Flower Pollination Algorithm for Power Quality Enhancement in Smart Grids

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Abstract— **In modern power systems, maintaining power quality has become a critical challenge, especially with the implementation of smart grids. Active Power Filters (APFs) are widely used to address these issues due to their ability to rapidly filter distortions and provide immediate compensation. To manage both voltage supply disturbances and load current variations, the Unified Power Quality Conditioner (UPQC) is commonly employed. The UPQC integrates both shunt and series active power filters in a unified system, utilizing a shared dc link capacitor. Effective regulation of the dc link capacitor voltage is crucial for the optimal performance of the UPQC. A PI controller typically used for this purpose. This study focuses on optimizing the PI controller parameters of the shunt active filter in the UPQC using the Flower Pollination Algorithm (FPA) to enhance power quality. A MATLAB simulation model of a microgrid incorporating the UPQC was developed, and the results have been analyzed and discussed.**

Keywords- Smart-grid, Power Quality, UPQC, Series APF, Shunt APF, Flower Pollination Algorithm, Optimization, Harmonics.

I. INTRODUCTION

Recent developments in power electronics have significantly increased the prevalence of non-linear loads in electrical systems. While these non-linear devices enhance operational capabilities, they also introduce harmonics into the power system. Harmonics can cause various issues, including nuisance tripping, malfunctioning of consumer equipment, overheating of transformers and wiring, and other operational inefficiencies [1-3]. The presence of these harmonics contributes to the degradation of power quality (PQ), leading to increased power losses and financial repercussions. Poor power quality negatively impacts both utilities and end-users by causing system damage and reducing overall reliability [4,5]. To address these challenges, power filters have been widely adopted to mitigate power quality issues. Historically, passive filters have been the primary solution for harmonic elimination and PQ improvement. However, their functionality is limited to specific harmonic frequencies, and they tend to be large and bulky. Additionally, passive filters suffer from drawbacks such as resonance issues and a lack of dynamic compensation capability, which restrict their overall performance and adaptability in modern power systems [6-8].

Power quality issues, such as voltage sags, swells, and harmonics, can disrupt the operation of sensitive equipment and compromise system stability. To mitigate these challenges, advanced techniques are necessary to ensure that microgrids deliver consistent and reliable power. One effective solution is the Unified Power Quality Conditioner (UPQC), a versatile device designed to address both voltage and current-related disturbances simultaneously. By actively compensating for power quality deviations and suppressing harmonics, the UPQC plays a crucial role in improving the overall power quality within a microgrid.

The performance of a UPQC significantly depends on the effectiveness of its control strategies, particularly the Proportional-Integral (PI) controllers used for managing voltage and current compensation. Proper tuning of the PI controller parameters, such as the proportional and integral gains, is crucial for achieving a fast dynamic response, reduced steady-state errors, and optimal power quality performance. However, conventional tuning methods often struggle to handle the nonlinear, time-varying, and multi-objective nature of modern power systems.

This paper presents an FPA-based methodology for tuning the PI controller parameters of a UPQC to enhance power quality. The proposed approach is evaluated under various operating conditions to assess its effectiveness in mitigating voltage and current disturbances. Simulation results demonstrate that the

FPA-optimized PI controllers outperform traditional tuning methods, achieving better dynamic response, lower harmonic distortion, and improved compensation capabilities.

II. UNIFIED POWER QUALITY CONDITIONER

UPQC comprises two Voltage Source Converters (VSCs) that share a common DC link capacitor, as depicted in Figure 1. One VSC is connected in series with the power line and operates as a controlled voltage source to address voltage-related disturbances, including unbalances, harmonics, sags, swells, flicker, and sequence components. The other VSC is connected in parallel with the load and functions as a controlled current source to compensate for current-related distortions, regulate reactive power, and stabilize the DC link voltage. Working together, these converters enhance power quality by effectively mitigating issues associated with voltage, current, and reactive power.

