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Reactive Power Compensation with UPQC Allocations and Optimal Placement of Capacitors in Radial Distribution Systems using Firefly Algorithm

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ABSTRACT

Shunt capacitor in power systems are very commonly used to provide reactive power compensation in distribution systems. The shunt capacitors are installed on the radial distribution system is essential for the power flow control, voltage profile management and losses minimization. This paper aims in reducing the losses by placing the capacitors in the distribution system. The usage of shunt capacitors is less expensive option in the distributed system expansion. A fast and new method of multi-objective optimal planning that can also be applied to the real-time system operations, is implemented in this study effectively. Also a Multi-objective planning algorithm for reactive power compensation of radial distribution networks with unified power quality conditioner (UPQC) allocation is used. In the proposed approach, the optimal location, and parameters of UPQC, a multi-objective planning model is formulated with three objective functions. They are minimization of: 1) the rating of the UPQC, 2) network power loss, and 3) percentage of nodes with under-voltage problem (PNUVP). The simultaneous optimization of these objectives is carried out using Pareto-dominance principle to obtain a set of non-dominated solutions called Pareto-approximation set, in which no solution is inferior to other. Their performances on the present problem are compared and the better one is used in subsequent studies. In this paper Firefly Algorithm for the IEEE33 and IEEE69 bus has been programmed in MATLAB to achieve better system performance.

1. INTRODUCTION

The increasing demand requires the distribution utilities to increase the capacity and also enhance the performance of their system. These goals are normally achieved by the substation and/or the network expansion. However, these above options are very expensive for the utility [1]. The usage of a shunt capacitors in the system are less expensive for the system upgrading.There is a need to optimally minimize the losses, improves the voltage stability by applying shunt capacitors to a system, and considering the trade-offs among the said objectives. Furthermore, increasing the capacity of the system, the capacitor placement can be typically used together with other capacity improving alternatives like network reconfiguration and distributed generation. This process of utilizing all the three alternatives for increasing the capacity will give us the best results for the system.

The optimal reactive power compensation can significantly improve the performance of a radial distribution network by reducing its power loss and improving its voltage profile, and line loadability. The latest addition is the distribution FACTS (DFACTS) device allocation. The unified power quality conditioner (UPQC) is one of the versatile DFACTS devices. To determine the optimal location and parameters of UPQC, a multi-objective planning model is formulated with three objective functions. They are minimization of: 1) the rating of the UPQC, 2) network power loss, and 3) percentage of nodes with undervoltage problem (PNUVP). The simultaneous optimization of these objectives is carried out using Pareto-dominance principle

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to obtain a set of non-dominated solutions called Pareto-approximation set, in which no solution is inferior to other.

The solution strategy used is Firefly Algorithm (FA) for its easy implementation, effective memory use, and an efficient maintenance of the solution diversity. Its performance is also tested on a number of power system problems. Since FA is a multi-point search algorithm, it can provide a set of non-dominated solutions in a single run. The planning approach is validated on a33-node and a 69-node distribution networks.

2. MULTI-OBJECTIVE PLANNING MODEL FOR REACTIVE POWER COMPENSATION WITH UPQC ALLOCATIONS

2.1. FA: Introduction

In this firefly algorithm[14], the optimization technique depends on the brightness of the fireflies and they move towards their brighter counterparts. All the fireflies are attracted towards the other flies that depend upon their brightness, since they are all unisexual.

The parameters required for the algorithm are, Brightness, Alpha (α), Beta (β), Gamma (γ), no of generations, Dimensions, no of flies, and R. The modified existing firefly algorithm code is done to evaluate the performance of algorithm by varying its parameter as mentioned above.

The algorithm starts by initializing the population of the fireflies and the fireflies are different from each other. The difference is based on the brightness of the flies. The brightness determines the internal movement of the flies. The brightness of one fly is compared with the other flies and their difference of brightness makes the movement. The travelling distance depends on the attraction between the flies. The best solution is continuously updated and the process carried out till the stopping conditions are met. The

