Voltage SAG/SWELL Emimination Using UPQC PSO ANN

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ABSTRACT
The efficiency of an electrical system heavily relies on power quality, making the integration of Unified Power Quality Conditioners (UPQCs) with Distributed Generation (DG) systems vital for mitigating issues like flicker, harmonics, voltage sags, and swells. In UPQC-DG systems, Proportional-Integral (PI) controllers are crucial for maintaining DC link voltage stability, ensuring consistent power delivery and smooth grid interaction. Properly tuned PI controllers reduce voltage ripples and enable rapid response to disturbances, thus enhancing overall system performance. However, traditional tuning methods like Ziegler-Nichols often fall short in dynamic and complex conditions.This paper introduces a novel real-time PI controller optimization method using Particle Swarm Optimization (PSO) combined with Artificial Neural Networks (ANN). This hybrid PSO-ANN approach adaptively adjusts PI parameters in real time, ensuring precise DC link voltage control across varying operating conditions. By integrating PSO's global search capabilities with ANN's predictive learning, the system achieves enhanced adaptability and robustness. The proposed method demonstrates significant improvements in power quality, reliability, and stability for UPQC-DG systems.

I. Introduction

The increasing complexity and sensitivity of industrial equipment and electronic devices have made power quality a critical concern in modern electrical systems [1]–[3]. Power disturbances can significantly affect system performance and reliability. Among the various solutions, the Unified Power Quality Conditioner (UPQC) has emerged as an effective and flexible tool to address these challenges [4]–[6]. UPQC enhances system efficiency, reduces energy waste, and prolongs the lifespan of equipment by mitigating power quality issues.

A UPQC consists of two main components: a shunt compensator that addresses current-related issues and a series compensator that mitigates voltage disturbances. Maintaining high power quality is especially vital with the growing adoption of renewable energy sources, such as distributed generation (DG) and photovoltaic (PV) systems.

In UPQC-DG systems, DG sources are typically connected to the DC link of Voltage Source Inverters (VSIs), which operate in both series and shunt active power filters (APFs) [7]–[9]. This configuration allows the DG sources to not only contribute power during outages or peak demand but also support the UPQC's compensation functions, enhancing overall system performance. Localized power generation reduces transmission losses, improves efficiency, and boosts reliability. Therefore, the integration of DG with UPQC creates a comprehensive solution for managing power quality in contemporary power systems.

The performance of a Unified Power Quality Conditioner (UPQC) system is heavily influenced by its control strategy, particularly the Proportional-Integral (PI) controllers that manage its operation. These controllers play a vital role in mitigating voltage sags, swells, and harmonics by maintaining a stable DC link voltage [10], [11]. This stability is essential for ensuring consistent power quality and enabling the system to respond swiftly to disturbances, thereby minimizing their impact on the electrical network.

PI controllers are widely preferred due to their simplicity, cost-effectiveness, and reliability. They are easy to implement and maintain, reducing system complexity and overall operational costs. Furthermore, their predictable control behavior contributes to system safety and dependable operation—key requirements in UPQC-DG applications [12]. However, the tuning of PI controller parameters remains a significant challenge, as their performance directly affects the system's efficiency and stability.

Conventional tuning methods such as trial-and-error or the Ziegler-Nichols (ZN) technique [13] often fail to deliver optimal results, particularly in dynamic and nonlinear environments. The ZN method tends to produce overly aggressive tuning parameters, leading to undesirable oscillations during transient recovery. Although it provides fast response, it may introduce significant overshoot, stress system components, and compromise stability. Additionally, these traditional methods do not consider specific system dynamics or stability margins, which can result in prolonged oscillations or instability, especially in systems with high feedback delays or nonlinear characteristics. They

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also rely heavily on mathematical models, which may not accurately capture real-world system behavior and often require operating at reduced output levels during tuning, posing risks to hardware safety.

Recently, optimization-based techniques have gained attention for tuning in complex systems. Grey Wolf Optimization (GWO), inspired by the leadership hierarchy and hunting strategy of grey wolves, is one such emerging algorithm known for its simplicity and ability to efficiently explore high-dimensional solution spaces.