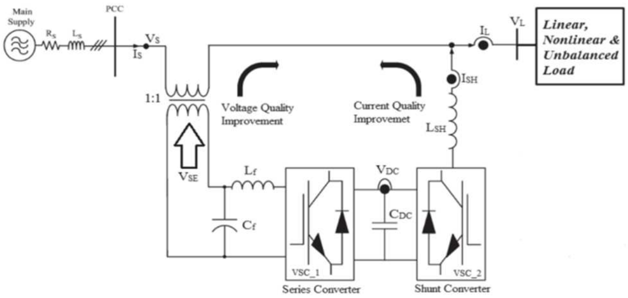

Fig. 1. Microgrid architecture with UPQC

III. SRF CONTROL FOR THE PROPOSED MODEL:

The SRF theory is widely used in UPQC (Unified Power Quality Conditioner) for generating reference signals to mitigate voltage and current disturbances such as harmonics, unbalances, voltage sag, and reactive power compensation. It involves the transformation of three-phase voltages and currents into a rotating reference frame (d-q) and then filtering out the unwanted components.First, the three-phase load currents (Ia, Ib, Ic) are converted into the stationary α-β reference frame using the Clarke transformation using Equation (1).

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$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

The stationary α-β components are further transformed into the synchronous rotating d-q reference frame using the Park transformation as shown in equation (2). In the d-q frame, the fundamental frequency component appears as a DC component, while harmonics appear as AC components. To separate them, a Low Pass Filter (LPF) is applied. The reference currents are transformed back to α-β frame using the inverse Park transformation and, then converted back to three-phase (abc) reference currents using the inverse Clarke transformation, producing the reference compensation currents used by the shunt active filter.

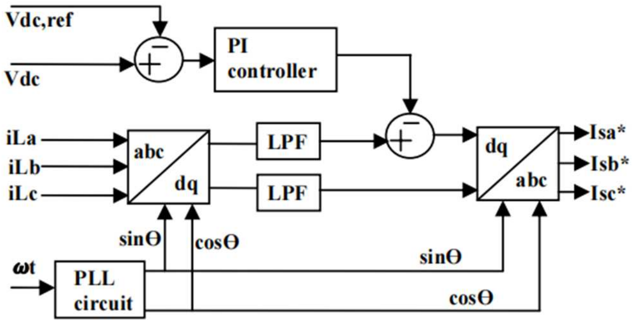

Fig. 2. SRF Control For Shunt Active Filter

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = [T_{abc}] \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \quad (4)$$

IV. PROBLEM FORMULATION:

This study primarily aims to reduce the voltage deviation between the reference DC voltage and the actual DC voltage of the DC link capacitor of UPQC. Additionally, it focuses on identifying the optimal values for the proportional (Kp) and integral (Ki) gain constants. The Flower Pollination Algorithm (FPA) is utilized to determine these optimal Kp and Ki values. The problem formulation is as follows:

$$\text{Minimize : Error} \quad e = \Delta V_{dc} = V_{dc}^* - V_{dc} \quad (5)$$

where: V_{dc}^* is the reference DC voltage of capacitor.
V_{dc} is the actual DC voltage of capacitor.

The proportional-integral (PI) controller parameters, Kp and Ki, are subject to the following constraints:

$$K_{Pmin} < K_P < K_{Pmax} \quad (6)$$

$$K_{i\,min} < K_i < K_{i\,max} \quad (7)$$

For the inverter to function properly, the DC link voltage of the capacitor must remain constant. However, the voltage V_{dc} across the capacitor (C_{dc}) tends to decrease due to switching power losses and conduction losses in the diodes and IGBTs of the inverter. The deviation between the reference voltage V_{ref} and V_{dc} is processed by the PI controller, and its output is then subtracted from the DC component of the direct axis current I_d.

$$I_d^* = I_{d\,dc} - I_{loss} \quad (8)$$

V. FLOWER POLLINATION ALGORITHM :

Pollination is a vital natural process essential for the reproduction of flowering plants. Scientists have discovered that this evolutionary mechanism can be utilized to address complex challenges, especially when traditional mathematical solutions become cumbersome. Pollination involves the transfer of pollen between plant species and is classified into two main types: (1) self-pollination, also known as biotic, and (2) cross-pollination, referred to as abiotic.

