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Research Article

Enhancement of power quality using UPQC integrated with renewable energy sources through an improved sparrow search-based PID controller

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Abstract
Conventional energy sources such as thermal power plants provide a significant amount of energy to the power system. However, these sources produce pollutants that contribute to environmental pollution. This problem can be mitigated by integrating renewable energy sources (RES) such as solar and wind power plants into the existing electrical infrastructure, helping to develop a pollution-free grid. However, integrating RES into the power grid causes various power quality (PQ) issues such as voltage sag, voltage swell, harmonics, and unbalanced voltages. Several methods have been examined in the literature to address PQ issues in power systems, including RES. The major issue is the PQ problems in grid-connected RES. The proposed study investigates the PQ issues arising from the source side of grid-connected RES. The sparrow search algorithm (SSA) optimization is used in the proportional-integral (PI) controller to efficiently control the switching pulses of the dynamic voltage restorer (DVR), thereby addressing PQ issues in an integrated solar-wind energy power grid. The integration of a DVR, connected in series with the unified power quality conditioner (UPQC), efficiently addresses PQ challenges such as voltage sag, swell, harmonics, and unbalanced voltages from the generator side of the power grid and its integration with solar and wind energy sources. This approach shows improved results compared to previous research and other optimization techniques. The performance of the proposed system has been investigated using the SimPower Systems toolbox of MATLAB Simulink version 2023b on an Intel i7 core processor, and the results demonstrate that the proposed technique efficiently resolves PQ issues in an integrated power grid system.

Keywords
Renewable energy, Power grid, Power grid integration, PQ, UPQC, DVR.

1.Introduction
By 2030, India intends to have a capacity of 500 gigawatts of renewable energy [1]. Historically, the electric power grid has not been designed with renewable energy production and integration. Electric utility companies utilize a variety of electric power system architectures based on distinctive equipment selections and design principles. The current electrical infrastructure in India is predominantly dependent on traditional power sources such as hydroelectric and thermal power facilities [2]. Thermal power plants that are powered by coal is used to generate the bulk electricity for the power grid. Predictions indicate the depletion of fossil fuels within the next two centuries, consequently, the power infrastructure may be unable to accommodate the rising energy demand [3].

Hence, it is imperative to improve the incorporation of renewable energy sources (RES) into the electrical grid. Additional research is required to address the insufficient integration of RES into India's electricity grid. As the cost of conventional energy sources increases, renewable power infrastructures emerge as a judicious measure to mitigate the expenditure associated with costly energy. Renewable energy is becoming increasingly cost-effective as expenses decline.

The production of renewable energy offers several benefits, such as meeting the increasing demand for electricity, facilitating the growth of clean energy companies, and enhancing the integration of non-conventional energy sources into the existing power grid. Solar and wind power are viable alternatives due to their well-established technological advancements and the support they receive from the government via various initiatives. To meet peak consumer demand,

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RES such as solar, wind, biomass, geothermal, and hydropower can be integrated with a central power plant, such as a thermal power plant within the power grid. Energy is crucial to the resolution of climate catastrophe and plays a pivotal role in it. The considerable amount of greenhouse gases, which envelop the Earth and retain solar heat, are discharged into the atmosphere during energy generation processes, including the combustion of fossil fuels for heat and electricity. The primary contributors to global climate change are fossil fuels, including coal, oil, and gas, which account for more than 75% of greenhouse gas emissions and nearly 90% of carbon dioxide emissions. Scientific research indicates that to mitigate the severe effects of climate change, emissions must be reduced by approximately 50 percent by 2030 and reach net zero by 2050[4]. The power grid must cease relying on fossil fuels and the grid should be connected with RES that are clean, accessible, affordable, sustainable, and dependable to reach this goal. Solar, wind, water, refuse, and geothermal heat are examples of RES that are abundant, naturally occurring, and produce few greenhouse gas emissions and contaminants. At present, fossil fuels constitute over 80% of worldwide energy generation, nevertheless, there is a growing inclination towards greener energy alternatives [5]. At present, nearly 29% of electricity is generated from renewable sources [6]. Progressions in power electronics facilitate the efficient transformation of RES into usable electrical energy. Possible consequences of integrating RES into the grid include power quality (PQ) concerns. Significant fluctuations occur in renewable electricity because of the intermittent and unpredictable nature of RES. The increased adoption of RES gives rise to significant PQ concerns stemming from excessive voltage fluctuations. Challenges encountered on the power grid, including fluctuations in frequency caused by demand and generation shifts and voltage drops resulting from short circuit failures, can affect interconnected RES, giving rise to operational circumstances that are intricate and unpredictable [7]. Potentially compromising the dependability and stability of forthcoming power systems is PQ. *Figure 1* shows the different RES that can be integrated with the existing power grid. Numerous findings regarding PQ issues and their resolutions because of renewable energy utilization have been documented [8]. Considering the increasing scholarly and commercial interest in smart grids, it is imperative to standardize current methodologies and technologies to provide direction for forthcoming research and engineering endeavors in this critical domain. Technological challenges are encountered when wind and solar energy are integrated into existing power infrastructures. These challenges include voltage management, sag and swell, transients, interruptions, flickering, harmonic distortion, and stability [9]. Concerns regarding PQ must adhere to international electrotechnical commission (IEC) and institute of electrical and electronics engineers (IEEE) standards. Various research papers [10–12] indicate that PQ issues can arise at the generation, transmission, and distribution stages. PQ is of the utmost significance for solar photovoltaic (SPV), and wind energy sources integrated with power grid. An important concern with the integration of renewable resources into the power grid is the PQ delivered to clients connected to the power grid. A study of several publications published in the recent decade has been conducted to examine PQ issues and associated mitigation strategies. The topic of voltage control has been addressed in [13]. In [14], the phenomenon of voltage sags and swells is explored, alongside various strategies for alleviating their effects. Meanwhile, [15] delves into the issue of flicker and proposes mitigation techniques. Furthermore, [16] discusses the investigation conducted by researchers on harmonics and suggests methods for minimizing their adverse effects. The authors also tackle issues related to active and reactive power, outlining compensatory approaches. Gao et al. [17] discuss various PQ challenges and associated mitigation approaches in a generic context. Solar and wind energy sources connected to the electrical grid can cause PQ problems such as imbalanced voltage sags and swells, harmonics, transients, and voltage interruptions. Many research articles have been published in recent years to tackle these PQ challenges.

Figure 2 and *Table 1* illustrate the PQ issues and their causes and effects produced by the existing power infrastructure respectively. The short circuit ratio (SCR) of RES is lower than that of conventional power plants. A power grid with a SCR between 2 and 3 is considered weak and can lead to PQ problems. Solar and wind power plants contribute to increased PQ issues in the existing electrical grid due to their reduced SCR and stability. Previous investigations have addressed the occurrence of unbalanced voltages resulting from different faults in grid-connected solar or wind power plants. However, the extended fault clearance time in these scenarios can potentially harm the electrical equipment linked to the load side of the grid-connected solar wind power plants.

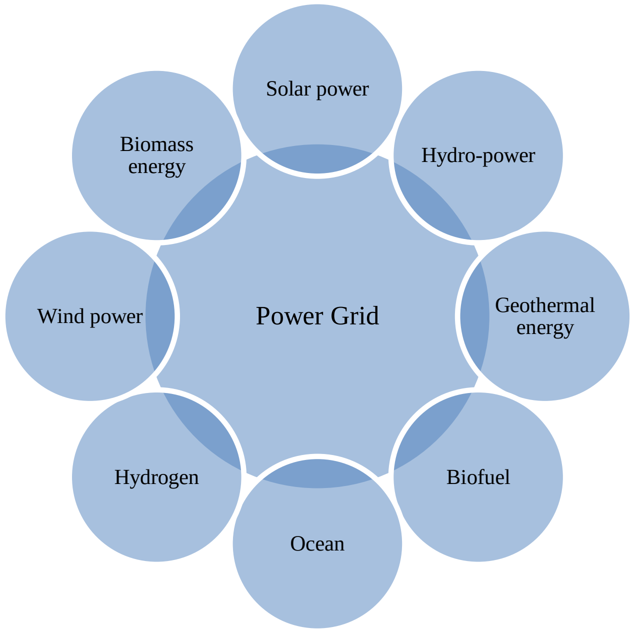

Figure 1 Power grid with RES

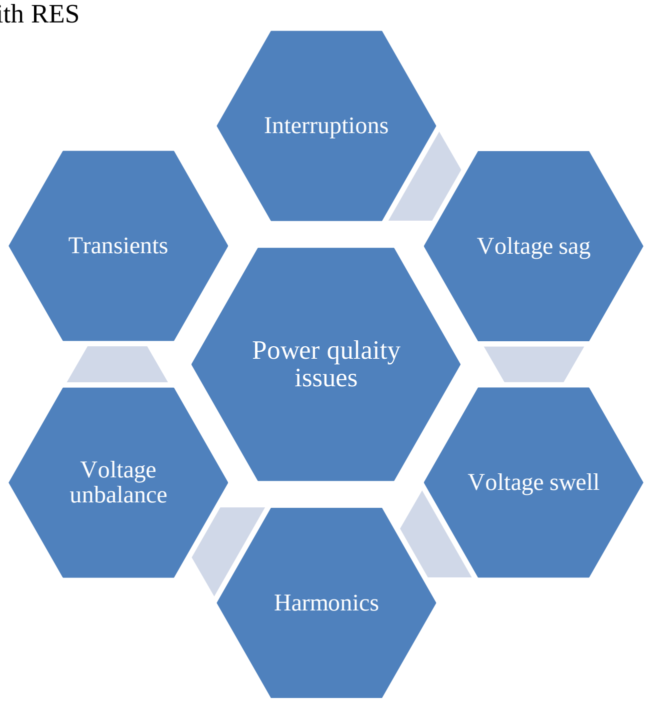

Figure 2 Power quality issues

Table 1 shows the causes and effects of PQ issues. Imbalances are caused by large single-phase loads such as induction furnaces and traction loads, as well as the inappropriate distribution of all single-phase loads throughout the three phases of the system. These imbalances can also be a result of a breakdown. Unbalanced systems indicate the presence of a detrimental negative sequence that affects all three-phase loads. Three-phase induction machines are the loads that are most affected. Voltage swell refers to a temporary rise in voltage at the power frequency that exceeds the standard limits. It lasts for more than one cycle but often less than a few second. Harmonics are generated because of the presence of RES in the power system. Excessive voltage can result in data loss, flickering of lighting and displays, as well as the halt or destruction of sensitive equipment. Malfunctions occur on the transmission or distribution network, sometimes on parallel feeds. Deficiencies in the consumer's installation. Heavy loads and the activation of powerful motors cause voltage sag. The ramifications of voltage sag Failure of information technology equipment, namely microprocessor-based control systems such as personal computers (PCs), programmable logic controllers (PLCs), adaptive software developments (ASDs), etc., which can result in a halt in the process. Malfunctioning of contactors and electromechanical relays. Electric rotating machines might experience disconnection and a decrease in efficiency.

Table 1 Causes and effects of PQ issues [18]

PQ problems	Definition	Cause	Effect
Transient	Voltage disturbances for a short duration time	Switching loads	Load equipment.
Voltage sag	Voltage dip in the nominal supply	Short circuit fault	Reduction in brightness of the light
Voltage swell	Root mean square (RMS) voltage rises above the specified voltage	Turning off large loads. Switching ON of heavy machine.	Causes PQ issues.
Interruptions	In less than one minute, the supply voltage is reduced to a level below 0.1 per unit.	Beginning of heavy loads. Incorrect compensation for volt-amps reactive (VAR).	Causes PQ issues.
Harmonics	Non-sinusoidal waveforms of higher-order frequency	Power electronic devices	Heating effect in the load centers

Flexible AC transmission systems (FACTS) can play an essential role in resolving PQ concerns in power networks integrated with RES [19]. The FACT system is based on power electronic devices and utilizes static devices to improve PQ, enhance power transfer capacity, and provide better control. FACTS devices improve the power transfer capacity of transmission lines by enhancing voltage stability, transient stability, voltage control, dependability, and thermal limitations of the transmission network. *Figure 3* shows the general configurations of the unified PQ conditioner (UPQC). UPQC is one of the efficient FACT devices. As an instrument for power conditioning, UPQC enhances PQ on the source and load sides of the power system network. Active power filters (APF's) in series dynamic voltage restorer (DVR), APF's in shunt distribution static synchronous compensator (DSTATCOM), and APF's in back-to-back configurations with a shared direct current (DC) capacitor are all part of this system. An integral part of the UPQC, the DVR is a series APF that mitigates fluctuations, harmonics, imbalances, and dips and spikes in the supply voltage. One part of the UPQC's shunt APF, the DSTATCOM, is responsible for reducing load-side current quality issues with linked renewable power sources.

The UPQC's general layout is shown in *Figure 3*.

a) This system contains two inverters. One of them serves as a shunt APF more specifically a DSTATCOM and is connected across the load. The second inverter serves as a series APF, or a DVR, by being connected in series with the line.
b) This system uses two inverters. One of them serves as a DSTATCOM, or shunt APF when it is connected across the load. The second inverter, which is connected to the line in series, performs as a series APF, or DVR.
c) The shunt inverter is linked to the network through the utilization of the shunt coupling inductor 'L'. It facilitates the reduction of irregularities in the existing waveform.
d) A frequently employed method for establishing a DC link involves the utilization of either an inductor or a capacitor.