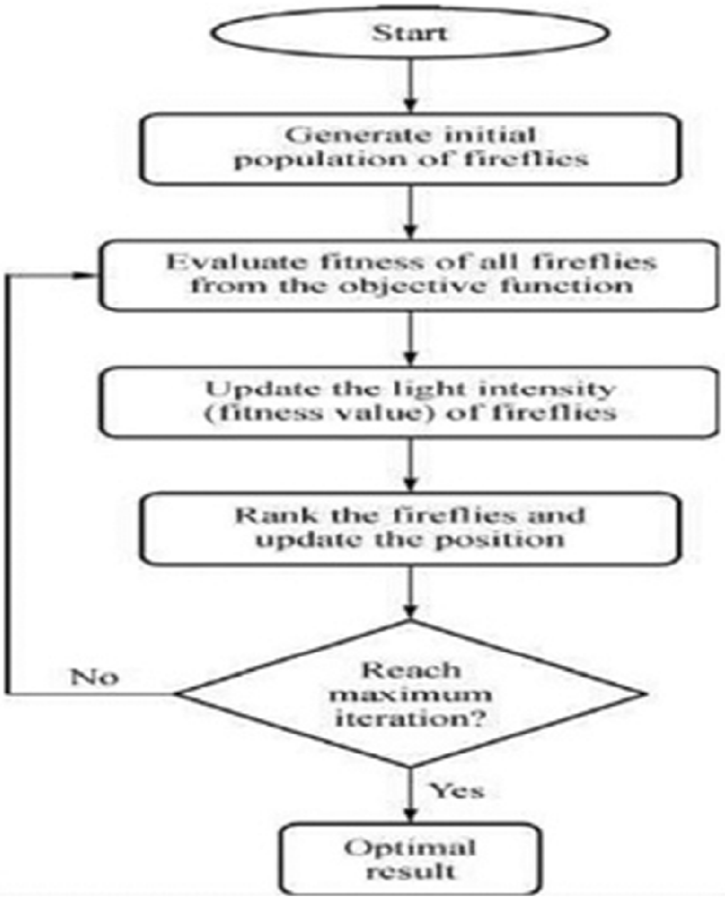

Figure 1: Flowchart for Firefly Algorithm

best solution is then determined to obtain the best results. The flowchart figure 1 explains the steps involved in the firefly algorithm.

2.2. Planning Algorithm

The planning algorithm consists of two important support subroutines, i.e., particle encoding/decoding scheme and load flow with UPQC-PAC model. A particle in MOPSO consists of three segments with the direct information of: 1) UPQC location in the network, 2) the amount of reactive power compensation required, and 3) Kse. During the decoding process, the first segment of a particle is always converted to its nearest integer number. The solutions violating the third constraint are penalized. The pseudocode for the complete planning algorithm are shown below

The pseudo code for the complete planning algorithm are shown below

```
Begin
    Generate initial population using encoding scheme (both position and velocity);
    Decode the particles and calculate the objective functions;
    Find the initial non-dominated solutions;
    Find out initial set of guides;
    Iteration = 1;
    While iteration ←
        For
            Assign a guide for particle i from the set of guides;
            Update velocity and position of the particle;
            Decode particle to get the location and parameters for UPQC;
            Perform load flow incorporating the UPQC-Pac model;
            Calculate the objective functions;
        Endfor
        Find out the non-dominated solutions;
        Find out the new set of guides;
        Iteration = iteration + 1;
    Endwhile
    The final set of non-dominated solutions consists of optimal location, size and the parameters for UPQC;
End
```

In the proposed planning approach, a multi-objective planning model is formulated for determining the optimal location for UPQC [2], the optimal amount of reactive power compensation required at the location, and the optimal value of kse. These optimizing variables are determined by minimizing three objective functions. They are: 1) VA rating of the UPQC, 2) network power loss, and 3) percentage of nodes with under voltage problem (PNUVP) compared to the uncompensated network (i.e., without UPQC). The objective function 1 deals with system economy and its minimization provides an economical solution. The objective functions 2 and 3 are the performance measures of a network.

2.3. Objective Functions

The minimization of the following objectives is required to obtain better performance a network. The expressions for objective functions are given as follows.

The optimization is carried out under the following constraints:

1) A UPQC is designed so that it can mitigate a given maximum value of voltage sag, if required. Thus, the value of is to be kept above the minimum value required to mitigate the given maximum amount of voltage sag.
2) The total reactive power delivered by a UPQC is to be kept below the sum of the reactive power demand of all nodes in a network.
3) The line current is to be kept below the thermal limit of the line. In this work, the Pareto based approach is used.

