Power Quality Improvement in HRES Grid Connected System with FOPID Based hybrid particle swarm Optimization Technique

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Abstract—**This project focuses on the Optimal Power Quality Enhancement (OPQE) of a grid- connected Hybrid Renewable Energy System (HRES) that integrates solar photovoltaic (PV), wind turbines (WT), and a Battery Energy Storage System (BESS). A Unified Power Quality Conditioner with real and reactive power compensation (UPQC-PQ) is designed using a Fractional-Order Proportional-Integral-Derivative (FOPID) controller optimized by a hybrid Particle Swarm Optimization (PSO) algorithm. The primary objective is to minimize Total Harmonic Distortion (THD) and power losses while improving voltage stability under dynamic operating conditions. The proposed system addresses key Power Quality (PQ) issues, including voltage sag, swell, interruptions, and unbalanced loads. Performance analysis under various operating modes (renewable power available, unavailable, and transition states) demonstrates that the hybrid PSO-FOPID control strategy outperforms traditional approaches like PI, GA, GSA, BBO, and GWO. MATLAB the system's enhanced efficiency and reliability**

Objectives
• To design a grid-connected Hybrid Renewable Energy System (HRES) integrating PV, wind, and BESS for reliable power supply
• To enhance power quality by mitigating voltage sag, swell, harmonics, and
unbalanced loads using a UPQC-PQ system.
• To implement a Fractional-Order PID (FOPID) controller optimized by hybrid Particle Swarm Optimization (PSO) for effective control.
• To minimize Total Harmonic Distortion (THD) and power losses for
improved system efficiency.

• To validate the proposed system's performance through MATLAB/Simulink simulations under dynamic operating conditions.

I. BACKGROUND

1. Growing demand for clean and reliable energy has led to the integration of Hybrid Renewable Energy Systems (HRES) combining PV, wind, and energy storage.
2. Grid-connected HRES often face Power Quality (PQ) issues such as voltage sag, swell, harmonics, and imbalance due to fluctuating renewable generation
3. Traditional controllers like PI/PID have limitations in handling non-linear and dynamic conditions effectively.
4. Unified Power Quality Conditioner (UPQC-PQ) is a promising solution to
address both real and reactive power disturbances.
5. Fractional-Order PID (FOPID) controllers, when optimized using advanced algorithms like Hybrid Particle Swarm Optimization (PSO), provide better accuracy and adaptability.
Methodology:
System Design
◦ Develop a grid-connected HRES using PV, wind turbine (WT), and Battery Energy Storage System (BESS).
◦ Integrate a Unified Power Quality Conditioner (UPQC-PQ) for PQ improvement.
Controller Implementation
◦ Design a Fractional-Order PID (FOPID) controller to regulate voltage and current.
◦ Optimize controller parameters using a Hybrid Particle Swarm Optimization (PSO)

algorithm.

Modeling & Simulation

◦ Model PV, WT, and BESS subsystems along with UPQC-PQ in MATLAB/Simulink.

◦ Apply control strategies for both series and shunt Active Power Filters (APF).

Performance Analysis

◦ Evaluate PQ issues (voltage sag, swell, harmonics, unbalanced loads).

◦ Compare performance of the proposed FOPID-PSO method with PI, GA, GSA, BBO, and GWO controllers.

Modelling Approach:

Hybrid Renewable Energy System (HRES)

PV, Wind Turbine (WT), and Battery Energy Storage System (BESS) are mathematically modeled.

Maximum Power Point Tracking (MPPT) is applied for optimal PV and WT performance.

Unified Power Quality Conditioner (UPQC-PQ)

Series and Shunt Active Power Filters (APFs) are modeled for voltage and current compensation.

DC-link capacitor is designed to maintain power balance during disturbances.

Modelling Approach:

FOPID Controller Design

Five control parameters are tuned for improved dynamic response.

Hybrid Particle Swarm Optimization (PSO) is used to achieve optimal gain values.

Unified Power Quality Conditioner (UPQC-PQ)

Series and PQ comparisons are performed before and after compensation. DC-link capacitor is designed to maintain power balance during disturbances.