The inductor and capacitor (LC) filter passively decrease the high frequency switching ripples in the inverter's voltage output. A series injection transformer links the network with the series inverter. Choosing the best turn ratio is a common method to decrease the voltage and current requirements of a series inverter. Although the usage of RES appears promising for transitioning away from non-RESs, it is crucial to find effective ways to mitigate power fluctuations experienced by end users due to the intermittent nature of these sources. The intermittent nature is mostly caused by its reliance on meteorological factors like wind speed and sun irradiation. With the progress in power electronics, industrial loads like semiconductor manufacturing and chemical industries are now highly sensitive to power fluctuations. Power companies and customers need to address this issue to ensure power fluctuations remain within acceptable limits. The sensitive load side will make use of custom power devices (CPD) in either a series or shunt configuration or a combination of the two. According to sources, a DVR is the most comprehensive, practical, and cost-effective series-type CPD [20]. Voltage sag, swell, interruptions, harmonics, and flickers are the main PQ concerns that a DVR is used to fix. These problems account for more than 80% of all PQ difficulties. To prevent losses caused by tripping, it protects critical consumer loads. Most voltage disturbances are sags, which can be caused by a problem on a faraway bus, severe load switching, starting large motors, or activating transformers. There are many reasons why a photo voltaic (PV) wind power system could experience sag, including intermittent sources and the ones already mentioned. A variety of power sources, including the mains without a storage component, self-storage capacitors, battery energy storage (BES), and superconducting magnetic energy storage (SMES), can be used to power the DVR [21]. *Figure 4* shows the power grid connected with solar wind hybrid power plant, nonlinear load and UPQC. Wind, PV, conventional, and hybrid systems all make use of the UPQC to improve PQ. To address PQ concerns, a power grid connected with solar wind hybrid power plant, nonlinear load and UPQC is used in conjunction with conventional power systems. A solar-wind hybrid power plant, nonlinear load, and UPQC are all depicted in *Figure 4* of the power grid. Here UPQC is used to address the PQ issues from the source and the load side. DVR part of the UPQC addresses the PQ issues from the source side while as DSTATCOM of the UPQC addresses the PQ issues from the load side of the power grid connected with the RES.

This research utilizes the sparrow search algorithm (SSA) for the proportional integral derivative (PID) as its optimization technique in the DVR part of the UPQC for mitigating the PQ issues produced in a power grid connected with solar wind RES. The performance of the suggested technique is validated using the Sim Power System toolbox in MATLAB 2023b on an Intel i7 core processor.

This paper presents an integrated power grid connected with solar wind energy source that effectively eliminates the following PQ issues produced from the source side of the power grid by utilizing the SSA optimization in the PID controller of the DVR part of the UPQC.

a) Balanced voltage sag
b) Balanced voltage swell
c)Balanced voltage sag with harmonics
d)Balanced voltage swells with harmonics
e) Source side harmonics.
f) Unbalanced voltage sag
g) Unbalanced voltage rise
h) Harmonics with unbalanced voltage sag
i) Harmonics with unbalanced voltage swell

When it comes to RESs and their grid integration through various interface units, this study starts by reviewing the current literature on PQ challenges. Subsequently, it suggests a way to optimize the PID controller with an effective SSA and incorporate the DVR to reduce PQ problems in grid-integrated RESs such as, solar wind power plants.

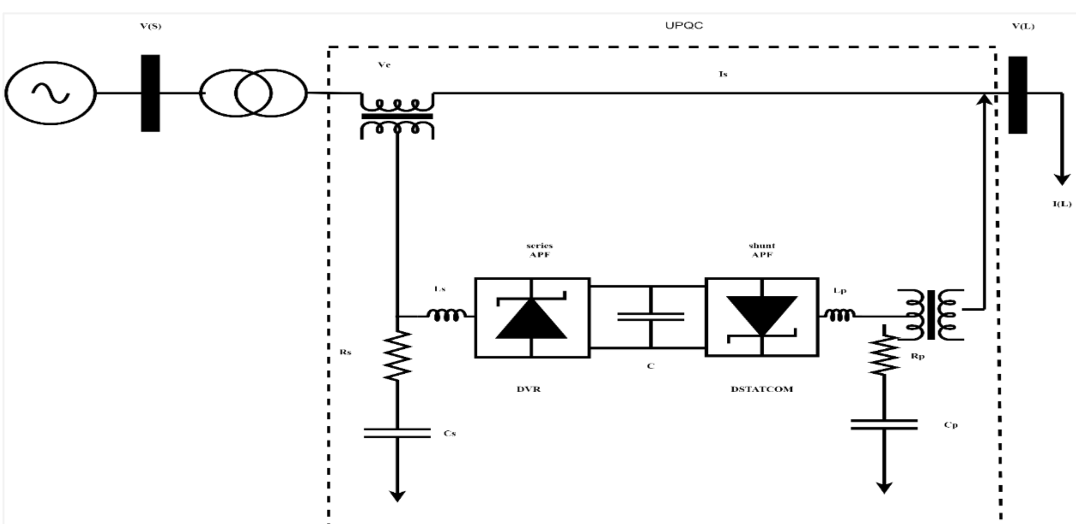

Figure 3 General configuration of UPQC

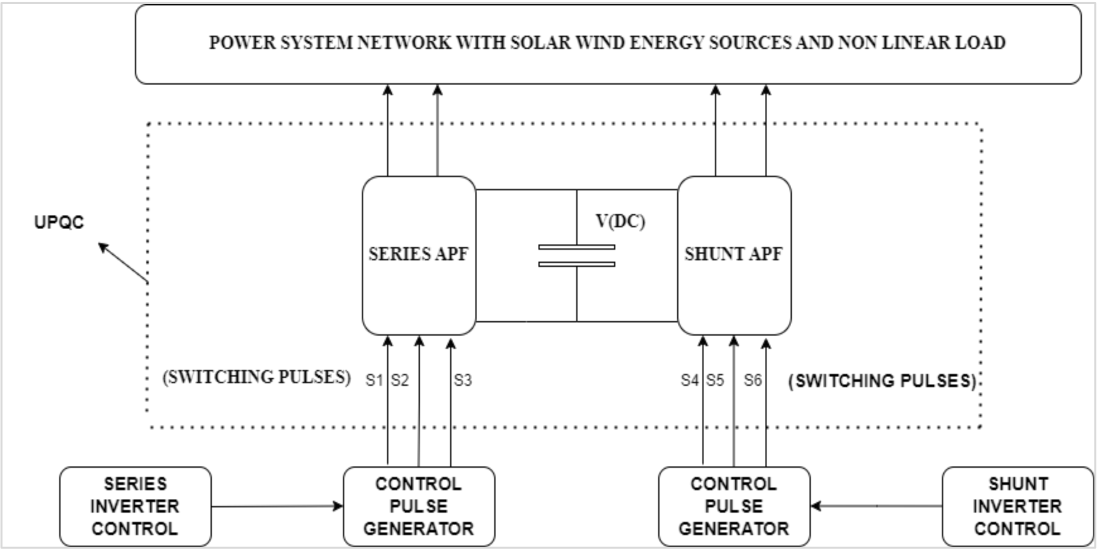

Figure 4 Power grid connected with solar wind hybrid power plant, nonlinear load and UPQC

Section 1 discusses the introduction of the paper. While Section 2 covers the literature survey of the previous research papers regarding PQ issues. Section 3 discusses the methodology to remove the PQ concerns in an integrated power grid system. Section 4 discusses the outcomes of the simulations for the suggested PID controller of the DVR, and section 5 investigates the analysis of those outcomes. The conclusion and future work are included in section 6.

2.Literature review

Numerous research endeavors have been dedicated to addressing PQ issues within integrated systems, particularly in the realm of RES. Scientists have explored diverse methodologies and control techniques to bolster the efficiency and reliability of these systems [22]. PQ enhancement is a crucial pursuit within the realm of power systems, with various proposed methods to tackle PQ challenges [23]. The latest advancements in this domain are discussed below:

One approach involves the creation of a hybrid APF aimed at PQ enhancement [24]. The performance of the UPQC scheme was assessed using adaptive neuro fuzzy inference system (ANFIS) techniques, effectively mitigating issues like swell and sag with advanced hybrid methodologies. In another study [25], a distributed power flow controller (DPFC) employing a fractional order proportional integral derivative (FOPID) controller, optimized using the black widow optimization approach, was introduced. While effective in managing voltage and harmonics, it may lack comprehensive power system problem identification.

Bharat et al. [26] proposed an integrated system combining an adaptive bald eagle optimization algorithm (ABEOA) based FOPID controller with a UPQC, aiming to minimize total harmonic distortion (THD) and address various PQ issues. However, further refinement of hybrid algorithms is recommended for enhanced control strategies. Additionally, the synchronous reference frame-power angle control (SRF-PAC) technique outlined in [27] was developed to distribute reactive power demand between two inverters using PI methodology. Despite its performance benefits, the system's cost remains a concern. Utilizing a fractional order proportional integral (FOPI) and fractional order fuzzy logic (FOFL) control approach for UPQC systems was proposed in [28] to improve overall PQ. This method enhances reliability, dynamic response, and reduces THD. Furthermore, the integration of wind energy systems with UPQC for improved energy output quality was explored in [29].

While effective, stability concerns were noted. A multi-converter unified fuzzy-based PQ controller introduced in [30] aimed to enhance PQ but may still require further refinement. Similarly, [31] suggested employing UPQC to enhance microgrid (MG) performance and address PQ issues related to sensitive loads. In another case, the PV-UPQC method examined in [32] utilized reinforcement learning and adaptive neuro-fuzzy control to enhance system efficiency and minimize THD. Meanwhile, [33] introduced an enhanced FOPID controller with a genetic search (GS) algorithm for DVR implementation, effectively resolving various PQ concerns. Similarly, [34] proposed a PQ strategy addressing light flickering, voltage stability, and harmonics in large-scale light emitting diode (LED) lighting networks. Addressing the need for improved PQ control techniques, [35] introduced the Cuckoo optimization approach for optimizing PI controller parameters in shunt controllers. Meanwhile, a multi-objective unified PQ conditioner (MO-UPQC) presented in [36] resolved PQ issues efficiently by managing voltage fluctuations and current at the grid side, along with incorporating PV panels and BES. Furthermore, innovative techniques such as variable phase angle control optimized using the JAYA optimization approach [37] and control techniques for UPQC in unbalanced and distorted weak grid conditions [38] were investigated. However, these strategies are often constrained by complexity, reliability, and cost concerns. Additionally, ensuring the effective performance of UPQCs in the presence of unbalanced and nonlinear harmonic loads is crucial for maintaining satisfactory PQ. However, the research discussed predominantly focuses on addressing PQ concerns within single MG operating in grid-connected mode. These strategies encounter various limitations, including complex design, suboptimal reliability, the need for enhancement, intricate structure, inadequate performance due to unstable voltage and current supply, and high cost. To overcome these challenges and enhance distribution system performance, the integration of FACTS is recommended. This integration aims to mitigate power supply issues and ensure a reliable power supply. Consequently, the proposed design introduces an innovative control technique for operating FACTS devices in hybrid renewable systems, targeting several PQ issues. In a specific study outlined in paper [39], researchers designed a three-phase single-stage SPV integrated PV-UPQC system. Voltage compensators within the system are connected in shunt and series configurations, interconnected via a shared DC link. These compensators not only rectify load current harmonics but also harness power from the PV array, thereby serving a dual purpose.

The advanced synchronous frame control techniques of the PV-UPQC, including a filter, enable precise extraction of the active current component of the load, enhancing the overall efficiency of the system. Moreover, the compensator addresses PQ concerns on the grid side, including challenges associated with grid voltage sags and swells.

In scenarios characterized by sag and swell, the compensator adjusts the voltage to be either in-phase or out-of-phase with the voltage at the point of common coupling (PCC). This integrated system combines the advantages of renewable energy production with improved PQ. Simulation using MATLAB-Simulink evaluates the system's performance under steady-state and dynamic conditions, considering nonlinear loads and various disturbances such as voltage sags and swells, imbalanced loads, and irradiation variations. The utilization of PV-UPQC effectively reduces harmonics generated by nonlinear loads, ensuring that the THD of the grid current remains within IEEE-519 standard limits. Furthermore, research conducted in [40] investigated harmonics in various RESs, including wind and solar. Various techniques for mitigating harmonics in wind power plants were explored, such as sequential energization of the three-phase transformer, the improved rider optimization algorithm (ROA), and the pre-insertion resistor method. Additionally, an improved method utilizing complex independent component analysis (ICA), complex linear regression modeling, and the stochastic subspace method for estimating harmonic impedance was proposed. The model's performance in reducing THD discharge voltage surpassed conventional models. Moreover, a study described in [41] focused on reducing voltage dips in a grid-connected hybrid PV wind power system using a battery and a dynamic voltage regulator based on SMES. By optimizing control strategies using power systems computer aided design (PSCAD) software for both symmetrical and asymmetrical voltage sag conditions, the research effectively controlled active and reactive power transfer between the alternating current (AC) and DC sides of the voltage source converters (VSCs). Notably, pre-sag compensation reduced phase shifts without increasing DC-link active power consumption. Additionally, research discussed in [42] evaluated PQ issues in a power grid connected to a PV system, examining strategies for minimizing and enhancing capabilities.

