Direct Torque Control of Dual Three Phase Induction Motor fed by Direct Power Control Rectifier using Fuzzy Logic Speed Controller

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Abstract

This paper presents an advanced Direct Torque Control (DTC) approach for a Dual Three-Phase Induction Motor (DTPIM) powered by a Direct Power Control (DPC) rectifier. Traditional control methods, such as Proportional-Integral-Derivative (PID) controllers, often face performance issues when motor system parameters vary or exhibit non-linearity. To tackle these challenges, we propose a fuzzy logic-based speed controller for DTC, which enhances adaptability to system dynamics without necessitating a precise mathematical model. The fuzzy logic controller (FLC) is particularly effective in regulating speed under varying load conditions, improving robustness, and minimizing torque ripple. Furthermore, the DPC rectifier enhances power quality by reducing harmonic distortions, maintaining a stable DC link voltage, and improving the power factor. Simulation results obtained using MATLAB/Simulink software demonstrate that the combined DTC-DPC approach with fuzzy logic control delivers a superior dynamic response with minimal overshoot. This framework offers a promising solution for high-performance industrial applications that require precise torque control and stability under fluctuating loads while also supporting sustainable energy practices through improved power efficiency.

Keywords: *DTPIM, DTC, DPC, Rectifier, Fuzzy Logic.*

1. Introduction

The performance of AC power drive systems can be significantly enhanced by employing a multiple-phase driving system, which features over three stator phases. Multi-phase drive systems offer several benefits over traditional 3-phase drives, such as higher torque pulsation frequency and decreased torque pulsation amplitude, minimized Total Harmonic Distortion (THD) of rotor current, reduced DC-Link current harmonics, and a decrease in phase's current without an increase in voltage, and improved reliability. Additionally, in the event of a phase fault, the motor continues to operate normally [1]. A typical example of a polyphase motor is the Dual Three Phase Induction Motor (DTPIM), also referred to as a six-phase induction motor. These motors are widely utilized in many applications because of their benefits in power segmentation, reliability, and reduced torque pulsations, including pumps, compressors, fans, cement mills, mining hoists, etc. [2].

The control of induction motors is crucial for optimizing performance across a wide range of applications. Several control strategies are available, including scalar control, direct torque control, and vector control. Among these, Direct Torque Control (DTC) has emerged as one of the most robust control techniques for alternating current motors, offering exceptional flux and torque control with fast response [3].

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PWM rectifier control has become an increasingly significant area of research, with several control schemes being proposed in recent studies. These include VOC, VFOC, and DPC which stand for voltage-oriented control, virtual flux-oriented control, and direct power control, respectively. DPC is based on instantaneous active and reactive power control. In this technique, the rectifier's switching states are chosen from a switching table based on the instantaneous errors between the estimated active and reactive powers and the reference values. Achieving a unity power factor and reducing total harmonic distortion (THD) are the goals of this strategy [4].

Most industrial systems are complex, nonlinear, coupled, and have variable parameters, which makes conventional control techniques, such as PID controllers inadequate due to their sensitivity to parametric variation. For this reason, robust control methods, which are less affected by system parameter variations, internal and external disturbances, and nonlinearity, are employed. Fuzzy logic control is one of the most well-known robust approaches, as it does not rely on a precise system model, making it resilient to parameter variations [4].

The novelty of this approach lies in the integration of Direct Torque Control (DTC) with a Direct Power Control (DPC) Rectifier and a Fuzzy Logic Speed Controller, which allows for precise control of torque and flux while optimizing power conversion. The inclusion of fuzzy logic allows the control to manage uncertainties and non-linearity of the system.

The importance of this study for the scientific community lies in its ability to enhance industrial motor drive systems' reliability, efficiency, and performance. It has potential applications in industrial automation, electric vehicles, and renewable energy systems, providing more efficient and high-performing solutions for various fields.

This article is organized into six sections. The next section presents the DTPIM modelling. Section three discusses the control method using DTC. Section four introduces Direct Power Control. Section five covers Fuzzy Logic Control. Finally, section six presents the simulation results, followed by a concluding summary of the work.