FOPID Controller:

FOPID Controller Design Controller Type:

Fractional Order PID (FOPID) with 5 tuning parameters:

$K_p, K_i, K_d, \lambda, \mu$

K_p = Proportional Gain K_i = Integral Gain

K_d = Derivative Gain

λ = Fractional Order of Integration

μ = Fractional Order of Differentiation

5 Tuning Parameter of FOPID:

K_p = Proportional Gain

◦ Determines the reaction to the current error. A higher K_p increases the controller's responsiveness.

K_i = Integral Gain

◦ Determines the reaction based on the accumulation (sum) of past errors. Helps eliminate steady-state error

K_d = Derivative Gain

◦ Determines the reaction based on the rate of change of error. Helps reduce overshoot and improves stability.

λ = Fractional Order of Integration

◦ Unlike traditional PI ($\lambda = 1$), FOPID allows λ to be any positive real number, giving smoother and more precise control over the integral action.

μ = Fractional Order of Differentiation

◦ Similar to λ, μ generalizes the derivative component. It allows better tuning of response time and noise sensitivity.

FOPID Controller Function:

Function:

Regulates voltage and current by controlling series & shunt Active Power Filters (APFs).

Minimizes error signals using optimally tuned gains.

Improved dynamic performance (settling time, overshoot, etc.)

Benefits over PI/PID:

Higher tuning flexibility

Better control over system dynamics

Reduced overshoot and faster settling

Optimization Algorithm:

Title: Hybrid Particle Swarm Optimization (HPSO)

Purpose :

To optimally tune the FOPID controller Parameters for enhanced PQ control

Hybrid Features:

Elite Opposition-Based Learning (EOBL) Spiral Search & DE/best/2 mutation

Adaptive inertia weight & acceleration coefficients

Advantages:

◦ Avoid premature convergence

◦ Better exploration-exploration balance

◦ Achieves global optima efficiently

Comparison:

Outperforms standard PSO, GSA, GA, and BBO in terms of speed & accuracy

Achieved best results on benchmark functions (f1–f13) with 80–85% optimality

1.   Generate an initial population with the strategy of Elite Opposition-Based Learning (EOBL)

2.   Evaluate the fitness of each individual

3.   Initialize $Pbest$ with a copy of X_i and select the best individual $Gbest$

4.   Initialize the iteration counter $k = 1$, $m = 0$, $BK = 0$

5.   **While** $k \leq Mk$

6.   Update the inertia weight

7. $\omega_{k+1} = \sin(b \times \pi / \omega_k) \times k/Mk$

8.   Update the acceleration parameters

9. $c_1 = c_{max} - (c_{max} - c_{min}) \times k/Mk$

10. $c_2 = c_{min} + (c_{max} - c_{min}) \times k/Mk$

11.   Select a random integer i_{rand} from $[1,n]$

12.   Update a, B, l

13.   for $i = 1 : n$

14.   Update the velocity V_i

15. $v_{ij}(k+1) = \omega \times v_{ij}(k) + r_1 \times c_1 \times (Pbest_i^g - x_{ij}(k)) + r_2 \times c_2 \times (Gbest - x_{ij}(k))$

16.   Update the position of individual X_i

17.   **If** $BK = 0$

18. $x_{ij}(k+1) = \omega \times x_{ij}(k) + \omega' \times v_{ij}(k+1) + \rho \times \psi \times Gbest$

19.   **else**

20.   **If** $rand(0,1) < Cr$ **or** $i = i_{rand}$

21.   Select four random individuals $x_i \neq x_{r1} \neq x_{r2} \neq x_{r3} \neq x_{r4}$

22. $x_{ij}(k+1) = x^* = Gbest + F \times (x_{r1} - x_{r2}) + F \times (x_{r3} - x_{r4})$

23.   **else**

24. $x_{ij}(k+1) = D \times e^{B \times l} \times \cos(2 \times pi \times l) + Gbest$