In self-pollination, pollen is carried by the wind between plants of the same genetic makeup. On the other hand, cross-pollination involves the movement of pollen by agents such as bees, birds, and bats. Interestingly, cross-pollination is responsible for 90% of all pollination activities, leaving self-pollination with just 10%. The Flower Pollination Algorithm (FPA), inspired by this process, operates based on specific principles to achieve optimal global solutions. The flow chart for FPA to optimize the PI controller parameter of Shunt active filter in UPQC is given in Figure 3.

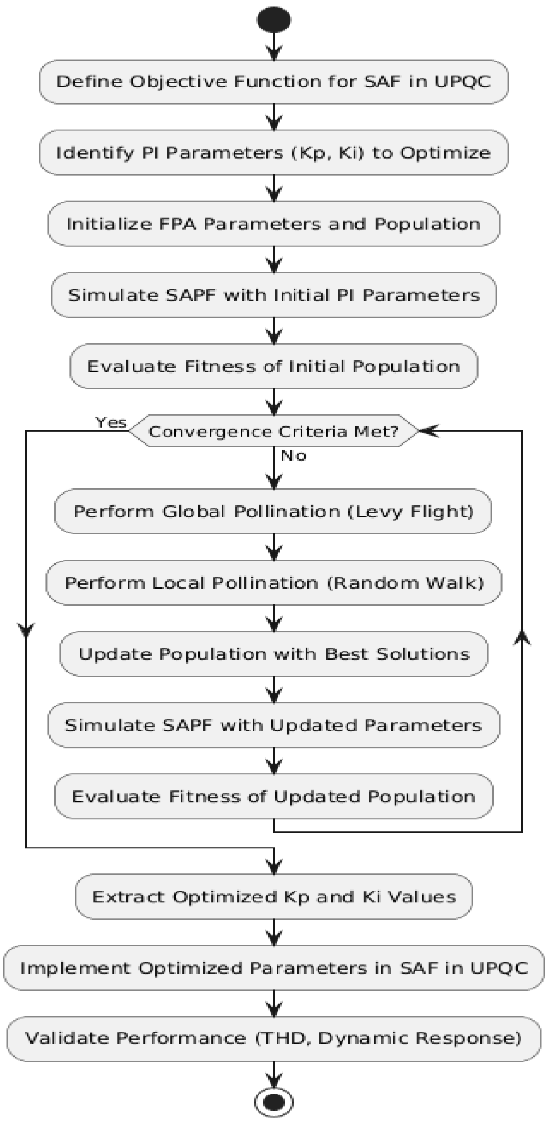

Fig. 3. Flower Pollination Algorithm Flow Chart

The parameters of the Flower Pollination Algorithm (FPA) and their magnitudes are shown in Table 1. Figure 4 represents the Gaussian surface analysis using FPA for gain optimization with: a) m1=0.48 & m2=0.34 b) m1=0.41 & m2=0.36 respectively. In this approach, a heat map-based analysis has been carried out to determine the optimum solution.

As observed in Case One, the optimization point lies on the critical boundary, where the valley point and the proposed optimization point do not coincide, thereby representing an unusual solution to the optimization problem stated in the problem formulation section. In Case Two, although the optimized solution and the valley point coincide, the accuracy in the second case is twice as high compared to Case One.

Table.1- Flower pollination algorithm parameters, their magnitude, and remarks

Sr. No.	Parameters	Magnitude	Remarks
1	No. of Generations	81	Total No. of Iterations
2	Switch Probability	0.26	probability of solution based on the attraction
3	Population Size	200	No. of Individual Solutions
4	Upper Boundary	0.13	Max. value of candidate solution
5	Lower Boundary	0.07	Min. value of candidate solution
6	Model Order	3rd	Order of optimization function
7	No. of Parameters	3	No. of gains