2. DTPIM Modeling

Figure 1 shows the rotor and stator winding layout for a DTPIM. The six phases of the stator are separated into two sets of 3 phases each: A_{s1}, B_{s1}, C_{s1}; A_{s2}, B_{s2}, C_{s2} where the angle a=30° shifts the axes. Both three-phase groups' windings are symmetrically oriented, with a 120° axis offset. The axis of the three-phase rotor windings—Ar, Br, and Cr—are offset by 120° and have a sinus wave form [5], [6]. The simplifying assumptions listed below are taken into account [4], [7]:

- Neglecting of magnetic saturation
- Neglecting of mutual leakage inductance
- Neglecting of the core losses
- Assuming a sinusoidal winding distribution.

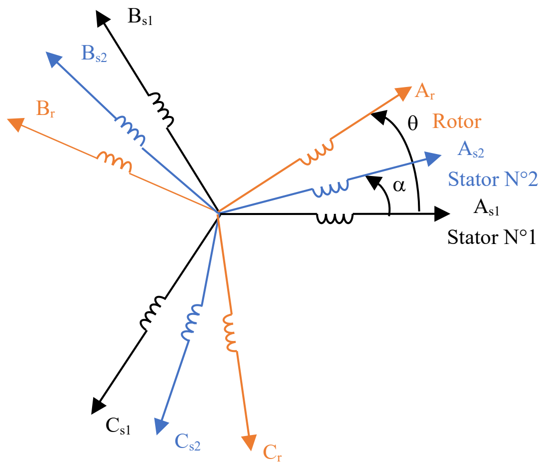

Figure 1. Windings of the DTPIM.

The voltage equations of the DTPIM, as described in references [2], [8], are presented below.

$$
\begin{aligned}
[V_{s1}] &= \begin{bmatrix} V_{sa1} \\ V_{sb1} \\ V_{sc1} \end{bmatrix} = [R_{s1}][I_{s1}] + \frac{d}{dt}[\Phi_{s1}] \\
[V_{s2}] &= \begin{bmatrix} V_{sa2} \\ V_{sb2} \\ V_{sc2} \end{bmatrix} = [R_{s2}][I_{s2}] + \frac{d}{dt}\left[\Phi_{s2}\right] \\
[0] &= \begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = [R_r][I_r] + \frac{d}{dt}[\Phi_r]
\end{aligned}
\tag{1}
$$

where:

R_{sa1}, R_{sb1}, R_{sc1} = R_{s1}: First stator resistance.

R_{sa2}, R_{sb2}, R_{sc2} = R_{s2}: Second stator resistance.

R_{ra}, R_{rb}, R_{rc}, R_r: Rotor resistance.

$$[R_{s1}]=\begin{bmatrix} R_{s1} & 0 & 0 \\ 0 & R_{s1} & 0 \\ 0 & 0 & R_{s1} \end{bmatrix};\ [R_{s2}]=\begin{bmatrix} R_{s2} & 0 & 0 \\ 0 & R_{s2} & 0 \\ 0 & 0 & R_{s2} \end{bmatrix};\ [R_r]=\begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \quad (2)$$

$$[I_{s1}]=\begin{bmatrix} I_{sa1} \\ I_{sb1} \\ I_{sc1} \end{bmatrix};\ [I_{s2}]=\begin{bmatrix} I_{sa2} \\ I_{sb2} \\ I_{sc2} \end{bmatrix};\ [I_r]=\begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} \quad (3)$$

$$[\Phi_{s1}]=\begin{bmatrix} \Phi_{sa1} \\ \Phi_{sb1} \\ \Phi_{sc1} \end{bmatrix};[\Phi_{s2}]=\begin{bmatrix} \Phi_{sa2} \\ \Phi_{sb2} \\ \Phi_{sc2} \end{bmatrix};[\Phi_r]=\begin{bmatrix} \Phi_{ra} \\ \Phi_{rb} \\ \Phi_{rc} \end{bmatrix} \quad (4)$$

The stator and rotor flux expressions are as follow [2], [8]:

$$\begin{bmatrix} [\Phi_{s1}] \\ [\Phi_{s2}] \\ [\Phi_r] \end{bmatrix} = \begin{bmatrix} [L_{s1s1}] & [L_{s1s2}] & [L_{s1r}] \\ [L_{s2s1}] & [L_{s2s2}] & [L_{s2r}] \\ [L_{rs1}] & [L_{rs2}] & [L_{rr}] \end{bmatrix} . \begin{bmatrix} [I_{s1}] \\ [I_{s2}] \\ [I_r] \end{bmatrix} \quad (5)$$

Where:

$[L_{s1s1}]$: The inductance of stator 1.