The optimization is performed considering three cases:

- Case A: Simultaneous optimization of the objective functions 1 and 2
- Case B: Simultaneous optimization of the objective functions 1 and 3
- Case C: Simultaneous optimization of the objective functions 1, 2, and 3

3. OPTIMAL PLACEMENT OF CAPACITOR IN A RADIAL DISTRIBUTED SYSTEM FOR IMPROVEMENT OF VOLTAGE STABILITY

3.1. Capacitor Placement

The shunt capacitor banks are commonly used to improve the quality of the electrical power supply and the efficient operation of power system. We can come to know from the studies that maintaining a flat voltage profile on the system can be able to reduce the line losses [4]. Therefore, by placing the capacitor banks on the optimal place in the line will be greatly useful in maintaining the voltage profile, reduce loss, maintain the voltage stability, etc. Since the shunt capacitor banks are very inexpensive compared to other alternatives and it is very to install anywhere in the system line network and so it is preferred and used the most. The placement of the capacitors in the system is a challenge. Therefore, the optimal placement of capacitor problem is to determine the exact location of capacitors that are placed on the distribution network in a very efficient way to improve the voltage profile of the system and to reduce the power loss. The shunt capacitor placement is done for both the IEEE33 and IEEE69 buses. The capacitors are placed at three places in both the IEEE33 and IEEE69 buses. The capacitor size is around 5Mvar is installed. Also the capacitor cost is calculated here.

3.2. Multi-Objective Problem

The multi-objective optimization problem [5] involves optimizing number of objectives by satisfying all the constraints related to the objective. It is formulated as,

$$\text{Minimize } [f1(X^*), f2(X^*), ..., fn\ \text{obj}(X^*)]T$$

Subject to

$$gj(X^*) = 0\ j = 1, 2, \dots \text{neq}$$

$hk(X^*) = 0$ $k = 1, 2, \dots$ nineq where fi = objective function i; X^* = optimal feasible solution ; nobj = number of objective function ; neq = number of equality constraints ; nineq = number of inequality constraints.

The aim is to optimize the power losses and voltage stability by placing the capacitors optimally.

3.3. Power Loss Objective Function

The most frequently considering objective when capacitor placement [6] is used is the power loss minimization. By minimizing the power loss, the utility can minimize its cost as well maximize its system capacity. The total real power loss PLoss is given as,

Min PLoss = $\sum$

Where ri = resistance of branch i; Ii = current in branch i ; and nb = number of branches.

3.4. Voltage Stability Objective Function

Voltage supporting elements like capacitors can reduce the risk of voltage instability and voltage collapse. Voltage instability is undesirable because it leads to unacceptable and unreliable quality of the power.

The approach to the voltage stability judgement involves finding the distance of system operating from the point of instability voltage. Using reactive and real power losses, the voltage stability index for the system can be identified without checking every line in network. It can quickly predict the stability without any changes in the algorithm. The voltage stability index is given by,

$$\text{MinVSI} = 4[(xeq\ Pleq - req\ Qleq)2 + xeq\ Qleq + req\ Pleq]$$

Where

$$req = Ploss / [(Pleq + Ploss)2 + (Qleq + Qloss)2]$$

$xeq = Qloss / [(Pleq + Ploss)2 + (Qleq + Qloss)2]$ where Pleq, Qleq = total real and reactive load; Ploss,Qloss = total real and reactive losses ; req, xeq = equivalent resistance and reactance of the system. The VSI should be less than 1.0 for the stable system.

3.5. Constraints

The constraints are implemented in both the load flow algorithms and the optimization, considering the inequality constraints like the current and the voltage limits. Even one constraint is violated in the load flow also needs a penalty to the objective functions. The constraints must be satisfied at feasible solutions: 1. The voltage of any bus must be within the allowable range. 2. All nodes must be energized throughout the process. 3. The system must remain in the radial topology itself.

4. TESTING AND RESULTS

The IEEE33 and IEEE69 bus test system are used for the evaluation performance of the proposed method. The IEEE33 bus consists of 32 branches and three tie lines. The IEEE69 bus consists of 68 branches and seven tie lines. The base values for both the buses are 100MVA and 11 kV.

4.1. IEEE 33 bus

The output for the placement of capacitor is as follows. The output is differentiated with colors for both with and without capacitors. The output for the capacitor placement is shown in Figure 2.

