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Enhancing Power Quality in Grid-Integrated Hybrid Renewable Energy System using ANFIS-FBSO

Special issue paper

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Abstract: The incorporation of hybrid renewable energy sources (RESs) into grid-integrated systems, comprising photovoltaic (PV) systems, wind turbines (WTs) and battery energy storage systems (BESSs), has become increasingly crucial in meeting global energy demands. In this paper, an enhanced adaptive neuro-fuzzy inference system (ANFIS)-based firebug swarm optimisation (FBSO) algorithm has been integrated with a unified power quality conditioner (UPQC) to mitigate power quality (PQ) issues in hybrid renewable energy systems (HRESs). An intelligent, adaptive and predictive control mechanism that combines machine learning (ANFIS) and optimisation (FBSO) is used in the adaptive neuro-fuzzy inference system-based firebug swarm optimisation (ANFIS-FBSO) framework to implement power balancing and frequency stabilisation. This allows for the dynamic management of energy flow and system stability in HRESs. The initial setup includes a WT, BESS and PV system connected to the load system. In HRESs, the primary objectives are to meet load demand and enhance PQ. To achieve these goals, a multi-resolution proportional-integral-derivative (MRPID) controller, alongside an ANFIS-FBSO-based controller in series and a shunt active power filter (SAPF), is used to address PQ issues in current and voltage, thereby enhancing UPQC performance. The FBSO algorithm optimises the learning function of the ANFIS for optimal outcomes. The proposed technique is implemented to validate its performance under various conditions, including voltage sag, current sag, real power, reactive power and total harmonic distortions (THDs). To assess the efficacy of the proposed technique, various cases are analysed and compared with existing methods.

Keywords: *hybrid renewable energy systems • multi-resolution proportional-integral-derivative • unified power quality conditioner • adaptive neuro-fuzzy inference system-based firebug swarm optimisation algorithm*

1. Introduction

In the contemporary era, the significance of renewable energy sources (RESs) has become paramount due to the environmental challenges associated with traditional energy sources. RESs, recognised for their effectiveness in reducing pollution and addressing global warming, have gained prominence (Naderi et al., 2019). The importance of distributed generation (DG) based on RES has grown alongside advancements in technology and increasing environmental awareness. Numerous optimisation strategies have been devised to effectively manage various power electronic devices, enhancing flexibility whilst integrating alternative sources such as solar, wind and batteries. This is a response to the escalating demand for power (Alshehri and Khalid, 2019; Gupta et al., 2020). DG is emerging as a pivotal solution, offering superior quality, heightened productivity and reliable electricity supply to end-users, especially considering the limitations of conventional energy sources (Reddy et al., 2019). The challenging landscape of electricity generation, driven by surging energy demand and population growth, has underscored the inadequacy of conventional sources, thereby elevating the importance of RES (Saggu et al., 2018; Samal and Hota, 2017).

To address the evolving landscape of energy needs, micro-grid (MG) systems have been introduced as a means to balance load requirements whilst incorporating RESs. However, the integration of RES into standalone MG

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systems presents challenges related to power quality (PQ) and stability (Elmetwaly et al., 2020; Poongothai and Srinath, 2020). Periodic fluctuations in weather affecting renewable sources and variations in load characteristics, encompassing unbalanced, non-linear and critical loads, can lead to disruptions, voltage sag, harmonics and swell within standalone MG systems. These PQ issues have repercussions, altering voltage levels on the load side and triggering load tripping, thereby compromising system dependability. Frequent tripping in a standalone MG is detrimental to system reliability and must be minimised to ensure proper functionality (Aljendy et al., 2022).

In the present era, a primary objective of electric power systems is the attainment of enhanced PQ. The significance of PQ has heightened because of the high usage of non-linear and electronically switched devices in distribution networks and industries. Consequently, consumers and facilities are adopting various compensators, including static and passive filters, to address PQ issues (Dash and Ray, 2019; Saggu et al., 2017). Emerging technologies, such as flexible AC transmission system (FACTS) and custom power devices (CPDs), offer promising solutions for electric utilities grappling with concerns related to PQ. Amongst the CPDs, the unified power quality conditioner (UPQC), distribution static compensator (DSTATCOM) and dynamic voltage restorer (DVR) are used consistently to rectify PQ issues affecting both current and voltage (Elmetwaly et al., 2022; Jeyaraj et al., 2020; Yazdi and Hosseinian, 2019). The FACTS, comprising power electronic devices such as the static synchronous series compensator (SSSC) and the unified power flow controller (UPFC), utilises voltage source converters (VSCs) based on power semiconductor components such as isolated gate bipolar transistors and gate turn-off switches. The integration of FACTS devices enhances the efficiency of power systems, offering additional advantages such as effective regulation of reactive power and voltage (Kuchibhatla et al., 2020; Naidu and Meikandasivam, 2020; Radhika et al., 2020).

Some studies have delved into PQ concerns, whilst others have focused on compensating for reactive power to improve the stability of a power system (Haq et al., 2021). In MGs, various meta-heuristic methods are used to mitigate changes in voltage and current within the system. The integration of RESs into MG aims to meet load demands influenced by diverse environmental conditions (Samal et al., 2020). Factors such as partial shadowing can impact photovoltaic (PV) systems. Consequently, techniques such as maximum power point tracking (MPPT) are crucial to maximise power generation from renewable sources such as PV and wind turbines (WTs) (Iqbal et al., 2021; Ni et al., 2022). Meta-heuristic algorithms such as particle swarm optimisation (PSO), the firefly algorithm (FA), the bat algorithm (BA), the random forest classification algorithm (Liu et al., 2019) and the object-based classification of hyperspectral data using the random forest algorithm (Amini et al., 2018) are used to extract maximum power from renewable sources and minimise voltage and current variations in MG systems (Jamil et al., 2019).

In many hybrid renewable energy system (HRES) implementations, the use of UPQC based on soft computing (SC) approaches proves more effective than traditional proportional-integral (PI) and proportional-integral-derivative (PID) controllers. However, there is a relatively limited number of studies exploring PQ issues using shunt and series FACTS devices based on SC techniques. A study has been conducted on an enhanced fuzzy-based multi-converter unified power quality conditioner (MC-UPQC) to improve PQ in grid-connected wind energy systems (WESs). The proposed controller, known as hybrid fuzzy incremental conductance-controlled MC-UPQC, incorporates fuzzy incremental conductance to find the highest power point in a wind energy conversion system (WECS). When combined with MC-UPQC, this controller enhances the WES's connection to the grid, simultaneously compensating for voltage and current faults in nearby feeders. This setup utilises a shared DC-link capacitor amongst converters, enabling power transmission between nearby feeders (Chaudhary and Singh, 2020).

Stable management of an adaptive power quality compensator (APQC) in multi-microgrids for PQ enhancement using a puzzle optimisation approach has already been demonstrated. The APQC comprises shunt and series compensators, utilising thyristor-controlled series capacitors (TCSCs) as a series compensator and a shunt active power filter (SAPF) as a shunt compensator. TCSCs enhance the dynamic voltage profile and reduce transient voltage, whilst SAPF lowers voltage and current harmonics and improves power factor. A swarm intelligence-based puzzle optimisation method is used to identify the best PID controller for self-tuning, revealing the APQC typology (Sindi et al., 2023). Furthermore, researchers have presented an optimal power quality improvement in a hybrid fuzzy-sliding mode MPPT control-based solar PV and battery energy storage system (BESS) with UPQC. The integration of MPPT for PV systems and artificial neural network controllers (ANNCs) for UPQC series is used. Shunt active filters are used to reduce total harmonic distortion (THD) and improve power factor, ensuring a stable DC-link voltage with a brief settling point (Thangella et al., 2022).

A distributed generating system based on renewable energy using an artificial neural network (ANN)-tuned UPQC has already been developed. The primary objective is to provide better steady and dynamic state performance compared to the PID controller. The UPQC-ANN renewable system integrates a solar array and a WT into the electrical grid, improving PQ indicators such as power factor and voltage and current harmonics whilst contributing active/real power to the utility grid (Zanib et al., 2022). An ANFIS-based solar-integrated UPQC for PQ enhancement in distribution systems has already been implemented. The fuzzy model-based controller, utilising linguistic principles for inferring system parameters, enhances system performance. The PV-UPQC performs effectively under various load scenarios, minimising the THD level when using the adaptive neuro-fuzzy inference system (ANFIS, Dheeban and Selvan, 2023). A fractional order PI controller with chicken swarm optimisation (CSO) has already been designed to improve PQ in hybrid energy systems (HESs) with integrated UPQC. The proposed models for RES, such as wind energy, BESS and PV arrays, aim to provide a steady power supply. The UPQC model, with series and shunt active filter compensators, reduces harmonics contributed by non-linear loads and enhances PQ during voltage sag/swell (Yadav and Yadav, 2023). To tackle PQ issues in HRESs, an atom search optimisation (ASO) algorithm using UPQC has already been presented. The UPQC system seeks to reduce PQ problems associated with voltage and current by using a fractional order proportional integral derivative (FOPID) in series with an ASO-based controller and a SAPF. A load system linked to PV, WT and a BESS is part of the HRES design. To assess the performance of the suggested controller, non-linear loads are added to cause PQ issues (Goud and Rao, 2021).

The number of research papers has already been published on PQ enhancement in UPQC-integrated HRESs with different algorithms and different controllers. Considering the research gaps in the reviewed literature, this paper presents the PQ enhancement in HRES using a novel technique adaptive neuro-fuzzy inference system-based firebug swarm optimisation (ANFIS-FBSO) with a multi-resolution proportional-integral-derivative (MRPID) controller. To improve the flexibility and accuracy of control in non-linear, time-varying systems, the main goal of combining ANFIS and firebug swarm optimisation (FBSO) is to optimise the fuzzy rules and membership functions in ANFIS using FBSO. Because of its precision control or forecasting tasks such as energy management, state of charge (SOC) control or dynamic power allocation, this method is best suited for highly non-linear systems such as HRESs with wind, solar and battery interactions, even though it increases computational complexity and causes significant delays in the control unit's operation.

