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Fuzzy Logic Method for Improving Power Quality in Industrial and Commercial Systems

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Abstract: This document presents an innovative control strategy based on fuzzy logic for multifunctional grid-tied inverters utilized in industrial and commercial power systems. The primary objective is to mitigate instantaneous power oscillations and improve overall power quality. The proposed strategy incorporates the principles of Conservative Power Theory (CPT), which facilitates the direct extraction and analysis of oscillating power components within the ABC frame. Additionally, fuzzy logic contributes adaptive intelligence to effectively manage uncertainties and nonlinearities associated with complex load conditions. To assess the efficacy of the proposed fuzzy control method, comprehensive simulations are performed on a three-phase multifunctional grid-tied inverter that is fitted with an LCL filter in a laboratory-scale prototype setting. The power system model encompasses a variety of load profiles, including linear, nonlinear, unbalanced loads, and a three-phase induction motor with capacitive compensation. The simulation outcomes reveal that the fuzzy logic-enhanced control strategy not only optimizes active power dispatch by the inverter but also guarantees constant torque operation of the induction motor, thereby enhancing power quality across the entire industrial/commercial system. Moreover, the strategy is experimentally validated using a 3.6 kVA inverter prototype. The experimental findings corroborate the successful compensation of the targeted oscillating power components, highlighting the practical viability and robustness of the fuzzy logic-based approach in real-world scenarios.

I. INTRODUCTION

Power quality (PQ) has emerged as an increasingly vital issue for both consumers and electric utilities worldwide. Its importance has escalated considerably in recent decades due to the extensive incorporation of electronic and nonlinear devices—such as computers, lighting systems, elevators, rotating machines, and electric vehicle (EV) chargers—into power systems. These devices inherently possess nonlinear operational characteristics that disrupt the ideal sinusoidal form of voltage and current waveforms. Consequently, power oscillations and resonance phenomena—resulting from asymmetrical and distorted electrical components—present significant challenges, particularly in commercial and industrial settings that depend on sensitive and high-cost equipment. The dense proliferation of nonlinear loads intensifies this problem by introducing and amplifying non-sinusoidal currents within the grid, thus severely impairing PQ indices. This deterioration adversely affects both utility providers and end-users. Technical issues stemming from poor PQ include excessive heating of transformers, interruptions in communication systems, audible noise, malfunctioning protection and metering equipment, and heightened mechanical vibrations in electrical machines. Moreover, harmonic currents interacting with the impedance of feeders result in distorted voltage drops, particularly at the point of common coupling (PCC), which directly influences the performance of connected equipment. One of the most susceptible components to such distortions is the induction motor—a crucial element in both industrial and commercial operations. Voltage distortions induced by harmonics not only elevate electrical losses but also produce unwanted torque pulsations. Furthermore, a low power factor exacerbates motor performance and system efficiency. The increasing integration of unconventional and dynamic loads, such as electric vehicle charging stations, introduces additional complexity by causing waveform distortions and operational instabilities during the charging process, which further contributes to power quality degradation. Traditionally, the most economical solution for correcting power factor and mitigating harmonics in commercial and industrial settings involves the implementation of passive filters and capacitor banks. Although this method is widely utilized, it is highly sensitive to the characteristics of grid impedance and can result in harmonic resonance issues if not designed correctly. Additionally, passive compensators lack the adaptability for dynamic adjustments, rendering them ineffective in responding to variations in grid voltage and current conditions. In contrast, active filtering techniques have garnered increasing interest in recent decades, primarily due to the declining costs of power electronic equipment and the rising use of power electronic converters (PECs) integrated with distributed energy

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resources (DERs), such as photovoltaics (PV), fuel cells, batteries, and wind turbines. Since the installation of separate compensation devices can be financially burdensome, utilizing the existing, often underused, capacity of PECs for power quality (PQ) enhancement offers an appealing alternative. Numerous control strategies have been suggested in the literature to enable PECs to undertake multiple functions, including reactive power compensation, harmonic filtering, and load balancing. However, the intermittent nature of renewable energy sources frequently leads to the underutilization of PECs. To improve cost-effectiveness and performance, hybrid approaches that combine passive and active filtering techniques are being explored.

TABLE 1. Comparison between proposed control strategy and some state-of-the-art control strategies.

Reference	MFGTI	Flexibility	Method Hybrid	Cost
[11]	No	No	No	Low
[17], [24]	No	No	Yes	Medium
[19], [21], [22], [25], [27]	Yes	YES	NO	Medium
[3], [20], [23]	Yes	YES	Yes	Higher
[30], [31]	Yes	Yes	NO	Medium
[32], [33]	Yes	YES	Yes	Higher
[35], [36]	Yes	NO	Yes	Higher
Proposed Method	**Yes**	**Yes**	**Yes**	**Medium**

TABLE 2. Parameters of the MFGTI and proposed system in computational simulation.

