Power Quantity Enhancement of UPQC-DG Using PSO and ANN

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ABSTRACT_ The efficiency of an electrical system largely depends on power quality, making the integration of a Unified Power Quality Conditioner (UPQC) with Distributed Generation (DG) systems essential to mitigate issues such as flicker, harmonics, voltage sags, and swells. In UPQC-DG systems, the Proportional-Integral (PI) controller plays a critical role in stabilizing the DC link voltage, ensuring consistent power quality and seamless grid integration. An effectively tuned PI controller minimizes voltage ripples and offers fast disturbance response, thereby enhancing overall system performance. However, conventional PI tuning techniques, such as the Ziegler-Nichols method, often yield suboptimal results under dynamic and complex operating conditions.
This paper proposes a novel real-time PI controller optimization approach for UPQC-DG systems using Particle Swarm Optimization (PSO) in conjunction with Artificial Neural Networks (ANN). The objective is to adaptively fine-tune PI controller parameters in real time, enabling stable and accurate regulation of the DC link voltage under varying system conditions. The proposed hybrid PSO-ANN strategy leverages the global search capability of PSO and the predictive learning strength of ANN to ensure dynamic adaptability and robustness. This study highlights the effectiveness of the PSO-ANN-based adaptive control in maintaining high power quality and improving the reliability and stability of UPQC-DG systems.

I. Introduction

The growing complexity and sensitivity of industrial equipment and electronic devices have made power quality a pressing issue in today's electrical systems [1], [2], [3]. These disturbances have the potential to cause a tremendous impact on performance and dependability. Among various solutions, flexible tools to mitigate these challenges are the Unified Power Quality Conditioner (UPQC) [4], [5], [6]. It can ensure that the electrical systems of such industries would be more efficient, less wasteful of energy, and longer lasting. UPQC encompasses two compensators: a shunt compensator that solves problems associated with current and a series compensator that counters the problem associated with voltage. Maintaining high power quality is particularly important in modern electrical systems, especially with the increasing use of renewable energy sources like distributed generation (DG) and photovoltaic (PV) systems.

UPQC can also support power generation through DG sources and thereby enhance the overall efficiency and reliability of the system. In UPQC-DG systems, the DG sources are generally connected at the DC link of the Voltage Source Inverters (VSIs) applied in the series and shunt active power filters (APFs) [7], [8], [9]. This integration enables the generated power to be seamlessly enhanced to improve the compensatory process with overall performance in the UPQC system. DG sources provide supplementary power during supply disruptions or high demand periods. Local generation enhances the efficiency of the system by minimizing the losses due to transmission. Thus, the inclusion of DG sources enhances UPQC-DG systems, which are a holistic solution for the management of power quality in modern systems.

The performance of a UPQC system is highly dependent on its control system, particularly the PI controllers that regulate its operation. PI controllers are critical in controlling voltage sags, swells, and harmonics by maintaining a stable DC link voltage [10], [11]. This ensures consistent power quality and enables the system to respond quickly to disturbances, minimizing their impact on the electrical network. PI controllers are cost-effective compared to advanced control systems, as they are relatively simple to install and maintain. Their simplicity reduces system complexity, leading to lower design and operational costs. Moreover, PI controllers ensure a reliable system as it provides stable and predictable control behaviour, which is very important for the safety and reliability of the system. Being easy to use and dependable, PI controllers are preferred for UPQC-DG systems [12]. The problem, however, is that the optimization of PI controller parameters is challenging as it directly influences the performance of the system.

Traditional tuning schemes, including the trial-and-error or Ziegler-Nichols (ZN) approach [13], do not always result in optimal performance, especially in the dynamic and nonlinear environments. A major drawback in the ZN method is its tendency to introduce overly aggressive settings for PI parameters, which tend to cause serious oscillations while the system comes out of the transient condition. In spite of fast response, overshoots along with severe component strain may develop. Moreover, the ZN method does not account for system-specific dynamics or stability margins, which can lead to prolonged oscillations or instability in systems with high feedback loop delays or nonlinear characteristics. Conventional methods also depend on mathematical modelling, which may not accurately represent real-world system dynamics, and often require reduced output limits during tuning, posing risks to hardware safety.

Optimization techniques in complex systems have lately become popular in parameter tuning. Grey Wolf Optimization is one of the recent algorithms that have emerged as simple and flexible to provide optimal solutions to complex high-dimensional spaces. Grey wolves, having a natural hierarchy and hunting patterns, inspire the use of GWO in dynamic PI controller parameter adjustments.

