Covenant Journal of Engineering Technology (CJET) Vol.4 No.1, June 2020
ISSN: p. 2682-5317 e. 2682-5325 DOI: xxxxxxxxxxxxxxxxxxx

An Open Access Journal Available Online

Implementation of Bacterial Foraging Algorithm Based Model for UPQC Placement in a Practical Distribution Feeder

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Received: 01.11.2019 Accepted: 16.03.2020
Date of Publication: June, 2020

Abstract: This paper proposes the implementation of a Bacterial Foraging Algorithm (BFA) based approach for optimal positioning and sizing of Universal Power Quality Conditioner (UPQC) in a radial distribution network. The objective here is to demonstrate the strength and capability of the approach in the placement of UPQC in not just standard test networks, but also in practical power distribution networks. A simple and direct power flow computation is performed to determine the network base-case scenario. Based on the power flow outcome, the network bus voltage deviation VD is formulated and combined with the total active power loss PLoaa(Total) to form a multi-objective function needed by the BFA in order to improve voltage stability and minimize losses, while at the same time maintaining the network constraints. The BFA approach is implemented on a practical 50-bus Canteen Feeder for steady-state normal loading condition. The performance of the technique on the standard IEEE 33-bus test network as established in an earlier literature is once again reported in this paper, after which the results obtained from the practical distribution feeder analysis is presented. Simulation outcomes from MATLAB R2017a virtual environment showed that the installation of UPQC in the practical distribution feeder using the BFA method has improved the overall feeder voltage profile and reduce the active power loss by 9.78 and 26.21% respectively as compared to the network base-case scenario.

Keywords: Universal Power Quality Conditioner, Bacterial Foraging Algorithm, 50-Bus Canteen Feeder

Nomenclatures: i and k – bus index; Vref – reference voltage; Vmin and Vmax – minimum and maximum voltages respectively; Vi and Vk – voltage magnitudes at bus i and k respectively; Ri and Xi – resistance and reactance of line section between bus i and i+1; Pi and Qi – active and reactive powers at bus i; PD,i and QD,i – active and reactive power demands at bus i; Pslack and Qslack – active and reactive powers injected from slack bus; Qc,i – size of UPQC at bus i; Qc,min and Qc,max – minimum and maximum sizes of UPQC; N – bus number; NB – branch number; NC – number of UPQC. Symbols excluded from the nomenclature are properly defined within the text.

1. Introduction

It is a common knowledge today that power networks across the globe are operated close to their tolerance limit due to the exponential increase in consumer demand [1]. Considered as the final stage of electric power transfer, distribution networks plays a key role in the design and operation of power systems. These networks, are however, characterized by high losses mostly related to the nature of power sinks [2,3]. Several literatures have reported a loss of up to 13% of the total generation at the distribution level of power systems [4,5]. Such magnitude of loss, if not mitigated, is capable of inflicting serious damage to the entire power system.

Presently, Custom devices are widely used to mitigate reactive power problems at the distribution level of power systems [5,6]. The incorporation of single or multiple D-FACTS devices in distribution networks have the tendency to enhance the system voltage profile and minimize its losses. Some of the well-known D-FACTS devices developed and deployed for enhancing power systems performance include Distribution Static Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Distribution Static Synchronous Series Compensator (DSSSC), Universal Power Quality Conditioner (UPQC) e.t.c. [7]. The UPQC is a power electronics based device that comprises of both series and shunt compensator [8,9]. An overview of this device will be presented in the subsequent section. BFA is a nature inspired algorithm that has found wide application in power systems optimization problems. Recently, the approach has been used to optimally install of D-FACT devices in radial distribution systems [10,11]. The use of a linear adaptive BFA which is an improved variant of the proposed algorithm has been reported in [12,13].

