# Design and Performance Analysis of a PDO-FOPID Controller-Based UPQC for Grid-Connected Hybrid Renewable Energy Sources

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ABSTRACT

Due to increased environmental concerns and the decline of non-renewable energy supplies, the integration of renewable energy sources in power systems has received a lot of attention recently. However, integrating these sources poses a number of difficulties, including output power swings and the voltage and current in the grid have harmonics. The unique control method presented in this paper is based on the Prairie Dog Optimization Fractional Order Proportional Integral Derivative controller (PDO-FOPID) for a Unified Power Quality Conditioner system to mitigate harmonics and compensate load demand in grid-connected hybrid renewable energy sources. The UPQC system is designed to compensate for voltage and current harmonics and control the voltage at the common coupling point. The proposed PDO-FOPID controller has the ability to adjust the control parameters according to the system dynamics and adapt to the load variations. Through simulated tests utilizing the MATLAB and Simulink tools, the effectiveness of the suggested control scheme is assessed.

## 1. INTRODUCTION

Distributed generators powered by renewable energy sources are becoming important as a result of technological advancements, concerns about the environment and the massive energy demand on the grid of electricity [1]. To govern various power electronics and control technologies, many optimization techniques have been developed with more flexibility while incorporating a variety of alternative energy sources, such as solar, wind, and other kinds of batteries etc., which are becoming more important in supplying the enormous power needs [2-3].

Distribution generation is very important since it provides more reliable, best-quality, and productive electricity to the commercial deliveries that need constant management owing to the drawbacks of producing power from traditional sources of energy [4]. Due to the rising population and demand, it is now difficult to generate enough electricity from conventional sources alone, As a result, distribution generators typically use alternative energy sources including solar, wind, and batteries. [5].

The proposed study's distributed generation system has a source connected to the DC connector of a grid-connected controlled via an inverter by an approximated search algorithm that is tightly regulated so as to feed actual DG power to the grid [6]. If a non-linear, unbalanced, or both loads are coupled at the common coupling point, the suggested fix balances and corrects harmonics even when a supply voltage is disturbed. [7]. In addition to grid-interfacing inverters and actual power injection from RES, we also wanted to account for load wattage power, current harmonics, and current imbalance [8].

## 2. A BRIEF REVIEW OF RECENT RESEARCH WORK

S. Dheeban et al. [9] provide an ANFIS-based control method for a photovoltaic integrated to improve power quality, a distribution system should have a UPQC. The UPQC is controlled by the suggested technique using a hybrid FOPID-ANFIS control scheme, which leads to better harmonic distortion reduction and voltage regulation. Experimental and simulated data were utilized to confirm how well the suggested plan of action works. In the distribution systems using renewable energy sources, the proposed control strategy is an effective technique to increase the quality of the electricity, as the paper's conclusion states.

S. Mahaboob et al. [10] explore the usage of a predator-prey-based firefly optimization algorithm for the finest shunt active power filter design to raise the quality of the power. For a given collection of harmonic currents, the procedure is used to determine the filter's ideal parameter values. The research also compares the performance of the proposed algorithm with existing optimization techniques, such as genetic algorithms and particle swarm

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optimization, and demonstrates that the new algorithm surpasses them in terms of convergence speed and accuracy.

K. Sarker et al. [11] suggest a modified hybrid UPQC system based on PV-wind-PEMFCS that operates as a combined DVR/STATCOM system to compensate for harmonics. Power quality from grid-connected renewable energy sources is enhanced by the suggested system using a permanent magnet field coupled system (PEMFCS). The suggested system's performance has been tested using simulations, which the authors use to demonstrate how much voltage sag and swell in the grid may be reduced.

K. Srilakshmi et al. [12] propose a new hybrid controller design for a football league optimization-based universal power quality conditioner (UPQC) that integrates solar and batteries. The suggested controller is intended to reduce voltage sag, voltage swell, and harmonic distortion to improve the electricity quality of a distribution network. The simulation results show how well the suggested controller works to enhance the distribution network's power quality under various load scenarios.

The proposed work's principal contribution is the following:

- To provide a unique controller-based UPQC to reduce harmonics, sag, and swell in Hybrid Renewable energy systems (HRES) under varied situations.
- To create a HRES with three-phase loads on the distribution side, together with solar, wind, and batteries on the source side.
- An UPQC, which controls both current and voltage changes, is connected between the load and source sides to regulate the power flows.
- A FOPID controller that analyses PCC power variation to provide command signals has been created to enhance the mitigation performance of UPQC.
- The FOPID controller must solve the optimal problem in order to create the proper command pulse. Here, the FOPID controller problem is solved via prairie dog optimization (PDO).

MATLAB/Simulink is used to create and test the suggested framework. The remaining sections of the study are structured as follows: The sections are as follows: the 2nd section, Currently Active Study; the 3rd section, Framework for HRE suggested using PDO; the 4th section, PDO; the 5th section, A Discussion of the Findings; and section 6, Conclusion.

