \times \bar{i}_s(k)) \quad (8)$$

2.4 Prediction of Stator Flux and Torque

The stator flux and electromagnetic torque are the control variables in PDTC, so their behavior should be predicted at the sampling time $(k+1)$. The stator voltage model of IM is typically used to predict the stator flux and may be written in discrete time as given in equation (9):

$$\bar{\psi}_s^p(k+1) = \bar{\psi}_s(k) + T_s \bar{V}_s(k) - T_s R_s \bar{i}_s(k) \quad (9)$$

The electromagnetic torque prediction is determined based on the predicted current and flux expressions (Chebaani et al., 2019). Hence, equations (10) and (11) are written as follows:

$$\bar{i}_s^p(k+1) = \left(1 + \frac{T_s}{\tau_\sigma}\right) \bar{i}_s(k) + \frac{T_s}{\tau_\sigma + T_s} \times \left\{ \frac{1}{R_\sigma} \left[\left(\frac{k_r}{\tau_r} - k_r j \omega_m(k) \right) \bar{\psi}_r(k) + \bar{V}_s(k) \right] \right\} \quad (10)$$

Here, $k_r = \frac{M_{sr}}{L_r}$ is the rotor coupling factor, $R_\sigma = R_s + k_r^2 R_r$ is the equivalent resistance with regard to the stator, while $\tau_\sigma = \frac{L_\sigma}{R_\sigma}$ and $\tau_r = \frac{L_r}{R_r}$ are the stator transient time constant and the rotor transient time constant respectively. $L_\sigma = \sigma L_s$ is the leakage inductance.

$$\bar{T}_e(k+1) = \frac{3}{2} \text{Im}(\bar{\psi}_s(k+1) \times \bar{i}_s(k+1)) \quad (11)$$

2.5 Voltage Vector Selection

The selection of the optimal voltage vector to control the switching states of the inverter represents the third step of the control algorithm. This is ensured through optimizing the cost function, which compares the flux and torque reference values with their corresponding predicted values. Therefore, the cost function can be defined by equation (12) as given below:

$$g_T = \frac{|T_c^* - T_c^p(k+1)|}{T_n} + \lambda_p \frac{|\psi_s^* - \psi_s^p(k+1)|}{\psi_{sn}} \quad (12)$$

Here, T_n and ψ_{sn} are the nominal torque and flux values, T_c^* and ψ_s^* are the reference values of torque and flux, while λ_p denotes the weighting factor. T_c^p and ψ_s^p are the predicted torque and flux, respectively.

3. Model Description of Speed Regulators for PDTC Strategy

3.1 SMC Controller Design

For a robust operation against load torque variations, an Integral Sliding Mode (ISM) based speed regulator is used. Its particular dynamic performance features include a quick response, a high resilience, and simplicity of implementation (Shiravani et al., 2022). There are two stages in conceiving the ISMC regulator. The first step is choosing the convenient integral sliding surface to accomplish the control aims. The second step is the construction of the control law that compels the system to reach the sliding surface and remain there.

The ISM controller requires a speed tracking error, given in equation (13), as well as its integral signal as given in equation (14):

$$e_\omega = \omega^* - \omega \quad (13)$$

where ω^* is the speed reference.

$$S_\omega = e_\omega + K_\omega \int e_\omega dt \quad ; K_\omega > 0 \quad (14)$$

By replacing the derivative of equation (13) in (14), the following is obtained:

$$\dot{S}_\omega = \dot{\omega}^* - \dot{\omega} + K_\omega (\omega^* - \omega) \quad (15)$$

The dynamic equation of the drive is expressed as:

$$J \frac{d}{dt} \omega = T_c - f \omega - T_{load} \quad (16)$$

Here, T_{load} is the load torque, f is the friction coefficient and J is the moment of inertia.