The integration of RESs into the current power grid is impeded by challenges related to PQ and synchronization with conventional power plants. Nevertheless, various conditioning devices with efficient control algorithms have been utilized in research papers to address PQ concerns such as unbalanced voltages, harmonics, and voltage sag/swell, including the ROA, ANFIS Controller, Perturb and Observe (P&O) algorithm, variable step based improved least sum of exponentials (VS-ILSE) control algorithm, in conjunction with enhanced phase locked loop (EPLL). Looking ahead, India's power grid is expected to witness increased penetration of RESs such as solar and wind energy power plants, with ongoing technological advancements aimed at addressing PQ and synchronization issues with grid-integrated RES. Integrating FACTS devices is recommended to improve distribution system performance and alleviate power supply issues. The suggested designs offer innovative control techniques for hybrid renewable systems, addressing various PQ challenges.

3.Methodology

The DVR is used to remove the PQ issues produced from the source side of the power grid.

3.1Dynamic voltage restorer (DVR)

The series configuration of the DVR, a specialized power device, and the distribution system is illustrated in *Figure 5*. An injection transformer, a harmonic filter, a series voltage source inverter (VSI), and an energy storage and control system comprise the DVR's primary components.

By connecting a booster transformer in series with the bus voltage, a converter generates a voltage that is capable of being adjusted dynamically. The implementation of dynamic amplitude adjustments for the injected three-phase voltages serves to mitigate any adverse effects that the source voltages may have on the load voltages. This indicates that transient disturbances in the AC feeder, particularly problems with PQ, are feasible. As long as the entire system remains connected to the power grid without interruptions from line breaker trips, and the DVR operates autonomously regardless of faults or events within the system, achieving a more economically efficient system is feasible. This can be applied in many real-world scenarios. The step-down transformer effectively obstructs the passage of the zero-sequence component of a disturbance in a conventional distribution bus configuration. The phenomena in question can be primarily attributed to the infinite impedance of the component. During this operational mode, a short circuit path is established for the transformer connection by activating specific legs of the converter. The sole factor responsible for the losses observed in this circuit is the relatively moderate conduction losses exhibited by the semiconductors. The DVR operates primarily in this configuration. When the DVR voltage surpasses zero, the booster transformer applies the compensating voltage into the power system in boost mode. The administration of this injection is prompted by the identification of an electrical power supply disturbance.

Researchers utilize the SSA as the foundation for developing a PI controller [43]. The SSA developers drew inspiration from the foraging and anti-predatory behaviors exhibited by sparrow populations to devise the metaheuristic algorithm. The SSA algorithm exhibits some limitations when compared to alternative metaheuristic algorithms.

The constraints encompass in *Figure 5* DVR with power grid restricted range of population diversity, constrained global search capabilities, and susceptibility to local optimality biases. Under typical circumstances, the DVR operates in standby mode. However, during disturbances, it compares the nominal system voltage with the voltage variation to determine the differential voltage necessary for the DVR to maintain the supply voltage to the load within specified limits. Both the amplitude and phase angle of the injected voltages can be adjusted, enabling control over the exchange of real and reactive power between the DVR and the distribution system. The DVR's DC input terminal is linked to an appropriately sized energy storage device. Notably, the DVR internally generates reactive power exchange with the distribution system without relying on AC passive reactive components. Real power exchanged at the DVR's output AC terminals is sourced from the DVR's input DC terminal via an external energy source or energy storage system. Furthermore, the technical approach of DVRs bears resemblance to providing low voltage ride-through (LVRT) capability in wind turbine generators. Particularly for line-supplied DVRs, their dynamic response characteristics are akin to LVRT-mitigated turbines. Additionally, as the device is connected in series, there are conduction losses, which can be mitigated by utilizing integrated gate-commutated thyristor (IGCT) technology in the inverters. The utilization of this specific method facilitates rapid convergence of the algorithm and diminishes the probability of encountering localization difficulties. Industrial applications widely recognize the PID controller as a critical type of controller. The controller exhibits both steady-state and transient defects. Disturbances reduce the effectiveness of the PID controller. Many consider these controllers as standard. In this article, a novel PID controller-based method for controlling the switching pulses of the DVR system is explored. By integrating an innovative meta-heuristic optimization, the SSA successfully acquired the optimal PID controller indicators.

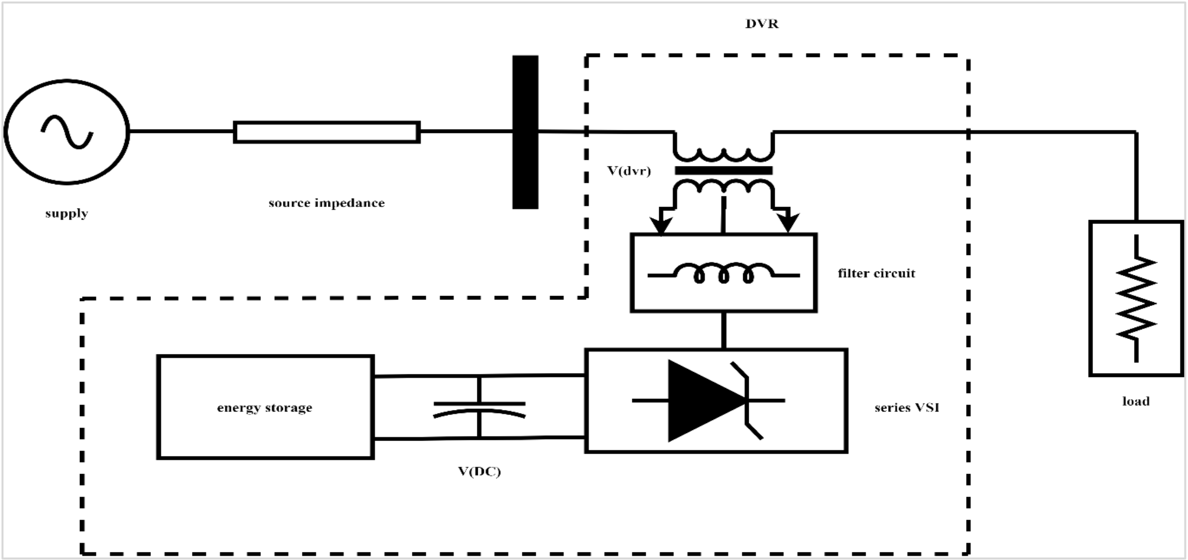

Figure 5 Components of the DVR

PID controllers, also known as ideal-PID controllers, are essential in industrial practice [44]. The error of state error is rendered steady and transitory by such a controller. When disturbances occur, the implementation of the PID as an ideal is compromised. Professionals identify these controllers as standard ones. The primary ideal PID controller block diagram is depicted in *Figure 6*. The subsequent Equation 1 represents the ideal-PID role transfer.

$$C(s) = \frac{Y(s)}{E(s)} = K_P + \frac{K_i}{s} + K_d s \quad (1)$$

In Equation 1, the proportional, integral, and derivative components are denoted by Kp, Ki, and Kd respectively. The comprehensive architecture of the efficient PID controller is illustrated in *Figure 7*. A PID controller is composed primarily of the following elements: fitness role, optimization techniques, sensor, and the process.

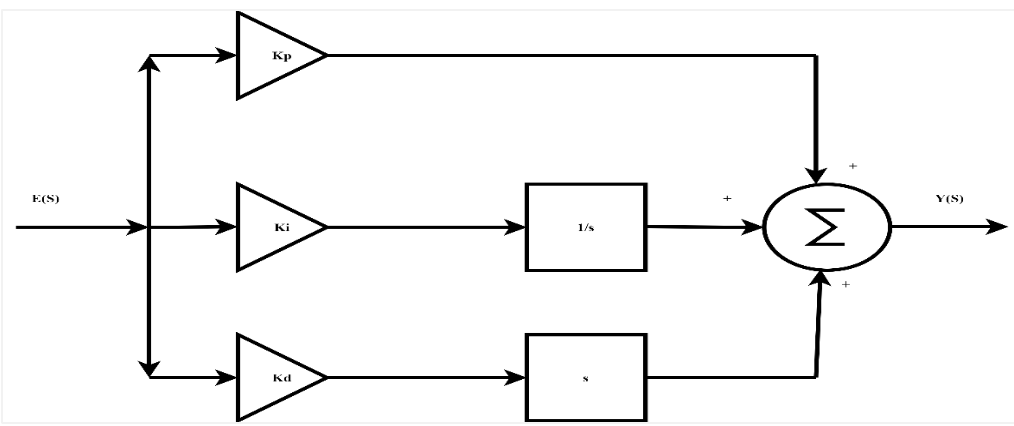

Figure 6 Ideal PID controller

The simulation model for the SSA optimization is based on the earlier description of sparrows. To simplify, the idealized behavior of the sparrows will be given in the following steps.

Step I: Producers usually possess abundant energy stores and offer foraging sites or guidance for all scavengers. It identifies areas with plentiful food supplies. Energy reserves are contingent upon the individual's fitness levels.

Step II: When the sparrow senses the predator, the individuals start chirping as warning signs. If the alert value above the safety level, the producers must guide all scavengers to the secure zone.

Step III: While each sparrow is capable of developing into a producer through the pursuit of enhanced food sources, the overall population maintains a constant ratio of producers to scavengers.

Step IV: Sparrows that possess greater amounts of energy will operate as producers. Numerous scavengers are likely to disperse to various destinations in pursuit of sustenance to preserve their vitality.

Step V: The scavengers trail the producer with the highest quality food to forage for sustenance. Meanwhile, certain scavengers may continuously observe the producers and vie for food to enhance their predation rate.

Step VI: Sparrows on the outside of the group swiftly relocate to a secure spot upon detecting danger, whereas sparrows in the center of the group wander haphazardly to stay near others. During the simulation experiment, virtual sparrows are utilized to locate food. Sparrows are in certain locations inside the grid.

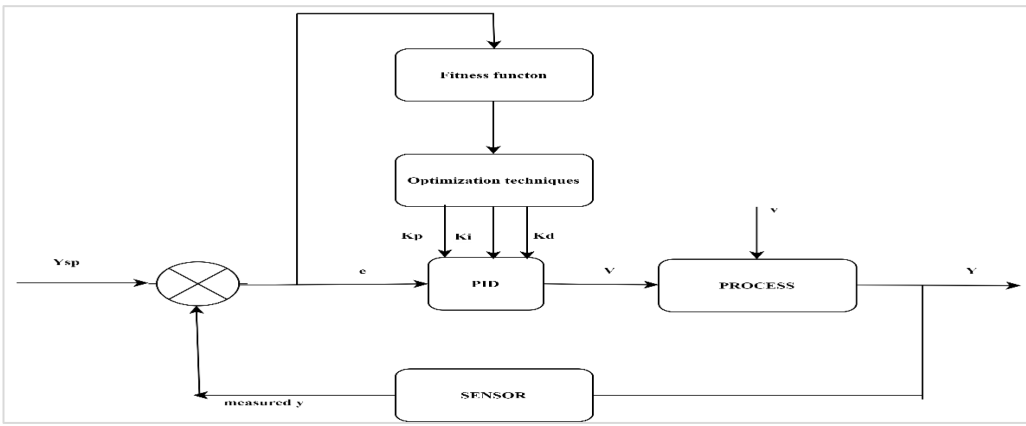

Figure 7 Tuning parameters of PID controller

When designing a controller, several optimal control parameters are necessary. Minimizing the objective function calculates these parameters. These goals functions to minimize the time response characteristics affected by the error in time dependence. The current work assigns a specific function to fitness for evaluating simulation performance [45]. The fitness function is derived from Equation 2.

$$\text{Fitness function} = \int_0^{\infty}[t^2 e(t)]^2 \qquad (2)$$

This algorithm was motivated by attentively monitoring the concept of foraging and the behavior of sparrow populations. Sparrows are categorized into two groups based on their behavior: producers, who actively look for food, and scroungers, who rely on others for food and are known as scroungers. The formula for SSA is derived from Equations 3 to 7. To ascertain the location of sparrows, the provided matrix is utilized.

$$X = \begin{bmatrix} X_{1,1} & \cdots & X_{1,d} \\ \vdots & \ddots & \vdots \\ X_{n,1} & \cdots & X_{n,d} \end{bmatrix} \qquad (3)$$

The quantity of sparrows is denoted by n, while d represents the dimension of the variables that require optimization. The fitness value of every sparrow can be mathematically represented as the subsequent matrix:

$$Fx = \begin{bmatrix} f(X_{1,1} & \cdots & X_{1,d}) \\ \vdots & \ddots & \vdots \\ f(X_{n,1} & \cdots & X_{n,d}) \end{bmatrix} \qquad (4)$$

The variable "n" represents the quantity of sparrows, while the fitness value of each bird is denoted in each row of Fx. Priority in obtaining food is granted to producers with greater fitness levels throughout the search process in the SSA. In addition, producers are responsible for coordinating the migration of the entire population and foraging for sustenance. Therefore, producers are in a more advantageous position to find sustenance in comparison to scavengers. The location of the producer is altered during each iteration following the steps (I) and (II):

$$X_{i,j}^{t+1} \begin{cases} X_{i,j}^{t} * exp\left(-\frac{i}{\beta * iter_{max}}\right) if\ R2 < ST \\ X_{\ i,j}^{\ t} + Q * L\ if\ R2 > ST \end{cases} \qquad (5)$$

j = 1, 2,..., represents the value of the jth dimension of the ith sparrow at iteration t, where t denotes the current iteration. The constant denoted as Itermax signifies the utmost number of iterations. The variable α is an integer of the form (0,1) selected at random. ST (where ST is between 0.5 and 1.0) and R2 (where R2 is between 0 and 1) represent the safety threshold and alert value, respectively. The random variable Q is characterized by a normal distribution. Each entry in the 1×d matrix L corresponds to the value 1. In the absence of predators, denoted by R2 being less than ST, the producer enters extensive search mode. When R2 is equal to or greater than ST, it signifies that a subset of the sparrows has detected the predator, causing the remainder to promptly seek refuge in alternative secure locations. In regard to the scroungers, it is their responsibility to assure adherence to steps (IV) and (V). As stated previously, specific individuals maintain a more frequent vigil over the manufacturers. Upon discovering that the producer has located quality food, they promptly abandon their present location to vie for the food. If they emerge victorious, they can promptly obtain the food from the producer, if not, they must adhere to the step V. The following formula describes how the position of the scrounger is modified:

$$X_{i,j}^{t+1} \begin{cases} Q * \exp\left(\frac{X_{worest}^{t} - X_{p}^{t+1}}{i^2}\right) \text{if } i > \frac{n}{2} \\ X_{p}^{t+1} + \left(X_{i,j}^{t} - X_{p}^{t+1}\right) x A^{+} \text{ x } L \ \ \text{Otherwise} \end{cases} \quad (6)$$

