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Firefly Algorithm-Based Optimal Deployment of Unified Power Quality Conditioner for Loss Minimization and Voltage Stability Enhancement in Distribution Networks

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ABSTRACT

The increasing penetration of nonlinear loads and distributed generation (DG) in distribution networks poses significant challenges to voltage regulation and power loss minimization. Although Unified Power Quality Conditioner (UPQC), has proven effective in enhancing power quality and system stability, determining its optimal location and size remains a complex optimization problem. This study examines the optimal siting and sizing of UPQC in radial distribution systems with the objectives of minimizing real and reactive power losses while improving voltage profiles. A multi-objective optimization model is formulated and solved using the Firefly Algorithm (FA), with validation carried out on the IEEE 33-bus test system and the 71-bus University of Maiduguri feeder of Yola Electricity Distribution Company. For the IEEE 33-bus system, optimal UPQC placement at bus 5, achieved loss reductions from 201.775 kW and 134.991 kVAr to 56.478 kW (72.01%) real and 45.127 kVAr (66.57%) reactive and eliminated voltage violations. For the 71-bus feeder, UPQC placement at bus 39, reduced real and reactive losses from 306.586 kW and 289.050 kVAr to 144.902 kW (52.74%) real and 193.035 kVAr (33.34%) reactive and significantly mitigated voltage violations. Comparative analysis with the Artificial Bee Colony (ABC) algorithm shows that FA achieved faster convergence and offered slightly better loss reduction compared to ABC. It also delivered slightly lower UPQC ratings of 2705 kW and 1580 kW compared to ABC with 2720 kW and 1584 kW for the IEEE 33-bus test system and 71-bus University feeder, resulting in improved capacity economic efficiency. These findings demonstrate the effectiveness of the proposed FA method in accurately determining the optimal location and size of UPQC and highlight its strong potential for practical power quality enhancement in radial distribution systems.

1. INTRODUCTION

Electric power distribution networks are increasingly challenged by voltage instability, power losses, and poor power quality due to the integration of non-linear loads and renewable energy sources. In practical power systems, power quality poses a major challenge to overall stability, as electrical devices primarily interact through terminal voltages. Traditional methods such as capacitor banks and load shedding offer limited control, especially under dynamic conditions [1]. Unified Power Quality Conditioner (UPQC) is a sophisticated device that comprises both series and shunt compensators designed to address multiple power quality issues faced by utility companies [2]. Nevertheless, the determination of the optimal placement and sizing of UPQC remains a complex optimization problem, primarily due to the nonlinearity and structural complexity of power distribution systems. Numerous optimization and computational intelligence methods have been explored to enhance UPQC performance.

Early methods such as [3] applied the data sharing algorithm for UPQC allocation using standard IEEE 33 and 69 bus test systems, to improve voltage profiles and reduce power loss in distribution networks. However, the study assumes a constant capacity for the UPQC parallel section, which contradicts the goal of optimal capacity determination. A gravitational search algorithm–based approach was proposed for the optimal deployment of UPQC, in which an ANN controller was used to regulate the DC-link voltage, thereby mitigating voltage sag and reducing harmonic distortion [4]. Comparative analysis revealed that the proposed controller outperformed both the base and ANN-based controllers in UPQC performance, albeit with a higher computational time. Hybrid metaheuristics gained prominence with combined Grey Wolf Optimization (GWO) and Cuckoo Search algorithm (CSA) for UPQC allocation, outperforming conventional algorithms in terms of system losses and enhance voltage stability. However, the hybrid approach combining GWO and CSA involved high computational complexity, making it less feasible for large-scale networks [5].

The Bacteria Foraging Algorithm was employed to determine the optimal location and capacity of UPQC in distribution networks, with results showing improved voltage profiles and reduced active power losses; however, the study did not include comparative evaluation with other optimization techniques [6]. A planning framework was developed for the deployment of Open UPQC in distribution networks, incorporating load growth considerations to minimize total cost while maximizing system benefits over the planning horizon; the approach was validated on the IEEE 69-bus and Iranian 95-bus test systems [7]. However, the reliance on a single practical test system limits generalizability, indicating the need for validation across more diverse real-world networks. GA was used for optimal UPQC allocation combined with network reconfiguration, resulting in reduced power losses; however, the approach suffered from high computational complexity and slow convergence [8]. Recent advancements have broadened UPQC applications with [9] proposed Improved UPQC allocation in a radial distribution network to enhance power quality. By using hybrid approach combined GA–Improve PSO, the study identifies optimal locations for I-UPQC to mitigate power quality issues such as voltage sags and power losses. The results show significant improvements in voltage stability and reduction in power dissipation, demonstrating the effectiveness of I-UPQC in maintaining regulatory standards for voltage and power loss. However, the approach introduced complexities and higher computational demand, this complexity stemmed primarily from the hybridization approach. A comprehensive review was presented covering the design, configurations, control strategies, and applications of UPQC for power quality enhancement in distribution systems [10]. The study highlighted various optimization techniques for the optimal placement of UPQC, ensuring maximum efficiency and cost-effectiveness. The review identified current challenges and potential future research directions. A multi-convertible universal UPQC allocation scheme employing a Generalized Vector Reference (GVR) control algorithm was proposed for multi-feeder distribution systems, leading to improved harmonic mitigation and enhanced overall system efficiency [11]. This advancement is crucial for modern automated industries and power distribution networks. However, executing the proposed GVR control algorithm is time-consuming and computationally complex.