Parameter	Value	Parameter	Value
V_{Grid}^{Line}	460 V / 60 Hz	R_G, L_G	0.08Ω, 0.315 mH
P_{DER}	15 kW	R_1, L_1	10 mΩ, 0.5 mH
P_{IM}	14.8 kW	R_2, L_2, C_0	10 mΩ, 0.5 mH, 3.3 µF
V_{IM}	460 V	R_Z , L_Z	0.28 Ω, 1.1 mH
$PF_{IM} = \lambda_{IM}$	0.87	R_U , L_U	9 Ω, 18 mH
T_{IM}	74 N.m	R_B , L_B	30 Ω, 70 mH
C_{Cap}	55.4 µF	L_N, R_N, C_N	1 mH, 33 Ω, 780 µF,

Significantly, this method enhances power quality by mitigating pulsating torques in three-phase induction motors that arise from the intermittency of renewable energy, load imbalances, voltage variations, and harmonic distortions frequently encountered in industrial and commercial environments. Consequently, it guarantees a more stable instantaneous power profile throughout the operation of induction motors and other rotating machinery.

II. PROPOSED COMPENSATION SYSTEM STRATEGY

Figure 1 depicts a standard industrial electrical system linked to the utility grid, featuring a Distributed Energy Resource (DER) represented as a non-dispatchable generation unit—such as a photovoltaic (PV) source—responsible for local energy production. The system consists of a three-phase voltage source inverter (also known as a Power Electronic Converter or PEC) with a current-controlled output, a capacitor bank (CB) for passive power factor correction, line impedances, and various types of local electrical loads. The inverter's grid interconnection is facilitated by an LCL filter, which functions to reduce high-frequency switching harmonics and ensure clean current and voltage waveforms. The addition of inductance L2L_2L2 further improves system stability and robustness by alleviating the impacts of fluctuations in grid impedance—a parameter that is generally uncertain and varies over time [37]. The industrial load configuration includes a three-phase squirrel cage induction motor (IM) linked to a mechanical load (ML), along with various types of electrical loads: a capacitor bank CCapC_{Cap}CCap associated with the IM for reactive power support, a balanced linear load (comprising LBL_BLB and RBR_BRB), an unbalanced load (consisting of LUL_ULU and RUR_URU), and a nonlinear load (composed of RNR_NRN, LNL_NLN, and CNC_NCN). The mechanical load attached to the IM's shaft has a rated power of 14.8 kW, a nominal torque of 74 N·m, and a power factor of 0.87. It is important to note that this power factor falls short of the minimum recommended standard of 0.92, as specified in [38].

The primary electrical parameters utilized in the design of the Circuit Breaker (CB) and Multi-Functional Grid-Tied Inverter (MFGTI), along with the characteristics of the grid and the connected loads, are compiled in Table 2. The design of the LCL filter adheres to the methodology specified in [39], and the CB, integrated with the induction motor, has been sized to improve the motor's power factor to 0.95.

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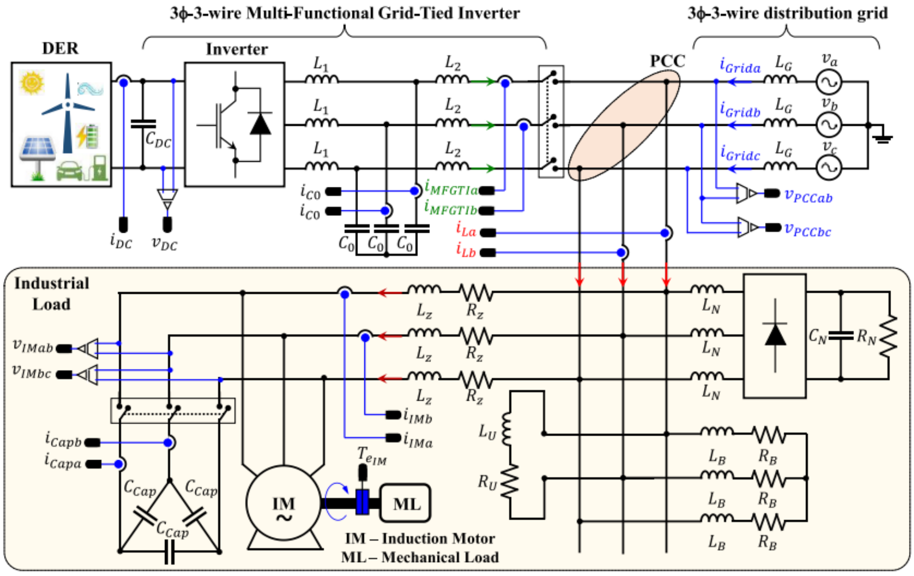

FIGURE 1. Interconnection of MFGTI to an industrial grid.

A. MFGTI CONTROL SYSTEM

The control algorithm for the Power Electronic Converter (PEC) is executed in the natural coordinate system (abc frame). A simplified representation of the control architecture is illustrated in Fig. 2, which demonstrates the generation of reference signals using the Conservative Power Theory (CPT), in addition to the primary control loops. The modeling and design of these control strategies are informed by the methodologies outlined in [40], [41], and [42].

