

Enhancing Power Quality and Mitigating Power Oscillations in Commercial and Industrial Systems through an Integrated Approach

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Abstract— The integration and operational performance of Distributed Energy Resources (DERs) like solar photovoltaic (PV), wind energy systems, and battery energy storage systems (BESS) in commercial and industrial settings are having an increasing impact on grid power quality. Voltage stability, power factor, and overall power quality all improve when DERs efficiently produce and deliver active power to the grid. However, power oscillations that impair system performance can be introduced by the intermittent nature of renewable energy as well as the presence of nonlinear and unbalanced loads. In order to address these issues, the hybrid control framework described in this paper combines a novel control strategy for multifunctional grid-tied inverters based on the Conservative Power Theory (CPT) with an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for DER coordination. While the CPT-based control directly extracts and compensates oscillatory power terms in the ABC frame, the ANFIS controller allows adaptive and intelligent regulation of active power injection from solar, wind, and battery DERs. A three-phase inverter with an LCL filter is used to effectively reduce power oscillations and provide load compensation when working with linear, nonlinear, and unbalanced loads, such as a three-phase induction motor. Verified by MATLAB/Simulink simulation results, the suggested approach improves power quality, lowers Total Harmonic Distortion (THD), stabilizes motor operation, and permits reliable DER-grid interaction. The results demonstrate how the suggested system could improve grid power quality in commercial and industrial power networks.

I. INTRODUCTION

The integration of Distributed Energy Resources (DERs), including solar photovoltaic (PV) systems, wind energy systems, and Battery Energy Storage Systems (BESS), has become a pivotal strategy for transforming power grids into more sustainable and resilient systems. The global transition towards renewable energy sources is paramount for addressing pressing environmental concerns, such as reducing greenhouse gas emissions, mitigating climate change, and enhancing energy security. However, while these renewable energy systems provide substantial environmental benefits, they also present challenges due to their intermittent and variable nature, particularly in grid-connected systems [1]. The integration of such resources requires careful management to ensure grid stability, power quality, and reliable electricity supply, especially in commercial and industrial applications where consistent and high-quality electricity is crucial [2], [3]. The intermittency of renewable energy sources like solar and wind is one of the primary challenges faced by grid operators. Solar power generation is influenced by weather conditions, cloud cover, and time of day, while wind energy is subject to variations in wind speed and direction. These fluctuations in generation can lead to significant power oscillations, resulting in voltage instability, frequency deviations, and poor power quality [4], [5]. Additionally, the presence of nonlinear, unbalanced, and dynamic loads, such as three-phase induction motors and other industrial machinery, can exacerbate these power quality issues. These loads are notorious for introducing harmonic distortion, voltage sags, and reduced power factor, which can disrupt the efficient operation of electrical systems and result in costly downtime and maintenance [6], [7]. In response to these challenges, considerable research has been devoted to developing advanced control strategies for integrating renewable energy sources into power grids. One promising approach is the application of Conservative Power Theory (CPT), a method that decomposes power into oscillatory and non-oscillatory components to help stabilize grid voltage and mitigate power fluctuations. CPT has proven effective in compensating for oscillatory power terms, making it a valuable tool for improving power quality in systems with variable renewable energy input [8], [9], [10]. By directly addressing oscillatory power components, CPT enables more reliable voltage regulation and reduces the risk of voltage sag or instability in grid-connected systems. Alongside CPT, Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have emerged as a powerful solution for managing the coordination of DERs. ANFIS controllers combine the strengths of artificial neural networks and fuzzy logic, enabling them to adapt to dynamic and uncertain operating conditions. These controllers are