The main contribution of this paper is to integrate the DG with the utility grid. The DG system comprises of PV, WT and BESS. The PV and WT generate the electric power as per the irradiance level and wind speed. To meet the required load demand under partial shading and environmental conditions, the BESS is used to store the extra power. PQ issues such as sag, swell and disturbances are produced in both current and voltage by applying non-linear load. A MRPID controller, along with an ANFIS-FBSO-based controller in series and a SAPF, is implemented to mitigate the PQ issues to improve the UPQC performance. The FBSO algorithm optimises the learning function of the ANFIS for optimal outcomes. The proposed technique is used to validate the achieved results in terms of voltage sag, current sag, real power, reactive power and THDs. To validate the effectiveness of the proposed approach, various cases are analysed and compared with existing techniques.

2. Modelling of Hybrid Renewable Energy Storage System

The system model depicted in Figure 1 integrates PV, WTs and batteries with a grid-connected system. These renewable energy storage systems are utilised to offset the consumer load requirements. The battery serves the dual purpose of storing excess power generated by solar panels and WTs, as well as providing essential electricity during emergencies. For steady, dependable and effective power supply in HRESs, energy management is essential. These systems have to maintain DC bus voltage, control battery SOC, optimise resource utilisation and balance variable generation from RESs with load demand. A MG's dynamic behaviour during a fault or disturbance is dependent upon a number of variables, including the type of energy source involved, system setup, control measures and the nature of the disturbance. In the context of a HRES connected to the smart grid, the primary focus is on addressing PQ concerns, which are identified as significant contributors to instability and reliability issues. The HRES, when grid-connected, incorporates a UPQC design to alleviate PQ issues such as sag, swell and interruptions. The UPQC utilises both shunt filters and series control methods to mitigate PQ problems. The optimal gain values for the filters are determined by the MRPID controller, ensuring the injection of the necessary power to compensate for sag and swell situations. The enhanced ANFIS-FBSO algorithm contributes to optimise the MRPID control settings.

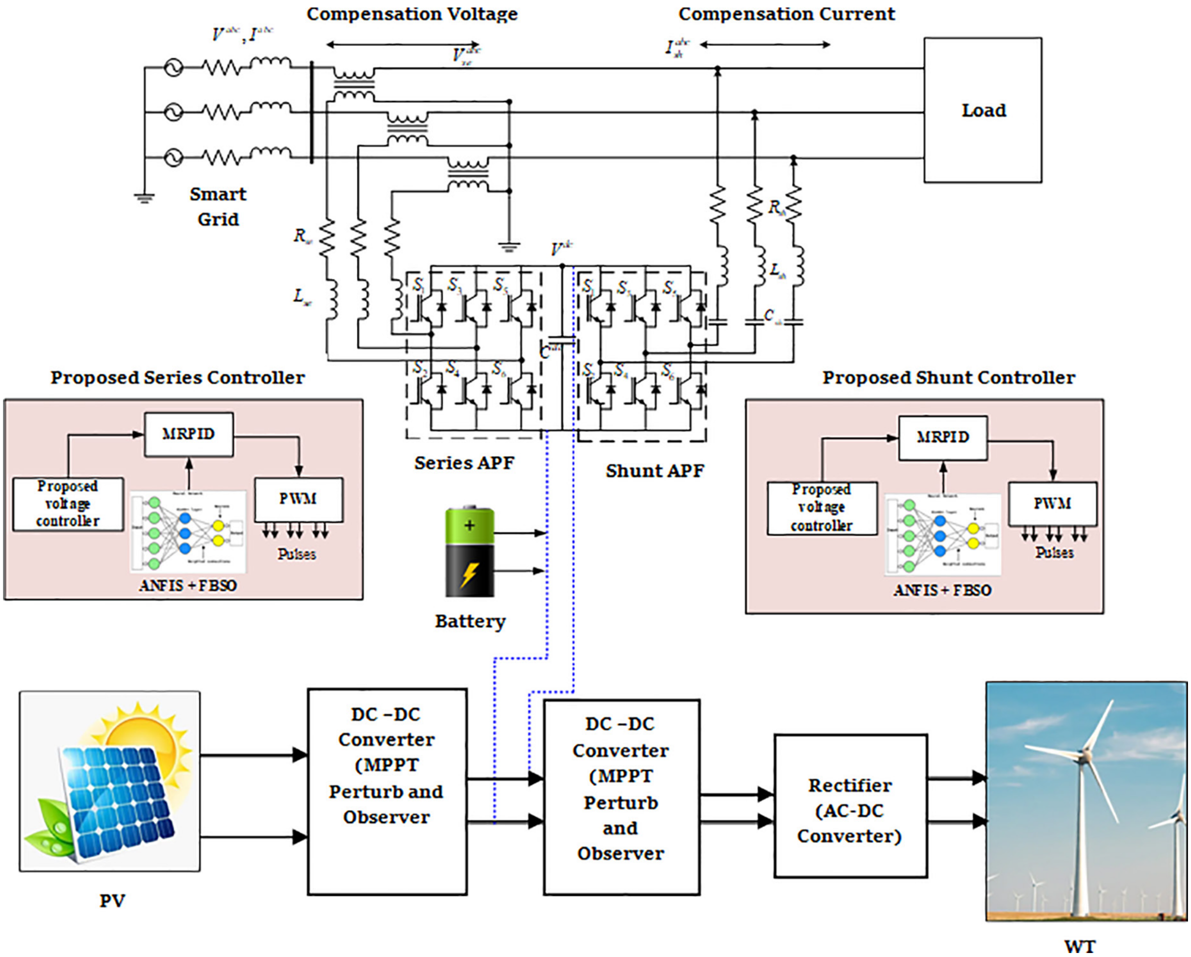


Figure 1. Architecture of a smart grid-connected hybrid renewable energy storage system.

2.1. PV system

Power is produced by the PV system by converting solar energy into electricity. The maximum power point tracker and DC-DC converter are incorporated into the PV system. In typical irradiance circumstances, obtaining maximum power output requires a maximum power point tracker. To maximise PV voltage and achieve the minimum power point voltage, it calculates the duty cycle for the converter. The duty cycle of a power electronic converter determines how long a converter's switch is turned on within one switching period. It is defined as the ratio of ON period of switch to the total switching period.

Consequently, data on the electricity produced by the PV are required by the HRES. The equation for power produced by PV is given as:

$$\mathrm{P_{PV}} = \mathrm{I_R} \times \mathrm{P_{Eff}} \times \mathrm{R_{Eff}} \times \mathrm{P_{Area}} \tag{1}$$

where P_{PV} is the PV's output power (W), I_R is the PV's irradiance $\left(\mathrm{W/m^2}\right)$, P_{Eff} is the PV's efficiency, R_{Eff} is the efficiency decrease factor because of shadows and direction and P_{Area} is the PV's total installed area (Rekioua et al., 2023).

2.2. Wind turbine energy conversion system (WTECS)

The WTECS transforms kinetic energy into electrical energy. The WTECS includes the WT, shaft and permanent magnet synchronous generator (PMSG) that are utilised to produce energy. A generator and a shaft are rotated by the wind energy in a WT, which transforms mechanical energy into electrical energy. The MPPT and tip speed ratio (TSR) are the factors that regulate the WT system. The power generated by WTECS is given as:

$$P_{Wind} = \frac{1}{2} \times P_{cof} \times \rho \times A \times V_{Wind} \tag{2}$$

where P_{Wind} is the power generated by WTECS, P_{cof} is the coefficient of power, ρ is the air density, A is the windswept area and V_{Wind} is the wind velocity (Prasad et al., 2022).

2.3. BESS

In a smart grid, the storage system is essential because load demand may sometimes exceed PV and WTECS production. Overage electricity is chemically stored in a battery bank. Through electrochemical processes, the battery may be charged and discharged, turning chemical energy into electrical energy whilst charging and vice versa when discharging. The power needed to fulfill load demand in the event of no generating power and to store extra power above and beyond load demand is taken into account whilst designing the size of the battery storage. When generation exceeds load demand, stored power makes up for a power loss during low generation. The SOC, which may be calculated at any given time using the following equation, is used to evaluate battery performance.

$$SOC(t) = SOC(t-1) + \frac{P_{Wind}(t) + P_{PV}(t) - P_{Grid}(t)}{V_B \times C_B} \tag{3}$$

where $P_{Wind}(t)$ is the WTECS power generation, $P_{PV}(t)$ is the PV power generation, $P_{Grid}(t)$ is the load demand, V_B is the battery voltage and C_B is the battery capacity.

- Battery charging occurs when the combined power output of PV and WTECS surpasses the load requirement i.e. $P_{Wind}(t) + P_{PV}(t) > P_{Grid}(t)$
- The battery will be discharged when $P_{Wind}(t) + P_{PV}(t) < P_{Grid}(t)$ i.e. the combined generating power of PV and WTECS is insufficient to meet the load requirement.

The battery discharge rate, which is commonly represented by the C-rate or current over time, is based on how rapidly energy is extracted from the battery. C-rate, which shows how quickly a battery is depleted in relation to its maximum capacity, is expressed as $I = C \times CAP$. Here, I represents the discharge current in amperes (A), C for C-rate and CAP for battery capacity in amp-hours (Ah). To develop the smart grid-connected HRES system, battery banks, WTECS and PV are used. The energy management of the smart grid-connected HRES system structure is accomplished with the help of the proposed UPQC controller (Lei et al., 2022).