The proposed control system consists of two primary loops:

• An inner loop that regulates the output current of the Multi-Functional Grid-Tied Inverter (MFGTI), denoted as iMFGTIi_{\text{MFGTI}}iMFGTI, and

• An outer loop that is responsible for maintaining a stable voltage level at the DC bus, represented by vCCv_{CC}vCC.

It is crucial to note that the system depicted in Fig. 1 functions as a three-wire, three-phase configuration. As a result, the phase 'c' current is derived from the other two phases, following the relation iMFGTIc=−(iMFGTIa+iMFGTIb)i_{\text{MFGTI}_c} = - (i_{\text{MFGTI}_a} i_{\text{MFGTI}_b})iMFGTIc=−(iMFGTIa+iMFGTIb), while the line voltages serve as voltage references, as elaborated in [43]. The current controller for the MFGTI utilizes a multi-resonant proportional control strategy [44], which facilitates accurate tracking of the reference currents across various harmonic components in the abc domain, thus improving compensation performance and system stability.

$$G_C(s) = K_C + \sum_{i=1,3,5} \frac{2K_{IPR}\omega_{CPR}s}{s^2+2_{\omega CpR}s+(h\omega_0)^2} \tag{1}$$

$$K_C = \frac{1}{|OLTFnc(\omega C)|} \tag{2}$$

In this context, the harmonic order is denoted, while ω0\omega_0ω0 signifies the fundamental frequency of the electrical grid. The parameters KCK_CKC, KIPRK_{IPR}KIPR, and ωCPR\omega_{CPR}ωCPR correspond to the proportional gain, integral gain, and bandwidth of the resonant controller, respectively. The proportional gain KCK_CKC of the current controller is specifically established to achieve a desired crossover frequency ωC\omega_CωC for the uncompensated open-loop transfer function OLTFnc(s)\text{OLTF}_{nc}(s)OLTFnc(s), as elaborated in [37].

$$PI_{DC}(s) = K_{PDC} + \frac{K_{IDC}}{s} \tag{3}$$

To manage the DC bus voltage, a Proportional-Integral (PI) controller is utilized, adhering to the design principles outlined in [40]. In order to meet the goals of this study, the PI controller is configured with a comparatively narrow bandwidth. This configuration helps to prevent variations in the peak value of the current reference and minimizes possible disruptions to the inner current control loop, as suggested in [37].

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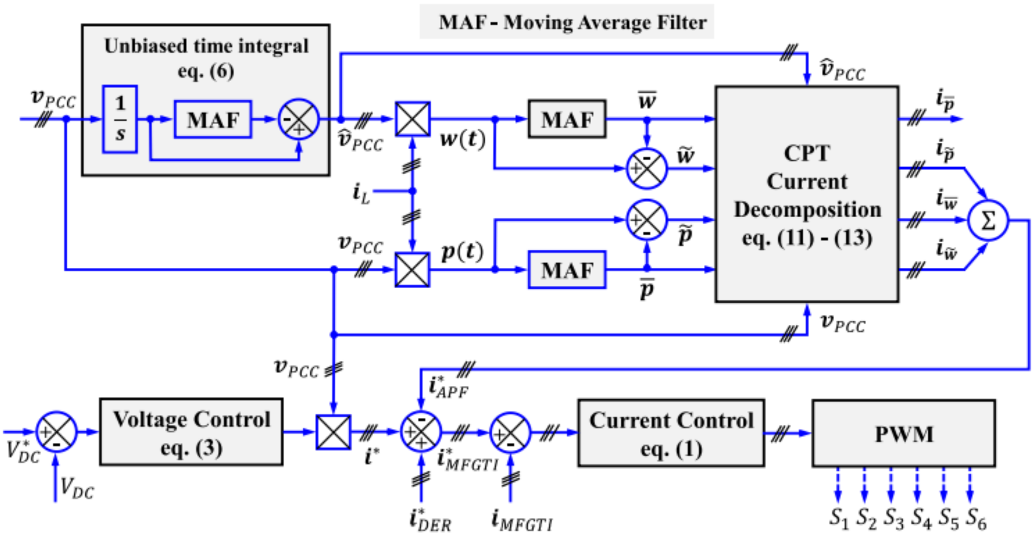

FIGURE 2. Control system and reference signals generation for proposed MFGTI.

TABLE 3. Parameters of current and voltage controllers.

Parameter	Value	Parameter	Value
K_C	2	K_{PDC}	5
K_{IPR}	100	K_{IDC}	50
ω_{CPR}	6.28 rad/s	ω_0	377 rad/s

The loop bandwidth has been established at 1.2 kHz to adequately counteract current harmonics and secure a phase margin of 45°. The PI controller designated for the DC bus voltage was set with a bandwidth of 7 Hz and a phase margin of 70°, thereby guaranteeing a well-compensated system with minimal overshoot, while sustaining a stable DC bus voltage of 400 V. A detailed account of the modeling and design process for these controllers is available in [40].