The position of XP is considered optimal for the producer. Xworest is the sparrow with the worst position in the population. $A^{+} = A^{\wedge}T(AA^{\mathrm{T}})^{\wedge} - 1$ Denoting a 1×d matrix in which each and every element is marked at random either 1 or -1. When i is greater than n/2, it signifies that the i^{th} scrounger with the lowest fitness value is probably hungry. It is assumed in the simulation experiment that 10-20% of the total sparrow population is vigilant in the face of the threat. The starting locations of the sparrows are determined at random across the entire population. The mathematical model may be denoted as follows, in accordance with rule of Equation 6:

$$X_{i,j}^{t+1} \begin{cases} X_{best}^{t} + \propto \times \left(X_{i,j}^{t} - X_{best}^{t+1}\right) \text{ x if } \ f_i > f_g \\ X_{i,j}^{t} + K * \left(\frac{X_{i,j}^{t} - X_{worst}^{t+1}}{(f_i - f_{\omega}) + \epsilon}\right) f_i = f_g \end{cases} \quad (7)$$

Presently, Xbest is the sparrow with the best position in the population. The step size control parameter takes the value of β, which is a normal distribution of random integers with a mean of 0 and a variance of 1.K is an arbitrary integer between -1 and 1 chosen at random. The fitness value of the sparrow at this moment is denoted by Fi. The world's current fitness levels are denoted by fg and fw, respectively. To avoid making a division by zero error, ε must be a minimal constant. For simplicity's sake, the sparrow is at the group's periphery when fi > fg. In addition to securely depicting the population's center, the Xbest point is also close by. According to the research, sparrows that are in the middle of the flock are more likely to be attacked, thus they should move closer to the rest of the flock. The parameter for determining step size is K, which indicates the sparrow's movement direction. Following algorithm can specify the basic steps of the SSA optimization for generating the gating pulses of the PID controller within the DVR system in order to address the PQ issues caused from the source side of an integrated renewable energy power grid system depending on the model's feasibility and idealization [46].

Maximum number of iterations is G
The quantity of producers is PD
The quantity of sparrows that signals the danger is SD.
The alarm number is R2.
n = the quantity of sparrows
Define the pertinent parameters for a population of n sparrows at the time of initialization.
The output is Xbest.fg.
Step 1: while (t<G)
Step 2: Rank the fitness values and determine who is currently the best and worst individual.
Step 3: R2 equals one rand (1)
Step 4: PD = 4: for i=1
Step 5: Update the location of the sparrow using Equation 3;
Step 6: End for
Step 7: for i =(PD+1):n
Step 8. Modify th location of the sparrow using Equation 4;
Step 9: end for
Step 10: for l=1SD
Step 11 Update the location of the sparrow using Equation 5;
Step 12 End for
Step 13 Retrieve the current new location;
Step 14 If the new location is superior to the previous one, update it;
Step 15:t=t+1
Step 16: end while
Step 17: Return Xbest, fg.

Figure 8 shows the tuning of the PID controller using the SSA algorithm. *Figure 8* illustrates the behavior of monitoring the position using the best fitness function. It has been shown that all practical values exceed the simulated values for all optimization strategies. Here the position of the PID controller tuned by SSA optimization is 1000µm and the PID controller touches this value at the 14^{th} second of the simulation time. The application of an SSA-based PID controller is utilized for the generation of switching pulses in the DVR component of the UPQC. This controller aims to efficiently regulate and reduce PQ disturbances originating from the generator side of the power grid. The empirical results suggest that the SSA-based PID controller, which has been optimized using the upgraded method, demonstrates enhanced control accuracy and improved stability of the system. The observed result provides empirical support for the practical use of the enhanced algorithm within engineering domains. PQ has been significantly impacted by the integration of RESs into the regional distribution network and the complex behavior displayed by advanced power electronic devices.

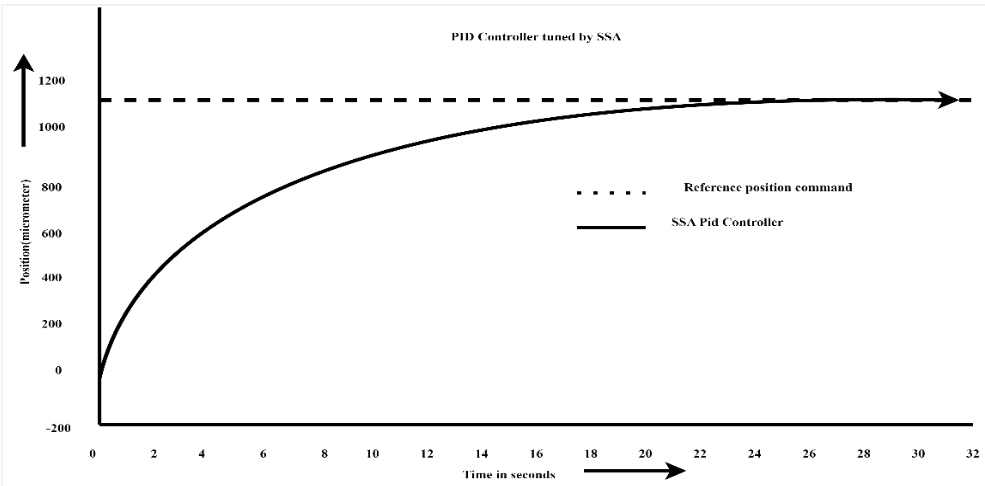

Figure 8 PID controller tuned by SSA

The UPQC is a versatile device belonging to the category of facts. It combines the functionalities of shunt active filters and series active filters by utilizing a common DC link. This research study presents a comprehensive overview of the development process involved in creating an SSA-based PI controller. The controller has been specifically developed for the series active filter of the UPQC, which is seamlessly linked with both a solar energy system and a wind energy system. The process of achieving integration is facilitated using boost converters and buck-boost converters. The primary objective of the suggested PI controller based on SSA in this study is to achieve a consistent voltage across the DC link capacitor while also addressing issues like voltage fluctuations, disturbances, harmonic distortions, and voltage imbalances in the grid. The assessment of the efficacy of the SSA-based PI controller is performed with MATLAB SIMULINK 2023b. Various sorts of loads and voltage situations are considered to assess the balance or imbalance during testing. The controller has the responsibility of producing switching pulses that are then sent to the series compensator, specifically referred to as the DVR. The objective of this endeavor is to efficiently address PQ concerns within the integrated solar wind power grid system. The PQ issues included in this discussion are voltage sag, voltage swell, and harmonics, as well as unbalanced voltage sag and swell. The main aim of the proposed work is to apply an innovative methodology that enhances PQ via the integration of a UPQC with a solar wind power system. The aim will be achieved by the construction of a PI controller that is based on the SSA. The primary objective of this work is to improve PQ inside the integrated solar wind power grid system by mitigating distortion. The algorithm's efficacy is derived from its ability to regulate the gains of a PI controller, hence leading to PQ improvement in an integrated power grid system via the use of a UPQC. The fundamental objective of the DVR is to use voltage injection as a method for reducing fluctuations and harmonics in the grid voltage while simultaneously ensuring a consistent load voltage. *Figure 9* shows the control structure of the DVR. The injected voltages exhibit adjustable amplitude and phase angles, facilitating the management of both real and reactive power exchange between the DVR and the distribution system. Connecting the DVR's DC input terminal to an appropriately sized energy storage device ensures operational efficiency. Notably, the DVR internally generates reactive power exchange with the distribution system, eliminating the need for AC passive reactive components. Real power transmitted through the DVR's AC terminals is derived from its DC input, which is linked to an external energy source or storage system. The DVR FACT device's operation, aimed at mitigating power PQ issues, is controlled by gating pulses optimized through SSA and PID controller integration, facilitating the injection of balanced voltages into the integrated power grid system. Additionally, a phase-locked loop (PLL) is employed to produce an output signal with a fixed phase relative to the input signal, ensuring synchronization between input and output phases, as well as frequencies. Integration of a frequency divider enables the PLL to maintain a consistent frequency multiple of the input frequency, effectively monitoring and adapting to changes in input frequency.

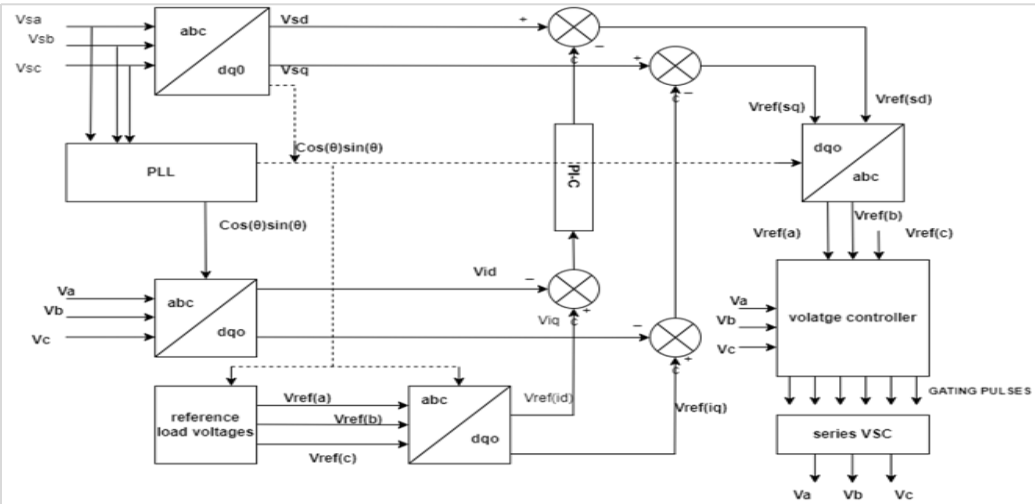

Figure 9 Control structure of DVR

The use of PLL is utilized to extract the basic components of the grid voltage. By analyzing the position with the highest fitness function in the SSA optimization for the PID controller of the DVR, the axis inside the d-q-0 domain can be determined. Injected voltage is the difference between the load and grid voltages. For both the d-axis and q-axis signals, the series compensators and actual voltages are evaluated. The PID controller uses the resulting disparity to provide injected voltages. *Figure 10* shows PID controller with SSA optimization. In *Figure 10* it is clear that the SSA is used to optimize the PID controller. Further PID controller sends switching pulses for efficient controlling of the DVR. The functioning of the DVR is dependent on these switching pulses which is being controlled by PID through SSA optimization. The DVR remains active in the system whenever PQ issue is produced from the source side of the power grid connected with the solar wind energy sources. The main goal of the PID controller is to generate the switching pulses used in the series VSC. The UPQC's DVR is responsible for investigating PQ concerns that occur due to the integration of unconventional energy sources like wind and solar into the current power infrastructure.

4.Results

The present study aims to solve PQ challenges originating from the generator side of the integrated power grid system. Following are the various types of PQ issues to be addressed from the source side of the integrated renewable energy power grid.

a) The concept of balanced voltage sag refers to a situation in which the voltage levels throughout a power system experience a temporary decrease symmetrically and uniformly.
b) The concept of balanced voltage swell refers to the occurrence of a symmetrical increase in voltage levels inside an electrical system.
c) Achieving voltage sag balancing in the presence of harmonics.
d) Achieving voltage stability with harmonics in equilibrium.
e) The phenomenon of source-side harmonics refers to the presence of harmonic frequencies in the electrical power supply originating from the power source.
f) Voltage sag with an unbalanced distribution.
g) The occurrence of voltage swell is characterized by an imbalance.
h) Voltage sag with harmonics resulting in an imbalance.
i) The phenomenon of unbalanced voltage swell harmonics.

