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Performance of Unified Power Quality Conditioner in radial distribution networks using Particle Swarm Optimization Method

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Abstract

This paper gives the performance of Unified Power Quality Conditioner (UPQC) in radial distribution systems. The main emphasis in this paper is to evaluate the performance of UPQC in steady state operating conditions. The two most important components of UPQC are series and shunt compensators. In normal practice, the series compensator injects series voltage to mitigate sag and swell in the supply voltage. In the proposed approach, the series compensator injects the series voltage in normal operating conditions. The series and shunt compensators take part in providing compensation to the distribution network. UPQC allocation in a large distribution network is solved by Particle Swarm Optimization (PSO) method. The optimization is carried out with the aim of minimization of network power loss. The UPQC is placed at each bus in the distribution network. The series compensator voltage is determined by using PSO method. Hence, the reactive power provided by the shunt compensator is determined. In order to include the effect of series and shunt compensator, a forward-backward sweep load flow algorithm comprising of UPQC is used. Two test systems are used to evaluate the performance of the proposed approach. The results of the proposed approach are compared with the approaches available in the literature.

Keywords : Particle Swarm Optimization Method; Unified Power Quality Conditioner; Network Power Loss; Distribution systems.

INTRODUCTION

The introduction of power electronics based devices such as Flexible Alternating Current Transmission Systems (FACTS) are a boon to the transmission and distribution systems to improve the performance of power system operation. Distribution network Flexible Alternating Current Transmission systems (DFACTS) are used in the distribution systems. The prominent among these DFACTS are Distribution Static Compensator (DSTATCOM) [1-4], Dynamic Voltage Restorer [5-6] and Unified Power Quality Conditioner (UPQC). UPQC [7] involves two main components: (i) shunt compensator and (ii) series compensator UPQC operates in distribution system. UPQC is the most preferred DFACTS device applied to mitigate voltage and current-related problems in the distribution systems. The series compensator of UPQC injects a series voltage. It mitigates the sag, swell in supply voltage. The two main important functions of shunt compensator are to provide load reactive power by way of injecting a shunt compensating current to the load and to provide compensation for the load harmonic distortions. There exist different UPQC models.

These UPQC models are classified on the criteria of series compensation methods, UPQC topology and control strategy of UPQC. UPQC models based on series compensation methods include UPQC-P [8], UPQC-Q [8], UPQC-S [9], UPQC-VAmin [10-11], etc. UPQC models based on topology include three phase four wire UPQC [12], interline UPQC [13], OPEN UPQC [14], etc. UPQC models based on control strategy include phase angle control [15], feedback controller using particle swarm optimization method [16], etc.

S. A. Taher et.al [17] has detailed the problem of UPQC allocation in the distribution system with differential evolution algorithm. M.Hosseini et al. [18] has detailed the placement of UPQC in a large distribution system, where the improvement in voltage profile is reported but the effect of UPQC on loss reduction is not evaluated.

The effect of UPQC on loss reduction and voltage improvement is evaluated in this paper. Also the impact of UPQC on reduction in branch current is investigated. The approach adopted in this paper is the series compensator injects series voltage. The shunt compensator provides reactive power compensation.

The main contributions of this work are:

(i) To evaluate the performance of UPQC in providing compensation in steady state operating conditions.

(ii) To evaluate the effect of UPQC placed at a specific location in the distribution network.

The distribution systems used to study the effectiveness of the proposed approach are 33-bus system and 69-bus system. The UPQC is incorporated in the Forward-Backward sweep load flow method. The optimization is carried out with the aim of minimizing the total power losses in the system. The optimization is carried out with Particle Swarm Optimization (PSO) method. The optimizing variables are the series injected voltage. Comparison of the proposed approach is given with respect to other compensation approaches available in the literature.