III. FOUNDATIONS FOR DECOMPOSITION OF OSCILLATORY POWER COMPONENTS

In this document, the breakdown of instantaneous power is founded on both average and oscillatory components, utilizing the Conservative Power Theory (CPT) as the analytical framework [45]. The CPT, which operates in the time domain, is applicable to both single-phase and multi-phase electrical systems, facilitating the separation of current and power signals into orthogonal components. This process yields physically significant quantities without necessitating Phase-Locked Loop (PLL) or coordinate transformations. Due to the decoupling of the derived current components, the CPT has demonstrated its efficacy as a tool for generating reference signals to mitigate disturbances in Active Power Filters (APF) [43], Multi-Functional Grid-Tied Inverters (MFGTI) [19], [21], [25], [41], and microgrids [15], [27], [31]. Several practical applications of the CPT are documented in [46]. The CPT delineates two conservative quantities: instantaneous power, p(t), and instantaneous reactive energy, w(t) [45]. Instantaneous power is characterized by the dot product of the voltage and current vectors, as illustrated in equation (4). In contrast, w(t) is defined through the vector of the unbiased time integral of voltages (vˆm) and the current vector, as presented in equation (5). Additional information regarding the CPT and its principal quantities is elaborated in [45]. The definition of vˆm is articulated in equation (6), where m signifies the phases a, b, and c, respectively.

$$p^{(t)} = [v_a \quad v_b \quad v_c].\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4}$$

$$w(t) = [\tilde{v}_a \quad \tilde{v}_b \quad \tilde{v}_c].\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

$$\hat{v}_m = \int_0^t v_m(\tau)d\tau - \frac{1}{T}\int_0^T[\Sigma_0^t v_m(\tau)d\tau]dt \tag{6}$$

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It is crucial to understand that the second term in equation (6) signifies the mean value of the voltage across a duration (T). To calculate the average values of p(t) and w(t), Moving Average Filters (MAF) are employed, as illustrated in equations (7) and (8), respectively. These filters produce the active power, P, and the reactive energy, W.

$$\bar{p}(t) = \frac{1}{T}\int_0^T p(t)dt = P \tag{7}$$

$$\bar{w}(t) = \frac{1}{T}\int_0^T w(t)dt = W \tag{8}$$

In a manner akin to the p-q theory [47], the expressions p(t) and w(t) articulated in equations (4) and (5) can be separated into their average and oscillatory parts, as illustrated in equations (9) and (10), respectively. Within this notation, the symbol "~" signifies the oscillatory components of each expression, whereas the symbol "−" indicates the average components.

$$p^{(t)} = \tilde{p} + \tilde{p} \tag{9}$$

$$w(t) = \widetilde{w} + \widetilde{w} \tag{10}$$

The average and oscillatory components are applicable irrespective of the voltage and current waveforms, thus making this methodology suitable for both sinusoidal and non-sinusoidal voltage conditions. Instantaneous power, denoted as p(t), signifies the useful energy per unit of time that flows from the source to the load, or conversely from the load to the source when negative. The average component, represented as p̄, indicates the energy transferred from the source to the load, which is referred to as useful power. The oscillatory component, denoted as p̃, has an average value of zero and pertains to the energy exchanged between the source and the load. At any given moment, it reflects the energy traversing the circuit due to undesirable currents, which are induced by harmonics (typically resulting from unusual harmonic orders in voltage and current) and imbalances in voltages or currents. A comparable analysis can be conducted for reactive energy, w(t). The average value, w̄, signifies the average reactive power, which is linked to energy storage elements within the network or circuits lacking energy storage capabilities, responsible for the phase shift between voltage and current. The oscillatory component, w̃, emerges from harmonic components in unbiased voltage integrals and currents, along with imbalances associated with the flow of reactive energy in the electrical grid. Prior studies such as [29], [47], and [48] have illustrated methods to mitigate oscillatory power components to maintain constant power on the grid side utilizing p-q theory. Nevertheless, these investigations have only applied such concepts to Active Power Filters (APF), revealing a trade-off between achieving constant power and the resultant current waveform in the electrical grid. The application of Capacitor Power Transfer (CPT) for the compensation of oscillating power through Multi-Functional Grid-Tied Inverters (MFGTI) in industrial and commercial systems, however, remains unexamined, necessitating further exploration into its validation and applicability. Furthermore, there exists a gap in the literature concerning the integration of this methodology with capacitor banks (CBs), which calls for additional research to evaluate whether their joint operation guarantees.