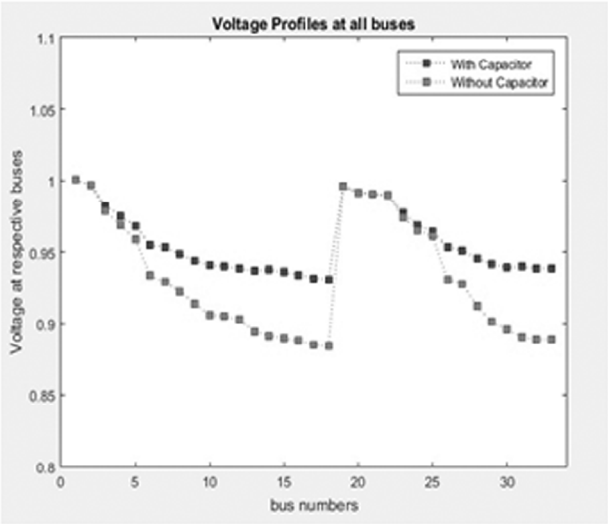

Figure 2: Output for with and without capacitor placement

Table 1
Output before and after placement (IEEE 33 Bus)

	Before Capacitor Placement	*After Capacitor Placement*
Total Power Loss	267.424178 kW	189.676201 Kw
VSI	0.065520 kW	0.046379 kW

The Table I listed above deals with the total power loss and voltage stability index for the placement of capacitors before and after the placement for IEEE33 bus. The Table II deals with the capacitor cost, size and locations for IEEE33 bus. Also provided with power loss and annual cost.

Table 2
Size and cost for the output (IEEE 33 Bus)

Capacitor Placement Locations	18 27 29
Power Loss Cost	31865.601831 $/yr
Proposed Capacitor Size	5485.829211 Kvar
Capacitor Cost	2842.914605 $/yr
Total Annual Cost	255.196314 $/yr

4.2. IEEE 69 bus

The output for the placement of capacitor is as follows. The output is differentiated with colors for both with and without capacitors. The output for the capacitor placement is shown in Figure 3.

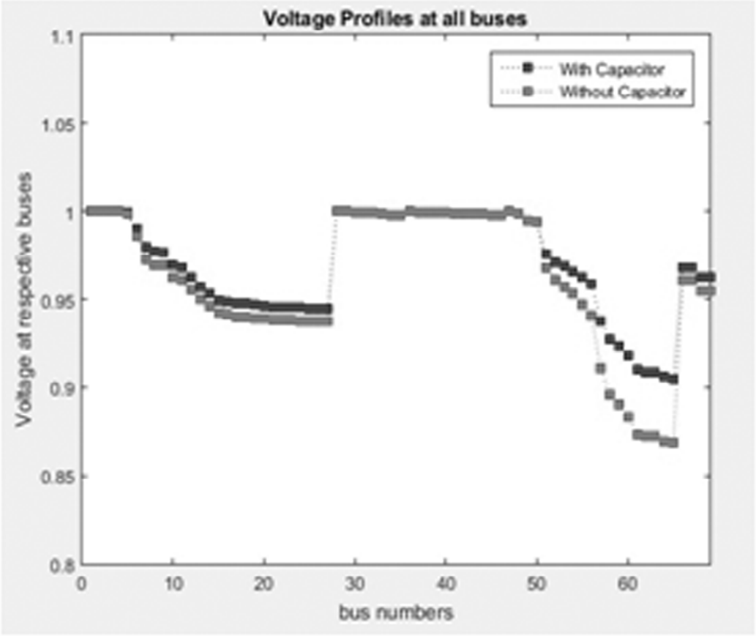

Figure 3: Output for with and without capacitor placement

Table 3
Output before and after placement (IEEE 69 Bus)

	Before Capacitor Placement	*After Capacitor Placement*
Total Power Loss	349.892434 kW	224.775383 kW
VSI	0.073563 kW	0.047480 kW

Table 4
Size and cost for the output (IEEE 69 Bus)

Capacitor Placement Locations	12 60 62
Power Loss Cost	37762.264350 $/yr
Proposed Capacitor Size	5531.544119 Kvar
Capacitor Cost	2865.772059 $/yr
Total Annual Cost	301.338813 $/yr

The Table III listed above deals with the total power loss and voltage stability index for the placement of capacitors before and after the placement for IEEE69 bus. The Table IV deals with the capacitor cost, size and locations for IEEE69 bus. Also provided with the power loss and annual cost.