Furthermore, to realize the operation of UPQC with VA capacity constraint, [12] proposed a hierarchical optimization method considering VA capacity, achieving improved outcome but neglecting losses and oversimplifying real conditions. [13] focused on voltage stability in railway electrification systems via UPQC implementation. The authors in [14] primarily reviewed the effect of UPQC models and structural configurations on their performance as well as that of the overall distribution system. Owing to the growing prevalence of nonlinear loads and associated power quality problems, UPQC has emerged as a promising solution for coordinated voltage support, real and reactive power compensation, and harmonic suppression. Hence, its optimal placement and sizing of UPQC form the central focus of this study.

Existing studies on UPQC allocation often assumed either fixed UPQC ratings, focused on a single test network or relied on computationally demanding hybrid optimization methods. These limitations highlight the need for a simple, scalable, and efficient optimization approach. To address this gap, the present study employs the Firefly Algorithm (FA) to simultaneously determine the optimal location and size of UPQC, exploiting its fast convergence and strong global search capability to achieve improved power loss reduction and voltage profile enhancement in practical radial distribution systems.

The key contributions of this research work are;

- To propose a power quality improvement by means of placing the UPQC device optimally with the aid of the FA model.
- To achieve the objective of optimal placement, the multi-objectives like "real power loss minimization, reactive power loss minimization and voltage profile improvement need to be satisfied.

The rest of the paper is organized as follows: Section 2 provides description and modelling of UPQC device. In Section 3, problem formulation and method is presented. while Section 4 delves and details into the results and discussion. Finally, the conclusion is entailed in Section 5.

2. MODELLING OF UPQC

The UPQC is designed to regulate both real and reactive power, thereby enhancing voltage stability and mitigating power quality problems in distribution systems [14]. The series and shunt inverters of the UPQC coordinate to control power flow at the point of common coupling. Fig. 1 presents the typical schematic diagram of the UPQC structure.

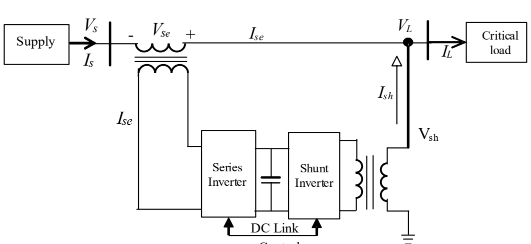

Fig. 1. Schematic of UPQC [15]

To address voltage-related power quality disturbances, the series converter injects a compensating voltage equal to the deviation between the reference and actual voltages. The injected voltage, which may be positive or negative depending on whether real power is supplied or absorbed, is defined with the reference phasor taken as the load voltage (V_L) for a load operating at a lagging power factor as expressed in [16];

$$v_L = V_L \angle 0^0 \quad (1)$$

$$i_L = I_L \angle -\theta \quad (2)$$

$$v_s = V_L(1+sf)\angle 0^0 \quad (3)$$

Instantaneous quantities are denoted by lowercase letters, while uppercase letters represent their peak values. The term v_L, i_L *and* v_s denote the instantaneous load voltage, load current and source voltage respectively. While V_L, I_L *and* V_s are the desired load voltage magnitude, load current magnitude and source voltage magnitude respectively. The term θ = Load power factor angle and sf in Eq. (3) denotes voltage disturbance factor (per unit), representing the magnitude of voltage sag / swell which defined in Eq. (4) as;

$$sf = \frac{V_s - V_L}{V_L} \quad (4)$$

where V_s is the source voltage magnitude (peak), and V_L is the desired load voltage magnitude. The series inverter-injected voltage (v_{se}) is expressed in Eq. (5).

$$v_{se} = V_L - V_s = -sf.V_L\angle 0^\circ \quad (5)$$

Assuming the UPQC operates as an ideal lossless device, the load active power demand (P_L) is equal to the active power drawn from the source PCC (P_s), as expressed in [16] using Eq. (6).

$$P_s = P_L \quad (6)$$

$$V_s I_s = V_L I_L \cos\theta_L \quad (7)$$

$$V_L(1+sf)I_s = V_L I_L \cos\theta_L \quad (8)$$

The expression for sf in terms of currents is

$$sf = \frac{I_L \cos\theta_L}{I_s} - 1 \quad (9)$$

From Eq. (9), it is evident that the factor sf directly affects the source current (I_s). The series active power filter, the active power (P_{se}) supplied or absorbed by the series converter is expressed in [16] using Eq. (10)

$$P_{se} = v_{se} I_s \cos\theta_s \quad (10)$$

$$P_{se} = -sfV_L I_s \cos\theta_s \tag{11}$$

where θ_s is the Phase angle between the injected series voltage (v_{se}) and source current (I_s). Similarly, the reactive (Q_{se}) power exchange by the series APF is defined in Eq. (12);

$$Q_{se} = v_{se} I_s \sin\theta_s \tag{12}$$

For $\theta_s = 0$, and UPQC power factor is maintained as unity, then, the active and reactive power (P_{se} and Q_{se}) of the series inverter can be expressed in Eqs. (13) and (14);

