Enhancing the Performance and Integrity of Grid-Tied Green Power Systems using Unified Power Quality Conditioner and Fractional Order Control

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Abstract- Renewable energies are crucial to current power systems for sustainability and the preservation of the environment, but their dependability is hampered by their reliance on environmental factors. The usage of what is called a Unified Power Quality Conditioner (UPQC) is described in this article as a way to improve the dependability and effectiveness of solar and wind power plants that are grid-connected. This integrated structure uses wind turbines together with solar cells as its two renewable energy sources. Based on its distinctive skills to manage active as well as reactive power regulation, UPQC was chosen. The Fractional Order PID (FOPID) controller explored to regulate the UPQC has had its settings adjusted using the Golden Eagle Optimization (GEO) technique. The effectiveness of the proposed controller in enhancing the performance and reliability of the hybrid energy system throughout a variety of chaos events, such as sags in voltage, swells, and imbalanced loading, is verified through simulation results. Furthermore, by reducing total harmonic distortion (THD), the UPQC-FOPID control strategy can enhance power quality. It's noteworthy that distinct maximum power point tracking (MPPT) Maximum power point tracking (MPPT) approaches have been incorporated for systems using PV and WT separately. The entire system, including the UPQC, FOPID controller, MPPT techniques, and renewable energy sources, has been modeled and simulated using MATLAB/SIMULINK R2022b software.

Keywords- Renewable energy sources, Unified Power Quality Conditioner (UPQC), Photovoltaic (PV) cells, wind turbines (WTs), Fractional Order Proportional–Integral–Derivative (FOPID) controller, Golden Eagle Optimization (GEO) algorithm, Power quality, Maximum power point tracking (MPPT).

1. Introduction

In the relentless pursuit of sustainable energy solutions, the world has unequivocally turned its gaze towards renewable energy sources. The importance of these contemporary power systems' sources cannot be overstated, as they offer a promising path to not only meet our growing energy demands but also mitigate the environmental consequences of conventional power generation. Renewable energy systems, harnessing the power of the sun, wind, and other natural resources, hold the key to a cleaner, greener future [1]. However, their inherent reliance on the ever-fluctuating forces of nature has raised significant concerns regarding their reliability.

This paper delves into the intricate world of grid-connected green energy systems, exploring a groundbreaking approach to enhance their performance and dependability. At the heart of this approach lies the Unified Power Quality Conditioner (UPQC), a sophisticated device renowned for its eccentric capabilities in control of power both active and reactive [2]. The integration of UPQC into grid-tied renewable energy systems represents a significant step towards addressing the issues of reliability and power quality that have long haunted these systems.

The renewable energy system under investigation combines two pivotal sources: photovoltaic cells (PV) and wind turbines (WTs) [3]. PV cells, powered by the sun's radiant energy, and WTs, harnessing the kinetic energy of the wind, together form a formidable duo in the pursuit of clean power generation. The UPQC, with its advanced control capabilities, promises to optimize the synergy between these sources, resulting in a more reliable and efficient hybrid power system.

The control of the UPQC in this study employs a novel approach - the Fractional Order PID (FOPID) controller [4]. The following controller, characterized by its fractional order differentiation and integration, offers a level of precision and adaptability that is crucial in managing the dynamic behavior of renewable energy systems. The parameters of the FOPID controller are fine-tuned using the Golden Eagle Optimization (GEO) algorithm, a powerful optimization technique that ensures the controller operates at its peak performance [5].

One of the primary objectives of this research is to investigate how the integration of the UPQC and the utilization of the FOPID controller can bolster the reliability of the hybrid power system in the face of disturbance events [6]. Voltage sags, swells, and unbalanced loading are among the disturbances that frequently challenge the stability of grid-tied systems. Through comprehensive simulations, the paper evaluates the efficiency of the proposed controller in mitigating the adverse effects of these disturbances, thereby fortifying the reliability of the hybrid power system.

In addition to addressing reliability concerns, this research also pays heed to power quality improvement. Total Harmonic Distortion (THD) is a critical variable in assessing the quality of power delivered by any system. By reducing THD, the UPQC-FOPID control strategy has the potential to significantly enhance power quality, ensuring that the energy fed into the grid meets stringent quality standards.

Furthermore, the paper takes into account the distinct tracking techniques required for PV and WT systems. Each source presents unique challenges in optimizing energy extraction, and the study incorporates two MPPT approaches tailored to the specific characteristics of solar PV cells and wind turbines [7].

The entire system, including the UPQC, FOPID controller, MPPT techniques, and renewable energy sources, is modeled and simulated using MATLAB/SIMULINK R2022b software.

2. Literature Review

Many research endeavors have investigated different approaches to manage hybrid forms of renewable energy. These investigations have introduced FACTS devices alongside diverse control techniques aimed at alleviating issues related to harmonics and other disturbances.

Ravi, T., and K. Sathish Kumar [8], highlight the importance of addressing power quality disturbances, the effectiveness of the MF-IUPQC system with ANFIS in improving voltage profiles and reducing harmonics, the challenges in implementing FACTS technology, and the significance of control schemes such as SRF and PQ-theory in the MF-IUPQC system.