25.   **end if**

26.   **end if**

Algorithm 1. The main procedure of NDWPSO.

```
27        Evaluate the fitness of all particles
28        If x* or Xᵢ is better than Pbestᵢ
29            Update Pbestᵢ
30        end if
31        If x* or Xᵢ is better than Gbest
32            Update Gbest
33        end if
34    end for
35    if k ≥ M
36        for j = 1:(M − 1)
37            if Gbest(j + 1) = Gbest(j)
38                m = m + 1
39            end if
40        end for
41        if m = M
42            BK = 1
43        else
44            m = 0
45        end if
46    end if
47    k = k + 1
48 end while
```

$$27 \quad \text{Evaluate the fitness of all particles}$$
$$28 \quad \text{If } x^* \text{ or } X_i \text{ is better than } Pbest_i$$
$$29 \quad \text{Update } Pbest_i$$
$$30 \quad \text{end if}$$
$$31 \quad \text{If } x^* \text{ or } X_i \text{ is better than } Gbest$$
$$32 \quad \text{Update } Gbest$$
$$33 \quad \text{end if}$$
$$34 \quad \text{end for}$$
$$35 \quad \text{if } k \geq M$$
$$36 \quad \text{for } j = 1:(M-1)$$
$$37 \quad \text{if } Gbest(j+1) = Gbest(j)$$
$$38 \quad m = m + 1$$
$$39 \quad \text{end if}$$
$$40 \quad \text{end for}$$
$$41 \quad \text{if } m = M$$
$$42 \quad BK = 1$$
$$43 \quad \text{else}$$
$$44 \quad m = 0$$
$$45 \quad \text{end if}$$
$$46 \quad \text{end if}$$
$$47 \quad k = k + 1$$
$$48 \quad \text{end while}$$

II. RESULTS

THD Reduction Achieved:
Voltage THD reduced significantly (e.g., from 25.01% to 20.01%). Current THD improved under different modes (Mode 1 & Mode 2). Power Quality Enhancement:

Effective mitigation of sag, swell, and unbalanced conditions. Improved voltage and current profiles at the PCC. Performance Comparison:
FOPID with Hybrid PSO outperformed conventional PI, GSA, BBO, GWO, and GA. Faster response, better dynamic control, and higher system reliability.

Table 2. Simulation results summary for mode 1 and mode 2 operations.