2.4. DC bus system (DCBS)

The DC bus in UPQC acts as an energy buffer between the input and output stages, keeps the voltage level steady for the inverter to operate properly, absorbs power imbalances from fluctuations in RESs and facilitates energy flow in both directions to and from energy storage (Gulzar et al., 2023). The intermittent nature of renewable sources, such as solar and wind, combined with storage, such as batteries in a hybrid renewable energy storage system, can result in changes in DC bus voltage. The shunt and series converters of UPQC exchange power primarily through the DC bus. Stability, PQ and energy management in a hybrid renewable energy storage system depend on accurate modelling and dynamic control of this DC bus (Axente et al., 2011). The dynamic behaviour of the DC bus can be expressed by the following equation

$$C\frac{d\ V_{dc}}{dt} = \frac{1}{V_{dc}}\left(P_{Sh} - P_{Se} + P_{Res} - P_L \right) \tag{4}$$

where V_{dc} is the DC link voltage, C is the capacitance of the DC bus, P_{Sh} is the power flow from the shunt converter, P_{Se} is the power delivered by the series converter, P_{Res} is the power generated by renewable sources (PV/wind) and P_L is the load power demand. The main control objectives of dynamic DC bus modelling include the maintenance of V_{dc} within specified limits, absorb or supply transient power through BESS and to coordinate power flow from PV/wind/battery to avoid over- or under-voltage (Fuyin et al., 2019).

3. PQ Enhancement using Proposed Technique

This section introduces an enhanced ANFIS-FBSO algorithm for improving PQ in HRES within the smart grids. ANFIS develops complex non-linear mappings between inputs (weather, power mismatch, SOC and rate of load change) and outputs (instructions for charging or discharging batteries). The presented approach utilises an integrated function incorporating the ANFIS-FBSO algorithm to derive optimal parameters for enhancing the search behaviour of the FBSO algorithm, specifically targeting optimal gain. Enhanced ANFIS is then applied to reduce the error function, thereby improving PQ for the HRESs. The reduction in the error function is achieved by optimising parameters related to the MRPID controller.

3.1. Design of MRPID controller

In a smart grid-connected HRES, the recommended MRPID controller is utilised in conjunction with the ANFIS-FBSO algorithm to manage PQ problems related to voltage and current disturbances. Compared to more conventional controllers such as FOPID, PI and PID, the MRPID controller offers more flexibility in frequency management. With its three parameters, the MRPID controller gives the best results in the control process. The MRPID controller significantly reduces error voltage and error current levels by providing optimal pulses. These perfect pulses are chosen using the enhanced ANFIS-FBSO algorithm, which aims to minimise error voltage and error current. Through the use of series and SAPFs to enhance the control method of the UPQC device, this MRPID controller effectively mitigates PQ issues in the smart grid-connected HRES. An extensive overview of the MRPID controller is provided in this section.

The MRPID controller is critical to achieving optimal performance in reducing error voltage and error current in the super control of the smart grid-connected HRES. It does this by mitigating undershoot and overshoot issues in the signal, thereby reducing error signals and speeding up controller response. Along with increasing system performance and demonstrating reduced susceptibility to parameter changes, the MRPID controller may be utilised to rapidly provide isodamping characteristics (Deepa et al., 2023). The MRPID controller leverages the multi-resolution property of wavelets by using several mother wavelet dilations and translations to convert the error signal into a linear mixture of basic functions. Eq. (5) represents the result of a PID controller, which is the sum of three gain parameters, denoted as K_P, K_I and K_D.

$$U_{PID} = K_P E + K_I \int E dt + K_D \frac{dE}{dt} \tag{5}$$

Here, U_{PID} is the PID controller output. The generated MRPID controller output signal is given by Eq. (6).

$$U_{MRPID} = K_H E_H + K_{M1} E_{M1} + K_{M2} E_{M2} + \ldots + K_{M(x-1)} E_{M(x-1)} + K_L E_L \tag{6}$$

where U_{MRPID} is the MRPID controller output, and K_M, K_H and K_L are used as gain parameters for medium frequencies, higher frequencies and low frequencies, respectively, in the case of the MRPID controller. This procedure is shown in Figure 2.

3.2. Optimisation of gain parameters for PQ improvement using ANFIS-FBSO

The best values for accomplishing power management in the smart grid structure are found using the ANFIS algorithm. The FBSO method is used to get the optimum values of the parameters of the fuzzy interference system (FIS). Optimising parameters minimises the discrepancy between the reference and actual values. With the assistance of the improved algorithm, a blend of FBSO and ANFIS, the error value is reduced. Using the FBSO, the settings of the ANFIS are optimised. In this case, the membership functions influence the ANFIS parameters, which are premise parameters. Upon representation of the membership function, optimisation procedures are implemented in order to minimise the error value. The ANFIS algorithm's parameter configuration enables FBSO to get data from the smart grid structure modelling. The rules listed below are part of the FIS system.

$$\text{If } M \text{ is } M_1 \text{ and } N \text{ is } N_1, \text{ then } Y_1 = i_1 M + j_1 N + k_1 \tag{7}$$

$$\text{If } M \text{ is } M_2 \text{ and } N \text{ is } N_2, \text{ then } Y_2 = i_2 M + j_2 N + k_2 \tag{8}$$

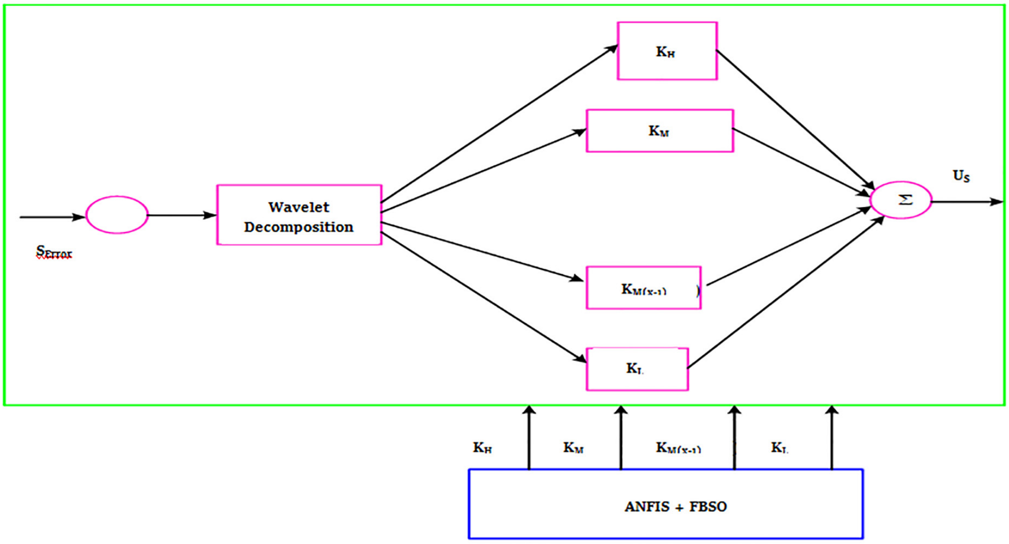


Figure 2. Diagram of the self-tuned, wavelet-based MRPID optimised controller. MRPID, multi-resolution proportional-integral-derivative.

The membership functions M and N in this case are represented by M_1, N_1 and M_2, N_2 as non-linear parameters, and the $i_1, i_2, j_1, j_2, k_1, k_2$ are the linear parameters. The structure of the ANFIS model is shown in Figure 3. The inputs to the ANFIS controller are the voltage and current errors, whereas the output of the ANFIS controller are error-minimised voltage and current values (Naphon et al., 2020).

The following steps provide a detailed explanation of the sequential procedure in each of the ANFIS layers.

3.2.1. First layer (fuzzy layer)

The nodes in this layer are referred to as adaptable. Eqs (9) and (10), which provide the fuzzy membership grade, use the first layer outputs as input.

$$L_{out}^{1} = \gamma_{mx}(m),\ x = 1, 2 \tag{9}$$

$$L_{out}^{1} = \gamma_{nx-2}(n),\ x = 3, 4 \tag{10}$$

On the other hand, γ_{mx} and γ_{nx-2} are node function's linguistic labels (such as high, low, etc.). m and n are the inputs of the node x. $\gamma_{mx}(m)$ and $\gamma_{nx-2}(n)$ are adhered to any fuzzy membership function. For example, a bell-shaped membership function results in $\gamma_{mx}(m)$, given by Eq. (11).

$$\gamma_{mx}(m) = \frac{1}{1 + \left|\frac{m - k_x}{i_x}\right|^{2 j_x}},\ x = 1, 2 \tag{11}$$

Eq. (12) is presented for the Gaussian membership function.

$$\gamma_{mx}(m) = \exp\left[-\left(\frac{m - k_x}{i_x}\right)^2\right] \tag{12}$$

Here i_x, j_x, k_x are the membership function's location.

3.2.2. Second layer (product layer)

Fixed nodes are the nodes that compose the layer. This layer supports fuzzy operators; the inputs are fuzzied using the AND operator. They are a simple multiplier since they have the label on them. The output of this layer is shown in Eq. (13).

