

CGA-FOPID BASED UPQC FOR MITIGATING HARMONICS AND COMPENSATE LOAD DEMAND IN GRID LINKED HYBRID RENEWABLE ENERGY SOURCES

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Received: August 23, 2023; Revised: December 28, 2023; Accepted: March 01, 2024

Abstract

Power Quality (PQ) explore the issues resulting from current and voltage deviations. Due to an extraordinary rise in nonlinear loads, such as power electronic-based loads, the issues with power quality in distribution systems have become severe. Non-sinusoidal current is drawn from the electric grid by the nonlinear loads. These non-sinusoidal currents contain harmonics and reactive power that lower the system's overall PQ. Unified Power Quality Conditioner (UPQC) was emerged as a promising compensator to provide a solution for all PQ issues. UPQC generally had two Voltage Source Converters (VSC), one was Shunt, and the second was a Series that act as a current controller and voltage controller, respectively. Yet the controlling strategy of this compensator was still complex to design. Here, an optimization based Fractional Order Proportional Integral Derivative (FOPID) was developed to manage UPQC for improving PQ in a hybrid Renewable Energy System (RES). The optimal problem of the FOPID controller was solved through the use of a novel optimization approach. The pulse signal of UPQC was done using the optimal controller, which analyzes the error value of reference voltage and actual load voltage to generate pulses. The proposed optimal controller based UPQC performance was validated under various conditions such as interruption, swell, harmonics, and sag. The optimal controller offered THD value in sag, swell, and interruption period at current have 10.19%, 9.77%, and 10.09%, at voltage have 0.09%, 0.07%, and 0.30%. Moreover, the issues mitigation performance was compared to another present approaches. The validated outcome demonstrates the proposed model provides a well mitigation performance in all PQ issues conditions, so it was well fit for real-time implementation.

Keywords: Fractional order proportional integral derivative; hybrid renewable energy system; power quality; THD; unified power quality conditioner

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DOI: <https://doi.org/10.55766/sujst-2024-01-e02177>

Suranaree J. Sci. Technol. 31(1):010286(1-17)

Introduction

With the advancement of technology, growing environmental awareness, and high demand for electricity on the RES with the utility grid, Distribution Generation (DG) is playing a more significant role today (Tan *et al.*, 2021). RESs will have a significant positive economic impact while lowering pollutants and global warming. RESs-based DG is gaining importance due to the present state of the global economy and the growing awareness of ecological problems (Bajaj *et al.*, 2020b). Numerous RESs, such as solar energy, fuel cells (FCs), bio-mass, and wind energy, have been developed and united into conventional power plants. Each RES, whether AC or DC, has unique qualities that set it apart from other sources. While wind energy can produce either AC or DC depending on the generator used in the Wind Energy Conversion System (WECSs), PV and FC offer DC voltages in various ranges (Mosaad *et al.*, 2021). These differences make it difficult to incorporate these RESs into the electrical grid. Another problem with integrating these RESs into the electrical grid is that the electricity they provide is unstable because they depend on various environmental parameters, such as irradiance and temperature in PV systems and wind speed in WECSs (Iweh *et al.*, 2021). An important answer to these issues is the employment of power electronic equipment to modify the DC levels of all DC sources using specific converters. The power output from each RES can also be increased using these converters (Madhana and Mani, 2022).

These RESs' electrical output is then connected to the electricity grid by means of DC-AC converters. Power quality (PQ) problems, including voltage sags and swells, disturbance harmonics, and other problems, will be made worse by the power electronic devices needed to link different types of RES to the grid (Bajaj and Singh, 2020a). These problems may lead to constant swings in the amount of electricity produced and the tripping of some RESs if grid needs or constraints are not satisfied. The Electric Power Research Institute (EPRI) then made a technological recommendation to improve the current power systems' power flow, system stability, and reliability (Shahzad, 2020). Flexible Alternating Current Transmission Systems (FACTS) is another name for this power electronics technology (Shair *et al.*, 2021). Modern control technologies have the potential to make power systems more manageable and more productive in terms of power flow and stability limits. The FACTS technology, which consists of a number of controllers that can be used

alone or in conjunction with other tactics, can be used to regulate a number of interrelated power system characteristics, including shunt impedance, current, voltage, series impedance, and oscillation damping (García-Triviño *et al.*, 2023). These controllers were made using the FACTS Controllers concept, which came from the FACTS technology.

FACTS controllers are more sophisticated and user-friendly than mechanical control switching methods. Without altering the topology, they may regulate the power flow and increase the power system's efficacy (Impram *et al.*, 2020). According to the needs of the power systems, numerous various FACTS controllers with sophisticated control methodologies have been developed since 1980. Dynamic Voltage Restorer (DVR) (Farooqi *et al.*, 2022), Unified Power Quality Conditioner (UPQC) (Jin *et al.*, 2020), and Distribution Static Synchronous Compensator (D-STATCOM) (Zhou *et al.*, 2021) are some of the most well-known custom power devices. Reactive power and unbalanced loading in distribution systems can be adjusted using UPQC well-known and affordable solutions. However, since the compensators operate depending on the controller output signal, managing compensators is problematic in various situations.

Several convolutional controlling models were proposed to address these problems. For the aim of managing the compensator, proportional integral controllers, namely Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers (Alam *et al.*, 2021) controller are typically employed. Fuzzy Logic Controllers (FLC) (Amirullah *et al.*, 2020) are then utilized to address any power quality issues. Nevertheless, the optimal problem for these devices is difficult. Additionally, the system's correctness depends on human abilities and expertise, and it performs poorly in controlling an integrated and lengthy process. An optimal controlling strategy is presented to address the problems with the best parameter selection in a controller. However, those models are unstable in cyclical situations and do not produce reliable results.

In the past ten years, researchers from business and academia have been interested in the FOPID controller. Because there are five factors that may be adjusted, they are more adaptable and perform better than traditional PID controllers. However, the FOPID controller's tuning becomes difficult. Various design and tuning techniques have been created in this controller to overcome these issues. But those models are more time-consuming, cannot provide a sufficient outcome, have poor tuning

performance, are difficult to implement efficiently, and are complex to solve the problems in all circumstances. An innovative meta-heuristic Chaos Game Optimization Algorithm (CGA) is developed to increase the tuning process of the FOPID controller to address these problems. CGA have high speed convergence to solve the optimal problems and have unique updating rule to find the suitable solution for a problem. The significant contributions made by the suggested PQ enhancement technique are given below,

- A new optimization-based FOPID controller for UPQC is proposed to maximize PQ in a hybrid RES-grid connected nonlinear distribution system.
- At first, grid with load system and hybrid RES is designed with a certain ranges, between load and RES, a UPQC is integrated.
- Pulse generation of UPQC compensation switches is done by using FOPID controller which compares actual load voltage/current and reference voltage/current to generate pulse signal of switches respectively.
- Parameters of FOPID controller are tuned by CGA optimization algorithm. A minimum error fitness function is used to select the best optimal values.
- The proposed mitigation performance is analyzed under sag, harmonics, interruption, and swell conditions. Moreover, the outcomes are compared to other existing models to confirm the efficacy of the proposed model.

The leftovers of the manuscript are organized as some relevant models that are significant to enhancing power quality in a distribution system are provided in section 2. Section 3 contains the proposed power quality improvement methodology working process and its numerical modelling. Section 4 presents the outcome of the proposed model and its discussions, and the overall conclusion of the suggested work is stated in section 5 last.

Related Work

Numerous techniques or controlling systems were introduced to improve PQ in a distribution system. Those models effectively operate and reduce power quality issues in a specified period. A few methods for improving PQ in a distribution system are discussed below.

Naidu and Meikandasivam (2020) developed to deal with the power quality issues, a coordinated PQ theory, a FOPID controller, and a distributed power flow controller based on FACTS are used.