$[L_{s2s2}]$: The inductance of stator 2.

$[L_{rr}]$: The inductance of rotor.

$[L_{s1s2}]$: The mutual inductance relating stator 1 and stator 2.

$[L_{s2s1}]$: The mutual inductance relating stator 2 and stator 1.

$[L_{s1r}]$: The mutual inductance relating stator 1 and rotor.

$[L_{s2r}]$: The mutual inductance relating stator 1 and rotor.

$[L_{rs1}]$: The mutual inductance relating rotor and stator.

$[L_{rs2}]$: The mutual inductance relating rotor and stator.

The electromagnetic torque expression is given by [4], [8]:

$$T_{em}=\left(\frac{p}{2}\right).\left([I_{s1}]\frac{d}{d\theta}[L_{s1r}][I_r] + [I_{s2}]\frac{d}{d\theta}[L_{s2r}][I_r]\right) \quad (6)$$

The analytical solution of the equations system (1) and (3) in the three-phase 'abc' reference frame is very complex. To address this issue, the Park transformation is used. This transformation allows for the conversion from a 3-phase system (abc) to an equivalent 2 phase system (dq) with preserving power [9], as presented in Figure 2.

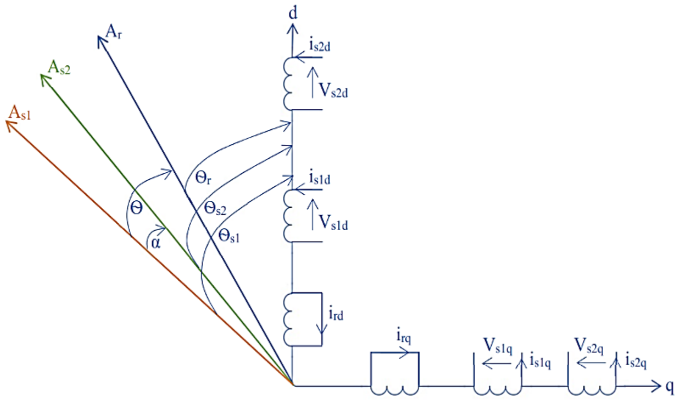

Figure 2. DTPIM's representation in the Park frame.

$$\begin{aligned}
V_{s1d} &= R_{s1}I_{s1d} + \frac{d}{dt}\Phi_{s1d} - \omega_s\Phi_{s1q} \\
V_{s1q} &= R_{s1}I_{s1q} + \frac{d}{dt}\Phi_{s1q} + \omega_s\Phi_{s1d} \\
V_{s2d} &= R_{s2}I_{s2d} + \frac{d}{dt}\Phi_{s2d} - \omega_s\Phi_{s2q} \\
V_{s2q} &= R_{s2}I_{s2q} + \frac{d}{dt}\Phi_{s2q} + \omega_s\Phi_{s2d} \\
0 &= R_r I_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_{sr}\Phi_{rq} \\
0 &= R_r I_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_{sr}\Phi_{rd}
\end{aligned} \quad (7)$$

Where:

$$\begin{aligned}
\Phi_{s1d} &= L_{s1}I_{s1d} + L_m(I_{s1d} + I_{s2d} + I_{rd}) \\
\Phi_{s1q} &= L_{s1}I_{s1q} + L_m(I_{s1q} + I_{s2q} + I_{rq}) \\
\Phi_{s2d} &= L_{s2}I_{s2d} + L_m(I_{s1d} + I_{s2d} + I_{rd}) \\
\Phi_{s2q} &= L_{s2}I_{s2q} + L_m(I_{s1q} + I_{s2q} + I_{rq}) \\
\Phi_{rd} &= L_r I_{rd} + L_m(I_{s1d} + I_{s2d} + I_{rd}) \\
\Phi_{rq} &= L_r I_{rq} + L_m(I_{s1q} + I_{s2q} + I_{rq})
\end{aligned} \quad (8)$$

L_m: rotor, stator 1, and stator 2's cyclic mutual inductance.

