Proceedings of 12th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: October Volume: 12

Performance Analysis of Radial Distribution System using Optimal Capacitor Bank Placement

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Abstract
This paper presents two stages of methods to identify the location and size of the capacitor bank. The load flow is carried out to find the losses of the system using the sweep algorithm in the initial stage. In the next stage, the particle swarm optimization algorithm is used to determine the location and sizes of the capacitors to be installed. Loss sensitivity factors are calculated using a single base case load flow study on the IEEE 15 bus system for the validation purpose which provides important information about the sequence of potential nodes for the capacitor placement. The fixed, switched capacitors are considered to obtain the optimal solution. The proposed procedure is applied to standard test systems as a 15-bus radial distribution system and on a real distribution scenario, a section of 11 kV Banepa Feeder which identifies sensitive buses and computes the optimal size and location of the capacitors that are to be installed. The optimal capacitor placement in a Banepa feeder was done in ETAP. The drop in voltage and power loss before and after installing the capacitor were compared for the system in the analysis. The output showed improvement in voltage profile and power losses after installing capacitors in the system.

Keywords
Distribution feeder, Loss minimization, Loss Sensitivity Factors, Particle Swarm Optimization, Voltage profile

1. Introduction

Compared to the power losses at the transmission and generation levels, a sizable amount of power is lost at the distribution level. This is because there are significant power losses at the distribution level due to the low voltage and high current [1]. In the Nepalese distribution system context, to feed the scattered loads over large areas, there is an extension of distribution lines. This causes high I^2R line losses and further results in a decrement of voltage in the load end. The voltage drop due to high load and rapid load growth is the major problem of the distribution system. Drop-in voltage and losses problem of distribution feeders are dependent on each other and those parameters vary with the feeder loading pattern [2]. There are a number of methods to improve the performance of the distribution system, including proper feeder and transformer selection, network reorganization, placement of shunt capacitors in suitable locations, penetration of distributed generation at various distribution network nodes, etc. Capacitor placement is one of those options that works best, especially for radial structures [3].

Capacitor installation in distribution systems also plays a key role to reduce power losses and enhance the voltage profile at varied loading circumstances. Due to its ability to produce reactive power during situations of high demand and so enhance the voltage profile of the system, it is mostly employed at the distribution level for compensatory purposes. Additionally, the power factor of the entire system is enhanced by the integration of capacitor banks near to the distribution level. Reactive power compensation must therefore be a local phenomenon for this reason. The advantages depend on where in the system the capacitors are positioned. Therefore, it is necessary to choose the position and size properly in order to maximize the benefits related to the placement of capacitor banks. However, it may also cause over voltage problems and high-power losses if its optimal location and size are not optimally determined [4].

2. Literature review

The load flow analysis of radial distribution systems has been applied using the forward-backward sweep algorithm. The backward load flow sweep method is used to calculate the effective real and reactive power flows in each branch line. The same methods are used to calculate the currents. The voltage of each node will be determined using forward load flow propagation starting from the substation. If the voltages at each node converge to the predetermined limit, the system's active and reactive power losses will then be assessed. [5] presented a forward technique, where the system convergence is primarily focused on the voltage at the transmitting end. In order to calculate voltage, the ladder network approach might be applied in two different directions: first, a backward sweep for current summing, and then a forward sweep. Since a few decades ago, several optimization methods have been proposed in numerous technical papers to solve distribution network problems. In [6] cuckoo search method is utilized to minimize the cost, which comprises capacitor cost and cost due to power loss, and the provided loss sensitivity factor is used to compute the location. [7] has used a novel method in which the loss sensitivity factors are used in part one to choose potential locations for the placement of capacitors, and the plant growth simulation algorithm is used in part two to estimate the ideal size of capacitors at the ideal buses determined in part one. Applications of the suggested technology include radial distribution systems with 33, 34, and 69 buses. [8] uses a genetic algorithm (GA) to estimate the size of the capacitor using particle swarm optimization (PSO), which is implemented on the 34-bus. A brand-new method for choosing the best position and size of capacitors on radial distribution networks has been introduced in [9]. Loss Sensitivity Factors and Particle Swarm Optimization, respectively, are used to size and place capacitors. On bus distribution systems of 10, 15, 34, 69, and 85 buses, the proposed method has been tested. In an optimization scenario, the size and placement of the capacitors are made dynamic and change depending on the system's current load. PSO AI methods have been used for accurate analysis.The optimization technique reduces the power losses by determining the location and size of the capacitors [10].