Many literatures have reported the use of different approaches, especially nature based algorithms for optimal placement of UPQC in radial distribution networks. Noticeable amongst these approaches are differential evolution algorithm [14], data sharing algorithm [15], hybrid method [16], multi-objective PSO algorithm [17,18], multi-objective ABC algorithm [19], firefly algorithm [20], particle swarm optimization algorithm [21,22,23], bacterial foraging algorithm [2], ant lion optimization algorithm [8], grey wolf optimization algorithm [24] and moth flame optimization algorithm [25].

Although all of the aforementioned approaches have been applied in optimal allocation of UPQC in several distribution networks, their effectiveness in the placement of UPQC in practical distribution networks cannot be guaranteed, as their applications have all been restricted to standard test networks. Hence, implementing the proposed algorithm on a practical network is highly necessary to ascertain the effectiveness of the approach in UPQC placement in real life power distribution networks.

Considering the above mentioned limitations, this paper which is an extension of the original work presented in [2] focuses on implementing a BFA based model in the optimal placement of UPQC in a 50-bus practical feeder with the intent of improving voltage stability and reducing losses, while at the same time satisfying the feeder's constraints.

2. An Overview of the UPQC

UPQC is among the most flexible power active filters. Its combined series and shunt compensators features allowing for simultaneous compensation of both voltage and current in the network [26]. Structurally, the UPQC is a combination of DVR and D-STATCOM linked to a common d.c. energy storage [9]. The shunt compensator (D-STATCOM) is usually connected across the loads to account for all current problems such as the reactive power compensation, enhanced power factor, current harmonic compensation and unbalance load compensation, whereas the series compensator (DVR) is connected in series with a line through a series transformer [2]. It serves as a regulated voltage supply and can compensate for all problems related voltage, such as voltage harmonics, voltage sag, voltage swell, flicker, etc. [27]. Figure 1 shows a typical single line diagram of the UPQC structure.

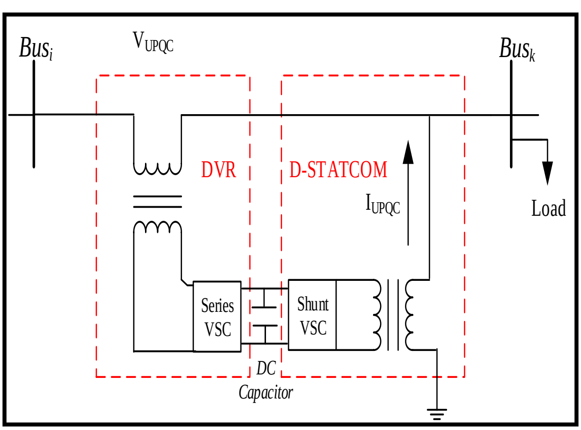

Figure 1: A Typical UPQC Structure [9]

3. Problem formulation

Detailed descriptions of radial power flow equations and the objective function employed for allocation of UPQC in power distribution network are presented as follows:

3.1 Network power flow analysis

An elaborate power flow analysis of radial distribution systems is adopted from [7] based on a simple distribution network illustrated in figure 2.

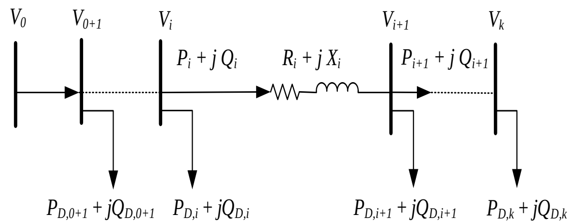

Figure 2: Single Line Diagram of Radial Distribution Network [7]

The network power flow computation is conducted using the equations obtained from Figure 2 given as:

$$P_{i+1} = P_i - P_{D,i+1} - R_i\left(\frac{P_i^2 + jQ_i^2}{|V_i|^2}\right) \tag{1}$$

$$Q_{i+1} = Q_i - Q_{D,i+1} - X_i\left(\frac{P_i^2 + jQ_i^2}{|V_i|^2}\right) \tag{2}$$

$$V_{i+1}^2 = V_i^2 - 2\left(R_iP_i + X_iQ_i\right) + \left(R_i^2 + X_i^2\right)\left(\frac{P_i^2 + jQ_i^2}{|V_i|^2}\right) \tag{3}$$