particularly effective in smoothing out power fluctuations and optimizing energy dispatch in real-time, ensuring that the grid remains stable and efficient even as renewable energy production varies. ANFIS controllers have been successfully employed to regulate the active power output of solar, wind, and battery storage systems, thereby improving overall system stability, power quality, and energy efficiency [11], [12], [13]. ANFIS controllers mitigate intermittency while multifunctional inverters with LCL filters regulate voltage, suppress harmonics, and balance loads, ensuring stable, high-quality power in renewable-integrated grids with nonlinear or unbalanced industrial loads. The use of LCL filters helps improve the overall efficiency of power conversion and enhances the interaction between DERs and the grid [14], [15], [16], [17]. The CPT-ANFIS hybrid strategy mitigates power oscillations, reduces harmonics, stabilizes voltage, and optimizes renewable energy output for reliable grid integration. This approach has been demonstrated through extensive simulations, which show substantial improvements in power quality, grid stability, and the overall reliability of DER-grid interactions [18], [19], [20]. Hybrid control strategies enhance renewable integration under high DER penetration and dynamic loads, requiring advanced adaptive techniques to maintain stability, power quality, and real-time responsiveness as renewable adoption rapidly expands. The proposed hybrid control approach, which combines CPT and ANFIS, offers an effective solution for addressing these challenges, providing a scalable and adaptable framework for managing the complex dynamics of renewable energy integration in grid-connected systems [21], [22], [23]. By addressing power quality challenges including voltage sags, harmonic distortions, and power oscillations, the proposed method enhances the stable and reliable operation of grid-connected renewable energy systems. The ability to improve system stability, enhance power quality, and optimize energy utilization makes this hybrid control strategy a valuable tool for modern power systems [24], [25]. Advanced control strategies like this are key to integrating renewables and enabling a sustainable, resilient energy future.

II. System Configuration

The hybrid energy system integrates solar PV, wind (PMSG), and battery storage with the grid via a multifunctional inverter that enhances power quality and mitigates oscillations. PV uses a DC-DC boost converter with MPPT, and wind employs an AC-DC converter with MPPT; both connect to a common DC bus linked to BESS through a bidirectional DC-DC converter for dynamic energy exchange. The DC bus feeds a VSI with an LCL filter for harmonic suppression and smooth grid injection. The system supports linear, unbalanced, nonlinear, and motor loads, controlled via ANFIS for power coordination and CPT-based VSI control for real-time compensation, ensuring stable, efficient, high-quality grid integration

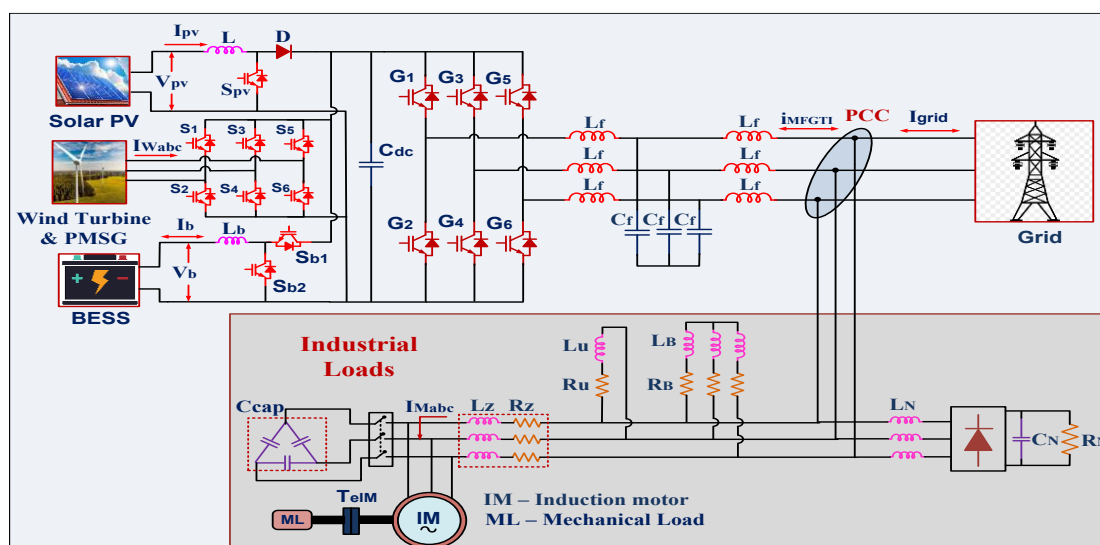


Fig.1 Interconnection of multi-functional grid tied inverter to an industrial grid.

III. Designing for Grid Connected AC-DC MFGTI Controller

The MFGTI integrates solar PV and wind into the grid, improving power quality and stability for industrial and commercial loads. CPT-based control mitigates harmonics and reactive imbalances, PFC optimizes power factor, and ANFIS regulates the DC-link voltage, ensuring efficient, reliable, and sustainable energy delivery.