UPQC STRUCTURE

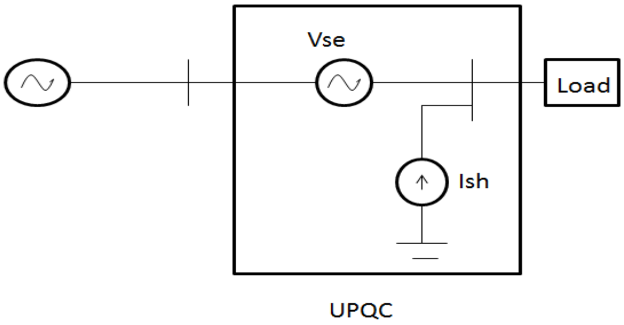

Figure 1: UPQC Structure

A UPQC composed of a series and a shunt compensator as shown in the Figure 1, injects series voltage and shunt compensating current respectively.

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

$$S_{se} = \overline{V}_{se}.\overline{I}_B^* \quad (1)$$

Here $\overline{V}_{se}$ is the series voltage injected by the series compensator, $\overline{I_B}$ is the branch current in which UPQC is placed.

The compensating current (I'_{sh}) is calculated as given in [19-20]. The compensating current is referred as capacitor current in [19]. The reactive power provided by the shunt compensating device is given by equation (2)

$$Q_{sh} = V_L{}'I'_{sh} \quad (2)$$

Here $V_L{}'$ is the voltage at the bus at which UPQC is placed.

The incorporation of $\overline{V}_{se}$ and Q_{sh} in the forward-backward sweep load flow method is detailed in the following section.

LOAD FLOW METHOD FOR UPQC ALLOCATION

The effect of UPQC is modeled in the load flow method characterized by forward and backward sweep [21]. These steps are as follows:

Backward sweep: Consider P_L and Q_L as the real and reactive load at the bus m, voltage at the load bus as $\overline{V}_L$. The load current $\overline{I}_L$ at bus m is calculated as:

$$\overline{I}_L(m) = \left(\frac{P_L(m)+jQ_L(m)}{\overline{V}_L(m)}\right)^* \quad (3)$$

Here m=1, 2, 3 ….N

N symbolizes the total number of buses

The branch current is calculated as

$$\overline{I_B}(j) = \overline{I}_L(\text{recv}(j)) + \sum \text{load currents beyond branch (j)} \quad (4)$$

Here j = 1, 2, 3 ….Nb

Nb symbolizes the total number of branches.

Forward sweep: The voltage at each bus is obtained as given in the equation (5)

$$\overline{V}_L(\text{recv}(j)) = \overline{V}_L(\text{send}(j)) - \overline{I}_B(j).Z_B(j) \quad (5)$$

Here $Z_B(j)$ is the impedance of the jth branch

The series compensator injects voltage ($\overline{V}_{se}$) in series with branch (very nearer to the receiving end bus) in which it is placed. It is incorporated in the load flow by modifying the voltage in the receiving end of the branch, determined as

$$\overline{V}_L{}'(\text{recv}(j)) = \overline{V}_L(\text{recv}(j)) + \overline{V}_{se} \quad (6)$$

The shunt compensator is modeled as the source of reactive power. It is included in the load flow by modifying the reactive power requirement at the bus at which UPQC is placed.

$$Q'_L(m) = Q_L(m) - Q_{sh} \quad (7)$$

Q_{sh} is obtained from equation (2)

PROBLEM FORMULATION

An Optimization method is introduced to find the performance of UPQC in distribution system. The performance of UPQC is evaluated with respect to minimization of network real power losses given by equation (8). Also the nodal voltage deviation in the system is obtained by equation (9) to assess the problem of under voltage problem mitigation in the distribution network. Mathematically these are stated as:

(i) Network Power Loss

$$P_{Loss} = \sum_{j\epsilon Nb} I_B(j)^2 * R_B(j) \quad (8)$$

(ii) Nodal voltage deviation among all the buses

$$V_{deviation} = \max(V_{substation} - V_L(m)) \quad (9)$$

$\forall$ m =1, 2 ….N

Here $\mathrm{V_{substation}}$ is the voltage at the substation, $V_L(m)$ is the voltage at the mth bus.

The associated constraints are:

(i) The reactive power supplied by the UPQC must not exceed the total reactive power requirement of the network.

$$0 \leq \mathrm{Q_{UPQC}} \leq \mathrm{Q_D} \tag{10}$$

(ii) The power losses associated with UPQC are negligible as compared to the total power losses of the network [27]. Hence power losses associated with UPQC are neglected.