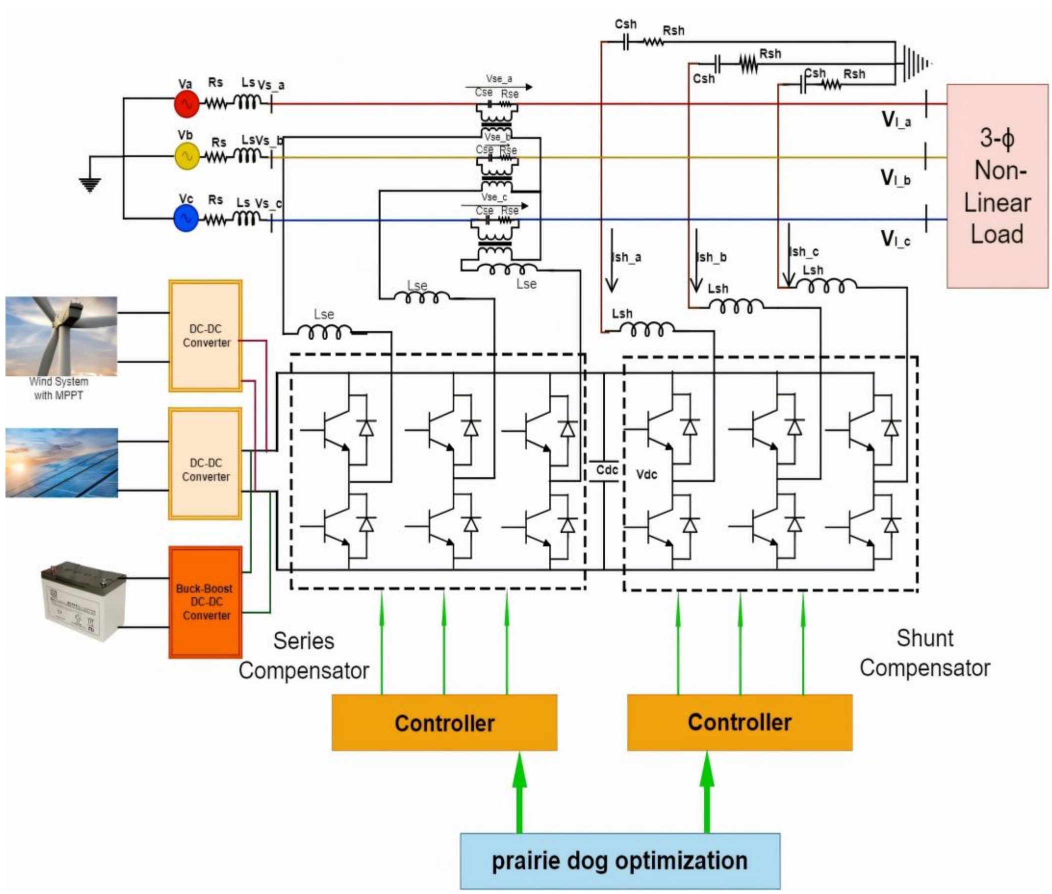


**Fig 1. Structure of integrated UPQC using solar PV, wind, and BESS.**

## 3. PROPOSED HRE SYSTEM WITH PRAIRIE DOG OPTIMIZATION

Structure of integrated UPQC using solar PV, wind, and BESS is shown in Figure 1, with external assistance provided by BESS with DC/DC BBC, solar PV system and wind system with DC/DC BC coupled to DC-link [13–14]. For making the most of FOPID that has been tailored to perfection, this article suggests PDO. The source phase voltages are VS_a, VS_b, and VS_c, and the grid voltages are Va, Vb, and Vc. Source-side resistance and inductances are Rs and Ls. The series and shunt converters that make up UPQC are linked together by a DC connection. The Series active Power filter (SAPF) removes the irregularities and imbalances caused by supply voltage by infusing the appropriate voltage compensation Vse through an isolating transformer. It is made up of a series capacitor Cse, a series inductor Lse, and a series resistor Rse.

The Shunt active power filter (SHAPF) is made up of three components: a shunt resistance Rsh, a shunt-fusing inductor Lsh, and a shunt-capacitance Csh. By injecting an appropriate compensating shunt current, it reduces current wave oscillations and keeps the DC-linked capacitor voltage (Vdc) constant throughout load and irradiance fluctuations.

BESS is intended to store energy and supplies in case of system breakdowns. P&O MPPT is used to harvest energy from wind and solar panels. From the PDO, an appropriate DC link voltage is produced. During the absence of solar energy, it is set to the default value for the DC attach voltage reference. Consideration is given to the power quality problems with the HRES, which are mostly caused by unanticipated loads, non-linear loads and grid-side faults [15–17].