The power losses (active and reactive) between buses *i* and *i+1* are given expressed as:

$$P_{Loss(i,i+1)} = R_i\left(\frac{P_i^2 + jQ_i^2}{|V_i|^2}\right) \tag{4}$$

$$Q_{Loss(i,i+1)} = X_i\left(\frac{P_i^2 + jQ_i^2}{|V_i|^2}\right) \tag{5}$$

The network power losses represented by equations (6) and (7) are computed by taking the summation of individual active and reactive power losses for n=1,2,3,…, NB using equations (4) and (5).

$$P_{Loss(Total)} = \sum_{n=1}^{NB} P_{Loss,n} \tag{6}$$

$$Q_{Loss(Total)} = \sum_{n=1}^{NB} Q_{Loss,n} \tag{7}$$

The overall system voltage profile can be improved by reducing the network voltage deviation given by:

$$V_D = \sum_{i}^{NB} \left(V_i - V_{ref}\right)^2 \tag{8}$$

3.2 Objective function

The idea of placing custom devices such as UPQC at the distribution levels of power systems is to minimize losses and improve the voltage stability, while maintaining the network constraint at the same time. A multi-objective function (*J*) consisting of total active power loss and voltage deviation is minimized to achieve the specified objective, as demonstrated in equation (9) subject to the equality and inequality constraints defined in equations (10)-(11) and (12)-(13) respectively.

$$Min(J) = Min\left(P_{Loss(Total)} + V_D\right) \tag{9}$$

$$P_{slack} = \sum_{i=1}^{N} P_{D,i} + \sum_{n=1}^{NB} P_{Loss,n} \tag{10}$$

$$Q_{slack} + \sum_{i=1}^{NC} Q_{c,i} = \sum_{i=1}^{N} Q_{D,i} + \sum_{n=1}^{NB} Q_{Loss,n} \tag{11}$$

$$V_{min} \le V_i \le V_{max} \tag{12}$$

$$Q_{c,min} \le Q_{c,i} \le Q_{c,max} \tag{13}$$

4. Algorithm structure

The BFA is an inspired algorithm focused on swarm-based nature that imitates the *Escherichia Coli* bacteria's food searching strategy [28,29,30,31]. The algorithm is developed based on the three main operations of chemotaxis, reproduction and elimination-dispersal explained as below:

4.1 Chemotaxis

This aspect of operation explains the motion of bacteria toward nutrients or away from noxious substances over a search space [32,33]. When situated in highly nutrition environment, a bacterium maintain its movement by swimming in the same direction. However, if its current position is less nutritious, the bacterium changes direction by tumbling in anticipation of finding nutrients [32]. The movement of the i^{th} bacterium over a landscape of nutrients is described by:

$$\theta^i\left(j+1,k,l\right) = \theta^i\left(j,k,l\right) + C\left(i\right)\phi\left(i\right)$$

where $\theta^i(j,k,l)$ is the location of i^{th} bacterium at j^{th} chemotactic, k^{th} reproductive, l^{th} elimination-dispersal step. $C(i)$ is the length of unit walk and $\phi(i)$ is the direction angle of the j^{th} step [2,34]. The cost function of the i^{th} bacterium represented by $J=J(i,j,k,l)$ is obtained based on its position [28]. The direction angle $\phi(i)$ describes the tumble of the bacteria expressed as:

$$\phi(i) = \frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \quad (15)$$

where $\Delta(i) \epsilon \boldsymbol{R}^p$ is a vector containing elements randomly generated within -1 and 1, while $\boldsymbol{R}$ and p represent real numbers and dimensions respectively.

