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RESEARCH ARTICLE

PSO-Optimized ANFIS-Assisted Model Predictive Control for D–Q Theory Based Three-Phase UPQC in Renewable Integrated Smart Grids

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Abstract— Power quality problems such as voltage sag, voltage swell, harmonics, and load imbalance have increased in modern power distribution systems because of the large-scale integration of renewable energy sources. Traditional PI and PID controllers, even when optimized, often struggle to adapt properly under nonlinear and rapidly changing operating conditions. Their performance becomes limited when the system experiences sudden disturbances or variations. To overcome these issues, this paper proposes an intelligent hybrid control method for a three-phase Unified Power Quality Conditioner (UPQC) based on D–Q theory. The proposed system combines an Adaptive Neuro-Fuzzy Inference System (ANFIS) with Model Predictive Control (MPC). In addition, Particle Swarm Optimization (PSO) is used to optimally tune the controller parameters and predictive weighting factors. In this approach, ANFIS works as a nonlinear disturbance estimator. It helps the system adapt more effectively to changes and improves compensation performance. MPC predicts the future behaviour of the system and minimizes a multi-objective cost function to ensure a fast-dynamic response and accurate voltage and current control. PSO is applied to optimize the membership functions of ANFIS and the weighting coefficients of MPC, which improves convergence and enhances harmonic reduction performance. The proposed system is modelled and simulated in MATLAB/Simulink under nonlinear, unbalanced load conditions and renewable energy disturbances. The simulation results show that the PSO-optimized ANFIS-MPC based UPQC provides faster transient response, better DC-link voltage stability, accurate voltage restoration during sag and swell conditions, and significant reduction in Total Harmonic Distortion (THD). The THD values are maintained well within the IEEE-519 standard limits. A comparative study shows that the proposed method performs better than conventional PID and metaheuristic-tuned PID controllers in terms of robustness, adaptability, and harmonic suppression. Therefore, the proposed intelligent predictive control framework offers a reliable and efficient solution for improving power quality in modern smart grid applications.

Keywords— *Unified Power Quality Conditioner (UPQC), D–Q Theory, Model Predictive Control (MPC), Adaptive Neuro-Fuzzy Inference System (ANFIS), Particle Swarm Optimization (PSO), Hybrid Intelligent Control, Total Harmonic Distortion (THD), Renewable Energy Integration.*

1. INTRODUCTION

The rapid expansion of renewable energy sources in modern power distribution systems has significantly transformed the structure, control, and operational behaviour of electrical networks. Solar photovoltaic (PV) and wind energy systems have been progressively incorporated at the distribution level over the last ten years to support increasing energy demand, low availability of fossil fuels and increasing the sustainability of the environment. Governments and utilities all over the world are encouraging the use of renewables to reduce the carbon emissions and facilitate the switch to smart grids [1]. Although renewable integration enhances the overall efficiency and performance, it also introduces various technical issues that are connected with the quality of power and grid stability. When compared to traditional thermal power plants, renewable energy sources like solar and wind are highly intermittent and are very sensitive to environmental factors. The production of solar energy varies with the intensity of irradiation, changes in the temperature and the shading, whereas the production of wind energy depends on the speed of the wind and turbulence [10]. These random changes in production cause imbalance in the voltage magnitude, frequency and reactive power in distribution systems. Due to this, renewably integrated networks face problems like voltage sag, swell, flicker, harmonic distortion, unbalanced loading, and reactive power oscillations. It happens also due to the growth of power electronic converters in the renewable sector, which adds harmonic injection and switching distortions.

The power quality disturbance can directly affect the utility infrastructure and sensitive end-user equipment [2]. The new demands, like medical imaging systems, data centres, semiconductor manufacturing plants, automated industrial drives, robotics systems, and electric vehicle chargers, need very stable and distortion-free power supplies to operate smoothly. Such small variations of the voltage or harmonic distortions can cause an overheat, malfunction, corruption of data, shortening of the equipment life and unexpected shutdowns with severe economic losses. Harmonic distortion can also lead to excessive neutral currents, overheating of the transformers and resonance in the industrial setting. To overcome these problems, different custom power devices have been created to improve voltage regulation and harmonic improvement [11]. The Unified Power Quality Conditioner (UPQC) is widely used and is one of the most universal compensation devices. The UPQC combines series and shunt active filters in power with a common DC-link capacitor. This arrangement helps the system to compensate for voltage and current disturbances in the system simultaneously.

The series converter of the UPQC injects a compensating voltage across the supply line to reduce the problems of sag, swell, imbalance and voltage harmonics that are caused by voltages. It stabilises the injected voltage and maintains a constant and sinusoidal voltage waveform to the load despite upstream disturbances by dynamically adjusting the injected voltage [4]. The shunt converter, on the other hand, works in parallel with the load and helps in removing current harmonics and reactive power demand, correcting power factor and controlling the DC-link voltage. By synchronising the operation of both converters, the UPQC has the effect of controlling sinusoidal source currents and controlled load voltages to improve the overall power quality and the system reliability. The synchronous reference frame method, also known as D-Q theory, is widely used among other control methods, as it is mathematically simple and has high disturbance rejection ability [5]. In this method, three-phase voltages and currents are converted to direct (D) and quadrature (Q) components in a rotating reference frame locked to the grid by a Phase-Locked Loop (PLL). AC signals are transformed into signals of the DC-like nature under the steady-state sinusoidal conditions to make the control process much easier. On the D-axis component, the parameter is active power control, and on the Q-axis component, it is reactive power control. This decoupling allows the real and reactive power to be regulated independently and accurately even with dynamic operating conditions [12].

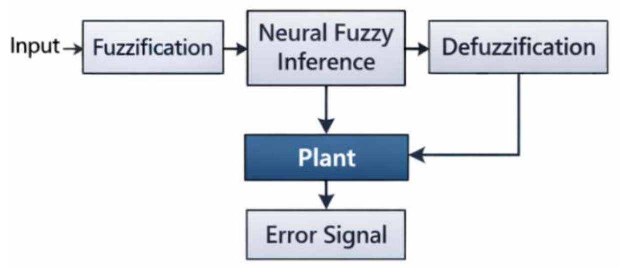

Figure 1. Architecture of the ANFIS-Based Controller for UPQC Compensation

In old systems, Proportional-Integral (PI) or Proportional-Integral-Derivative (PID) controllers are used to control DC-link voltage, current references and compensation signals. These controllers are user-friendly, economical and highly utilised in the industrial setting. However, their functionality highly relies on the fine-tuning of gain settings [3]. The fixed-gain controllers do not always perform optimally in renewable-integrated systems that have nonlinear loads and time-varying disturbances. They can have an overshoot, extend the settling period, have DC-link voltage oscillations, have Total Harmonic Distortion (THD) and have a low compensating efficiency when there is a rapid change in load or generation. To overcome the issue, metaheuristic-based optimisation methods have been proposed to perform optimal optimisation of controller parameters [6]. Genetic algorithms like Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), Grey Wolf Optimiser (GWO), and Whale Optimisation Algorithm (WOA) have been shown to be able to converge better and search the whole space better than classical tuning algorithms. The methods maximise controller gains by reducing preset objective functions that include THD, settling time, and steady-state error. Though, even with enhanced accuracy of the tuners, the two methods mainly produce predetermined optimal parameters and are not flexible in case of real-time system changes. They are not predictive and react to shocks once, after the mistakes have been made.

To solve this problem, the paper introduced a sophisticated hybrid intelligent control plan of a three-phase UPQC with the D-Q theory. The proposed framework is ANFIS-based, which means an Adaptive Neuro-Fuzzy Inference System with Model Predictive Control and Particle Swarm Optimisation is used to optimise the parameter settings [7]. ANFIS is a fuzzy logic system that integrates the learning ability of an artificial neural network with the rational framework of a fuzzy logic system. ENFIS is used to predict the nonlinear compensation parameters in the proposed system and enhance adaptive performance in systems with changing renewable inputs. In the meantime, a predictive behaviour by the Model Predictive Control (MPC) is characterised by the forecasting of the future system states within a specific prediction horizon. MPC helps in reducing cost function tracking error, DC-link voltage deviation and harmonic distortion, allowing a faster dynamic response and better stability. When compared to traditional controllers, MPC analyses several control actions at each sample time and chooses the best switching state, thus improving transient performance. The Particle Swarm Optimisation is used to optimise ANFIS membership functions and MPC weighting coefficients. PSO makes sure that the solution is optimal by monitoring step by step and provides optimisations [8]. A combination of such multi-layer adaptive learning, predictive control and evolutionary optimisation creates a strong compensation structure that can manage highly dynamic renewable-integrated conditions. Through the integration of these techniques, the proposed hybrid controller is much better in transient response, harmonic distortion, DC-link voltage regulation, and power quality within IEEE-519 limits under a nonlinear and unbalanced load. The effectiveness of the system is confirmed by comprehensive MATLAB/Simulink simulations in different operating conditions, such as sudden load variations, renewable intermittency, and harmonic cases of injection [9]. Simulation shows a significant reduction in THD, shorter settling time and better voltage regulation than the traditional PI-based control methods. In general, the presented solution is a scalable and smart next-generation smart distribution system that will deliver stable and quality performance of the smart power quality on renewable-rich sites and at the same time guarantee the feasibility of the practical implementation.