The FOPID controller improves the voltage profile regarding the amplitude peak of the transition rise/fall voltage and the voltage correction with fewer oscillations. However, the model consume more time to process, and the optimal problem of the FOPID controller was not focused. Rajesh *et al.* (2021) suggested a control strategy based on the IBSMFO protocol to manage the PQ in RES-microgrid systems. The strategy pertains to the system's overall efficiency of the energy storage components for power improvement. However, the model cannot maintain a constant frequency and high voltage fluctuation issues.

Amir *et al.* (2022) developed a d-q controller solution to maintain equilibrium between the grid side network and the DG network. In order to control and improve the performance of the hybrid power generation systems, a super-capacitor was used to lessen the ripple on the distribution side of the power grid. Although it performs badly when there are power quality issues, the inner control loop is utilized to control the current. Jamil *et al.* (2019) developed a model for improving PQ for effective power transfer in a hybrid grid-connected solar and wind energy system. Independent hybrid systems, grid-integrated systems, and grid-integrated systems using STATCOM are the three primary contexts in which the model can be applied. However, the model is only designed for non-linear systems, not linear, unbalanced systems, so it is unsuitable for real-time processes.

Babu *et al.* (2020) developed a solution to increase the PQ of a grid-tied PV distribution system using a fuzzy logic PID in a shunt active power filter and multiple complex coefficient filters in multiple second-order generalized integrator frequency-locked loops. FLPID is mostly used to maintain steady power among the ac and dc sides by controlling the dc-link voltage constant during transient situations. The controller's performance is affected if the lower frequency dc offset rejection is taken into account, even if the controllers are adequate for offset rejection. Ravinder and Bansal (2019) developed to address the issues with PQ, a hybrid energy system that is intelligently regulated and combined with a shunt active power filter. Neural networks, Fuzzy logic, and ANFIS-based control system are used to optimize the dynamic performance of SAPF. The approach, however, has a slow response time and a heavy computing weight, making it ineffective for handling dynamic load variations.

Sharma *et al.* (2019) developed a grid-connected hybrid scheme with the goal of PQ, built using cascaded H-Bridge multilevel inverters. Along with additional benefits, the characteristics of this system and the control strategy enable maximal

power from RES and inject power into the grid. However, the model has some impacts, like poor balancing performance and variation of PV, causing power variation. Brinkel *et al.* (2020) suggested a system for reducing PV output fluctuations by changing how electric vehicle chargers work and evaluating the suggested solution's viability. The location of the grid, the installed PV capacity, and the grid configuration all have an effect on the amount that the voltage varies. Capacitors' capacity is constrained, though, and the cost of battery systems is rather high.

Molla and Kuo (2020) developed a model that aims to endure and safeguard the effect of fluctuations in voltage on grid-connected hybrid PV-wind generation systems. By perceiving the grid's voltage at the PCC and the SOC levels of the battery and SMES, the operations and control of SMES and BES devices are established. Even though the model runs for a prolonged period of time, its response time will be slow. Kumar and Mallesham (2020) developed a hybrid technical approach that uses renewable energy sources to generate power and lower carbon emissions. A highly promising custom power device based on UPQC and an artificial neural network controller was considered to improve the quality of electricity. However, this model was unsuitable for various issues and conditions due to poor response time.

The abovementioned literature have various power quality improvement models in a distribution system. Those models effectively performance at its process, yet it's have some impacts like poor response time Kumar and Mallesham (2020), runs for a prolonged period of time Molla and Kuo (2020), more time to make the process (Ravinder and Bansal, 2019), poor balancing performance (Brinkel *et al.*, 2020), variation of power (Sharma *et al.*, 2019), only designed for non-linear system and not suitable for real time implementation (Jamil *et al.*, 2019). A novel controlling system based on FACTS in a hybrid RES system is developed to overcome these impacts to improve PQ in a distribution system. The working process of the proposed model was discussed with its architecture in the following section.

Proposed Methodology for Improving Pq in the Res System

A hybrid renewable energy system is one in which two or more different power producing sources must supply the system's electrical load. A wind-PV hybrid generating system with grid integration could be a viable choice for generating electricity, given that it utilizes the benefits of both solar and wind

energy systems. This combination will provide the finest solution in standalone and grid connected mode to satisfy the growth in load demand. The distribution system's HRES can handle the consumers' required load demands, even though there are issues with power quality's flexibility and stability. To keep the system running well, these PQ problems must be avoided. Through the growth of power electronics, FACTS devices were invented to reduce PQ issues, including swell, harmonics, sag, etc. A UPQC is used in this proposed approach to reduce PQ issues such as sag, THD, swell, and interruption. UPQC is improved by using the Chaos Game Optimization Algorithm (CGA). The design of the proposed model working process is stated in Figure 1.

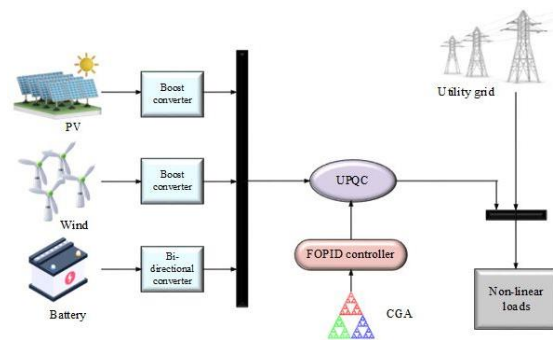


Figure 1. Architecture of CGA-FOPID based UPQC for PQ improvement

Power quality problems in grid-connected systems are effectively reduced at all times by the proposed CGA-FOPID based UPQC. In the source side grid system, PV, wind, and battery sources are designed, as in load side 3 phase non-linear load is designed. Due to the irregular condition of the sources, BESS was designed to manage load demand during adverse environmental conditions. The grid source supplies power to fulfill the load demand during a normal period. PQ issues are caused by the HRES system's non-linear loads and abrupt loads. These issues lead to voltage instability and reactive power imbalances, which result in load failure or financial losses. To overcome these issues, a UPQC is integrated between HRES and load. UPQC is a most advantageous controlling system which have the capacity to control both voltage and current issues simultaneously. The controlling performance of UPQC mostly depends on the pulse signal of switches. Here, the pulse generation depends on the FOPID controller, which works based on its five parameters to generate a pulse of switches. Yet the optimal problem of the FOPID controller was solved through the Chaos Game

Optimization Algorithm (CGA). CGA's effectiveness can be attributed to its ability to manage many constraints that are part of this problem well and to strike a balance among exploitation and exploration of the search area. By using these optimal parameter values, the FOPID controller was performed. In each period, the load system's voltage ranges are analyzed, generating a corresponding pulse signal for UPQC. The proposed PQ improvement model provide a better PQ issues mitigation performance under all condition. The numerical modelling of the proposed model is discussed as follows.

PV Array Modelling

The rays of sunlight from the radiation are converted into usable power using a photovoltaic system. It comprises the solar panel system and the remaining system components. The proposed model photovoltaic cell's current is stated in Equation (1),

$$I = I_{PV} - I_0 \left(e^{\left(\frac{V + IR_s}{V_{ta}} \right)} - 1 \right) - \left(\frac{V + IR_s}{R_p} \right) \quad (1)$$

Where, $V_t = \frac{KT}{q}$, V_t signifies the thermal voltage of a cell, T denotes temperature in kelvin, K denotes boltzmann constant, I_0 denotes saturation current, I_{PV} denotes photovoltaic current, R_s and R_p denotes series and parallel resistance, respectively and q denotes electron charge. In proposed work, totally 29 pannels were utilized for power generation, among them 19 pannels are series connection and 10 pannels are parallel connection. The maximum power of PV module is gathered through p and O MPPT which was discussed as follows.

P and O MPPT

This study proposes a charge controller with MPPT functionality to maximize power harvesting from the PV panel. The perturb and observe (P&O) technique monitors the resulting PV power after varying the PV voltage. The measured values of the PV array's current (I) and voltage (V) are used to estimate PV power (P) in the P and O model. Based on the change in P caused by the following rule, the algorithm provides a perturbation (ΔV) in V .

$$\begin{aligned} V_{new} &= V_{old} + \Delta V \times \text{slope} \quad (\text{if } P > P_{old}) \\ V_{new} &= V_{old} - \Delta V \times \text{slope} \quad (\text{if } P < P_{old}) \end{aligned} \quad (2)$$

The above equation mentioned slope is the direction of perturbation, i.e., to left (descending) or right (climbing), that is relate to PV power. Here, V_{new} denote new voltage level of PV module. Proposed MPPT, ΔV and the slope of perturbation are crucial, when the ΔV is low, the result is a fast

convergence. However, the power cause high fluctuation and vice versa. Figure 2 displays the MPPT model's flowchart.