A. REFERENCE SIGNALS FOR APF FUNCTION TO POWER QUALITY IMPROVEMENT

It is crucial to understand that the current vectors related to the instantaneous power p(t)p(t)p(t) and reactive energy w(t)w(t)w(t) can be divided into two subcomponents: the average components (ip̄ and iw̄) and the oscillatory components (ip̃ and iw̃). The terms ip̃ and iw̃ denote the effects of harmonic components and/or current imbalances that induce oscillations in instantaneous power and energy, resulting in additional losses within the power system. From the perspective of the load, the decomposed components in (11) and (12) do not accurately represent the load's behavior. It is only when the voltage is sinusoidal and balanced that ip̄ and iw̄ align with the originally defined balanced active and reactive currents in the CPT framework [45]. Since the oscillatory component ip̃ does not contribute to active power (P), the reference signals for compensation can be formulated as the sum of iw̄, ip̃, and iw̃, as indicated in (13). These compensation reference signals can be applied selectively: the sum of the oscillatory components (ip̃ + iw̃) is associated with the oscillation, while iw̄ pertains to the flow of reactive power within the system. From (13), the oscillatory components (ip̃ and iw̃) and iw̄ can be compensated independently using an MFGTI (functioning as an APF), or by integrating a capacitor bank (CB) to compensate iw̄ (either partially or fully) alongside an MFGTI to address ip̃ + iw̃. Consequently, the main aim of this study is to maintain constant instantaneous power by compensating for oscillations. Therefore, the sum of the oscillatory components, ip̃ + iw̃, will be regarded as the reference for compensation.

$$i_p(t) = i_{\bar{p}} + i_{\tilde{p}} = \frac{\bar{p}}{V_{abc}^2}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + \frac{\tilde{p}}{V_{abc}^2}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{11}$$

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$$i_w(t) = i_{\bar{w}} + i_{\tilde{w}} = \frac{\bar{w}}{\hat{v}_{abc}^2}\begin{bmatrix}\hat{v}_a\\ \hat{v}_b\\ \hat{v}_c\end{bmatrix} + \frac{\tilde{w}}{\hat{v}_{abc}^2}\begin{bmatrix}\hat{v}_a\\ \hat{v}_b\\ \hat{v}_c\end{bmatrix} \tag{12}$$

$$i_{comp} = i_{\bar{w}} + i_{\tilde{p}} + i_{\tilde{w}} = i_{APF} \tag{13}$$

B. REFERENCE SIGNALS FOR DER FUNCTION TO INJECT ACTIVE POWER

In this research, the Sinusoidal Current Synthesis (SCC) strategy [21], [49] is employed to introduce the power produced by the DER into the grid. As per the SCC approach, the current waveform that is injected must correspond with the fundamental positive-sequence component of the voltage at the interconnection point, as indicated in equation (14).

$$i_{DER} = \frac{P_{DER}}{(V_1^+)^2}\begin{bmatrix}v_{1a}^+\\ v_{1b}^+\\ v_{1c}^+\end{bmatrix} \tag{14}$$

$$P_{DER} = \frac{1}{T}\int_0^T vDC(t)iDC(t)dt \tag{15}$$

C. REFERENCE SIGNAL GENERATION TO M

In accordance with the reference signals utilized for compensation (iAPF) and the active power injection into the grid (iDER), the current reference, referred to as iMFGTI, is established. This reference current will be produced by the multifunctional active power injection and compensation system, and its formulation is as follows:

$$i_{MFGTI} = i_{DER} - i_{APF} = i_{DER} - i_{\bar{w}} - \left(i_{\tilde{p}} + i_{\tilde{w}}\right) \tag{16}$$

From the viewpoint of incorporating the MFGTI into commercial or industrial systems that already utilize conventional compensation systems such as CB, compensation strategies can be allocated in multiple manners. For instance, to enhance the operational adaptability of the MFGTI, the reference current, which is currently generated by the integrated MFGTI and CB system, leads to:

$$i_{ref} = i_{MFGTI} + i_{CB} = i_{DER} - i_{APF} - i_{CB} \tag{17}$$

$$i_{\bar{w}} = i_{\bar{w}\_APF} + i_{\bar{w}\_CB} \tag{18}$$

$$i_{MFGTI} = i_{DER} - i_{\bar{w}\_APF} - (i_{\tilde{p}} + i_{\tilde{w}}) \tag{19}$$

In this context, iw¯APFiw¯_{APF}iw¯APF denotes the residual reactive current that is not compensated by the CB. Consequently, the structure for generating current references facilitates the synthesis of the reference signal to counteract oscillating torque in rotating machines (ip˜+iw˜ip˜ + iw˜ip˜+iw˜) through the MFGTI, while the CB addresses reactive power (iw¯iw¯iw¯). Nevertheless, in actual industrial and commercial electrical systems, power factor correction is frequently determined by limits established by standards and regulatory guidelines. As a result, the CB is generally engineered to adjust the power factor to a predetermined value, such as 0.92. In this scenario, the residual reactive power that remains uncompensated by the CB is managed by the MFGTI, as illustrated in equation (19). Furthermore, iw¯APFiw¯_{APF}iw¯APF facilitates dynamic reactive power compensation, providing greater flexibility in comparison to the nearly static function of the CB, which contributes to enhancing the overall power quality in industrial and commercial electrical systems.

