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Moth Flame Optimization Method for Unified Power Quality Conditioner Allocation

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Article Info	ABSTRACT
	This paper introduces a new optimization method to determine the optimal allocation of Unified Power Quality Conditioner (UPQC) in the distribution systems. UPQC is a versatile Custom Power Device (CPD) to solve problems related to voltage and current by the series and shunt compensator in the distribution systems. The task of UPQC highlighted in this paper is the required load reactive power is provided by both the series and shunt compensators. The UPQC's steady state compensation capability has given a solution for providing reactive power compensation in large distribution systems. The optimization method adopted is Moth Flame Optimization (MFO). The best location and series compensator voltage are determined using MFO. The voltage injected by the series compensator and reactive power injected by the shunt compensator is incorporated in the load flow method. The effectiveness of the proposed method is validated with standard distribution systems.

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1. INTRODUCTION

For productive operation of the electric utility the necessary condition is to operate the system at its maximum efficiency. The losses in the system can be curtailed by minimizing the total flow of reactive power. Reactive power is essential to maintain the quality of supply. Some of the industrial load imposes on the supply large demand for reactive power. Hence reactive power compensators assume a key part in meeting the reactive power needs of the system. The compensators include shunt capacitors and series voltage regulators. Shunt capacitors cannot create variable reactive power constantly. Series voltage regulators drive the source to produce reactive power. Hence, to overcome these disadvantages the static compensators utilizing power electronic devices are employed for effective operation of the system.

The static compensators include Distributed Flexible Alternating Current Transmission System (DFACTS). These devices can provide continuously variable reactive power. The most generally used DFACTS devices for reactive power compensation is DSTATCOM [1] and Unified Power Quality Conditioner (UPQC).

UPQC [2] is a device which consists of a DVR and DSTATCOM. DVR is a series connected device which handles all the voltage related problems in the system. Unified Power Quality Conditioner [2-4] has the potential to inject the necessary amount of reactive power into the network when the network is in shortage of the reactive power and vice versa. Another advantage of this device is, its output reactive power can be continuously varied. Hence, the shortages of capacitors, which cannot meet the network demands as required, are abolished. The application of UPQC for two bus systems and for sensitive loads to address the problems of power quality is practical as detailed in [5-7].

The most common classification of UPQC is based on voltage compensation methods. These include UPQC-P (active power injection), UPQC-Q (reactive power injection), UPQC-S (active and reactive power injection) and UPQC-VAmin (minimum apparent power injection). Another classification is based on the physical structure. These include UPQC-R (right shunt), UPQC-L (left shunt), UPQC-I (interline) UPQC-MC (multi-converter), UPQC-MD (modular), UPQC-ML (multi-level), UPQC-D (distributed) and UPQC-DG (distributed generator integration).

In this paper, the application of UPQC for improving the voltage is realized for large distribution system by way of utilizing the series compensator i.e. DVR. The problem with UPQC placement has been solved by numerous methods as detailed in [8-12].

Boutebel et al. [8] has used the hybrid optimization technique combining differential evolution and PSO for determining the optimal sizing and location of the UPQC device in radial distribution systems. Ganguly et al. [9] has introduced the phase angle control model of UPQC known as UPQC–PAC to validate the concept of maximal utilization of series inverter. The series inverter also shares the load reactive power along with the shunt inverter in steady state conditions, leading to a decrease in the rating of shunt inverter. Atma Ram Gupta et al. [10] has modeled the shunt compensator as the source of 1 MVAr reactive power and by assuming the voltage at the candidate bus as 1 p.u. The value of series reactive power compensation is calculated in the steady state. The total power losses are calculated by placing the acquired size of UPQC at the respective buses. The bus having the minimum value of losses is selected as candidate bus for UPQC installation. M. Hosseini et.al [11] has demonstrated the effectiveness of UPQC to improve steady state voltage. S. A. Taher et.al [12] has used Differential Evolution (DE) algorithm to decide the optimal location of unified power quality conditioner for different loading conditions and also the savings with UPQC are obtained. DE results are compared with Genetic Algorithm (GA) and Immune Algorithm (IA).