3. Methodology

The flowchart shown in Figure 1 summarizes the methodology used in this study. The substation included in the study is where the load data was obtained. MVA loadings, power factor, and bus voltages are examples of data parameters. Similar to this, line resistance is computed using the substation's line length, the conductor table's standard resistance, and normalization at 75 degrees Celsius. In light of the line configuration and conductor type, line reactance is estimated appropriately.

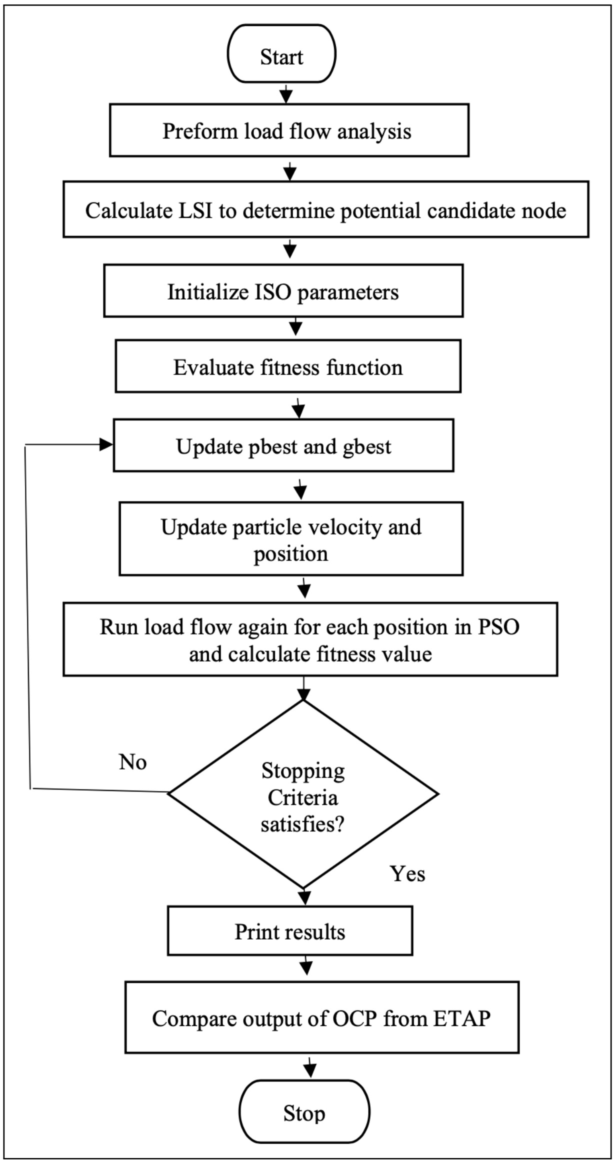

Figure 1: Flowchart of the optimization problem

3.1 Load flow analysis of IEEE 15 bus

Considered as a case study, the IEEE 15-bus radial distribution test system in Figure 2 with time-varying loads comprises of 15 buses and 14 branches. The voltage level on each bus is 11 kV. A substation supplies the network, and the system's total active and reactive power outputs—3715 kW and 2300 kVar, respectively—are connected to 14 buses using various power factors. The forward-backward sweep algorithm was used to perform the load flow in MATLAB.

3.2 Capacitor Bank Sizes

It is possible to switch or fix the capacitor banks built into the distribution system. However, switched capacitors are more practical for time-varying loads since their corresponding size may be changed in response to load variations, as opposed to fixed capacitors, which have just a few sizes and cannot be increased or decreased as the load changes. Equation 1 is used to determine how much the system's power factor improves when the capacitor is introduced..

$$P_{\text{corrected}} = \left[100 - \%\text{ loss reduction } * (P_{\text{initialized}})^2\right]^{1/2} \tag{1}$$

The required capacitor bank is also determined by equation 2.

$$\text{kVar} = \text{kW} * \left[\tan\left(\cos^{-1}\text{pf old}\right) - \tan\left(\cos^{-1}\text{pf new}\right)\right] \tag{2}$$

3.3 Loss Sensitivity Factors

The distribution system's Loss Sensitivity Index has been used to pinpoint the bus that will see the greatest loss reduction as a result of the insertion of a capacitor. Consequently, these delicate buses could be candidates for capacitor installation. The calculation of these potential buses aids in limiting the optimization technique's search space. Think about a distribution line that connects the buses 'p' and 'q'.