IV. SIMULATION RESULTS

This section presents the computational simulation of the system illustrated in Fig. 1, aimed at showcasing the adaptability of the proposed compensation system and its efficacy in mitigating power oscillations, which in turn leads to diminished torque fluctuations for induction motors (IMs) that are frequently utilized in industrial and commercial applications. The parameters for the simulated system and controller are detailed in Table 2 and Table 3. The simulation outcomes are analyzed in relation to the voltage and current waveforms at the point of common coupling (PCC) and the IM connection point, as depicted in Fig. 3 and Fig. 4. For t < 1.7 s, the system functions without any compensation, as evidenced in Fig. 3 and Fig. 4. During this timeframe, the grid demonstrates a low power factor (λGrid = 0.82) and exhibits highly unbalanced and distorted current (iGrid). The IM operates with an initial power factor (PFIM = λIM = 0.87) and displays fluctuations in instantaneous power alongside torque oscillations. For t > 1.7 s, the capacitor bank (CB) is connected to

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the IM terminals. As anticipated, the power factor at the IM terminals improves, approaching λIM = 0.95. Consequently, the power factor at the PCC also enhances, reaching λGrid = 0.89. However, the current at the IM terminals becomes increasingly distorted due to the interaction between the CB and the harmonics introduced by the non-linear load. At t > 1.9 s, the MFGTI commences its operation by injecting solely active power into the grid. The inverter current (iMFGTI) remains sinusoidal, indicating that no disturbance compensation has yet been implemented. As a result, power and torque oscillations continue in the IM, and the current at the grid remains unbalanced and distorted. With the injection of active power, the net active power in the grid decreases, which leads to a reduction in the power factor at the grid.

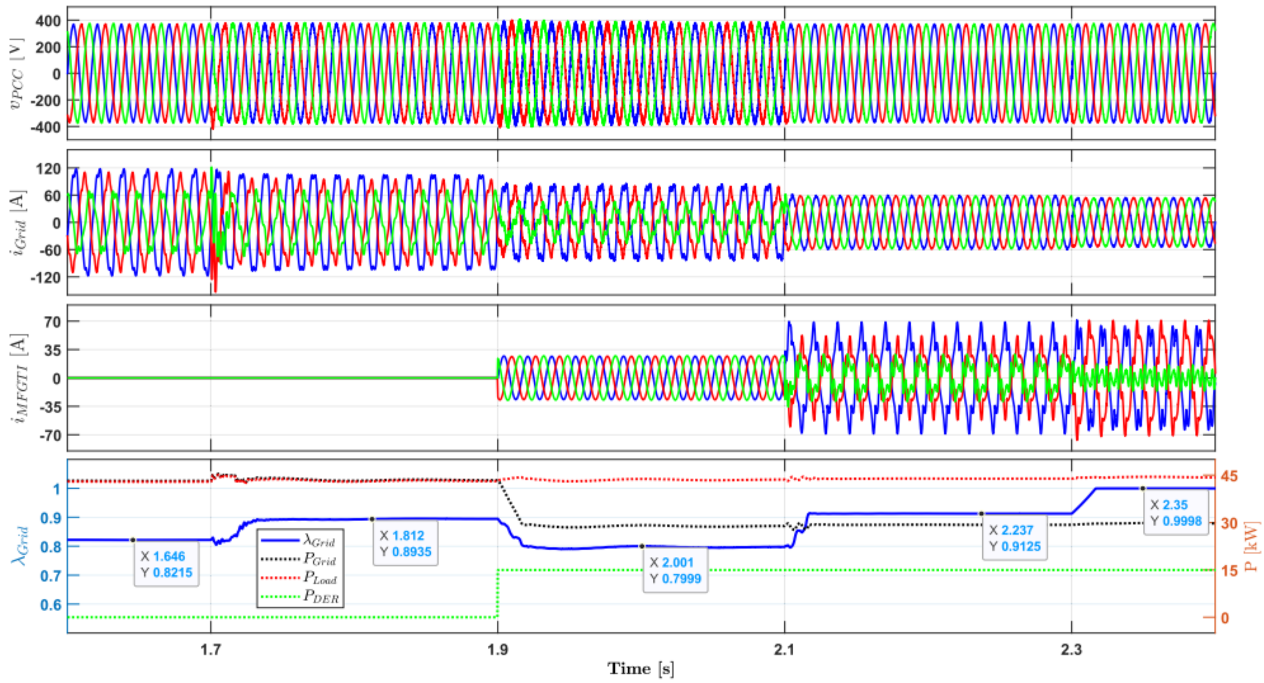

FIGURE 3. Waveforms of voltage, currents, active powers and power factor considering different compensation objectives