(iii) The voltage at the UPQC location is maintained at substation voltage.

PARTICLE SWARM OPTIMIZATION METHOD

PSO [22] is used as the optimizing method. PSO is a population based optimizing method. It is based on the communal behavior of a group. The group consists of birds and fishes. The search agents are called as particles. These particles are generated randomly initially which includes information about the optimizing variables. The velocity vector dictates the next position of the particles. The particles update their positions based on pbest and gbest.

Consider

$\mathrm{Vel_{ij}^{t+1}}$: the velocity of the particle in $(\mathrm{t}+1)^{\mathrm{th}}$ iteration

k : Constriction factor

c_1, c_2 : the learning constants

random$_1$ and random$_2$: random numbers in the range [0 -1]

$\mathrm{X_{ij}^{t}}$: Position of the particle in the tth iteration

w : Inertia weight

$\mathrm{pbest_{ij}^{t}}$: Personal best of the particle

$\mathrm{gbest_{j}^{t}}$: Global best of the particle

T : Maximum iterations

t : Current iteration

The equations symbolizing the velocity updation is given by equation (11). The equation symbolizing the position updation is given by equation (14).

$$\mathrm{Vel_{ij}^{t+1}} = \mathrm{k}\,.\,[\mathrm{w.Vel_{ij}^{t}} + \mathrm{c_1.random_1.}\big(\mathrm{pbest_{ij}^{t}} - \mathrm{X_{ij}^{t}}\big) + \mathrm{c_2.random_2.}\big(\mathrm{gbest_{j}^{t}} - \mathrm{X_{ij}^{t}}\big)] \tag{11}$$

$$\mathrm{w} = \mathrm{w_{max}} - ((\mathrm{w_{max}} - \mathrm{w_{min}}).\mathrm{t/T})) \tag{12}$$

$$\mathrm{k} = \frac{2}{|[2-(c1+c2)-\mathrm{sqrt}((c1+c2)^2-4.(c1+c2))]|} \tag{13}$$

$$\mathrm{X_{ij}^{t+1}} = \mathrm{X_{ij}^{t}} + \mathrm{Vel_{ij}^{t+1}} \tag{14}$$

The velocity of the particles is dependent on the momentum, knowledge of individual particles and knowledge of the group.

The particle consists of the information of complex voltage. The algorithm for UPQC allocation based on PSO in radial distribution networks is given in the following section.

A. Algorithm to find the rating of UPQC by using PSO:

Step 1: Initialize the total number of particles, maximum iterations and dimension, minimum and maximum limits of voltage injected by the series compensator, inertia weights and velocity of the particles.

Step 2: Run the load flow for the base case without UPQC.

Step 3: Generate the particles and velocities randomly within the boundaries. Here the particles are complex voltage injected by the series compensator.

Step 4: Run the load flow by compensating the voltage at the desired location as given in equation (6). Compute the reactive power provided by the shunt compensating device given by equation (2). The reactive power demand at the mth bus at which the UPQC is placed is given by equation (7). Find the fitness. Here the fitness is the minimization of real power losses.

Step 5: Recognize the best particles (pbest) based on the fitness values. Check for the constraints. The particles which violate the constraint are set to base case. The best particle from the pbest (gbest) is recognized.

Step 6: Set the iteration count to one.

Step 7: Find the velocity of the particles for all the dimensions using equation (11).

Step 8: The position of each particle for all the dimensions is updated as given in equation (14).

Step 9: Run the load flow. Compensate the voltage at the desired location as given in equation (6). Compute the reactive power provided by the shunt compensating device given by equation (2). The reactive power demand at the mth bus at which the UPQC is placed is given by equation (7). Determine the new fitness values. Update the pbest particles if the voltage at the desired location does not exceed the substation voltage. Update the gbest from the most recent obtained pbest.

Step 10: Increment the iteration. If the number of iterations does not reach its maximum or convergence criterion is not satisfied, then repeat the steps starting from step 7, else go to step 11.

Step 11: The gbest particle specifies the voltage injected by the series compensator.

Step 12: Print the results for complex power provided by the series compensator and reactive power provided by the shunt compensator.

Reprise the steps 4 to 12 by placing UPQC at each bus in the distribution network.