$$P_{se} = v_{se} I_s = -sfV_L I_s \tag{13}$$

$$Q_{se} = 0 \tag{14}$$

Thus, the series inverter of the UPQC regulates active power, whereas the shunt inverter generates the current (i_{sh}). i_{sh} represents the compensation current provided by the shunt APF to meet the difference between the source and load currents with harmonic or reactive load connected [16]. Thus, i_{sh} is defined as;

$$i_{sh} = I_L - I_s \tag{15}$$

$$i_{sh} = I_L \angle -\theta_L - I_s \angle 0^0 \tag{16}$$

Express the load current in rectangular form

$$i_{sh} = I_L\,(\cos\theta_L - \mathrm{j}\sin\theta_L) - I_s \tag{17}$$

$$i_{sh} = (I_L \cos\theta_L - I_s) - jI_L sin\theta_L \tag{18}$$

The Shunt inverter complex power

$$S_{sh} = \mathbf{V}_L \cdot i_{sh}^* = V_L[(I_L \cos\theta_L - I_s) + jI_L \sin\theta_L] \tag{19}$$

Thus, the corresponding real power injected by the shunt inverter (P_{sh}) and reactive power injected (Q_{sh}) due to shunt APF are given in Eqs. (20) and (21), respectively.

$$P_{sh} = V_L(I_L \cos\theta_L - I_s) \tag{20}$$

$$Q_{sh} = V_L I_L \sin\theta_L \tag{21}$$

In practice, the shunt inverter primarily regulates reactive power (Q) and maintains the DC-link voltage, while the series inverter compensates voltage disturbances and manages active power (P) flow. The coordinated operation ensures effective control of both real and reactive power, leading to enhanced power quality and reliable system performance.

3. PROBLEM FORMULATION

Distribution networks are typically weakly meshed, characterized by long feeders, many branches, and relatively high R/X ratios. Under such condition, conventional load flow techniques such as Newton–Raphson or Gauss–Seidel, fast Decoupled methods, (suited for transmission systems) often exhibit slow convergence or become unstable in such cases [17]. To address this, the Bus-Injection-to-Branch-Current (BIBC) Matrix and forward sweep technique has been introduced for distribution load flow analysis as it directly leverages the radial structure of these networks. The BIBC matrix expresses the relationship between load bus injection currents and line (branch) currents, while the forward sweep step computes the voltages by propagating voltage drops along the distribution feeder, starting from the known slack bus voltage, towards the terminal buses using the calculated branch currents. Further details of the approach can be found in [18].

3.1 Objective function

A multi-objective optimization model is formulated to minimize real and reactive power losses as well as voltage deviations in the distribution network. In this study, two objective functions have been optimized with integration of UPQC, which can be represented as follows;

3.2 Power loss minimization

The total power loss (P_{Tloss}) reduced by UPQC deployment is given in Eq. (22) as;

$$P_{Tloss} = \frac{P_{T,loss(ik)\,after\_UPQC}}{P_{T,loss(ik)\,before\_UPQC}} \tag{22}$$

Where the $P_{T,loss(ik)\,after\_UPQC}$ is total power loss reduced after UPQC placement and $P_{T,loss(ik)\,before\_UPQC}$ is the total power loss of the radial distribution system before placement.

3.3 Voltage improvement

The following objective function is to minimize bus voltage deviation in the network given by Eq. (23);

$$V_D = \sum_{i=1}^{N_{Bus}} \left(V_i - V_i^{ref}\right)^2 \quad (23)$$

Where V_i is the per unit (p.u) voltage values at bus *i* and V_i^{ref} is the reference bus voltage, respectively. Based on the rated system voltage, the deviation of each bus voltage is computed, and the squared deviations corresponding to both voltage rise and voltage drop conditions are evaluated. The optimization algorithm aims to minimize this objective function value, thereby maintaining voltage profiles within acceptable limits. The multi-objective function is formulated as a minimization problem, mathematically represented in Eq. (24),

$$F_{obj} = Min(w_1 P_{Tloss} + w_2 V_D) \quad (24)$$

Here, w_1 and w_2 are weight metrics assigned to adjust the function of net power loss and voltage deviation, where 1 was assigned for both weights. The optimization model is subject to the following constraints power flow constraints and bus voltage limits, and constraints as expressed in Eqs. (25) and (26).

The real and reactive Power balance equation constraints;

$$\begin{Bmatrix} \sum_{i=1}^{NBus} P_{Gi} + P_{UPQC} - P_{Di} - P_{Loss} = 0 \\ \sum_{i=1}^{NBus} Q_{Gi} + Q_{UPQC} - Q_{Di} - Q_{Loss} = 0 \end{Bmatrix} \quad (25)$$

The bus voltage constraint;

$$(0.95\text{pu}) \quad V_i^{\min} \leq V_i \leq V_i^{max} \quad (1.02\text{pu}) \quad (26)$$

At bus k, P_{Gi} & Q_{Gi} denote the utility active and reactive power supplied in to the system P_{UPQC} & P_{UPQC} are real and reactive power delivered by the UPQC, P_{Di} and Q_{Di} the system power demand, P_L & Q_L are the system losses, and $NBus$ refers to the total number of buses in the network. The min and max represent the minimum and maximum values of the parameters.