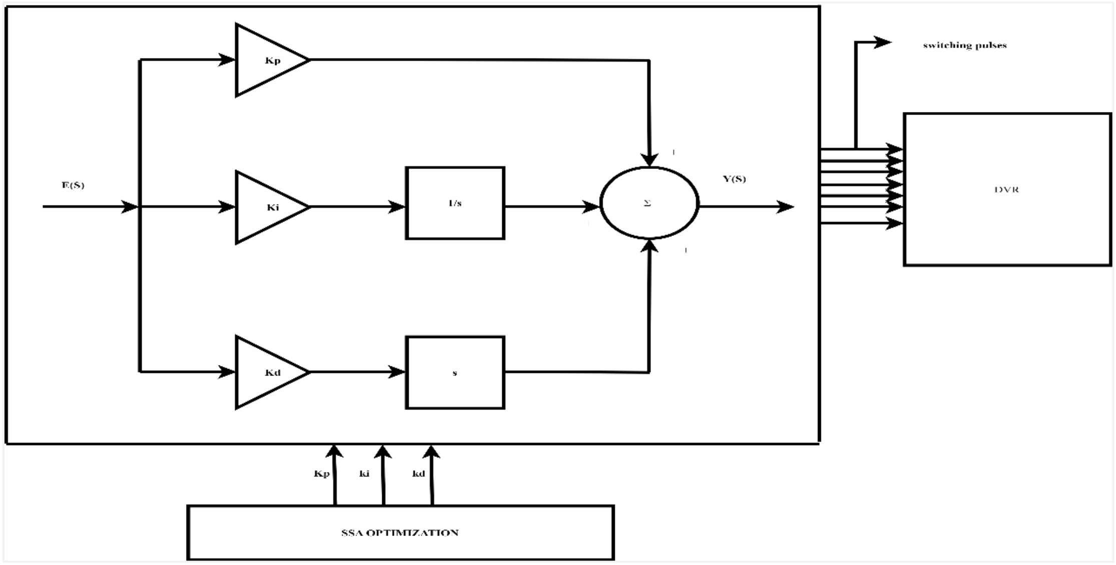

Figure 10 PID controller with SSA optimization

MATLAB 2023b was used to run the simulation. Through the use of the UPQC, the power system and the integration of solar and wind generation with a nonlinear load are simulated. To manage PQ concerns in RESs that are linked to the power grid, the UPQC, also known as a FACTS device, is used. The interconnection of non-conventional energy sources with the power grid has been shown to cause problems with the power system's PQ. The source or generating side is the subject of three voltage-related difficulties that are especially examined in this research. Voltage fluctuations may be divided into three groups: balanced voltage sags, balanced voltage swells, and unbalanced voltage sags. The following characteristics outline the system evaluation of the power grid that is integrated with solar, wind, and UPQC facilities. *Table 2* and *Table 3* shows the System evaluation parameters of solar, wind power plants, power grid and DVR. These system evaluation parameters are used to design the power grid connected with solar wind RES and DVR. The solar and wind power plant injects 245W and 500W of active power into the power grid. Further the DC bus voltage is maintained at 700V. *Figure 11* depicts the DVR DC voltage variation with respect to the changes in the power grid connected RES and it demonstrates that the DC voltage nearly remains constant (V_{DC}=700V) in response to voltage changes.

Table 2 System evaluation parameters of solar and wind power plants

S. No.	Solar power plant	Ratings	Wind power plant	Ratings
1	Maximum Power (P_{Max})	245W	P_{Max}	500W
2	Voltage at P_{Max}	30.5V	Stator resistance	12.875Ω
3	Current at P_{Max}	8.04A	Inductance on D axis	0.0085H
4	Short circuit Current	8.73A	Inductance on the Q-axis	0.0085H
5	Open circuit Voltage	37.5V	Permanent magnet flux	0.175Wb
6	-	-	Pole pairs	2
			Moment of inertia	0.0008kgm-2

Table 3 System evaluation parameters of Power grid and DVR

S. No.	System parameters	System Ratings
1	three-phase AC supply source (*Vs*)	415 V
2	Frequency	50 Hz
3	internal source resistance (*Rs*)	0.02 Ω
4	internal source inductance *(Ls)*	0.1 mH
5	interfacing inductor (*LDSTAT*)	4 mH
6	DC bus capacitance (*CDC*)	5,000 μF
7	DC bus voltage (*VDC*)	700 V

S. No.	System parameters	System Ratings
8	ripple filter resistance (*Rf*)	5 Ω
9	ripple filter capacitance (*Cf*)	7.14 μF
10	Load power (KVA)	31.25 KVA
11	Load power factor	0.8 pf lag
12	Series transformer turns ratio	1:2
13	Load inductance	200mH
14	Load resistance	200ohm

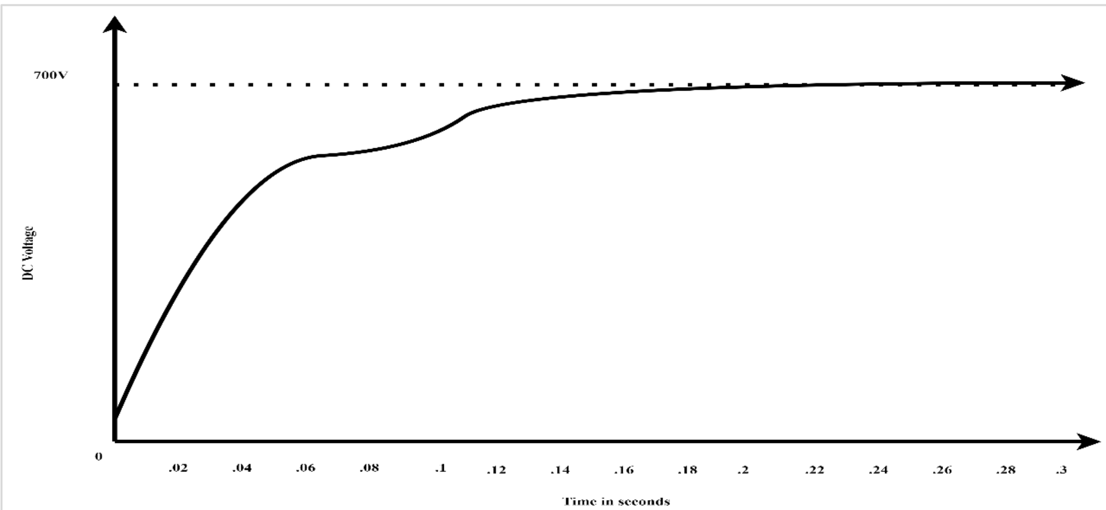

Figure 11 DC voltage of the DVR

a) Balanced voltage sag

The production of a symmetrical voltage sag in the power grid system is a matter of concern in terms of PQ, as it is caused by the power grid's source side. The pursuit of resolving this matter involves the integration of the UPQC into the power system. A sag mode arises in a three-phase balanced sag when certain heavy loads can be deactivated in each of the three phases. Thus, it was determined to employ the sag mode for the test carried out from t = 0.1 to t = 0.2 s. The simulation results elucidate the voltage at the load bus for each of the three phases under this condition. *Figure 12* illustrates the load voltage both before and after the FOPID-UPQC is connected to the system. Based on the data depicted in *Figure 12,* it is apparent that during a time interval of 0.1 second, the power grid source side, which is linked to the solar and wind power plants, undergoes a reduction in voltage referred to as voltage sag. This phenomenon consequently has an impact on the PQ on the load side of the system as well. The UPQC is designed to inject a balanced voltage into the power grid at a time interval of 0.1 second. This injection ensures that the power grid load side consistently receives a balanced voltage, thereby preventing any occurrence of voltage sag. The *Figure 12* demonstrates that the load voltage remains balanced while experiencing a voltage sag originating from the power grid's source side. This phenomenon is readily observable from the perspective of the load voltage segment of the power system.

b) Balanced voltage swell

A three-phase balanced swell develops when some heavy loads are eliminated from the system. Therefore, it was likely that the swell mode would occur from t = 0.1s to t = 0.2s throughout the test. *Figure 13* depicts the load voltage, comparing the results with and without the utilization of enhancement using the FOPID-UPQC. The occurrence of a balanced swell in the power grid, resulting from the connection of the source voltage to the solar wind power grid, leads to the induction of a voltage swell. Consequently, this induction of voltage swell gives rise to PQ difficulties. Between the time intervals of 0 and 0.1 second, both the grid and load voltage exhibit a state of equilibrium. However, starting from 0.1 second, the introduction of non-conventional energy sources leads to PQ difficulties in the form of voltage swells from the grid side. These voltage swells on the grid voltage side are also depicted in the accompanying image. The DVR, or series compensator, known as the UPQC, is designed to mitigate voltage swells on the load side of the power grid. By injecting balanced voltages from the grid side, the UPQC ensures that the load voltage remains balanced, even when voltage swells occur from the power grid source side. Specifically, during the time interval of 0.1 to 0.2 second, the load voltages are maintained in a balanced condition as shown in *Figure 13*. The figure demonstrates that during the first 0-0.1 second, there is no voltage injection caused by the UPQC. The absence of voltage sag and swell is caused by the absence of disruptions coming from the source side of the non-conventional energy power system. If the source side of the power grid experiences a voltage surge lasting 0.1 second, the instruments connected to the load side of the grid system may experience issues. Every 0.1 second, the UPQC enters the electrical system with a balanced voltage. By doing this, the load voltage is ensured to remain balanced even in the presence of voltage swells coming from the power grid's source side. As a result, voltage swell from the generator side has no impact on the loads that are linked to the power system.

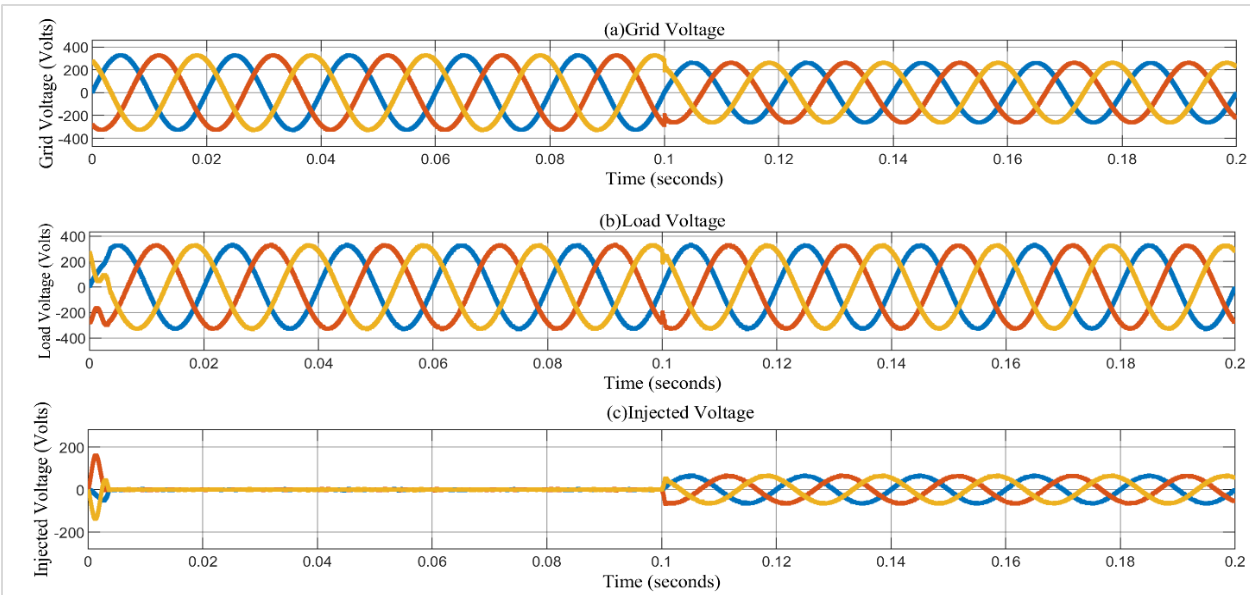

Figure 12 Voltage sag from the source side (a)Grid voltage (b)Load voltage (c)Injected voltage

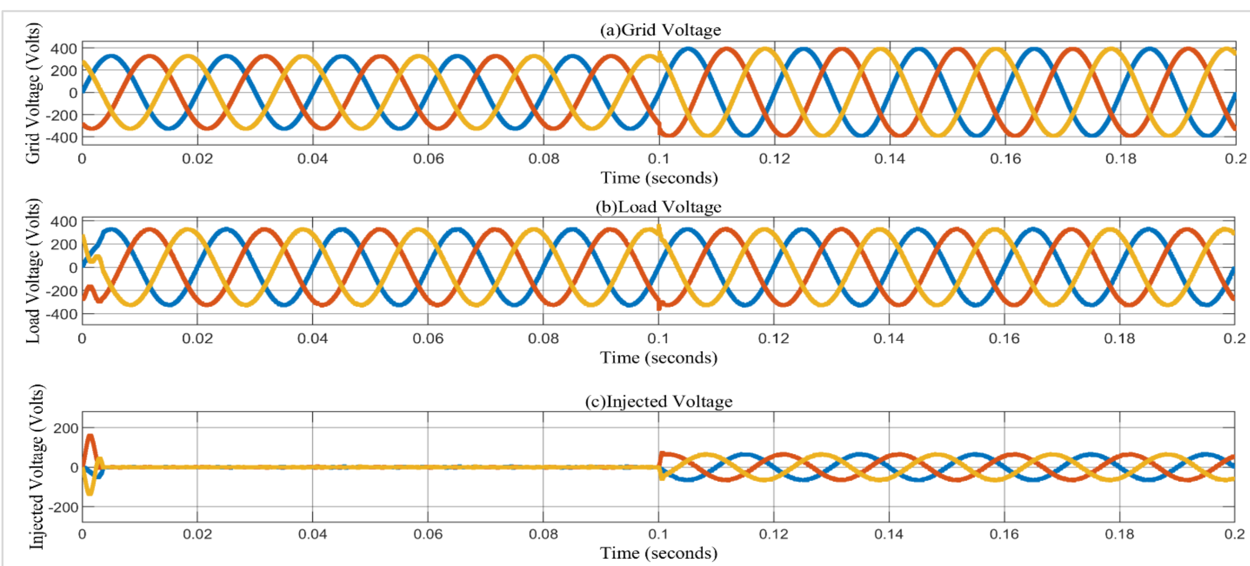

Figure 13 Voltage Swell from the Source Side(a)Grid voltage (b)Load voltage (c)Injected voltage

c) Balanced voltage sag with harmonics

The generator side of the power grid, which is integrated with the solar-wind energy sources, causes voltage sag and harmonics. From *Figure 14*, the harmonics and voltage sag are both induced at 0.16 second and 0.1 second.it can be noted that the source voltage at 0.1 second is sagging without the UPQC being connected. This situation is extremely critical for a power system because it causes an imbalance and may result in severe PQ problems for the distribution system. Immediate penetration of the phase harmonic voltage by the series-APF verifies that the load voltage is not distorted as it begins compensating for voltage harmonics. The series compensator of the UPQC eliminates these two PQ problems by injecting the balanced voltages at 0.16 second and 0.1 second from the load voltage and voltage sags, preventing harmonics from being transmitted to the consumer side of the power grid. The UPQC effectively maintains the sinusoidal supply currents to the load side of the integrated power grid connected with the RESs like solar wind energy plants irrespective of harmonics and voltage sags from the source side of the power grid.