Then, equation (17) is given as follows:

$$\dot{S}_\omega = \dot{\omega}^* - \frac{1}{J} T_c + \frac{1}{J} T_{load} + \frac{f}{J} \omega + K_\omega (\omega^* - \omega) \quad (17)$$

Based on the equivalent control approach within the sliding mode control theory the torque reference is expressed as:

$$T_c = T_{eq} + T_n \quad (18)$$

The equivalent control action $T_{c_{eq}}$ that guarantees the system convergence toward the sliding surface is obtained by assuming that $\dot{S}_\omega = 0$. The discontinuous component is identified as:

$$K_\omega |S_\omega| \text{sign}(S_\omega) \quad (19)$$

Here, $\text{sign}(\cdot)$ represents the sign function.

To analyze the stability of the system based on the suggested controller, the Lyapunov function is defined using equation (20):

$$V = \frac{1}{2} S^2 \quad (20)$$

The first order derivative of equation (20) is:

$$\dot{V} = \dot{S}S = -\frac{K_\omega}{J} |S_\omega| \text{sign}(S_\omega) < 0 \quad (21)$$

Thereby, the system with a SM speed regulator is proved to be stable.

3.2 Fuzzy Logic Anti-windup Controller

Several researchers have worked on the fuzzy logic control during the last few years since it simulates complex industrial processes using linguistic description rather than numerical tools. Thus, FL represents an interesting choice for speed regulation due to its independence from the IM model, the ability to control a nonlinear system, and its inherent robustness. Hence, in this work, an anti-windup PI controller combined with a FL regulator is proposed for motor speed control to overcome the instability of the dynamic response and the lengthy settling time.

The suggested hybrid fuzzy logic anti-windup PI controller is given in Figure 2.

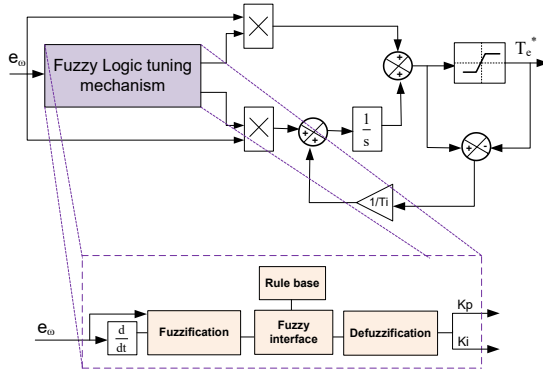


Figure 2. Fuzzy logic anti-windup speed controller

The control strategy combines a conventional PI controller with fuzzy logic-based adaptive

gain tuning and an anti-windup mechanism. The fuzzy block dynamically adjusts the proportional K_p and integral K_i gains based on the error and its rate of change, enabling a rapid response to large deviations while maintaining stability in the case of small deviations. The PI controller computes the corrective action, which is limited by actuator saturation, and the anti-windup path constrains the integral term to prevent overshoot. This hybrid design ensures an accurate, fast, and robust regulation.

Referring to Figure 2, the error e_ω and its derivative $\frac{d}{dt}e_\omega$ are the inputs of the fuzzy logic tuning process (Bouguenna et al., 2021). These inputs are converted into linguistic variables during the fuzzification stage as illustrated in Figure 3.

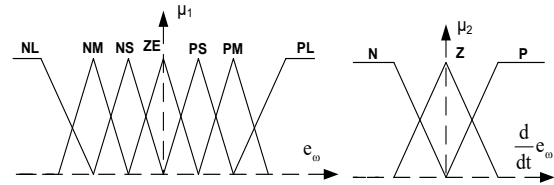


Figure 3. Membership functions of the input variables

The input fuzzy sets are: Positive (P), Zero (Z), Negative (N), Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero Error (ZE), Positive Small (PS), Positive Medium (PM), and Positive Large (PL).

Memdani's approach is used for fuzzy inference and the center of gravity method is employed for the defuzzification step to determine the output of this controller.

As the first input is described using seven linguistic values and the second one is described based on three linguistic variables, there are $7 \times 3 = 21$ rules for each output as given in Table 2.

Table 2. Fuzzy rule of output variables

$\frac{d}{dt}e_\omega$ \ e_ω	NL	NM	NS	ZE	PS	PM	PL
N	L	M	S	M	S	M	L
Z	L	M	L	Z	L	M	L
P	L	M	L	Z	L	M	L

4. Simulation Results and Discussion

The simulations of the IM drive controlled with the proposed PTC strategy using different speed regulation loops were conducted in the MATLAB/Simulink software. The load torque variation is assessed as an external disturbance for the asynchronous machine. Several operating conditions, such as sudden load change and varying set speed covering the rated speed, reverse speed, and low speed, are used in the simulation as illustrated in Figure 4.