Active power loss in the k-th line is given by:

$$P_{\text{lineloss}}[q] = \left(P_{\text{eff}}^2[q] + Q_{\text{eff}}^2[q]\right) R[k] / (V[q])^2 \tag{3}$$

Now the Loss Sensitivity Factors can be obtained as below:

$$\delta \text{P}_{\text{line loss}} / \delta \text{Q}_{\text{eff}} = \left(2^* \text{Q}_{\text{eff}}[\text{q}]^* \text{R}[\text{k}] / (\text{V}[\text{q}])^2\right. \tag{4}$$

where, Peff[q]=Total effective active power supplied beyond the node 'q' and Qeff [q]=Total effective reactive power supplied beyond the node 'q'. The loss sensitivity factors are derived from the base case load flows, and the values are listed for each line in the given system in descending order.

3.4 Problem Formulation

The main goal of reactive power optimization is to reduce real power losses in the system and enhance voltage quality as a result of capacitor placement and loss with limitations. With discrete locations and sizes for shunt capacitors, the ideal capacitor placement and sizing problem is written as a constrained nonlinear integer optimization problem.

3.4.1 Objective Function

The goal is to minimize feeder loss and the objective function is derived from equation 5:

$$\text{F} = \text{ Min. P}_{\text{L}} \sum_{k=1}^{n} I\text{k}^{2*}\text{R}_{\text{K}} \tag{5}$$

3.4.2 Constraints

The objective function is subjected to the following constraints.

3.4.3 Constraints

a. Voltage constraints

$$\text{Vmin} \leq \text{Vi} \leq \text{Vmax} \tag{6}$$

where, Vmin (0.95 p.u) and Vmax (1.01 p.u) are the lower and upper bound of bus voltage limit respectively and Vi is the voltage at the bus i.

b. The total reactive power injection is not to exceed the total reactive power demand.
c. The optimal number of capacitors (NC) must be less than or equal to the maximum number of possible locations:

$$\left(N^{\max}\right) \text{ as } N_C \leq N^{\max} C \tag{7}$$

3.5 Particle Swarm Optimization

The metaheuristic parallel search method known as Particle Swarm Optimization (PSO) is used to optimize continuous nonlinear problems. Drs. Kennedy and Eberhart first presented the PSO algorithm in 1995 (reference 13). It performs searches using a population of particles that represent people. Each particle stands for a potential fix for the capacitor sizing issue. In a PSO system, particles move throughout a multidimensional search space to alter their positions until a largely unchanging position is found or computational restrictions are reached. In the social science context, a PSO system combines a social and cognition model [11].

3.5.1 Performing Particle Swarm Optimization in IEEE 15 bus radial system

The proposed method for loss reduction by capacitor placement is tested on 15 bus radial distribution systems by the particle swarm optimization in MATLAB. The network data, fitness functions are entered for optimization. The various constants used in the proposed algorithm are cap min=200kvar, cap max=1200kvar, K=0.7259, c1=c2=2 and w=1.The number of particles used in the optimization technique is 100 and the iteration is performed 100 times. To determine the best solution, the following two capacitor types are taken into consideration:
1) Fixed capacitors having 150 and 1200 kVar as their minimum and maximum ratings.
2) Standard commercially available switched capacitor sizes range from 150 to 1200 by 150 kVar step.
To evaluate the effectiveness of the suggested strategy, two case studies are used as follows:
Case 1: Optimal positions and fixed capacitor sizes.
Case 2: Optimal position and switched capacitor sizes