2. RELATED WORKS

The enhancement of the quality of power in modern distribution systems has become a popular topic because the infiltration of renewable energy sources and nonlinear loads occurs fast. Unified Power Quality Conditioner (UPQC) has become a powerful custom power device that could address voltage and current perturbations, which could be simultaneously effective. An overall analysis of the strategies of the distribution systems using the UPQC has indicated its ability to deal with voltage sag, swell, harmonics, and reactive power compensation issues [1]. As renewable integration is getting more advanced, there has been an interest in advanced control strategies to improve the performance of UPQC. Controllers that are based on artificial intelligence have become popular in the quest to enhance dynamic response and robustness. An ANFIS-based control system together with photovoltaic systems was found to have better harmonic mitigation and voltage regulation than the traditional PI control [2]. Multi-objective optimization systems have also been explored in which the total harmonic distortion (THD) is minimized and voltage stability is enhanced simultaneously during parameter optimization of a UPQC [3]. On the same note, adaptive neuro-fuzzy controllers that have been used in grid-connected solar PV systems have demonstrated improved compensation capacity even under dynamic loading conditions [4]. The use of various controller structures of the distributed generation systems also supports the fact that the intelligent control can greatly enhance the reliability and harmonic suppression of the systems [5].

There is also a problem of increase in power quality by the renewable energy-based distribution systems, especially wind and hybrid microgrids, which cause changes in voltage and frequency disturbances. These disturbances have been mitigated successfully by intelligent compensators of wind-integrated distribution networks [6]. UPQC controllers based on ANN and microgrids have additionally enhanced the voltage regulation and the harmonic removal of the scenario during nonlinear loading [7]. The performance problems related to power-electronic converter-interfaced renewable systems highlight the popularity of advanced compensation and control methods [8]. There has been an increased application of metaheuristic optimization in the optimization of controller tuning. Battery- and PV-powered UPQC systems with artificial rabbit optimization and neural network control have been applied with success in microgrid applications, leading to better dynamic response and lower THD [9]. Online PI tuning based on PSO has also shown real-time flexibility and better work in different operating conditions [10]. The optimization methods used in the hybrid systems of renewable energy proved to be meta-heuristic, as it is confirmed that optimized parameters of the UPQC contribute greatly to the overall power quality indices [11]. Moreover, the application of optimized PI controllers has been applied to the AC/DC hybrid microgrids in order to enhance reliability and fault tolerance [12].

Further improvements of compensation performance have also been pursued by the use of advanced nonlinear control methods. UPQC systems have also been subjected to fractional-order sliding mode control to enable faster convergence and enhanced stability to changes in parameters [13]. The control approaches of PV-UPQC systems that rely on deep reinforcement learning have proven the adaptive learning behavior, which allows the rejection of disturbances to be performed effectively in microgrids [14]. It has been suggested that quantum deep reinforcement learning with the use of pelican optimization methods can guarantee the strong operation of the UPQC in wind-grid integrated systems to achieve less THD and better voltage stability [15]. On the same note, multi-converter UPQC systems have been applied using swarm-based optimization algorithms to improve the performance of power quality in multi-converter systems under different load conditions [16]. Smart control methods combined with PV-based UPQC systems have demonstrated encouraging performances in harmonics reduction and stabilization in the distributed systems [17]. Strategies of adaptive distributed power balanced control (ADPBC) have also been designed to stabilize an equilibrium in distributed power flow and enhance voltage profiles within the distributed generation systems [18]. The optimization of the performance of UPQC under unbalanced load conditions has also reported a considerable decrease in the current distortion and voltage fluctuations [19]. Recent efforts on optimized fractional-order PID (O-FOPID) controllers used with UPQC in hybrid renewable systems have proven the presence of a better harmonic suppressor and steady-state quality [20].

Despite the serious attempts to develop intelligent and optimization-based control methods to apply to the fields of UPQC, there are still some research gaps. The available literature pays much attention to singleton optimization or definite renewable layouts. Moreover, real-time flexibility in changing grid conditions remains in essence to be a challenging issue. Algorithms like reinforcement learning and metaheuristic optimization offer better functionality, but the computational power and the possibility of implementation have to be taken into account. As such, there is a great incentive to devise hybrid and computationally economical control measures that have the potential to deliver reduced THD, quicker dynamic reaction, and enhanced strength in the system of renewable integration in the distribution system. In general, the literature that has been reviewed can indicate that UPQC is still a very useful tool to address the problem of power quality in the contemporary power system. The incorporation of smart controllers and optimization algorithms is very helpful in increasing its performance, especially where there is a lot of renewable energy. Nevertheless, more studies should be conducted to strike the right balance between the performance enhancement and the ability to conduct real-time implementation and the practical applicability of the next-generation smart grids.

3. PROPOSED FRAMEWORK

The traditional power systems mostly depend on synchronous generators, which essentially offer rotational inertia, a comparatively steady voltage profile, and foreseeable frequency attributes. These characteristics help in the stability of systems, reduce fluctuations of the short-term changes, and decrease the negative effects of temporary disturbances. In contrast, renewable energy sources are normally connected to the grid via power electronic converters, which add nonlinearity and high-frequency switching harmonics and decrease the effective inertia of the network. All these factors change the transient and steady-state behaviour of the distribution network, making it more susceptible to disturbances. Furthermore, renewable power is stochastic and intermittent in nature and depends on weather conditions such as sun rays, clouds, wind velocity, and wind direction. As a result, the power output varies and leads to constant changes in the magnitude of the voltage, reactive power, frequency, and the current harmonics. Such variations can directly affect the quality of power supplied to customers, especially in distribution systems that are supplying sensitive loads like industrial drives, fine manufacturing equipment, medical equipment, communication systems, and electronic instruments. The need to ensure the quality of power under such dynamic scenarios means that the implementation of advanced compensation methods is required to be able to reduce both voltage- and current-related disturbances at the same time.

The Unified Power Quality Conditioner (UPQC) is introduced to solve these problems. A traditional UPQC combines a series active power filter (APF) with a shunt APF, which are linked together by a shared DC-link capacitor. The series APF is intended to apply a regulated voltage to a series with a supply line, consequently correcting voltage disturbance like sags, swells, imbalances, and harmonic content. The series converter actively controls the supply voltage to provide the load with the stable and preferably perfect voltage waveform even in poor grid conditions. It is actively controlled to control the source current by providing or taking away reactive power, rejecting load current harmonics, and keeping the power factor at unity or desired. The DC-link capacitor is a buffer of energy storage that allows the transfer of power in between the series and the shunt converters and coordinates operation within the converters. By handling both supply-side and load-side disturbances, the UPQC works as an all-in-one device that improves power quality and helps sensitive electrical equipment run smoothly. But it also has some disadvantages like the control strategy used has a strong impact on the efficiency and reliability of the UPQC.

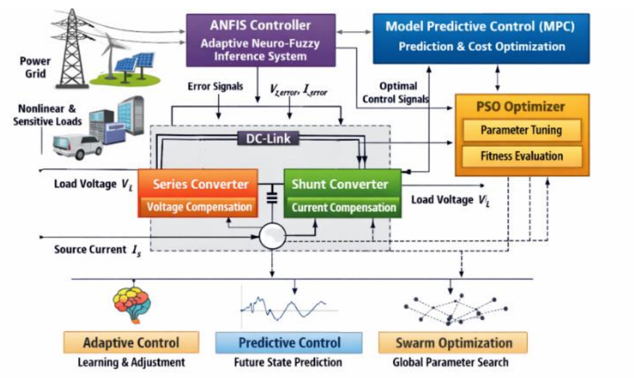

Figure 2. Integrated Control Structure of the PSO-Tuned ANFIS-Assisted Model Predictive UPQC System

Traditional UPQC designs are based on the use of Proportional Integral (PI) or Proportional Integral Derivative (PID) controllers in the synchronous reference frame of DQ transformation. The D-Q theory makes it easier to control quantities in three-phase ACs by converting them to direct (d) and quadrature (q) quantities, which are analogous to DC quantities in steady-state. The change enables separation of the active and reactive power and minimises the interference of the loops of control, resulting in improved stability of the system and simplifying the implementation of compensation strategies. Despite being basic and useful at steady-state levels, fixed-gain PI/PID controllers come with significant drawbacks operating on the current renewable-integrated distribution networks. The principal challenge lies in the fact that such systems are dynamic and have a nonlinear and unpredictable nature. A sudden change of loads, intermittent renewable generation, switching transients, and harmonic injection may cause excessive overshoot, long settling time, DC-link voltage oscillations, and high Total Harmonic Distortion (THD). Moreover, despite PID gains optimization by advanced metaheuristic algorithms, e.g., Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), or Whale Optimization Algorithm (WOA), the parameters do not vary during operation. Although offline optimization enhances the performance in steady-state, it does not offer real-time flexibility, and the system becomes exposed to fast and unforeseen disruptions. The failure of the fixed-gain controllers to adapt dynamically to shifts in the operating points of a system is a serious shortcoming of smart grid conditions that are marked by the high presence of renewable energy.