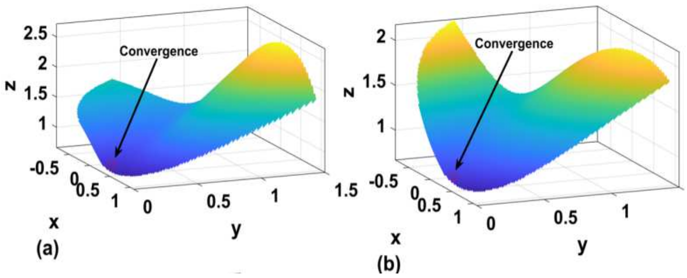

Fig. 4- Gaussian surface analysis using FPA for gain optimization a) m1=0.48 & m2=0.34 b) m1=0.41 & m2=0.36

VI. RESULT ANALYSIS AND DISCUSSION:

A MATLAB simulation model was developed for the proposed system, as shown in Figure 5. To assess various parameters of the PI controller, a reference voltage of 400 V was considered. The proportional gain parameters, optimized using the Flower Pollination Algorithm (FPA), were manually input into the main controller. These parameters were then used to generate the control sequence for the grid-side converter through space vector modulation.

A comparative analysis of the performance between a standard PI controller and an FPA-optimized PI controller is provided in Table 2, with both tested under the same dynamic conditions. The FPA-optimized PI controller has a proportional gain of 0.24, while the standard PI controller has a slightly higher value of 0.32.

This suggests that the FPA-optimized PI controller operates with a lower proportional gain, which may indicate enhanced stability compared to the standard PI controller under identical conditions. Additionally, the evaluation error for each controller was considered. The PI controller exhibits an error of 17.22%, whereas the FPA-optimized PI controller demonstrates a reduced error of 10.83%. This indicates that the FPA-optimized PI controller offers superior accuracy and precision compared to the standard PI controller.

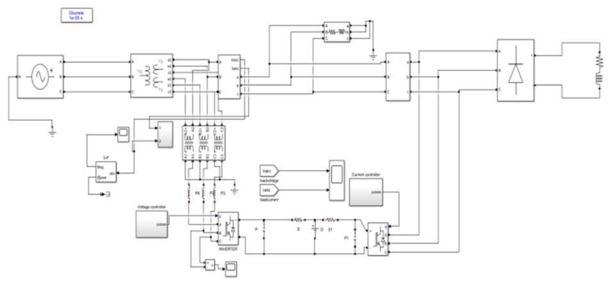

Fig. 5. Matlab Simulation of The Proposed Model

Table.2. Comparison between Controller gain between PI controller, GA-Optimized PI Controller and FPA-Optimized PI Controller.

Sr. No.	Parameter	PI Controller (Ziegler-Nichols)	GA-Optimized PI Controller	FPA-Optimized PI Controller
1	Proportional Gain	$K_{P1}(0.32)$	$K_{P1}(0.29)$	$K_{P1}(0.24)$
2	Integral Gain	$K_{i1}(2)$	$K_{i1}(1.6)$,	$K_{i1}(1.7)$
3	Derivative	0.05	0.05	0.05
4	Sampling Time	0.01 sec.	0.001 sec.	0.001 sec.
5	Error	17.22%	13.06%	10.83%
6	Std. Deviation	1.652	1.221	1.171

The power quality assessment across various cycles, as presented in Tables 3, 4, and 5, reveals performance disparities among the GA-optimized PI controller, the FPA-optimized PI controller, and the standard PI controller. The FPA-optimized PI controller generally demonstrates better power quality characteristics, aligning with international standards and reducing THD levels. However, certain parameters, such as voltage fluctuations and flicker analysis, may still require further optimization. Ultimately, selecting the appropriate control strategy depends on balancing power quality demands and economic factors under dynamic load conditions.