Figures 5, 6 and 7 illustrate the speed response and tracking error by using three different speed regulators, namely the PI, SMC and fuzzy logic anti-windup PI controller, on the basis of Table 3.

As it can be noted, FLC has the ability to track its reference quickly without overshooting.

Furthermore, the fuzzy logic controller proved to be top-performing when it was subjected to external disturbances since the speed drop was about 0.41% at $t=7s$ due to the application of the load torque, while the SMC and PI regulators achieved a speed drop percentage of 0.44% and 0.92%, respectively. These results indicate that the fuzzy regulator achieves a satisfactory accuracy and a good tracking capability without requiring any mathematical calculations.

- W_{load} : Weakening of the speed due to the application of the load torque;
- T_{s1} : Time required for the speed to return to its initial value after the decrease in speed caused by the application of the load torque;
- THD_i : Total Harmonic Distortion of the current;
- D: Speed overtaking

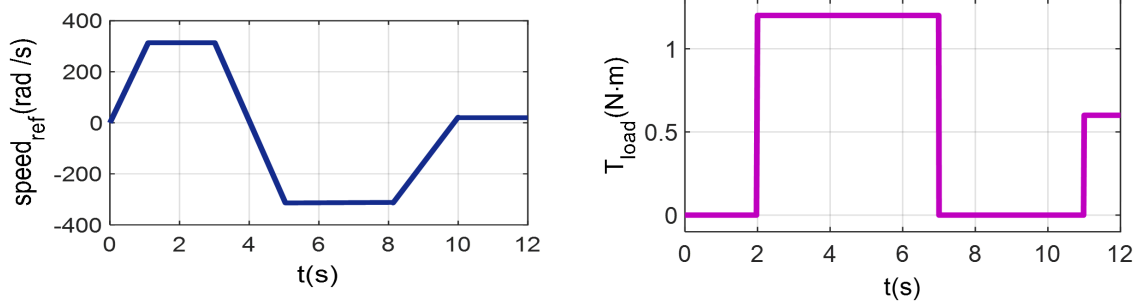