d)Balanced voltage swells with harmonics

Voltage swells are usually caused when large loads are turned off or due to the power line switching. If voltage swells are very high, they can damage the equipment connected to the load side. Harmonics are also produced from the source side due to the solar wind power plants. This is because solar and wind power plants are dependent on variable inputs like light intensity and wind speed. The DVR plays a significant role in removing the voltage swells from the source side. The power grid source side connected to the nonconventional energy sources cause voltage swells and harmonics. The voltage swell is induced at 0.1 sec, and the harmonics are induced at 0.16 second as shown in *Figure 15*. These two PQ issues are removed by the series compensator of the UPQC from the load voltage and the voltage swells, harmonics are not transmitted to the power grid load side. From *Figure 15* the harmonics and the voltage swells are presented on the grid side and these disturbances can travel to the load side and can damage the sensitive equipment connected to the load side. The DVR is turned on with the help of gating pulses controlled efficiently by the SSA-PID controller injects the balanced voltages at the instant of 0.1second where the voltage swell occurs and at the instant of 0.16second where the harmonics occur in the integrated power grid system.

e) Source side harmonics

The generation part of the power grid connected with the nonconventional energy sources causes harmonics. These harmonics affect the performance of the different types of loads like linear and non-linear loads connected at the load side of the integrated power grid system. From *Figure 16* the harmonics are induced at 0.1 sec. These harmonics are removed by the series compensator of the UPQC from the load voltage and harmonics are not transmitted to the consumer side of the power grid. From 0.1 sec to 0.2 sec, the load voltage does not show any harmonics, even though during this duration there are harmonics from the power grid source side as shown in *Figure 16.*

The THD at the source side is reduced to 0.18% with the help of DVR compensation which in turn improves the performance of the linear and non-linear loads at the load side of the power grid. *Figure 17* shows the THD of the source side of the power grid. Harmonics are efficiently eliminated from the different loading conditions like linear and nonlinear loads by the injection of sinusoidal voltages by DVR controlled by SSA optimization based PID controller under harmonic conditions.

f) Unbalanced voltage sag

The generation part of the power grid that is connected to nonconventional energy sources induces an unbalanced voltage sag. The unbalanced voltage sag is created at 0.1 second, as shown in *Figure 18*. The series compensator of the UPQC removes the unbalanced voltage sag from the load voltage and prevents it from being transferred to the power grid load side. Even if there is an unbalanced voltage sag from the source side of the power grid currently, the load voltage does not exhibit any throughout 0.1 to 0.16 second.

g) Unbalanced voltage swell

The generation part of the power grid connected to nonconventional energy sources causes an unbalanced voltage swell. The unbalanced voltage swell is induced at 0.1 second as shown in *Figure 19*. The series compensator of the UPQC removes the unbalanced voltage swell from the load voltage and prevents it from being transferred to the consumer side of the power grid. Although there is an unbalanced voltage swell on the source side of the power grid throughout 0.1 to 0.16 second, the load voltage does not exhibit it.

h) Harmonics with unbalanced voltage sag

The generation part of the power grid associated with RESs can cause unbalanced voltage sag and harmonics. *Figure 20* illustrates the occurrence of an unbalanced voltage sag at 0.1 second, followed by the induction of harmonics at 0.06 second. The series compensator of the UPQC effectively mitigates two

PQ concerns: load voltage fluctuations and unbalanced voltage sags. Additionally, the UPQC prevents the transmission of harmonics to the consumer side of the power grid.

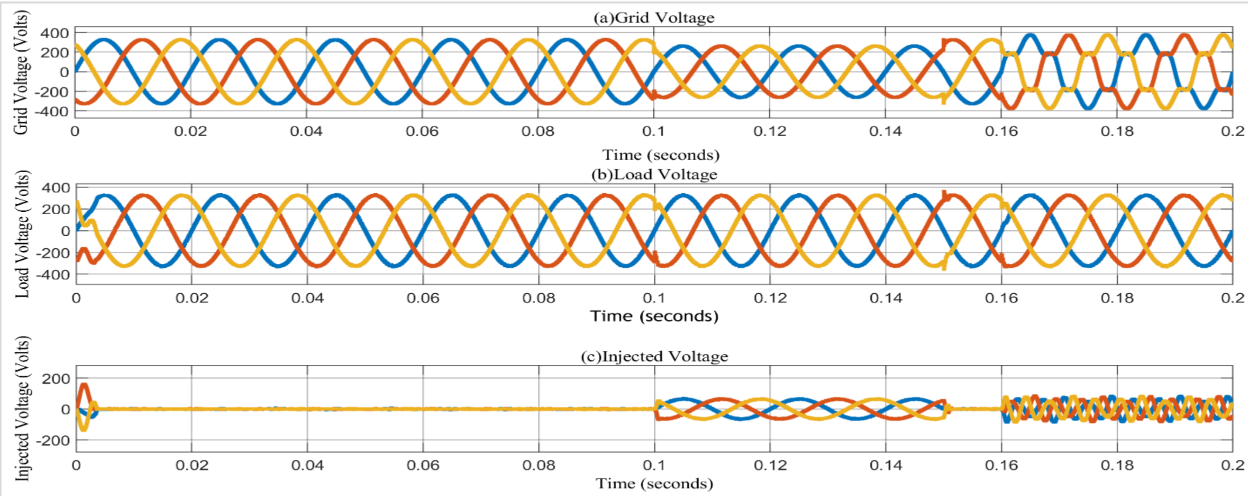

Figure 14 Balanced voltage sag with harmonics (a)Grid voltage (b)Load voltage (c)Injected voltage

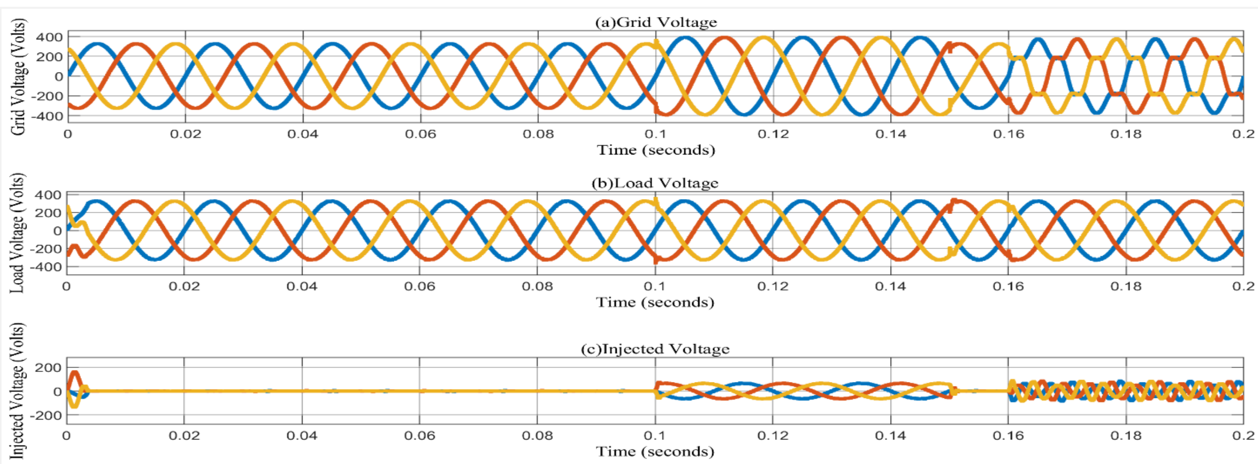

Figure 15 Balanced voltage swells with harmonics (a)Grid voltage (b)Load voltage (c)Injected voltage

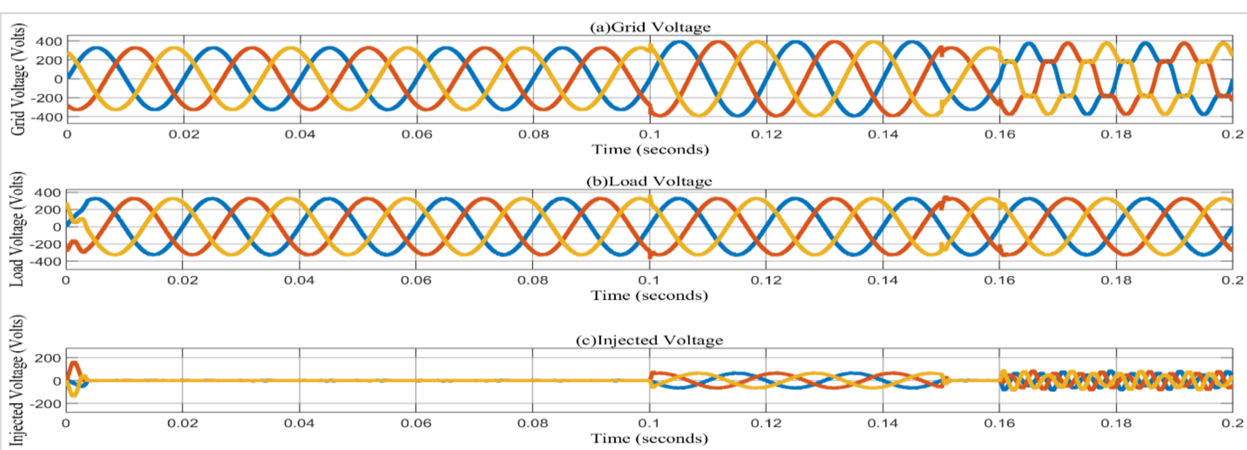

Figure 16 Source side harmonics (a)Grid voltage (b)Load voltage (c)Injected voltage

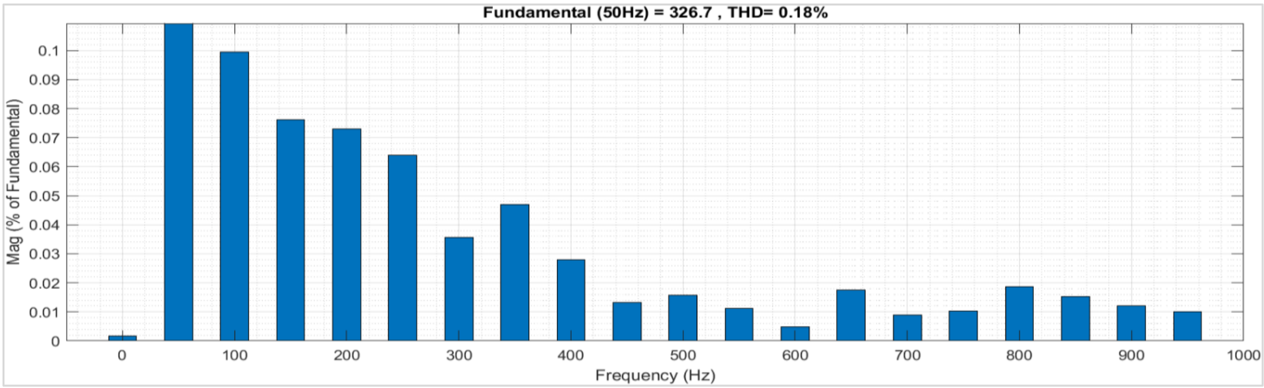

Figure 17 Source side harmonics with THD

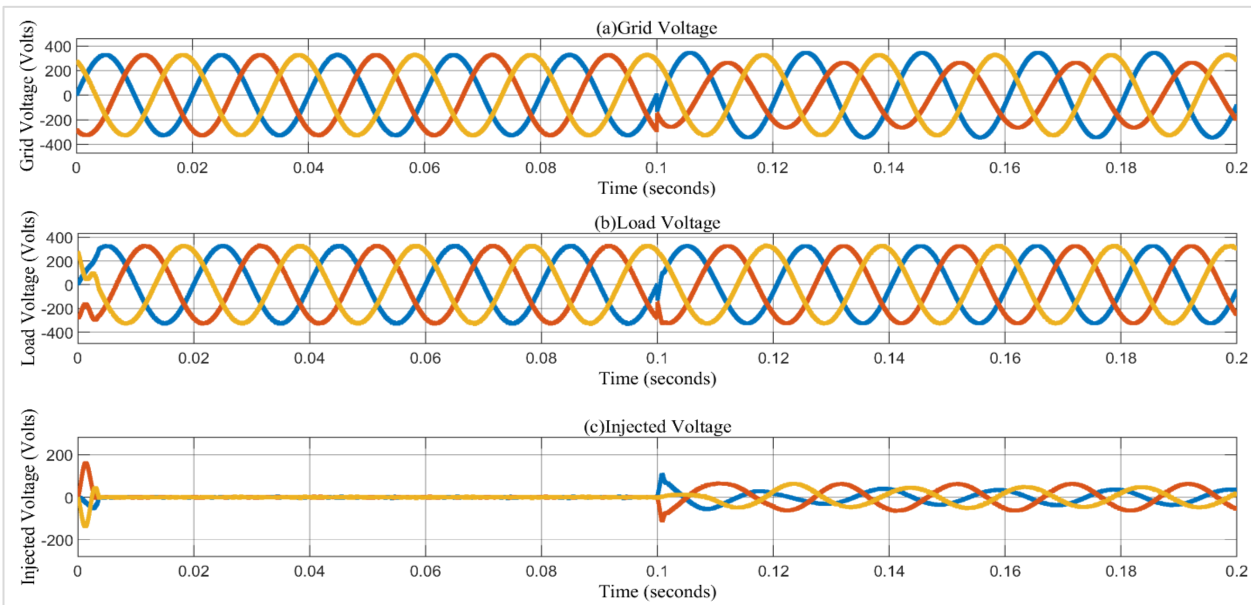

Figure 18 Unbalanced voltage sag (a)Grid voltage (b)Load voltage (c)Injected voltage