The suggested approach is built with UPQC, which uses control methods in conjunction with series and shunt controllers to make up for the faults and ensure stable performance. Power reimbursement in sag conditions can be achieved by supplying the FOPID controller with the correct gain characteristics so that it can screen and inject the required amount of power. PDO is used to control FOPID controllers and is aiming to select the necessary values to execute the control procedure under PQ circumstances [18–22].

### *3.1. UPQC's control structure: Series and Shunt active power filter*

*3.1.1 Control technique for a series active power filter*

First, the reference voltage is examined with the assistance of a PLL. Equation (1)'s Clarke transformation is used to translate the three-phase voltages from all of the calculations into d-q axes, and Figure 2 shows a series active power filter.

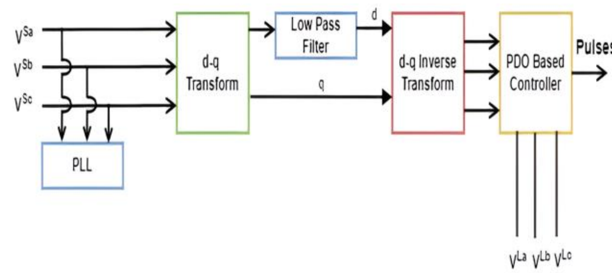


**Fig. 2. Series active Power filter(SAPF).**

$$\begin{bmatrix} V^0 \\ V^d \\ V^q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin(\alpha t) & \sin(\alpha t-\frac{2\Pi}{3}) & \sin(\alpha t+\frac{2\Pi}{3}) \\ \cos(\alpha t) & \cos(\alpha t-\frac{2\Pi}{3}) & \cos(\alpha t+\frac{2\Pi}{3}) \end{bmatrix}\begin{bmatrix} V^a \\ V^b \\ V^c \end{bmatrix} \quad (1)$$

$V^d$ stands for direct axis voltage, $V^q$ for quadrature axis voltage, and $V^a$, $V^b$, and $V^c$ for 3-ø voltages. A low-pass filter can be used to smooth the D-axis voltage, which is mathematically represented by (2).

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

The component voltage for AC is $V^{d(ac)}$ . The component voltage for DC is $V^{d(dc)}$. The voltage is then divided into 3 stages:

$$\begin{bmatrix} V^{Ra} \\ V^{Rb} \\ V^{Rc} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin(\alpha t) & \frac{1}{2} & 1 \\ \sin(\alpha t) & \sin(\alpha t-\frac{2\Pi}{3}) & 1 \\ \cos(\alpha t) & \cos(\alpha t-\frac{2\Pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} V^{d(dc)} \\ V^q \\ V^0 \end{bmatrix} \quad (3)$$

The 3-ø reference voltages are designated as$V^{Ra}$, $V^{Rb}$, and $V^{Rb}$ (3).

***3.1.2 Control technique for a shunt active power filter***

3-ø voltages as well as currents are turned into α and β as given in mathematical equations (4-5), and the construction of a SHAPF is shown in Fig. 3.

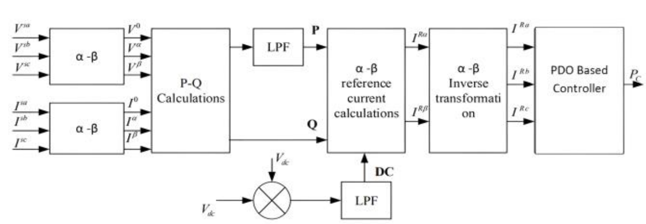


**Fig.3. Shunt active power filter (SHAPF).**

$$\begin{bmatrix} V^{s0} \\ V^{s\alpha} \\ V^{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V^{sa} \\ V^{sb} \\ V^{sc} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} I^{l0} \\ I^{l\alpha} \\ I^{l\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I^{La} \\ I^{Lb} \\ I^{Lc} \end{bmatrix} \tag{5}$$

Phase-neutral currents $I^{l\alpha}$, $I^{l\beta}$ The 3-ø load currents$I^{La}$, $I^{Lb}$, and $I^{Lc}$, $V^{s\alpha}$ and $V^{s\beta}$ represent phase neutral voltages, whereas $V^{sa}$, $V^{sb}$, and $V^{sc}$represent 3-ø supply voltages [23]. Equations 6-7 are used to compute real and reactive power.

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V^{s\alpha} & V^{s\beta} \\ -V^{s\beta} & V^{s\alpha} \end{bmatrix} \begin{bmatrix} I^{l\alpha} \\ I^{l\beta} \end{bmatrix} \tag{6}$$

The expression for reference currents is provided

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

The SHAPF reference currents are $I^{Ra}$, $I^{Rb}$, and $I^{Rc}$. The error current is calculated by comparing reference currents, and FOPID-based controller using PDO is to be used to help rectify it, which develops the pulses needed by the SHAPF.