This paper also explores the capability of series and shunt compensator of UPQC to participate in load reactive power compensation in steady state by a new Optimization method known as a Moth Flame Optimization method. The losses and voltages for the network are obtained with the load flow method described in the following section

2.   RADIAL DISTRIBUTION SYSTEM LOAD FLOW

Load flow is an important tool to assess the performance of the distribution system. S. D. Chiang et.al [13] has developed decoupled and fast decoupled load flow method. S. Ghosh et al. [14] has developed a load flow method based on estimation of effective real and reactive power loads. J. H. Teng et.al [15] has proposed two matrices Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV) to solve the load flow equations.

Here the active power load and reactive power load at the mth bus is denoted by $P_L(m)$ and $Q_L(m)$ respectively.

$V(m)$: Voltage at the mth bus
I_b : Branch current and I_L : Load current
$V_L(i), V_s(i)$ are the receiving end node voltage and sending end node voltage respectively.
$Z_b(i)$, $R_b(i)$ and $X_b(i)$ are the impedance, resistance and reactance for the ith branch respectively.

Calculation of load currents:

$$I_L(m) = \left(\frac{P_L(m) + jQ_L(m)}{V(m)}\right)^* \qquad (1)$$

Formation of BIBC matrix:

By applying the Kirchhoff's Current Law to the distribution network, BIBC matrix can be formed. Consider a six bus network which is shown in Figure 1.
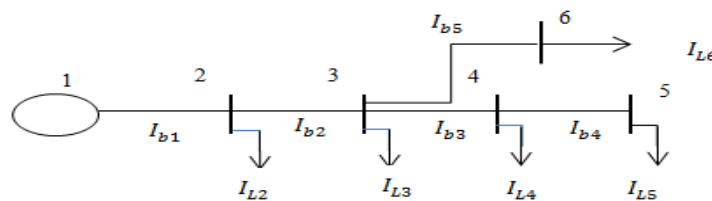

Figure 1. Six bus system network configuration

The BIBC matrix, which gives the relation between load and branch currents, for Figure 1 is given as

$$\begin{bmatrix} I_{b1} \\ I_{b2} \\ I_{b3} \\ I_{b4} \\ I_{b5} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{L2} \\ I_{L3} \\ I_{L4} \\ I_{L5} \\ I_{L6} \end{bmatrix}$$

$$[I_b] = [BIBC][I_L] \tag{2}$$

Bus voltage is obtained by Equation (4)

$$\Delta V(i) = I_b(i) . Z_b(i) \tag{3}$$

$$V_L(i) = V_s(i) - \Delta V(i) \tag{4}$$

The error in voltage is calculated. If the error is less than tolerance then the load flow converges. The power losses in a distribution system are given by (5) and (6)

$$P_{Loss} = \sum_{i=1:n}(I_b(i))^2 * R_b(i) \tag{5}$$

$$Q_{Loss} = \sum_{i=1:n}(I_b(i))^2 * X_b(i) \tag{6}$$

Here n is the total number of branches.

3. UPQC STRUCTURE

A UPQC as the combination of series and shunt compensator is displayed in Figure 2 [3].
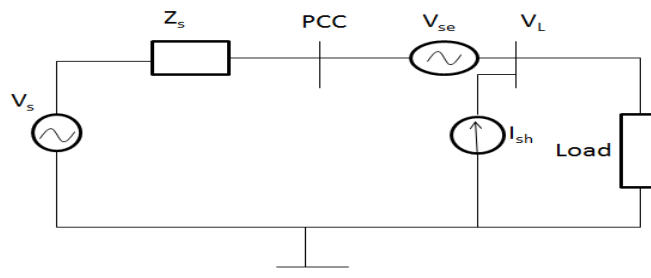

Figure 2. Equivalent circuit of UPQC

Here V_s is the sending end voltage, Z_s is the source impedance, PCC is the pont of common coupling, V_{se} is the voltage injected by series compensator, I_{sh} is the shunt compensating current and V_L is the load bus voltage.

The series compensator generates a voltage and injects it in series with the line near to the receiving end such that the voltage at the load side is always maintained at desired voltage magnitude.