THD	Phase	Mode 1				Mode 2			
		t₁	t₂	t₃	t₄	t₅	t₆	t₇	t₈
THD of Vₐ (%)	a	21.98	21.78	20.05	20.64	21.98	20.32	20.05	20.01
	b	18.08	16.86	14.41	14.91	18.08	14.40	18.40	17.4
	c	25.01	25.06	23.54	23.95	25.01	23.27	23.54	23.54
THD of Iₛ (%)	a	17.12	17.96	18.99	18.98	17.12	19.12	17.99	18.99
	b	26.82	25.17	27.21	27.18	26.82	27.02	26.21	27.21
	c	18.23	16.32	16.32	16.32	18.23	26.32	16.32	16.32
THD of Iₗ (%)	a	25.12	20.92	20.92	20.92	25.12	20.92	20.92	20.92
	b	27.31	12.33	12.32	12.32	27.31	25.32	26.32	12.32
	c	24.31	19.33	17.33	16.33	24.31	17.33	18.33	18.33
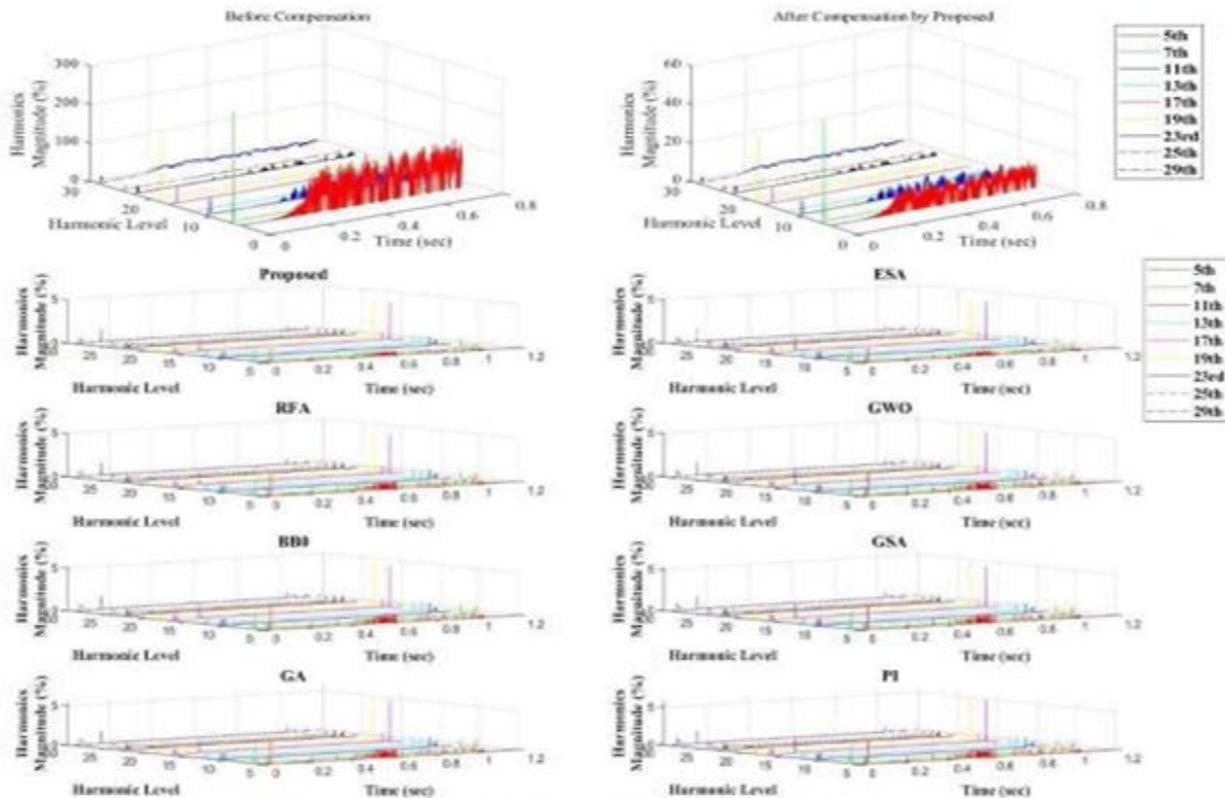
Figure 8 Analysis of THD comparison.
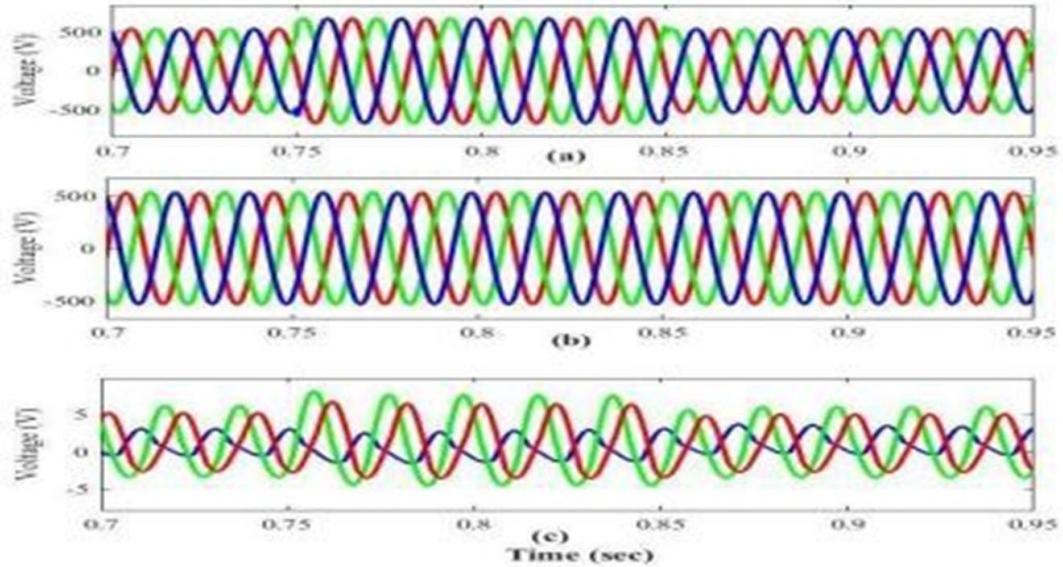
Figure 9 Analysis of voltage swell conditions (a) Source Voltage (b) Load Voltage (c) Injected Voltage.