Bacterium communicate with each other through the secretion of attractants or repellants. A bacterium in the nutrient setting release attractants to signal bacteria to swarm together, while repellents are secreted to signal others to maintain a minimum distance in a dangerous environment [2,31,34]. The bacteria's cell-to-cell signaling function is described with:

$$J_{cc} = \left(\theta, P(j,k,l)\right)$$
$$= \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-\omega_{attract}\sum_{m=1}^{p}\left(\theta_m - \theta_m^i\right)^2\right)\right]$$
$$+ \sum_{i=1}^{S}\left[h_{repellant}\exp\left(-\omega_{repellant}\sum_{m=1}^{p}\left(\theta_m - \theta_m^i\right)^2\right)\right] \quad (16)$$

where J_{cc} explains the parameter to be added to the original cost function, S is the number of bacteria, p is the number of variables present in each bacterium to be optimized, $\theta = [\theta_1\ \theta_2\ \ldots\ \theta_p]^T$ denotes a point in the p-dimensional search domain. $d_{attractant}$ and $\omega_{attractant}$ are the depth and measure of the width of the attractant released by the cell respectively, while $h_{repellant}$ and $\omega_{repellant}$ are the height and measure of the width of the repellent respectively [28].

The effect of equation (16) is considered by determining the fitness of each bacterium using:

$$J(i,j,k,l) = J(i,j,k,l) + J_{cc}\left(\theta, P(j,k,l)\right) \quad (17)$$

4.2 Reproduction

The fitness functions are sorted by the reproduction operation explained by equation (17). Half of the bacteria population (S_r) with worst health die off leaving behind those with better fitness. Each of the remaining bacteria split into two in order to maintain the bacteria population. The number of reproduction steps that should be taken by each bacterium is represented by N_{re}.

$$J_{health}^{i} = \sum_{j}^{N_c+1} J(i,j,k,l) \quad (17)$$

4.3 Elimination-dispersal

In order to prevent the risk of storing the bacterium in a local optimum and to maximize the capacity to search for the bacterium, some of the bacteria are removed and others are spread inside the search space as per the probability (P_{ed}). N_{el} represents the number of elimination-dispersal each bacterium is expected to perform [28,29].

A simple pseudo-code of the proposed BFA is ad presented and further explained by figure 3 [1,25]:

[Step 1] Initialize parameters:
$p, S, N_s, N_c, N_{re}, N_{ed}, P_{ed}, C(i), \theta^i (i=1,2,\ldots,S)$

[Step 2] Elimination and the dispersal loop:

for l = l + 1

[Step 3] Reproduction loop:

for k = k + 1

[Step 4] Chemotaxis loop:

for j = j + 1

4.1. ***for*** *each bacterium i = 1,2,…,S,*

4.2. *Determine the cost function J(i,j,k,l) using equation* ***Error! Reference source not found.***

4.3. $J_{last} = J(i,j,k,l)$

4.4. *Tumbling: Create a random vector set Δ(i)ϵ**R**^{p}*

4.5. *Move: Compute* $\theta^i(j+1,k,l)$ *using equation (14)*

4.6. *Compute cost function* $J(i,j+1,k,l)$ *using equation* ***Error! Reference source not found.***

4.7. *Swim: m=0 (counter for swim length)*

while m<N$_S$

m= m+1,

if $J(i,j+1,k,l) < J_{last}$ ***then***

$J_{last} = J(i,j+1,k,l)$

Move: Compute $\theta^i(j+1,k,l)$ *using equation* (14)

Compute cost function $J(i,j+1,k,l)$ *using equation* ***Error! Reference source not found.***

else

m<N$_S$

end

end

[Step 5] if j<N$_c$, *move to step 4*

[Step 6] Reproduction

for *i = 1,2,…,S ,*

6.1Compute J^i_{health} *using equation (17)*

end

6.2 Sort bacteria in order of ascending. The smallest healthier bacteria (S_r) die and others divided into two bacteria and placed in the same place.

end

[Step 7] if k<N$_{re}$*go to step 3*

[Step 8] Elimination-dispersal:

for*,m=1,2,…,S*

8.1 ***if*** *P_{ed} >rand (create a random number for each bacterium and if any number is lower than P_{ed} then discard or destroy the bacterium)*

Create new random locations for the bacteria

else

Bacteria remain in their place.

end

end

if l<N$_{ed}$, *move back to step 2;*

else

end.