The work presents a novel GWO-based online PI tuning approach for UPQC-DG systems in overcoming the deficiencies of traditional approaches. Unlike the traditional tuning approaches, GWO does not require mathematical modelling in great detail. It observes the system's performance in real time and continuously changes the PI parameters to cope with the time-varying condition of the system in real time. This way, the responsiveness of the system can be improved along with the capacity to cope with variation, ensuring optimum performance even at time-varying operating conditions.

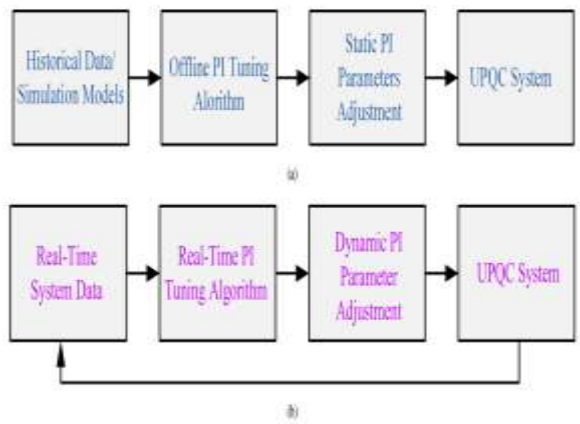

Figure.1 Approaches for tuning the proportional-integral (PI) controller (a) Traditional ZN Method (b) Proposed tuning method

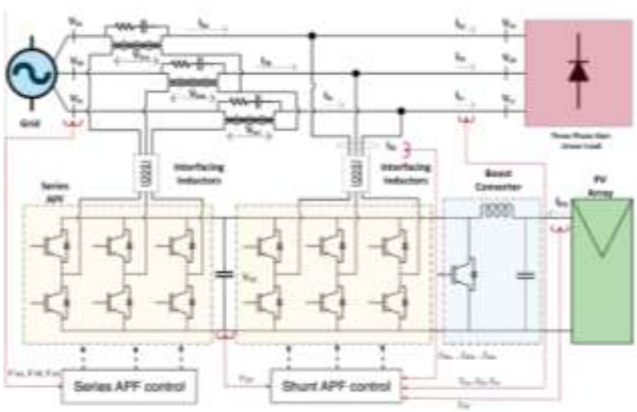

Figure 2 Power circuit diagram of UPQC-DG

Validation proves the proposed approach leads to improved resiliency and efficiency of UPQC-DG systems in real-world applications.

One of the significant contributions of this paper is to propose an online GWO-based PI tuning method that is to be implemented in real time, without needing mathematical modelling. With dynamic adaptation of PI controller parameters under intrinsic output limitation, it also ensures hardware safety. A PV-integrated UPQC-DG system has been simulated in real time for verification purposes; and its performance regarding maintaining the DC link voltage over various operational conditions has been phenomenal.

The paper consists of five primary sections. In Section II, UPQC configuration and construction are stated along with shunt and series APFs designing principles, that were introduced in Section I. Section III develops the PSO-Based PI Control in UPQC-DG Systems, state-of-the-art variations, and its application for the UPQC model. Artificial Neural Networks (ANNs) along with its analysis, will be presented in Section IV followed by conclusions stated in Section V.

II. UPQC-DG'S PHYSICAL CONFIGURATION

An innovative power electronic device called UPQC-DG was created to improve electrical systems' power quality (Fig. 2). It combines the capabilities of distributed generation (DG) units, including wind turbines, photovoltaic (PV) systems, or other renewable energy sources, with the features of a UPQC.

A series compensator (Series Active Power Filter) and a shunt compensator (Shunt Active Power Filter) coupled to the distribution system are the two primary components of the UPQC-DG system. Furthermore, the system comprises theThe shunt compensator is usually integrated with the DG unit. The distribution feeder and the series compensator are connected in series. It is made up of a coupling transformer, a voltage source inverter (VSI), and related control circuits. The load and the shunt compensator are linked in parallel. It consists of control circuits, a filter inductor or transformer, and a VSI.