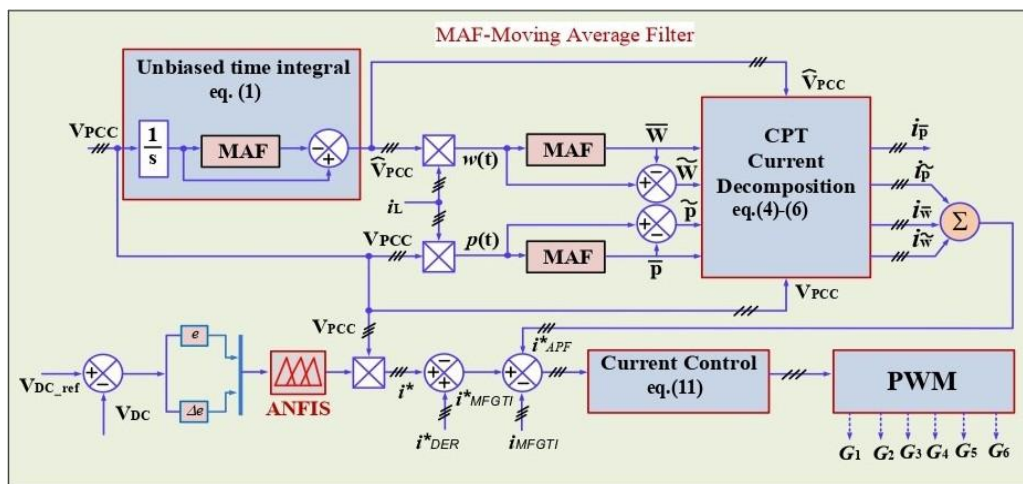


Fig.2 Controller designing of MFGTI for grid tied DERs system

$$\hat{v}_m = \int_0^t v_m(\tau) d\tau - \frac{1}{T} \int_0^T \left(\int_0^t v_m(\tau) d\tau \right) dt \quad (1)$$

Equation (1) removes the DC component from the voltage, isolating the oscillatory part for accurate reactive energy and instantaneous power calculations, essential for Active Power Filters and microgrids to manage disturbances and maintain stability.

$$w(t) = \bar{w} + \tilde{w} \quad (2)$$

$$p(t) = \bar{p} + \tilde{p} \quad (3)$$

$p(t)$ represents instantaneous real power, and $w(t)$ represents reactive energy. Decomposing them into average and oscillatory components distinguishes useful power from energy exchange, aiding analysis under non-sinusoidal conditions.

$$i_w(t) = \bar{i}_w + \tilde{i}_w = \frac{\bar{w}}{\hat{v}_{abc}^2} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} + \frac{\tilde{w}}{\hat{v}_{abc}^2} \begin{bmatrix} \hat{v}_a \\ \hat{v}_b \\ \hat{v}_c \end{bmatrix} \quad (4)$$

$$i_p(t) = \bar{i}_p + \tilde{i}_p = \frac{\bar{p}}{v_{abc}^2} \begin{bmatrix} v_a \\ v_a \\ v_a \end{bmatrix} + \frac{\tilde{p}}{v_{abc}^2} \begin{bmatrix} v_a \\ v_a \\ v_a \end{bmatrix} \quad (5)$$

Equations (4)-(6) decompose load current into active, reactive, and harmonic components. Using CPT, an Active Power Filter (APF) compensates unwanted currents, improving power quality, efficiency, and reducing system losses.

$$i_{comp} = \bar{i}_w + \tilde{i}_p - \tilde{i}_w = i_{APF} \quad (6)$$

This reference current is what the APF will inject to eliminate power quality issues like harmonics and reactive power.

$$i_{DER} = \frac{P_{DER}}{(V_1^+)^2} \cdot \begin{bmatrix} V_{1a}^+ \\ V_{1b}^+ \\ V_{1c}^+ \end{bmatrix} \quad (7)$$

Equation (7) defines the DER reference current i_{DER} for injecting only active power, synchronized with the grid. Equations (8)-(10) generate the MFGTI current reference by combining i_{DER} , APF current, and capacitor compensation to ensure sinusoidal, balanced power and improved grid quality.