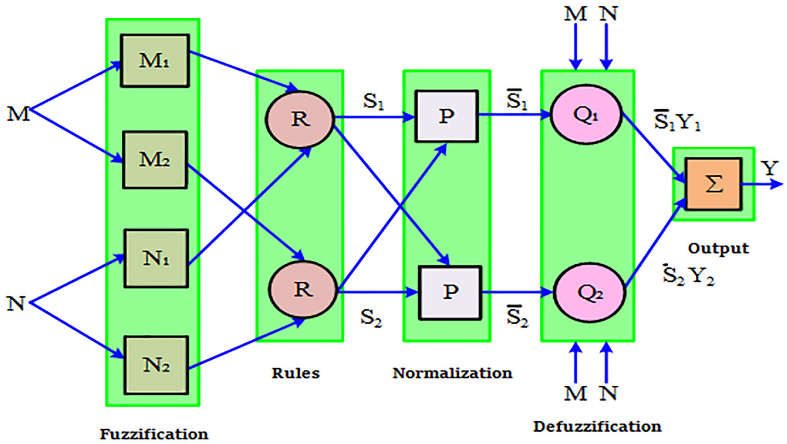


Figure 3. Structure of ANFIS model. ANFIS, adaptive neuro-fuzzy inference system.

$$L_{out}^{2} = S_x = \gamma_{mx}(m) \times \gamma_{nx-2}(n),\ x = 1, 2 \tag{13}$$

These are exactly the rules referred to as their firing strengths.

3.2.3. Third layer (normalised layer)

Nodes that are identified and designated as fixed constitute this layer. The firing strength from the second layer is used by the layer that carries out the normalisation procedure. Eq. (14) provides the output of the layer.

$$L_{out}^{3} = \overline{S_x} = \frac{S_x}{S_1 + S_2},\ x = 1, 2 \tag{14}$$

The outputs of this layer are called normalised activation strengths.

3.2.4. Fourth layer (defuzzy layer)

In this layer, nodes are designated as adaptable. The layering process is defined as the product of the first-order polynomial and the normalised firing strength. The output of this layer is given by Eq. (15),

$$L_{out}^{4} = \overline{S_x}\ Y_x = \overline{S_x}\left(i_x\ m + j_x\ n + k_x\right),\ x = 1, 2 \tag{15}$$

3.2.5. Fifth layer (total output layer)

The incoming signals from layer 4 produce the node process. Eq. (16) describes the output of layer 5,

$$L_{out}^{5} = \sum_{x} \overline{S} Y_x = \frac{\sum_x S_x\ Y_x}{\sum Y_x} \tag{16}$$

This section explains the different layer structures of the ANFIS algorithm. The training sets are obtained through the FBSO algorithm, which will be detailed in the following section.

3.3. The FBSO's method for obtaining ANFIS learning

The ANFIS algorithm's learning function is accomplished via the FBSO algorithm. The way that bugs are sought is what drives the algorithm. *Pyrrhocoris apterus*, often known as firebugs, exhibit two primary behavioural types: firebugs may either walk and investigate in solitude or exhibit gregarious activity and form aggregations. The firebugs use these gatherings to lessen predator pressure and locate suitable partners for procreation. These are the gatherings that firebugs establish throughout the summer. It makes sense to think of firebug movement as an optimisation process as they search for the ideal spouse (Subarnan et al., 2023). The FBSO algorithm's process is as follows:

Step 1: Initialisation

The initialisation step involves entering the population, voltage, higher and lower bounds, female and male bug input and algorithmic current values. The method generates the gain levels K_H, K_M *and* K_L for MRPID controller settings at random.

$$P = \left(Fb_1^{mf}, Fb_2^{mf}, \ldots, Fb_n^{mf} \right) \tag{17}$$

where $Fb_1^{mf}, Fb_2^{mf}, \ldots, Fb_n^{mf}$ are the male and female bug inputs.

Step 2: Fitness function calculation

To provide the best pulses for the MRPID controller's settings, the ANFIS-FBSO algorithm is used. ANFIS-FBSO algorithm's initial population consists of MRPID controller settings and error values. Through an optimisation process powered by a fitness function, optimal pulses are produced. The following is the formulation of the optimisation problem for figuring out the MRPID controller parameters:

$$FF = Min\left(S_{error}\right) \tag{18}$$

where S_{error} is the error signal's value and FF is the fitness function, respectively.

Step 3: Formation of female colonies

The FBSO method begins with male bugs B_{male} and of female bugs B_{female} in a randomly dispersed colony in the search space. Every bug has a real scalar cost function value and a location (represented as a column vector). That is, within the search space, each female insect's beginning location is regarded as a uniform vector random variable.

Step 4: Mate selection

The location of every male insect in a colony is initialised to that of the best female bug, as males only mate with the most physically fit females. Because of this, the location of every male insect in a colony is continuously adjusted to correspond with the best female.

Step 5: Chemotactic movement of female bugs

Each female insect inside a certain male's colony has her position stored in a single, synchronously updated matrix. Using effective Hadamard multiplication operations, the following matrix update equations are used for the simultaneous updating of all female bugs in a given colony:

$$M_i \leftarrow repmat\left(m\left(m'\right)\cdot i, 1, B_{female}\right) \tag{19}$$

$$M_j \leftarrow repmat\left(m\left(r'\right)\cdot i, 1, B_{female}\right) \tag{20}$$

where r' is the random integer within the range $\left[1 - B_{female}\right]$. In response, a matrix containing m' and n' copies of the matrix R in row and column dimensions, $repmat\left(R, m', n'\right)$ is obtained, which replicates a matrix R to obtain a higher order matrix. Thus, if R is a u by v matrix, returns a matrix of $m'u$ by $n'v$.

$$m\left(m'\right)\cdot F \leftarrow m\left(m'\right)\cdot F + T_1 \odot \left(\mathrm{M_i} - m\left(m'\right)\cdot F\right) + T_2 \odot \left(\mathrm{M_j} - m\left(m'\right)\cdot F\right) \tag{21}$$

The term $T_1 \odot \left(\mathrm{M_i} - m\left(m'\right)\cdot F\right)$ represents the pull in the direction of the target, $\mathrm{M_i}$.The difference between the desired position and the current position of the firefly *m* is first calculated, and the difference is then scaled using the parameters in T_1. In the same manner, the term $T_2 \odot \left(\mathrm{M_j} - m\left(m'\right)\cdot F\right)$ represents the pull in the direction of the target, $\mathrm{M_j}$.The difference between the desired position and the current position of the firefly *m* is first calculated, and the difference is then scaled using the parameters in T_2. Eventually, the attraction parameters $T_1 \odot \left(\mathrm{M_i} - m\left(m'\right)\cdot F\right)$ and $T_2 \odot \left(\mathrm{M_j} - m\left(m'\right)\cdot F\right)$ are added to the present location $m\left(m'\right)\cdot F$ of the firefly to obtain the revised position. The FBSO algorithm simulates the movement and attraction behaviour of fireflies towards brighter spots by repeatedly applying this equation to every firefly in the swarm. Its goal is to converge towards optimal or nearly optimal solutions. Here T_1 and T_2 stand for the colonies of male and female insects, respectively. *F* is the matrix that shows the position of female bugs. Also $\odot$ is the Hadamard product symbol.

Step 6: Attracting male insects to update female insects
Not in its colony, but to fit females, each male beetle is also drawn to them. The males migrate in the direction of the most fit female, which keeps the whole colony contained inside a certain area and prevents the swarm from spreading. To drive male bugs in the direction of the most fit female bug, the following updated rule is used:

$$m(m')\cdot i \leftarrow m(m')\cdot i + T_3 \odot \left(\mathrm{x} - m(m')\cdot i\right) \tag{22}$$

The term $m(m')\cdot i$ shows the male bug's modified position following the application of the movement equation, T_3 is a coefficient that regulates the bug's motion in the direction of the global optimal position. x symbolises the top position in the search space on a worldwide scale. Amongst all the fireflies, it is frequently the position linked to the highest fitness or objective function value.

Step 7: Swarm cohesion
The individual bugs do not scatter; instead, the whole swarm travels as a cohesive entity. The swarm travels randomly as a single entity; therefore, each insect needs to mimic the path taken by its peers. A herd cohesion model is suggested using Eq. (23), which causes every male bug to migrate in the same direction as a randomly selected male bug in the direction of the most fit female bug.

$$m(m')\cdot i \leftarrow m(m')\cdot i + T_4 \odot \left(\mathrm{x} - m(b)\cdot i\right) \tag{23}$$

Here b is the number of defects, and the investigation of new solutions x is reduced. T_4 is a coefficient that affects how bugs go in the direction of the locations of the fourth colonies.

Step 8: Weak solution
Similarly, Eq. (24) explains why female insects move so weakly in the direction of a different male insect:

$$m(m')\cdot F \leftarrow m(m')\cdot F + T_1 \odot \left(\mathrm{M_i} - m(m')\cdot F\right) + T_2 \odot \left(\mathrm{M_j} - m(m')\cdot F\right) \tag{24}$$

The two terms, $T_1 \odot \left(\mathrm{M_i} - m(m')\cdot F\right)$ and $T_2 \odot \left(\mathrm{M_j} - m(m')\cdot F\right)$, describe the movement of the random male insect and the dominant male bug, respectively.

Step 9: Termination
The calculation process halts upon meeting the stopping criteria, or the process repeats, returning to Step 2. To fulfil the fitness function and ultimately address PQ concerns, the optimal solution is selected during the updated process. The gain parameters of the MRPID controller are determined using these fitness functions. A final condition check becomes essential before implementing the optimal solutions, considering factors such as reaching the maximum number of iterations and verifying constraints. The perfect power flow in the HRES linked to the smart grid is then achieved by using the optimal solutions. The system's PQ problems are successfully mitigated by using the improved ANFIS-FBSO algorithm. Additionally, the ANFIS-FBSO framework offers frequency stability and power balancing. In HRES s, this enables the dynamic control of energy flow and system stability. In addition to storage charging and discharging, power balancing ensures that total generation always meets the total demand. ANFIS predicts the ideal output levels from each source and learns non-linear mappings from system states (such as PV/ wind power, load and SOC of battery) to necessary management actions. The FBSO optimises ANFIS parameters, battery charging and discharging levels, demand response, load-side management and generator dispatch. The subsequent section provides a comprehensive overview of the findings and discussions.