3.5.2 Performing Particle Swarm Optimization in modified Banepa feeder

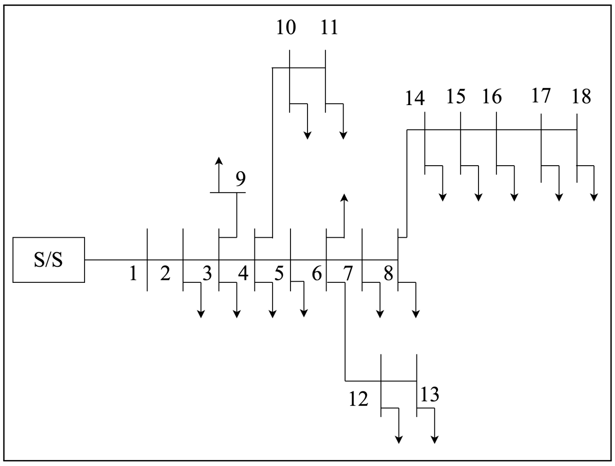

Figure 2: SLD of modified Banepa feeder

On the modified Banepa feeder, the proposed method for loss reduction via capacitor placement is evaluated again with particle swarm optimization to determine the feeder's loss and voltage profile. Banepa feeder has ben modified taking the transformer full loading scenario at power factor of 0.8. The transformers within the radius of 100 meters are lumped together forming a combined load. The same system is taken for capacitor placement by identifying the optimal location and optimal sizes by using the particle swarm method. For optimization, a small portion of the 11 kV Banepa feeder, which has 18 buses and 17 branches, is chosen. The voltage level on each bus is 11 kV. The system's total active and reactive power is 869.584 KW and 652.18 kVar, respectively, and it is coupled to 17 buses at various power factors. The network is fueled by a substation.

3.6 Optimal Capacitor Placement of Modified Banepa Feeder in ETAP

The modified Banepa feeder's single line diagram was designed in ETAP. Bus voltages, power factor, and MVA loadings are the data parameters entered. In a similar manner, line resistance is estimated using the substation's line length, the conductor table's standard resistance, and normalization at 75 °C. Line reactance is estimated based observing the line configuration and conductor type. The feeder was used to find out the loss of the feeder from load flow analysis and to find out the ideal position and sizing of the capacitor and the results from ETAP were compared with those of the results obtained from the optimization technique.

4. Results and discussion

The proposed method for optimal capacitor allocation for loss reduction was tested in the IEEE standard 15 bus radial distribution feeders and implemented on real radial distribution feeders of the Nepalese system using the MATLAB code and Electrical Transient Analyzer Program. The algorithm was implemented by coding on MATLAB, and ETAP.

4.1 Results of Load Flow Analysis

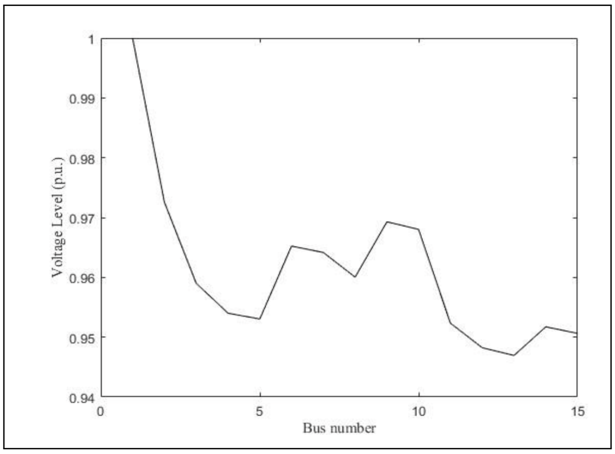

Figure 3: Voltage profile of IEEE-15-bus distribution system

The voltage decreases up to bus no. 5 and there was the increment in voltage profile further as shown in Figure 3. From bus 10, the voltage again decreases. Voltage is maximum at bus 2 i.e., 0.9726 p.u and minimum at bus 13 i.e.,0.9469 p.u. The active and reactive power losses are 61.775 KW and 57.03VAr respectively. Rank bus vector of 15-bus Radial Distribution System obtained from the analysis of Loss Sensitivity Factors arranged in descending order contains set of sequence of buses given as 6,3,11,4,12,15,14,7,13,8,5. Those buses are considered sensitive buses.