3.4 Firefly algorithm

The Firefly Algorithm (FA), proposed by [19] is a nature - inspired algorithm which is based on the social flashing behavior of fireflies. The two key aspects of FA are the variation of light intensity and the formulation of attractiveness; both directly related to the objective function value. In the simplest case for maximum optimization problems, the brightness I of a firefly at a given position x is directly proportional to the objective function value, expressed in Eq. (27);

$$I(x) \ \alpha \ f(x) \quad (27)$$

Where; $I(x)$ denotes the light intensity (or brightness) at position *x*, and $f(x)$ represent the objective (fitness) function. The brightness diminishes with increasing distance. Considering a constant light absorption coefficient γ, the light intensity *I*, as a function of distance *r* given in [20] as expressed in Eq. (28) is

$$I_i = I_o e^{(-\gamma r^2)} \quad (28)$$

Where; I_o denotes the initial brightness at the light source, γ represent the light absorption coefficient and *r* is the distance between two fireflies. Assuming that a firefly's attractiveness is proportional to the light intensity perceived by neighboring fireflies, the attractiveness function *β(r)* which decreases with distance r given in [20] as formulated in Eq. (29),

$$\beta(r) = \beta_o e^{(-\gamma r^2)} \quad (29)$$

Where; β_o denotes the attractiveness at distance (*r* = 0). Also, the distance between firefly *i* at position x_i and firefly *j* at positions x_j can be determined using Eq. (30),

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} (x_{i,k} - x_{j,k})^2} \quad (30)$$

Where *d* denotes the dimension of the optimization problem. The movement of a less bright firefly *i* which is attracted towards a brighter firefly *j* is described in [20] by using Eq. (31),

$$x_i^{t+1} = x_i^t + \beta_o exp^{(-\gamma rij^2)} . \left(x_j^t - x_i^t\right) + \alpha \xi_i^t \quad (31)$$

Where x_i^t is the position of firefly *i* at iteration t_i, $\beta_o exp^{(-\gamma rij^2)} . \left(x_j^t - x_i^t\right)$ is the attraction term and

$\alpha\xi_i^t$ is the randomization term (ξ is a vector of random numbers with Gaussian distributions). The α is the randomness parameter. Proper parameter tuning improves both the flexibility and reliability of the algorithm The parameters employed for the proposed FA method in this paper are adopted from [21] and given in Table 1.

Table 1. Optimal FA Based UPQC Parameters Settings

S/No.	Parameters	Selected Values
1	No of Firefly	30
2	Maximum Iteration	100
3	Scaling factor (α)	0.25
4	Attractiveness Coefficient (β_{min})	0.2
5	Absorption Coefficient (Υ)	1

The maximum iteration number was set to 100 based on the convergence performance considerations analysis and recommendations from related studies [22]. Also, preliminary simulations carried out, where additional iterations beyond 100 produced insignificant improvement in the objective function while increasing computational cost. Therefore, setting the maximum number of iterations to 100 provides a good balance between solution quality and computational efficiency. The flowchart of the firefly algorithm is shown in Fig. 2.

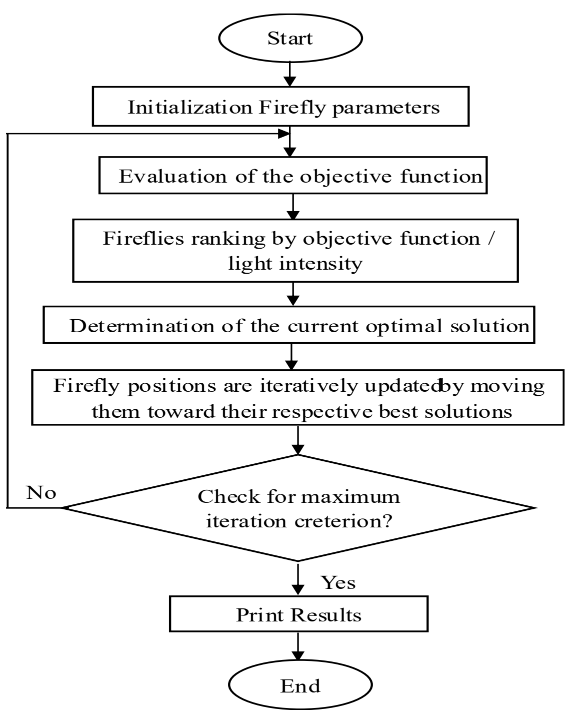

Fig. 2. Flowchart of firefly algorithm [23]

3.5 Implementation of UPQC placement using firefly algorithm

This section present steps involved in implementing the proposed UPQC optimal placement and sizing as follow;

Step 1: Define the parameters of the firefly including the number of fireflies = 30, the maximum number of generations = 100, the scaling parameter α = 0.25, absorption coefficient γ = 1, minimum value of attractiveness β = 0.2.

Step 2: Read the network bus and line data

Step 3: The base case power flow was carried out to obtain the initial voltage profile and power losses at each bus.

Step 4: The FA parameters were Initialized and generate random solution (firefly) was generated, each firefly is a potential solution that consists of (UPQC location and size).

Step 5: The objective function for each firefly was formulated using Equation (24).

Step 6: All fireflies were ranked by their light intensity and the current best solution was determined.

Step 7: All firefly were updated with the firefly current best solution i.e current best location and size of UPQC compensator

Step 8: After updating the light intensity, the new solutions were evaluated to determine the optimal UPQC location and size.

Step 9: Steps (5) through (8) was repeated until the maximum number of iterations is reached.

Step 10: The final power flow analysis was conducted using the optimal UPQC location and capacity to determine the resulting active and reactive power losses and the system's voltage profile. The flow char for the implementation of the proposed UPQC optimal placement and sizing given in Fig 3.