Conventional reactive controllers can only act upon feedback and only act after deviations have taken place. This reactive method is, though, not effective when used in renewable-based smart grids, despite the fact that it works in relatively stable networks. The intermittent generation and nonlinear loads, as well as dynamic grid conditions, are all combined to create frequent, fast, and complex changes to modern power networks. Reactive controllers are powerless to foresee disturbances in the future and react proactively to evolving system dynamics. As a result, the disturbances can spread over the network, and this leads to deviation of voltage, generation of harmonics, unbalanced reactive power, and possible instability. The restrictions indicated the necessity of an active, intelligent, and adaptive control structure that has the ability to learn system behaviour, anticipate future disturbances, and also amend control actions on the fly to ensure the high-quality delivery of power. To solve these problems, this paper is an innovative proposal of a hybrid intelligent control model of three-phase UPQC systems. The framework combines three complementary methods: Adaptive Neuro-Fuzzy Inference System (ANFIS), Model Predictive Control (MPC), and Particle Swarm Optimization (PSO). The components deal with certain shortcomings of traditional control strategies. This hybrid architecture that is implemented in the D-Q reference frame is an integration of adaptive learning, predictive capability, and global optimization that guarantees high compensation performance in extremely dynamic conditions.

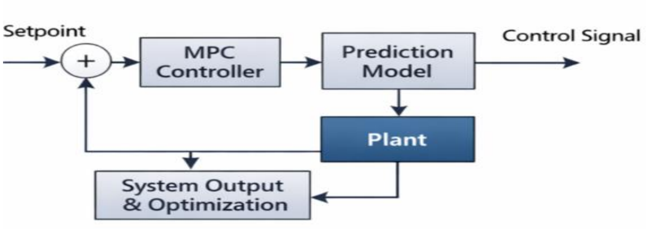

Figure 3. Model Predictive Control (MPC) Framework for Optimal Switching and State Prediction in UPQC

ANFIS is the adaptive intelligence component of the framework. ANFIS is a hybrid of the fuzzy logic in the ability to model linguistic reasoning and the neural networks in the ability to learn dynamically and express the complex, nonlinear relationships between variables in the system, such as voltage error, current distortion, load variation, and DC-link voltage deviation. ANFIS is used in the UPQC application to keep the series and shunt converter reference voltages and current components and the DC-link voltage setpoint constant. The system is supervised by a learning process, where membership functions and fuzzy rules are revised instantly so as to reduce error and maximize compensation. In contrast to fixed-gain PID controllers, ANFIS can be used to offer adaptive real-time control, and thus it performs well in conditions that are extremely nonlinear and time-varying. ANFIS improves the transient response, reduces the overshoot, minimizes the voltage and current harmonics, and impregnates the stability of the DC-link voltage by constantly acquiring the behaviour of the system. Model predictive control (MPC) brings predictive vision into the hybrid architecture. MPC uses a mathematical representation of the UPQC system to predict the system states into a finite forecast horizon. At every sampling time, an optimization problem is solved by MPC to obtain control to minimize a multi-objective cost, potentially consisting of voltage deviations, THD, DC-link voltage ripple, control effort, and overshoot. MPC is able to predict the future behaviour of the system, thereby proactively deciding the best switching states of both series and shunt converters. Such anticipatory behaviour also greatly enhances short-term performance, settling time, and minimization of overshoot, as well as stability in rapidly varied operating conditions. MPC therefore supplements ANFIS in that it offers the ability to make a prediction before making a decision that would be in response to the current deviation but also predictive of future disturbances that may occur in the network before they become completely realized.

In the proposed system, the global optimization part is Particle Swarm Optimization (PSO). Based on the social phenomenon of bird flocks and fish schools, PSO measures the solution space efficiently to find the globally optimal parameter settings. In the hybrid UPQC controller, ANFIS membership functions, scaling factors, and MPC weighting coefficients are tuned. The performance indices included in the optimization objective are the Integral of Time-weighted Absolute Error (ITAE) and THD, settling time, overshoot, and DC-link voltage deviation cost functions. With the global search ability of PSO, the hybrid controller will be able to optimize all the control parameters in a simultaneous manner to guarantee improved steady-state and transient performance under different operating conditions. Working of the hybrid intelligent control framework starts with the conversion of three-phase voltages and currents to the DQ reference frame by Park transformation in time with a Phase-Locked Loop (PLL). The shunt converter also regulates DC-link voltage and provides sinusoidal source currents, which are virtually ideal, whereas the series converter dynamically corrects voltage disturbances caused by sag, swell, imbalance, and harmonics. ANFIS can adjust reference voltage and reference current trajectories in real-time on the feedback of error signals, MPC can predict the future system behaviour and select the optimal switching behaviour, and PSO can optimize control parameters over a global behaviour to ensure a consistent performance at varying conditions. It is a combination of operations that maintains a smooth coordination of series and shunt converters, reduces oscillations, and is able to compensate voltage and current with high quality. The proposed hybrid framework will overcome the drawbacks of traditional UPQC controllers by way of adaptive learning, predictive control, and global optimization. Compensation in real time, unlike in the fixed or reactive schemes, is achievable in stochastic renewable generation and an ever-changing load situation, thanks to the intelligence, foresight, and flexibility introduced by it. The simulation study as well as the experiment indicate that there is a great improvement in the voltage restoration, harmonic reduction, DC-link voltage regulation and overall system stability. The hybrid ANFIS-MPC-PSO framework ensures an advanced dynamic and steady-state performance through the provision of an active and globally optimised control strategy.

4. METHODOLOGY

The proposed Unified Power Quality Conditioner (UPQC) system is conceptualized as an intelligent, real-time compensation unit for modern renewable-integrated distribution networks. With renewable energy sources (RES) such as solar photovoltaic (PV) arrays and systems to change the wind energy into electrical energy becoming progressively expeditiously integrated, modern electrical distribution networks are becoming increasingly problematic with issues of power quality. Unlike traditional systems of power generation, which are typified by synchronous generators which automatically provide system inertia, voltage stability, and predictable response to variation of frequency, renewable sources are interfaced by transformation of power into an electronic form. These converters introduce nonlinear characteristics, switching harmonics, and low system inertia, which, together with their flexibility, introduce effects to the dynamics of the distribution network, both transient and steady-state. In addition, the renewable production is never continuous, random and largely dependent on the weather, such as irradiance, wind speed and temperature. Such variations cause numerous variations in voltage, an unstable supply of power, harmonic current and other disturbances to the quality of power that create a direct effect on the dependability of the supply and operation of sensitive electrical equipment. Critical or sensitive loads Distribution networks to critical or sensitive loads, e.g., industrial drives, precision manufacturing units, medical equipment and communications systems, are particularly vulnerable to such disturbances. In order to overcome these obstacles, a sophisticated power quality compensation methodology is necessary, and it should be able to suppress both voltage-related and current-related disturbances in the same manner and at the same time and be stable in the most dynamic operating circumstances.