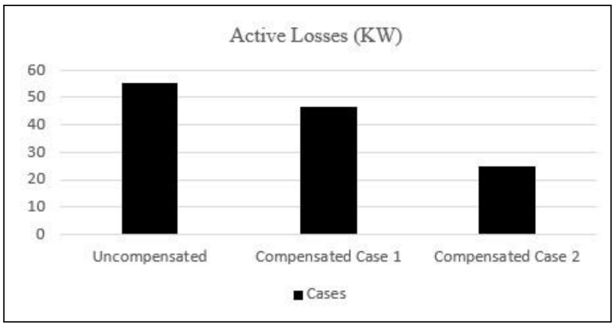

Figure 4: Power loss profile of IEEE 15 bus with and without capacitor

4.2 Capacitor Placement In 15 Bus Radial System Through Particle Swarm Optimization

The results of the 15 bus systems without compensation and after compensation are as shown in Figure 4 and 5 and discussed in Table 1. The minimum voltage is obtained at bus 13 and the maximum voltage is at bus 2 whose values are shown in Table 1 for the uncompensated case and the two cases of compensation. It is seen that the losses go on decreasing when we add capacitors.

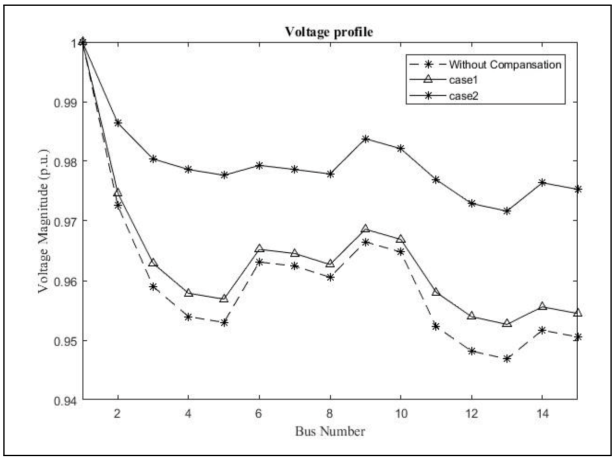

Figure 5: Voltage loss profile of IEEE 15 bus with and without capacitor

The loss is less when the switched capacitors are used i.e., Case 2 than that of the compensation by fixed capacitors i.e., Case 1 as shown in Figure 4. The voltage has been improved at the buses also for both cases of compensation. It is shown in Table 3 that the optimization gives the placement of a fixed capacitor at bus 11 with the size of 174.93 kVar. The placement and sizing of the switch capacitors are at buses 8, 9, 4, 11 with sizes of 300, 150, 450, and 300 kVar respectively in case 2.

4.3 Optimal Capacitor Placement in Banepa Feeder

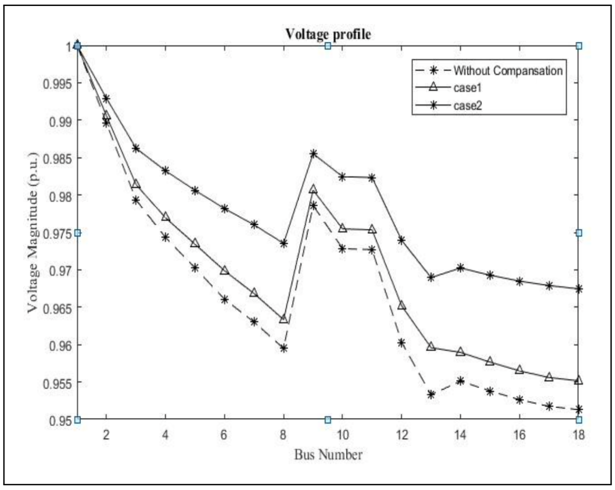

Figure 6: Voltage profile of modified Banepa feeder with or without capacitor

Table 1: Results of IEEE 15 bus with or without compensation

Case		Active Losses (KW)	Min. voltage value at bus 13	Max. Voltage value at bus 2
Uncompensated		55.3674	0.94686	0.97254
Compensated	Case 1	46.6525	0.95625	0.9764
	Case 2	24.978	0.97164	0.98639

Table 2: Results of modified Banepa feeder with or without compensation

Case		Active Losses (KW)	Min. voltage value at bus 18	Max. Voltage value at bus 2
Uncompensated		43.3064	0.9513	0.98957
Compensated	Case 1	31.9711	0.95516	0.99056
	Case 2	20.9831	0.96873	0.99352