Vidhya, K., & Krishnamoorthi, K [9], introduces an innovative PV system that is connected to the grid with an interleaved inverter, employing a hybrid technique called LA-HBO. This approach effectively mitigates power quality issues caused by high DC voltage deviations. LA techniques enhance PV power generation and control the DC-link voltage, achieving impressive results compared to existing methods.

Ibrahim, Ahmed Mohamed, et al [10], presents an optimization approach for the design of a Static Synchronous Compensator (STATCOM) to enhance the dynamic performance of a grid-connected hybrid PV/wind energy system in Gabal El Zayt, Egypt. The algorithm known as Particle Swarm Optimization (PSO) is employed to tune the STATCOM parameters. The study validates the optimized STATCOM's effectiveness under varying climatic conditions and assesses its impact on grid performance during load changes and fault scenarios. Results indicate significant improvements in power injection, grid and load voltage profiles, and power factor control when utilizing the optimized STATCOM, compared to conventional strategies.

Guo, Qiang, et al [11], presents a method for estimating parameters utilizing an enhanced Whale Optimization Algorithm to determine parameters within a static var compensator (SVC) model. It establishes a computational SVC model and incorporates reverse learning and Levy flight disturbance strategies to strengthen the optimization process. The enhanced algorithm is then applied for parameter identification in the SVC model. Additionally, a stepwise identification approach, focusing on local parameter sensitivities, is introduced to enhance accuracy in multi-parameter identification. The results demonstrate the effectiveness of this method in accurately identifying SVC model parameters, addressing challenges in parameter identification for SVC systems.

While shunt FACTS devices improve hybrid system performance by reducing harmonics and stabilizing voltage during disturbances, they lack the ability, unlike series devices, to modify line reactance or enhance transmission line capacity.

Kumar, Ashwani, Vishnu Mohan Mishra, and Rakesh Ranjan [12], Explores the use of water cycle algorithm (WCA) with particle swarm optimization (PSO) in improving the low voltage ride through (LVRT) efficacy of a hybrid renewable energy system (HRES) by incorporating a battery energy storage system (BESS) connected to a dynamic voltage restorer (DVR). The suggested technique enhances compensation capabilities and increases the voltages on the DC-link and PCC lines. The article proposes numerous remedies, safety measures, and management techniques to address the LVRT issue in HRES and discusses the performance of these strategies using different control schemes and voltage profiles. Using a BESS in combination with a Dynamic Voltage Restorer (DVR) improves the LVRT capability of a HRES consisting of DFIG-based wind plants and PV plants. The performance of the DVR is optimized using a PI controller tuned by PSO and WOA. The PSO-tuned PI controller outperforms the WOA-tuned controller in terms of the Integral Time Absolute Error (ITAE). Simulation results demonstrate that the BESS-enabled, PSO-tuned DVR significantly improves the LVRT capability of the HRES.

Sahu, Preeti Ranjan, Prakash Kumar Hota, and Sidhartha Panda [13], discusses the use of a modified whale optimization algorithm (MWOA) in designing a fractional-order controller for improving power system stability. The algorithm is based on the behavior of humpback whales and aims to find the best solution by updating the positions of search agents in the search space. The proposed MWOA technique outperforms other optimization methods and is applied to a single-machine infinite bus system with a static synchronous series compensator-based controller. The performance of the fractional-order PID controller is compared to a conventional PID controller. The paper proposes a new MWOA optimized FO MISO-type SSSC controller for power system stability improvement. The controller parameters are optimized using the MWOA technique. The proposed controller demonstrates superior damping characteristics compared to other optimization techniques.

Goud, B. S., & Rao, B. L [14], discusses the use of hybrid distributed generation systems and power electronic equipment's to increase the efficiency of renewable energy sources. It addresses power quality issues and proposes the use of a FOPID controller-based GWO algorithm for power quality compensation. The system includes series and shunt APF's and utilizes techniques such as PLL reference voltage and hysteresis voltage control. It also mentions the hierarchical structure of a wolf pack in the GWO algorithm. The system uses FOPID-GWO based controlling technique and UPQC device to mitigate power quality issues caused by non-linear loads. The proposed method reduces harmonics and improves power quality in the HRES system.

Srilakshmi, Koganti, et al [15], proposed intelligent hybrid controller combines Integral Sliding-Mode and Fuzzy Logic Control to enhance the performance of Unified Power Quality Conditioners (UPQC). Utilizing a Self-Tuning Filter with the Unit Vector Generation Method eliminates the need for Phase-Locked-Loops and other filters. The controller's primary objectives include maintaining stable DC-Link voltage, reducing current waveform harmonics, improving power factor, mitigating voltage sags and swells, and compensating for unbalanced supply voltages.