The equation of mechanical part is provided by:

$$J\frac{d\Omega}{dt} = T_{em} - T_r - F_r\Omega \quad (9)$$

with:

$$T_{em} = p\frac{L_m}{L_r + L_m}\left[\Phi_{rd}(I_{s1q} + I_{s2q}) - \Phi_{rq}(I_{s1d} + I_{s2d})\right] \quad (10)$$

3. Direct Torque Control

DTC is widely recognized as one of the most popular linear control, valued for its simplicity in implementation and fast dynamic response compared to several other methods. The concept of this approach relies on the direct control of torque and flux, the cornerstone of this technique rests on defining the control sequence for the converter switches, which is crucial for achieving the reference torque and flux (Φ_s^{*}, T_{em}^{*}).

Figure 3 illustrates a synoptic schematic of the DTC method for the DTPIM. The DTC method relies on estimating flux and torque, as this estimation plays a key role in determining the torque and flux errors.

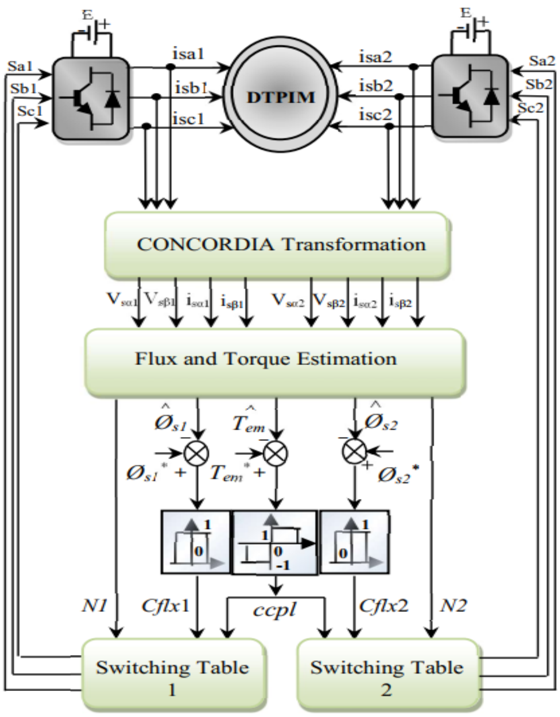

Figure 3. Direct Torque Control block schematic for DTPIM.

The torque and flux error values serve as inputs to hysteresis controllers (Figure. 4) which maintain the torque and flux amplitude within specified hysteresis bounds by selection the appropriate inverter output voltage. When the torque and flux amplitude attain the higher or lower bound of the hysteresis controller, the system applies an appropriate voltage vector to ensure to keep torque and flux within its specified bands [10].

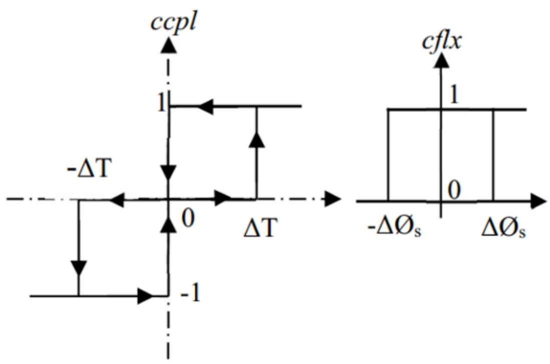

Figure 4. Hysteresis comparator of torque and flux.

When the vector of stator flux is placed in the first sector (Figure 5), To increase its magnitude, the voltage vectors V_1, V_2, and V_6 can be selected. Oppositely, the selecting of V_3, V_4, V_5 will decrease the magnitude. However, the vectors V_2, V_3, and V_4 must be utilized in order to increase the electromagnetic torque, while a reduction in torque can be achieved by selecting V_1, V_5, V_6.

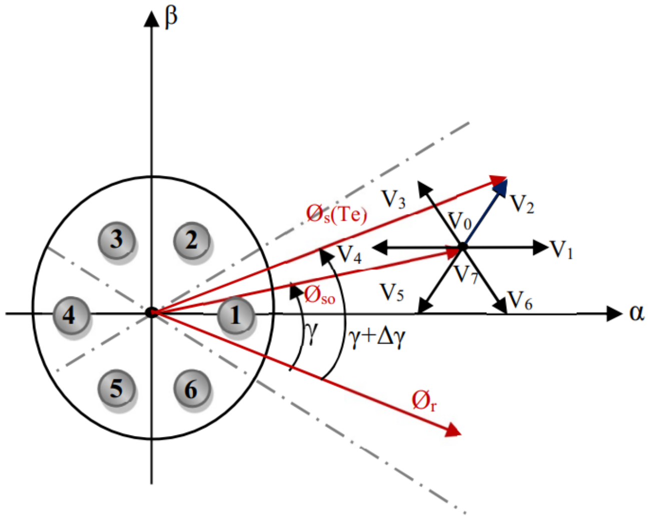

Figure 5. Selection of voltage vector.