The new load bus voltage V_L' , after injecting voltage by the series compensator is calculated as given in Equation (7)

$$V_L' \angle \delta = V_L + V_{se} \angle \gamma \tag{7}$$

The complex power obtained by the series compensator is obtained as follows:

$$S_{se} = V_{se} . I_b^* \tag{8}$$

Here I_b is the branch current in which series compensator is included.
The function of shunt compensator is to provide load VAr support.
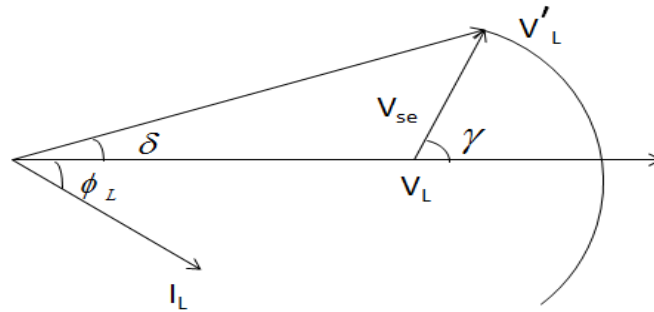Figure 3 shows the phasor diagram for series voltage injection.

Figure 3. Phasor diagram for series voltage injection

The UPQC series compensator is modeled as a source of real and reactive power whereas shunt compensator is modeled as the source of reactive power.
With the injection of voltage by the series compensator, the receiving end voltage is changed to V_L'. The reactive power to be injected is calculated as given in Equation (9).

$$Q_{comp} = V_L' I_c' \tag{9}$$

I_c' compensating current after series compensation which is calculated as given in [16].

4.   MOTH FLAME OPTIMIZATION

The inspiration of this algorithm [17] is the navigation method of moths known as transverse orientation. Moths fly at night using the moonlight. By keeping a constant angle concerning the moon, moths fly in straight line to achieve the goal. The convergence of moths is towards the light. Similar to moths, flames are the key elements of this optimization based on which the moths update their positions. Flames are the best solutions. In each iteration the flames are sorted based on fitness. The moths update their positions with respect to their corresponding flames. The principal moth dependably updates its position concerning the best flame. The number of flames decreases adaptively over the course of iterations.

4.1. Algorithm for finding the Location and Series Compensator Voltage of UPQC

Step 1: Initialize the moth population size, maximum iterations, dimensions of the search space, minimum and maximum limits of the moth positions.
Step 2: Run the load flow and find the real power loss before optimization.
Step 3: Generate randomly the moth positions of the order $[m \times n]$ within the limits, where m denotes the moth population size and n denotes the dimension. The dimensions are location, real and imaginary part of series injected voltage, for one UPQC.Hence, n is assumed as 3.
Step 4: Set the iteration count to 1.
Step 5: Find the number of flames using Equation (10).

$$\text{Number of flames} = N - m * \frac{(N-1)}{T} \tag{10}$$

Here N is the maximum number of flames, m is the current iteration number and T is the maximum number of iterations.
Step 6: Run the load flow by injecting the voltage at the corresponding location as given in Equation (7) and by injecting the reactive power as given in Equation (9).
Step 7: Evaluate the fitness. Discard the moths which violate the constraint that the voltage at the corresponding location should not exceed 1 p.u. Sort the moths based on fitness values.
Step 8: Initialize these moths as flames and fitness values as flame fitnesses. If current iteration number is greater than 1 then sort the moths based on fitness values of the moths in the previous iteration and the

current iteration and assign these to flames. Select the best flame fitness and its corresponding flame position known as best flame position.

Step 9: Initialize a given by Equation (11)

$$a = (-1) + m * (-\frac{1}{T})$$ (11)

Step 10: Calculate the distance of the pth moth for the qth flame using Equation (12)

$$Dist_p = Flame_q - Moth_p$$ (12)

Step 11: Update the position of the moth using Equation (13)

$$Moth_p = S(Moth_p, Flame_q)$$ (13)

Where S=Spiral function.The Spiral Function is given in Equation (14)

$$(Moth_p, Flame_q) = Dist_p * e^{bt} * \cos(2\Pi t) + Flame_q$$ (14)

Where $t = (a - 1) * random + 1$ (15)

        b is a constant which defines the shape of the spiral function (logarithmic spiral). It is assumed as 1 in this paper.
Step 12: Increase the iteration number.
Step 13: Reprise the steps from 5-12 until the iterations reach their maximum limit.
Step 14: Display the best flame fitness and the corresponding best flame position which gives the location of UPQC and voltage injected by the series compensator.Print the results for real and reactive injected by the series compensator and reactive power injected by the shunt compensator.

