Optimum placement of capacitor in radial distribution system using PSO algorithm

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Abstract

Passing power through transmission and distribution lines causes a loss of some electrical energy in these lines. The amount of these losses is more significant at the distribution level than the losses at the transmission level due to the low voltage level and high currents. According to the Electricity Distribution Company, the losses of this power are the difference between the delivered energy from the upstream and the delivered output energy downstream.

If we consider at losses economically, losses are the difference between the energy bought and the energy sold.

In other words, losses are equal to costs. The large cost of losses can be shown by an example.

Introduction

Suppose a distribution company buys 600 million kilowatt hours of electricity annually, 10% of which is wasted. In addition, assume that the electricity distribution company pays an average of 5 cents per kilowatt hour of energy, taking into account energy demand and costs. The cost of annual losses of this distributor can be easily calculated as follows

0.05($/KWh)*0.1*600000000(KWh)=30000000 $

The importance of reducing losses in distribution systems can be recognized by these figures. Using capacitors is one of the most efficient methods in reducing system losses and improving the voltage profile. In this paper, using approximate logic, we present a new method for finding candidate Bus distributions for capacitors. This solution method consists of two parts: In the first part, by calculating the sensitivity coefficients, the system candidate buses are selected for capacitance. In the second part, the PSO algorithm [1-2]is used to achieve the optimal size of capacitors to reduce the cost of losses as well as the cost of capacitors. In this paper, we use a new method to obtain the load distribution rate, which is suitable for load distribution from radial networks. The concept of this method is very simple and we will fully explain it in the following. Finally, the performance evaluation of the proposed method is tested on two radial distribution systems of 15 and 33 Bus.

The distribution system is the last link-like link between the high voltage transmission system and the consumers. A distribution circuit starts at distribution substations and passes through large load centers (consumers). Lateral distribution sources (feeders) also connect separate load points to the main feeders, thus creating radial distribution systems. Radial systems are very popular because of their easy design and usually low cost.

In the distribution system, due to low voltage and therefore high current compared to high voltage transmission system, power losses are significantly higher. In order to improve system performance efficiency, these losses should be reduced as much as possible, especially at the distribution level [3].

There are many ways to reduce losses in the system, including network reset, the use of voltage regulators, capacitors, and so on.

Capacitors are widely used to compensate for reactive power in distribution systems. These can be used to reduce power and energy losses, as well as to improve the voltage profile and keep it within the allowable range. The amount of compensation depends on the location of the capacitor in the distribution system and necessarily the size, type and number of capacitors [4-7].

Therefore, the issue of capacitor placement is a good case study in system studies.

In the issue of capacitor placement in the distribution system, it is necessary to distribute the load regularly. The distribution system has the following inherent characteristics:

1- Radial network structure

2. Unbalanced distributed load and unbalanced performance

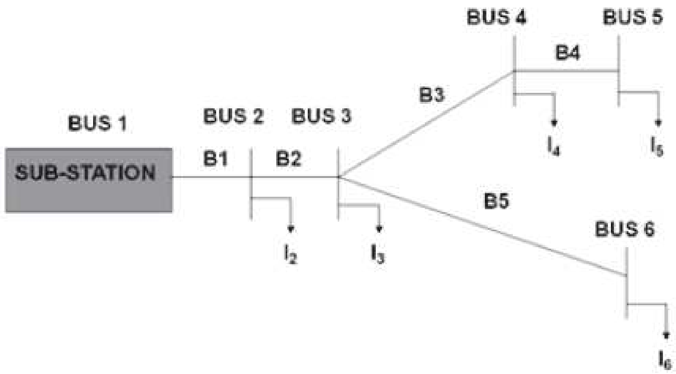
3. A large number of nodes and branches

4. Wide range of resistance and reactance values and high R / X ratio.

These features make traditional load distribution methods, including Gauss-Seidel and Newton-Raphson, ineffective on these networks, and their responses may diverge. Various papers have provided methods to overcome these problems. In this paper, a new technique including two Bus-Injection to Branch-Current (BIBC) and branch current to Bus voltage (BCBV) and simple multiplication of these two matrices are used to calculate the load distribution. Candidate buses for the location of shunt capacitors are identified using sensitivity reduction coefficients, and finally the PSO algorithm is used to find the size of the capacitors and optimize costs.