The expressions of stator flux and electromagnetic torque are as follows [11]:

$$\phi_s(Te) = Vs + \phi_{so} \tag{11}$$

$$\mathrm{T_{em}} = Kc.\left\|\overrightarrow{\phi_s}\right\|.\left\|\overrightarrow{\phi_r}\right\|\sin(\gamma) \tag{12}$$

K_c: constant related to the motor parameters.

γ: Angle bounded by the stator and rotor flux vectors.

The use of zero voltage vectors (V_0, V_7) blocks the stator flux vector rotation. Although, the rotor flux continues to evolve and attempts to align with the stator flux. As a result, there will be a decrease of the angle γ bounded by stator and rotor flux vectors decreases, leading to a gradual reduction in electromagnetic torque.

The switching table has the role of the selection of appropriate commutation inverter state founded on the hysteresis comparators outputs (*cflx* for the flux, and *ccpl* for the torque) and the sector which the stator vector flux is positioned, for the purpose to keep the magnitudes of both electromagnetic torque and stator flux in the bands of hysteresis. The previous considerations form the basis of the switching table construction, as shown in Table 1.

Table 1. Switching table with zero voltage vectors.

Flux	Torque	Sectors 1	2	3	4	5	6	Comparator
	Ccpl=1	V_3	V_4	V_5	V_6	V_1	V_2	2 level
Cflx=0	Ccpl=0	V_0	V_7	V_0	V_7	V_0	V_7	
	Ccpl=-1	V_5	V_6	V_1	V_2	V_3	V_4	3 level
	Ccpl=1	V_2	V_3	V_4	V_5	V_6	V_1	2 level
Cflx=1	Ccpl=0	V_7	V_0	V_7	V_0	V_7	V_0	
	Ccpl=-1	V_6	V_1	V_2	V_3	V_4	V_5	3 level

4. Direct Power Control

The DPC technique is fundamentally equivalent to the Direct Torque Control (DTC) approach, with the primary distinction being the quantities they regulate. Unlike DTC, DPC directly regulates the active (P) and reactive power (Q) of the machine without internal control loops, making it highly suitable for controlling electrical machines. This strategy offers advantages such as a superior power factor, reduced total harmonic distortion (THD), improved dynamic of response, and enhanced robustness. Consequently, DPC has garnered significant attention from researchers [12], [13].

The block diagram of PWM Rectifier-Direct Power Control is given by the Figure 6.

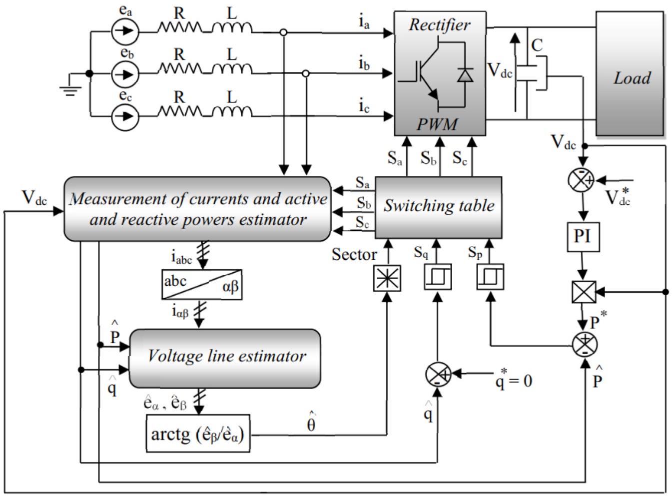

Figure 6. PWM rectifier direct power control.

5. Fuzzy Logic Control

Fuzzy control, as used in technical applications, describes algorithms or programs that use fuzzy logic to let machines make decisions that correspond to the real-world experience of an expert operator. The basic challenge of automatic control is identifying the optimal response of the system or industrial unit to any given set of variables. Traditionally, control strategies rely on precise mathematical representations of the system, usually in the form of a collection of differential equations with a limited number of variables. However, fuzzy control does not require a perfect theoretical model; instead, it only requires the actual competence of a trained operator [14].