The PSO parameters and the effect of UPQC placement on real power losses, branch current reduction and under voltage problem mitigation are discussed in the succeeding section.

SIMULATION RESULTS

The distribution systems used to examine the impact of UPQC are 33-bus system and 69-bus system. The data of the distribution systems is given in [23-24]. The base MVA and base kV are taken as 100 MVA and 12.66 kV for 33–bus system and 69-bus system. The representation of the networks is shown in Figure 2 and Figure 3.

The PSO parameters are:

The maximum limit of inertia weight (w_{max}) is taken as 0.9.

The minimum limit of inertia weight (w_{min}) is taken as 0.4.

The learning constants (c_1) and (c_2) are taken as 2.05.

The total number of particles is 30.

The maximum iterations are 1000.

The convergence criterion is set as 0.00001.

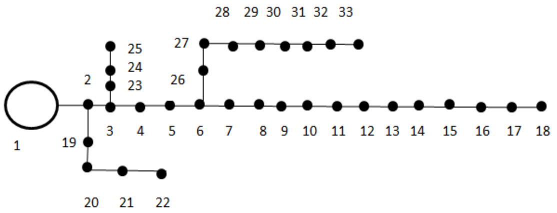

Figure 2: Network representation of 33-bus system

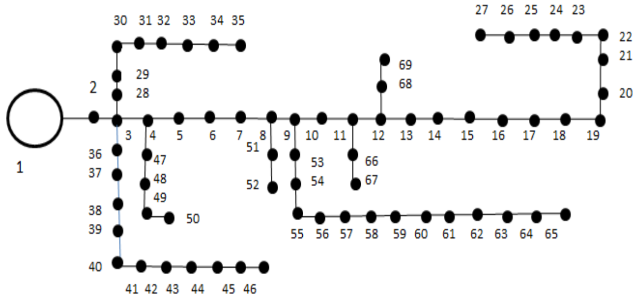

Figure 3: Network representation of 69-bus system

UPQC is placed at each and every bus in the distribution network with the optimization carried out to minimize network real power losses. The impact of UPQC placement on reduction in network power losses, reduction in branch current and under voltage problem mitigation of 33-bus system and 69-bus system is discussed in the following section.

- ***Impact of UPQC on network power losses***

The total real power loss for 33-bus system before placing UPQC is 202.6771 kW.

UPQC is placed at each and every location in the system. Bus 1 is not considered for the placement of UPQC since it is the substation bus. The total real power losses are obtained for every bus at which UPQC is located. The power loss obtained with UPQC placed at the buses 2 to 33 for 33-bus system is shown in Figure 4. The bus which is having minimum power loss is considered as the location for the placement of UPQC. The results of the determination of UPQC location based on minimum power loss for 33-bus system are given in Table 1.

Table 1: Results of UPQC placement for 33-bus system for minimization of network power loss

Sr No.	**33-bus system**		
	Description	***Without UPQC***	***With UPQC***
1	UPQC Location	-	31
2	Total real power loss (kW)	202.6771	123.4237
3	Total reactive power loss (kVAr)	135.141	83.6298
4	Voltage injected (p.u.)	-	0.3080i
5	Injected real power by series compensator (kW)	-	256.39
6	Injected reactive power by series compensator (kVAr)	-	59.241
7	Injected reactive power by shunt compensator (kVAr)	-	954.2685
8	Minimum voltage (p.u.)	0.9131 @bus 18	0.9273 @bus 18
9	Number of Nodes with under voltage problem	21	10

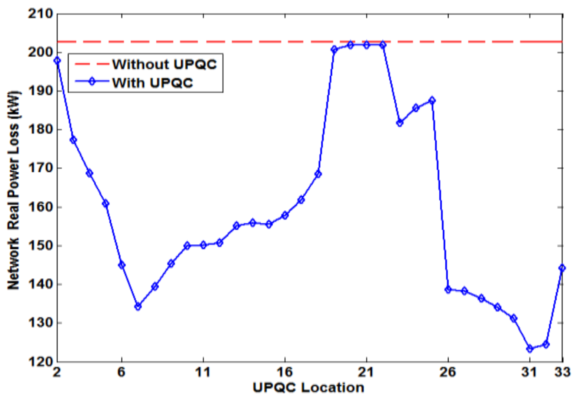

Figure 4: Network real power losses after placing UPQC in 33-bus system

From Table 1, the location for UPQC placement is obtained as bus 31.The real power loss of 123.4237 kW is obtained with UPQC placed at bus 31. The reduction in real power loss is 79.2534 kW. The percentage reduction in real power loss is 39.10%.