This paper proposes a novel GWO-based real-time PI tuning method for UPQC-DG systems to overcome the limitations of traditional approaches. Unlike classical methods, GWO does not depend on detailed mathematical modeling. Instead, it dynamically observes system performance and adaptively adjusts PI parameters in real time to handle time-varying operating conditions. This approach significantly enhances system responsiveness and adaptability, ensuring optimal performanceacross a range of operating scenarios

Figure.1Approaches for tuning the proportional-integral (PI) controller (a) Traditional ZN Method (b) Proposed tuning method

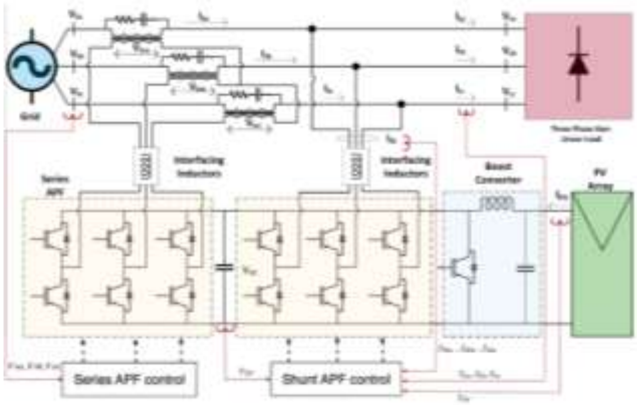

Figure 2 Power circuit diagram of UPQC-DG

The validation results confirm that the proposed approach significantly enhances the resiliency and efficiency of UPQC-DG systems in real-world scenarios. A key contribution of this work is the introduction of an online, real-time PI controller tuning method based on Grey Wolf Optimization (GWO), which operates without the need for detailed mathematical modeling. By dynamically adjusting PI parameters within intrinsic output limits, the method also ensures hardware safety during operation. To verify its effectiveness, a PV-integrated UPQC-DG system was simulated in real time, demonstrating exceptional performance in maintaining DC link voltage under varying operational conditions.

This paper is organized into five main sections. Section I introduces the topic and highlights the motivation behind the work. Section II describes the configuration and construction of the UPQC system, including the design principles of the shunt and series Active Power Filters (APFs). Section III details the development of the PSO-based PI control strategy for UPQC-DG systems, discussing recent advancements and its practical implementation. Section IV presents the integration and analysis of Artificial Neural Networks (ANNs) within the system. Finally, Section V provides the concluding remarks.

II. Structure of UPQC

An advanced power electronic system known as UPQC-DG has been developed to enhance power quality in electrical distribution networks (Fig. 2). It integrates the functionalities of a Unified Power Quality Conditioner (UPQC) with Distributed Generation (DG) sources such as wind turbines, photovoltaic (PV) systems, or other renewable energy units.

The UPQC-DG system primarily consists of two components: a Series Active Power Filter (series compensator) and a Shunt Active Power Filter (shunt compensator), both connected to the distribution network. The shunt compensator is typically integrated with the DG unit and connected in parallel with the load, while the series compensator is connected in series with the distribution feeder. The series compensator includes a coupling transformer, Voltage Source Inverter (VSI), and control circuits. The shunt compensator consists of control circuitry, a filter inductor or transformer, and a VSI.

For the PV-based DG unit, the system uses SPR-305E-WHT-D PV modules. Ten modules are connected in series to form a string, and five such strings are connected in parallel to construct a 15.3 kW PV array with a nominal output voltage of 547 V under standard temperature and irradiance conditions. The PV array is interfaced with the shunt compensator's DC link via a DC-DC boost converter. This converter, equipped with Maximum Power Point Tracking (MPPT) control, optimizes energy capture by boosting the PV voltage to match the 700 V DC-link voltage. The PV system contributes approximately 38.25% of the total load power (40 kW) and supports both the load and the grid, helping to regulate the DC link voltage and enhance overall power quality.The performance of the shunt inverter—including its kVA rating and current capacity—is determined by the combined demands of PV active power generation and load reactive power compensation. As reactive power injection or absorption is closely tied to the DC link voltage, maintaining voltage stability is crucial.

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To maximize its effectiveness, the UPQC-DG system is typically installed at strategic points in the distribution network, such as the Point of Common Coupling (PCC) between the utility grid and consumer load, ensuring efficient DG integration and improved power quality across the system

A. SERIES APF CONTROL

In a UPQC-DG system, the Series Active Power Filter (APF) is responsible for mitigating voltage-related disturbances such as harmonics, sags, and swells. To ensure accurate and efficient voltage compensation, the control strategy commonly employs Unit Vector Template Generation (UVTG). The series APF generates a compensating voltage that is injected in series with the line voltage, thereby maintaining a stable and distortion-free supply to the load.