Generally, the treatment of fuzzy logic problem based on three steps [15]:

1. The role of the fuzzification block is presented in mapping the physical values of input data into corresponding normalized values of domain and converting input data into linguistic sets and fuzzy sets.
2. The fuzzy rules form a central component of fuzzy controller and represent the intelligence of each stage of the control algorithm. Founded on the knowledge and expertise of the operator, a set of rules must be formed correctly. The fuzzy rule is of the form IF-THEN, where the premise (IF...) describes the conditions, and the consequence (THEN...) explains the consequential actions of the control activity.

3. Defuzzification, which is the inverse operation of fuzzification: it allows to transforming linguistic variables back into real or numerical values.

The Figure 7 presents the basic diagram of a fuzzy logic control system [15].

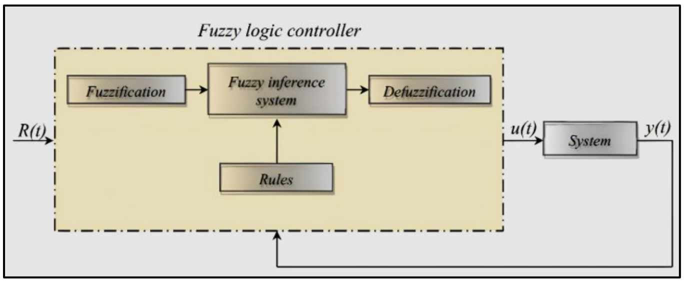

Figure 7. Fuzzy logic control system

Figure 8 illustrates how the inputs (error *e* and derivative of error *de*) and output are fuzzified in five membership functions.

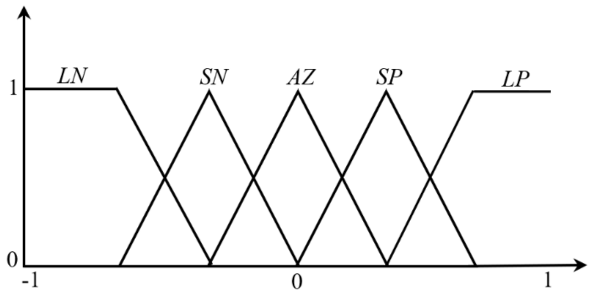

Figure 8. Fuzzification with five membership functions

with:

- LN: Large Negative.
- SN: Small Negative.
- AZ: Around Zero.
- SP: Small Positive.
- LP: Large Positive.

The inference table containing the rule bases for speed control is given as follows (Table 2):

Table 2. Inference table with five membership functions

du		***e***				
		LN	*SN*	*AZ*	*SP*	*LP*
de	*LN*	*LN*	*LN*	*LN*	*SN*	*AZ*
	SN	*LN*	*SN*	*SN*	*AZ*	*SP*
	AZ	*LN*	*SN*	*AZ*	*SP*	*LP*
	SP	*SN*	*AZ*	*SP*	*LP*	*LP*
	LP	*AZ*	*SP*	*LP*	*LP*	*LP*

The global proposed method diagram is given by the Figure 9.

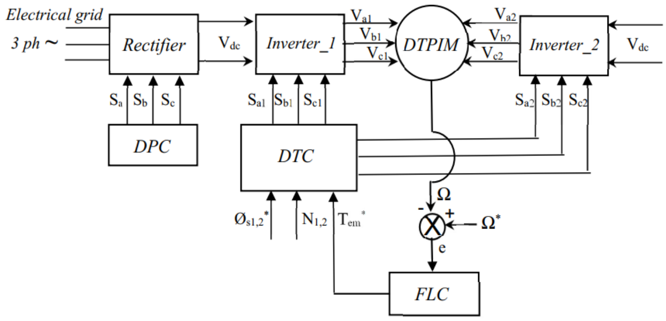

Figure 9. Proposed control technique diagram

6. Results and Discussion

In Figure 10, the DC voltage tracks its reference with a slight overshoot during the dynamic state. The voltage and current waveforms are in phase, indicating a power factor of 1, which signifies an efficient use of electrical energy. The active and reactive powers track their references with some oscillations.