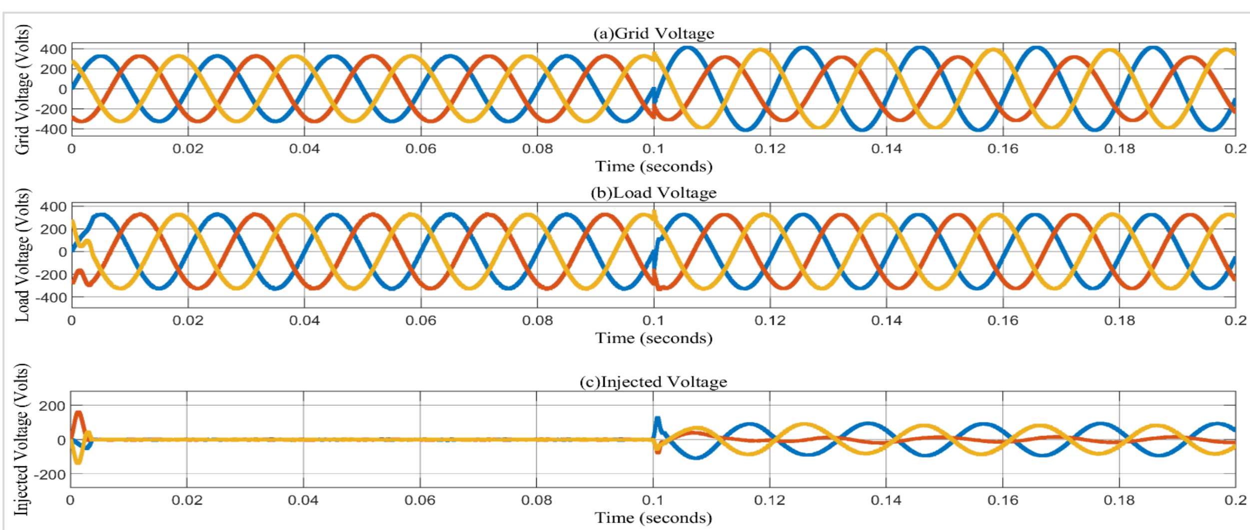

Figure 19 Unbalanced voltage swell (a)Grid voltage (b)Load voltage (c)Injected voltage

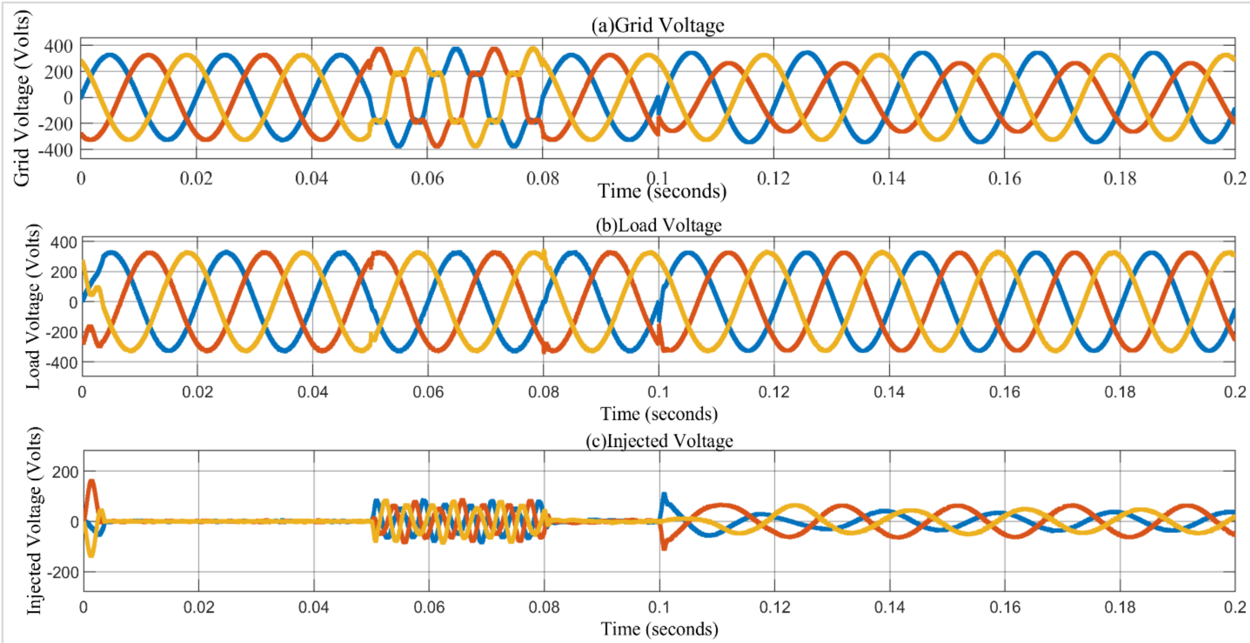

Figure 20 Harmonics with Unbalanced voltage sag (a)Grid voltage (b)Load voltage (c)Injected voltage

j) Harmonics with Unbalanced voltage swell

By connecting the generation side of the power grid to the RESs, unbalanced voltage surges and harmonics are produced. From *Figure 21*, it is clear that the unbalanced voltage swell is induced at 0.1sec and the harmonics are induced at 0.06sec. These two PQ issues are removed by the DVR of the UPQC from the load voltage, and the unbalanced voltage swell and harmonics are not transmitted to the power grid load side.

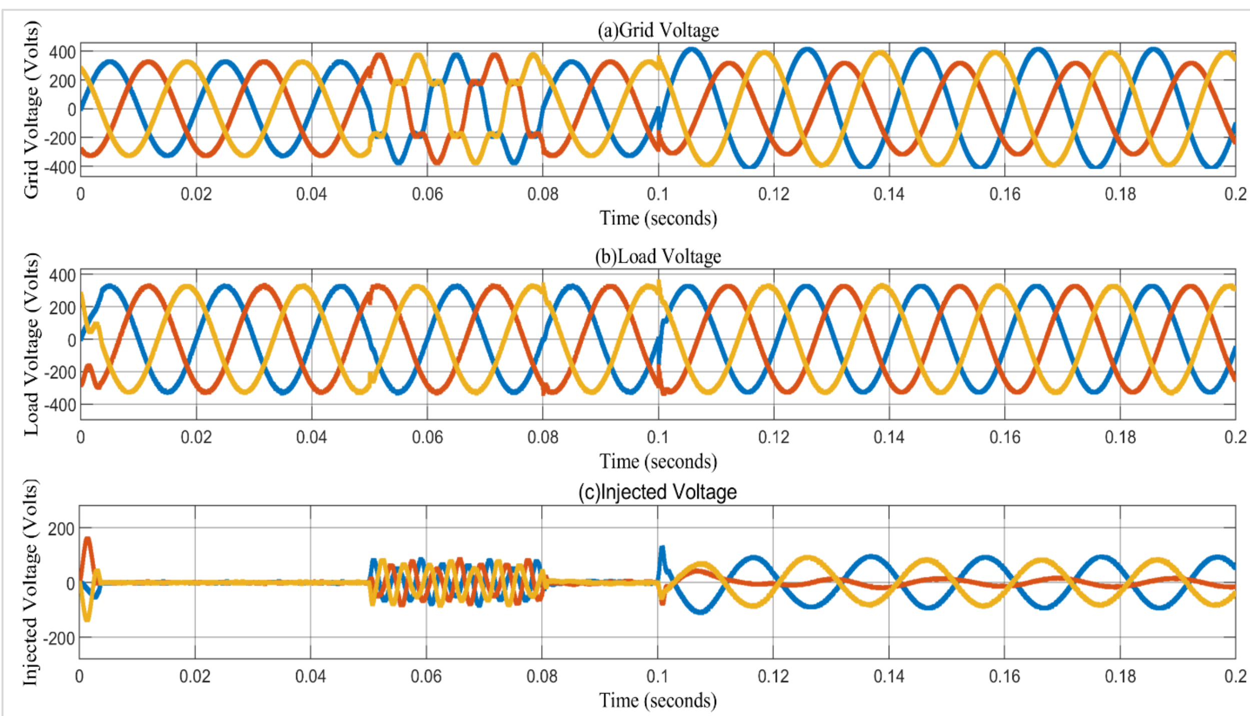

Figure 21 Harmonics with unbalanced voltage swell (a)Grid voltage (b)Load voltage (c)Injected voltage

5.Discussion

The simulation tests are conducted on a Windows 10 operating system, utilizing an Intel(R) Core i7-2.3GHz processor. The machine is equipped with a 64-bit operating system and has 16 GB of RAM. The population size for the algorithm is fixed at 30, and the maximum number of iterations is limited to 500. The optimization efficiency of the method is directly determined on the quality of the population during the initialization step. The SSA commonly utilizes random initialization of the population to solve optimization issues. However, this approach might result in an unequal distribution of the population, leading to a decrease in variety. The simulation findings demonstrate that the SSA has robust optimization capabilities for removing the PQ issues caused by the source side of the integrated renewable power grid. Whether the load is linear or non-linear, the design maintains PQ problems to a minimum. Furthermore, the SSA demonstrates a level of competitiveness when compared to other advanced algorithms. The accuracy of the SSA in the test function surpasses that of all other comparison algorithms. Furthermore, all optimization techniques i.e., SSA, grey wolf optimizer (GWO) [47], particle swarm optimization (PSO) [48] and gravitational search algorithm (GSA) [49] are analyzed for mitigating the PQ issues. *Table 4* shows the comparison of SSA, GWO, PSO, GSA optimization techniques with the PQ problems in nonconventional energy sources connected to the power grid. It has been seen that the convergence accuracy, convergence speed of the SSA algorithm is great as compared to the other optimization techniques. An evaluation was carried out to compare the performance of the (SSA)-based PID controller with other optimization methods to determine their efficacy and robustness. Further SSA-based PID controller takes less computing time as compared to other optimization techniques. To manage balanced swells, sags, and other PQ issues, the proposed model underwent testing on the MATLAB/Simulink platform. The collected data indicate that the SSA based UPQC-FOPID control approach is preferable due to its rapid reaction and minimum error. The system is capable of displaying and evaluating various grid states, such as voltage sag, swell, and other PQ issues. The data indicates that the UPQC-FOPID control approach is preferable due to its rapid reaction and minimum error.

Table 4 Comparison of different algorithms

S. No.	PQ issues	Computing time(s)			
		SSA-based PID controller	**GWO- based PID controller**	**PSO- based PID controller**	**GSA- based PID controller**
1	Sag in balanced voltage	110	187	200	220
2	Swell in Balanced voltage	120	190	180	200
3	Harmonics with Balanced voltage sag	127	185	190	180
4	Harmonics with Balanced voltage swells	130	200	180	190
5	Generation side harmonics	101	220	210	200
6	Unbalanced voltage dip	125	186	188	187
7	Unbalanced voltage rise	128	189	200	210
8	Harmonics with Unbalanced voltage dip harmonics	130	220	190	200
9	Harmonics with Unbalanced voltage rise	122	210	190	188

The suggested SSA demonstrates a much higher speed compared to other options. It achieves highly competitive solutions for various functions. The SSA exhibits superior search efficiency and convergence rates compared to the other three algorithms across many functions, and its processing is highly stable. Based on previous examinations, it can be inferred that the SSA possesses global search capability and significant adaptability. This is governed by the SSA mechanism. The sparrow's various behavioral patterns in the SSA have significantly contributed to global search efforts. However, the optimization method shows reduced efficiency in addressing complex PQ challenges, exhibiting inconsistencies in local and global search. Additionally, the SSA optimization method requires an increased number of iterations as the complexity of the problems expands. A complete list of abbreviations is listed in *Appendix I.*

6.Conclusion and future work

The power system grid has widely adopted renewable energy technologies, mainly because of their environmental sustainability, potential to improve stability, and power grid reliability. The synchronization of renewable energy resources such as PV and wind power plants with the power grid, offers PQ issues. The proposed research investigated the PQ issues, that arise when solar and wind energy are integrated into the power system from the generation side of the power system network. The concurrent occurrence of the PQ issues was successfully addressed by the UPQC's DVR component. In response to the PQ issues coming from the generation side of the power grid connected with RESs, the DVR which consumes less energy efficiently removed the PQ problems from the generation side of the power grid connected with RES. The switching signals are sent to the DVR component of the UPQC using an SSA-based PID controller. On the generation side of the integrated power grid with RESs, the proposed controller reduced the PQ issues efficiently. In the future work, the DSTATCOM part of the UPQC can be used to address the PQ issues caused by the load side of the integrated renewable energy power grid system.

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None.