Additionally, due to the implementation of the Power Angle Control (PAC) technique, the series compensator injects voltage at a specific phase angle, enabling it to contribute to reactive power support. As a result, reactive power management becomes a shared responsibility between the series and shunt APFs.

The distribution of reactive power is governed by the maximum power angle (δ_m), which is calculated using Equation 1. This ensures that reactive power is allocated proportionally based on the apparent power (VA) ratings of the converters, optimizing overall system performance.

It stands for the maximum power angle that a system can manage without experiencing any problems. This estimate takes into account the series converter's voltage and VA restrictions. It comprises the source voltage magnitude (VS), the rated load voltage (VL,rated), and

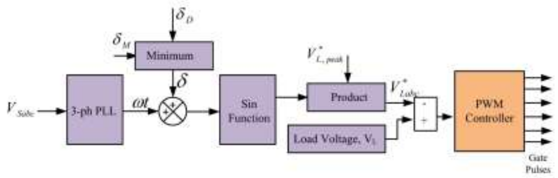

Fig 3 Series APF control.

The rated series APF voltage ($V_{Sr,rated}$).

$$\delta_M = \cos^{-1}\left[\frac{1+\left(\frac{V_S}{V_{L,rated}}\right)^2-\left(\frac{V_{Sr,rated}}{V_{L,rated}}\right)^2}{2\left(\frac{V_S}{V_{L,rated}}\right)}\right] \quad (1)$$

The optimal sharing of reactive power by the series APF—corresponding to the point at which the system achieves maximum power quality enhancement—is defined by the desired power angle (δ_D). This angle is determined based on the load's reactive power (Q_l), active power (P_l), and the power generated by the PV source (P_{pv}). As shown in Equation (2), the parameter λ represents the ratio of the series APF's power rating to the total combined ratings of both the series and shunt APFs.

$$\delta_D = \sin^{-1}\left(\frac{\lambda Q_L}{P_L - P_{PV}}\right) \quad (2)$$

The precise value of the power angle, denoted as δ, is determined by selecting the minimum of δ_M (maximum power angle) and δ_D (desired power angle). This ensures compliance with voltage and converter VA rating limits while maintaining balanced reactive power sharing between the series and shunt APFs. The complete control structure for the series APF is illustrated in Fig. 3.

The control method employed is known as Unit Vector Template Generation (UVTG). In this approach, a three-phase Phase-Locked Loop (PLL) processes the voltage source signal to generate a set of three unit vectors. The extracted angular position (ωt) is then combined with the calculated power angle (δ).As depicted in the control diagram, the load voltage signal (V^L) is subtracted from a reference waveform, which is obtained by multiplying the unit vector with the peak load voltage (V^{*L},peak). This results in the error signal required for voltage compensation. The resulting signal is then used to generate appropriate switching pulses via a Pulse Width Modulation (PWM) controller, completing the control loop.

B. PV INTEGRATED WITH SHUNT APF CONTROL

The shunt Active Power Filter (APF) in a UPQC-DG system is responsible for mitigating current-related issues such as load imbalance, harmonic distortion, and reactive power compensation. The Synchronous Reference Frame–Power Angle Control (SRF-PAC) method is an advanced control strategy particularly effective when photovoltaic (PV) generation is integrated into the DC link. This combination ensures high power quality while enabling efficient utilization of renewable energy sources.

As illustrated in Fig. 4, the Park transformation—represented in Equation (3)—is used to convert the load currents (I_{la}, $I_{l\beta}$, and I_{lC}) from the three-phase stationary reference frame (a-b-c) into the synchronous reference frame (d-q-0). This transformation is synchronized using the output of a three-phase Phase-Locked Loop (PLL) and a load voltage ramp signal. Synchronization is achieved by aligning the transformation angle αt, calculated as αt = ωt + δ, where ωt is the PLL output and δ is the power angle.

This alignment ensures that the reference frame is matched with the rotating reference frame of the system's fundamental frequency component, allowing accurate and effective current control.