In Figure 11, the speed tracks its reference (120 rad/s) within 0.5 seconds. The electromagnetic torque peaks at 35 N.m during start-up and then stabilizes at a value close to zero in steady state. A load torque of 10 N.m is applied in the interval [1, 2s], prompting the motor to generate electromagnetic torque to counter the resistive torque. A slight speed drop is recorded during the load torque application, which is quickly corrected by the fuzzy controller to restore the speed to its reference. An increase in stator current is observed during the load torque application.

As illustrated in Figure 12, the simulation results clearly demonstrate the effectiveness of Direct Power Control applied to a 3 phase PWM rectifier for achieving a unit power factor (Q~0). The FFT analysis of the line current indicates that the waveform exhibits an acceptable THD (Figure 13).

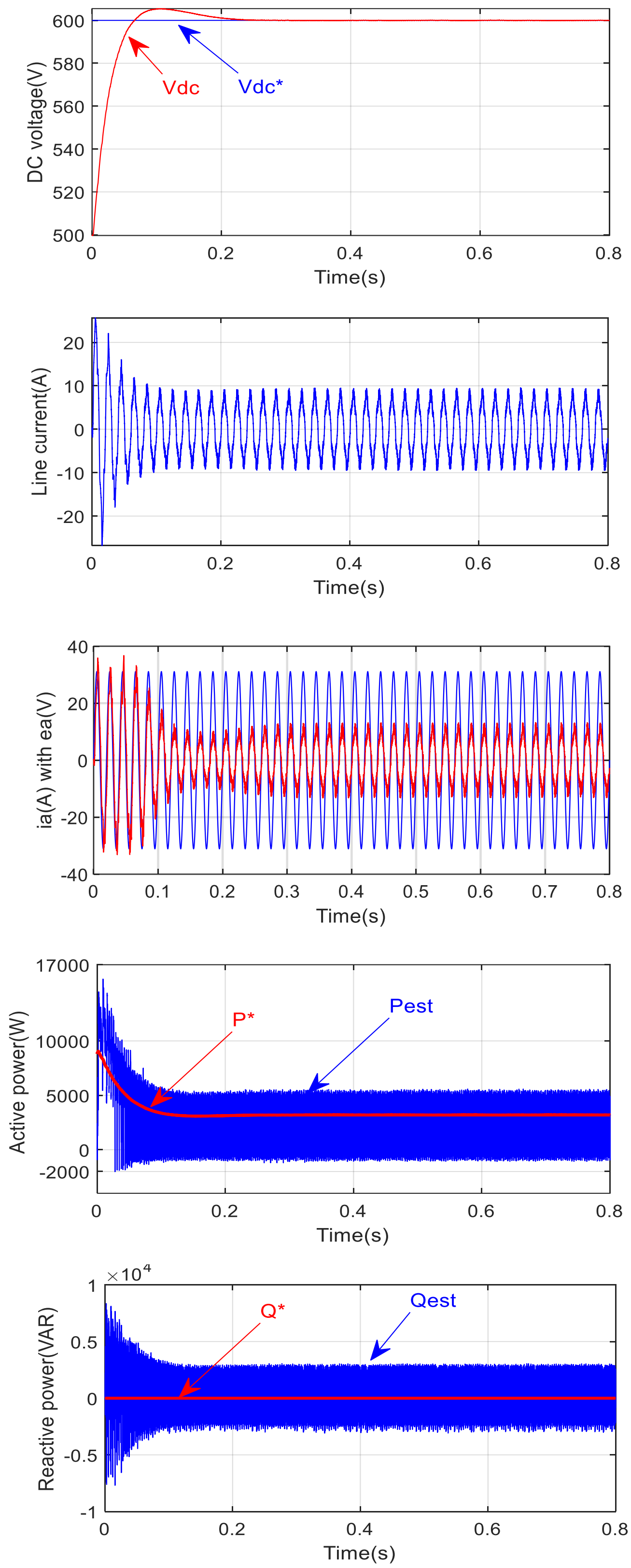

Figure 10. Waveforms for input and output DPC rectifier.