4. Results and Discussion

To enhance PQ within the proposed system, an MRPID controller, along with an ANFIS-FBSO-based controller is implemented to mitigate the PQ issues to improve the UPQC performance. The FBSO algorithm optimises the learning function of the ANFIS for optimal outcomes. The proposed technique is used to validate the achieved results in terms of voltage sag, current sag, real power, reactive power and THD s. To validate the effectiveness of the proposed approach, results are compared with existing techniques, such as cuttlefish algorithm (CFA), elephant herding optimisation (EHO), PSO and grey wolf optimisation (GWO). Figure 4 shows the proposed ANFIS-FBSO controller's MATLAB/Simulink implementation model in the smart grid-connected HRES system. Table 1 shows the parameters used for the simulation of the proposed technique.

The primary evaluation tool is the solar and wind power orientation voltage graphs. The PQ difficulties are then assessed whilst using the visual assistance. As the performances are evaluated, the source voltage is supplied to the system. Most PQ disturbances, such as voltage sags, occur within the system. After analysing the altered voltage, the mentioned methods are used to mitigate PQ disturbances by implementing UPQC. The goal of this proposed technique is to effectively reduce harmonics. The three analysis scenarios are used to examine the simulation's output findings using the recommended methodology.

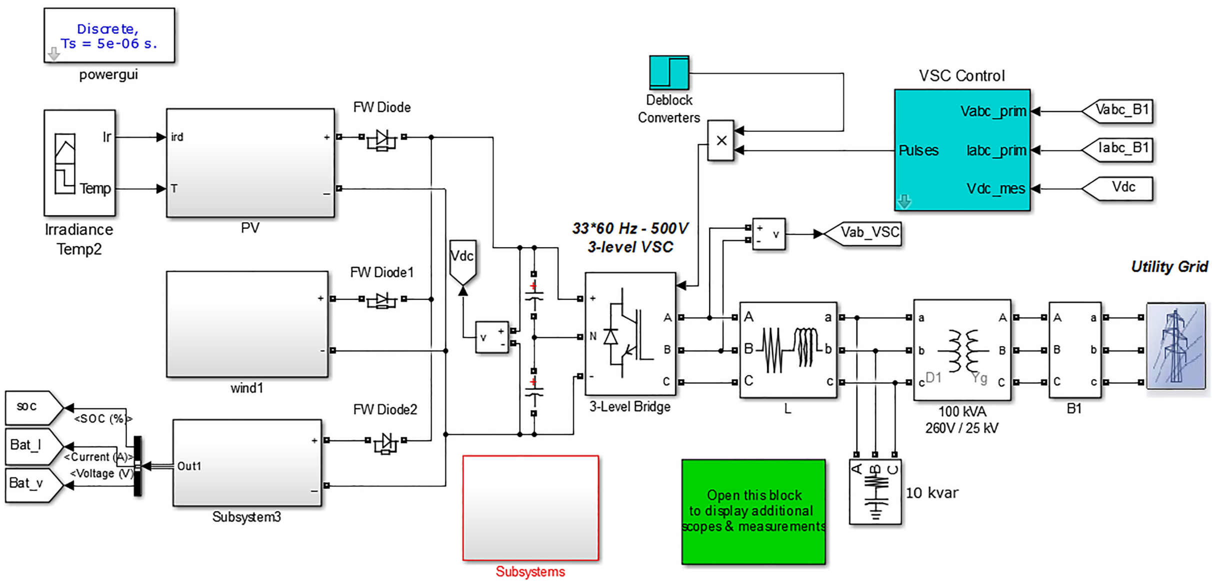


Figure 4. MATLAB/Simulink model of the HRES system with the proposed controller. HRES, hybrid renewable energy system.

Table 1. Characteristics of proposed technique.

Parameters	Techniques	Values
Nominal voltage	Battery	26.4 V
Rated capacity		6.6 Ah
Discharge current		2.86 A
Voltage at open-circuit conditions	PV	64.2 V
Current at short circuit conditions		5.96 A
Voltage at maximum power point		54.7 V
Current at maximum power point		5.58 A
Maximum value of current	WT	19 A
Maximum value of voltage		500 V
Number of membership functions	ANFIS	5
Membership function		Gaussian bell
No. of populations	FBSO	50
No. of iterations		50

ANFIS, adaptive neuro-fuzzy inference system; FBSO, firebug swarm optimisation; PV, photovoltaic; WT, wind turbine.

Case 1: Sag condition of voltage and current (constant source)
Case 2: Swelling conditions for voltage and current (variable source)
Case 3: Disruptions in voltage and current (continuous source)

4.1. Case 1: Sag condition of voltage and current

When loads are introduced into systems connected to the smart grid's intended HRES, sag faults may occur. To mitigate and balance the load demand, the proposed system is designed using an MRPID controller based on the ANFIS-FBSO algorithm. In these systems, the WT speed and PV irradiation are maintained at constant levels. Specifically, the PV irradiance is set at 1,000 W/m^2, whilst the WT speed is held at 12 m/s. Additionally, the battery is in the charging state. This hybrid system is carefully configured to meet load requirements and address PQ issues.

Figure 5(a) illustrates that the power generated by the PV system is 7 × 10^4 W at irradiance 1,000 W/m^2, whilst Figure 5(b) shows the power generated by the WT is 5,120 W at a constant wind speed of around 12 m/s. The battery power and SOC are depicted in Figure 5(c), with battery power ranging from 2,000 W to 1,400 W.

The smart grid-connected load system encounters a non-linear load, leading to sags in system voltage and current. The occurrence known as voltage sag arises when incorporating a non-linear load into the HRES. Addressing this phenomenon is crucial to ensure the system operates linearly and stably. The UPQC is used to supply the necessary electricity for meeting load demand and resolving PQ issues. The impact of voltage sag, corrected voltage and injected voltage from the UPQC is depicted in Figure 6(a). Similarly, Figure 6(b) illustrates the existing sag, corrected current and injected current from the UPQC. The implementation of the proposed controller

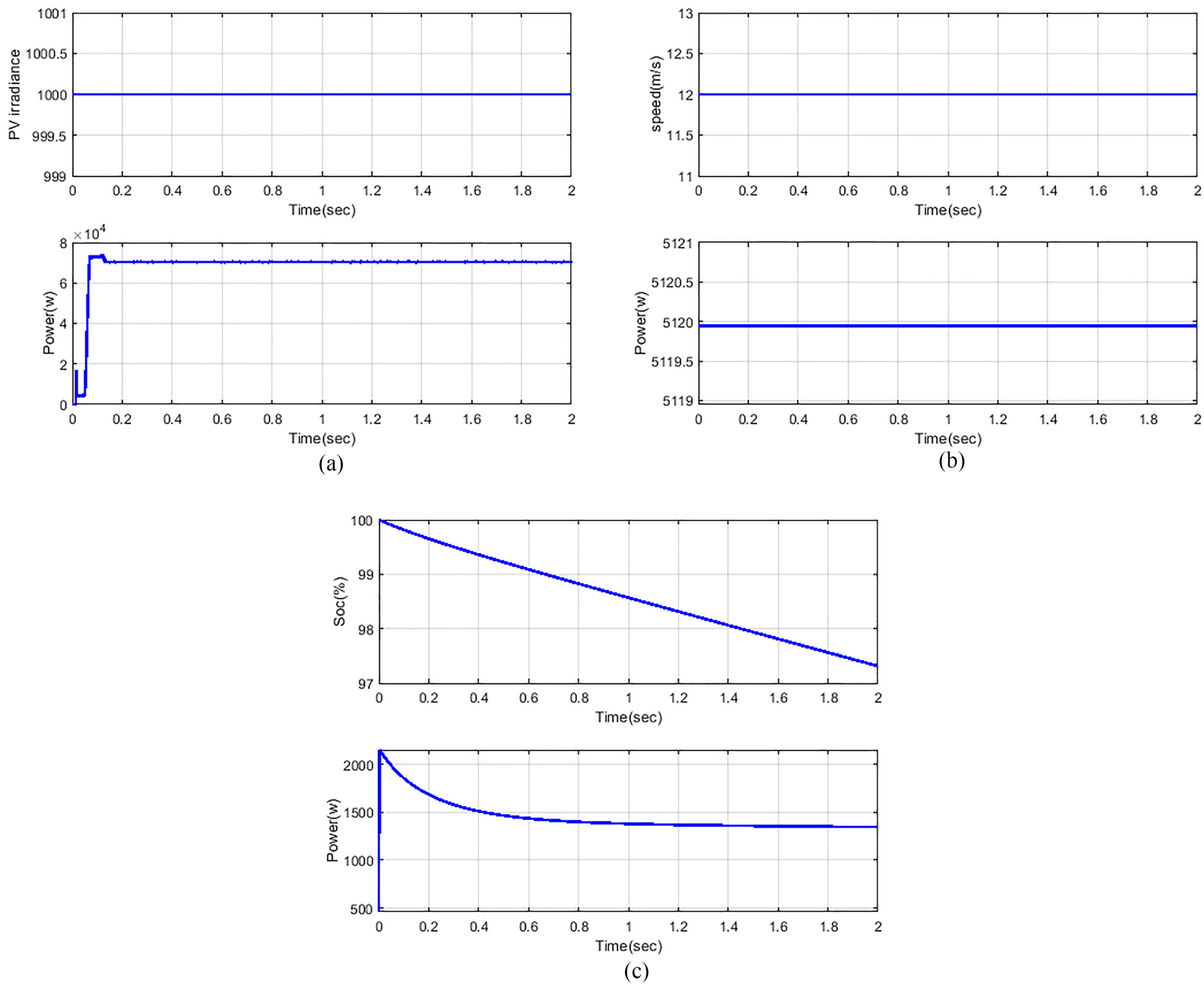


Figure 5. Simulation output of (a) PV irradiance and power, (b) wind speed and power and (c) battery SOC and power. PV, photovoltaic; SOC, state of charge.