5.   RESULTS
        The test systems considered for checking the effectiveness of the proposed method are 10-bus, 34-bus and 33-bus systems. The losses, voltage profile, location and real and reactive power injected by UPQC are determined.

5.1. Results of 10-bus System
        10-bus system is a 23 kV system. The data of the system is taken from [20]. The real and reactive load on the system is 12368 kW and 4186 kVAr respectively. 6 buses out of 10 buses have under voltage problem.
        From Table 1, it can be concluded that bus 7 has the least loss in real power which is 599.6457 kW. The voltage to be injected by the series compensator is 0.0134 + 0.3929i p.u. The voltage improvement is from 0.8375 p.u. @bus 10 to 0.9377 p.u. @bus 10 which is shown in Figure 4.

Table 1. Results of 10 bus System

| Description	Without UPQC	With UPQC
Bus No	-	7
Total real power loss (kW)	783.7785	599.6457
Total reactive power loss (kVAr)	1036.5	793.8046
Complex Voltage injected by the series compensator (p.u.)	-	0.0134 + .3929i
Real power injected by the series compensator (kW)	-	607.50
Reactive power injected by the series compensator (kVAr)	-	1751.6
Reactive power injected by the shunt compensator (kVAr)	-	499.7686
Minimum voltage (p.u.)	0.8375@bus 10	0.9377@bus 10
Nodes with under voltage problem (<0.95)	6	2
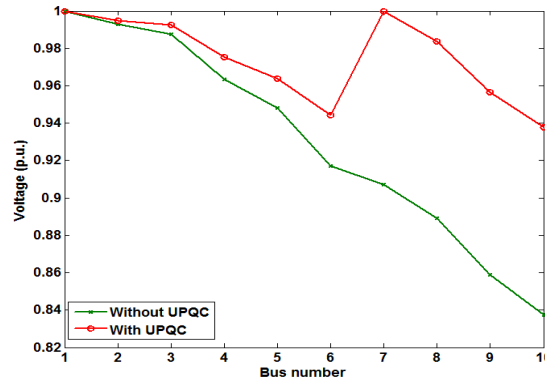
Figure 4 Voltage Profile for 10 bus system without and with consideration of UPQC

5.2. Results of 34-bus System

34-bus system is a 11 kV system. The data of the system is taken from [18]. The real and reactive load on the system is 4636.5 kW and 2873.5 kVAr respectively. 6 buses out of 34 buses have under voltage problem.

Table 2. Results of 34 bus System

Description	Without UPQC	With UPQC
Bus No	-	26
Total real power loss (kW)	221.7235	149.5901
Total reactive power loss (kVAr)	65.1100	43.9272
Complex Voltage injected by the series compensator (p.u.)	-	0.3021i
Real power injected by the series compensator (kW)	-	302.75
Reactive power injected by the series compensator (kVAr)	-	23.412
Reactive power injected by the shunt compensator (kVAr)	-	1163.1
Minimum voltage (p.u.)	0.9417 @bus 27	0.9563@ bus 25
Nodes with under voltage problem (<0.95)	6	0

From Table 2, it can be concluded that bus 26 has the least loss in real power which is 149.5901kW. The voltage to be injected by the series compensator is 0.0000 + 0.3021i p.u. The voltage improvement is from 0.9417 p.u. @bus 27 to 0.9563 p.u. @bus 25 which is shown in Figure 5.
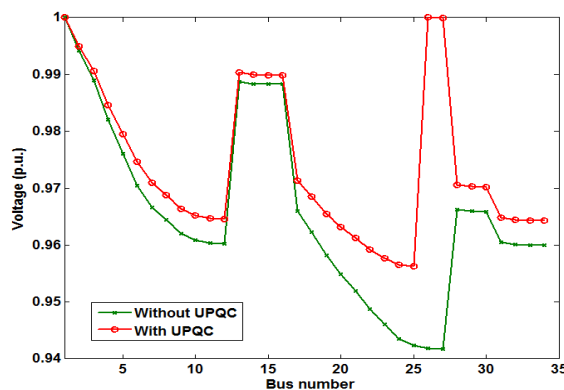