Figure 3: Flow chart for bacterial foraging algorithm [1]

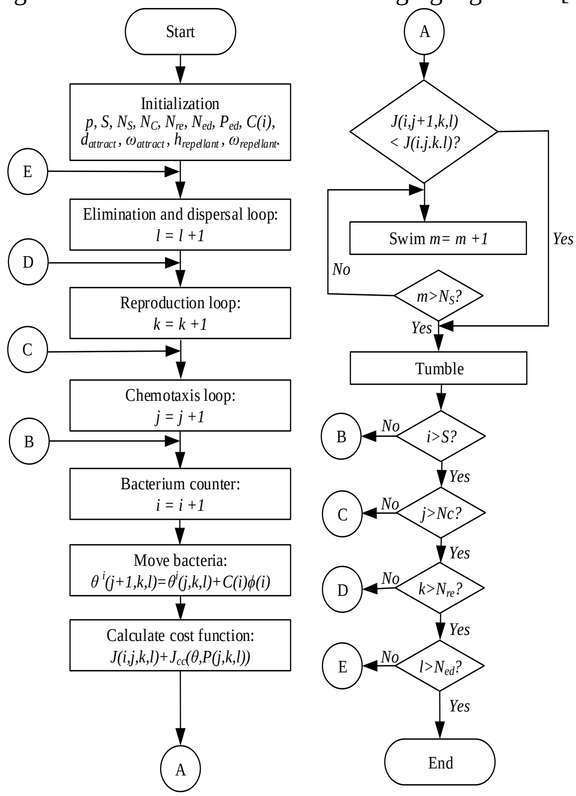

Figure 3: Flow chart for bacterial foraging algorithm [1]

5. Materials and method

In this study, a program code for optimal UPQC placement in radial distribution networks based on bacterial foraging algorithms is written and implemented in MATLAB 2017a environment using a HP EliteBook 6930p personal computer with the following specifications:

i. Intel Core Dual P8700 processor;
ii. 2.53 GHz and 4 GB installed RAM.

The parameters employed by the proposed BFA method in this paper are adopted from [1,2] and given in table 1.

Table 1: BFA parameters

No.	Parameters	Values
1	Dimension of search space, p	2
2	Number of bacteria, S	10
3	Number of chemotactic steps, N_c	4

4	Number of swim steps, N_s	4
5	Number of reproductive steps, N_{re}	4
6	Number of elimination-dispersal steps, N_{ed}	3
7	Run-length unit $C(i)$	0.1
8	Number of bacteria reproductions (splits) per generation, S_r	$S/2$
9	The probability that each bacteria will be eliminated/dispersed, P_{ed}	0.25
10	Depth of attractant, $d_{attract}$	0.1
11	Width of attractant, $\omega_{attract}$	0.2
12	Height of repellent, $h_{repellant}$	0.1
13	Width of repellent, $\omega_{repellant}$	10

A simple and concise flowchart for implementation of the BFA based optimization approach is illustrated in figure 4.

