



# OPTIMAL PLACEMENT OF UNIFIED POWER QUALITY CONDITIONER IN DISTRIBUTION SYSTEMS USING PARTICLE SWARM OPTIMIZATION METHOD

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## ABSTRACT

This paper elucidates a Particle Swarm Optimization method (PSO) for optimal placement of Unified Power Quality Conditioner (UPQC) for loss reduction and voltage profile improvement in the radial distribution systems. UPQC comprises of a series and a shunt compensator. The shunt compensator delivers reactive power to meet the load reactive power demand. The series compensator takes part in voltage compensation. This paper gives an insight into the usefulness of UPQC in which the series compensator also shares part of the reactive power in steady state conditions such that the UPQC is utilized optimally. PSO is utilized to decide the optimal location and rating of UPQC. The proposed optimization method is applied to standard distribution systems.

**Keywords:** unified power quality conditioners, series compensator, shunt compensator, reactive power, particle swarm optimization method.

## 1. INTRODUCTION

The increase in the use of consumer electronics has led to an increase in the need for maintaining the voltage at the consumer terminals. Each and every load in the distribution system can be considered to be sensitive. To maintain the voltage at acceptable limits is obligatory on the part of the utility. The conventional approaches employed to maintain the voltage standards are capacitor placement, reconfiguration and distributed generation units placement [1-3]. The dawn of Flexible Alternating Current Transmission System (FACTS) has led to their usage in transmission and distribution system for relieving the system from the problem of congestion. With the increase in technology, these devices are also used for voltage and reactive power compensation in steady state operating conditions of the system. The development of research in this direction is evident in [4-6]. In [4-6], the application of Static Series Voltage Regulator (SSVR), Distribution Static Compensator (DSTATCOM) and UPQC is emphasized to provide voltage compensation in steady state conditions. SSVR provides voltage compensation by injecting the voltage in quadrature with the branch current by injecting reactive power. ADVF [7] is another series connected Custom Power Device which provides voltage compensation by injecting the active and reactive power. DSTATCOM [7] is shunt connected Distributed FACTS (DFACTS) device which regulates the load voltage by providing reactive power support. The Unified Power Quality Conditioner is a power electronics DFACTS device, comprising of a shunt and a series compensator. The common structure of UPQC consisting of two compensators connected back to back with a DC link as explained in [8]. Based on voltage compensation methods, the models of UPQC are UPQC-P, UPQC-Q [9] and UPQC-S [10]. In UPQC-P, the series compensator provides active power by injecting an in-phase voltage. The series compensator in UPQC-Q offers the reactive power by injecting a quadrature voltage. In UPQC-S

model, the series compensator provides both real as well as reactive powers. The minimization of the VA rating of the UPQC is presented in [11]. The problem of UPQC placement is a nonlinear problem. In large distribution system, the UPQC placement and sizing problem has been solved by using various algorithms. Taher S.A. *et al*, [12] has elucidated the problem of UPQC allocation with the differential evolution algorithm. Boutebel M. *et al*, [13] has elucidated the problem of UPQC placement by using hybrid method. In this paper, the UPQC placement problem is evaluated with the Particle Swarm Optimization method. PSO method based on swarm intelligence is superior to evolutionary methods.

The main inspiration behind this work is on the application of series compensator in steady state conditions to compensate the voltage to desired value such that the reactive power delivered by using the shunt compensator is reduced.

In Section 1, introduction to the problem is presented. Section 2 provides the objective of the problem; Section 3 defines the load flow method used in the distribution system. In Section 4, UPQC modeling is presented. In Section 5, introduction to PSO is detailed; the results and conclusions are discussed in Section 6 and 7 respectively.

## 2. PROBLEM FORMULATION

The objective function used for the goal of real power loss minimization and improvement in voltage is defined as follows:

$$\text{Minimization of } P_{Total} = \sum_{i=1}^{nb} P_{loss}(i) \quad (1)$$

$$P_{loss}(i) = \sum_{i=1}^{nb} (I_b(i))^2 R(i) \quad (2)$$

Where  $P_{Total}$  = the total system real power loss.  
 $P_{loss}(i)$  = the  $i^{th}$  branch real power loss.  
 $nb$  = the total branches in the network.



The real power loss in a branch is dependent on branch resistance and branch current.

The equality constraints related to the objective function are as follows:

The total power in the network must be balanced.

$$P_i = P_L + P_{Loss} \quad (3)$$

$$Q_i = Q_L + Q_{Loss} \quad (4)$$

Where

$P_i, P_L$  and  $P_{Loss}$  = the real power input, real power demand and real power losses.