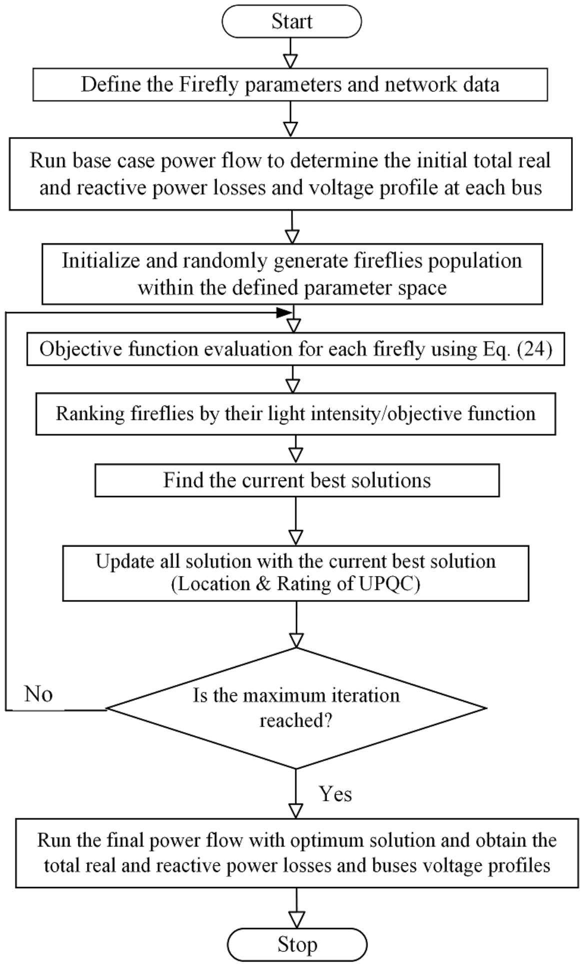

Fig. 3. Flowchart of the proposed optimal allocation of UPQC

3.5.1 IEEE 33-bus standard test network

This is a medium-sized radial distribution network consisting of thirty-three (33) buses and thirty-two (32) line sections, as the first bus serves exclusively as the slack bus. The system's total load amounts to 3.72 MW and 2.3 MVAR. The substation voltage was 12.66 kV and the base power of 100 MVA respectively. The single-line diagram and network data of the standard IEEE 33-bus network system are presented in [24].

3.5.2 Description of 71-bus University feeder network

The University of Maiduguri feeder comprises 71 buses and 70 branches, with base power and voltage values of 100 MVA and 11 kV, respectively. The network's total real and reactive power demands are 4400.1 kW and 1961.4 kVAr. The single line diagram of the 71-bus University feeder is shown in Fig. 4 while network data of the 71-bus University network feeder is provided in [25].

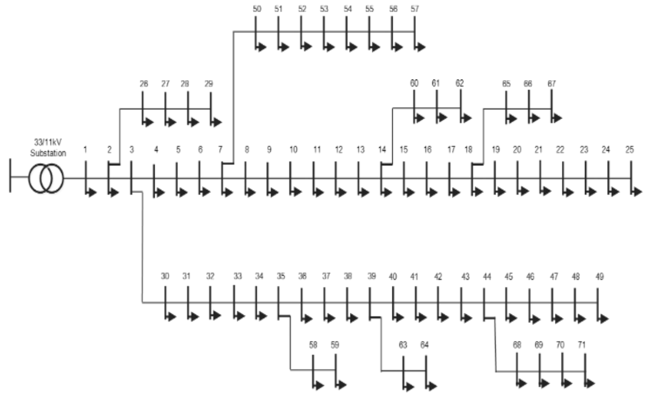

Fig. 4. Single line diagram of 71-bus University feeder Maiduguri [25]

4 RESULTS AND DISCUSSIONS

The study was carried out on the standard IEEE 33-bus test system and practical 71-bus University radial distribution systems feeder, Maiduguri. In both networks, two distinct cases were analyzed.

Case I: Network without UPQC (Base-case).

Case II: Network with UPQC optimally installed.

4.1 Simulation results of the IEEE 33-bus test system before and after UPQC Allocation

The base case power flow of the network (case I) was carried out using the Bus Injection to Branch Current matrix (BIBC) equations combined with a forward sweep approach. The total base case active and reactive power losses of the test system was 201.7749kW and 134.9912kVAr. Following the base case power flow analysis, the FA method was applied to identify the optimal location and sizing of the UPQC for integration into the IEEE 33-bus test system (Case II) to determine the overall power loss reduction and voltage profile improvement in the test system. The optimal UPQC capacity was determined to be 2705 kW, 1799 kVAr, with the optimal location at bus 5. After performing the final power flow analysis with the UPQC in optimal position, total active and reactive power losses were reduced to 56.4782 kW and 45.127 kVAr, respectively. Table 2 summarizes the results for Cases I and II on the standard IEEE 33-bus test system.