This study aimed to enhance the performance of a grid-connected Hybrid Renewable Energy System (HRES) consisting of Solar Photovoltaic (PV) and Wind Turbine (WT) components, employing a Doubly Fed Induction Generator (DFIG) as the primary generator [16]. The research focuses on developing a Fractional Order Proportional-Integral-Derivative (FOPID) controller for the Unified Power Quality Conditioner (UPQC), with controller parameters optimized using Golden Eagle Optimization (GEO). The UPQC controller effectively reduces total harmonics, enhances PQ, and provides voltage support amid unusual occurrences. Furthermore, the study explores two Maximum Power Point Tracking (MPPT) methods for optimizing solar power and wind energy turbine performance.

3. Proposed System

The proposed grid-connected Hybrid Renewable Energy System (HRES) comprises a Doubly Fed Induction Generator (DFIG) powered by wind turbine and a Photovoltaic (PV) plant utilizing Maximum Power Point Tracking (MPPT), as illustrated in Figure 1. This HRES is made to alleviate problems with power quality caused by disruptions and voltage variations. MPPT is implemented in the grid-connected hybrid PV/wind power system, to maximize power output using the Perturb & Observe method. A boost converter (DC-DC) links to the DC bus, and an inverter connects to the AC bus. The HRES's use of semiconductor switches and transformers can degrade system quality, necessitating power compensation. In this study, the Unified Power Quality Conditioner (UPQC), which compensates real and reactive power via series and parallel APF's, is employed. To optimize UPQC performance, a Fractional Order PID (FOPID) controller is chosen, with Golden Eagle Optimization (GEO) assisting in achieving maximum compensation.

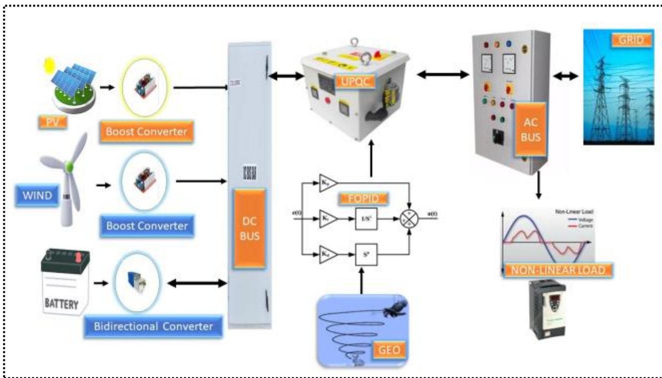

Fig.1 The designed hybrid model includes UPQC.

3.1 Solar energy system

As depicted in Figure 2, the photovoltaic facility comprises PV panels designed to meet the necessary energy demands. This system incorporates a DC-DC boost converter that employs the Perturb and Observe (P&O) technique for Maximum Power Point Tracking (MPPT) [17]. Subsequently, an inverter for DC/AC is employed to link the DC output from the conversion system the electric grid.

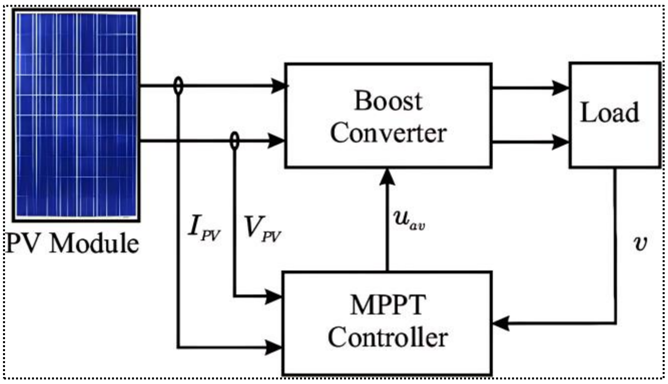

Fig.2. MPPT-based photovoltaic array.

3.2. Wind System

In this study aims to explore the impact of Unified Power Quality Conditioner (UPQC) on Hybrid Renewable Energy Systems (HRES). Climate variations, including fluctuations in wind speed, are considered among the system disturbances. The Doubly-Fed Induction Generator (DFIG) is recognized as the most suitable generator for applications involving variable speeds [18]. Although other generators, namely switching reluctance [19], self-excited asynchronous [20], and PM synchronous [21] generators, are used, as depicted in Figure 3, DFIG's perspective for more than half of the generators used in turbines for wind energy [22].

DFIG is made up of two different converters, the rotor side conversion device (RSC) and the converter that interfaces with the grid (GSC), which service the rotor and stator, respectively. As seen in Figure 3, two of these converters are interconnected through a DC-link.

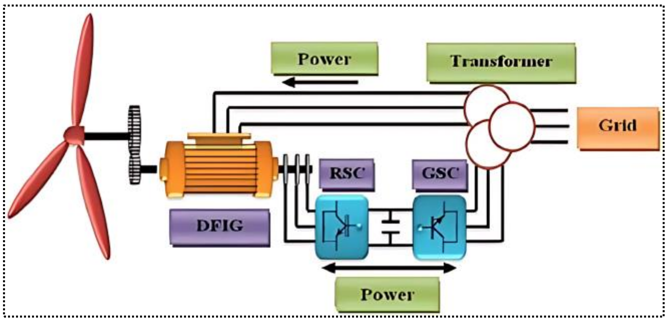

Fig.3. DFIG Wind Turbine system.