The PV array will be equipped with the SPR-305E-WHT-D PV module. Ten photovoltaic modules are connected in series to create a string, and five of these strings are connected in parallel to create a 15.3 kW PV array with an output voltage of 547 V under typical temperature and irradiance circumstances. Through the use of a DC-DC boost converter, the PV unit is linked to the shunt compensator's DC link, supplying 38.25% of the load's total power (40 kW). The boost converter efficiently captures the maximum power from the PV source through MPPT control, which raises the voltage at the PV terminal to match the 700 V DC-link voltage. This enables the PV unit to directly power the load or the grid, aiding in the regulation of the DC link voltage and total quality of power. Reactive power injection or absorption by the shunt APF is directly impacted by the DC link voltage. The shunt inverter's kVA rating and maximum current are determined by the combined needs of PV active power and load reactive power.

To optimize the UPQC-DG system's ability to integrate dispersed generation sources and improve power quality, it is usually placed at key locations across the distribution network, such as the point of common coupling (PCC) between the utility and the customer.

A. SERIES APF CONTROL

A UPQC-DG system's series active power filter (APF) is in charge of adjusting for voltage disturbances such harmonics, sags, and swells. To provide precise and efficient voltage compensation, the control approach for the series APF frequently uses Unit Vector Template Generation (UVTG). To maintain a steady and distortion-free voltage supply to the load, the series APF creates a compensating voltage that is injected in series with the line voltage. But because of the PAC technique, the series compensator introduces voltage at a specific angle to supply some reactive power.

As a result, both APFs share responsibility for reactive power management. The maximum power angle (δM), which is established by using Equation 1, guarantees that the reactive power is distributed proportionately to the converter's VA rating.

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

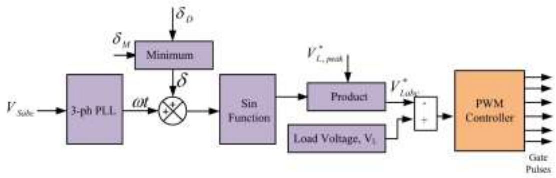

Fig 9.1 Series APF control.

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

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

Reactive power shared by series APF at which the system achieves the best power quality improvement is estimated as the desired power angle (δD), and it depends on the amount of load reactive power (QL), load active power (PL), and PV power (PPV). As seen in (2), the λ is the series APF rating divided by the sum of the series and shunt APF ratings.

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

The exact value of power angle, represented by δ, is determined by considering the minimum of δM and δD. In this manner, the system meets voltage and VA rating restrictions while achieving balanced reactive power sharing. The entire series APF control block is shown in Fig. 3. Unit Vector Template Generation is the name of the technique. A three-phase phase-locked loop

(PLL) is used to process the voltage source signal in order to create a three-unit vector signal. The extracted ωt is then added to the actual power angle (δ). According to the control figure, The load voltage signal (VL) is subtracted from the basic signal after the basic signal is multiplied by the peak voltage signal (V ∗ L,peak). To deliver the required switching pulse produced by the PWM controller, this procedure is repeated.

B. PV INTEGRATED WITH SHUNT APF CONTROL

A UPQC-DG's shunt APF is in charge of addressing current-related problems such load balancing, reactive power compensation, and harmonics. Synchronous Reference Frame-Power Angle Control (SRF-PAC) is a complex control method for the shunt APF that works particularly well in situations when photovoltaic (PV) generating is included into the DC connection. Power quality is maintained while the efficient use of renewable energy sources is made possible by this combination.

Figure 4 shows how the park transformation (in Eq. (3)) is used to convert the load currents (ILa, ILb, and ILc) from the three-phase stationary frame (a-b-c) to the synchronous reference frame (d-q-0). Using the output of the three-phase phase-locked loop in conjunction with the load voltage ramp signal, which is obtained to make sure the transformation is in sync

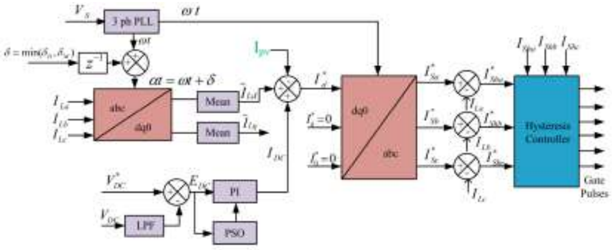

Fig 9.2 Shunt APF Control

(PLL) with the power angle, using the formula αt = ωt + δ.

The reference frame and the rotating reference frame of the fundamental frequency component are aligned by this change.

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

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 drive the PV array to the MPP, the MPPT controller modifies the boost converter's duty cycle. This integration contributes to a more sustainable and effective power system by optimizing the usage of renewable energy sources while also improving electricity quality.