$$i_{ref} = i_{DER} - i_{APF} - i_{CB} \quad (8)$$

This equation represents the total reference current (i_{ref}) that needs to be generated by the MFGTI and the capacitor bank to manage active power and compensation [9]. Eq (9) defines the decomposition of the average reactive current component ($i_{\bar{w}}$), which is split between the active power filter and the capacitor bank:

$$i_{\bar{w}} = i_{\bar{w}_{APF}} + i_{\bar{w}_{CB}} \quad (9)$$

This equation explains how reactive current compensation can be divided between the MFGTI's active power filter and the capacitor bank, improving operational flexibility. Eq (10) shows the final reference current for the MFGTI, taking into account the compensation for both reactive power and oscillating torque components:

$$i_{MFGTI} = i_{DER} - i_{\bar{w}_{APF}} - (i_{\bar{p}} + i_{\tilde{w}}) \quad (10)$$

The MFGTI injects active power while compensating reactive and oscillatory components to enhance power quality. A multi-resonant proportional-integral controller (MRPC) targets key harmonics, minimizing distortion and ensuring a sinusoidal, grid-synchronized current.

The transfer function for this controller is given by:

$$G_c(s) = k_c + \sum_{i=1,3,5} \frac{2K_{IPR}\omega_{CPR}S}{s^2 + 2\omega_{CPR}S + (h\omega_0)^2} \quad (11)$$

Where: k_c : Proportional gain, K_{IPR} : Integral gain, ω_{CPR} : Bandwidth of the resonant controller, h : Harmonic order, ω_0 : Fundamental frequency of the grid

This transfer function is used in the frequency domain (Laplace domain) to manage the harmonics effectively and ensure that the output current matches the required power quality standards.

IV. DC Link Voltage Control Using ANFIS Controller

The ANFIS-based DC-link voltage controller combines neural networks and fuzzy logic to dynamically regulate the DC bus in hybrid renewable systems. Replacing conventional PI loops, it adapts in real time using online-tuned fuzzy rules to maintain voltage at the reference V_{dc}^* .

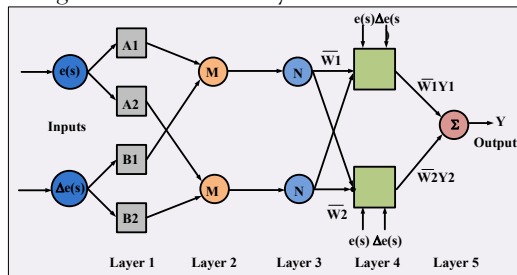


Fig.3 designing of ANFIS controller structure

Define the voltage error

$$e(k) = v_{dc}^* - v_{dc}(k) \quad (12)$$

and its change

$$\Delta e(k) = e(k) - e(k - 1) \quad (13)$$

These two signals from the ANFIS inputs. In layer 1, each input is fuzzified by Gaussian membership functions

$$\mu_{i1}(e) = \exp \left[-\frac{(e - e_{i1})^2}{2\sigma_{i1}^2} \right] \quad (14)$$

$$\mu_{i2}(\Delta e) = \exp \left[-\frac{(\Delta e - e_{i2})^2}{2\sigma_{i2}^2} \right] \quad (15)$$

where c_{ij} and σ_{ij} are the center and width of the i th fuzzy set for input j . In layer 2, rule firing strengths are computed as

$$w_i = \mu_{i1}(e) \times \mu_{i2}(\Delta e) \quad (16)$$

Layer 3 normalizes them:

$$\bar{w}_i = \frac{w_i}{\sum_j w_j} \quad (17)$$

In layer 4, each rule produces a linear “consequent” function

$$f_i(e, \Delta e) = p_i e + q_i \Delta e + r_i \quad (18)$$

with parameters p_i, q_i, r_i . Finally, layer 5 computes the ANFIS output (the duty-cycle increment ΔD) as the weighted sum

$$\Delta D = \sum_i \bar{w}_i f_i(e, \Delta e) \quad (19)$$

The new duty cycle is then updated each sampling instant:

$$D(k) = D(k - 1) + \Delta D \quad (20)$$

subject to $0 \leq D \leq 1$.