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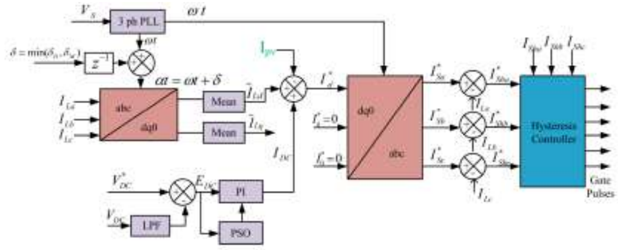

Fig 4 Shunt APF Control

$$\begin{bmatrix} I_{Ld} \\ I_{Lq} \\ I_{L0} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\alpha t & \sin\left(\alpha t-\frac{2\pi}{3}\right) & \sin\left(\alpha t+\frac{2\pi}{3}\right) \\ \cos\theta & \cos\left(\alpha t-\frac{2\pi}{3}\right) & \cos\left(\alpha t-\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{LC} \end{bmatrix} \quad (3)$$

The active and reactive power components are used to determine the power angle (δ), as explained in the preceding subsection. The d-q frame's reference currents (ILd&ILq) are produced in order to produce the required compensation. To maintain the active power, ILd is usually set to the fundamental active current's average value, and to accomplish unity power factor operation, ILq is set to zero. A PI controller analyses the error (EDC) that results from comparing the DC link voltage (VDC) to the reference DC link voltage (V ∗ DC) in order to determine the intended DC link current (IDC).To generate the reference daxis current in the synchronous frame, the average value of ILd is added to IDC and deducted from Ipv. The inverse park transformation is used to convert the reference currents in the d-q frame back to the a-b-c frame, producing the compensating current references (I∗sa,I∗sb,I∗sc). To create the reference shunt APF current (I∗sha,I∗shb,I∗shc), the reference source current is subtracted from the real load current signal (ILa,ILb,ILc). The acquired signal and the measured shunt APF current (ISha, IShb, and IShc) in the hysteresis controller are compared to provide the necessary switching gate signal.

The PV system is incorporated into the shunt APF's DC link. The DC link receives the generated PV power, stabilizing the DC voltage and supplying the energy required for the APF to function. Through a boost converter, which is managed by the Maximum Power Point Tracking (MPPT) methodology utilizing the Incremental Conductance method, the PV system is connected to the DC link of the shunt APF. By comparing the incremental conductance (I/V) to the instantaneous conductance (I/V), the incremental conductance method determines the MPP. The fundamental idea is that the derivative of power with respect to voltage is zero at the MPP.

$$\frac{dI}{dV} = -\frac{1}{V} \quad (4)$$

To operate the PV array at its MaximumPower Point (MPP), the MPPT controller dynamically adjusts the duty cycle of the boost converter. This integration not only enhances the efficiency and sustainability of the power system by maximizing renewable energy utilization but also significantly improves overall power quality.

III. Enhancing Power Quality with PSO-Based PI Control in UPQC-DG Systems

Particle Swarm Optimization (PSO) is a simple and efficient population-based algorithm inspired by the social behavior of birds and fish. It requires minimal parameter tuning and excels in dynamic, nonlinear environments, making it ideal for real-time control applications. PSO works by updating candidate solutions (particles) based on both personal and group best positions to find the global optimum. In UPQC-DG systems, PSO is used to tune PI controller gains (K_p and K_i) by minimizing the Integral of Time-weighted Absolute Error (ITAE), ensuring stable DC link voltage and improved power quality.

In real-time tuning, each PI controller candidate is evaluated in the UPQC system using the ITAE criterion. Based on performance feedback, particles update their positions to improve voltage regulation. The PSO-based strategy allows the UPQC-DG system to adapt to changing conditions, enhancing power quality, disturbance rejection, and DG integration. Its simplicity and efficiency make PSO ideal for real-time control optimization.

IV. Artificial Neural Networks (ANNs)

Artificial Neural Networks (ANNs) are AI models inspired by the human brain, made up of interconnected layers of artificial neurons. Each neuron processes inputs using weighted connections and activation functions to produce outputs. ANNs operate in two phases: forward propagation, which generates predictions, and backpropagation, which adjusts weights to minimize error using algorithms like gradient descent. This iterative learning improves model accuracy. Common types include Feedforward Neural Networks (FNNs) for classification/regression and Convolutional Neural Networks (CNNs) for image-related tasks.

Specialized for image processing, using convolutional layers to detect spatial patterns. Recurrent Neural Networks (RNNs) are designed for sequential data, incorporating memory elements that allow information retention across time steps, making them useful for tasks like speech recognition and language modeling. Long Short-Term Memory (LSTM) networks and Gated

Recurrent Units (GRUs) are advanced RNN variants that overcome the problem of vanishing gradients, improving performance on long sequences. Generative Adversarial Networks (GANs) consist of a generator and a discriminator, competing in a game-like process to generate realistic synthetic data.