3.3 Unified Power Quality Conditioner

FACT devices play a crucial role in improving system reliability and addressing issues related to power quality [23]. Among the various FACTS devices available, the Unified Power Quality Conditioner (UPQC) was selected for its extensive capability to enhance system quality and equilibrium. According to Figure 4, the UPQC includes both a shunt and a series active power filter. To achieve optimal performance, the UPQC was controlled using a Fractional-Order PID (FOPID) controller, and its regulation was fine-tuned using the Golden Eagle Optimization (GEO) algorithm [24]

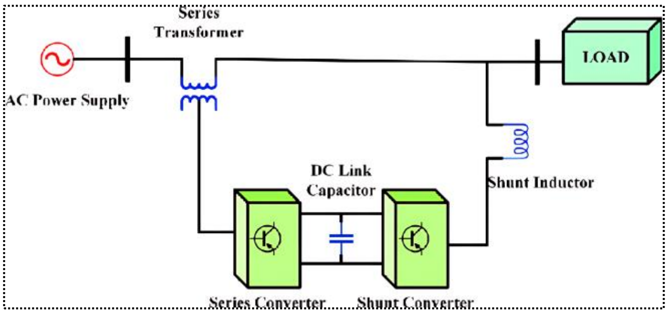

Fig.4. Modeling of UPFC system.

2. Adjusting the UPQC's Performance: Important Steps

The controller oversees the UPQC's operation by monitoring the system voltage for any deviations. It generates signals to control the two UPQC converters, thereby producing pulses to align with the desired reference voltage, effectively mitigating power quality issues. The UPQC system employs two separate components, one for the series component and another for the shunt component, as outlined below:

4.1 Series Active Power Filter's Control

Figure 5 illustrates the control mechanism based on the series APF. We start by measuring the reference voltage. Subsequently, we measure the 3-ø voltage and the dq transformation technique is used to convert it into the d-q axis, also known as the Clarke transformation [25]. Eq. (1) depicts this change from the 3-ø voltage in mathematical terms,

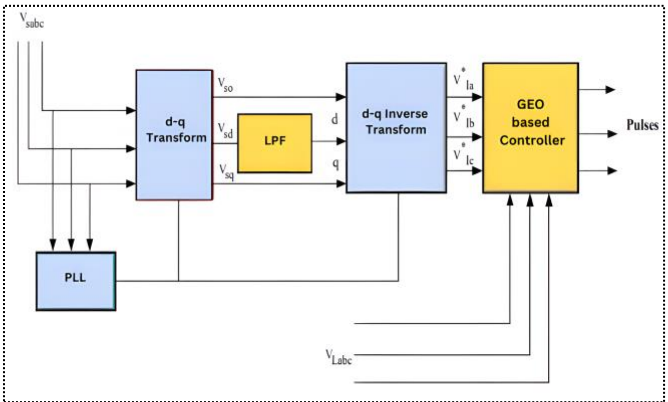

Fig.5. Block diagram of Series Active Power Filter.

$$\begin{bmatrix} V_{s0} \\ V_{sd} \\ V_{sq} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin(\alpha t) & \sin\left(\alpha t - \frac{2\Pi}{3}\right) & \sin\left(\alpha t + \frac{2\Pi}{3}\right) \\ \cos(\alpha t) & \cos\left(\alpha t - \frac{2\Pi}{3}\right) & \cos\left(\alpha t + \frac{2\Pi}{3}\right) \end{bmatrix}\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{1}$$

In this context, V_{sq} represents the voltage in the quadrature axis, V_{Sa}, V_{Sb}, V_{Sc} refers to the 3-ø voltage, and V_{sd} represents the voltage in the direct axis, applicable to both direct and cyclic components. These voltage components can be filtered and smoothed using a LPF, as described in Eq. (2).

$$V^{d(dc)} = V^{d} - V^{d(ac)} \tag{2}$$

Here, $V^{d(ac)}$ is the voltage component associated with the alternating current (AC), while $V^{d(dc)}$ represents the voltage component associated with the direct current (DC). Following this, the voltage is converted back into 3-ø's, as shown in Eq. (3).

$$\begin{bmatrix} V^{la} \\ V^{lb} \\ V^{lc} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin(\boldsymbol{\alpha}t) & \frac{1}{2} & 1 \\ \sin(\boldsymbol{\alpha}t) & \sin(\boldsymbol{\alpha}t - \frac{2\Pi}{3}) & 1 \\ \cos(\boldsymbol{\alpha}t) & \cos(\boldsymbol{\alpha}t - \frac{2\Pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V^{d(dc)} \\ V^{q} \\ V^{0} \end{bmatrix} \tag{3}$$

In this equation, V^{la}, V^{lb}, V^{lc} represent the 3-ø reference voltages. The width of the hysteresis band for voltage control is determined by the regulating signals, which are figured and fine-tuned using the FOPID controller with the GEO algorithm. Likewise, the subsequent section introduces the control algorithm for the shunt active power filter.