V. Simulation Results and Discussion

A. DER-Based Power Quality Enhancement Using CPT and ANFIS Control

The simulation was run for a total duration of 2 seconds to observe the dynamic behavior of the proposed grid-connected system supported by distributed energy resources (DERs) such as solar, wind, and battery storage. During this period, various types of loads including balanced, unbalanced, nonlinear, and induction motor loads with a combined demand of 48 kW were connected to the grid. From the start of the simulation to 0.3 seconds, none of the DERs were injecting power, so the grid alone supplied the entire load. During this period, significant power quality issues were observed, including harmonic distortions, voltage fluctuations, and a poor power factor falling below 0.94 due to the nature of the nonlinear and motor loads. At 0.3 seconds, the solar system began contributing 18 kW of active power

and continued up to 0.5 seconds. This injection helped stabilize the grid by reducing harmonic content and voltage distortion, and it improved the power factor to around 0.96. As a result, the overall quality of power delivered to the loads improved considerably during this interval. Later, from 0.7 to 0.9 seconds, the wind power system became active and supplied 25 kW to the grid. This further enhanced the power quality by smoothing the voltage waveform and reducing current harmonics. During this period, the power factor rise to nearly 0.92, and voltage oscillations were significantly damped. In the absence of solar and wind contributions between 1.1 and 1.3 seconds, the battery system took over and injected 15 kW of power as shown in Fig.4. This ensured uninterrupted support to the load, maintaining grid stability and helping sustain a power factor around 0.91.

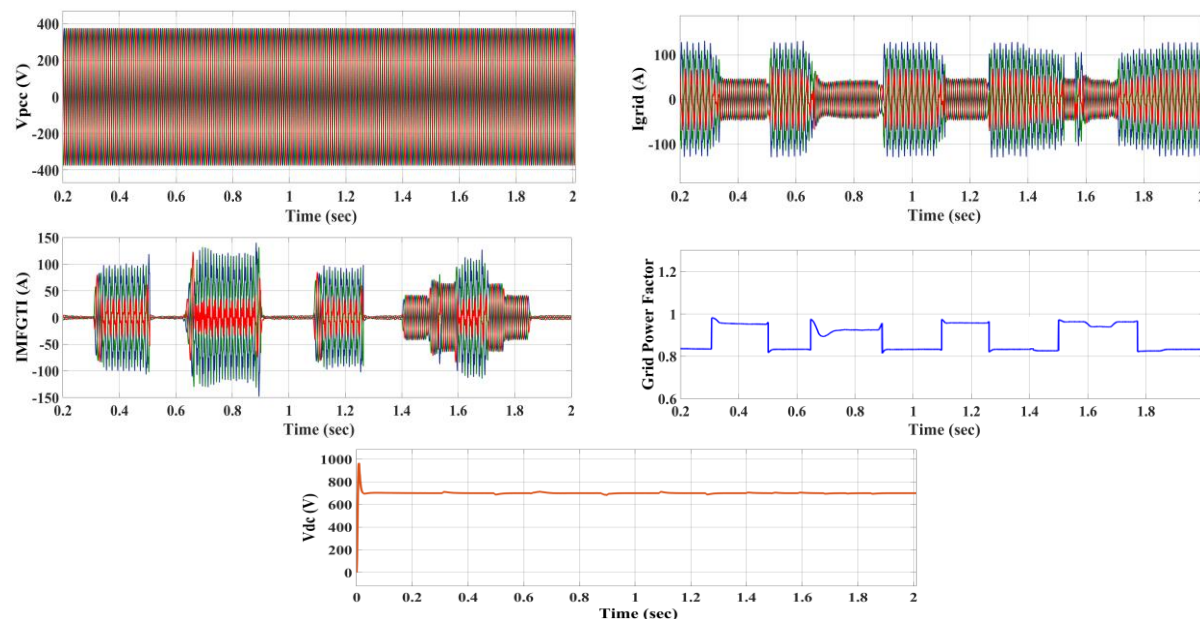


Fig.4 Simulation Results and Performance Analysis of DER-Integrated Grid System

From 1.4 to 1.9 seconds, all three DERs operated simultaneously at lower individual outputs, sharing the load support dynamically as shown in Fig.7. The solar system contributed between 1.4 and 1.8 seconds, the wind source was active from 1.5 to 1.8 seconds, and the battery delivered power from 1.6 to 1.7 seconds. The combined operation resulted in effective power balancing and sustained power factor improvements up to 0.99. The coordinated control under Conservative Power Theory (CPT) effectively minimized oscillations, reduced total harmonic distortion, and enhanced overall system performance as shown in Fig.5. These results clearly demonstrate that the intelligent coordination of DERs under CPT-based control can significantly improve power quality, support dynamic load conditions, and maintain a high power factor across varying operational periods.