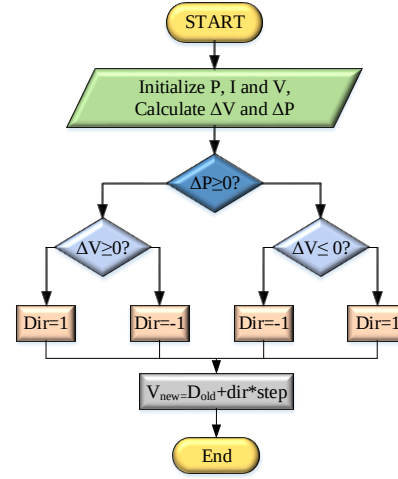


Figure 2. Flow process of proposed MPPT model

PV panel current and voltage at the k^{th} iteration are represented by $V(k)$ and $I(k)$. The selection of C 's value is crucial because it determines how long the voltage perturbation lasts. Small C causes moderate tracking, while large C causes fast tracking, albeit with a significant oscillation around the peak. When the system is far from the MPP, its value is high, and as the system approaches the MPP, its value decreases until zero. This is the solution to the problem. Here, it is demonstrated that taking the value of C at the k^{th} iteration, i.e., $C(k)$, according to the above equation, can result in a quick convergence speed and nearly minimal oscillation around the MPP.

$$C(k) = N \log_{10} (\text{abs}(\Delta P / \Delta V)) \quad (3)$$

Based on the above mentioned equation, maximum power of PV panel is observed. In the following section, wind turbine modelling was provided.

Wind Turbine Modelling

The modeling of wind power systems is contingent upon the electrical power generation and wind turbine being demonstrated. Wind turbine's (WT) input velocity determines its output power, which is known as mechanical power. The aerodynamic torque is supplied by Equation (5), and the output power of WT is stated as in Equation (4),

$$P_w = 0.5 C_p \rho A v_w^3 \quad (4)$$

$$T_w = \frac{P_w}{\omega_w} \quad (5)$$

Equation (4) provides the total power produced by the wavepower system. It is believed that the accessibility of wind velocity affects the wave power output. Where, P_w denotes wind turbine power (W), ω_w density turbine rotor speed (rad/s), C_p denotes power coefficient, A denotes rotor area (m^2), ρ denotes air density (kg/m^3), and v_w denotes wind velocity (m/s). In proposed work, the wind speed of WT is consider as 12 m/s for 1.2 kW power generation. In proposed microgrid, battery sources also used for power supply that was clearly discuss as below.

Battery Source Modelling

In proposed work, lead acid battery is employed for backup power generation in a microgrid. Lead acid batteries can be employed as an economically viable, sustainable, and technically practicable BESS technology in utility applications, including spinning reserve, frequency regulation, load following, and load levelling. Since the values of these resistances and the battery's internal voltage depend on the State of Charge (SOC), SOC should be taken into consideration when defining the output voltage and resistances. SOC, which is one of the most crucial signals used for battery control, is described as

$$SOC = \frac{Ah - Ah_{used}}{Ah} \quad (6)$$

$$Ah_{used} = Ah \times (1 - SOC_{(0)}) + \int \frac{I_b}{3600} dt \quad (7)$$

$$I_b = \frac{V_{OC} - \sqrt{4R_{int}P_{el}}}{2R_{int}}$$

Where Ah_{used} , A , h , P_{el} , R_{int} and V_{OC} represent battery used capacity, nominal capacity, output power, internal resistance, and battery open circuit voltage. In proposed work, 350 Ah with 650 V nominal voltage capacity battery is designed for backup power supply.

Modelling of the Utility Grid

The utility grid is created using a Thevenin equivalent circuit gathered using a series sinusoidal voltage of (415V, 50 Hz) by means of ($Z = R + jX$) impedance. Proposed grid systems power is computed using the following formula,

$$P_{utility} = \Delta V / I \quad (8)$$

Where I represents PCC current, and ΔV denotes potential difference of PCC. In this work, the PCC voltage is maintained at 415 V at any period. Further the microgrid RES sources have power variation issues, so a boost converter is placed in a system to

maintain a constant power, the modelling of boost converter is provided in below.

Boost Converter

In proposed model, boost converter is placed near the PV and wind sources for maintain a constate power supply at any atmospheric conditions. They are typically employed in PV inverter and wind systems to determine the best way to apply MPPT algorithms for controlling power extraction in PV systems. Two energy storage elements of the boost converter are one diode and one n-channel MOSFET. Throughout the switching process, a diode and a MOSFET complement one another; specifically, when a MOSFET is OFF, a diode is ON, and vice versa, when a diode is OFF, a MOSFET is ON at a specific point in time. The capacitor and inductor in the boost converter's storage components are the foundation for mathematical modeling. Equations (9) and (10) provide the inductor voltage and capacitor current computation, respectively.

$$v_L = L \frac{di_L}{dt} \quad (9)$$

$$i_C = C \frac{dv_C}{dt} \quad (10)$$

While inductor V_L for switching conditions of OFF and ON are shown in Equations (11) and (12) respectively.

$$v_L = v_{in} * PWM \quad (11)$$

$$v_L = (v_{in} - v_{out}) * \overline{PWM} \quad (12)$$

The PWM switching frequency and its duty cycle, as shown in Equation (13), define the switching time between (11) and (12). Switching duty cycle is the ratio of ON period to switching time duration. The duty cycle is the ratio of $V_0 - V_{in}$ to V_0 in Equation (13).

$$PWM = \frac{(v_o - v_{in})}{v_o} f_{PWM}^{-1} \quad (13)$$

By integrating in Equation (14) one can determine the current passing through the proposed converter is computed as,

$$i_L = \frac{1}{L} \int v_L dt \quad (14)$$

The current through the capacitor can therefore be calculated using Equation (15), where is the current flowing through the load resistor.

$$i_C = i_L - i_R \quad (15)$$

After obtaining i_c , the capacitor voltage can be computed in Equation (16), which, in the case of an ideal condition of proposed work, gives the load voltage of the boost converter.

$$v_c = \frac{1}{C} \int i_c dt \quad (16)$$

This boost converter was utilized for the PV panels and wind turbine outcome, and it was connected to the SST's dc-link from the power grid side.

UPQC

Due to interconnected RES and loads, including critical, unbalanced, and non-linear loads in the standalone microgrid system, power quality problems are regarded as the primary challenge. To address the concerns about PQ in an island microgrid, UPQC is outfitted with technology that can fix voltage and current power quality issues. The UPQC design includes two active power filters: a shunt and a series. Both active power filters are connected back-to-back by the dc-link capacitor. The series-active filter has the ability to correct voltage flicker/imbalance, voltage control, and harmonic compensation at the utility-consumer PCC. The main tasks of the shunt active filter are harmonic current absorption, reactive power and current compensation with a negative sequence, and dc-link voltage regulation between the two active filters. The design of the UPQC is illustrated in Figure 3. In proposed work, to offset the harmonic content that the load injects, PAF is connected in parallel to the nonlinear load. To maintain an optimal voltage profile, SAF is connected in series at the source side.