4.2. Shunt Active Power filter's Control

In Figure 6, the regulating system initiates by transforming both current and voltage into α and β components, following Eq. (4) and (5) [26].

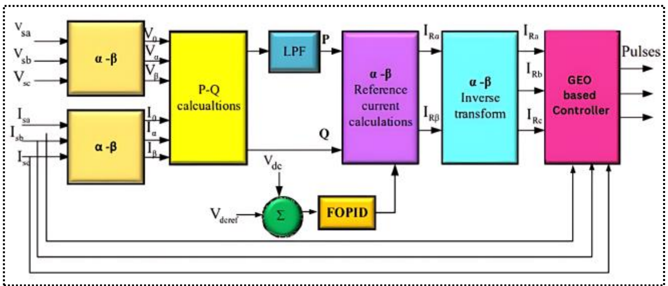

Fig.6. Block diagram of Shunt Active Power Filter.

$$\begin{bmatrix} V_{s0} \\ V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} I_{s0} \\ I_{s\alpha} \\ I_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} \tag{5}$$

Here, "$I_{s\alpha}$" and "$I_{s\beta}$" represent the phase-neutral currents, while "I_{sa}," "I_{sb}," and "I_{sc}" stand for the three-phase load currents. "Vsα" and "Vsβ" refer to the phase-neutral voltages, and "Vsa," "Vsb," and "Vsc" represent the 3-ø supply voltages.

Using these phase neutral voltages and load currents, we calculate both the real and disregarded instantaneous power values. In the shunt active filter, we compute both active and reactive power using Eq. (6)[27],

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix} \tag{6}$$

Following this step, we calculate the reference currents using Eq. (7).

$$\begin{bmatrix} I_{Ra} \\ I_{Rb} \\ I_{Rc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{R\alpha} \\ I_{R\beta} \end{bmatrix} \tag{7}$$

In this context, "I_{Ra}, I_{Rb}, I_{Rc}" denote the current reference values for the shunt APF. These reference currents serve as a basis for calculating the error current, which requires compensation through the FOPID controller using the GEO algorithm [28].

Within the shunt APF, the best pulses are chosen and generated based on the erroneous values within the system. The GEO algorithm plays a crucial role in generating these optimal pulses. A comprehensive explanation of the FOPID controller with GEO optimization is provided in the subsequent sections.

3. Proposed Control Strategy

This section illustrates the control approach for UPQC using the FOPID controller, which is fine-tuned with the assistance of the GEO algorithm to optimize the controller parameters.

5.1. Fractional-Order PID (FOPID) Controller

The proposed approach involves the utilization of the Fractional-Order PID (FOPID) controller, tailored through the Golden Eagle Optimization (GEO) Algorithm, to handle Power Quality (PQ) concerns in the interconnected grid Hybrid Renewable Energy System (HRES). These PQ issues stem from voltage and current disturbances. In contrast to traditional controllers, such as PID and PI controllers, the FOPID controller offers superior performance due to its five adjustable parameters.

By fine-tuning the gain parameters of the FOPID controller using the GEO technique, we successfully reduced voltage and current errors. GEO is employed to generate optimal control pulses for the FOPID controller, further diminishing error values in voltage and current.

The UPQC device, equipped with both a series and a shunt controller, leverages the FOPID controller for enhancing the performance of the HRES system by mitigating PQ concerns [29]. The FOPID controller excels at minimizing voltage and current errors, eliminating signal undershoot and overshoot, and enhancing controller response speed crucial factors for achieving maximum HRES system regulation.

Furthermore, the FOPID controller improves device speed, alleviates iso-damping, and has improved robustness to parameter changes [30].

$$G(s) = \frac{u(s)}{e(s)} = K_P + K_i D^{-\lambda} + K_d D^{\mu} \quad (8)$$

In Eq. (8), G(s) signifies the FOPID controller transfer function within the HRES system, while u(s) stands for the results of the controller, and e(s) corresponds to the error indication of the HRES system.

Figure 7 depicts the interface configuration of an FOPID controller.

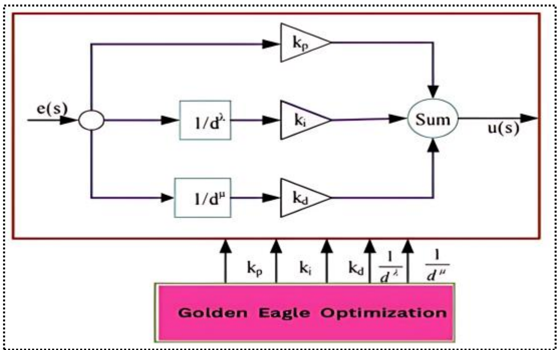

Fig.7. Design Structure of the FOPID Controller.

4. Discussion of the Findings

The assessment of system quality and stability involved studying various fault scenarios both with and without the UPQC system connected. These scenarios included sag and swell conditions. The impact of integrating UPQC into the system during these fault conditions was examined by analyzing system voltage and current waveforms.