## 4. PRAIRIE DOG OPTIMIZATION ALGORITHM

The Prairie Dog Optimization Method (PDO) is a recently suggested nature-inspired method for tackling optimization challenges. It is based on the behaviors of prairie dogs in the wild, where they live in vast communities and interact with one another through vocalizations and movements.

A prairie dog population depicts the possible solutions to the optimization issue in PDO. The program is based on prairie dog social interaction and communication concepts. To efficiently explore the search space, the algorithm employs a combination of local and global search algorithms.

One of PDO's benefits is its ability to handle both continuous and discrete optimization challenges. It has been used to solve a variety of optimization issues, including feature selection, picture segmentation, and structure optimization, among others.

### *4.1 PDO pseudo-code*

Algorithm 1 provides the pseudocode for the PDO optimization process. PDO begins by producing a set of evenly distributed, random potential solutions. The program then employs its established procedures to iteratively examine all potential sites for near-optimal solutions. Based on the stated rule, the algorithm chooses the best answer replaces the prior as of right now obtained solution each time. To achieve exploration and exploitation, the algorithm that is being presented uses four prairie dog actions. When iter<Maxiter/2 is reached, PDO begins the exploring stage, and when iter>Maxiter/2 is reached, the exploitation phase begins. Finally, when the end criteria are fulfilled, the suggested algorithm comes to a halt. In the literature, several stopping criteria have been used, containing the maximum number of repeats, maximum execution time, and function tolerance. In this study, the PDO algorithm's termination criterion is the number of iterations at its most. The maximum number of iterations, though, needs to be carefully set since if it's too high or too low, it might lead to a bad solution and a waste of computer resources, respectively. Figure 4's flow chart shows the suggested PDO algorithm's straightforward and thorough optimization approach.