The series converter between the supply and the load, as it passes via transformers, is shown in Figure 3. A shunt converter is also connected in parallel by the PCC. In the UPQC configuration, the series filter is a voltage source, while the shunt filter is a current source. The UPQC can be utilized in the standalone microgrid system to compensate for poor PQ in the current and voltage signals. The UPQC design connects the converter to the power line using an inductor known as a shunt connection. By raising the dc-link voltage to the required level while employing this architecture, power quality concerns can be compensated for. The main objectives of the shunt converter are to dampen harmonics in load current and regulate the dc-link voltage. Unquestionably, the shunt converter is employed to adjust the voltage swell and sag in the supply side of RES. The converter uses a low pass filter to cut down on high-frequency switching ripple. The transformer attached to the converter's

output protects the converter from the power lines. In the shunt, also a series converter, anti-parallel diodes with insulated gate bipolar transistors (IGBTs) are utilized to change the switching pulses in order to address PQ issues. The equivalent circuit diagram and phasor diagram of UPQC is shown in Figures 4(a) and 4(b) respectively.

The phasor diagram of UPQC shows the load current of I_{L1} is equal to I_{L2} . Source voltage (V_{S1}) of the UPQC is equal to the voltage of linear loads (V_{L1} and V_{L2}). Ψ represent the angle between shunt current (I_{sh}) and active shunt current (I_{ash}). Φ is the angle between load current (I_{L1}) and source current (I_{S1}). The switching sequence of both the filters is decided according to the control algorithm.

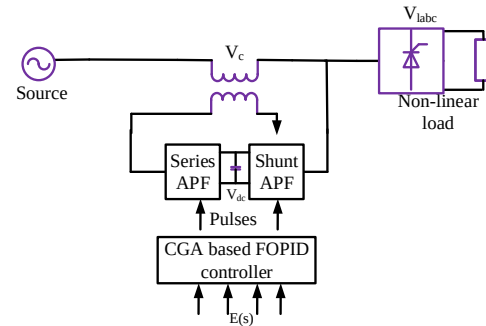


Figure 3. Equivalent circuit of UPQC in island microgrid

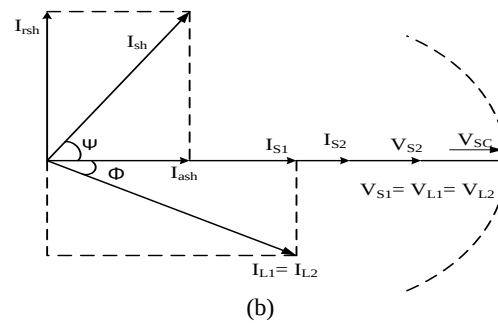
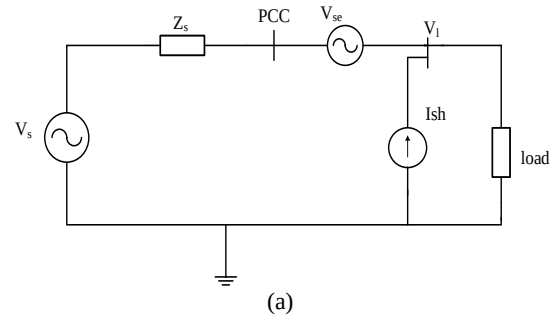


Figure 4. Structure of UPQC (a) Equivalent circuit (b) Phasor diagram of linear load

i) Series Inverter Control

A series inverter's function is to compensate for oscillations in source side voltage caused by distribution line failures. The observed voltage signal is then processed by a control algorithm to create a reference voltage waveform that has less distortion and the same frequency as the load voltage. After receiving signals from the control algorithm for the compensating voltage, the active filter injects the voltage into the load. The reference value which can be supplied by the series inverter is calculated by comparing the positive-sequence element to the disturbed source voltage. The state equation of the series inverter is shown in Equation (17),

$$\begin{pmatrix} V^{s0} \\ V^{sd} \\ V^{sq} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{pmatrix} \times \begin{pmatrix} V^{sa} \\ V^{sb} \\ V^{sc} \end{pmatrix} \quad (17)$$

Where, V^{sq}, V^{sd} is described as quadrature and direct axis generated voltage and V^{sa}, V^{sb}, V^{sc} is described as a source voltage of phases: phase a , phase b , and phase c , respectively. The load voltage $V^{l(abc)}$ is computed based on the below equation,

$$\begin{pmatrix} VR^{la} \\ VR^{lb} \\ VR^{lc} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \end{pmatrix} \times \begin{pmatrix} \overline{V^{sd}} \\ 0 \\ 0 \end{pmatrix} \quad (18)$$

Where, $VR^{la}, VR^{lb}, VR^{lc}$ is described as a reference load voltage. Due to its opposite phase and harmonic content to the voltage distortion, the compensating voltage effectively cancels out the distortion. In addition to rectifying voltage harmonics, the series active filter may also correct voltage swells and sags. Control diagram of series active filter is showed in Figure 5.

ii) Shunt Inverter Control

The shunt active power filter can reduce the standalone microgrid system's current disturbances. It is intended to lessen or completely get rid of current harmonics and make up for reactive power. To counteract system disturbance currents, the shunt

controller injects the necessary current. The current sag, harmonics, swell, and disturbances are all corrected in this shunt controller architecture. The measured current signal is processed by a control algorithm to produce a reference current waveform that has reduced harmonic content and the same fundamental frequency as the load current. The three-phase currents and voltages are converted into coefficients α and β that are formulated as below,

$$\begin{pmatrix} V^0 \\ V^\alpha \\ V^\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} V^{sa} \\ V^{sb} \\ V^{sc} \end{pmatrix} \quad (19)$$

$$\begin{pmatrix} I^0 \\ I^\alpha \\ I^\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} I^{sa} \\ I^{sb} \\ I^{sc} \end{pmatrix} \quad (20)$$

Where, I^{sa}, I^{sb}, I^{sc} is described as phase a, b , and c current on the microgrid source side. After receiving signals, the active filter injects the compensatory current into the load, eliminating the harmonic components of the load current. Control diagram of series active filter is showed in Figure 6.

iii) DC link

The dc link voltage in a UPQC can diverge substantially from its reference in a transient event

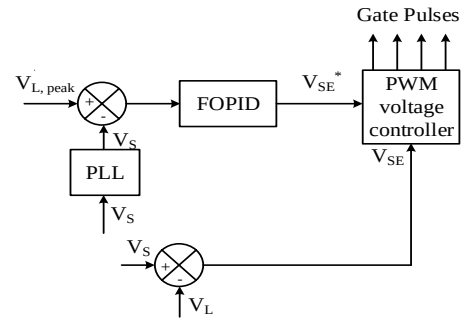


Figure 5. Schematic diagram of Series active filter

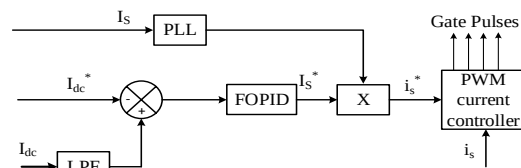


Figure 6. Schematic diagram of series filter

caused by load disconnection/connection and supply side voltage swell/sag even though the average dc link voltage is retained at a constant present level in the steady state. The magnitude of the series injected voltage must remain constant because of the considerable dc link voltage deviation during such transients, which affects the varied load voltage magnitude. In proposed work, DC link voltage is constantly maintain at 700V which is maitiani through adjusting the capacitor.