The initial phase involves fine-tuning the parameters of the FOPID controller using the Golden Eagle Optimization (GEO) Algorithm. The FOPID controller parameters, as outlined in Table 1, will be adjusted to enhance voltage and current levels and reduce their Total Harmonic Distortion (THD). GEO-FOPID controllers will play a crucial role in governing the UPQC system, thereby enhancing the overall performance of the hybrid system.

Table 1. FOPID gain settings.

Kp	Ki	Kd	λ	μ
9.66	18.64	1	1.62	0.27

The primary objective of this study is to enhance the performance of a Hybrid Renewable Energy System (HRES) by implementing optimal control strategies for the Unified Power Quality Conditioner (UPQC). Specifically, a Fractional-Order PID (FOPID) controller is employed to regulate the DC-link potential of the UPQC whenever a fault occurs. To evaluate the system's performance with the proposed Golden Eagle Algorithm-based optimization technique (GEO), it is compared with another widely recognized optimization approach, the Genetic Algorithm (GA), which acts as a standard for optimization techniques.

The convergence of the objective function is illustrated in Figure 8, comparing the performance of GEO and GA.

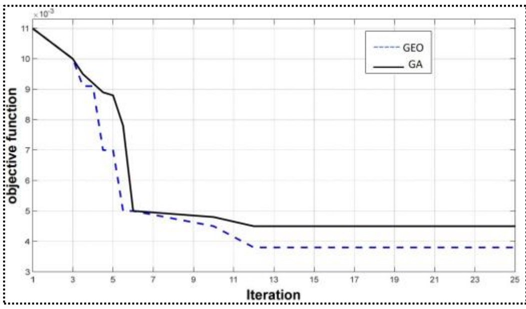

Fig.8. Objective function convergence.

Test case 1: Sag condition for voltage and current

During this scenario, a sag is intentionally induced in the Hybrid Renewable Energy System (HRES) by simulating a fault. It is imperative to rectify both the voltage and current sags to ensure the system operates smoothly and consistently. The Unified Power Quality Conditioner (UPQC) is employed to furnish the necessary energy to satisfy the load demand while addressing Power Quality (PQ) constraints.

In Figure 9, the plots depict the voltages from the source, the load, and the injected voltage. Additionally, Figure 10 illustrates the currents from the source, the load, and the injection facilitated by the UPQC device. The injected voltage and current, controlled by the proposed controller, play a crucial role in mitigating PQ problems. In the case of UPQC, both the series and shunt Active Power Filters (APFs) work together to balance the voltage and current within the system.

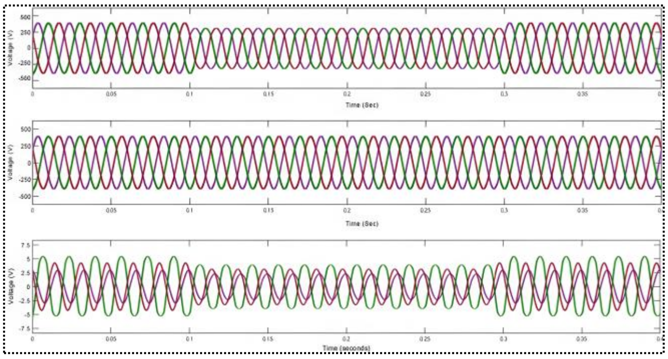

Fig.9. Voltage Sag situation (i) Input Voltage (ii) Voltage at load (iii) Injected Voltage.

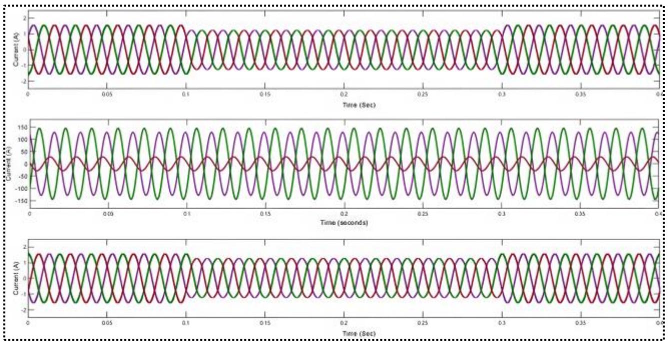

Fig.10. Current Sag Situation (i) Input current (ii) Current at load (iii) Injected current.

In this particular scenario, we have examined the impact of an error on the system's output power. This analysis was conducted while considering the initial power calculation under stable irradiance conditions of 1000 W/m2 for the solar system and determining its output. Similarly, the analysis involved wind speed stabilization at the regional average of 12 m/s and determining the wind system's output. These findings are visualized in Figure 11.