$Q_i, Q_L$  and  $Q_{Loss}$  = the reactive power input, reactive power demand and reactive power losses

The inequality constraints related to the objective function are as follows:

A. The load bus voltage magnitude should be kept within acceptable operating limits. That is  $\pm 5\%$  of the nominal voltage value.

$$V_{min} \leq V_m \leq V_{max} \quad (5)$$

B. The inequality constraint associated with reactive power compensation is

$$Q_{UPQC} \leq Q_D \quad (6)$$

$Q_{UPQC}$  = the reactive power supplied by UPQC at the node m.

$Q_D$  = the sum of reactive power demand beyond node m.

### 3. RADIAL DISTRIBUTION SYSTEM LOAD FLOW METHOD

There are different Load Flow methods which are detailed in [14, 15 and 16]. The load flow method used involves estimation of load currents, the construction of BIBC matrix and forward sweep. The load current for the  $m^{\text{th}}$  bus is estimated as given in equation (7)

$$I_L(m) = \left( \frac{P_L(m) + jQ_L(m)}{V(m)} \right)^* \quad (7)$$

The branch currents are calculated on the basis of BIBC matrix

$$[I_b] = [BIBC][I_L] \quad (8)$$

Voltage drop in the  $i^{\text{th}}$  branch is calculated as

$$\Delta V(i) = I_b(i) \cdot Z(i) \quad (9)$$

Bus voltage is obtained by equation (10)

$$V_R(i) = V_s(i) - \Delta V(i) \quad (10)$$

Where

$V_R$  = voltage at the receiving end.

$V_s$  = voltage at the sending end.

$I_b$  = branch current.

$P_L(m)$  = load active power demand at the  $m^{\text{th}}$  bus.

$Q_L(m)$  = load reactive power demand at the  $m^{\text{th}}$  bus.

### 4. MODELING OF UPQC

The UPQC is a unified device. It is also named as unified power quality conditioning system, universal active filter, universal power line conditioner and so on [17]. It consists of a series and a shunt compensator. Various UPQC models are available. The model adopted is presented in Figure-1.

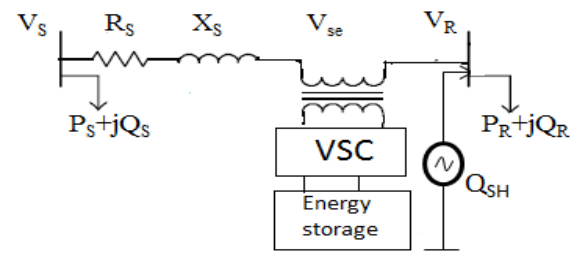


Figure-1. UPQC Structure.

The shunt compensator is modeled as the source of reactive power. The energy storage unit provides the required real and reactive power to generate compensating voltage. Independent operation of the two compensators is as follows:

**Series compensator:** It injects voltage ( $V_{sc}$ ) in series with the branch by means of the series transformer in such a way that the voltage at the desired node is compensated to the desired value. The related phasor diagram of the injected voltage by the series compensator is presented in Figure-2.

The amount of compensation dictates the need for real and reactive power. The energy storage unit serves this purpose.

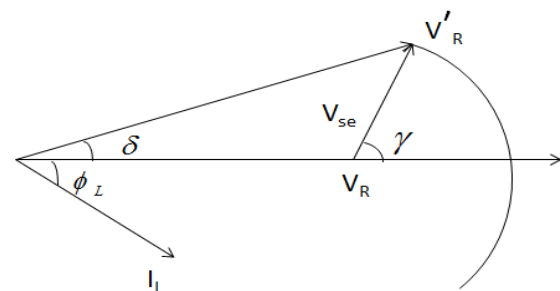


Figure-2. Phasor diagram for voltage injected by the series compensator.

The voltage injected by the series compensator is estimated as given in equation (11)

$$V_R \angle \delta = V_R + V_{sc} \angle \gamma \quad (11)$$



The complex power injected by the series compensator is obtained as given in equation (12)

$$S_{se} = V_{se} \cdot I_b^* \quad (12)$$

Where  $V_{se}$  = voltage injected by the series compensator.

**Shunt compensator:** The purpose of shunt compensator is to offer the required reactive power to compensate the load reactive power demand.

Since UPQC is the integration of shunt and series compensators, the series compensator operates in minimum complex power injection mode [13] to improve the load bus voltage to desired voltage (1 p.u.) and the shunt compensator provides less reactive power.

With the injection of voltage by the series compensator, the receiving end voltage is changed to  $V_R'$ . The reactive power to be injected is calculated as given in equation (13)

$$Q_{SH} = V_R' I_c' \quad (13)$$

Where  $V_R' I_c'$  is the compensating node voltage and compensating current described in [1, 2] after the compensation provided by the series compensator.