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

Particle Swarm Optimization (PSO) is a population-based optimization technique inspired by the social behavior of bird flocking or fish schooling. Unlike other metaheuristic techniques that rely on complex operations like crossover and mutation, PSO is known for its **simplicity**, **computational efficiency**, and **minimal parameter tuning**, making it particularly suitable for real-time applications. Its **flexibility** and **robustness** have made it widely applicable in dynamic, nonlinear, and discontinuous optimization environments. Several PSO-based algorithms have been successfully applied to enhance control performance in a variety of power system applications. Table 1 highlights the inherent advantages of PSO over other optimization techniques, including its fast convergence rate, reliable global search capabilities, and consistent performance across different problem domains.

PSO optimizes a problem by iteratively improving a set of candidate solutions, referred to as particles, based on a defined objective function. Each particle adjusts its position in the search space by learning from its own best-known position and the best-known positions of its neighbors, which helps maintain a balance between **exploration** and **exploitation**, ultimately converging to the global optimum.

In the context of PI controller tuning for UPQC-DG systems, PSO begins with an initial swarm of particles, where each particle represents a potential solution defined by a pair of proportional (K_p) and integral (K_i) gains. The fitness of each particle is evaluated using an objective function, typically the **Integral of Time-weighted Absolute Error (ITAE)**, which quantifies the difference between the actual and desired DC link voltage over time. Lower ITAE values correspond to better-performing PI parameter sets.

Here, w is the inertia weight balancing exploration and exploitation, c_1 and c_2 are acceleration coefficients, and r_1 and r_2 are random values in [0,1].

During real-time tuning, each candidate PI controller is tested in the UPQC system, and its performance is measured using the ITAE criterion. Based on this feedback, particles adjust their positions, iteratively improving the controller performance until the DC link voltage is effectively stabilized.

The proposed PSO-based PI tuning strategy enables the UPQC-DG system to **adapt dynamically** to changing load and source conditions. This real-time optimization enhances power quality, ensures robust disturbance rejection, and enables seamless integration of distributed generation resources. The simplicity and efficiency of PSO make it an attractive solution for optimizing complex control systems in real-time environments.

IV. Artificial Neural Networks (ANNs)

Artificial Neural Networks (ANNs) are a fundamental aspect of artificial intelligence, inspired by the structure and functioning of the human brain. They consist of multiple layers of artificial neurons, which are computational units that process information. The architecture of an ANN typically includes an input layer, one or more hidden layers, and an output layer.

Each neuron receives input signals, processes them using weighted connections, applies an activation function to introduce non-linearity, and passes the result to the next layer. The working of an ANN involves two main phases: forward propagation and backpropagation. In forward propagation, the input data is passed through the network layer by layer, where each neuron applies a mathematical function to generate an output. The final layer produces the predicted result, which is then compared to the actual output using a loss function to determine the error. In the backpropagation phase, the network learns by adjusting the weights of connections using optimization algorithms like gradient descent. The gradients of the loss function with respect to each weight are computed using the chain rule, and the weights are updated in a direction that minimizes the error. This iterative learning process continues until the model achieves a satisfactory level of accuracy. ANNs can be classified into various types based on their architecture and application. Feedforward Neural Networks (FNNs) have unidirectional connections and are commonly used for classification and regression tasks. Convolutional Neural Networks (CNNs) are specialized for image processing, using convolutional layers to detect spatial patterns.

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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.