4.3. Reactive Power Compensation in Radial Distribution Networks

A simulation study is performed to validate the proposed planning approach using two test distribution networks:

1) 33-node system and
2) 69-node system.

The optimal reactive power compensation is determined considering the peak load demand at each node. Firstly, a performance comparison between SPEA2-MOPSO and NSMOPSO is given.

Then, the results of different planning cases are presented and analyzed. The results obtained with different load levels are provided. A comparative study with PSO is also shown.

4.4. Results Obtained With Different Planning Cases

The PAFs obtained with the planning *Case A* are shown in Figs. 4 and 6 for both the networks. Each solution represents a different combination of the location and size for UPQC. The power losses of the uncompensated networks (i.e., without UPQC) are 202.67 kW and 224.98 kW for the 33- and 69-node networks, respectively. The result shows that significant amount of loss reduction can be obtained with UPQC allocation. The voltage at any node less than the allowable limit is said to have the undervoltage problem. With a limit of 0.95 p.u., 21 nodes of the 33-node (i.e., 63.63%) and 9 nodes of the 69-node (i.e., 13.04%) networks have the under voltage problem without UPQC. The PAFs obtained with the planning *Case B* are shown in Figs.5 and 7 for both the networks. The results illustrate that a UPQC rated around 0.8 MVA is sufficient to bring out all nodes from the under voltage problem. On the contrary, the rating of UPQC as determined in for the same purpose is above 2 MVA for the 33-node network. Hence, the proposed approach provides more economical solution. In the 69-node system, the number of nodes with under voltage problem without UPQC is 9. Thus, there exist only few solutions in the PAF.

i. PAFs obtained with the 33 node system for planning case A

Fig. 4 and Fig. 5 shows the simulation graph of 33 node system for planning case A and case B.

ii. PAFs obtained with the 33 node system for planning case B

iii. PAFs obtained with the 69 node system for planning case A

Fig. 6 and Fig. 7 shows the simulation graph of 69 node system for planning case A and case B.