## 5. PARTICLE SWARM OPTIMIZATION METHOD

Particle Swarm Optimization is motivated from the behavior of swarm [18]. Swarm can be a flock of birds or fish group. It has stable convergence characteristics. The ability of birds to search for food is modeled in this optimization. PSO is found to be superior to evolutionary optimization methods. The terms associated with PSO are personal best, which indicates the best position of the particle and global best, which indicates the best position of the particles. The searching mechanism of PSO involves velocity update and position update. The pbest and gbest are updated in every iteration. The number of particles in this method does not get affected in this optimization process.

### 5.1. Pseudo code:

Begin:

Generate the particles randomly.

Find the fitness. Obtain the pbest and gbest.

While iteration < maximum iterations

Update the velocity of each particle

Update the position of each particle

Find the fitness. Obtain the gbest and pbest

End

Print the gbest

### 5.2. ALGORITHM TO FIND THE LOCATION AND RATING OF UPQC BY USING PSO:

**Step 1:** Initialize the 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:** Create the particles and velocities randomly within the boundaries. Here the particles are locations and real and imaginary part of the voltage injected by the series compensator.

**Step 3:** Run the load flow by compensating the voltage at the desired location as given in equation (11). Compute the shunt compensation value by using equation (13). Find the fitness. Here the fitness is the minimization of real power losses.

**Step 4:** Recognize the best particles (pbest) based on the fitness values. Discard the particles which violate the constraint that the voltage at the desired location does not exceed 1 p.u. The best particle from the pbest (gbest) is recognized.

**Step 5:** Set the Iteration count to one.

**Step 6:** Find the velocity of the particles for all the dimensions using equation (14)

$$Vel^{t+1} = k * (w * Vel^t + c_1 random_1(pbest^t - X^t) + c_1 random_1(gbest^t - X^t)) \quad (14)$$

Where  $k$

=constriction factor

$c_1, c_2$

= the learning constants.

$random_1, random_2$

= random numbers in the range [0 -1]

$Vel^{t+1}$

=velocity of the particle.

$X^t$

= position of the particle.

$pbest^t$

= personal best of the particle.

$gbest^t$

= global best of the particle.

$w$  is the inertia weight given by

$$w = w_{maximum} - (w_{maximum} - w_{minimum}) * t/T \quad (15)$$

Where,  $w$

=an adjustable parameter between

$w_{maximum}$  and  $w_{minimum}$

$t$

=present iteration.

$T$

=maximum iterations.

**Step 7:** Update the position of each particle for all the dimensions as given in equation (16)

$$X^{t+1} = X^t + Vel^{t+1} \quad (16)$$

**Step 8:** Run the load flow. Compensate the voltage at the desired location as given in equation (11). Calculate the shunt compensation value by using equation (13). Determine the new fitness values. Update the pbest particles if the voltage at the desired location does not exceed 1 p.u. Update the gbest from the most recent obtained pbest.

**Step 9:** Increment the iteration. If the number of iterations does not reach its maximum, then repeat the steps starting from step 6, else go to step 10.

**Step 10:** The gbest particle specifies the location and voltage injected by the series compensator.



**Step 11:** Prints the results for complex power injected by the series compensator and reactive power injected by the shunt compensator.

## 6. RESULTS

15 and 33 bus systems are used to study the performance of UPQC and explain the proposed approach. PSO parameters:

Number of particles=100.

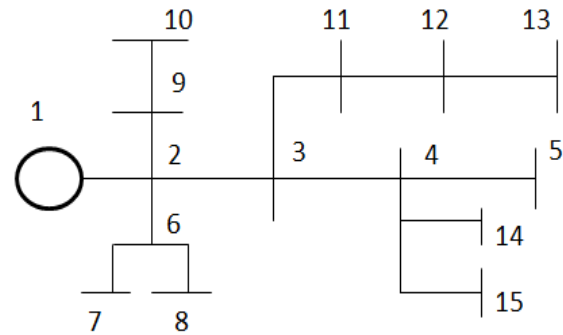
$w_{maximum}$  and  $w_{minimum}$  are chosen as 0.9 and 0.4 respectively.

Learning constants  $c_1=c_2=2.05$ .

Constriction factor  $k=0.7298$ .

### 6.1 Results of 15-Bus test system

The network configuration of the 11kV, 15-bus radial distribution system is shown in Figure-3. The data of the system is acquired from [16].