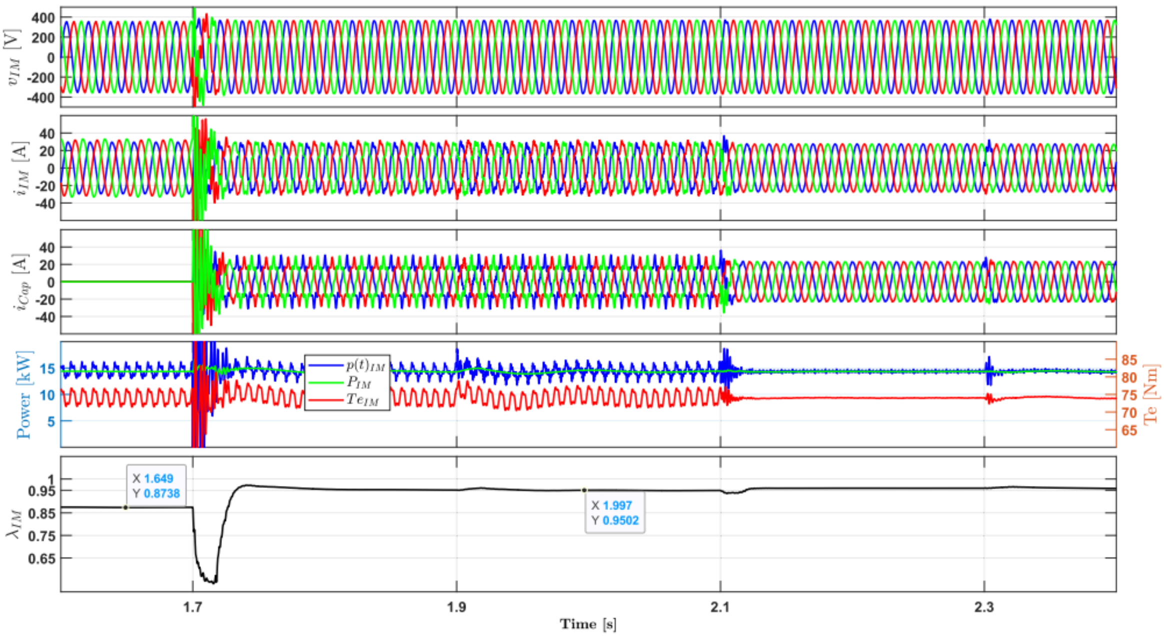

FIGURE 4. Waveforms of voltage, currents, active power, instantaneous power, torque and power factor at the connection point of the IM.

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Fuzzy Logic Operation

The fuzzy logic control mechanism utilized in this project aims to enhance the compensation of oscillating power and reactive power within the system. Fuzzy logic is used to address uncertainties in system behavior, including imbalances, harmonic distortions, and fluctuations in load, which are often challenging to model with traditional control systems. In this setup, the fuzzy logic controller (FLC) functions by processing inputs such as instantaneous power oscillations, reactive power requirements, and deviations in power factor from the target value. These inputs are fuzzified through established membership functions to classify the system's states into fuzzy sets like low, medium, or high.

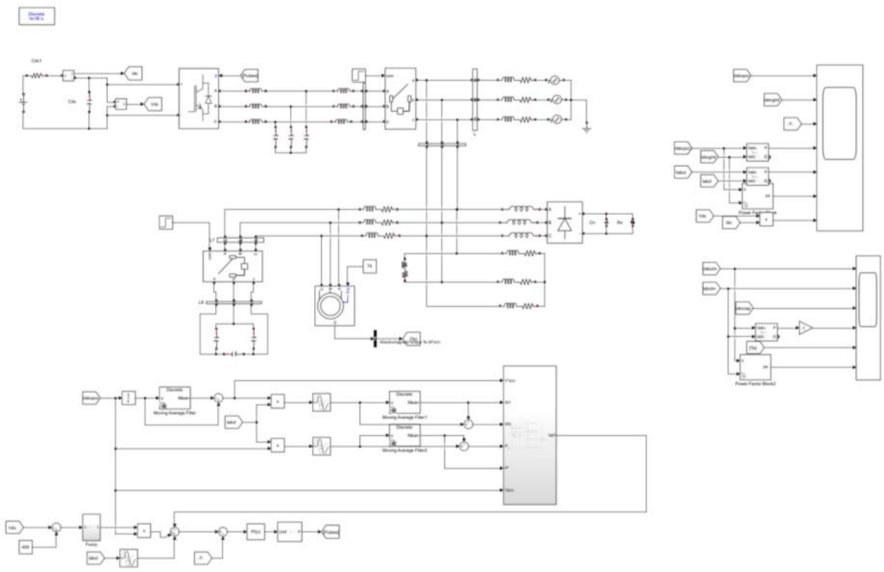

FIGURE 5: Fuzzy logic control diagram showing input variables (oscillating power, reactive power demand) and output (current reference for MFGTI).

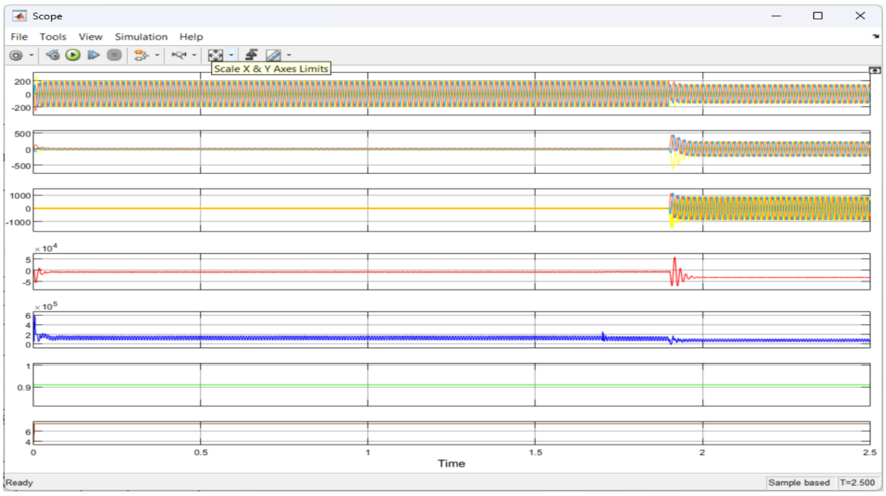

FIGURE 6: Waveforms of voltage, currents, active powers and power factor considering different compensation objectives