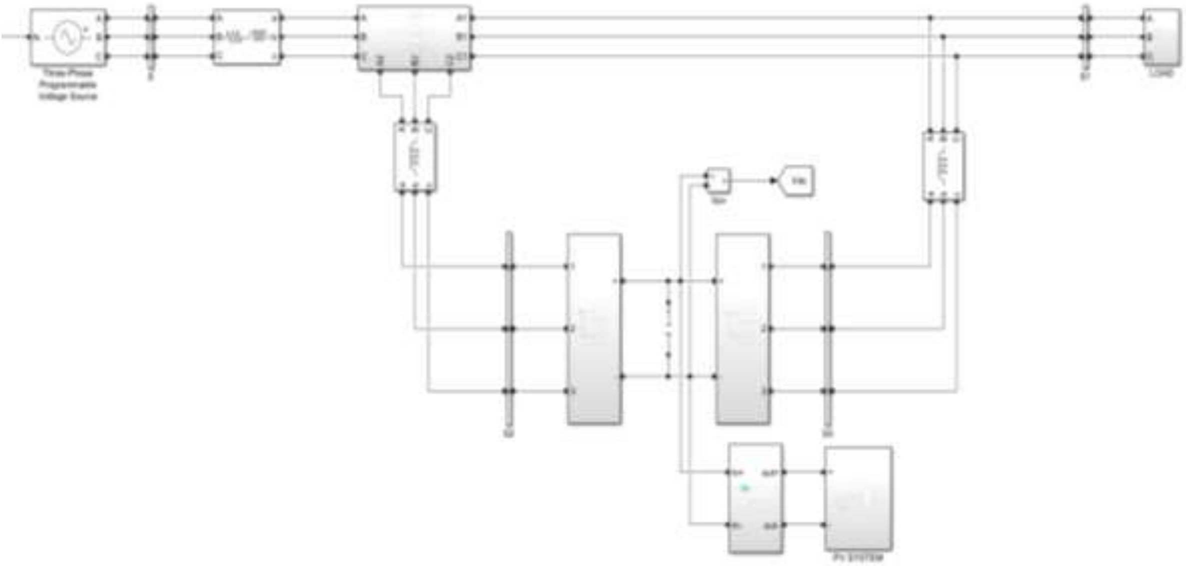

Fig 10: Ann circuit diagram of UPQC-DG

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.

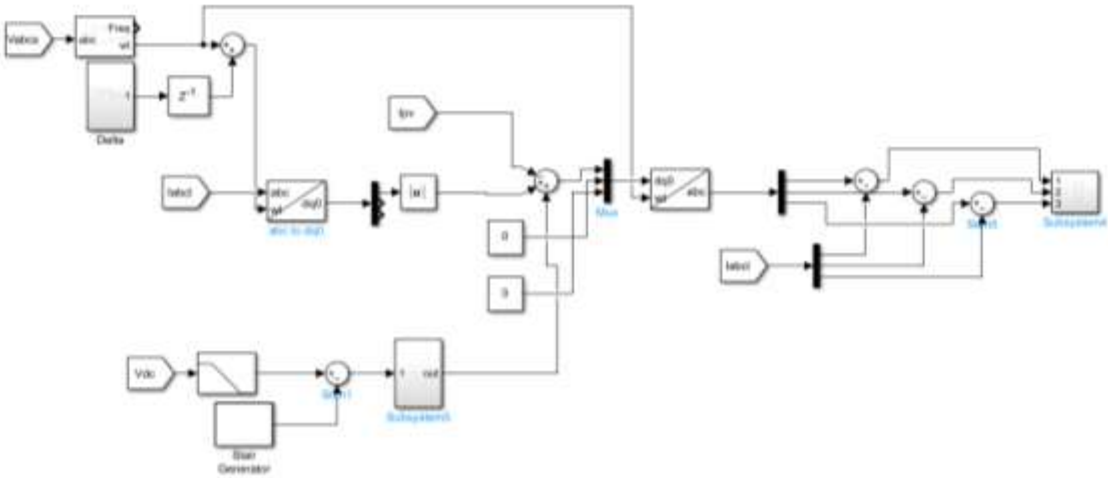

Fig 11: Artificial neural network controller

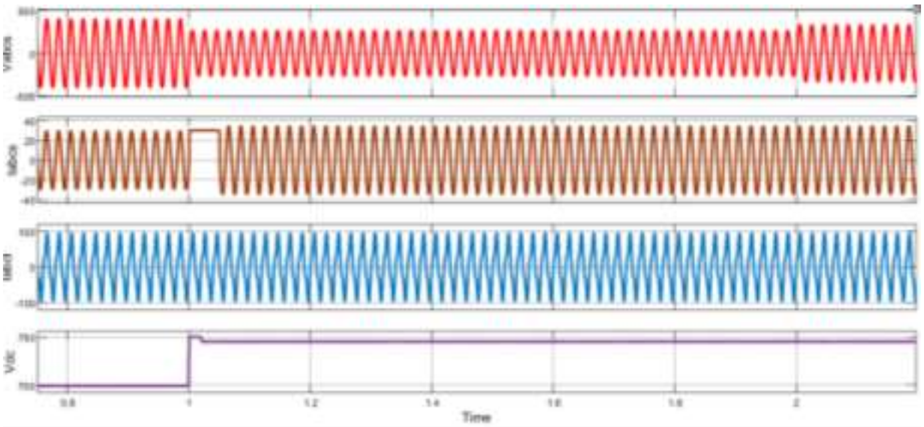

Fig 12: a) Single-phase voltage source input b) Single-phase current source input c) Single-phase load current d) DC voltage