Conflicts of interest
The authors have no conflicts of interest to declare.

Data availability
The data considered in this study has been collected from the library database of the Matlab 2023b software. The data is not publicly available. However, the data may be provided by the corresponding author upon reasonable request.

Author’s contribution statement
Ishtiyaq Shafi Rafiqi: Data compiling, analysis, investigation. preparing first version, reviewing and revising written content. analysis and interpretation of findings. **Abdul Hamid Bhat:** Inspection of data, conception, design, examination of issues, and drafting of the text.

References
[1] https://www.investindia.gov.in/sector/renewable-energy. html. Accessed 26 October 2023.
[2] https://www.iea.org/reports/india-energy-outlook-2021. html. Accessed 2 October 2021.
[3] Holechek JL, Geli HM, Sawalhah MN, Valdez R. A global assessment: can renewable energy replace fossil fuels by 2050? Sustainability. 2022; 14(8):1-22.
[4] https://www.un.org/en/climatechange/science/causes-effects-climate-change.html. Accessed 2 October 2022.
[5] Upadhyay T, Jamnani JG. Grid integration of large scale renewable energy sources: challenges, issues and mitigation technique. In Asian conference on innovation in technology 2021 (pp. 1-6). IEEE.
[6] https://www.iea.org/reports/global-energy-review-2021/renewables.html. Accessed 2 July 2021.
[7] Impram S, Nese SV, Oral B. Challenges of renewable energy penetration on power system flexibility: a survey. Energy Strategy Reviews. 2020; 31:100539.
[8] Gowtham N, Shankar S, Rao KU. Enhanced firefly algorithm for PQ improvement of wind energy conversion system with UPQC. In TENCON IEEE region 10 conference 2017 (pp. 757-62). IEEE.
[9] Ahmed SD, Al-ismail FS, Shafiullah M, Al-sulaiman FA, El-amin IM. Grid integration challenges of wind energy: a review. IEEE Access. 2020; 8:10857-78.
[10] Rajkumar K, Parthiban P, Lokesh N. Control of transformerless T-type DVR using multiple delayed signal cancellation PLL under unbalanced and distorted grid condition. Engineering Science and Technology, an International Journal. 2021; 24(4):925-35.
[11] Ali BM, Ariff MA, Ramli SN. An improved method for efficient controlling of the dynamic voltage restorer to enhance the power quality in the distribution system. International Journal of Power Electronics and Drive Systems. 2020; 11(4):1958.
[12] Al-masri HM, Ehsani M. Feasibility investigation of a hybrid on-grid wind photovoltaic retrofitting system. IEEE Transactions on Industry applications. 2015; 52(3):1979-88.
[13] Xu X, Wei Z, Ji Q, Wang C, Gao G. Global renewable energy development: influencing factors, trend predictions and countermeasures. Resources Policy. 2019; 63:101470.
[14] Hache E, Palle A. Renewable energy source integration into power networks, research trends and policy implications: a bibliometric and research actors survey analysis. Energy Policy. 2019; 124:23-35.
[15] Liang X. Emerging power quality challenges due to integration of renewable energy sources. IEEE Transactions on Industry Applications. 2016; 53(2):855-66.
[16] Tang A, Zhou H, Han T, Xie L. A chaos sparrow search algorithm with logarithmic spiral and adaptive step for engineering problems. Computer Modeling in Engineering & Sciences. 2022; 130(1).
[17] Gao B, Shen W, Guan H, Zheng L, Zhang W. Research on multistrategy improved evolutionary sparrow search algorithm and its application. IEEE Access. 2022; 10:62520-34.
[18] Gao CF, Chen JQ, Shi MH. Multi-strategy sparrow search algorithm integrating golden sine and curve adaptive. Application Research of Computers. 2022; 39(2):491-9.
[19] Ren X, Chen S, Wang K, Tan J. Design and application of improved sparrow search algorithm based on sine cosine and firefly perturbation. Mathematical Biosciences and Engineering. 2022; 19(11):11422-52.
[20] Elmetwaly AH, Eldesouky AA, Omar AI, Saad MA. Operation control, energy management, and power quality enhancement for a cluster of isolated

microgrids. Ain Shams Engineering Journal. 2022; 13(5):101737.

[21] Mahmoud MM, Atia BS, Esmail YM, Ardjoun SA, Anwer N, Omar AI, et al. Application of whale optimization algorithm based FOPI controllers for STATCOM and UPQC to mitigate harmonics and voltage instability in modern distribution power grids. Axioms. 2023; 12(5):1-26.

[22] Sepasi S, Talichet C, Pramanik AS. Power quality in microgrids: a critical review of fundamentals, standards, and case studies. IEEE Access. 2023; 11:108493-531.

[23] Amini M, Jalilian A. Modelling and improvement of open-UPQC performance in voltage sag compensation by contribution of shunt units. Electric Power Systems Research. 2020; 187:106506.

[24] Goud BS, Reddy CR, Bajaj M, Elattar EE, Kamel S. Power quality improvement using distributed power flow controller with BWO-based FOPID controller. Sustainability. 2021; 13(20):1-33.

[25] Hannan MA, Mohamed A. Unified series-shunt compensator: modeling and simulation. In PECon, proceedings, national power and energy conference, 2004 (pp. 55-60). IEEE.

[26] Bharat MN, Rajagopal B, Hari KD. Power quality enhancement of hybrid renewable energy source-based distribution system using optimised uPQC. Journal of Control and Decision. 2023: 1-22.

[27] BUDI SR, Kumar DV, Kumar KK. Power quality improvement using cuckoo search based multilevel facts controller. Journal of Engineering Research. 2022; 10(4A): 252-61.

[28] Krishna D, Sasikala M, Kiranmayi R. FOPI and FOFL controller based UPQC for mitigation of power quality problems in distribution power system. Journal of Electrical Engineering & Technology. 2022; 17(3):1543-54.

[29] Samal S, Hota PK. Wind energy fed upqc system for power quality improvement. Bulletin of Electrical Engineering and Informatics. 2018; 7(3):495-504.

[30] Nafeh AA, Heikal A, El-sehiemy RA, Salem WA. Intelligent fuzzy-based controllers for voltage stability enhancement of AC-DC micro-grid with D-STATCOM. Alexandria Engineering Journal. 2022; 61(3):2260-93.

[31] Elmetwaly AH, Younis RA, Abdelsalam AA, Omar AI, Mahmoud MM, Alsaif F, et al. Modeling, simulation, and experimental validation of a novel MPPT for hybrid renewable sources integrated with UPQC: an application of jellyfish search optimizer. Sustainability. 2023; 15(6):1-30.

[32] Dheeban SS, Muthu SNB. ANFIS-based power quality improvement by photovoltaic integrated UPQC at distribution system. IETE Journal of Research. 2023; 69(5):2353-71.

[33] Das SR, Ray PK, Sahoo AK, Ramasubbareddy S, Babu TS, Kumar NM, et al. A comprehensive survey on different control strategies and applications of active power filters for power quality improvement. Energies. 2021; 14(15):1-32.

[34] Abdel MSE, Ibrahim AM, Elbarbary ZS, Omar AI. Unified power quality conditioner using recent optimization technique: a case study in Cairo airport, Egypt. Sustainability. 2023; 15(4):1-23.

[35] Mosaad MI, El-raouf MO, Al-ahmar MA, Bendary FM. Optimal PI controller of DVR to enhance the performance of hybrid power system feeding a remote area in Egypt. Sustainable Cities and Society. 2019; 47:101469.

[36] Monteiro V, Moreira C, Lopes JA, Antunes CH, Osório GJ, Catalão JP, Afonso JL. A novel three-phase multiobjective unified power quality conditioner. IEEE Transactions on Industrial Electronics. 2023; 71(1):59-70.

[37] Gade S, Agrawal R. Optimal utilization of unified power quality conditioner using the JAYA optimization algorithm. Engineering Optimization. 2023; 55(1):1-8.

[38] Aldosary A. Power quality conditioners-based fractional-order PID controllers using hybrid jellyfish search and particle swarm algorithm for power quality enhancement. Fractal and Fractional. 2024; 8(3):1-22.

[39] Devassy S, Singh B. Modified pq-theory-based control of solar-PV-integrated UPQC-S. IEEE Transactions on Industry Applications. 2017; 53(5):5031-40.

[40] Eroğlu H, Cuce E, Cuce PM, Gul F, Iskenderoğlu A. Harmonic problems in renewable and sustainable energy systems: a comprehensive review. Sustainable Energy Technologies and Assessments. 2021; 48:101566.

[41] Molla EM, Kuo CC. Voltage sag enhancement of grid connected hybrid PV-wind power system using battery and SMES based dynamic voltage restorer. IEEE Access. 2020; 8:130003-13.

[42] Kulkarni NG, Virulkar VB. Enhancing the power quality of grid connected photovoltaic system during fault ride through: a comprehensive overview. Journal of The Institution of Engineers (India): Series B. 2023; 104(3):821-36.

[43] Liu X, Bai Y, Yu C, Yang H, Gao H, Wang J, et al. Multi-strategy improved sparrow search algorithm and application. Mathematical and Computational Applications. 2022; 27(6):1-28.

[44] Xue J, Shen B, Pan A. A hierarchical sparrow search algorithm to solve numerical optimization and estimate parameters of carbon fiber drawing process. Artificial Intelligence Review. 2023; 56(Suppl 1):1113-48.

[45] Dongre AA, Mishra JP, Majji RK. A new six-switch converter based unified power quality conditioner for improving power quality in single-phase system. International Transactions on Electrical Energy Systems. 2021; 31(12):e13221.

[46] Darvish FA. Half-cascaded multilevel inverter coupled to photovoltaic power source for AC-voltage synthesizer of dynamic voltage restorer to enhance voltage quality. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields. 2021; 34(5):e2883.

[47] Nagadurga T, Narasimham PV, Vakula VS, Devarapalli R. Gray wolf optimization-based optimal grid connected solar photovoltaic system with

enhanced power quality features. Concurrency and Computation: Practice and Experience. 2022; 34(5):e6696.
[48] Poongothai S, Srinath S. Power quality enhancement in solar power with grid connected system using UPQC. Microprocessors and Microsystems. 2020; 79:103300.
[49] Nagaraju G, Shankar S. Gravitational search algorithm for power quality improvement of WECS with UPQC. International Journal of Intelligent Engineering and Systems. 2019; 12(1):133-41.

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Appendix I

S. No.	Abbreviation	Description
1	AC	Alternating Current
2	ABEOA	An Adaptive Bald Eagle Optimization Algorithm
3	APF	Active Power Filter
4	ANFIS	Adaptive Neuro Fuzzy Inference System
5	ASDs	Adaptive Software Developments
6	BES	Battery Energy Storage
7	C_{DC}	DC Bus Capacitance
8	Cf	Ripple Filter Capacitance
9	CPD	Custom Power Devices
10	DC	Direct Current
11	DDSRF	Decoupled Double Synchronous
12	DPFC	Distributed Power Flow Controller
13	DFT	Discrete Fourier Transformation
14	DGs	Distributed Generation Systems
15	DSTATCOM	Distribution Static Synchronous Compensator
16	DVCC	Dual Vector Current Control
17	DVR	Dynamic Voltage Restorer
18	EPLL	Enhanced Phase Locked Loop
19	FACTS	Flexible AC Transmission System
20	FRT	Fault Ride Through
21	FOPID	Fractional Order Proportional Integral Derivative
22	FOFL	Fractional Order Fuzzy Logic
23	GSA	Gravitational Search Algorithm
24	GS	Genetic Search
25	GWO	Grey Wolf Optimizer
26	ICA	Independent Component Analysis
27	IEC	International Electrotechnical Commission
28	IEEE	Institute Of Electrical And Electronics Engineers
29	IGCT	Integrated Gate-Commutated Thyristor
30	Kp	Proportional Gain
31	Ki	Integral Gain
32	Kd	Derivative Gain
33	L	Inductor
34	LC	Inductor and Capacitor
35	LDSTAT	Interfacing Inductor
36	LED	Light Emitting Diode
37	Ls	Internal Source Inductance
38	LVRT	Low Voltage Ride-Through
39	MAF	Moving Average Filter
40	MG	Microgrid
41	MO-UPQC	Multi-Objective Unified PQ Conditioner
42	PCC	Point of Common Coupling
43	PCs	Personal Computers
44	PLCs	Programmable Logic Controllers
45	P&O	Perturb and Observe
46	PI	Proportional Integral
47	PID	Proportional Integral Derivative
48	PLL	Phase-Locked Loop
49	P_{Max}	Maximum Power
50	PQ	Power Quality
51	PSO	Particle Swarm Optimization
52	PSCAD	Power Systems Computer Aided Design
53	PV	Photo Voltaic
54	RESs	Renewable Energy Sources
55	Rf	Ripple Filter Resistance
56	RMS	Root Mean Square
57	ROA	Rider Optimization Algorithm
58	Rs	Internal Source Resistance
59	SCR	Short Circuit Ratio
60	SMES	Superconducting Magnetic Energy Storage
61	SRF-PAC	Synchronous Reference Frame-Power Angle Control
62	SSA	Sparrow Search Algorithm
63	SPV	Solar Photovoltaic
64	THD	Total Harmonic Distortion
65	UPQC	Unified PQ Conditioner
66	VAR	Volt-Amps Reactive
67	V_{DC}	DC Bus Voltage
68	Vs	Three-Phase Ac Supply Source
69	VS-ILSE	Variable Step Based Improved Least Sum of Exponentials
70	VSC	Voltage Source Converter
71	VSI	Voltage Source Inverter