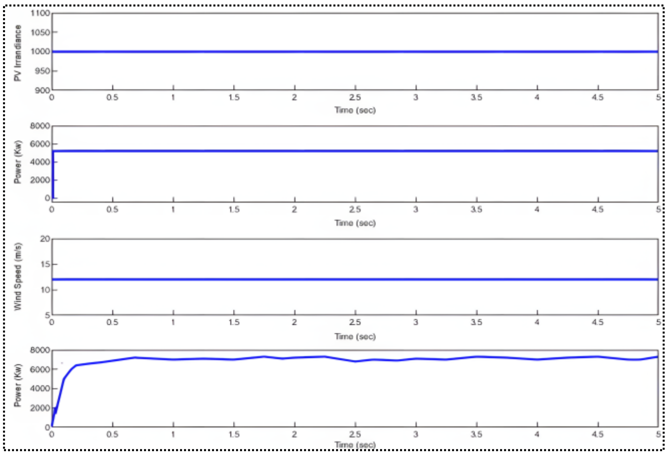

Fig.11. Solar and wind power thrive in stable environments. (i) Solar irradiance, (ii) Solar power, (iii) wind velocity, and (iv) wind turbine power.

Test case 2: Swell Condition for Voltage and Current

We will simulate voltage swell incidents to evaluate the controlled UPQC's capability to supply reactive energy to the Integrated Renewable Energy System and subsequently stabilize the voltage. To simulate this swell condition, a nonlinear RL load will be removed from the system. As depicted in Figures 12 and 13, during this timeframe, both voltage and current values experience an increase, triggering the activation of the UPQC to counteract this surge. The UPQC's capacitor plays a pivotal role in mitigating this increase by utilizing stored energy, which is managed through the FOPID controller. The controller's objective is to minimize the error as effectively as possible, a task facilitated by the Golden Eagle Optimization (GEO) Algorithm.

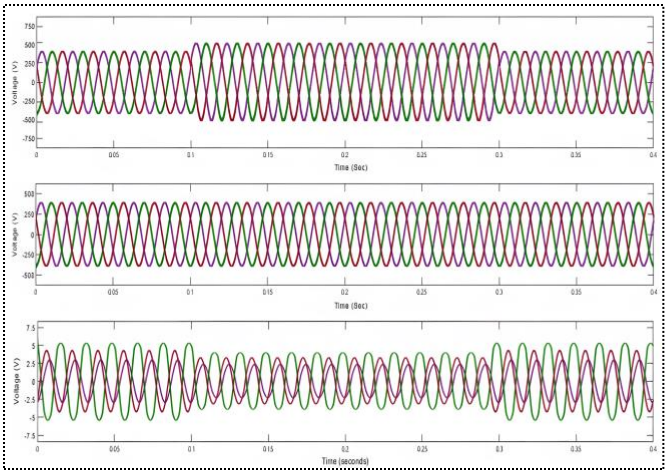

Fig.12. Voltage Swell Condition (i) Input Voltage

(ii) Voltage at Load (iii) Injected Voltage.

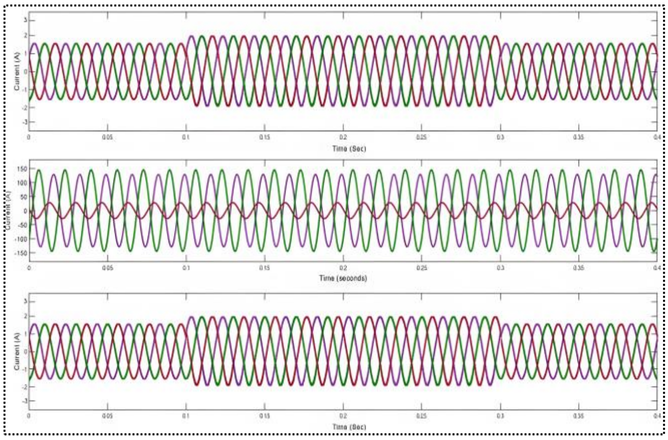

Fig.13. Current Swell Condition (i) Source current (ii) Load current (iii) Injected current.

Figure 14 illustrates the resulting power output of the Hybrid Renewable Energy System (HRES) as environmental conditions evolve.

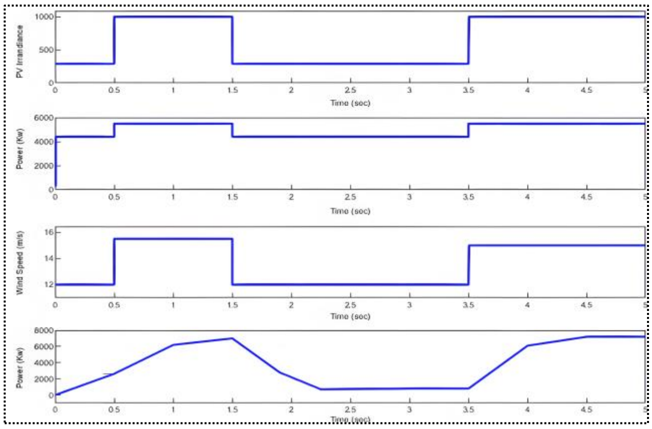

Fig.14. the HRES's output power under different environmental circumstances (i) Solar irradiance, (ii) Solar power, (iii) wind velocity, and (iv) wind turbine power.