Table 2. The Standard IEEE 33-Bus Test System

Performance Index	**Case I**	**Case II (FA based UPQC)**	**Case II (ABC based UPQC)**
Optimal UPQC location	-	Bus 5	Bus 25
Optimal UPQC size (kW, kVAr)	(0, 0)	(2705,1799)	(2720,1800)
Active power loss (kW)	201.775	56.4782	56.4788
% active loss reduction	-	72.01%	72.01%
Reactive power loss (kVAr)	134.991	45.127	45.127
% Q_{loss} reduction	-	66.57%	66.57%
No. of violated buses	21	0	0

The results in Table 2 indicate that the proposed method optimally place UPQC at bus 5 and significantly reduced the overall power losses in the IEEE 33-bus test system. The overall real and reactive power losses after UPQC placement reduces from 201.775 kW and 134.991 kVAr to 56.4782 kW and 45.127 kVAr which correspond to a percentage power loss reduction of 72.01% and 66.57% respectively. Comparative analysis with the ABC method shows FA minimizes the real power loss reduction optimum value of 56.3782 kW and required smaller UPQC ratings of 2705 kW, 1799 kVAr as compared to ABC minimal value of 56.4788 kW with a ratings of 2720 kW, 1800 kVAr. This result demonstrated that FA offered improved solution quality and enhanced the UPQC economic size efficiency as compared to ABC method. Fig. 5 and 6 illustrate the voltage profile of the standard IEEE 33-bus test system before and after the optimal allocation of the UPQC, respectively.

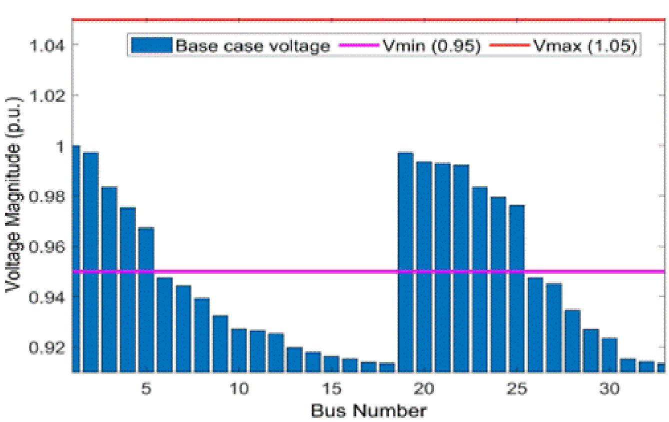

Fig. 5. Base case voltage profile of the standard IEEE 33-bus test system (without UPQC)

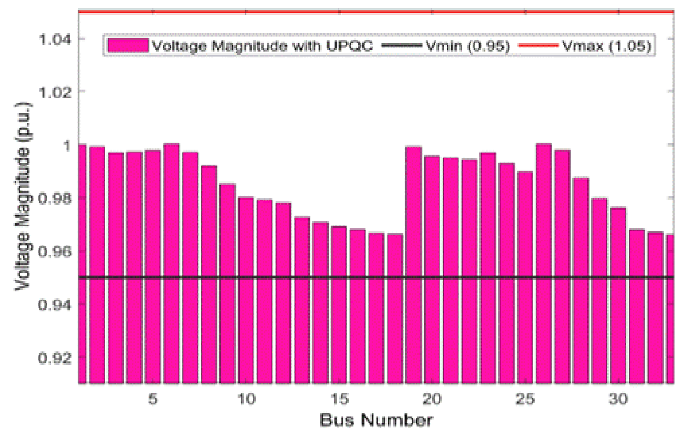

Fig. 6. Voltage profile improvements with UPQC for the IEEE 33-bus test system

The voltage magnitudes listed in Fig 5 and 6 were plotted against their respective bus numbers. From the base case analysis depicted in Fig. 5, the minimum voltage was observed to drop to 0.910 p.u. at buses 18 and 33. However, after applying the proposed FA UPQC placement, the minimum voltage improved significantly to 0.976 p.u., on the buses as illustrated in Fig. 6. Furthermore, an improved voltage profile was virtually observed across all the buses in the network after incorporating UPQC with FA, reflecting a more stable and improved system network. Fig. 7 presents a comparison of the bus voltage profile performance on the standard IEEE 33-bus test system before and after UPQC allocation, as optimized using the proposed FA method.

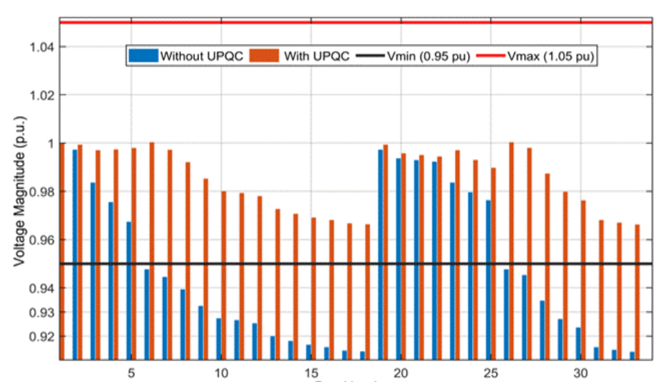

Fig. 7. Performance comparison of voltage profile improvement on the standard IEEE 33-bus test system with and without UPQC allocation

The Fig. 7 shows that Case II exhibits an improved voltage profile compared to the base case. The base case minimum bus voltage of 0.910pu at bus 33 has improved to 0.966pu after optimal UPQC allocation. Accordingly, the optimal UPQC placement offered better voltage improvement of the entire network compared to base case (case I). Also, the number of bus voltage limit violations has reduced considerably from twenty-one (21) buses in case I to zero bus violation in case II. Thus, the optimal UPQC allocation using the proposed FA method has led to an improved voltage profile within the acceptable bus voltage range of (0.95 Vmin - 1.05 Vmax) p.u and significantly lowers voltage variations and improves the system voltage stability of the distribution network. The FA optimally located UPQC in bus 5 after few number of iterations, while the ABC optimally placed UPQC in bus 25 as summarized in Table 2. To show the efficiency of the FA and ABC algorithms, the results of Fig. 8 compared the convergence characteristics graph of the objective function obtained by the proposed FA and ABC methods in solving optimal UPQC allocation problem.