FOPID Controller

The suggested FOPID controller uses CGA optimization to reduce PQ problems brought on by disturbances in voltage and current in the hybrid RES interface grid-connected system. In order to lower current and voltage errors, the FOPID controller is used in shunt and series active power filters. The FOPID controller is a complex variant of the common PID controller. It is possible to achieve damping qualities, which control the phase margin over a certain frequency range, by utilizing a fractional controller. In proposed model, the error value of load voltage and its reference voltage is given to the controller for pulse generation. It is crucial to remember that before the system settles to the intended voltage value, it may experience longer-term oscillations and greater overshoots/undershoots due to improper tuning of the controller. Therefore, getting the best dynamic response from the AVR system under consideration requires careful controller tuning. Ultimately, with the appropriate amplification, the signal is supplied to the exciter circuit, which produces the regulated flux needed for the capacitor to produce electricity at the required voltage level. The FOPID controller, whose gain parameters were monitored using the CGA approach, minimized the error in voltage and current. The mathematical formulation of the FOPID controller transfer function is as follows,

$$FOPID(u(t)) = K^P E(S) + K^I S^{-\lambda} E(S) + K^D S^{\mu} E(S), (\lambda, \mu > 0) \quad (21)$$

Where, $E(S)$ denote as error current and voltage, $u(t)$ is denoted as outputs, K^P denote proportional gain constants, K^I denote integral gain constants, $S^{-\lambda}$ describe the fractional order of integral terms, also S^{μ} describe the fractional order of derivative terms. FOPID controller can be used to minimize error voltage and current by reducing error signals, eliminating signal undershoot and overshoot problems, and increasing the controller's speed of response of critical factors in achieving the maximum output to regulate the hybrid RES system. Error values are minimized by selecting optimal pulses of filter switches. The optimal gain

parameters are used to tunes the pulses to reduce the error in the filter. The proposed FOPID with a CGA controller reduced the oscillations of the standalone microgrid system and improved its stability and dependability. Under differential load, the error is computed by comparing the reference and real values. Optimal pulses needed for the FOPID are produced using CGA methods. The FOPID controller and CGA with the proper suggested controller have minimized the oscillations in the HRES system, allowing for system dependability and stability. Thus, the recommended Shunt and Series APF control system compensates for power quality issues.

Chaos Game Optimization Algorithm (CGA)

A subfield of mathematics known as chaos theory focuses on the properties of dynamical systems, which are very sensitive to their beginning conditions. Even though they are chaotic, these dynamical systems display some basic behavioural patterns, such as fractals, repetitive templates, comparable loops, and many sub-systems, which characterize them as self-similar and self-organized dynamical systems. According to the chaos theory, a dynamical system's dependence on its initial conditions results in even little changes to those conditions, significantly impacting the system's future states. The concept holds that the approximate present condition of a system, which cannot accurately predict its future state, could predict the future state of the system. Fractal graphics are used to represent the bulk of chaotic processes. A fractal in mathematics is a region of Euclidean space where a particular geometric pattern appears at various scales. Fractals are systems that are self-similar because they have almost identical shapes at various scales. The Mandelbrot set is one of the most well-known fractals. It is a complex infinite barrier in which numerous recursive properties are slowly exposed at various scales.

The main shape of the fractal, in this case, a triangle, must first be constructed by choosing three vertices. A blue, red, or green colour is used to symbolize each of the chosen vertices. It will roll a die with two blue, two red, and two green faces. In this illustration, the initial random point that acts as the fractal's "seed" is selected. Depending on the colour of the dice, the beginning point's seed is shifted towards the associated vertex by half the distance between them as they are thrown. According to its new position, the seed is moved to the desired vertex, where it serves as the beginning point for the subsequent iteration. The Sierpinski triangle is finally formed by repeatedly rolling the dice. The flow chart of proposed CGA model is given in Figure 7.

Optimal Parameter Selection

Shunt and series APF controllers are available for UPQC. Applying these controllers to unbalanced loads, non-linear loads, and critical load conditions allows them to detect changes in the load side's current and voltage. The FOPID controller receives variations in voltage/current and reference voltage/current. The FOPID controller alters the series and shunt APF pulses in order to reduce faulty current and voltage. The best tuning setting for FOPID controller is discovered using CGA method. It is a new optimization technique that provides best results for fitness function of error minimization. Based on these optimal solutions, FOPID controller modifies series and shunt APF pulses to manage the PQ issues. The flow of optimal parameter selection is stated as follows,

i) Initialization

For the purposes of the optimization algorithm, the Sierpinski triangle is the search space for potential solutions. These viable seeds' starting places are randomly chosen in the search space. Set the CGA's initial parameters, such as the problem's dimension, population size, and the maximum number of iterations, lower bound, upper bound and five parameters of the FOPID controller as an input of the total population in CGA.

$$P = \{K^P, K^I, K^D, S^\lambda, S^\mu\} \quad (22)$$

Where P denotes the problem population that varies from 1 to n .

ii) Fitness function

In order to discover a solution to a given problem that is close to the desired problem's ideal solution, an objective function known as a fitness function is used. At each population test is done to find the best fitness that find the optimal decision of parameters. Here, the fitness is considered as Mean Square Error (MSE). Smaller error is closer to the controller system's desired values.

$$Fitness = \min(J) \quad (23)$$

$$J = \sum_{i=1}^n |y_r(t) - P_n| \quad (24)$$

where, $y_r(t)$ denotes the reference value, P_n denotes the observed value of each population set, and J represent MSE.

iii) Updation

The seeds position based on fitness function is updated. The last of the follower are advancing

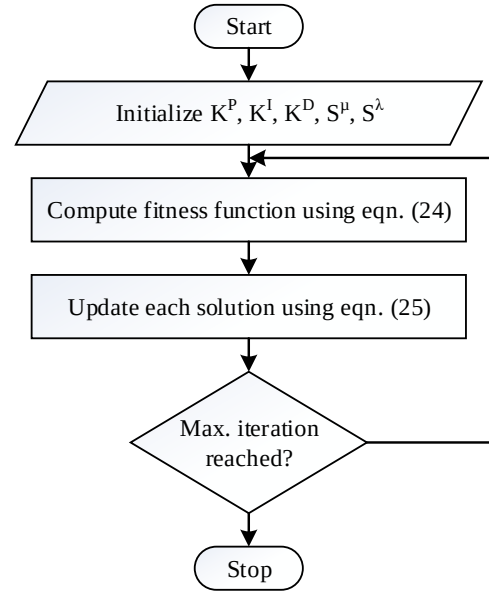


Figure 7. Flow chart of proposed CGA model

toward the position of seeds. The location updates for this seed are performed based on some random variations in the arbitrarily chosen decision factors. The updation of each process is done through the use of the following equation,

$$Seed_i^k = X_i(x_i^k = x_i^k + R), \quad k = [1, 2, \dots, d] \quad (25)$$

Where, X_i denote the i th solution candidate, R signifies uniformly distributed random number $[0, 1]$ and x_i denote the initial position of the eligible seed. The FOPID controller's benefit settings can be selected using the fitness functions.

iv) Termination

Terminating is the stopping process when the optimal solution of the FOPID controller is obtained, and the process goes to an end otherwise, repeat it.

After the upgrading procedure, the optimal plan for accomplishing the workout function and reducing power quality issues can be chosen. The FOPID controller's benefit settings can be selected using the fitness functions. Prior to utilizing the best solutions, which are the maximal iteration obtained and limitations are assessed, the final condition should be confirmed. The HRES system's ideal power flow is ascertained using the best solutions. The CGA algorithm's power quality reduction strategy can be used to accomplish them. The section that follows provides a detailed analysis of the efficiency metrics of the suggested approach.

Result and Discussion

For reducing power quality problems in a grid-integrated hybrid RES, use UPQC based on a CGA controller. The grid is used to continually supply electricity to the non-linear load. During the PQ fault period, the grid supply is interrupted so an UPQC is placed between the grid and the load. The UPQC supplies power from the hybrid RES system at the PQ issues period. The controlling strategy of UPQC was done using an optimized FOPID controller. The new controller-based UPQC secures the system by reducing the harmonics content and mitigating PQ concerns under all conditions. The proposed model was designed, and the performance are observed using MATLAB/SIMULINK tool. The parameters used for the proposed model design are demonstrated in Table 1.

The simulation of an ideal FOPID controller-based UPQC was created using these parameters to reduce PQ issues in grid-integrated hybrid RES systems. Figure 8 displays the Simulink model of the proposed system.

The proposed mitigation process was mainly done through the use of an optimal FOPID controller. Here, the CGA was introduced to select the optimal values of a controller for appropriate pulse generation. The CGA objective was defined as an error that is minimized in order to determine the controller's ideal value. Figure 9 shows the convergence curve for both the current algorithm and CGA. The objective function's value is plotted against the computing time throughout the minimization process in the convergence curve. The proposed model have 1.015×10^7 values, and the existing Aquila Optimization (AO) offer

1.125×10^7 value. This demonstrates the proposed model provides a low error than the traditional approach.