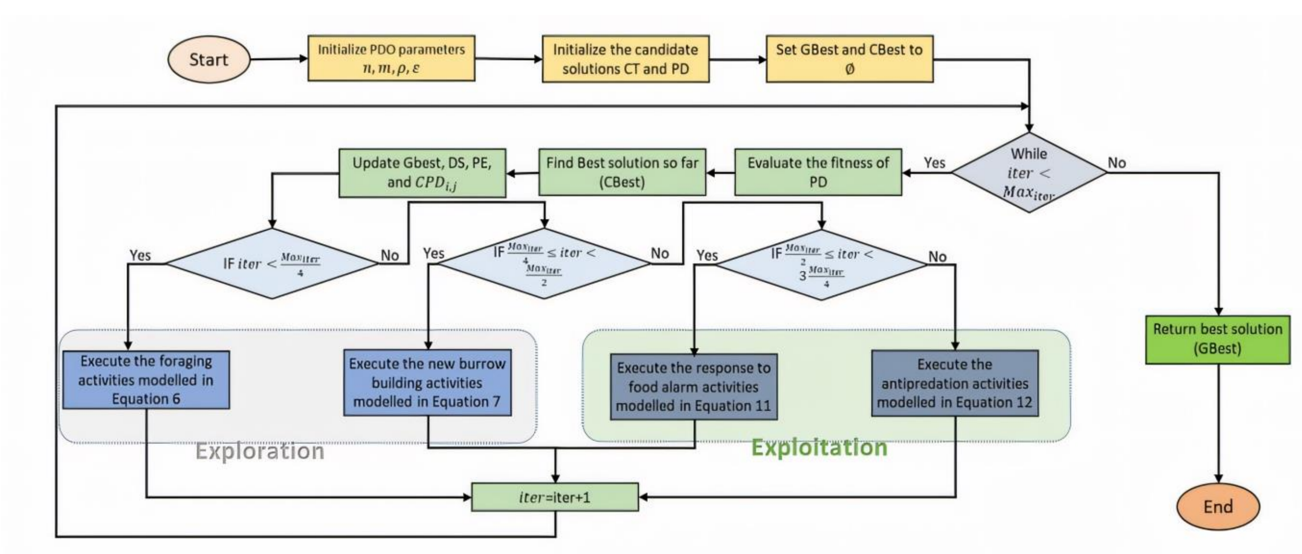


**Fig. 4 Flowchart for the PDO method that has been suggested.**

**Algorithm 1.** pseudo code of the optimization process of the PDO

**Initialization**
Set the PDO parameters: $n, m, \rho, \varepsilon$
Set $GBest$ and $CBest$ as $\emptyset$
Initialize the candidate solutions $CT$ and $PD$
**While** $iter < Max_{iter}$ **do**
  **For** (i=1 to m) **do**
    **For** (j=1 to n) **do**
      Calculate the fitness of PD
      Find the Best solution so far (CBest)
      Update GBest
      Update DS and PE using Equations 9 and 12
      Update $CPD_{i,j}$ using Equation 8.
      **If** $(iter < \frac{Max_{iter}}{4})$ **then** **{foraging activities}**
        $PD_{i+1,j+1} = GBest_{i,j} - eCBest_{i,j} \times \rho - CPD_{i,j} \times Lévy(n)$
      **Else if** $(\frac{Max_{iter}}{4} \leq iter < \frac{Max_{iter}}{2})$ **then** **{burrowing activities}**
        $PD_{i+1,j+1} = GBest_{i,j} \times eCBest_{i,j} \times DS \times Lévy(n)$
      **Else if** $(\frac{Max_{iter}}{2} \leq iter < 3\frac{Max_{iter}}{4})$ **then {food alarm}**
        $PD_{i+1,j+1} = GBest_{i,j} - eCBest_{i,j} \times \varepsilon - CPD_{i,j} \times rand$
      **Else** **{antipredation alarm}**
        $PD_{i+1,j+1} = GBest_{i,j} \times PE \times rand$
      **End If**
    **End For**
  **End For**
  $iter = iter + 1$
**End While**
***Return*** *best solution* (**GBest**)
**End**

### *4.2 FOPID controller*

Fig. 5 depicts the fundamental diagram of FOPID. The error signal e(s)aids in the process of creating the control output(s). The FOPID with PDO optimization is intended to reduce problems with power quality caused by voltage and current oscillations in the HRES platform. The FOPID controller's signal of control is in mathematics stated as follows:

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

During the controller design process, the following actions must be taken:

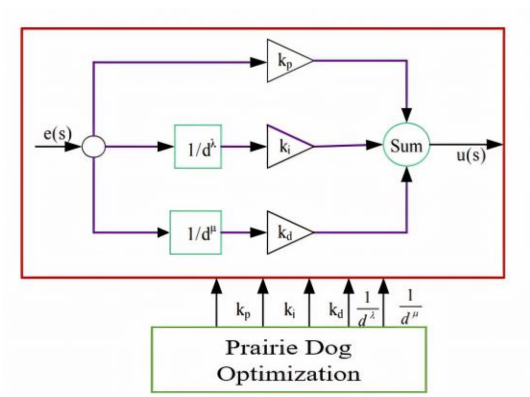


**Fig.5 Fractional order proportional integral derivative (FOPID) Controller.**

1. $K_P$ is controlled to minimise steady-state error and rising time.

2. $K_d$ is controlled to reduce settling time and overshoot.

3. $K_i$ is adjusted in order to eliminate the steady-state error.

4. The parameters for fractional orders $D^{-\lambda}$ and $D^{\mu}$.

## 5. A DISCUSSION OF THE FINDINGS

The suggested UPQC was tested on a 3-ø AC distribution system that is grid-connected. Fig.6 depicts the simulation model created in Matlab R2022b.

Eq. (9) calculates voltage fluctuations with PDO

$$V_{sag/swell} = \frac{V_l - V_s}{V_l} = \frac{V_{se}}{V_l} \qquad (9)$$

The series compensator injected voltage to adjust for voltage sag or swell and UPQC disturbance is provided by Eq. (10) [24].

$$V_{se} = V_l - V_s \qquad (10)$$

The shunt compensator's injected current is provided by Eq. (11) [24].

$$i_{sh} = i_i - i_s \qquad (11)$$

In general, traditional approaches produce more precise findings, although they are time-consuming and have significant limits. Meta-heuristic algorithms can be used for speedier processing.