The number of under voltage nodes has been reduced from 21 in the base case to 10 after UPQC placement. As observed from Table 1, the improvement in voltage is from 0.9131 p.u. @bus 18 to 0.9273 p.u. @bus 18. The loss reduction is appreciable, but the problem of under voltage still persists.

The total real power loss for 69-bus system before placing UPQC is 225.0044 kW. Each and every bus in the 69-bus system is considered as a possible location for the placement of UPQC, except the substation bus. The total real power losses evaluated at the buses 2 to 69 in the 69-bus system are shown in Figure 5.

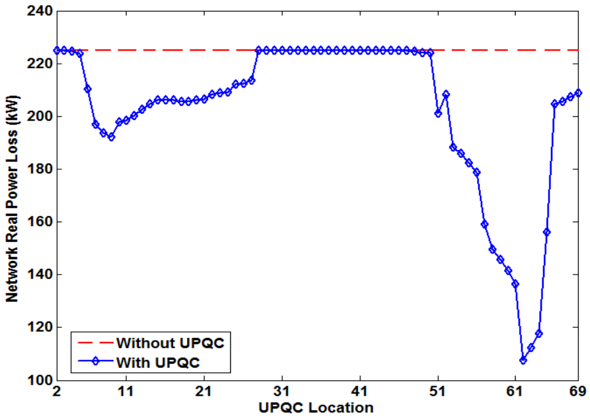

Figure 5: Network real power losses after placing UPQC in 69-bus system

The bus which is having minimum power loss is selected as the location for the placement of UPQC. The results of determination of location of UPQC based on minimum power loss for 69-bus system are given in Table 2.

As seen from Table 2, the location of UPQC at which minimum power loss is obtained is bus 62. The real power loss is obtained as 107.5717 kW. The reduction in real power loss is 117.4327 kW. The percentage reduction in real power loss is 52.19%.

Table 2: Results of UPQC placement for 69-bus system for minimization of network power loss

Sr No.	69-bus system		
	Description	***Without UPQC***	***With UPQC***
1	UPQC Location	-	62
2	Total real power loss (kW)	225.0044	107.5717
3	Total reactive power loss (kVAr)	102.2057	51.784
4	Voltage injected (p.u.)	-	0.3302i
5	Injected real power by series compensator (kW)	-	337.94
6	Injected reactive power by series compensator (kVAr)	-	0
7	Injected reactive power by shunt compensator (kVAr)	-	1194.4
8	Minimum voltage (p.u.)	0.9092 @bus 65	0.9448 @ bus 61
9	Number of Nodes with under voltage problem	9	2

The number of under voltage nodes has been reduced from 9 in the base case to 2 after UPQC allocation. Also, the improvement in voltage is from 0.9092 p.u. to 0.9448 p.u. The loss reduction is appreciable but the problem of under voltage persists.

- ***Impact of UPQC on Branch Current***

The placement of UPQC for reduction in the branch current in which maximum current flows is assessed in this section. The result of the impact of UPQC on branch current reduction is given in Figure 6. The maximum branch current for 33-bus system before placing UPQC is 364.3617 A.

From Figure 6, the reduction in the maximum branch current is observed at certain locations such as bus 7 with UPQC placement. The maximum branch current is 289.5296 A when UPQC is placed at bus 7.

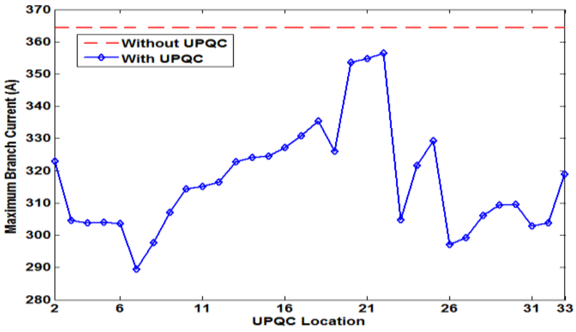

Figure 6: Maximum branch current after placing UPQC in 33-bus system

The maximum branch current for 69-bus system before placing UPQC is 387.2909 A. Figure 7 illustrates the reduction in maximum branch current with UPQC placed at different locations in the network for 69-bus system.