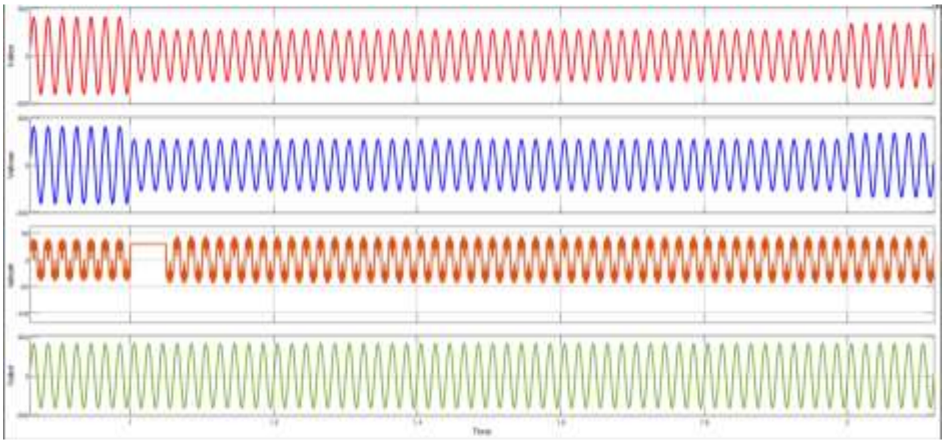

Fig 13: a) Single-phase voltage source input b) Series inverter single-phase voltage c) Shunt inverter single-phase current d) Single-phase load voltage

Despite their powerful capabilities, ANNs have challenges such as high computational requirements, large data dependency, and interpretability issues, often making them function as "black boxes" where decision-making is not easily explainable. Researchers are working on solutions like Explainable AI (XAI) to improve the transparency of neural networks, neuromorphic computing to make them more efficient, and quantum AI to enhance their computational power. With continued advancements, ANNs are expected to drive further innovations in artificial intelligence, leading to smarter automation, real-time decision-making, and breakthroughs that bring machines closer to human-like intelligence.

V. FINAL RESULTS

Significant improvements in the DC link voltage control performance were shown when PSO-based online PI tuning was applied in a UPQCDG. With lower ITAE values, less oscillations, and quicker settling periods, the PSO-tuned PI controller outperformed the conventional Ziegler-Nichols (ZN) technique. The PSO-based
In contrast to the ZN-tuned parameters of kp = 3.15 and ki = 350, which produced an ITAE of 4.82%, the technique obtained PI values of kp = 2.376 and ki = 175, yielding an ITAE of 2.38%. Using the ZN method, the load voltage has a THD of 4.22% while the source current's THD is 10.3%. Nevertheless, the THD is reduced to 3.21% for the load voltage and 7.44% for the source current when the online PSO approach is used. Reduced THD and better power quality are the outcomes of the PSO-tuned system's lower harmonic content in both source current and load voltage.
These results highlight how well PSO works to dynamically optimize PI controller parameters, guaranteeing a more responsive and stable control system under a range of operating circumstances.
In addition to significantly lowering the overshoot value (from 190 V to 40 V), the PSO-based approach also decreases oscillations in the DC link voltage response,

resulting in a 16.03% reduction in voltage ripple. A more stable and dependable power quality conditioner that can continue to operate at peak efficiency under a range of operating circumstances is the end consequence of these enhancements. The PSO algorithm improves the UPQC-DG system's stability and responsiveness by dynamically adjusting the PI parameters. This guarantees higher power quality and lowers the possibility of hardware stress from excessive voltage overshoot and oscillations. These discoveries have significant ramifications for the field of control systems and power quality management.

The PSO-based approach's proven capacity to adjust PI controllers in real-time suggests that UPQC-DG systems can attain greater efficiency and dependability. By dynamically refining the PI controller's parameters, the PSO-based tuner removes the need to loosen integral bounds, preventing integrator windup and improving control performance overall. In distributed generating systems, this dynamic tuning capability is essential for reducing the effects of disruptions and preserving peak performance, which improves the overall stability and calibre of power delivery.

Additionally, a lower ITAE indicates better resilience and long-term performance, both of which are essential for maintaining steady power quality in the face of shifting loads and environmental factors. In order to compare their performance with PSO and possibly create hybrid approaches that combine the advantages of several approaches, future research can further explore the integration of other sophisticated algorithms, such as Artificial Intelligence (AI) or Neural Network-based Algorithms (ANN).

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