The Unified Power Quality Conditioner (UPQC) significantly contributes to enhancing the power quality of the system by lowering Total Harmonic Distortion (THD). In this scenario, we have simulated the introduction of certain harmonics to assess the controlled UPQC's effectiveness in reducing THD. These harmonics were simulated by connecting various loads, including resistive (R) and resistive-inductive (RL) loads.

The finely-tuned FOPID controller successfully managed the UPQC, resulting in reduced THD when exposed to different load conditions, as depicted in Figures 15 and 16, representing voltage and current profiles, respectively.

Table.2 % THD comparison

Type Controller	Case 1	Case 2
Without UPQC	27%	15%
PI	4.97%	5.68%
SMC	4.74%	3.74%
FLC	4.01%	3.43%
PDO FOPID	2%	2.4%
GEO FOPID	0.52%	0.23%

Table 2 compares suggested controllers with various already existing controllers.

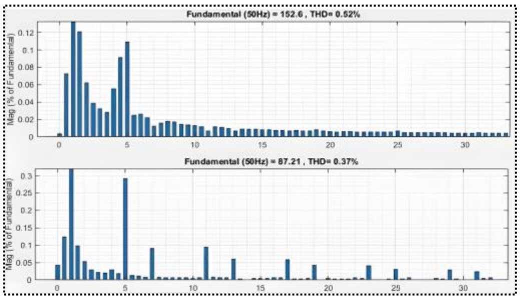

Fig.15. THD for voltage signals (i) R load, (ii) RL load.

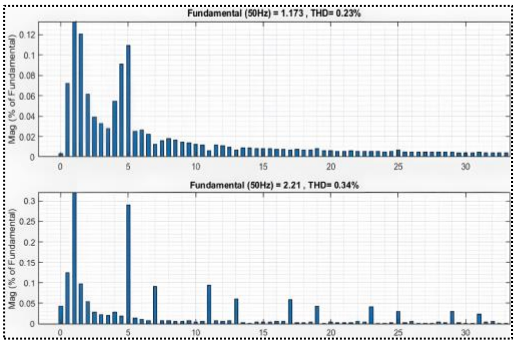

Fig.16.THD for current signals (i) R, (ii) RL load.

To validate the proposed methodology, an analysis was conducted using a GEO-based FOPID controller within the interconnected Hybrid Renewable Energy System (HRES) under drooping and enlarging conditions. Figures 17 & 18 display the active and reactive power outputs achieved through this control technique. The results indicate significantly low error rates, which translate to efficient energy conservation from the grid side.

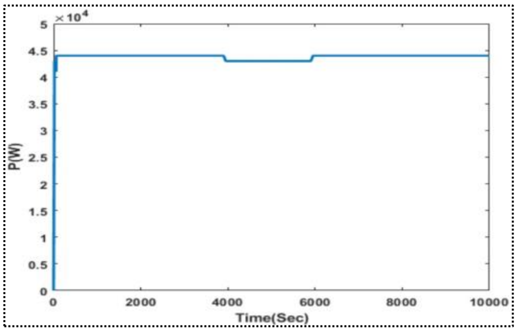

Fig.17. Results of active power

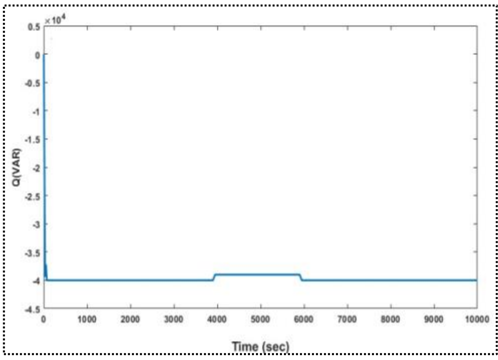

Fig.18. Results Reactive power.

5. Conclusions

This paper focuses on enhancing the power system quality of a Hybrid Renewable Energy System (HRES) in a grid-connected state. The improvements are achieved by reducing harmonics and providing voltage support during voltage sag and swell events. This is accomplished by integrating the Unified Power Quality Conditioner (UPQC) device with the proposed HRES, which is designed to harness the benefits of two sustainable energy sources, mostly, PV and wind energy, in conjunction with the electrical grid.

The control of the HRES, based on the Fractional-Order PID (FOPID) controller, allows for rapid responses to changes in both load and generation, resulting in smoother power delivery. The FOPID controller was applied to the UPQC with the assistance of Golden Eagle Optimization (GEO) Algorithm to determine optimal parameter values.

The proposed FOPID-GEO controller demonstrated superior performance in terms of system voltage and HRES power. Moreover, the UPQC controller successfully maintained continuous connections between the PV/wind sources and the system, even during prolonged intervals for clearing faults. Implementing this hybrid system with UPQC provides benefits that can improve the efficiency of grid-connected Hybrid Power Systems (HPS).

The investigation results have been verified and shown becoming successful in enhancing system quality and improving efficiency. Future versions of this work hold the potential for real-world implementation in hybrid power systems.

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