From Figure 7, the maximum branch current reduction is observed at the bus 62 with UPQC allocation. After UPQC placement at bus 62, the maximum branch current is 307.6174 A.

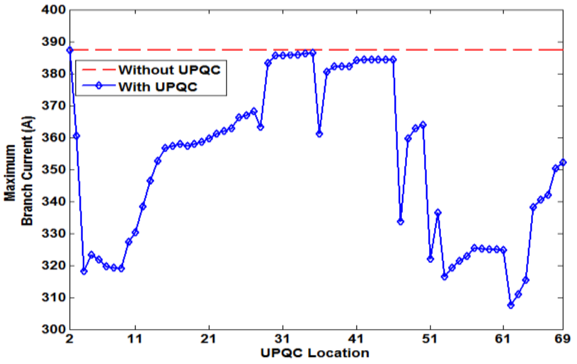

Figure 7: Maximum branch current after placing UPQC in 69-bus system

The impact of UPQC on under voltage problem mitigation is discussed in the following section.

- ***Impact of UPQC on under voltage problem mitigation***

The placement of UPQC for under voltage problem mitigation is discussed in this section. A particular bus is said to suffer from the problem of under voltage if the voltage at that particular bus is less than the specified limit of 0.95 p.u. The under voltage problem is expressed in terms of percentage. The percentage of buses suffering from under voltage problem is 63.63% in 33-bus system. The under voltage problem is severe in 33-bus system. After UPQC placement, the number of buses with under voltage problem in percentage is shown in Figure 8. The UPQC location at which the under voltage problem has been completely mitigated and maximum nodal voltage deviation is minimized is identified. The corresponding results are presented in Table 3.

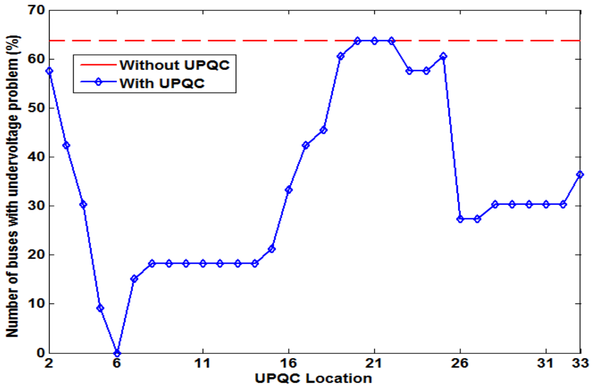

Figure 8: Number of buses with under voltage problem (%) after placing UPQC in 33-bus system

Table 3: Results of UPQC placement for 33-bus system for minimization of nodal voltage deviation

Sr No.	**33-bus system**		
	Description	***Without UPQC***	***With UPQC***
1	UPQC Location	-	6
2	Total real power loss (kW)	202.6771	144.9812
3	Total reactive power loss (kVAr)	135.141	98.5724
4	Minimum voltage (p.u.)	0.9131 @bus 18	0.9654 @bus 18
5	Number of Nodes with under voltage problem	21	0

From Table 3, it is observed that the problem of under voltage mitigation depends upon the location of UPQC. There are no buses with under voltage problem when UPQC is placed at bus 6. The under voltage problem has been completely mitigated when UPQC is located at bus 6.

For 69-bus network, the number of under voltage buses is 9. The number of buses suffering from under voltage problem is 13.04% in 69-bus system. The effect of UPQC placement on under voltage problem alleviation with UPQC placed at all possible locations in the 69-bus system is shown in Figure 9. The corresponding results are given in Table 4. The under voltage problem is completely mitigated, when UPQC is located at the buses 57 and 58, since the number of buses with under voltage problem is 0 %.