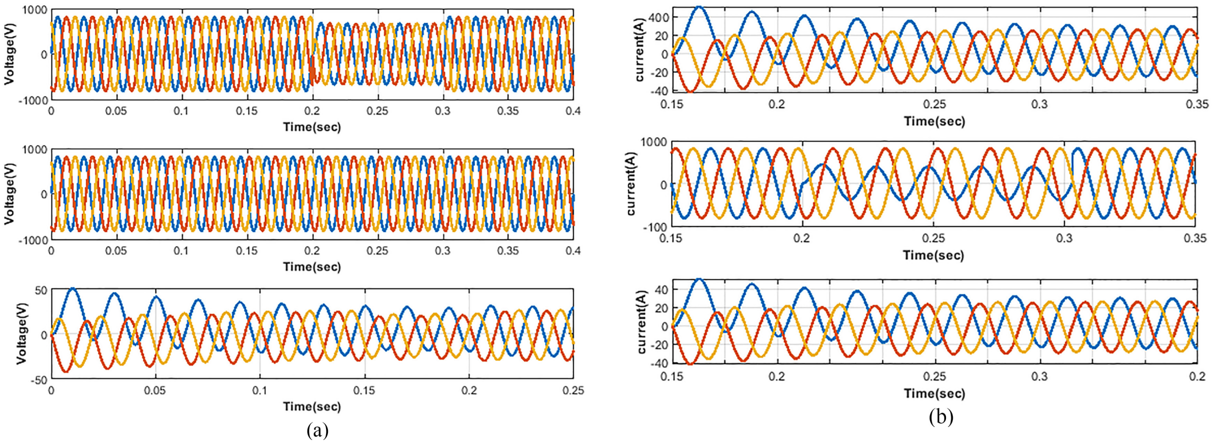


Figure 6. Simulation output in a sag condition (a) source voltage, load voltage and injected voltage and (b) source current, load current and injected current.

alongside the UPQC effectively tackles PQ issues associated with voltage and current sags. The shunt and series active power filters serve as the primary controls for regulating voltage and current in the HRES system.

4.2. Case 2: Swelling conditions for voltage and current

The proposed technique's performance is evaluated under swell conditions, induced by connecting a non-linear load to the system. This assessment of the swell state encompasses various scenarios and analyses their performances. PQ issues related to voltage and current swell scenarios are examined by altering PV irradiation conditions and WT speed. Figure 7 illustrates the variations in PV irradiance, WT speed, WT power and PV power. PV irradiance can be adjusted within the range of 0.7–1 s, with a default setting of 300 W/m^2 and 0.5–0.7 s. Additionally, it can be set within 0–0.5 s with a range of 1,000 W/m^2 to 300 W/m^2.

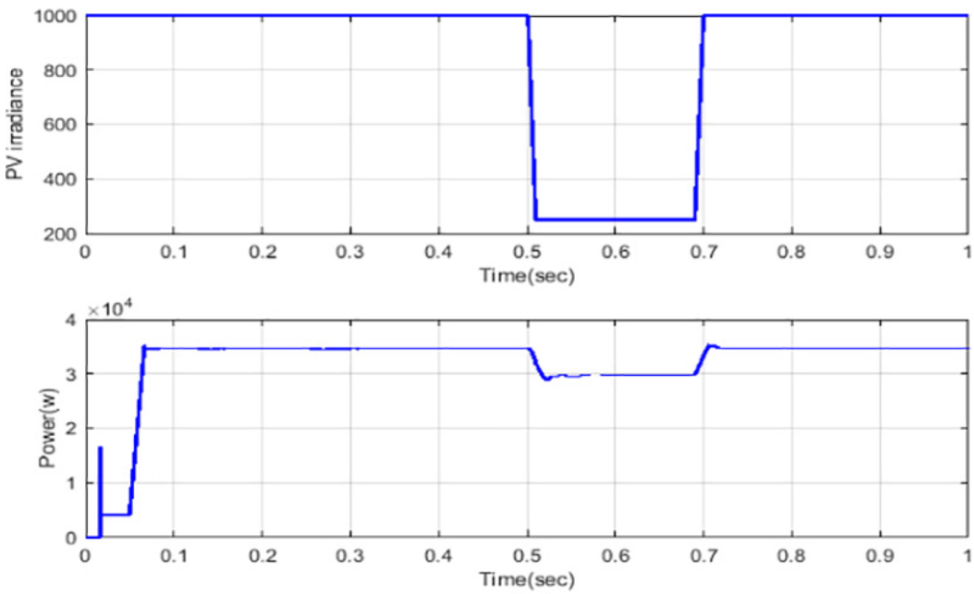
Figure 8 depicts the voltage and current swell scenarios. The introduction of a non-linear load induces a voltage surge within the system. As depicted in Figure 8(a), a voltage swell occurs between 0.2 -0.3 s, which is subsequently corrected using a UPQC. The required power is stored in the dc-link capacitor and utilised to alleviate PQ issues and meet load demand. The injected voltage and the corrected output voltage during the swell are also presented. Similarly, Figure 8(b) demonstrates the swell conditions for the current scenario. The proposed controller contributes to achieving load demand objectives and addressing PQ concerns. The selection of optimal system parameters is crucial for the series and SAPFs, which utilise the FBSO and the ANFIS controller-based MRPID controller, in detecting and rectifying incorrect values.

4.3. Case 3: Disruptions in voltage and current

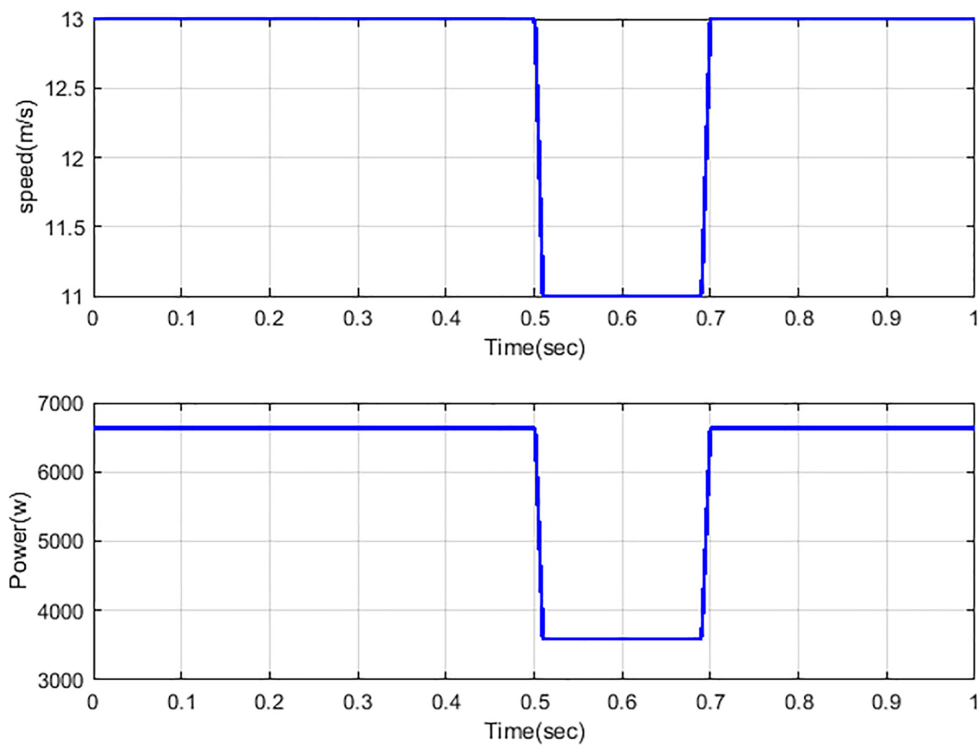
Using the disturbance condition, the proposed technique's performance is examined. By connecting the non-linear load, the disturbance conditions are introduced into the system. This examination of the swell state looks at a variety of sources and analyses performances. Problems with PQ are analysed with different WT speeds and PV irradiation levels. The changes in WT power, PV power, WT speed and PV irradiance are shown in Figure 9.

Analysing voltage and current disturbance circumstances caused by the application of non-linear loads in grid-connected load systems is necessary for the evaluation of the proposed technique. The corrected, injected and perturbations in voltage are shown in Figure 10.

Signal disturbances are usually caused by the interaction of uneven load circumstances, critical loads and non-linear loads. Voltage disturbances in the system occur naturally when a non-linear load is introduced on the load side. In order to guarantee the steady functioning of the HRES, the proposed controller is implemented to rectify PQ concerns and adjust for load demand. When the proposed controller is used, the HRES system may operate steadily and lessen PQ issues in non-linear, critical and imbalanced load scenarios. The optimal gain parameters for the MRPID controller are determined through the ANFIS-FBSO technique, aiming to minimise error values in voltage and current signals. The demonstrated flexibility of the proposed controller in responding to load demand and mitigating PQ issues in the HRES is illustrated. To assess the efficacy of the proposed approach, a comparative analysis is conducted against existing design methodologies, and the outcomes of this comparison are presented



(a)



(b)

Figure 7. Simulation output of (a) PV irradiance and power and (b) wind speed and power. PV, photovoltaic.

in the following section. The HRES generating system with a storage system is shown in Figure 11, compensating grid power under various environmental circumstances, such as GWO-FUZZY, CFA-ANFIS, PSO-ANFIS and EHO-FUZZY. The proposed controller is essential for maintaining stable operation on the grid side since it uses the ANFIS-FBSO technique, which ensures the stability and reliability of system performance by achieving better results than the existing methods. The proposed controller is used in the HRES to compensate for load demand