Table.3. Power Quality Comparison by using PI controller and FPA-Optimized PI Controller at 3rd Cycle

Sr. No.	Parameter	PI-Controller	GA-Optimized PI Controller	FPA Optimized PI Controller
1	Frequency Variation	2.38%	2.04%	1.46%
2	Voltage Variations	7.34%	5.52%	5.41%
4	Asymmetry	Moderate	Moderate	Less
5	THD-Current	11.22	10.91	7.53
6	THD-Voltage	8.73	7.44	6.12
7	Transient Over Voltages	1.42%	1.38%	1.18%

Table.4. Power Quality Comparison by using PI controller and FPA-Optimized PI Controller at 5th Cycle

Sr. No.	Parameter	PI-Controller	GA-Optimized PI Controller	FPA Optimized PI Controller
1	Frequency Variation	1.77%	1.45%	1.41%
2	Voltage Variations	6.82%	6.31%	5.07%
4	Asymmetry	Moderate	Moderate	less
5	THD-Current	9.68	9.11	6.83
6	THD-Voltage	7.81	7.19	5.83
7	Transient Over Voltages	1.39%	1.36%	1.12%

Table.5. Power Quality Comparison by using PI controller and FPA-Optimized PI Controller at 7^{th} Cycle

Sr. No.	Parameter	PID-Controller	GA-Optimized PI Controller	FPA Optimized PI Controller
1	Frequency Variation	1.61%	1.36%	1.36%
2	Voltage Variations	6.67%	5.19%	3.19%
4	Asymmetry	High	Moderate	Moderate
5	THD-Current	9.13	8.49	5.29
6	THD-Voltage	6.53	7.08	3.08
7	Transient Over Voltages	1.24%	1.21%	1.11%

A voltage sag of 25% was introduced in the source voltage from 0.1 sec to 0.15 sec. The voltage sag reduction by UPQC, both with and without optimization, is shown in Figure 6. The corresponding Total Harmonic Distortion (THD) analysis is presented in Figure 7. From this figure, it is evident that the THD decreases from 4.93% to 2.16% when the FPA-optimized PI controller is used for UPQC during the voltage sag. Similarly, a voltage swell of 25% was introduced in the source voltage from 0.2 sec to 0.25 sec. The voltage swell reduction, both with and without optimization, is shown in Figure 8, while Figure 9 presents the corresponding THD analysis. The analysis indicates that the THD is reduced from 5.43% to 2.78% when the FPA-optimized PI controller is used for voltage swell mitigation.

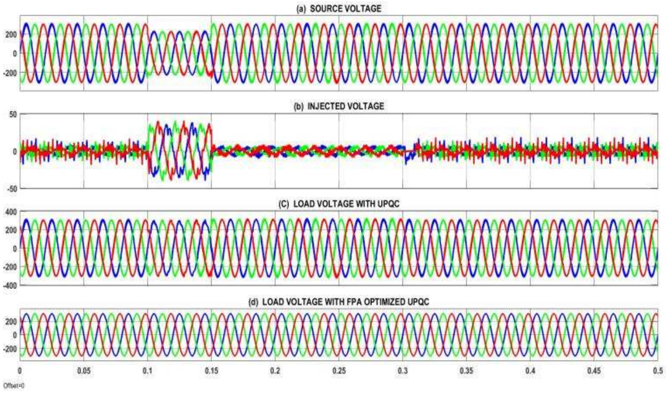

Fig. 6 a. source voltage with 25% sag, b Injected voltage c. voltage Compensation without FPA d. voltage Compensation using FPA