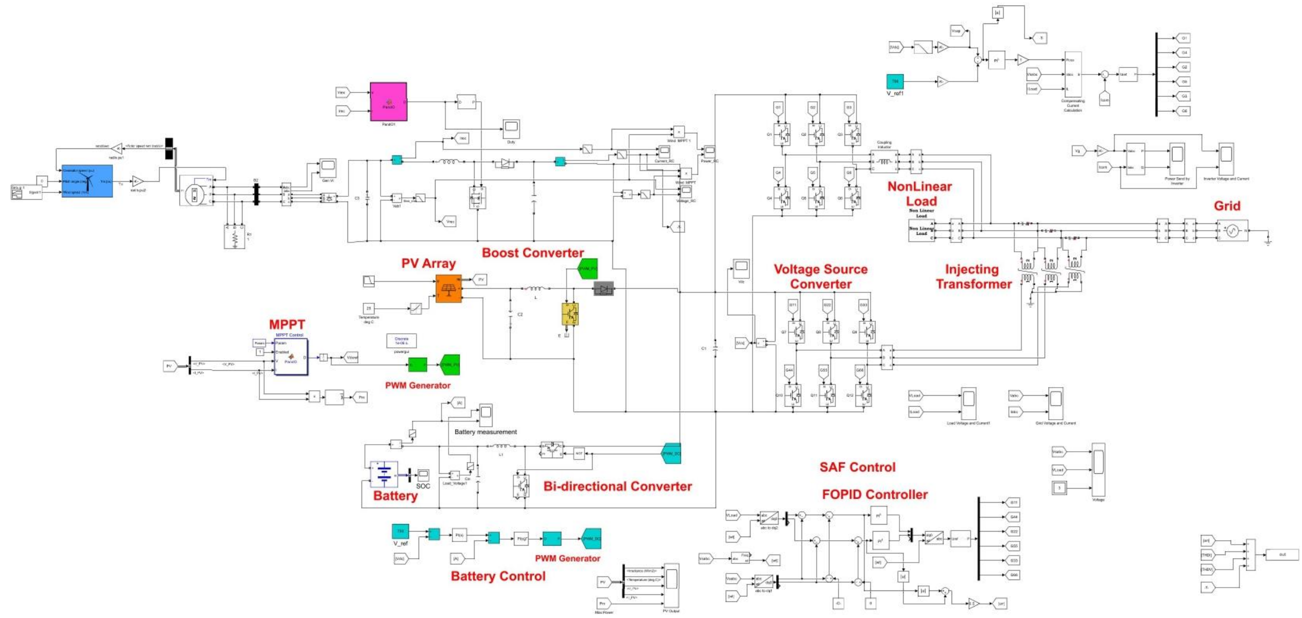


**Fig.6 Simulink model of an HRES-integrated UPQC with loads.**

Regarding Case 1, 30% of the source voltage dropped during 0.25-0.35 sec; the suggested UPQC injects a sufficient quantity of needed voltage to enhance the load voltage(Vl), as illustrated in fig. 7(a). Furthermore, as showing in fig. 7(b), the load current (Il) was found to be non-sinusoid but balanced, with a THD of 27%. Fig.7 clearly shows that the proposed UPQC efficiently eliminates sag by injecting an appropriate compensating voltage and enhancing source current that is sinusoidal. However, improvements in current waveforms are reflected in THD levels. As a result, by ingesting appropriate shunt currents, the load current's Total Harmonic Distortion(THD) was lowered from 27% to 2%.

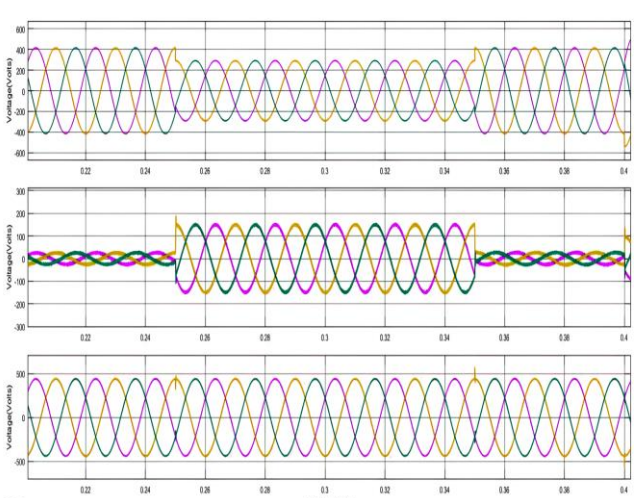


**Fig.7. (a) (Vs), (Vse), (Vl).**

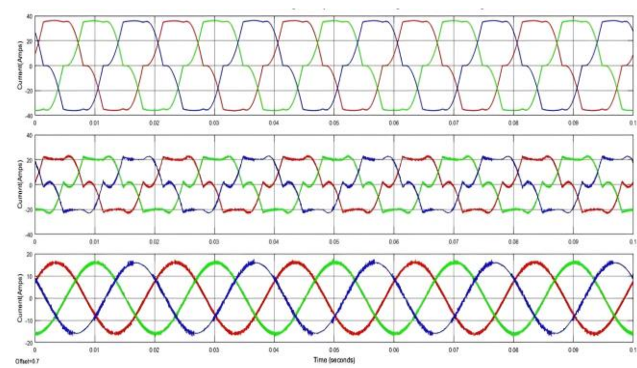


**Fig.7.(b) (Il), (Ish), (Is)**

Regarding Case 2, a voltage swell was created between 0.4 and 0.5 s; the suggested method successfully removes it by injecting a sufficient compensatory voltage, as illustrated in figure 8(a). During steady state, however, a tiny quantity of voltage always escapes across the series converter. Figure 8(b) shows that the non-sinusoidal load current existed yet balanced with a THD of 15%. The UPQC was capable successfully control swell and lower THD from 15% to 2.4% by injecting appropriate shunt currents.

Regarding Case 3, a substantial voltage fluctuation at the supply voltage was introduced. The load current in this case was imbalanced and non-sinusoid, with a 33% THD. The UPQC was capable minimize voltage anomalies extremely successfully by using the appropriate compensatory voltage and reducing THD from 33% to 2.4% while also enhancing the sinusoidal waveform's appearance, as illustrated in figures 9(a)–9(b).