In order to meet the load requirement, the generated power is transmitted. When more energy is produced, it can be stored in the battery and used when necessary. The PV, wind, and grid power is analyzed, and the ranges are plotted in Figure 10. It demonstrates the PV generates 16,000 W at normal irradiance, and the temperature period is shown in Figure 10(a), wind generate 12 kW at normal 12 m/s wind speed, which is provided in Figure 10(b), and the grid supply constant power of

Table 1. Parameter and its ranges for modelling

Description	Parameters	Values
Grid	Frequency	50Hz
	Voltage	415V
	Resistance	0.8929Ω
	Inductance	$16.58e-3H$
DC link	DC link capacitor	$5000e-6 F$
	The voltage at the DC link	700V
Unbalanced 3 ϕ RLC load	L	100 H
	C	100 F
Wind	Rated power	1.2 kW
	Frequency	50Hz
	Voltage	258 V
	Speed	12 m/s
Li-ion battery	Rated capacity	350Ah
	Open circuit voltage	48.3V
	Max capacity	450Ah
	Full charge voltage	756V
	Short circuit current	5.8A
	Nominal voltage	650V
PV panel	Voltage or current at max power	39.80V/5.40A
	Total series cells	19
	Total parallel cells	10

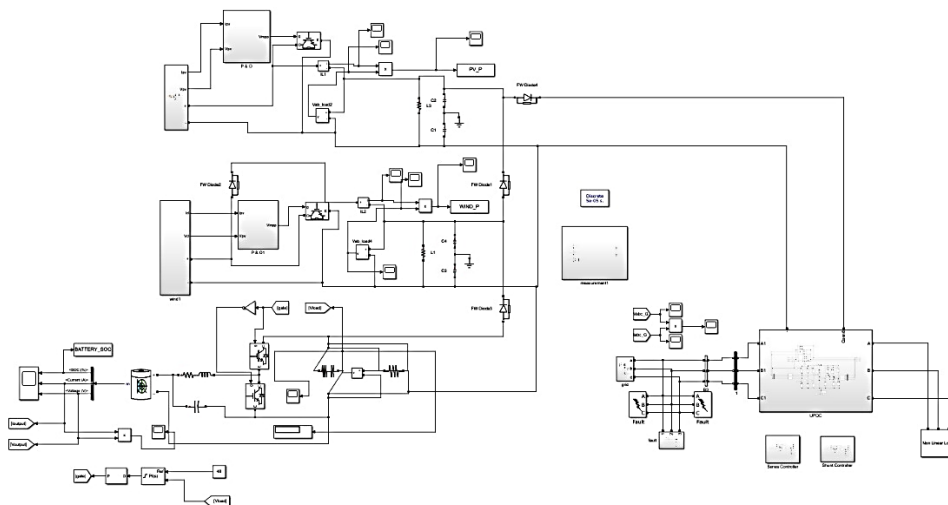


Figure 8. Simulink structure of proposed optimal FOPID-based UPQC in a grid-hybrid RES system

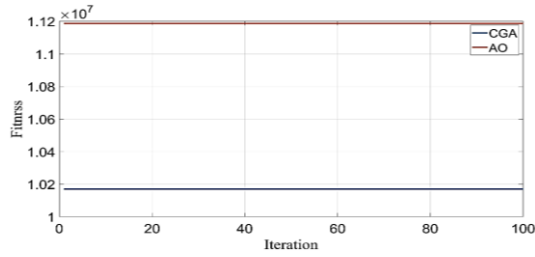
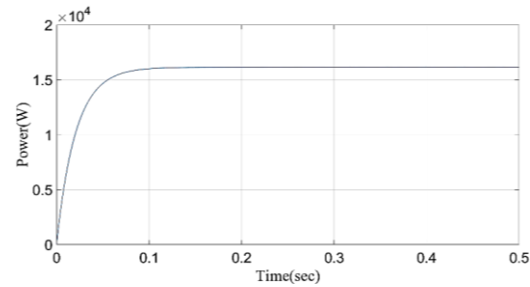
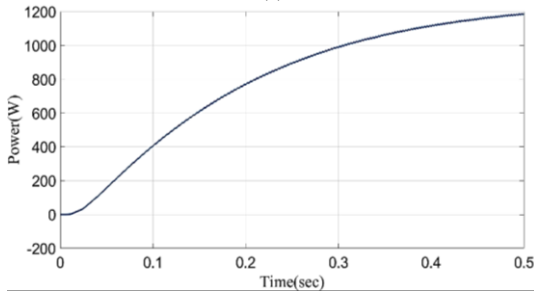


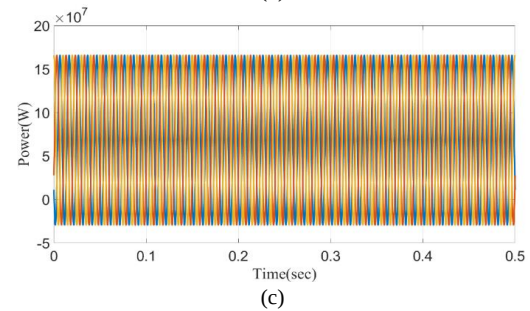
Figure 9. Convergence curve of proposed CGA model



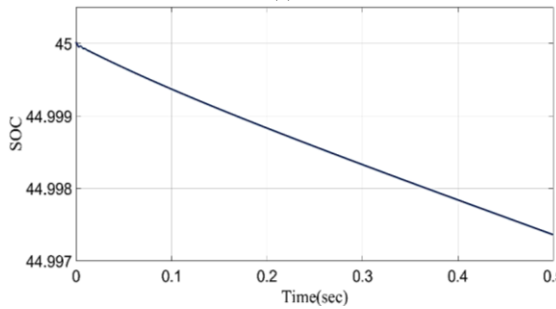
(a)



(b)

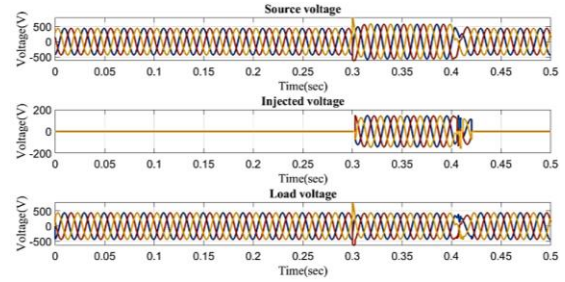


(c)

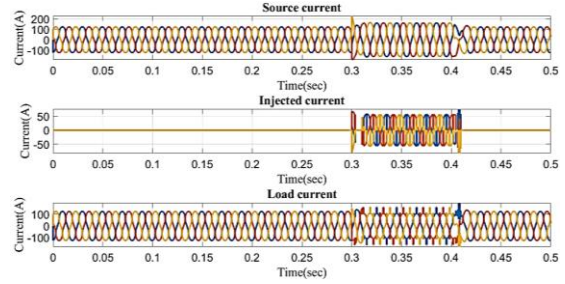


(d)

Figure 10. Power generation of (a) PV, (b) wind, (c) grid and (d) SOC



(a)



(b)

Figure 11. Analysis of (a) source voltage, injected voltage, and load voltage, (b) source current, injected current and load current at the swell condition

16×10^7 W that is illustrated in Figure 10(c) and the SOC also provided in Figure 10(d).

The proposed model was investigated under various conditions like a swell, interruption, and sag issues, and its corresponding harmonics were also investigated. The below section discusses the PQ issues mitigation process individually.

i) Swell fault

In this instance, a fault is causing a systemic problem by applying it to the system. The reference current/voltage and load bus current/voltage are compared to produce an error signal. The FOPID controller continues to operate despite the error indication. The controller analyzes the error to generate a corresponding pulse signal to the UPQC. That is, there is no error value during the normal period, but there are some values for error in the fault period. Based on this, the controller generates a pulse signal. At the suitable period of fault time, the UPQC injects voltage and current corresponding to mitigate the issues.