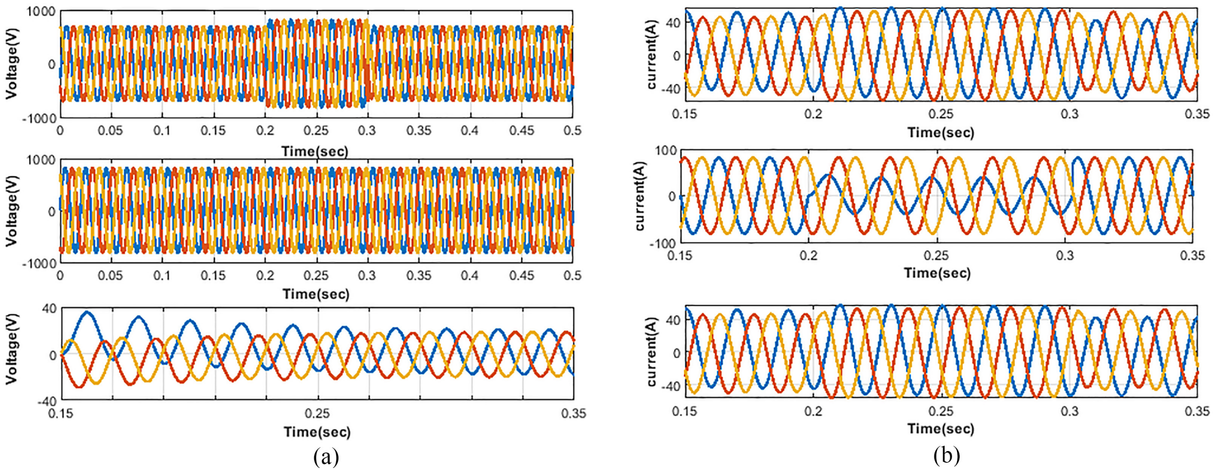


Figure 8. Simulation output in a swell condition (a) source voltage, load voltage and injected voltage and (b) source current, load current and injected current.

and handle PQ problems such as sag, swell, disturbances and harmonics. It also effectively mitigates current and voltage oscillations within the grid-connected HRES by generating optimal control pulses for the series and SAPFs.

Using comparative analysis, the assessment of the proposed methodology is investigated in various harmonic situations. THD is a general term used to measure the harmonic distortion present in a signal. THD is the fundamental measure of PQ, which includes both voltage and current THD. There is more distortion when the THD value is higher. THD of the proposed system is compared with already existing techniques, such as CFA-ANFIS, PSO-ANFIS, EHO-FUZZY and GWO-FUZZY. The signals' harmonics before and after applying compensation were also examined and confirmed via the proposed method in Figure 12(a). Figure 12(b) provides the comparative analysis of the projected technique in terms of harmonics.

Table 2 presents the comparison of THD achieved in the proposed technique with already existing techniques, and results are compared with the ASO algorithm (Goud and Rao, 2021). The calculation times of several methodologies are shown in Table 3, along with the operating times of different controlling schemes. The proposed controlling technique is the MRPID controller, which operates more quickly than other controlling strategies. The proposed technique for optimisation-based controllers achieves an execution time of 480 ms, which is less than the other techniques. Consequently, it works well for the PQ problem in real time.

4.4. Real-world challenges of using ANFIS-FBSO

- **Implementation Cost**
  Hardware requirements: High-performance digital signal processors, field programmable gate arrays or industrial PCs may be needed for real-time implementation, which would raise capital expenses.
  Software development: It takes a lot of work to design and fine-tune the ANFIS structure, integrate it with FBSO and validate it using simulations and hardware-in-the-loop (HIL) testing.
  Training data: For training and validation, large amounts of high-quality data are needed, which can be challenging to acquire or precisely replicate.
- **Computational Overhead**
  Unless done offline, the iterative optimisation cost introduced by FBSO is typically unacceptable in time-sensitive systems. Although runtime adaptation with optimisation can result in latency, real-time ANFIS inference is comparatively efficient.

4.5. Cost-benefit analysis: ANFIS-FBSO

There are numerous drawbacks and costs associated with ANFIS-FBSO, including a lengthy development period; the potential need for hardware such as graphics processing unit, digital signal processors and field programmable gate arrays if real-time optimisation is desired; complexity in the software that makes integration and maintenance challenging; low explain-ability due to the difficulty in interpreting fuzzy rules after tuning of FBSO; and a high

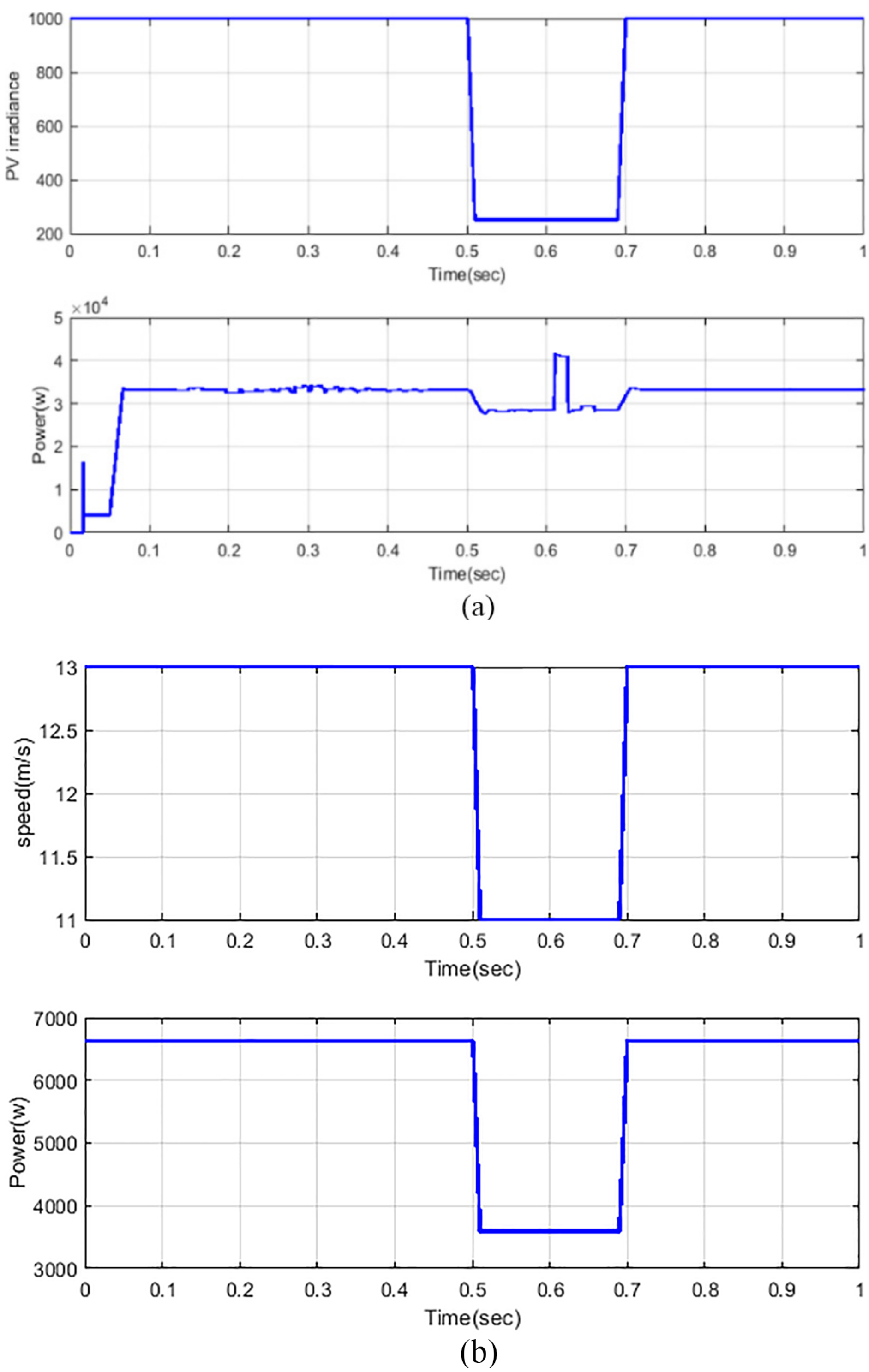


Figure 9. Analysis of (a) PV irradiance and power and (b) wind speed and power. PV, photovoltaic.

operational delay during training or re-optimisation. Despite numerous drawbacks and costs, the benefits of ANFIS-FBSO outweigh its high cost. These include improved handling of complex inputs and disturbances, fine-tuned control logic for non-linear systems, the potential for adaptive and self-learning control and the ability to minimise operational delay through offline optimisation.

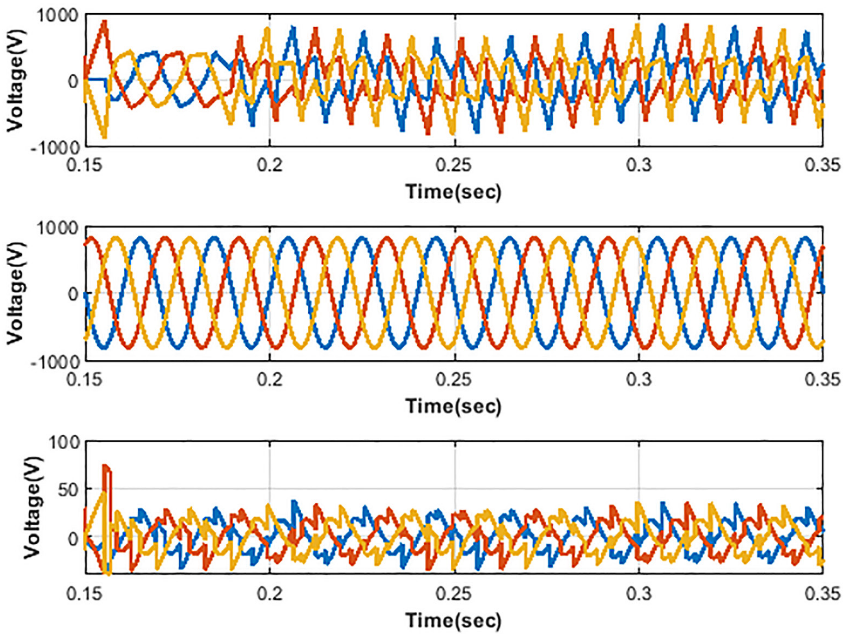


Figure 10. Simulation output of voltage disturbance circumstances in the source, load and injected voltage.