Figure 4. Reference speed and load variation

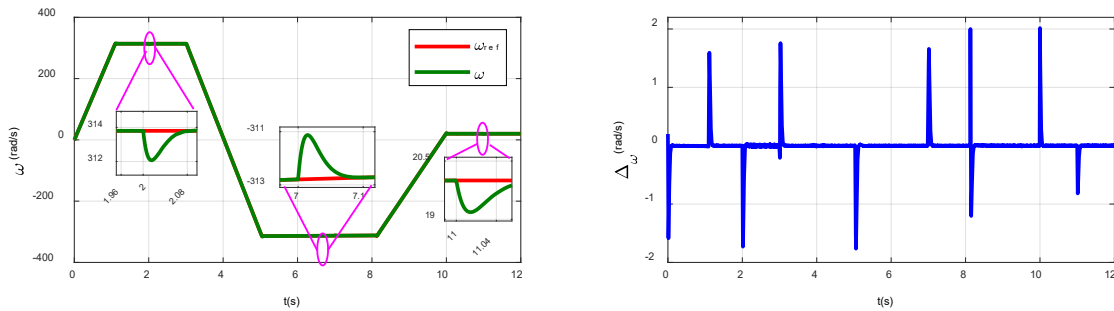


Figure 5. Speed behavior and tracking error using the PI controller

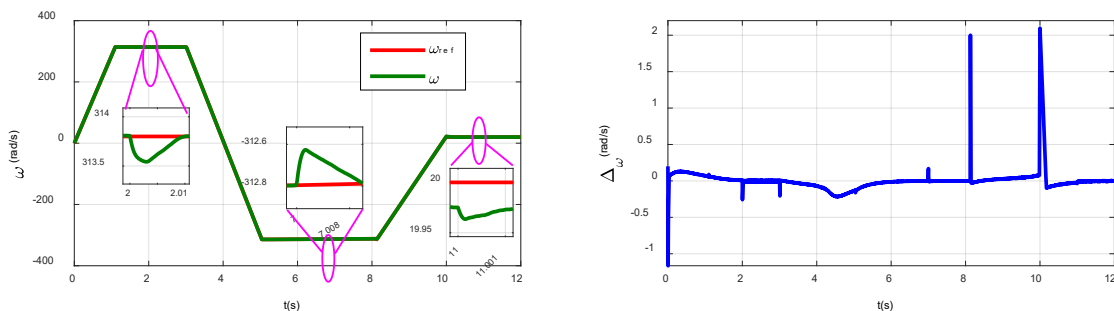


Figure 6. Speed behavior and tracking error using the SM controller

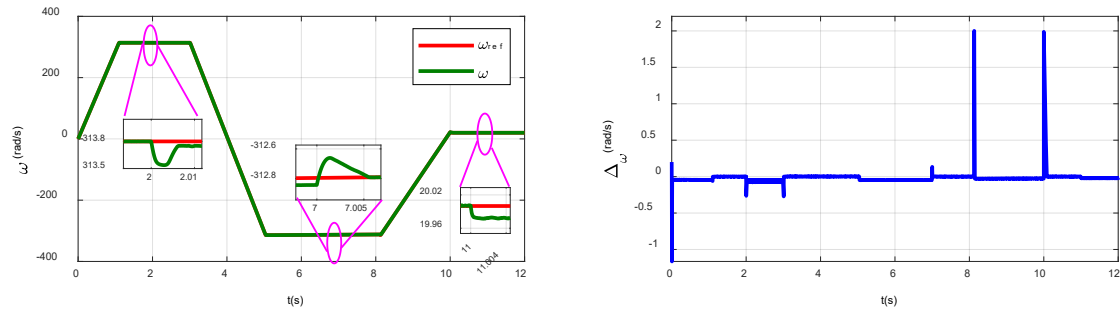


Figure 7. Speed behaviour and tracking error using the FL anti-windup PI controller

Table 3. Comparative analysis of the PI, SMC and FL anti-windup PI controller speed regulation loops

	PI	SMC	FL anti-windup PI controller
THD _i %	7.39	3.76	3.66
W _{load} %	At $t=2$ s: 0.61	At $t=2$ s: 0.15	At $t=2$ s: 0.15
	At $t=7$ s: 0.92	At $t=7$ s: 0.44	At $t=7$ s: 0.41
	At $t=11$ s: 4.1	At $t=11$ s: 0.2	At $t=11$ s: 0.1
D %	0.45	0.03	≈ 0
T _{sl}	0.08	0.009	0.006

Figures 8 and 9 depict the stator current magnitude and the electromagnetic torque of the IM controlled with the PTC strategy under the implemented speed regulators. When compared with the PI and SMC based techniques, it is evident that the FL anti-windup based approach has a significantly better trajectory with a lower current THD rate (3.66%).