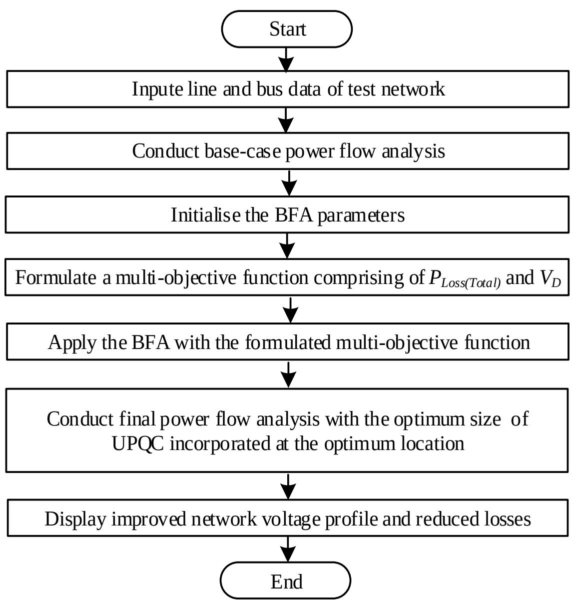

Figure 4: Flow Chart for proposed BFA Approach

6. Results and discussions

6.1 Standard IEEE 33-bus test network

The test network is a radial distribution system of medium scale with 33-buses and 32-branches. For thus network, the single line diagram, line data and bus data are given in [14]. Line voltage, base MVA, total real and reactive loads of the network are provided respectively as 12.66 kV, 100 MVA, 3.72 MW and 2.3MVAr.

Bus 30 and 1276 kVAr were obtained as the optimal location and size of UPQC respectively by the proposed technique. With the installation of the compensator, the minimum voltage at the 18th bus has been enhanced to 0.9276 from 0.9134 p.u., resulting in overall improvement of the system voltage profile by 42.32% as compared to the base-case. This is further explained by the improved value of the network mean voltage magnitude from its base-case value of 0.9486 to 0.9614. Also with respect to the base-case, the proposed approach has recorded a 29.7% reduction in total active power loss. This achievement is clearly supported by the decrease recorded in the network mean power values. Both the active and reactive mean power values have dropped from their respective base-case values of 6.309 and 4.2076 to 4.4337 and 2.9790. Figures 5 and 6 display the improvement of the test network's voltage profile and the reduction of real power loss respectively. Through these estimates it can be seen that UPQC's implementation across all three methods has greatly enhanced and that the voltage profile and total network losses reduced.

A summary of the results obtained before and after UPQC placement in the test network using the proposed approach and their comparison with Artificial Intelligence (AI) and Differential Evolution (DE) techniques are presented in table 2. From the findings it is clear that all strategies have succeeded in achieving a decrease in losses to some percentages. Nevertheless, it is evident from the number of improved parameters in table 2, that the proposed BFA based approach showed better results over the IA and DE techniques.