The compensation level of UPQC at the sag fault is demonstrated in Figure 11. It shows the source voltage and current have swell issues due to external or manual issues. To offset the power of the load, the UPQC injects the voltage and current at the appropriate time. According to the analysis, the swell fault occurs between 0.3 and 0.4 sec.

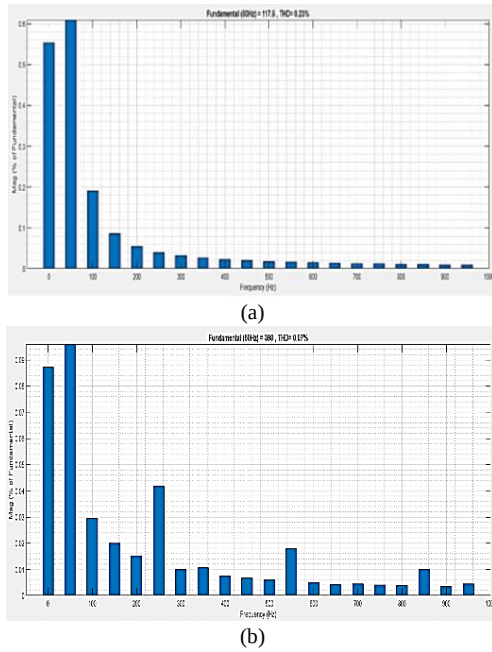


Figure 12. Analysis of (a) current (b) voltage THD at swell fault

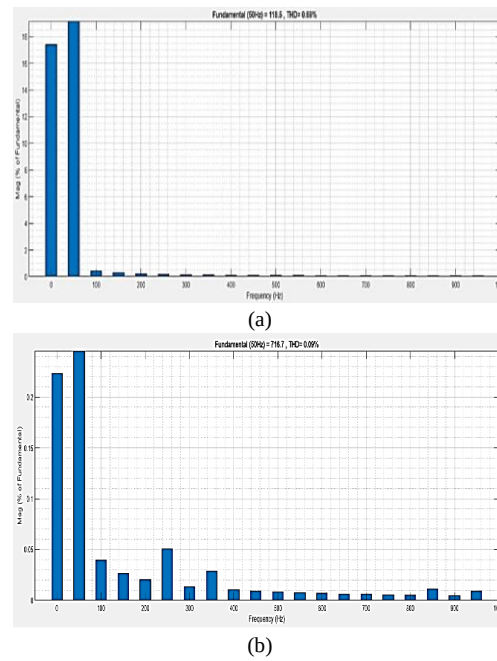


Figure 14. Evaluation of (a) current (b) voltage THD at sag fault

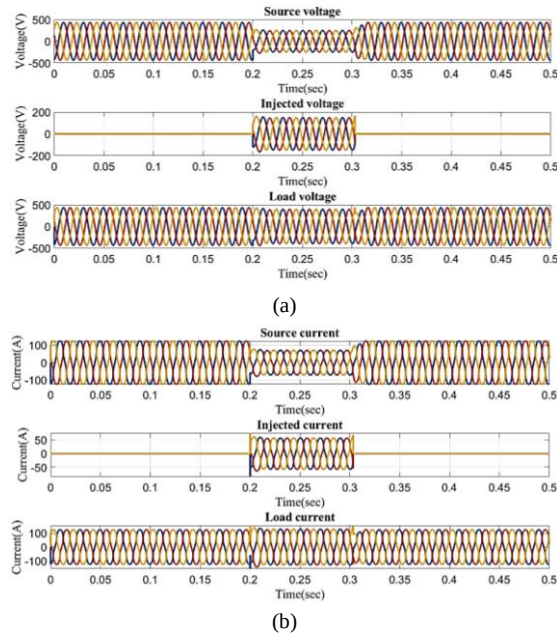


Figure 13. Analysis of (a) source voltage, injected voltage, and load voltage, (b) source current, injected current and load current at sag condition

During this time, the injection was made to address security-related problems.

The total harmonic distortion (THD) was also analyzed and sketched in Figure 12 during the swell compensation. The most important problem with

a system is its harmonics since they lead to serious load-side economic problems. The UPQC injection process is made possible by the CGA-based FOPID controller, which pulses out a voltage of 0.07% and a current of 0.23%. The sag condition was investigated in the following part, and the values were observed.

ii) Sag fault

A fault is applied in the system to create sag issues and analyze the corresponding issues mitigation performance. The swell fault increases the power to 10% above the normal power. The optimal controller analyses the load voltage error value and its reference to make a pulse signal. Based on this signal, the UPQC injects the power to compensate for the load requirement.

The sag issues resolved graphical representation is shown in Figure 13. This illustrates the CGA-based controller reduces the sag problems from 0.2 to 0.3 seconds by providing a suitable pulse signal. This illustrates how the suggested ideal controller-based UPQC injects current and voltage, respectively, to lessen issues on the load side.

After that, the sag fault THD is investigated, and the gathered values are demonstrated in Figure 14. The pictorial representation shows the optimal controller to reduce the THD via recompense of the issues. The THD value of sag fault is 0.69% for current and 0.09% for voltage, which are acceptable values of power system standards. In the upcoming

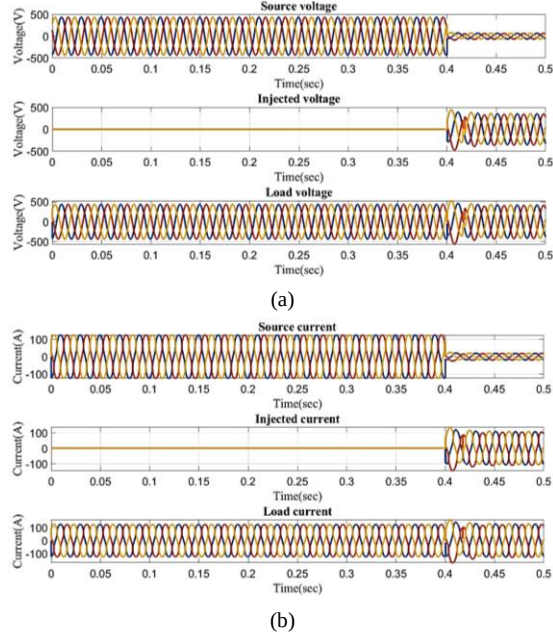


Figure 15. Analysis of (a) source voltage, injected voltage, and load voltage, (b) source current, injected current and load current at interruption condition

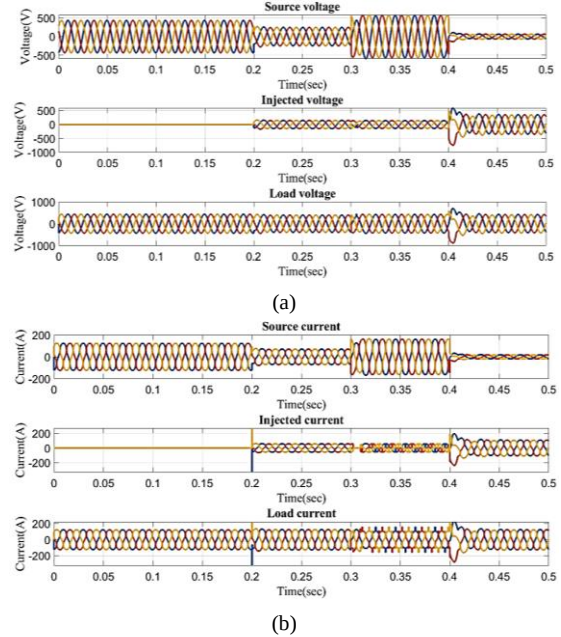


Figure 17. Analysis of (a) source voltage, injected voltage, and load voltage, (b) source current, injected current, and load current at combined fault condition

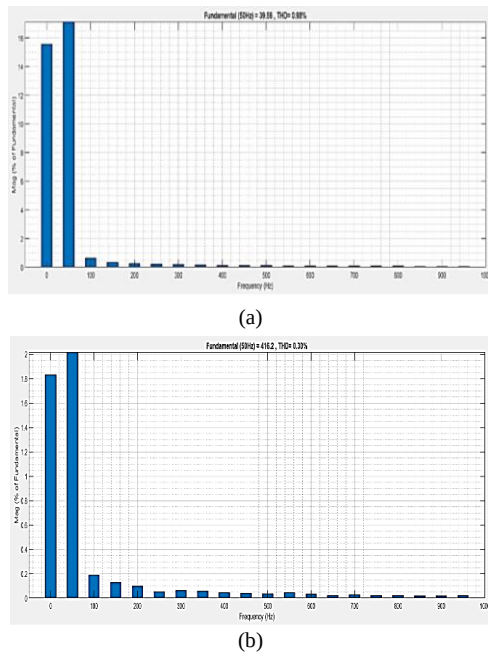


Figure 16. Analysis of (a) current (b) voltage THD at interruption fault

part, the interruption issues mitigation process is investigated and verified the working states.

iii) Interruption fault

Interruption issues are created in the system, and the mitigation process is analyzed using the proposed optimal FOPID controller based UPQC model in this part. A brief drop in power due to the interruption leads to a load failure or power outage. The CGA-FOPID controller analyzes the error signal and generates the necessary pulse signal in order to reduce the interruption fault.