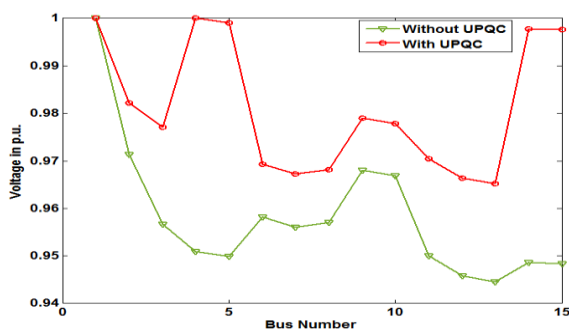
**Figure- 3.** Network configuration of 15 bus system.

The real and reactive load of the system is 1226 kW and 1251kVAr respectively. 6 out of 15 buses have under voltage problem. The results of UPQC placement for 15 bus system are presented in Table-1.

**Table-1.** Results of 15 bus System.

Description	Without UPQC	With UPQC
Bus No	-	4
Total real power loss(kW)	61.7944	33.2480
Total reactive power loss (kVAr)	57.2977	29.4799
Complex Voltage injected by the series compensator (p.u.)	-	0.2295i
Real power injected by the series compensator (kW)	-	101.10
Reactive power injected by the series compensator (kVAr)	-	70.959
Reactive power injected by the shunt compensator (kVAr)	-	768.5101
Minimum voltage (p.u.)	0.9445 @bus 13	0.9652 @bus 13
Nodes with under voltage problem (<0.95)	6	0

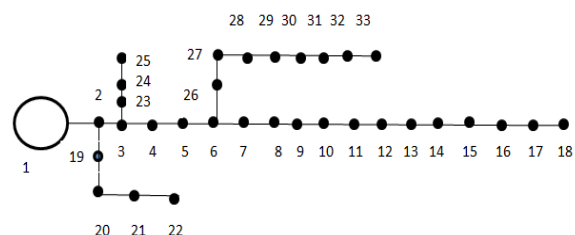
The shunt compensation required after UPQC placement is 768.51 kVAr. The minimum voltage has increased from 0.9445 p.u. to 0.9652 p.u. at 13<sup>th</sup> node as shown in Figure-4. The reduction in real power loss is 46.2%.



**Figure-4.** Voltage profile without and with consideration of UPQC in 15 bus system.

### 6.2 Results of 33-Bus test system

The network configuration of the 12.66 kV, 33-bus radial distribution system is shown in Figure-5. The data of the system is acquired from [20]. The real and reactive load of the system is 3715 kW and 2300 kVAr respectively. 21 out of 33 buses have under voltage problem. The results of UPQC placement for 33 bus system are presented in Table-2.



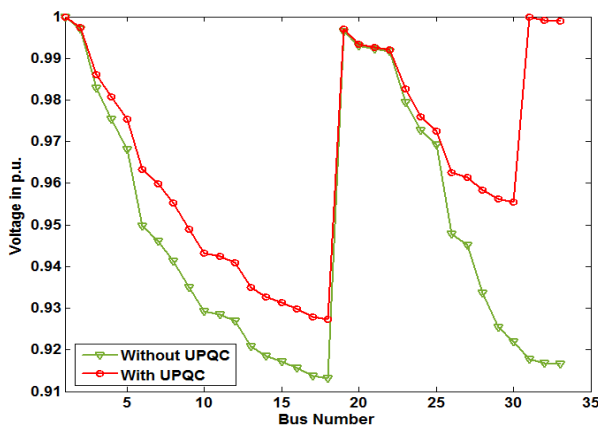
**Figure-5.** Network configuration for 33 bus system.

**Table-2.** 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

The shunt compensation required after UPQC placement is 954.2685kVAr. The minimum voltage has increased from 0.9131p.u. to 0.9273p.u. at 18<sup>th</sup> node. The reduction in real power loss is 39.1%.

The improvement in voltage for 33 bus system is shown in Figure-6.

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

The results obtained with 33 bus system, presented in Table-3, are compared with Differential Evolution (DE) method and the method available in [19].

**Table-3.** Comparative results for 33 bus system.

Description	DE[12]	Method in [19]	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

From the results, the proposed method of UPQC placement is the most efficient since the losses are considerably reduced and the voltage profile is also improved.

## 7. CONCLUSIONS

Unified Power Quality Conditioner's usefulness with respect to reduction in power loss and voltage profile improvement is evaluated. The injection of series voltage by the series compensator aids in voltage compensation. The shunt compensator provides reactive power to meet the load reactive power demand. The location and size of UPQC are acquired by means of the Particle Swarm Optimization method. The results specify the efficacy of the proposed optimization method for standard distribution systems.

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