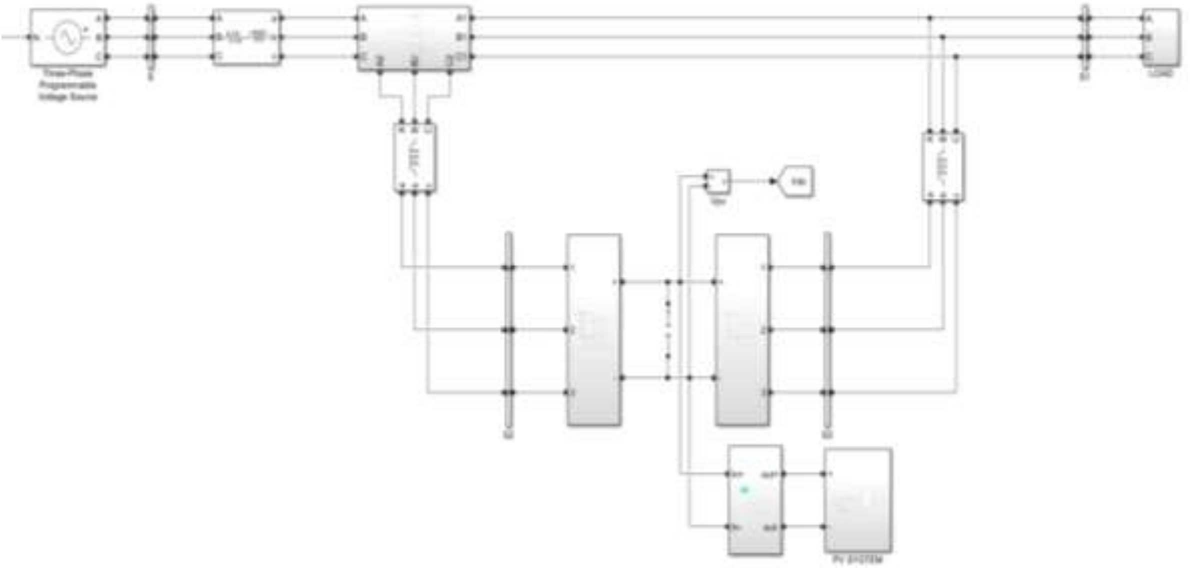

Fig 5: Ann circuit diagram of UPQC-DG

Autoencoders are another class of ANNs used for data compression and feature learning by encoding input data into a lower-dimensional representation and reconstructing it back. The practical applications of ANNs span multiple domains, including healthcare for disease prediction, finance for fraud detection, robotics for autonomous decision-making, and natural language processing for speech recognition and machine translation.