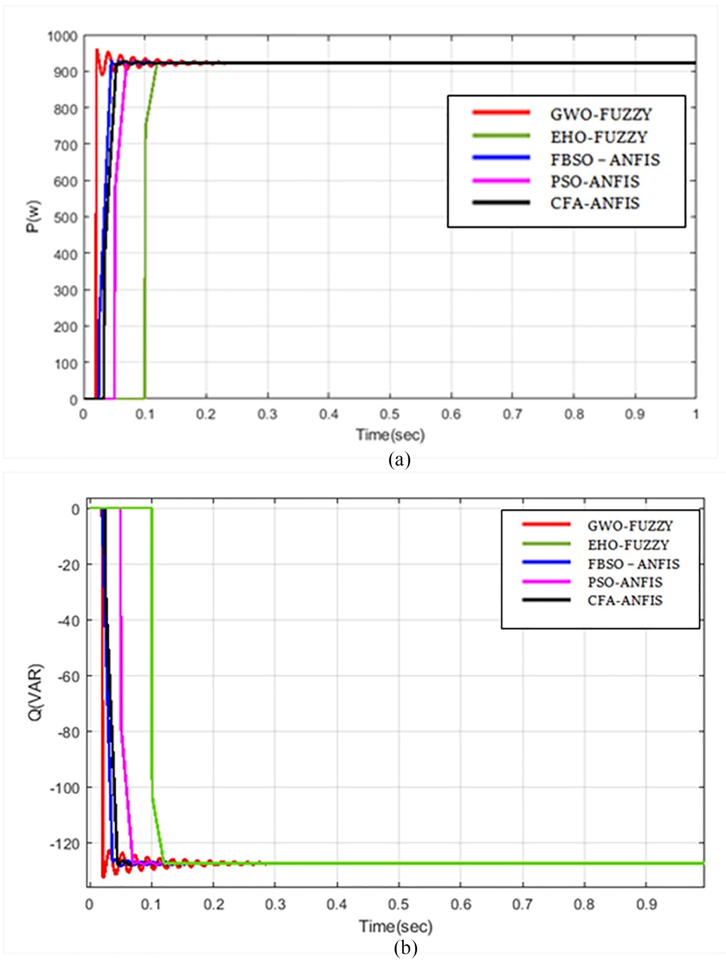


Figure 11. Comparative analysis of output (a) real power and (b) reactive power.

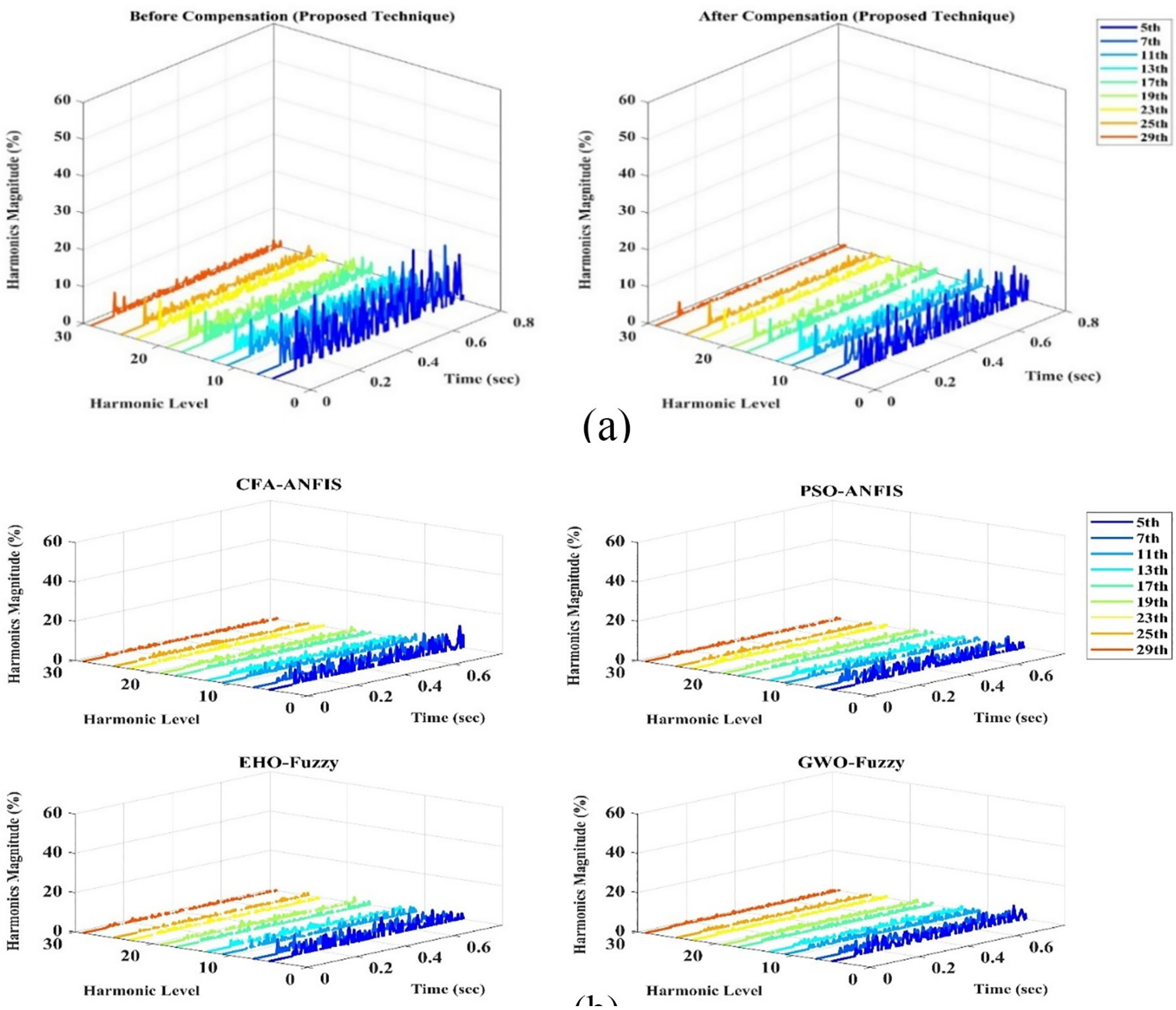


Figure 12. (a) Comparative analysis of THD of the proposed method and (b) comparative analysis of THD of existing methods. THD, total harmonic distortion.

Table 2. THD comparison between existing and proposed method.

Method	THD level								
	5	7	11	13	17	19	23	25	29
Proposed system without compensation	25	29	23	49	19	9	20	9	5
Proposed technique (ANFIS-FBSO)	10	4	2	4	8	2	4	1	0
CFA-ANFIS (Daweri et al., 2020)	8	8	3	5	10	4	5	6	2
PSO-ANFIS (Robati and Iranmanesh, 2020)	14	8	4	7	13	3	8	4	2
EHO-FUZZY (Drias and Drias, 2024)	23	15	16	20	9	7	6	4	4
GWO-FUZZY (Sun et al., 2023)	36	10	12	19	10	5	5	3	2
ASO (Goud and Rao, 2021)	12	6	3	5	10	3	5	0	1

ANFIS, adaptive neuro-fuzzy inference system; ANFIS-FBSO, adaptive neuro-fuzzy inference system-based firebug swarm optimisation; ASO, atom search optimisation; CFA, cuttlefish algorithm; EHO, elephant herding optimisation; GWO, grey wolf optimisation; PSO, particle swarm optimisation; THD, total harmonic distortion.

Table 3. Comparison of computational time.

Techniques	Proposed technique (ANFIS-FBSO)	CFA-ANFIS (Daweri et al., 2020)	PSO-ANFIS (Robati and Iranmanesh, 2020)	EHO-FUZZY (Drias and Drias, 2024)	GWO-FUZZY (Sun et al., 2023)	ASO (Goud and Rao, 2021)
Execution time (ms)	480	497	510	510	514	590

ANFIS, adaptive neuro-fuzzy inference system; ANFIS-FBSO, adaptive neuro-fuzzy inference system-based firebug swarm optimisation; ASO, atom search optimisation; CFA, cuttlefish algorithm; EHO, elephant herding optimisation; GWO, grey wolf optimisation; PSO, particle swarm optimisation.

5. Conclusion

The objective of this paper is to develop MRPID and ANFIS-FBSO controller for PQ improvement in grid-connected HRESs. The MRPID controller and ANFIS-FBSO technique are used to improve the PQ concerns. To address PQ issues and balance load demand, the UPQC is implemented. The series active power filter and SAPF are the two controllers that UPQC is outfitted with. The supervisory control process and the HRES structure are implemented using the MATLAB/Simulink working environment, and the outcomes are examined. Using the proposed technique and existing techniques, the performance of grid power, battery power, PV and WT power is investigated under three distinct scenarios in order to verify the results. The results are compared with the existing techniques such as CFA-ANFIS, PSO-ANFIS, EHO-FUZZY and GWO-FUZZY in terms of computational time and are validated with already published work. THD analysis showed the strongest results when the suggested strategy was applied efficiently. Result analysis depicts that the proposed ANFIS-FBSO-based MRPID controller is better than the existing techniques to enhance PQ in grid-integrated HRES.

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