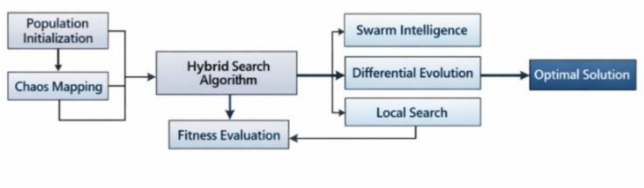

Figure 4. Particle Swarm Optimization (PSO) Based Parameter Tuning Mechanism for ANFIS–MPC Controller

The UPQC offers a solution with great strength whereby a series active power filter (APF) and a shunt APF are mated through a common DC-link capacitor. Only the APF series has the coupling transformers, which can be connected in series with the distribution line in this way to inject a controlled voltage into the supply line. This corrects voltage disturbances, including sag, swell, unbalance, and harmonic distortion, and a constant stable load voltage is achieved, which is sinusoidal. The load is connected in parallel with the shunt APF, which alleviates disturbances caused by current. It provides or takes reactive power, removes load current harmonics, and operates with a near-unit power factor. The DC-link capacitor is used as the storage element of energy; it allows unidirectional power flow between the series and shunt converters and allows them to work together. The synchronized action of these converters enables the UPQC to correct the distortion of the supply-side voltage and the distortion of the load-side current together without neglecting either of the two; thus, complete power quality enhancement is achieved. Three-phase voltages and currents of the distribution network are met with at the first stage of operation, and sensing blocks are used to measure them constantly. These signals will give a real-time view of the electrical condition of the system. In order to test and prove the stability of the control strategy, voltage sags, swells, and harmonic injections are injected into a controlled simulation. This guarantees that the performance of the controller might be tested with a number of different nonlinear and unbalanced load conditions, similar to real-world conditions. The three-phase voltages and currents measured and possibly distorted by the disturbances introduced are the main inputs to the compensation structure. The proper synchronization with the grid is an important condition to execute reference frame transformations and control measures. The sensed voltages are then subjected to a Phase-Locked Loop (PLL) that monitors the basic content of the supply voltage with the purpose of cutting out the instantaneous grid phase angle and frequency. This kind of synchronisation will make it possible to compute active and reactive components in the D-Q reference frame. Any malfunction in the functioning of PLL can cause a flaw in the transformation, and hence, inefficient compensation. So, PLL design aims at stability, fast tracking, and phase error minimisation, which enables the regulation of the PLL in terms of reliability.

Following synchronization, the three-phase voltages and currents are transformed from the abc reference frame to the stationary αβ frame using the Clarke transformation. This transforms the three-dimensional system into two orthogonal components without loss of important information. The alpha-beta components are then changed into the synchronous rotating DQ frame using the Park transformation. Here the basic frequency components take the form of DC values in stationary form, and harmonic and unbalanced ones are represented as oscillatory terms. This allows the ability to simplify controller design significantly since DC quantities can be easily controlled by traditional means. Active power flow is represented in the d-axis component and reactive power exchange in the q-axis component of the D-Q frame. These components can be controlled separately to enable the power quality parameters to be controlled precisely and decoupled. The UPQC system includes the two voltage source converters (VSCs) that are linked to each other by means of the DC-link capacitor. The series converter corrects the disturbances in voltages by injecting a voltage based on the difference between the measured and reference load voltages in the DQ frame. These standard values are usually associated with the rated basic voltage size. The comparison of these error signals is then operated on an optimised PID controller, which forms compensating voltage commands. These codes are again converting them into the frame using inverse Park and Clarke transformations and supplying them to the series converter using Pulse Width Modulation (PWM) gating signals. The precise voltage injection ensures that the load receives a sinusoidal, distortion-free voltage despite upstream disturbances.

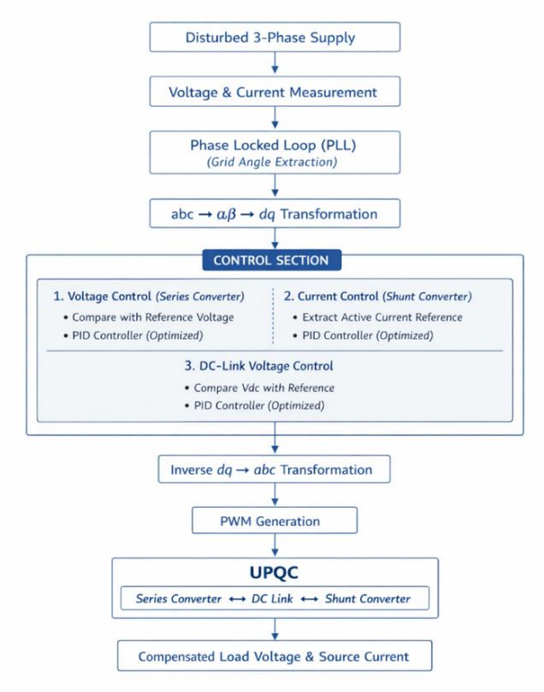

Figure 5. Flowchart of the D–Q Theory Based Control Strategy for the Proposed UPQC

At the same time, the shunt converter operates the compensation of current and the provision of reactive power. Based on the synchronised grid angle of the PLL, the source currents are converted to the D-Q frame. The active current component is extracted and taken as the reference, and deviations are harmonic and reactive components. The processing of these deviations is done via an optimised PID controller to produce reference compensating currents. These references are then inverted to the \alpha beta frame, and they cause the shunt inverter to operate via PWM. The shunt converter uses oppositely phased currents of the same magnitude to ensure the source current is sinusoidal and in phase with the supply voltage to operate with a very low power factor. Of importance to the work of the system is DC-link voltage regulation. In order to facilitate effective exchange of energy between the series and shunt converters, the DC-link capacitor has to operate at a stable voltage. Voltage ripples may be caused by changing loads or by disturbances of sources. In order to counter this, the real DC voltage is continuously compared with a reference, and the error is fed into the hybrid-optimised PID controller. This controller modulates control outputs to keep the DC-link voltage within nominal limits to ensure stability of the system and also safeguard the power electronic apparatus. The novelty of the suggested methodology is the hybrid metaheuristic optimisation algorithm, which would be used to adjust the PID gains. However, it is contrasted with the traditional fixed-gain controllers which, due to being often founded on the line-based model, do not work best in dynamic circumstances; the hybrid algorithm enjoys the benefits of both the global search and the rapid convergence to the optimal gain values. A multi-objective fitness measure is established, which includes the indices of total harmonic distortion (THD), integral of absolute error, settling time, overshoot, and DC-link voltage ripple. The gains of candidate PID are repeatedly tested and optimised until an optimum solution with minimum fitness is reached. This guarantees better disturbance rejection and better transient response.

Both converters switch the IGBT devices with precision using sinusoidal pulse width modulation (SPWM). The reference compensating voltages and currents are compared with signals of high-frequency triangular carriers to produce PWM pulses. The switching frequency and the modulation index are chosen to maximise the harmonic performance versus the switching losses trade-off. This is where the exact control is needed to inject the compensating signals so that the waveforms of the load voltage and source current are of high quality even in the case of severe disturbances. The system runs in a complete closed-loop system. At each sampling point the signals are measured, converted to the DQ frame, matched with references, processed by the optimised PID controllers, converted back to the ABC signals, and used as switching commands. This continuous feedback allows disturbance to be mitigated quickly, in most cases, within milliseconds. The controller response time is very important, particularly in case of abrupt changes in loads or the variation in renewable power. The load voltage thus compensated is sinusoidal and has been shown to be stable even during violent voltage sag, swell or harmonic conditions. Also, DC-link voltage is stable with low ripple and shows that the energy management system between series and shunt converters is effective.

In order to formally describe the predictive optimisation and performance evaluation of the proposed hybrid controller, the control objective and optimisation procedure can be mathematically expressed as follows. The discrete-time prediction model used in the MPC framework is given by

$$\mathrm{x}(k+1) = \mathrm{Ax}(k) + \mathrm{Bu}(k) \tag{1}$$

where $\mathrm{x}(k)$represents the state vector and $\mathrm{u}(k)$denotes the control input at sampling instant k. The overall fitness function used in the PSO optimisation process is expressed as

$$F = \alpha_1 THD_v + \alpha_2 THD_i + \alpha_3 E_{dc} + \alpha_4 T_s + \alpha_5 M_p \tag{2}$$

where $THD_v$and THD_irepresent voltage and current total harmonic distortion, E_{dc}denotes DC-link voltage deviation, $T_s$is settling time and $M_p$is peak overshoot.

The PSO velocity and position update equations are given by

$$\mathrm{v}_i^{t+1} = \omega \mathrm{v}_i^t + c_1 r_1 (\mathrm{p}_i - \mathrm{x}_i^t) + c_2 r_2 (\mathrm{g} - \mathrm{x}_i^t) \tag{3}$$

$$\mathrm{x}_i^{t+1} = \mathrm{x}_i^t + \mathrm{v}_i^{t+1} \tag{4}$$

where $\mathrm{x}_i$is the particle position, $\mathrm{v}_i$is velocity, $\mathrm{p}_i$is personal best, gis global best, $\omega$is inertia weight, and $c_1, c_2$are acceleration constants. Finally, the Total Harmonic Distortion (THD) used for performance validation is calculated as,

$$THD(\%) = \frac{\sqrt{\sum_{n=2}^{N} X_n^2}}{X_1} \times 100 \tag{5}$$

where $X_1$is the fundamental component and $X_n$represents the n^{th}harmonic component.