iv. PAFs obtained with the 69 node system for planning case B

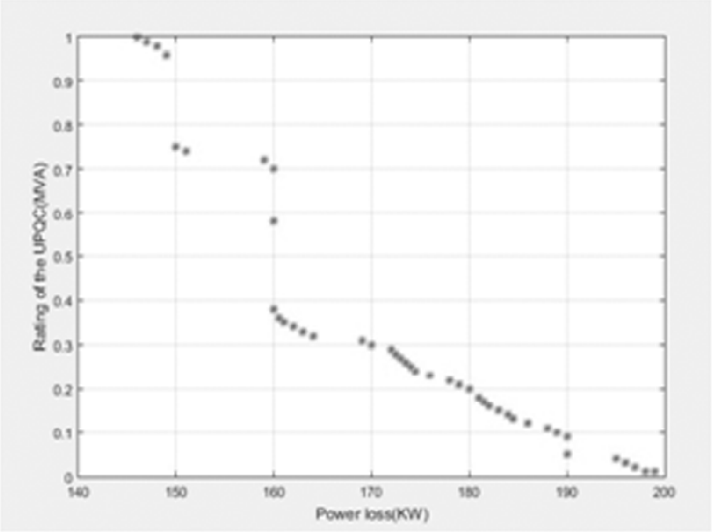

Figure 4: Simulation Result of 33 node system for case A

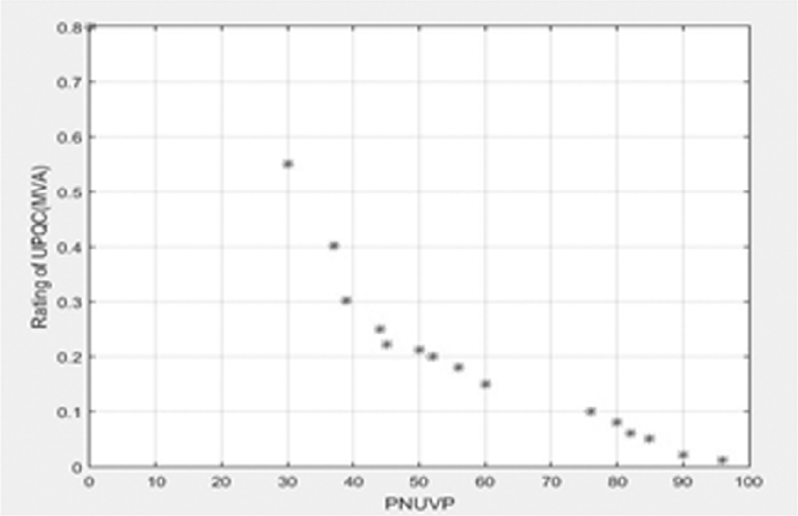

Figure 5: Simulation Result of 33 node system for case B

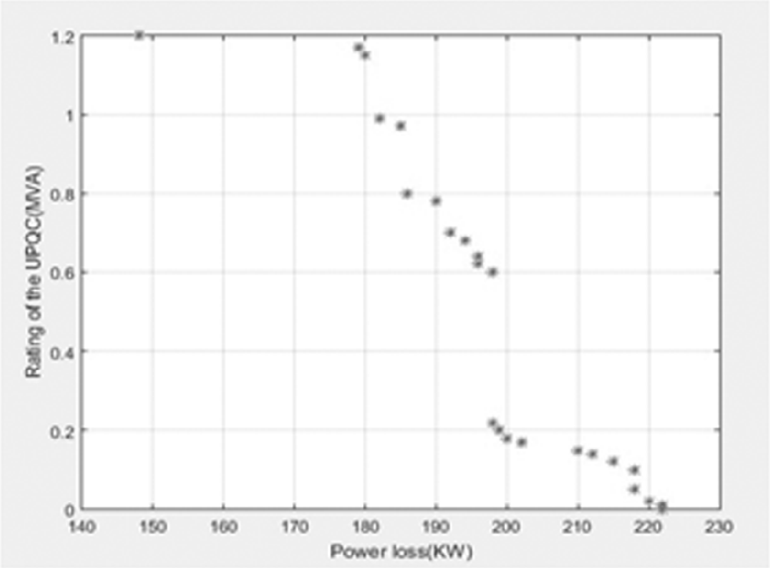

Figure 6: Simulation Result of 69 node system for case A

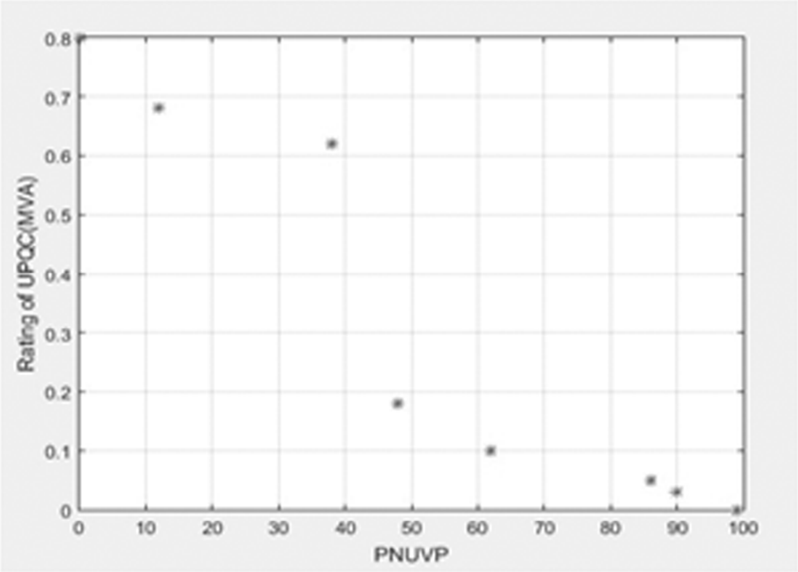

Figure 7: Simulation Result of 69 node system for case B

Table 5
Power Losses without UPQC

Test Network	*Power Loss (KW)*
33	202.67
69	224.98

4.5. Results Obtained With Different Load Levels

The peak load demand of each node of a network is used in the determination of the optimal reactive power compensation. The reason is that a UPQC designed to operate at peak load demand can be operated in any other loading condition. The PAFs obtained with the 33-node system are shown in Fig. 8. The result illustrates that the PAFs are of same pattern. However, the network power loss and the MVA rating for UPQC are