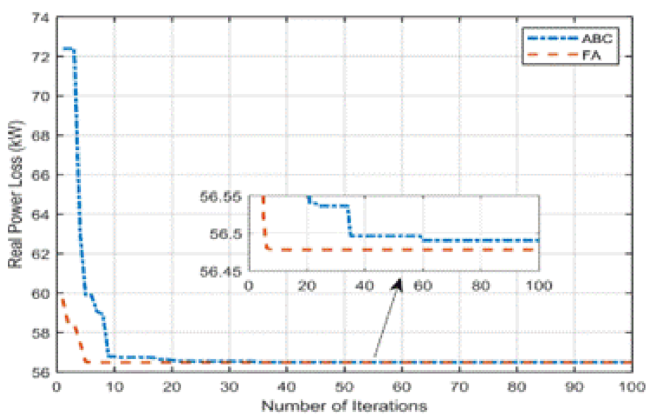

Fig. 8. Convergence characteristics of FA compared with ABC method for the IEEE 33-bus system

The proposed FA exhibited better solution quality by minimizes the function to the most optimum value and demonstrated fast convergence around 5th iteration compared to ABC method which converge at 60th iteration as indicated in Fig 8. The reason for the fast convergence is as a result of the FA's initial searching point starting near the optimum solution.

4.2 71-busUniversity feeder network before and after UPQC Allocation

The base case power flow of the network (Case I) was conducted with total active and reactive power losses for the base case obtained at 306.586 kW and 289.5929 kVAr.

Following the base case power flow analysis, the proposed Firefly Algorithm (FA) was employed to identify the optimal location and sizing of the UPQC for incorporation into the 71-bus feeder network. The optimal size of UPQC was found to be 1584 kW 641 kVAr, while bus 39 was selected as optimal location using the FA method. The results obtained showed a reduction of the total active and reactive power losses to 144.9025 kW and 193.0322 kVAr. Table 3 provides a summary of the simulation results for Cases I and II on the 71-bus University radial distribution feeder.

Table 3. the 71-bus University Radial Distribution System Network

Performance Index	Case I	Case II (FA based UPQC)	Case II (ABC based UPQC)
Optimal UPQC location	-	Bus 39	Bus 39
Optimal UPQC size (kW, kVAr)	(0, 0)	(1580, 641)	(1584, 641)
Active power loss (kW)	306.586	144.902	144.903
% active loss reduction	-	52.74%	52.74%
Reactive power loss (kVAr)	289.050	193.035	193.035
% Q_{loss} reduction	-	33.34%	33.34%
No. of violated buses	57	27	27

The results in Table 3 indicate that the optimal UPQC placement significantly reduced power losses in the 71-bus University feeder. Following the optimal allocation of UPQC at bus 39, the total real and reactive power losses decreased from 306.586kW, 289.050 kVAr in case I to 144.903 kW and 193.0322 kVAr in case II, representing reductions of 52.74% and 33.34%, respectively.

Comparative analysis with the ABC method shows that FA achieved marginal solution quality of 144.902 kW and required smaller UPQC ratings of 1580 kW compared to ABC solution quality of 144.903 kW with a rating of 1584 kW. The result demonstrated that the proposed FA offered better solution quality by minimizing the function to the most optimum value and enhanced the UPQC size economic viability compared to ABC method. Fig. 9 and 10 depict the voltage profile of the 71-bus University network before (Case I) and after (Case II) UPQC allocation, respectively.

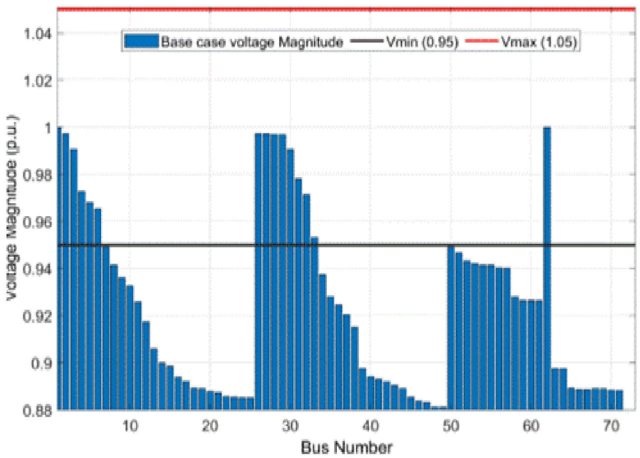

Fig. 9. Base Case voltage profile case I on the 71-bus University network feeder (without UPQC)