The interruption compensation using the proposed CGA-FOPID based UPQC is shown in Figure 15. The investigation proves the fault is caused in the period of 0.4 sec to 0.5 sec, in this period, the power is below 1 pu. To mitigate the issues, the optimized controller generates a suitable pulse signal to inject the current and voltage at this period.

The current and voltage THD are analyzed, and the recorded values are shown in Figure 16. The most important system problems are harmonics since they seriously hurt the load side's economy. The pulse used in the UPQC injection process is produced by the CGA-based FOPID controller, which has a THD of 0.30% for voltage and 0.98% for current. The combined fault condition was examined, and the following section noted the values.

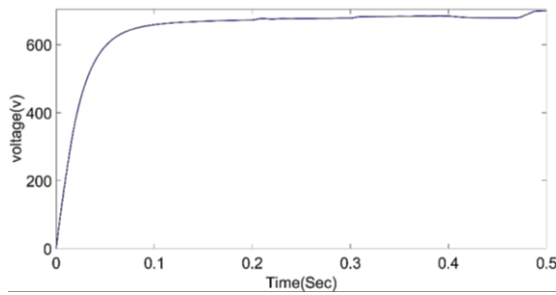


Figure 18. Evaluation of DC link voltage

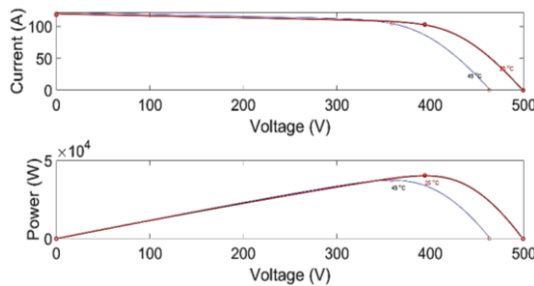


Figure 19. Evaluation of PV characteristics

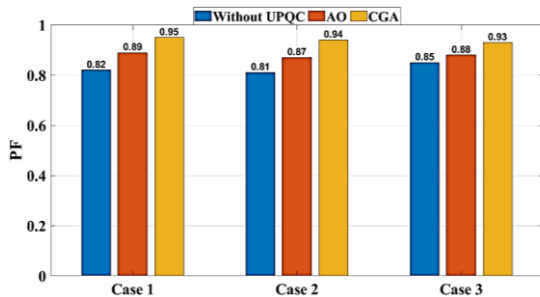


Figure 20. Comparison of power factor at various conditions

iv) Combined faults

In this period, swell, interruption, and sag issues are applying in the system to analyze the recompense performance. Each and every second, the controller analyses the error value to recompense the issues to provide a stable output power. The optimal controller generates a suitable pulse for the compensator to inject the power to mitigate the issues.

The current and voltage compensation of the proposed design is illustrated in Figure 17. The study established that the fault occurred from 0.2 to 0.5 seconds, which was sag (0.2 sec to 0.3 sec), swell (0.3 sec to 0.4 sec), and interruption (0.4 sec to 0.5 sec). In order to address these problems, the optimized controller generates a suitable pulse signal to inject current and voltage at this time.

The DC link voltage is evaluated, and the values are shown in Figure 18. The proposed UPQC design maintains a stable voltage at 700 V in any circumstance. Then the PV's IV and PV characteristics are analyzed and plotted in Figure 19.

Afterwards, In Figure 20 the proposed model power factor (PF) contrasted with existing approaches like AO and without UPQC. In sag condition (case 1), the PF without UPQC is 0.82, AO based controller is 0.89, and the proposed controller is 0.95. Same as in swell fault, the absent of UPQC is 0.81 PF, the AO-based controller is 0.87 PF, and the proposed controller is 0.94 PF. Also, the interruption fault was analyzed. In this period, without UPQC have 0.85 PF, the AO-based controller have 0.88 PF, and the proposed CGA have 0.93 PF. This proves the proposed CGA model provides an effective power factor over traditional models.

Table 2. Comparison of THD at sag

Techniques	Load voltage THD	Load current THD
PSO-UPQC (Rao <i>et al.</i> , 2021)	5.41	3.34
KF-UPQC (Alam and Arya, 2020)	3.16	26.83
Proposed	0.09	10.19

Comparative Analysis

This section compares the efficacy of the proposed system to different existing approaches in order to validate the work. The suggested model performance contrasts with Particle Swarm Optimization (PSO) based UPQC and Kalman Filter (KF) based UPQC.

The comparative analysis of performance parameters in the proposed and existing model are shown in Table 2. The PSO-UPQC controller provides 5.41% THD at the load voltage and 3.34% THD at the load current during sag mitigation, the same as the KF-UPQC controller provides 26.83% at the load current and 3.16% THD at the load voltage. Compared to these, the proposed model provides 0.09% THD at load voltage and 10.19% THD at the load current after mitigating the sag fault. It demonstrates that the suggested approach yields superior results than the ones currently in use.

Conclusions

An optimal FOPID controller based UPQC model was developed to validate the performance in a grid linked hybrid RES system under various PQ disturbances. Increased power demand due to nonlinear loads, critical loads, and unbalanced loads

on the load side creates power quality issues in the system. Poor power quality demagnetizes electrical and mechanical equipment, increases electricity costs, and has an adverse effect on the economy. A lot of research is going on reducing these power quality concerns. A UPQC is employed to decrease these PQ concerns in this proposed system to meet the power demand. A FOPID controller based on CGA is placed to enhance the UPQC and provide an efficient operation. BESS, PV, and WT are used for power generation. BESS is used only in the critical condition of PV and wind turbines with insufficient load power. FOPID has the potential to offer greater control performance due to its tenable differential and integral orders. It has five optimal parameters selected properly to make the operation effective. The best parameter values for a controller were chosen using CGA, which reduces the objective function to solve the FOPID controller's optimal issue. Root mean square error was The objective function for choosing the optimal solution. The lower error value was chosen as an optimal solution for the controller. The reference and load voltages were compared every second, and the error was given to the FOPID controller, which evaluated the signal to generate a pulse signal for the UPQC. The optimal controller-based UPQC model provides low THD values at all cases, an accepted range of IEEE standards. The suggested model offers THD value at sag, swell, and interruption period of current was 10.19%, 9.77%, and 10.09%, and voltage have 0.09%, 0.07%, and 0.30%. Its performance was compared to a few other recent methods to confirm the proposed controller would operate. In the future, a novel artificial intelligence based controller will be developed to overcome the optimal problems and enhance the mitigation performance of the compensator in a hybrid RES system.

Declarations

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Conflict of Interest: The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Availability of data and material: Not applicable

Code availability: Not applicable

Author contributions: The corresponding author claims the major contribution of the paper including formulation, analysis and editing. The co-author provides guidance to verify the analysis result and manuscript editing.

Compliance with ethical standards: This article is a completely original work of its authors; it has not been published before and will not be sent to other publications until the journal's editorial board decides not to accept it for publication.

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