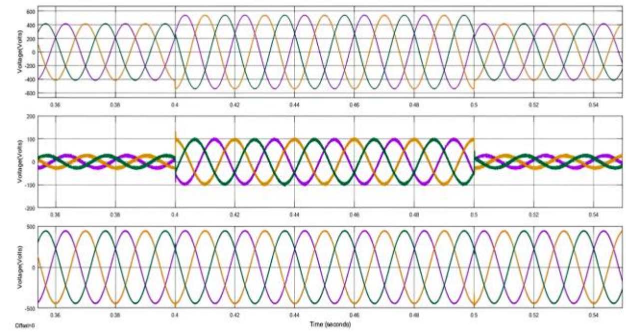

**Fig.8. (a) (Vs), (Vse), (Vl)**

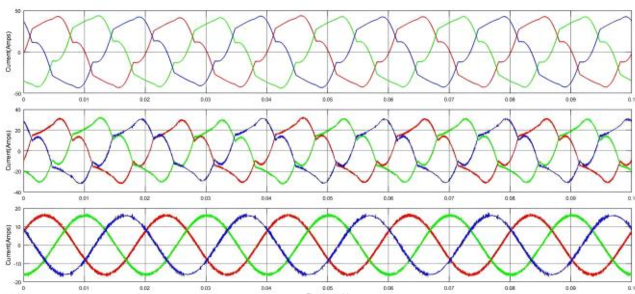

**Fig.8. (b) (Il), (Ish), (Is)**

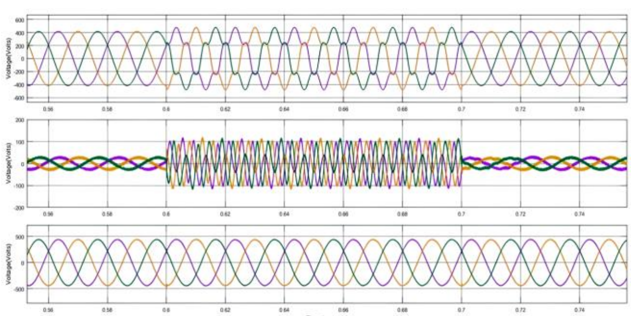

**Fig.9. (a) (Vs), (Vse), (Vl)**

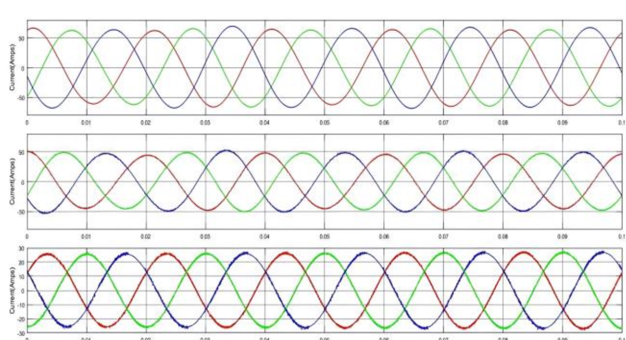

**Fig.9. (b) (Il), (Ish), (Is).**

Regarding Case 4, the supply voltage that is not balanced was evaluated; however, the suggested UPQC effectively supplies a symmetrical load voltage, as displayed in Fig 10(a). It appears that the load current is sinusoidal and imbalanced in this case, with a THD of 7.33% fig.10(b). THD was reduced from 7.3% to 2.3% with the PDO. The suggested method's performance was evaluated using solar irradiation variations of 1000W/m2 to 800W/ m2 and 800 W/ m2 to 1000 W/ m2 at a consistently warm of 25 degrees Celsius.