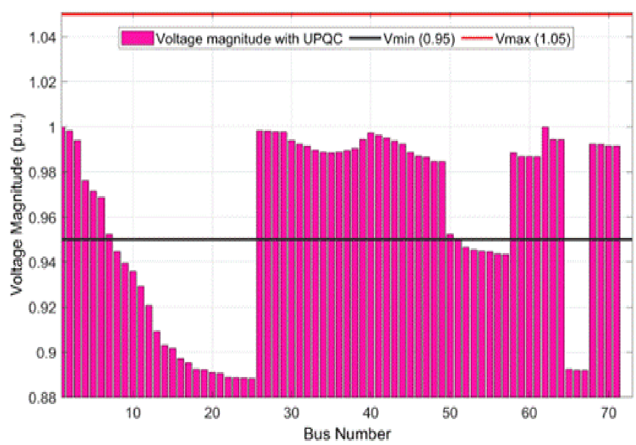

Fig. 10. Voltage profile improvement of Case II on the 71-bus University network feeder (With UPQC)

The initial base case analysis (case I) shown in Fig. 9, revealed significant voltage limit violations, affecting 56 buses. However, after optimal integration of UPQC using the proposed FA, the minimum bus voltage profile improved considerably across most of the buses in the network, as illustrated in Fig 10. This reflects enhancement in overall system performance and stability. Comparison of the outcome of the 71-bus University feeder voltage profile performance before and after UPQC allocation for each of the 71 buses using the proposed FA method is presented in Fig. 11

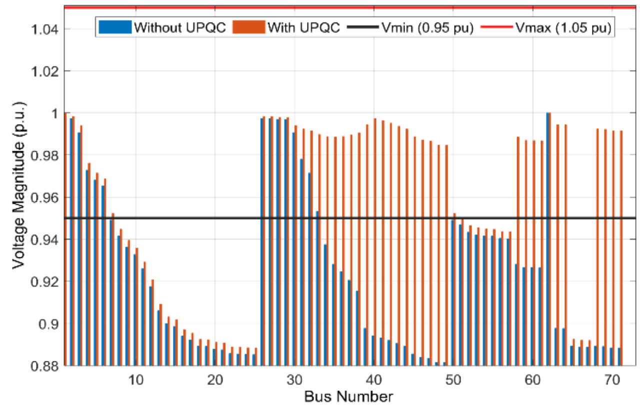

Fig. 11. Performance comparison of voltage profile improvement, based case versus FA based UPQC allocation on the 71-bus University network feeder

Fig. 11 illustrates the bus voltage profile of the University feeder. It is observed that Case II exhibits an improved voltage profile compared to the base case, with the minimum bus voltage rising from 0.88146 p.u. at bus 49 to 0.969 p.u. following the optimal UPQC placement. Accordingly, the optimal UPQC placement offered better voltage improvement of the entire network compared to the base case. Also, the number of bus voltage limit violations has significantly reduced to twenty-seven (27) buses in case II compared to fifty-six (56) buses in case I. Hence, the optimal UPQC allocation using the proposed FA method have led to an improved voltage profile significantly and improves the system voltage stability of the 71-bus University network feeder.

The results of Fig 12 displayed the comparison of the convergence graph obtained by the FA and ABC methods in solving optimal UPQC allocation problem.

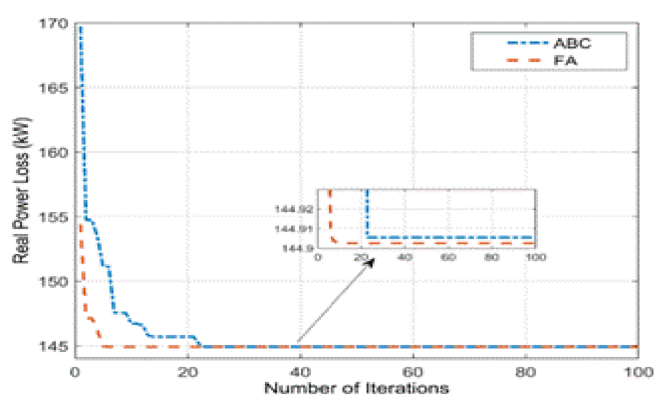

Fig. 12: Comparison of the convergence behavior of the proposed FA and ABC for the 71-bus University feeder

The proposed FA and ABC algorithms were each executed independently for 100 iterations to assess their effectiveness in reducing power losses within the system. The FA demonstrated significantly faster convergence, reaching the optimal solution within 6th iterations as compared to the ABC algorithm, which converged at 29th iteration. It also minimizes the function to the most optimum value compared to ABC method as indicated in Fig 12. The results indicate the effectiveness of proposed FA method in the optimal deployment of the UPQC, leading to reduced total system power losses and improved voltage regulation in the distribution networks.

5 CONCLUSION

In this study, the FA was proposed for the optimal deployment of UPQC in radial distribution systems with the aim of minimizing power losses and improving voltage profiles. The effectiveness of the proposed approach was validated on the IEEE 33-bus test system and 71-bus University radial distribution network system, where significant improvements were achieved compared to the base case conditions. Optimal UPQC deployment resulted in substantial reductions in real and reactive power losses, enhanced voltage regulation, and improved overall system performance. Furthermore, comparative evaluation with the ABC demonstrated that FA provides faster convergence, minimizes the function to the most optimum value and reduced UPQC capacity requirements, thereby improving the economic viability of the UPQC compensation. These findings confirm the suitability of FA as an efficient optimization tool for UPQC allocation. Future extension of this work will be the application of real-time implementation using advanced intelligent control techniques in practical distribution systems.

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