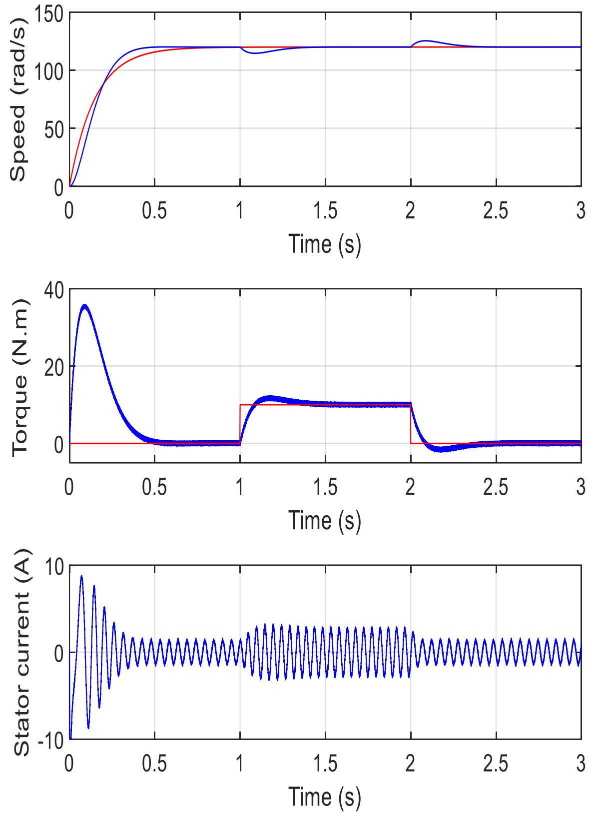

Figure 11. DTC Speed regulation with application of load torque =10 N.m in [1 2] s.

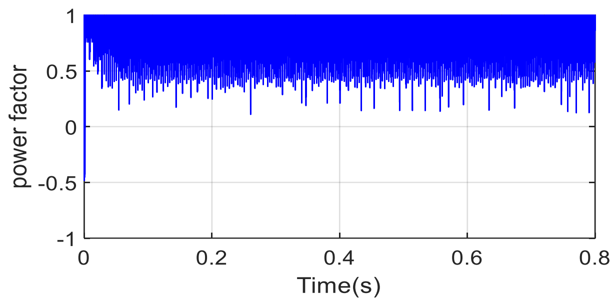

Figure 12. Power factor approximately equal to 1.

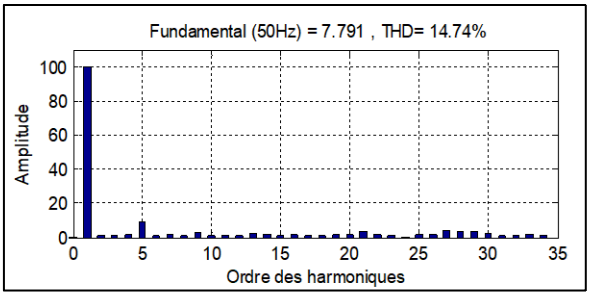

Figure 13. Total harmonic distortion of line current.

7. Conclusion

This paper has effectively demonstrated the robustness and efficacy of integrating a Fuzzy Logic Speed Controller (FLSC) into the Dual Three-Phase Induction Motor (DTPIM) Direct Torque Control (DTC) method powered by a Direct Power Control (DPC) rectifier. The proposed control strategy addresses the limitations of conventional DTC methods, enabling robust control against parametric variations and achieving good static and dynamic performance. This is due to the fuzzy controller's design, which is independent of the system model; the system is treated as a black box. Furthermore, the direct power control ensures a stable and variable DC voltage rectifier output, a unit power factor, and reduced Total Harmonic Distortion (THD).

Overall, this research advances the field of motor control technologies, offering tangible benefits that enhance energy efficiency, reliability, and performance. For practitioners, it provides innovative tools and methodologies that can be directly applied to improve industrial processes, reduce costs, and support the development of sustainable technologies. For society, these advancements promote environmental sustainability, economic savings, and the adoption of cleaner and more efficient technologies in various sectors.

For the continuation of research on this theme, some recommendations are proposed: integration with advanced control algorithms (neural fuzzy logic, genetic algorithms, particle swarm optimization) for better performance, improvements in real-time implementation (DSP, FPGA, etc.), extend the study to include fault diagnosis and tolerance in DTPIM systems, industrial and automotive applications (electric vehicles, industrial robotics, etc.), sustainability and green technology. These future directions highlight the potential for significant advancements in both theoretical research and practical applications, enhancing efficiency, robustness, and adaptability across various industries.

Conflicts Interest Statement

All authors affirm that none of the research described in this paper could have been impacted by any known financial interests, personal connections, or conflicts of interest.

Data Availability Statement

The research reported in this paper did not use any outside data or supplemental resources.

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