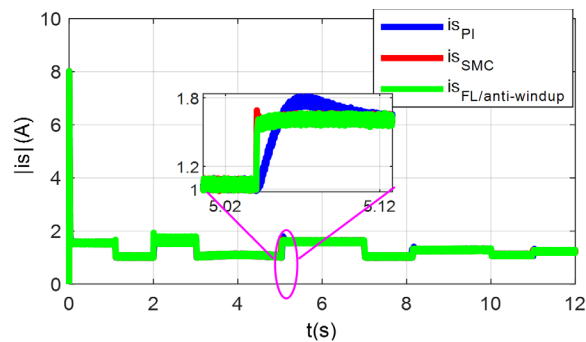


Figure 8. Stator current magnitudes with different speed regulators

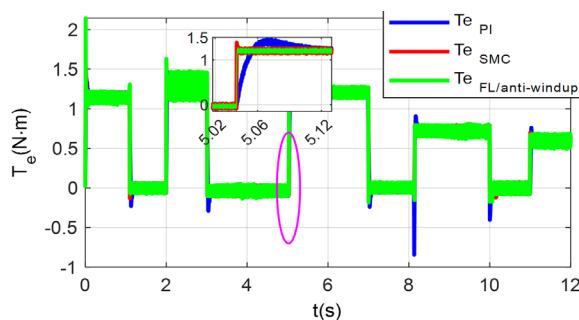


Figure 9. Torque responses with different speed regulators

5. Experimental Validation

The DPTC scheme was implemented with a conventional PI controller including the anti-windup mechanism and using a constant speed profile. The fuzzy adaptation and sliding-mode compensation blocks have not been experimentally validated yet. In this paper, the focus was on establishing a robust and experimentally safe baseline by validating the DPTC-PI anti-windup configuration. The fuzzy and SMC extensions significantly increase the computational complexity and real-time processing demands, which may compromise the timing accuracy on the available DSP platform. Therefore, a stepwise validation strategy is chosen: first confirming the feasibility and stability of the core DPTC structure experimentally, before integrating the hybrid elements and load torque variation in the future hardware implementation. Nevertheless, the experimental setup reproduces the same operational conditions and measurement conditions used in the simulation, ensuring the consistency of the comparative analysis.

The synoptic diagram in Figure 10 summarizes the structure of the experimental predictive control platform, detailing the interaction between the sensing units, DSP controller, power converter, and induction motor.

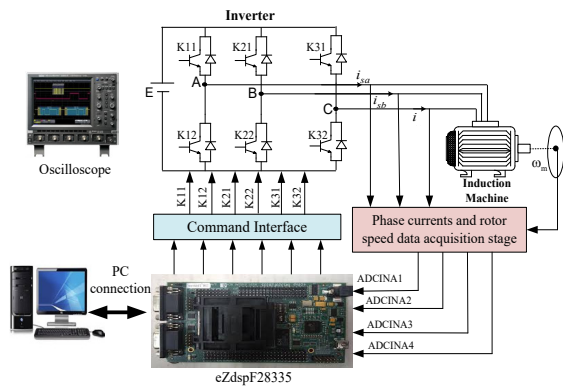


Figure 10. Structural diagram of the experimental platform

The real-time implementation of the DPTC control scheme was carried out using a data-acquisition interface enabling the measurement and conditioning of the motor phase currents and rotor speed. These measured values were transmitted to the analog-to-digital converters of the TMS320F28335 DSP board for processing. The control algorithm was developed in the MATLAB/Simulink environment, from which the corresponding C code and executable “.out” file were automatically generated through the Code Composer Studio (CCS) toolchain. Figure 11 depicts the laboratory setup employed for real-time testing.

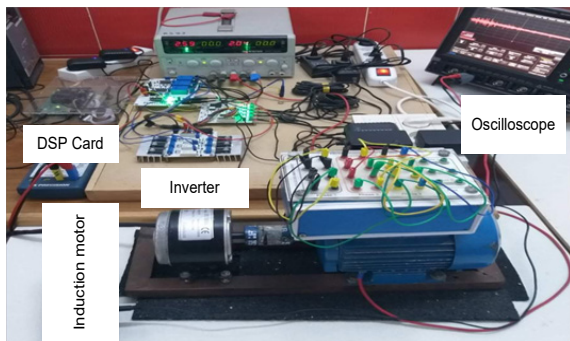


Figure 11. Photo of the laboratory prototype

Time delay Compensation: In practical implementations, the computation of the optimal stator voltage vector requires one sampling period, so the vector calculated using the measurements at time k is applied at time $k+1$, introducing a delay in contrast with ideal simulations, as illustrated in Figure 12. To address this, a two-step prediction is used: the previous voltage vector predicts the machine state at time $k+1$, then the current voltage vector refines the prediction of the stator flux and torque. Based on these predictions, the

controller selects the appropriate voltage vector for application at $k+1$, ensuring a consistent reference tracking at $k+2$ and maintaining a time-aligned control performance.