Figure 5. Voltage Profile for 34 bus system without and with consideration of UPQC

5.3. Results of 33-bus system

33-bus system is a 12.66 kV system. The data of the system is taken from [19]. The real and reactive load on the system is 3715 kW and 2300 kVAr respectively. 21 buses out of 33 buses have under voltage problem.

Table 3. Results of 33 bus System

Description	Without UPQC	With UPQC
Bus No	-	31
Total real power loss (kW)	202.6771	123.4237
Total reactive power loss (kVAr)	135.141	83.6298
Complex Voltage injected by the series compensator (p.u.)	-	0.3080i
Real power injected by the series compensator (kW)	-	256.39
Reactive power injected by the series compensator (kVAr)	-	59.241
Reactive power injected by the shunt compensator (kVAr)	-	954.2685
Minimum voltage (p.u.)	0.9131@bus 18	0.9273 @bus 18
Nodes with under voltage problem (<0.95)	21	10

From Table 3, it can be concluded that bus 31 has the least loss in real power which is 123.4237 kW. The voltage to be injected by the series compensator is 0.0000 + 0.3080i p.u. The voltage improvement is from 0.9131 p.u. @bus 18 to 0.9273 p.u. @bus 18 which is shown in Figure 6.
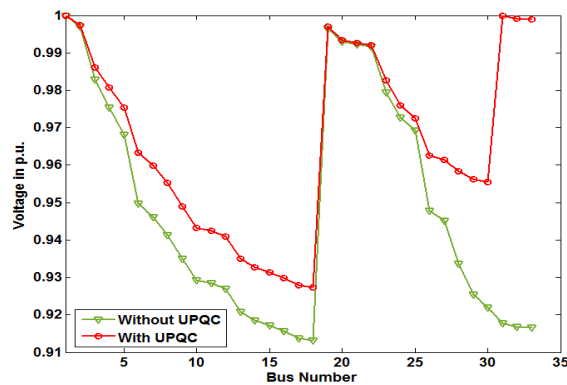

Figure 6. Voltage profile without and with consideration of UPQC in 33 bus system

Table 4 shows the comparison of UPQC placement results for 33-bus distribution system. The method proposed in Reference [12] is Differential Evolution optimization method. The corresponding reduction in real power loss is 25.84 %. The method proposed in Reference [10] is based on placement of UPQC at each and every bus in the distribution system and obtaining the real power losses. The reduction in real power losses is 27.99 %. The method proposed in this paper is placement of UPQC by using Moth Flame Optimization method. The reduction in real power losses is 39.10%.

Table 4. Results of 33 bus System

Description	Ref [12]	Ref [10]	Proposed method
Optimal location	29	30	31
Real power loss (kW)	150.3	151.94	123.4237
Minimum voltage (p.u.)	-	0.9177	0.9273
Real Power Loss reduction (%)	25.84	27.99	39.10
Size of shunt compensator	914.1 kVAr	1000 kVAr	954.2685 kVAr
Size of series compensator	0.0015 kVAr	385.44 kVAr	256.39+j59.241 kVA

6.   CONCLUSION

A new optimization method known as Moth Flame Optimization method is used to determine the optimal allocation of Unified Power Quality Conditioner in the distribution system. UPQC's series compensator provides both real and reactive power and shunt compensator provides the required load reactive power. This functionality of UPQC allows the series compensator to take part in reactive power compensation. The best location and complex voltage injected by series compensator of UPQC is obtained by using MFO. MFO has strong convergence characteristics for solving the problem of UPQC placement. The

results prove the effectiveness of the proposed method to reduce real power losses and improve the voltage profile. Comparative results demonstrate the effectiveness of the proposed method.

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