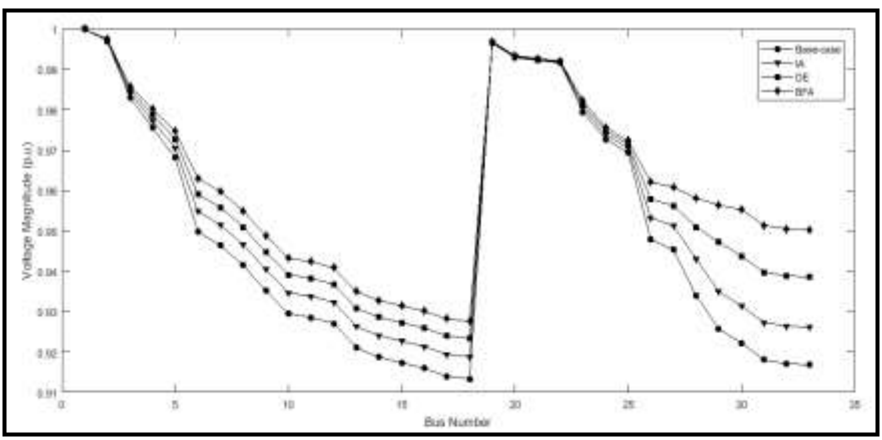

Figure 5: Voltage profile improvement

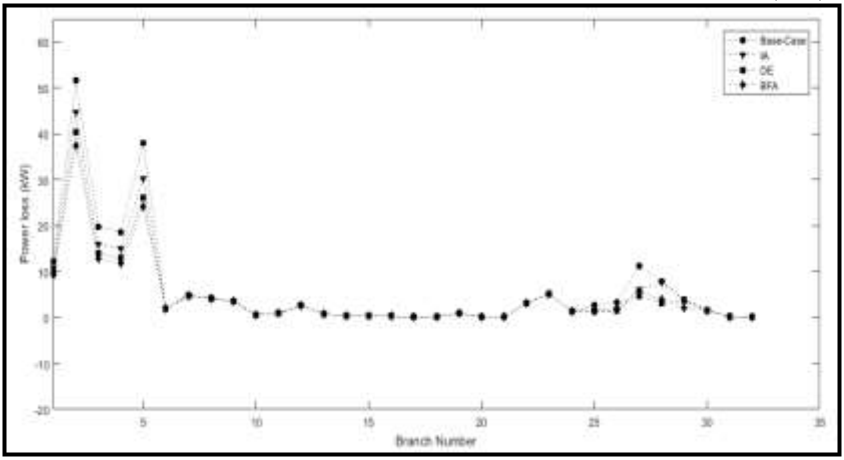

Figure 6: Active power loss reduction

Table 2: Summary of simulation outcomes for the IEEE standard test network

Parameters	Base-case	IA [14]	DE [14]	BFA [1]
UPQC Position & Size (kVAr)	-	Bus 28 (509.002)	Bus 29 (914.102)	Bus 30 (1276.0)
V_{min} (p.u) at bus 18	0.9134	0.9188	0.9234	0.9276
Overall Voltage Improvement (%)	_	_	_	42.32
P_{loss} (kW)	201.9	170.0	150.0	141.9
% P_{loos} reduction	-	15.8	25.7	29.7
Q_{loss} (kVAr)	138.6	113.6	99.4	95.3
% Q_{loos} reduction	-	18.0	28.3	31.2
No. of buses out of constraint settings	21	17	15	10
Mean Voltage Magnitude	0.9486	_	_	0.9614
Mean P_{loss}	6.3091	_	_	4.4337
Mean Q_{loss}	4.2076			2.9790
Computational Time (sec)	_	_	_	10.67

6.2 The practical 50-Bus Canteen feeder

The 50-Bus Canteen feeder is a practical distribution feeder that forms part of the Zaria distribution network.

The network is characterized by an appreciable number of buses and branches (50-buses and 49-branches), thus making it a relatively large network. The single line diagram of the network as well as its data (line and bus) can be found in [35]. The line voltage, base MVA and total active and reactive loads of the network are given as 11kV, 100MVA, 0.388MW and 0.297MVAr respectively.

The proposed BFA method obtained the optimal UPQC value and position as 2212 kVAr and bus 21 respectively. The consequence of placing a UPQC of such magnitude at the attained position in terms of the network voltage profile is evident in figure 7.

The minimum bus voltage of the feeder which is at bus 27 has improved to 0.9940 p.u from its base-case value of 0.9892 p.u. Thus, increasing the overall voltage profile of the feeder by 9.78%. This improvement in voltage profile is supported by a reasonable increase in the feeder mean voltage magnitude (from base-case value of 0.9942 to 0.9962). Similarly, the allocation of UPQC has caused a reasonable reduction in active and reactive power losses experienced in each branch of the feeder. Figure 8 clearly shows the impact of the installed UPQC in terms of active power loss as compared to network base-case condition. The presence of the compensator at the appropriate location has reduced the overall feeder losses (active and reactive) from their base-case values of 2.8066 and 1.7799 to 2.2237 kW and 1.4101 kVAr respectively. As such leading to 22.21 and 22.23% reduction in total active and reactive power losses respectively. Furthermore, the feeder mean active and reactive losses have also reduced to 0.0442 and 0.0280 respectively as compared to their base-case values of 0.0570 and 0.0363.

A comprehensive summary of all the results obtained with and without the UPQC in the practical 50-bus Canteen feeder using the proposed approach are given in table 3. From all of the items considered, it is clear that the practical feeder has been improved with the installation of UPQC by the proposed BFA method.