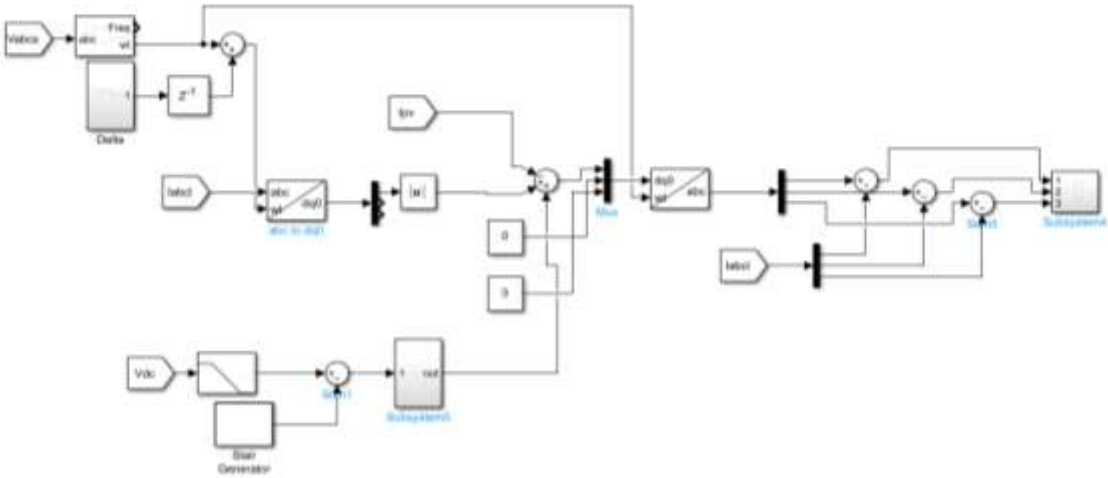

Fig 6: Artificial neural network controller

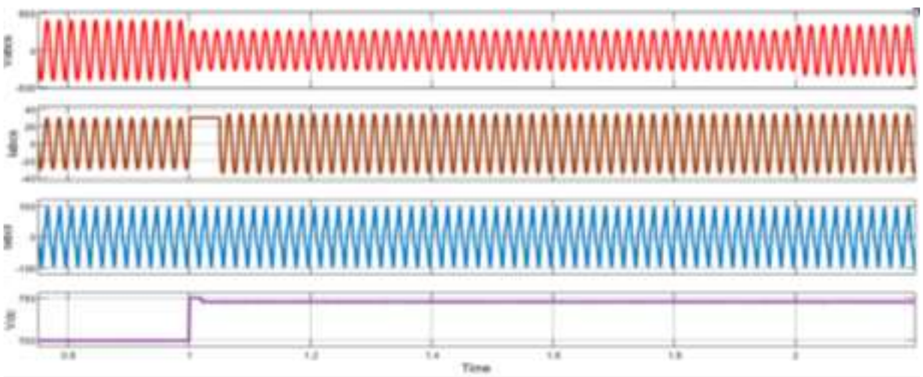

Fig 7: a) Single-phase voltage source input b) Single-phase current source input c) Single-phase load current d) DC voltage

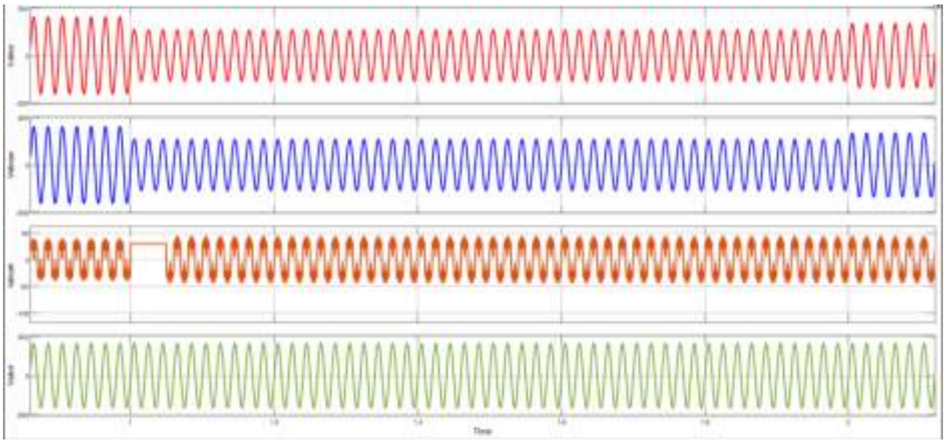

Fig 8: a) Single-phase voltage source input b) Series inverter single-phase voltage c) Shunt inverter single-phase current d) Single-phase load voltage

While ANNs offer impressive capabilities, they face challenges such as high computational demands, reliance on large datasets, and limited transparency—often operating as “black boxes.” To address these issues, ongoing research focuses on Explainable AI (XAI) for better interpretability, neuromorphic computing for efficiency, and quantum AI for enhanced processing power. As these technologies evolve, ANNs are expected to drive smarter automation, real-time decision-making, and progress toward more human-like intelligence in machines..

V. FINAL RESULTS

The application of PSO-based online PI tuning in UPQC-DG systems significantly improved DC link voltage control. Compared to the conventional Ziegler-Nichols (ZN) method (K_p = 3.15, K_i = 350, ITAE = 4.82%), the PSO-optimized controller (K_p = 2.376, K_i = 175) achieved a lower ITAE of 2.38%, indicating better dynamic performance.

Total Harmonic Distortion (THD) was also reduced: the load voltage THD dropped from 4.22% (ZN) to 3.21% (PSO), and source current THD from 10.3% to 7.44%. These reductions reflect improved power quality due to lower harmonic content.

Furthermore, the PSO method reduced DC link voltage overshoot from 190 V to 40 V and cut voltage ripple by 16.03%, resulting in a more stable and reliable system. Real-time PI tuning allows the system to respond efficiently to varying load and generation conditions, minimizing hardware stress and integrator windup.

Overall, the PSO-based controller enhances both performance and robustness in distributed generation systems. Its adaptability makes it well-suited for modern power networks. Future work can explore hybrid approaches combining PSO with AI or ANN methods for even greater optimization and resilience.

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