Table 3: Placement and sizing of capacitors of IEEE 15 bus after optimization

Cases	Buses	Sizes
Case 1	11	174.93
Case 2	8	300
	9	150
	4	450
	11	300

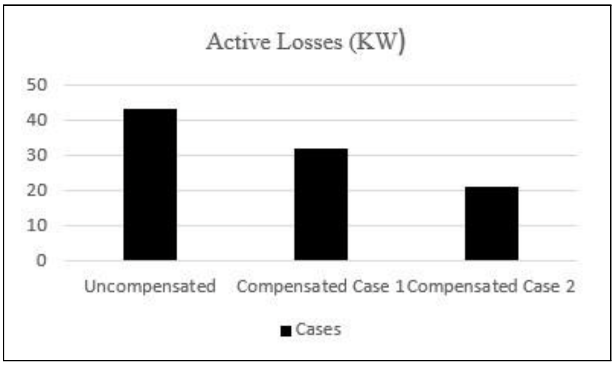

Figure 7: Active loss of a modified Banepa feeder with or without capacitor

Table 4: Placement and sizing of capacitors after optimization in Banepa feeder

Compensation Cases	Buses	Sizes
Case 1	13	213.65
Case 2	5	300
	9	150
	13	300

The results of the modified Banepa feeder without compensation and after compensation obtained are presented in Table 2.

The minimum voltage is obtained at bus 18 and the maximum voltage is at bus 2 as shown in Figure 6 whose values are shown above in Table 2 for the uncompensated case and the two cases of compensation. It is seen that the losses go on decreasing when we add capacitors. The loss is less when the switched capacitors are used i.e., Case 2 than that of the compensation by fixed capacitors i.e., Case 1. The voltage has been improved at the buses also for both cases of compensation. From Table 4, in case 1, it is shown that the optimization gives the placement of a fixed capacitor at bus 13 with the size of 213.65 kVar. The placement and sizing of the switch capacitors are at buses 5, 9, 13, 17 with sizes of 300, 150, 300, and 150 kVar respectively in case 2.

4.4 Optimal Capacitor Placement in Modified Banepa Feeder Using ETAP

The results of the 18 bus systems of modified Banepa feeder are as shown in Table 5.

Table 5: Placement and sizing of capacitors in ETAP

Buses	Size (KVAr)
13	191.55
14	95.74

Figures 7 illustrate the active losses for different cases of compensation and no compensation. The optimal placement of capacitors is at bus 13 and bus 14 with sizes of 191.55 kVar and 95.74 kVar respectively. The results are given by the optimization and that of ETAP are somehow similar.

5. Conclusion

The main issues addressed in this work's conclusion are the reduction of power loss and improvement of the voltage profile. An objective function and a number of constraints are included in the optimization algorithm. The main techniques applied in this study include PSO, sensitivity factor analysis, and load flow analysis. All the necessary parameters in the test system are computed using the backward and forward load flow analysis. Different standard test systems, including the 15-bus distribution system, are subject to the suggested approach. In addition, the proposed procedure is applied to a real distribution system, a section of Banepa Feeder. The sensitivity analysis criteria are well formulated and employed successfully to minimize the search space of the optimization method. PSO is used to select design variables depending on optimal capacitor sizing. The algorithm is efficient in terms of reducing loss. The voltage drops and power loss before and after installing the capacitor were compared for the system in this work and the percentage reduction of power loss is obtained to be 15.74% and 20.17% for IEEE 15 bus and Banepa feeder respectively. The voltage has also been improved after adding the capacitors i.e., fixed and switched. Decrement in power loss and voltage improvement are obtained better in the case of placement of switched capacitors rather than fixed capacitors. The results obtained from ETAP are quite similar to the result obtained from optimization. Shunt capacitors are used to minimize losses by reducing the current flowing through each feeder section, which lowers the voltage drop in that section. As a result, after the feeder line is compensated, the voltage profile is enhanced and the power quality is raised. The outcome demonstrated improved voltage profiles and reduced power losses in the distribution system, which could be advantageous for the distribution networks. This demonstrates that the proposed approach is more efficient at enhancing the voltage profile and significantly lowering power losses.

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