5. CONTROL STRATEGY BASED ON D–Q THEORY BOTTOM OF FORM

The Unified Power Quality Conditioner (UPQC) control strategy relies on the synchronous reference frame approach commonly referred to as D-Q theory. It finds widespread application in 3-phase power electronic systems, as it gives the ability to control alternating current (AC) quantities by transforming them into signals that resemble DC in one rotating reference frame (or system). Through this the complexities of harmonic extraction, reactive control of power and DC-link voltage regulation are greatly simplified. This allows better design of controllers, especially when operating in a dynamical environment where traditional control techniques might fail. Both the voltage and current are sinusoidal in three-phase distribution networks and time-varying. These quantities are not easily controllable in the three-phase (abc) frame directly since they vary continuously with time. This is solved by the DQ transformation, which converts the three-phase voltages and currents into a phase-rotating reference frame that rotates in step with the fundamental component of grid voltage. A Phase-Locked Loop (PLL) is used to extract the exact grid angle to achieve the grid synchronisation. This angle is then carried out to transform the reference frame into the form in which the basic constituents of voltage and current are equal values, and harmonics and imbalances are converted to oscillatory components which can be readily separated and compensated.

The UPQC control structure is designed in the form of two looping coordinated controls: the series converter control loop and the shunt converter control loop. The series converter is the circuit that is mainly used in controlling the voltage compensation, and the shunt converter controls the sinusoidal current sources of the source, controls the DC-link voltage and reduces reactive power and harmonics. The load voltage, which has been converted to the DQ frame, is compared with the reference voltage within the series converter loop. The reference makes sure that the direct axis component has the same rated magnitude, yet the quadrature axis component is established at zero, in effect removing reactive voltage. Any change in these reference values produces error signals which are fed into the optimised PID controller. The controller drives the series converter to inject a compensating voltage in the supply line. The converter injects the necessary voltage to the load to reconstruct the load voltage to its nominal sinusoidal value using sinusoidal pulse-width modulation (PWM). This system guarantees that the load is delivered stable, balanced voltage during disturbances like voltage sag, swell or harmonic injection and also prevents damage to sensitive equipment as well as the continuity of operation.

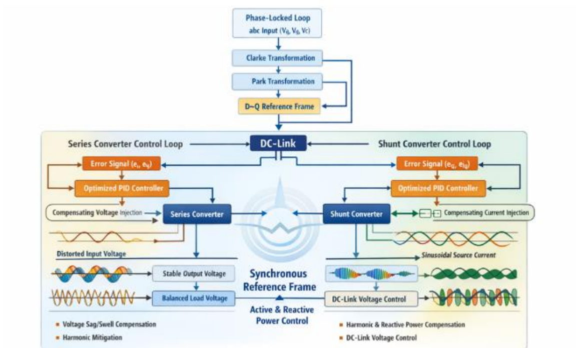

Figure 6. D–Q Control Architecture of the UPQC

At the same time, the shunt converter is concentrated on the regulation of the source current, as well as the stabilisation of DC-link voltage. The load currents are converted to the DQ frame to isolate active and reactive components. The current reference source is optimally designed in such a way that the grid provides only the basic active power, with the shunt converter having to offset the reactive power and harmonics. The direct axis current reference is modified according to the change in DC-link voltage, and the quadrature axis current reference is held at zero to allow unity power factor. The optimised PID controller works with the error signals of the current comparison, producing commands to the shunt converter to inject the required corrective currents back into the system. The shunt converter, by dynamically adjusting these currents, maintains the source current as almost sinusoidal and in phase with the voltage, minimising the harmonic distortion and increasing the overall power quality. The constant DC-link voltage between the series converter and the shunt converter is an important requirement in the successful operation of the UPQC. The DC-link capacitor is a storage of the energy, and smooth exchange of the energy amongst the converters is maintained. Any error in the DC-link voltage is noticed and rectified by the shunt converter control loop, which changes the direct axis current reference. It is a control mechanism that avoids the degradation of the performance and guarantees stability of the voltage as well as current compensation.

There are a number of intrinsic benefits of the D-Q control strategy. It enables active and reactive power to be independently controlled, makes it simpler to extract harmonics, and also increases stability in the system under nonlinear load conditions. The fact that the basic elements are transformed into constant DC values in the synchronous frame simplifies the design and tune of the conventional PID controllers. The system in combination with the hybrid optimisation method of PID gain selection exhibits better transient behaviour, lower overshoot, lower settling time and lower total harmonic distortion. The advantages of these benefits render the proposed UPQC control strategy specifically effective for contemporary power systems incorporating renewable energy sources, in which the problems of voltage change, harmonics, and load imbalance often occur. Furthermore, the DQ-based solution gives a predictive benefit, since the oscillating components that signify harmonic and unbalanced are easily resolvable and could be eliminated in real time. A combination of series and shunt converters under this structure would make sure that both the voltage and current disturbances are taken care of at the same time. The series converter reduces voltage sags and swells, and the shunt converter controls current harmonics and reactive power compensation, leading to a complete solution to power quality issues. The given strategy is scalable and adaptable; that is why it can be employed in any type of grid with a varying renewable penetration. The UPQC is very reliable, sensitive and non-disturbing and can be used to supply power to the delicate loads in the smart grid implementation since they combine synchronised frame regulation and optimised PID regulation, thus sustaining stable and quality power delivery.

The Unified Power Quality Conditioner (UPQC) control strategy is based on the synchronous reference frame theory, commonly called D–Q theory. In a three-phase system, voltages and currents are sinusoidal and continuously varying with time, which makes direct control in the frame difficult. To simplify the control process, the three-phase quantities are first transformed into a two-axis stationary frame using Clarke transformation, and then into a rotating reference frame using Park transformation. In this rotating frame, the fundamental components appear as constant DC quantities, while harmonic and unbalanced components become oscillatory, making them easier to separate and compensate. The Clarke transformation is given as,

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (6)$$

Similarly for currents,

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (7)$$

After converting to the αβ stationary frame, the Park transformation rotates the reference frame synchronously with the grid voltage using the angle obtained from a Phase Locked Loop (PLL). This converts AC quantities into DC quantities in the steady state. The Park transformation is expressed as,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (8)$$

Similarly for currents,

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

Thus, the d-axis controls active power and the q-axis controls reactive power independently. The DC-link capacitor stores energy and ensures proper power exchange between the series and shunt converters. The energy stored in the capacitor is:

$$E = \frac{1}{2}CV_{dc}^2 \quad (10)$$

The dynamic equation governing DC-link voltage is,

$$C\frac{dV_{dc}}{dt} = \frac{P_{shunt} - P_{series}}{V_{dc}} \quad (11)$$

6. CONTROLLER DESIGN AND OPTIMIZATION ALGORITHM

The performance of the Unified Power Quality Conditioner is strongly dependent on the accuracy and robustness of its controller design. Whereas the DQ theory makes the control of three-phase quantities simpler and more straightforward since they are transformed to DC-like terms, the overall system performance is inherently dependent on the ability to choose the control gains. Traditional PID controllers have commonly been applied in UPQC applications because they are easy to apply, simple, and their structure is well understood. Nevertheless, there are severe drawbacks with fixed-gain PID controllers in nonlinear and time-varying operations, especially in renewable-integrated distribution systems. Dynamic operating conditions with rapidly changing loads, harmonic distortion, voltage sag or swell, and intermittent power generation cause such dynamic operating cases that fixed parameters do not offer the best compensation. This will tend to prolong the settling period, overshoot, ineffective DC-link voltage regulation, and Total Harmonic Distortion (THD). To address these constraints, the proposed work uses a hybrid optimisation-based controller design method in the tuning of the PID parameters of the series and shunt converters. The parameters of the controller are received by the solution to an optimisation problem instead of manually choosing proportional, integral and derivative gains by trial-and-error methods. The main aim is to find the best gain set that reduces the disturbance in the quality of power and at the same time provides a rapid dynamic response and stability of the system.

The design process of the controller starts with the definition of a multi-objective fitness function that is measured quantitatively in order to assess the system performance. The fitness criterion uses various performance parameters such as voltage THD, current THD, DC-link voltage deviation, settling time, overshoot, and steady-state error. The optimisation algorithm is directed to solutions that give a balanced improvement in all performance measures by summing all these factors into a weighted cost function. Generalised form The generalised form of the fitness function can be written as.

$$J(K_p, K_i, K_d) = w_1 THD_v + w_2 THD_i + w_3 E_{dc} + w_4 T_s + w_5 M_p \quad (12)$$

and w_1, w_2, w_3, w_4, w_5 are weighting coefficients that define the relative importance of each parameter.