Power Quality Improvement

Significant reduction in Total Harmonic Distortion (THD) for both voltage and current at the Point of Common Coupling (PCC).

Voltage sag and swell effectively mitigated by the UPQC-PQ.

Performance of Controller

FOPID with Hybrid PSO outperforms conventional PI, GA, GSA, BBO, and

GWO controllers in terms of dynamic response and accuracy.

Faster settling time, minimal overshoot, and improved steady-state stability.
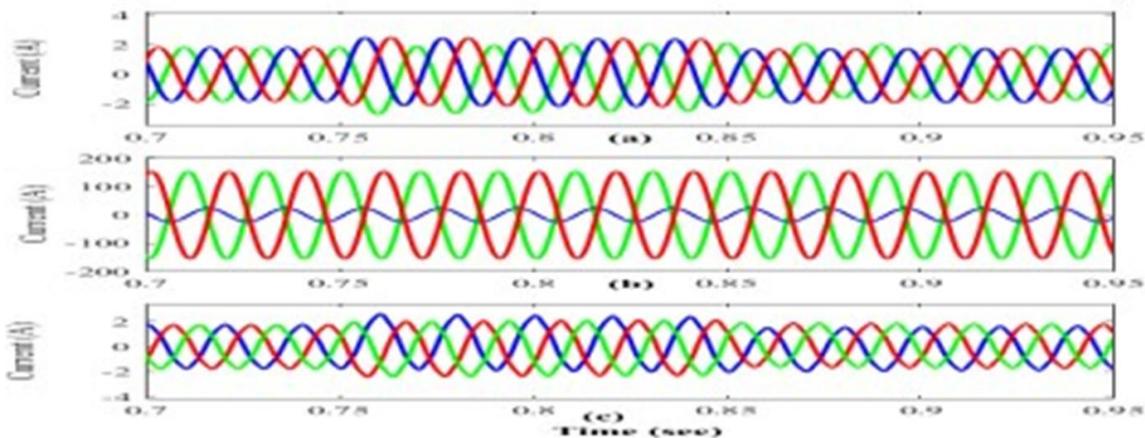
Figure 10 Analysis of current swell conditions (a) Source Current (b) Load Current (c) Injected Current.

System Reliability

Stable operation achieved under varying renewable energy conditions (P_RES

> 0 and P_RES = 0).

Improved load balancing for nonlinear and unbalanced loads.

Performance of Controller

FOPID with Hybrid PSO outperforms conventional PI, GA, GSA, BBO, and GWO controllers in terms of dynamic response and accuracy.

Faster settling time, minimal overshoot, and improved steady-state stability.

III. CONCLUSION

1. The proposed Hybrid Renewable Energy System (HRES) with UPQC-PQ and FOPID- based Hybrid PSO controller significantly improves Power Quality (PQ).

2. Achieves reduction in THD, voltage regulation, and compensation for sag, swell, and unbalanced loads.

3. Outperforms conventional PI and other metaheuristic-based controllers in terms of accuracy, stability, and dynamic response.

IV. FUTURE SCOPE

1. Implementation of the proposed system on real-time hardware (HIL testing) for practical validation.

2. Integration with smart grids and IoT-based monitoring for advanced PQ management.

3.Exploring AI-based optimization techniques (e.g., Deep Reinforcement Learning) for improved controller performance.

4.Extension to microgrid systems with multiple renewable sources and electric vehicle integration.

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