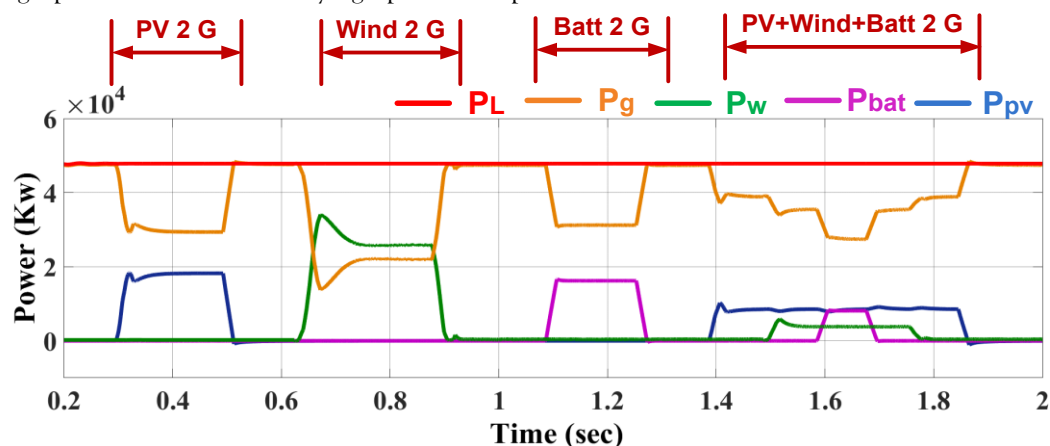


Fig.5 Simulation results for Dynamic power management of MFGTI configuration

B. Induction Motor Performance with Capacitor Bank-Based Reactive Power Compensation

The simulation of the three-phase induction motor was carried out to evaluate its dynamic performance and reactive power demand under different operating conditions. The motor is rated at 1.55 kW, delivering a torque of 74 Nm and operating at a synchronous speed of 1500 RPM. Initially, during the time interval from 0 to 1 second, the capacitor banks were disconnected, resulting in the motor drawing

significant reactive power directly from the grid. This increased reactive demand led to a lower system power factor and higher apparent power consumption, which contributed to increased system losses and reduced efficiency. At 1 second, the capacitor banks were switched ON and connected across the motor terminals. As a result, the local injection of reactive power significantly reduced the burden on the grid. This compensation improved the system's power factor to nearly 0.95, reducing the current drawn from the grid and enhancing the voltage stability at the motor terminals. The activation of the capacitor banks also contributed to smoother motor operation, maintaining stable torque and reducing electromagnetic oscillations as shown in Fig.6. The improved power factor translated into better efficiency and overall performance of the motor drive system. These simulation results clearly demonstrate that reactive power compensation using capacitor banks is an effective technique for improving the power factor, minimizing losses, and ensuring reliable operation of induction motors in grid-connected systems.