The FLC processes these fuzzy inputs to produce fuzzy output signals that control the current references of the multifunctional grid-connected inverter (MFGTI). It employs a collection of fuzzy rules that outline the system's response to various conditions of power oscillations and reactive power imbalance. These rules are generally formulated based on expert knowledge, such as "If the power factor is low and power oscillations are high, then increase active power compensation." The fuzzy inference system (FIS) utilizes these rules and subsequently defuzzifies the output to create accurate control signals, including modifications to the inverter's current reference. By utilizing fuzzy logic, the system can dynamically adapt to real-time changes, compensating for harmonics, load imbalances, and deviations in power factor while ensuring stability and reducing oscillations. This capability allows the MFGTI to operate in harmony with other compensation devices, such as the capacitor bank (CB), thereby providing a balanced and high-quality power supply to the grid.

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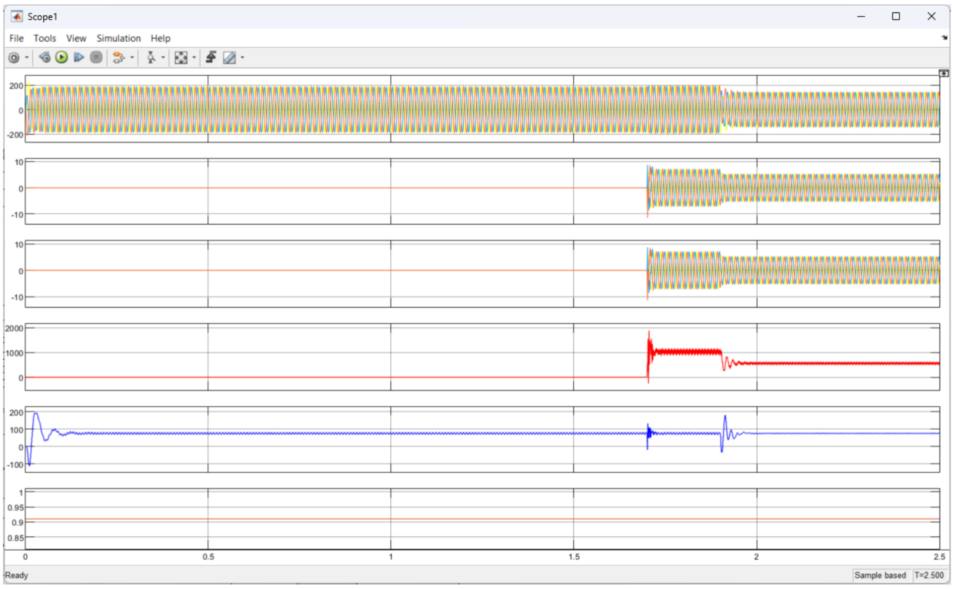

FIGURE 7: Waveforms of voltage, currents, active power, instantaneous power, torque and power factor at the connection point of the IM.

V. CONCLUSION

This document has presented an innovative compensation strategy designed to enhance power quality in industrial and commercial electrical systems by tackling the issues associated with instantaneous power oscillations and reactive power requirements. The foundation of this compensation method is based on the separation of instantaneous power into mean and oscillatory components through the Conservative Power Theory (CPT). Experimental and simulation findings validate that the proposed system, which employs a grid-connected inverter, not only injects active power into the network but also effectively reduces oscillatory power components. This capability is essential for industrial settings where electric machines, especially induction motors, are widely utilized, as minimizing power oscillations significantly lowers torque ripple. Consequently, this results in improved mechanical stability, reduced heat generation, enhanced operational efficiency, and an extended lifespan of electrical equipment. A significant advancement in this research is the incorporation of a Fuzzy Logic Controller (FLC) to dynamically oversee the compensation process. The fuzzy controller facilitates intelligent real-time decision-making by addressing non-linearities, uncertainties, and transient behaviors that are common in commercial power systems. By assessing input variables such as instantaneous power deviations, power factor, and levels of harmonic distortion, the FLC modifies the reference current for the Multifunctional Grid-Tied Inverter (MFGTI) to concurrently manage active power injection and compensate for oscillatory and residual reactive currents. This adaptive methodology allows for smoother transitions, more precise control, and quicker system responses compared to conventional techniques. Furthermore, this paper illustrates how the integration of multifunctional inverters with traditional Capacitor Banks (CBs) already present in industries can result in cooperative and intelligent power compensation. While CBs address a portion of the reactive demand statically

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