The optimization algorithm initializes a population of candidate solutions defined as,

$$x_i = [K_p \quad K_i \quad K_d] \quad (13)$$

where the solutions denote possible combinations of PID, (K_p, K_i, K_d) .Candidacy solutions are tested on the basis of the simulation of the UPQC system with disturbance conditions that are predetermined in terms of voltage sag, switching load in the form of nonlinear loads, and harmonic injection. The value of the fitness of each candidate is computed by the cost function $J(K_p, K_i, K_d)$. According to this analysis, the algorithm refines the candidate solutions sequentially to search for the global optimum. The hybrid optimisation structure bases its approach on the global exploration and rapid convergence. In the initial phases of optimisation, the algorithm searches a broad space in an attempt to prevent the local minima premature convergence. The search is slowly transformed into exploitation as more and more iterations are completed, which narrows the gain values towards what is likely to be the most promising solution. This exploration-exploitation mechanism offers stability and high performance to the end gain set through this balanced mechanism.

Mathematically, the PID controller in the time domain is represented as,

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \tag{14}$$

where $e(t)$represents the error signal. In the proposed design, separate PID controllers are used for the d-axis and q-axis voltage control in the series converter, as well as for current control and DC-link regulation in the shunt converter. The optimized gain parameters are embedded within these control loops to ensure coordinated operation between voltage and current compensation mechanisms. An important aspect of the optimization process is constraint handling. The PID parameters are restricted within predefined upper and lower bounds to maintain system stability and prevent excessive control action. Additionally, the DC-link voltage ripple and converter switching limits are considered during optimization to ensure practical feasibility of implementation.

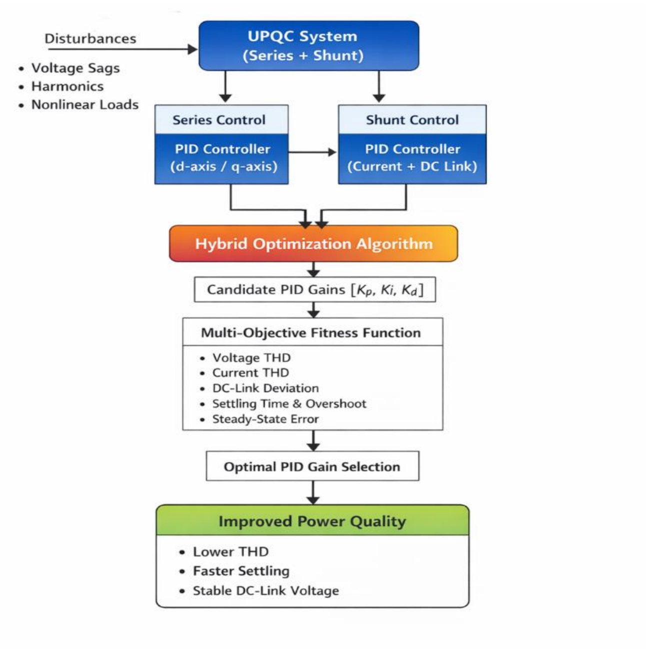

Figure 7. Hybrid ANFIS–MPC Controller Design for the Proposed UPQC

Once the optimal gain values are obtained, they are fixed within the controller and validated under multiple operating scenarios. The optimized controller demonstrates significantly improved transient response compared to conventional tuning methods. Voltage sag is compensated within a shorter duration, harmonic content is substantially reduced, and DC-link voltage deviation remains minimal even during abrupt load changes. The coordinated control of series and shunt converters becomes smoother, reducing oscillations and improving overall power quality. The hybrid optimization-based controller design enhances system robustness by allowing the controller to operate efficiently across varying grid conditions. Unlike manually tuned controllers that perform well only under specific operating points, the optimized controller maintains consistent performance under nonlinear loads, renewable fluctuations, and unbalanced conditions. The reduction in THD and improvement in settling time confirm the effectiveness of the proposed algorithm.

7. RESULT AND DISCUSSION

The simulation results provide a clear insight into the dynamic performance and effectiveness of the proposed hybrid GW-OA optimized PID-controlled UPQC system in a three-phase distribution network. The waveforms record the response of the system to many perturbations, such as voltage sags, current swells and nonlinear load effects, and they show how the UPQC can keep power quality. The input and compensated output voltage, as well as the source current behaviour, point out the ability of the series and shunt converters to restore the voltage, align current and voltage and attenuate harmonics. The entire simulation model shows how the D-Q theory-based control, the series and shunt converters and the DC-link regulation are integrated, and the FFT analysis proves how the total harmonic distortion is considerably reduced. All of these findings are indicative of the resilience and flexibility of the suggested control strategy in smart grids with a high concentration of renewable energy.

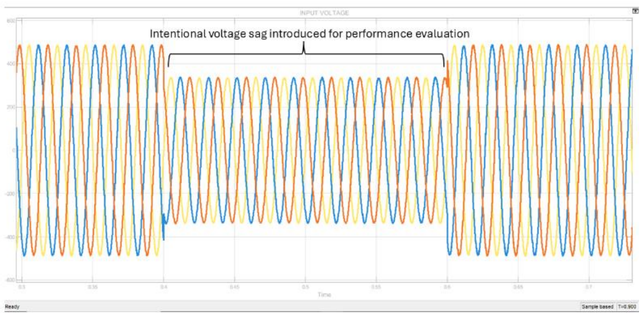

Figure 8. Three-Phase Input Voltage with Sag

To compare the dynamic functioning and robustness of the proposed hybrid GW-OA optimised PID-based UPQC system, the three-phase input voltage waveform in Figure 8 shows clearly the use of wilful voltage sag disturbances, which were induced to test the system. Voltage sags are also typical of the present-day power systems, which can be triggered by sudden increases or decreases in load, switching, or the character of renewable energy sources, like solar or wind, which are intermittent. In the waveform, it is noticeable that the voltage magnitude is much lower in the disturbance period, forming a conspicuous deviation of the nominal voltage level. Uncompensated, such disturbances may cause adverse impact on sensitive industrial and commercial loads and may lead to malfunction and tripping of equipment or delays in operation. The waveform marks this period of disturbance, which can be considered a reference point by the series compensator of the UPQC that has a visual interpretation of the compensation requirement. Such a representation is essential, as it will be possible to evaluate the reaction of the system in real-time and indicate where the voltage deviation is most noticeable. This waveform analysis is used to assess the quality of the proposed controller in restoring the magnitude of the voltage and power quality and, therefore, shows the importance of intelligent control as one of the elements in reducing transient disturbances in a renewable integrated grid.

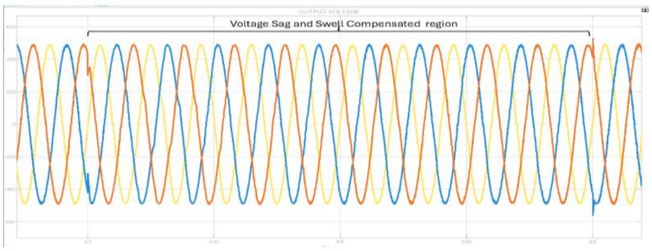

Figure 9. Three-Phase Output Voltage

Figure 9. shows the compensated three-phase output voltage waveform, which proves the usefulness of the proposed hybrid GW-OA optimised PID controller to reduce the voltage sag. Within the disturbance interval that it sees in the input voltage, the series converter of the UPQC applies the correct compensating voltage in phase with the supply to regain the load voltage to a nominal, sinusoidal waveform. The compensated region indicates that the output voltage has a relatively constant amplitude in all three phases with little harmonic distortion. This is to say that the series converter as controlled by the optimised PID controller can be able to respond quickly and precisely to the unexpected changes in voltage and provide a stable and balanced output. The restoration is nearly immediate, which is characteristic of the short-term response ability of the system. In addition, the low relative variance of the voltage amplitude indicates the fine-tuning of the controller gains obtained with the help of the GW-OA optimisation, which results in the accuracy and the response time improvement. The waveform is a good indication that the controller can stabilise the voltage in dynamic load conditions, and therefore the proposed hybrid UPQC would be able to deliver the required high-quality power continuously to sensitive electrical devices even when the supply is subjected to sudden sags or fluctuations due to variations in the loads or due to intermittency of renewable sources.