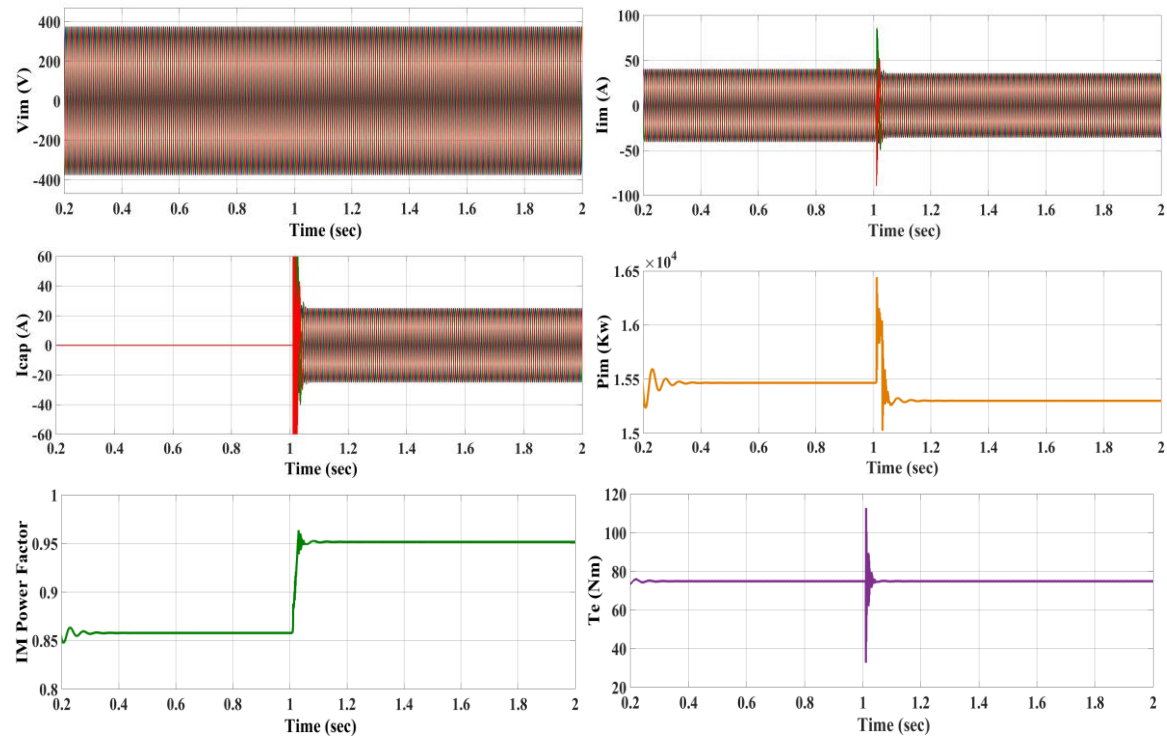


Fig.6 Simulation Results of Induction Motor Performance with Capacitor Bank Compensation

C. Performance Analysis of ANFIS Controller Under Dynamic Load and DER Conditions

The ANFIS controller was tested using MATLAB/Simulink simulations to evaluate its ability to reduce DC-link voltage fluctuations, mitigate Total Harmonic Distortion (THD), and maintain high power quality during active power injection from Distributed Energy Resources (DERs). The analysis demonstrates that the ANFIS controller significantly outperforms the conventional PI controller in reducing Total Harmonic Distortion (THD). For the solar and wind hybrid system, the PI controller resulted in a THD of 12.46%, whereas the ANFIS controller reduced it substantially to 4.15%. Furthermore, when an EV battery was integrated with the solar-wind system, the THD decreased further to 4.12% with the PI controller and an impressive 1.19% with the ANFIS controller. These findings highlight that not only does the addition of an EV battery enhance system performance, but also the ANFIS controller proves to be a highly effective solution for improving power quality in renewable energy systems. The ANFIS controller effectively coordinated active power injection from solar, wind, and battery energy sources, ensuring continuous compensation and robust power quality even under fluctuating and nonlinear load conditions as shown in Fig.7 and 8. These simulation results confirm the ANFIS controller's robustness and outperform the PI controller in dynamic response, harmonic mitigation, and overall power quality improvement, especially in complex, real-world grid conditions involving DERs and industrial loads.