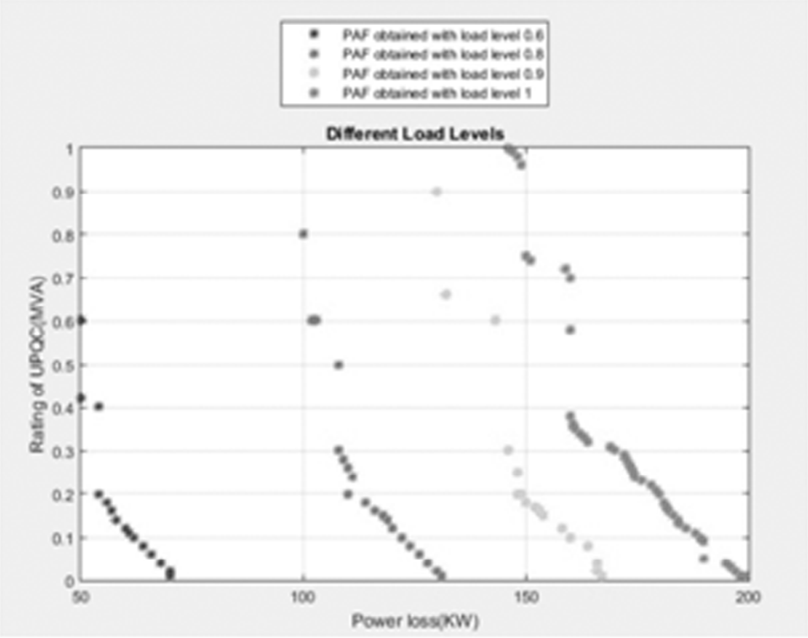

Figure 8: PAFs obtained with different load levels for 33 node system

obviously lower for the solutions obtained with lower load level because of the lesser load current at each line at lower load level.

4.6. Comparison Of PSO And FA

The performance of both algorithms PSO and FFA seems to be not so different to approach to the optimum. FFA tends to be better, especially on the functions having multi-peaks. Complexity or difficulty level of the functions had no effect to the FFA as expected. However, execute time in each replication is dramatically higher when they are compared. PSO seems to be better in terms of speed of convergence. This might be due to the effect from generating the completely different random numbers to be used in the iterative procedures of the algorithm. This implies that the FFA is potentially more powerful in solving noisy non-linear optimization problems. The FFA seems to be a favorable optimization tool in part due to the effect of the attractiveness function which is a unique to the firefly behavior. The FFA not only includes the self-improving process with the current space, but it also includes the improvement among its own space from the previous stages. Also Firefly is better than PSO in terms of the time taken for the optimum or near optimum value to be generated provided certain high level of noise where the difference in time taken becomes more evident with the increase in the level of noise. The comparative results of reactive power compensation with FFA and PSO are shown in Table VII.

Table 6
Solutions with the lowest power loss and PNUVP

Solution	Test Network	UPQC Location	Q_{UPQC} (MVAR)	Rating of UPQC(MVA)	Power Loss (KW)	PNUVP
A	33	8	0.9	1.25	146.5	29.57
	69	63	1.1	1.38	149	30.33
B	33	7	0.85	0.9	184.75	0
	69	59	0.8	0.7	193.77	0

Table 7
Comparative results of reactive power compensation with FFA and PSO

Operational aspects	*FFA*		*PSO*	
	A	*B*	*A*	*B*
UPQC LOCATION	63	59	61	61
POWERLOSS(KW)	150	194	158.61	211.04
MVA RATING	1.38	0.7	0.92	2.68

V. CONCLUSION AND FUTURE SCOPE

A multi-objective planning for the reactive power compensation of radial distribution networks with UPQC allocation has been done. A UPQC which is traditionally used in power quality improvement of a single load can efficiently be used in reactive power compensation of a distribution network as well. Based on the simulation results the following conclusions are arrived.

- It is shown that if a UPQC is optimally allocated and operated at healthy operating condition it can significantly reduce the power loss and improve the node voltage of a distribution network.
- The multi-objective planning approach with UPQC allocation provides a number of non-dominated solutions which facilitates in decision making for a utility to choose a final solution according to its capital expenditure budget and acceptable power loss and voltage profile of a network.

- The quantitative performance comparison shows that better solutions are obtained with the proposed approach and also provides economical solutions.
- The multi-point reactive power compensation provides better solution for higher rated UPQCs.
- The optimal locations for UPQC remain unchanged if the optimization is carried out with different load levels.

Application of various optimization techniques in UPQC can be incorporated, so as to mitigate the power quality issues like voltage stability limit, line load ability, and load balancing.

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