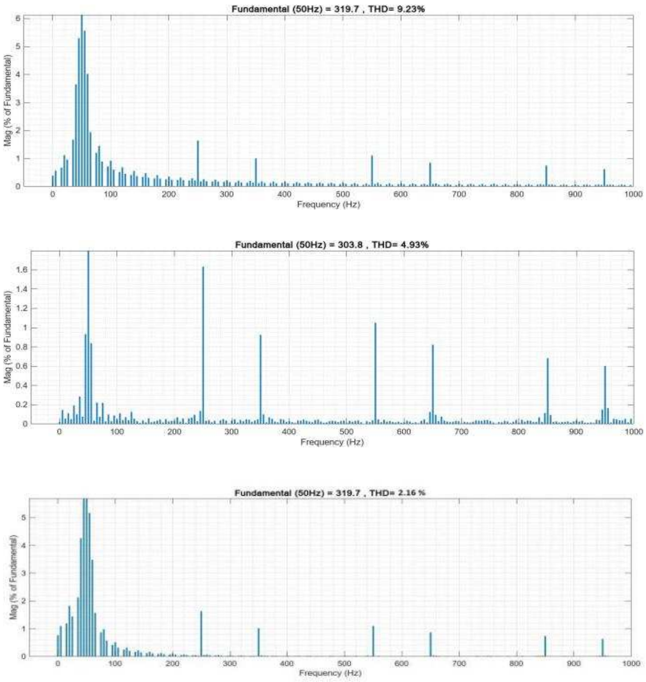

Fig. 7 FFT analysis (During voltage sag): a THD of the source voltage prior to compensation, b. voltage THD without FPA, c. voltage THD using FPA.

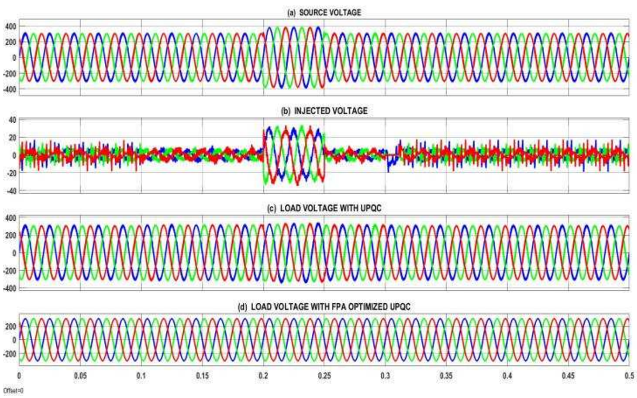

Fig. 8 a. source voltage with 25% swell, b. Injected voltage , c. voltage Compensation without FPA d. voltage Compensation using FPA

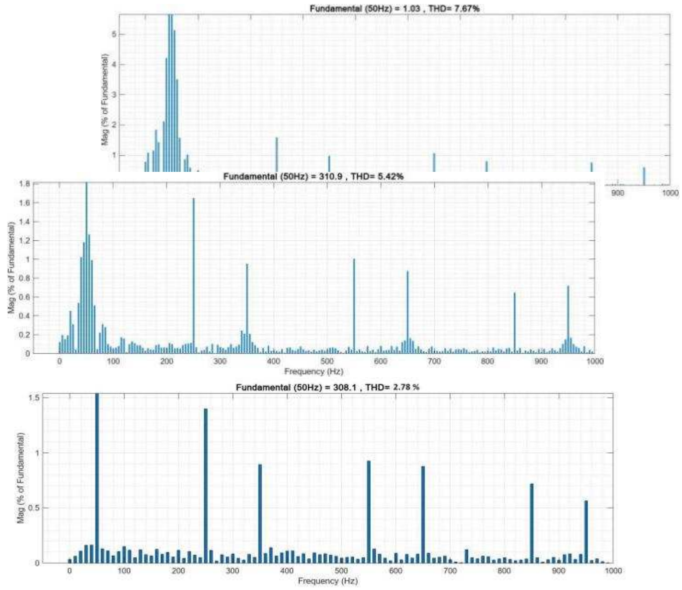

Fig. 9 FFT analysis (During voltage swell): a. THD of the source voltage prior to compensation, b. voltage THD without FPA, c. voltage THD using FPA.

VII. CONCLUSION

The primary focus of this study was to develop a power quality enhancement model using UPQC. The performance of the UPQC was improved by using the Flower Pollination Algorithm (FPA) to optimize the PI control parameters of the shunt active filter in the UPQC, thereby stabilizing the DC link voltage. The proposed model compensates for reactive power along with current and voltage harmonics when connected to nonlinear loads or under unbalanced load conditions. Additionally, this new power quality model can mitigate voltage fluctuations, short-term interruptions, transient overvoltages, etc. A comprehensive performance evaluation was conducted, analyzing parameters such as load voltage, harmonic orders, and THD values. The results of a comparative analysis between the FPA-optimized PI controller, the Genetic Algorithm (GA)-optimized PI controller, and the conventional PI controller for the shunt active filter in the UPQC reveal that the FPA-optimized PI controller outperforms the others in mitigating power quality issues in smart grids.

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