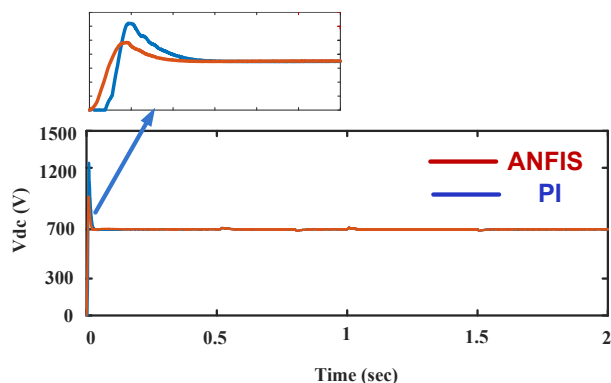


Fig.7 comparison results of ANFIS and PI controller for DC-link voltage Vdc

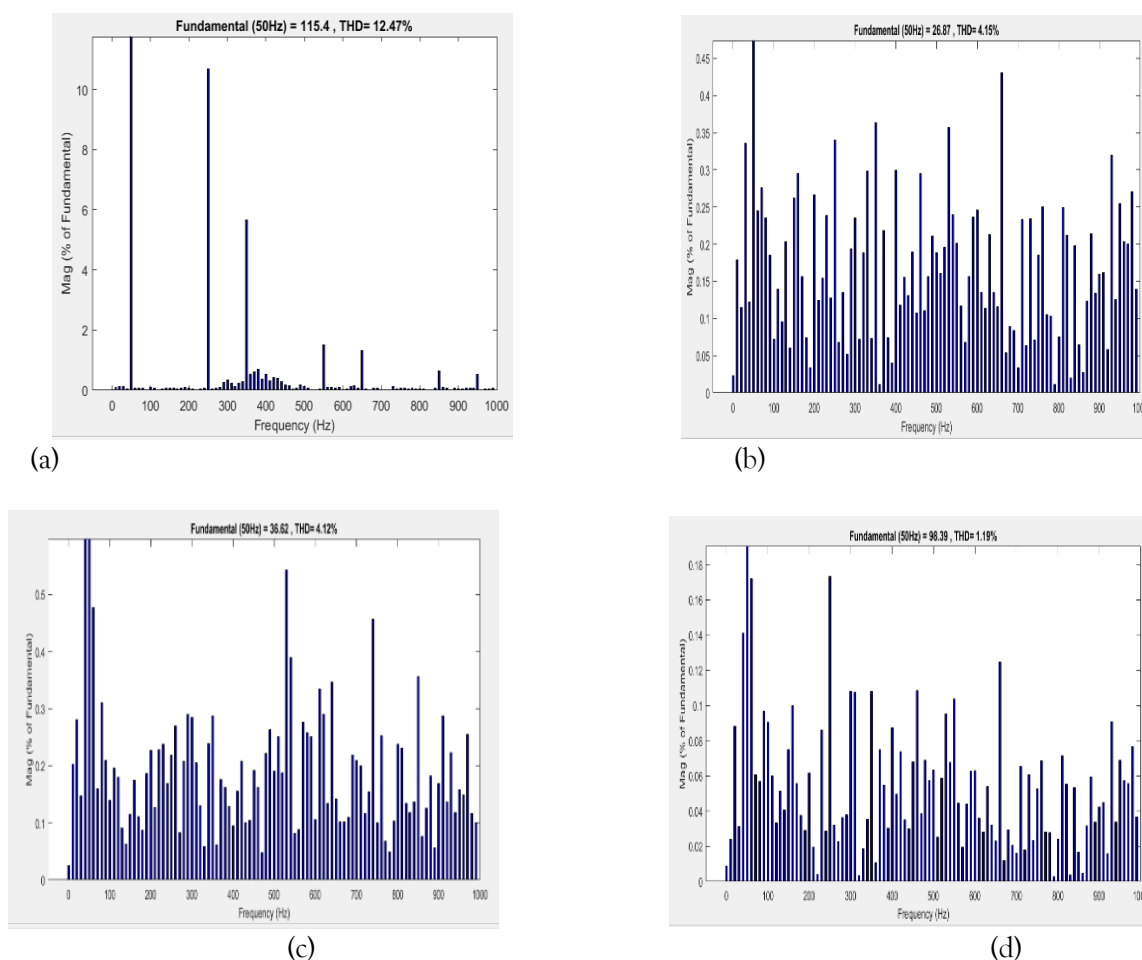


Fig. 8 grid current THD values (a) Hybrid Solar Wind with PI Controller (b) Hybrid Solar Wind with ANFIS Controller (c) Hybrid Solar Wind EV with PI Controller (d) Hybrid Solar Wind EV with ANFIS Controller

VI. CONCLUSION

This paper presented a hybrid control framework for enhancing grid power quality and mitigating power oscillations through the coordinated operation of solar PV, wind energy, and battery energy storage systems using an Adaptive Neuro-Fuzzy Inference System (ANFIS) in conjunction with Conservative Power Theory (CPT). The proposed system effectively addresses challenges related to the intermittent nature of renewable energy sources and the presence of nonlinear and unbalanced loads that degrade voltage stability, power factor, and overall power quality. The CPT method was employed to extract and compensate oscillatory power components in real time, while the ANFIS controller enabled intelligent regulation of active power from distributed energy resources. Simulation results validated that the system significantly reduces total harmonic distortion, stabilizes voltage and current waveforms, and improves the grid power factor, reaching values close to unity when DERs are actively injecting power. Additionally, the use of capacitor banks with three-phase induction motors was shown to enhance reactive power

compensation and motor performance, particularly during transitions between grid and DER operations. The integration of multifunctional grid-tied inverters with LCL filters further improved harmonic mitigation and ensured smooth interaction between DERs and the grid. This combination resulted in improved load compensation and system stability even under varying load and generation conditions. The proposed hybrid CPT and ANFIS-based control strategy offers a reliable, scalable, and intelligent solution for improving power quality and grid stability in modern power systems with high renewable energy penetration. This approach supports the development of resilient and sustainable energy infrastructures necessary for future smart grids.

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