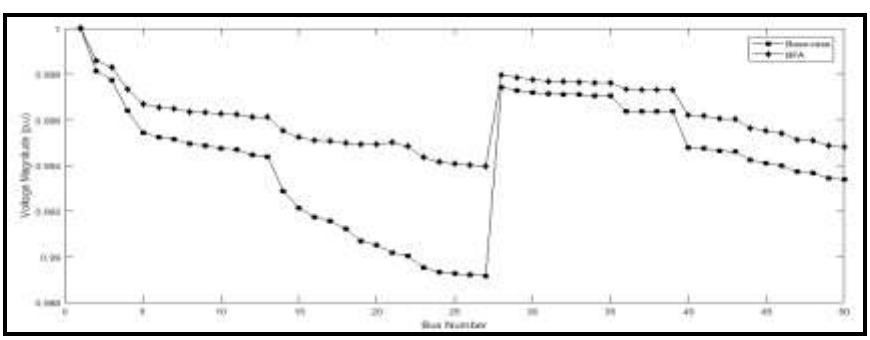

Figure 7: Voltage profile improvement

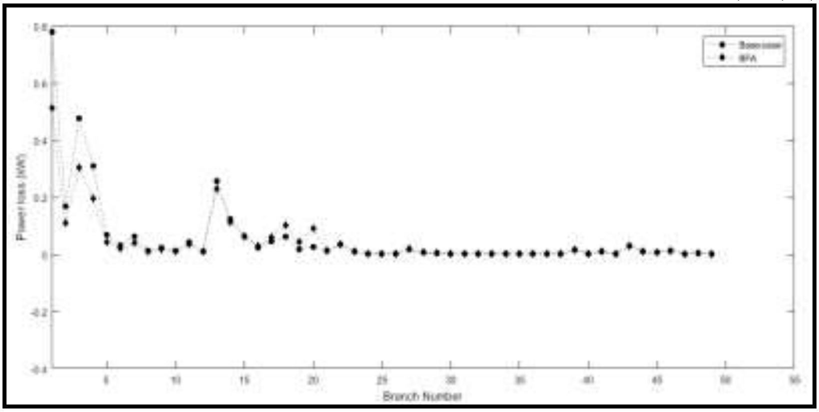

Figure 8: Active power loss reduction

Table 3: Summary of simulation outcomes for the practical 50-bus Canteen feeder

Parameters	**Base-case**	**BFA**
UPQC Position & Size (kVAr)	_	Bus 21 (2212)
V_{min} (p.u.) at bus 27	0.9892	0.9940
Overall Voltage Improvement (%)	_	9.78
Total P_{Loss} (kW)	2.8066	2.2237
P_{Loss} Reduction (%)	_	26.21
Total Q_{Loss} (kVAr)	1.7799	1.4101
Q_{Loss} Reduction (%)	_	26.23
Number of buses out of constraints	5	0
Mean Voltage Magnitude	0.9942	0.9962
Mean P_{loss}	0.0573	0.0442
Mean Q_{loss}	0.0363	0.0280
Computational Time (s)	_	8.87

7. Conclusion

In this paper, a BFA base model has been implemented in the optimal placement of UPQC in a practical distribution feeder. A simple and direct power flow method has been employed to ascertain the feeder condition before and after allocating UPQC. From the outcomes of the direct power flow analysis, a multi-objective function containing the overall system active power loss and voltage deviation was formulated and employed for the minimization problem. The effect of the injected reactive power into the feeder by UPQC has been considered in terms of voltage profile and line losses. Analysis on the IEEE standard test network using the proposed approach which has been reported in an existing literature was once again reported in this work, after which the effectiveness of the approach tested on a practical 50-bus local Canteen feeder. The overall result recorded in terms of the feeder voltage profile improvement and power loss reductions due to the placement of UPQC by the proposed approach has demonstrated its ability to tackle reactive power compensation problems in real life distribution networks. Future work will consider the application of some of the latest swarm based nature inspired algorithm based models in solving reactive power compensation problems in the same practical distribution feeder.

Acknowledgement
The authors will like to acknowledge Prof. G. A. Bakare of the Department of Electrical and Electronics Engineering, ATBU Bauchi for his immense contributions
.

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