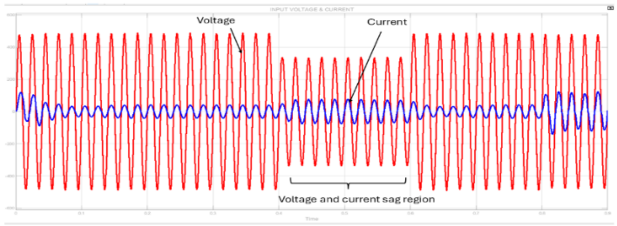

Figure 10. Single-Phase Voltage and Current

The voltage and current waveforms in Figure 10 indicate the voltage agrees with the source current, which is a fundamental indicator of a successful reactive power compensation by the shunt converter. In this figure the voltage and current waveforms are almost in phase, which indicates a unity power factor at the common coupling. The fact that the zero crossing points are aligned shows that the UPQC is effectively counteracting phase jitter due to nonlinear loads and enhancing system performance and minimising reactive power loss. Also, the waveform shows a decrease in the current harmonics of the compensation interval, which proves the capability of the system to sustain sinusoidal currents in dynamic and nonlinear conditions. This plays an important role in the minimisation of losses, reduction of heating in conductors and also in the reliable functioning of downstream equipment. The graphical data of the waveform highlights the success of the hybrid D-Q control scheme in synchronising the series and shunt converters in a bid to respond to both voltage variations and quality of current simultaneously. The exact current injection of the shunt converter is important so that the harmonic content is reduced and reactive power is properly compensated, which is vital in the modern distribution systems with high renewable penetration and varying load states.

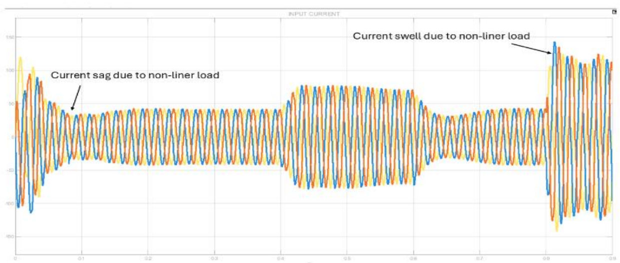

Figure 11. Three-Phase Input Current

Figure 11 shows the waveform of the three-phase input current that experiences the disturbances in the shape of current swell and sag. The nonlinear loads and abrupt variations in load conditions cause these variations and pose serious challenges to traditional controllers. The swell regions are the instances of current amplitude increases, and the sag regions are instances of decreases. The two forms of disturbance may have a negative impact on the supply chain and the downstream equipment, which may lead to inefficiency, overheating, or even breakages. This is the waveform used to provide a base point on the performance of the shunt converter in the UPQC system in regard to compensation. Comparing the source current before and after compensation, one can realise that the deviations are successfully reduced by the proposed hybrid control approach so that the source current can be balanced and sinusoidal. The close examination of the waveform illustrates that there is a need to have intelligent real-time control mechanisms, particularly in contemporary grids with non-linear and dynamic operating conditions. It also stresses the role of adaptive compensation methods, including the hybrid GW-OA optimised PID controller, in addressing both reactive and harmonic disturbances, which are normally not dealt with by standard fixed-gain controllers effectively.

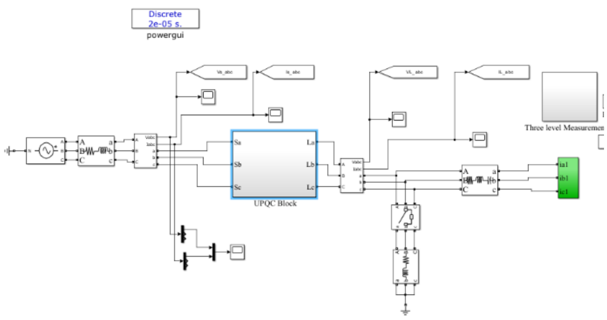

Figure 12. Overall Simulation Model of the Proposed Hybrid UPQC

The overall simulation model in Figure 12 provides a comprehensive view of the proposed hybrid UPQC system controlled by the GW-OA optimized PID controller. It shows the combination of the series and shunt voltage source converters joined by a common DC-link capacitor that is synchronised by a control framework based on a D-Q theory. Mitigation of voltage disturbances is the duty of the series converter and current compensation and DC-link voltage regulation of the shunt converter. Other important elements that are noted on the figure include the phase-locked loop (PLL) to synchronise the output of the grid and the pulse-width modulation (PWM) module to create the correct switching signals to the converters. This block-level representation gives a clear insight into the interaction between components of the system to give coordinated voltage and current compensation. The model shows the integration of the adaptive learning, predictive optimisation, and global PID tuning of the hybrid control framework to improve the power quality. It is especially useful in aiding the visualisation of signal flow and control commands by showing the exact and synchronised action that must be taken to keep the voltage constant, harmonic reduction and reactive power compensation under different disruptions in the grid.

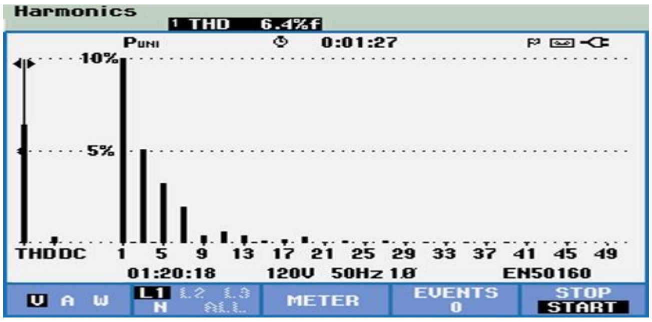

Figure 13. Hardware Harmonic Spectrum of the Existing UPQC System

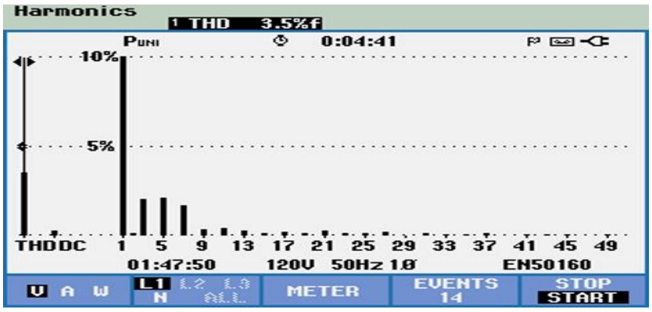

Figure 14. Hardware Harmonic Spectrum of the Proposed UPQC System

The effectiveness of the optimised control strategy is evident in the harmonic performance comparison between the current conventional controller and the proposed control strategy that is optimised. In the existing system, the Total Harmonic Distortion (THD) is 6.4, and it is more than the IEEE-519 desired value of 5% in low-voltage distribution systems. The harmonic spectrum reveals evidently lower-order harmonic contents, especially the 3rd, 5th and 7th harmonic contents, which is a sign of inadequate compensation ability in nonlinear loading conditions. These high levels of harmonic distortion cause poor quality of waveforms, power losses, loss of total system efficiency and possible overheating of electrical equipment. The proposed system, on the other hand, considerably decreases THD down to 3.5%, which is much below the allowed limit. The harmonic spectrum of the proposed controller indicates significant suppression of the lower-order harmonics which makes it more efficient. This is a large improvement in reducing harmonic performance from 3.5% down to 6.4%. The outcomes are clear and show that the proposed control strategy is able to improve the quality of power, provide greater stability, and guarantee a more stable operation in contrast to the traditional approach. Thus, the hardware validation proves that the proposed solution has a greater harmonic suppression and higher adherence to international standards of power quality.

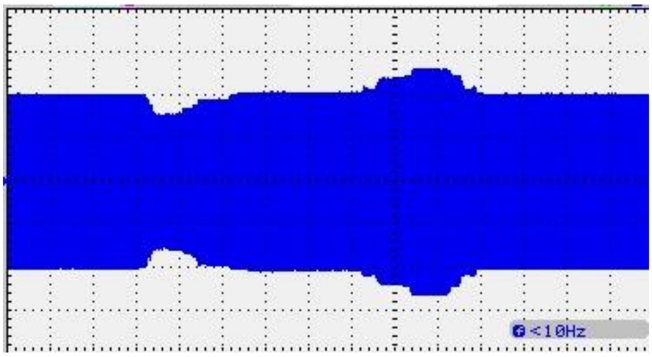

Figure 15. Distorted Input Voltage Waveform Under Disturbed Condition

The input voltage waveform under disturbed operating conditions was recorded before compensation, as shown in Figure 15. As shown in the figure, the waveform is not constant in amplitude and has observable variances over time. Some of the periods exhibit some decrease in the magnitude of the voltages, whereas other areas exhibit irregular changes which prove voltage distortion and instability in the supply. This can be due to nonlinear load switching, sudden load changes, or supply-side anomalies that are often found in real-world systems. These dynamic voltage situations may have a serious impact on sensitive loads, causing them to operate improperly, cause thermal stress, and decrease equipment life, and may result in tripping of the system. The uneven distribution of voltage also means poor power quality, which is a very serious concern in renewable-integrated and dynamic power systems. Hence, such a waveform deformity can be used as a reference point to assess the performance of the proposed UPQC hardware implementation in improving the quality of voltage restoration.