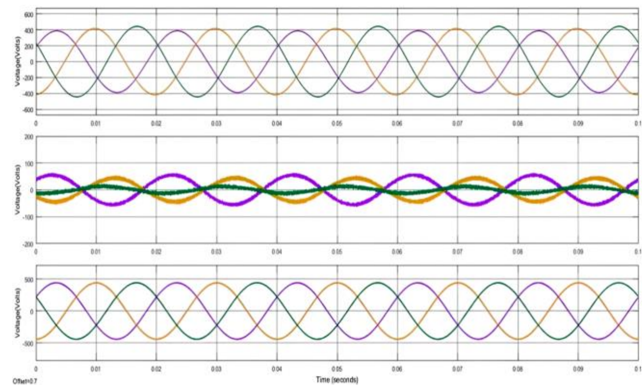

**Fig.10. (a) (Vs), (Vse), (Vl).**

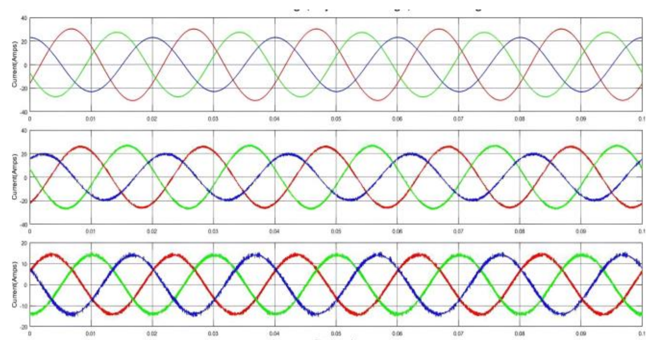

**Fig.10. (b) (Il), (Ish), (Is).**

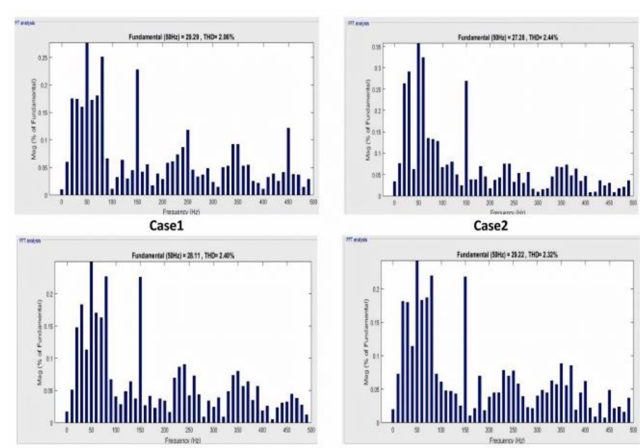


**Fig.11. Case studies1,2,3 and 4 using the THD spectrum.**

Fig. 11 displays the THD spectrum for each of the four test scenarios. Table 1 compares various suggested controllers with already existing controllers. However; it is obvious from fig.12 that the suggested system maintains a steady DC-Link voltage during irradiation fluctuations better than other devices. Additionally, the PV panel's output power, voltages, and duty cycle were reported.

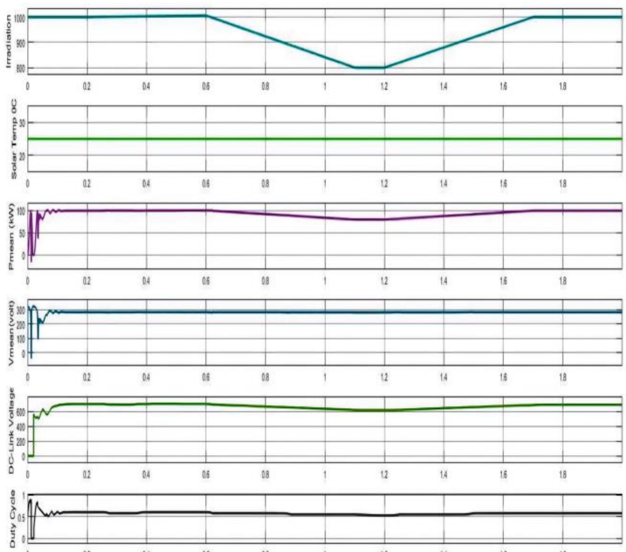


**Fig.12: irradiation, Solar Temp, $P_{out}$, voltage, DC-Linked voltage, and duty cycle waveforms.**

**Table.1 % THD comparison .**

| Type Controller | Case 1 | Case 2 | Case 3 | Case4 |
|---|---|---|---|---|
| Without UPQC | 27% | 15% | 33% | 7.3% |
| PI | 4.97% | 5.68% | 4.25% | 5.02% |
| SMC | 4.74% | 3.74% | 4.23% | 4.09% |
| FLC | 4.01% | 3.43% | 3.14% | 4.14% |
| Proposed FOPID | 2% | 2.4% | 2.4% | 2.3% |

## 6. CONCLUSIONS

The proposed UPQCS system: Innovative Control Technique based on the Prairie Dog Optimization (PDO) FOPID controller to mitigate harmonics and compensate load demand Combination renewable energy sources that are grid-connected. The suggested PDO-FOPID controller may alter the control parameters in response to system dynamics and load fluctuations, resulting in a stable and dependable power supply.

Simulations using the MATLAB/Simulink software showed that the suggested control technique efficiently mitigates harmonics and adjusts for load demand while managing voltage at the common coupling point. The suggested control strategy's performance was assessed under various operating situations, and the simulation results revealed that it beat existing control techniques in terms of harmonic mitigation and load compensation.

As a result, the recommended control method based on the PDO-FOPID controller is a promising solution for the integration of HRES in power systems, as it effectively mitigates the challenges associated with fluctuating alternatives to fossil fuels while securing a steady and dependable electricity source. The suggested control technique has the potential to contribute to the development of environmentally friendly and sustainable power systems.

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