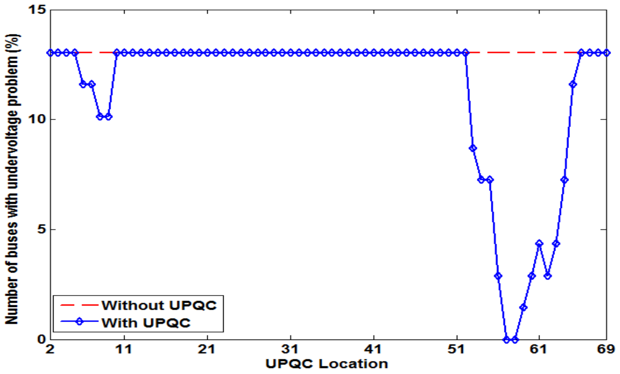

Figure 9: Number of buses with under voltage problem (%) after placing UPQC in 69-bus system

Table 4: Results of UPQC placement for 69-bus system for minimization of nodal voltage deviation

Sr No.	**69-bus system**		
	Description	***Without UPQC***	***With UPQC***
1	UPQC Location	-	57
2	Total real power loss (kW)	225.0044	159.0949
3	Total reactive power loss (kVAr)	102.2057	72.5639
4	Minimum voltage (p.u.)	0.9092 @bus 65	0.9616 @bus 27
5	Number of Nodes with under voltage problem	9	0

PERFORMANCE COMPARISON OF UPQC PLACEMENT APPROACH

A comparison of the results obtained for 33-bus system and 69-bus system is given in the following section:

As seen from Table 5, there is a significant reduction of 39.10% in the network real power losses when UPQC is placed at bus 31 in the 33-bus system with the aim of minimizing the network real power losses. Also, the under voltage problem is completely alleviated when UPQC is placed at bus 6 with the criteria of minimizing the nodal voltage deviations.

Table 5: Comparative results of UPQC placement for 33-bus system for minimization of network power loss

Description	Ref [26]	Ref [25]	Proposed Method
UPQC Location	30	29	31
Real Power Loss (kW)	151.94	145.10	123.4237
Real power loss reduction (%)	27.99	28.40	39.10

As observed from Table 6, UPQC placement has the maximum reduction in real power losses of 52.19% with the proposed approach as compared to the methods reported in reference [26] and reference [25].

Table 6: Comparative results of UPQC placement for 69-bus system for minimization of network power loss

Description	Ref [26]	Ref [25]	Proposed method
UPQC Location	61	61	62
Real Power Loss (kW)	153.96	137	107.5717
Minimum voltage (p.u.)	0.9275	0.941	0.9448
Real power loss reduction (%)	31.6	39.10	52.19

From Table 7, it can be seen that the improvement in minimum voltage is 0.9654 p.u. when UPQC is placed at bus 6 for minimizing the nodal voltage deviations.

Table 7: Comparative results of UPQC placement for 33-bus system for minimization of nodal voltage deviation

33-bus system		
Description	Ref [25]	Proposed Method
UPQC Location	6	6
Minimum voltage (p.u.)	0.9654	0.9654

From Table 8, it can be seen that the improvement in minimum voltage is 0.9616 p.u. when UPQC is placed at bus 57 for minimizing the nodal voltage deviations.

Table 8: Comparative results of UPQC placement for 69-bus system for minimization of nodal voltage deviation

69-bus system		
Description	Ref [25]	Proposed approach
UPQC Location	57	57
Real Power Loss (kW)	162.6574	159.0949
Minimum voltage (p.u.)	0.9613	0.9616
Real power loss reduction (%)	27.70	29.29

CONCLUSION

UPQC allocation in the distribution network to provide compensation is discussed. The effect of UPQC allocation is evaluated in steady state conditions. UPQC is placed at every bus in the distribution network. The impact of UPQC in the distribution network is assessed. In the given approach, the optimal series voltage is determined by using PSO. Hence the required load reactive power provided by the shunt compensator is inferred. The salient outcomes of the proposed approach are:

- The series compensator of UPQC injects series voltage to improve the voltage during normal operating conditions.
- UPQC significantly reduces the power loss and improves the voltage of a distribution network.
- The performance comparison shows that the proposed approach is better.

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