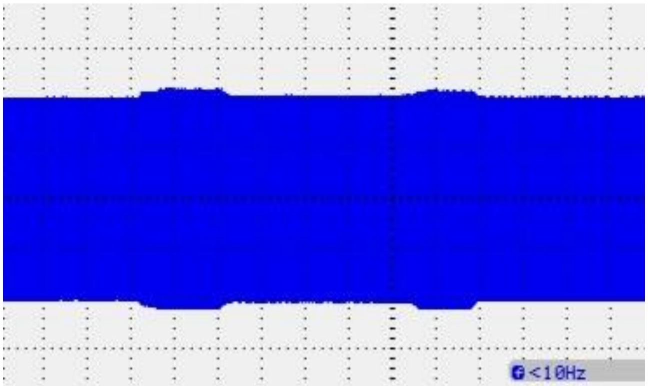

Figure 16. Compensated Output Voltage Waveform After UPQC Control

The compensated output voltage waveform as shown in Figure 16 shows the stability in the output. In comparison to the distorted waveform of the input, the quality of the output voltage shows an unmistakable high in stability and quality of the waveform. The amplitude does not vary during the operating period, and the waveform is close to that of a perfect sinusoidal signal. The surges and non-uniform changes in the input are eliminated by the series compensator of the UPQC that injects the necessary compensating voltage. The smooth and controlled waveform means that the controller is fast in reacting to disturbance and keeps the voltage in acceptable values. The reconstruction of voltage magnitude and shape ensures that the system is working properly in coordination of sensing, control and switching mechanisms in the hardware system. This stabilisation provides a stable power supply to the loads connected, eliminates faulty functioning of the delicate equipment, and enhances the efficiency of the system in general. The validation of the hardware outcomes clearly confirms that the proposed control strategy improves the voltage regulation operation and is able to ensure the high-power quality even with the changing supply conditions.

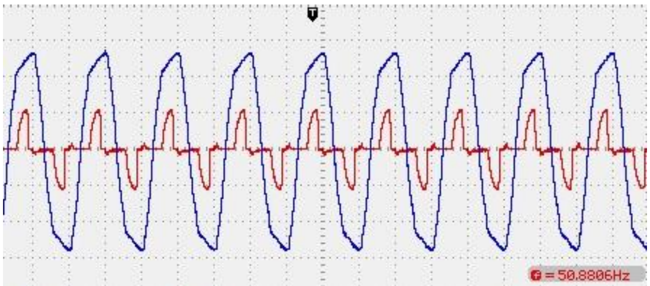

Figure 17. Voltage and Current Waveforms of the Existing System Showing Poor Power Factor

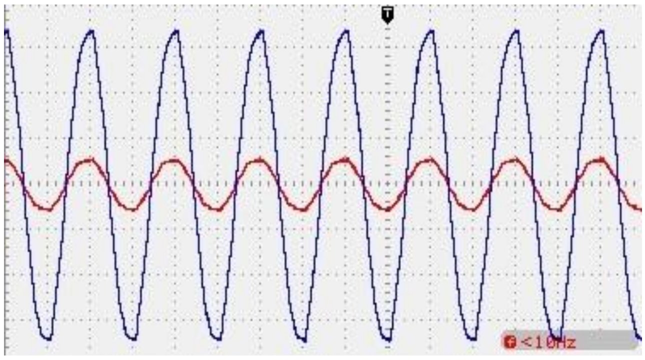

Figure 18. Voltage and Current Waveforms of the Proposed System Showing Near-Unity Power Factor

The comparison between the existing system and the proposed controller in terms of voltage–current alignment clearly demonstrates the improvement in power factor and reactive power compensation as shown in Figure 18. The resulting waveform is behind the voltage waveform, which means that there are a reactive power and the condition of poor power factor. This behaviour of the waveforms clearly shows the incapacity of the conventional controller to effectively compensate reactive power and suppress harmonics. The proposed system on the other hand, represents the voltage and current waveforms, which are proper waveforms without any distortion. The proposed waveform is nearly in phase with the voltage waveform, and the zero cross points happen very close to the same time, which means that the power factor is almost operating with unity. The distortion that exists in the present is greatly minimised, and the waveform looks smoother and more sinusoidal than the current system. This enhancement validates the fact that the proposed controller successfully corrects reactive power and reduces harmonic content in real-time functioning. The hardware evaluation confirms the fact that the suggested approach improves the efficiency of power transfer and minimises the losses and the overall power quality in comparison to the traditional control technique.

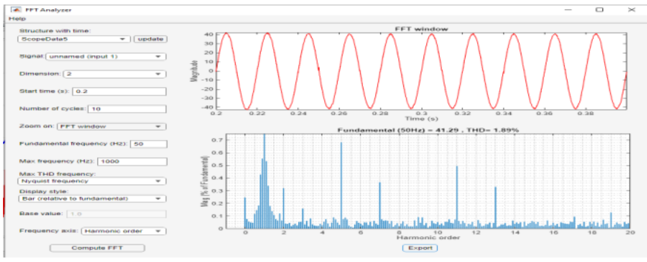

Figure 19. FFT Analysis of Compensated Voltage

The FFT analysis of the compensated voltage in Figure 19 presents the harmonic spectrum, highlighting the effectiveness of the proposed hybrid UPQC controller in reducing total harmonic distortion (THD). The figure shows that the THD has been minimised to a considerable extent of 1.89, much less than the IEEE 519 suggested limit of 5 per cent, which is a good indication that the higher-order harmonics have been successfully suppressed and the fundamental component is at the fore. This analysis analytically validates the qualitative waveform observations in previous figures showing that the optimised PID controller is effective in eliminating both voltage and current distortion. A steep decline in harmonic contents will guarantee high quality of power, low losses and high reliability of sensitive loads. The balancing and stability of the voltage under dynamic operating conditions of the controller is also justified by the FFT results, as is the need to incorporate advanced control principles like the D–Q theory-based control and the hybrid optimisation techniques in the current smart grids with renewable bases.

Figure 20 depicts the hardware experimental design of the proposed UPQC system. It is made up of the main power circuit, the control boards, the sensing circuits and the loading setup mounted on a small laboratory base. The control area contains the microcontroller/digital control board which performs the proposed optimised control algorithm and produces the necessary switching pulses to the converters. The gate driver circuits are employed in supplying correct isolation and amplification of the control signals to the power semiconductor devices. The power stage is comprised of converter modules, DC-link capacitors, and passive elements on distinct boards to enable easy modular implementation. The right side of the setup is loaded with large resistive load banks in order to simulate nonlinear and variable load conditions on which performance is to be evaluated. A compensatory capability is tested by adding voltage disturbances like sag and swell conditions by using an adjustable AC source. This hardware platform allows implementing harmonic mitigation, voltage stabilisation, and power factor improvement validation in real time under realistic operating conditions. The experimental setup validates the control strategy proposed in the proposed control strategy policy in a real-life distribution setting outside of the simulation analysis.

Figure 20. Hardware setup

8. CONCLUSION

This research proposed a hybrid intelligent control framework for a three-phase Unified Power Quality Conditioner (UPQC) based on D–Q theory, aimed at enhancing power quality in renewable-integrated smart grids. Integration of renewable energy sources, such as solar PV and wind turbines, introduces benefits in sustainability and efficiency but also brings power quality challenges like voltage sag, swell, harmonics, reactive power oscillations, and load imbalance. Conventional fixed-gain PI or PID controllers struggle under these dynamic conditions, often causing overshoot, longer settling times, increased total harmonic distortion (THD), and DC-link voltage fluctuations. To address these issues, a hybrid strategy combining Adaptive Neuro-Fuzzy Inference System (ANFIS), Model Predictive Control (MPC), and Particle Swarm Optimization (PSO) was proposed. ANFIS adapts to nonlinear disturbances and adjusts controller parameters in real time, MPC predicts future system behavior and optimizes control actions over a finite horizon, and PSO tunes both ANFIS and MPC parameters to achieve globally optimal performance. This combination ensures fast, accurate, and adaptive compensation for voltage and current disturbances. Simulation results in MATLAB/Simulink under nonlinear loads, unbalanced conditions, and sudden renewable fluctuations demonstrate significant improvements. The PSO-optimized ANFIS-MPC UPQC exhibits faster transient response, precise DC-link voltage regulation, and superior voltage restoration during sag and swell events By anticipating disturbances and proactively adjusting controls, it ensures reliable, stable, and high-quality power delivery even in complex renewable-rich networks. Its modular design allows scalability for varying grid configurations and renewable penetration levels. In summary, the PSO-optimized ANFIS-MPC UPQC presents an effective, adaptive, and intelligent solution for next-generation smart grids, providing improved power quality, system stability, and resilience in dynamic operating conditions.

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