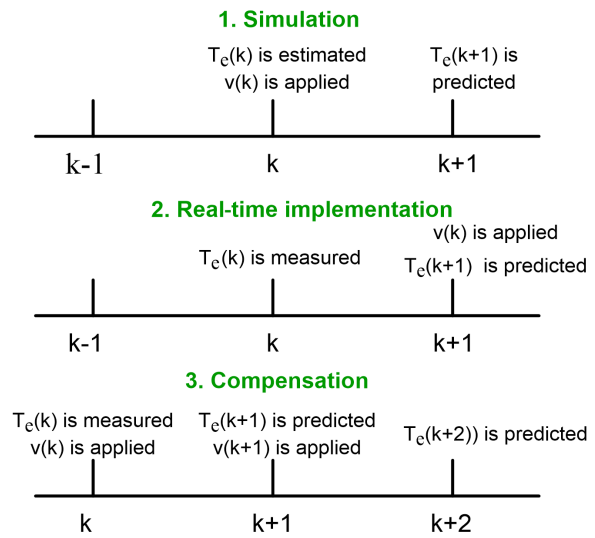


Figure 12. Compensation of the time delay

The preliminary results were obtained using the DPTC scheme with a PI anti-windup regulator to validate the real-time operation of the control algorithm as presented in Figure 13.

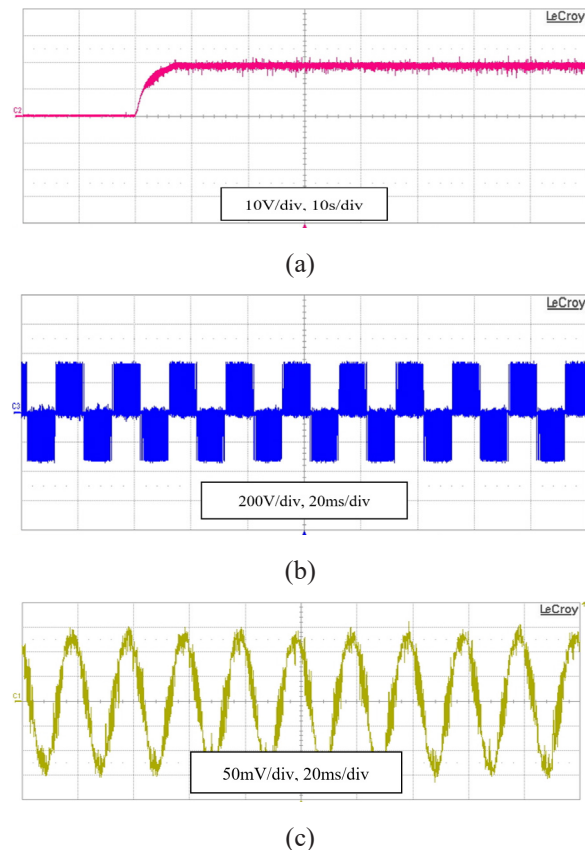


Figure 13. Measured signals from the induction motor operated under DPTC: (a) speed response; (b) U_{AB} voltage; (c) stator current waveform

6. Conclusion

The purpose of this paper is to propose a simplified robust PTC algorithm (PDTC) applying a set of three voltage vectors, rather than the eight vectors used in the traditional strategy. In order to test the robustness of the designed control approach against load torque variation at different speed ranges, a sliding mode and a fuzzy logic anti-windup controller are inserted instead of the conventional PI regulator. It has been proved that by leveraging on the fuzzy logic approach, the control scheme can achieve a superior dynamic performance and an accurate reference tracking without relying on a predefined model. Additionally, the FLC is capable of generating

faster and more precise torque reference signals with a lower current THD rate. Conclusively, the proposed model predictive control approach achieves a significant performance when combined with artificial intelligence techniques at different speed ranges under load torque variation.

Appendix A: Motor Parameters

Rated power = 0.5Kw; Motor speed = 3000 tr/min; Stator resistance: $R_s = 24 \Omega$; Stator inductance: $L_s = 0.66H$; Rotor Resistance: $R_r = 10.88 \Omega$; Rotor inductance: $L_r = 0.66H$; Mutual inductance: $L_m = 0.63 H$; Friction coefficient: $f = 0.00159$; Moment of Inertia: $J = 0.004Kg.m^2$; Number of pair poles: $p=1$.

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