Section 1: Load distribution of radial distribution system.

Consider the simple distribution system shown in Figure 1. Using Equation (1), power injection can be converted to current injection and the Bus current can be calculated. By applying the Kirchhoff current law (KCL) to the distribution system, the branch currents can be written in terms of injected currents to the buses[8,9]. For example, the flow of branches B_3 ، B_5 و B_1 can be expressed as follows.



Therefore, the Bus injection matrix (BIBC) can be obtained as follows

$$I_i = (P_i + jQ_i / V_i) \qquad (1)$$

$$B_5 = I_6$$

$$B_3 = I_4 + I_5$$

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6 \qquad (2)$$

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix}$$

[B] [BIBC] [I]

1-1 BIBC matrix formation algorithm

Power injection can be converted to current injection. The relationship between Bus injection current and line injection current is obtained with KCL The result of this work is the production of the BIBC matrix. It should be noted that BIBC is a matrix of m*(n-)1 Where m is the number of branches and n represents the number of system buses. The algorithm for forming a BIBC matrix in a radial distribution system is as follows.

$$\begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

Step 1: Create an empty matrix with order m * n where m represents the number of branches and n represents the number of Bus. Then fill the first column with the column matrix m * 1 as below [8-10].

Step 2: If the line Bk was between the i and j buses, copy column i in column j and then fill in kj with 1.

Step 3: Repeat the second step for all lines (all Bk) and then delete the first column (the first column is the slack Bus and has no role in calculating the BIBC)

1-2 BCBV matrix formation algorithm

The BCBV matrix represents the relationship between branch current and Bus voltage. For Figure 1, we write the following equations by writing the Kirchhoff voltage law (KVL). Using the relations (5) -(2) the Bus voltage equation 4 can be written as follows.

$$V_2 = V_1 - B_1 Z_{12} \quad (3)$$

$$V_3 = V_2 - B_2 Z_{23} \quad (4)$$

$$V_4 = V_3 - B_3 Z_{34} \quad (5)$$

$$V_4 = V_1 - B_1 Z_{12} - B_2 Z_{23} - B_3 Z_{34} \quad (6)$$

Equation (6) indicates that the Bus voltage can be written in terms of substation voltage. Slack Bus voltage $=V_1$, branch current and line impedance. This method can be used to find other Bus voltages, thus creating a branch current-to-Bus voltage matrix (BCBV), as shown in Figure 1. To form a step-by-step BCBV matrix of order (n-1) * m, as follows.

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}$$

$$[\Delta V] \qquad [BCBV] \qquad [B]$$

Step 1: Create an empty matrix with order n * m in which n represents the number of Buses and m represents the number of branches. Then fill the first row of this matrix with the 1 * m line vector below.

$$\begin{bmatrix} Z_{12} & 0 & \cdots & 0 \end{bmatrix}$$

Step 2: For each line Bk (k = 1, 2…, m) between the two buses i and j, copy the i row to the j row and fill the jk of the matrix with the impedance Z_{ij}.

Step 3: Repeat the second step for all lines (all B_k) and then delete the first row of the matrix.

1-3 Load distribution algorithm from radial distribution system

After forming the BIBC and BCBV matrices, the Bus voltage can be calculated using the following simple algorithm.

1. Enter the problem data including network structure, line impedance, Bus injection power and ...

2. Formation of BIBC matrix

3. Formation of BCBV matrix

4. formation of DLF (Data Load Flow) Matrix

$$[DLF] = [\text{BIBC}][\text{BCBV}]$$

5- Repeat k = 0

6. Repeat k = k + 1

7. Solve the following equations in each iteration and update the voltage values at the end of each iteration.

$$I_i^k = (P_i + j\, Q_i / V_i)^*$$

$$[\Delta V^k] = [DLF][I^k]$$

$$V^{k+1} = V_{slack} - \Delta V^k$$

In the above relation, V is a column matrix n * 1, which represents the Bus voltage, and V_{slack} is a column matrix n * 1, all its components are equal to the slack Bus voltage, which is one. V is updated at each step, but V_{slack} It is always constant.

Convergence condition: If Ii^{k+1}-Ii^k is greater than one tolerance, go to step 6, otherwise print the results.

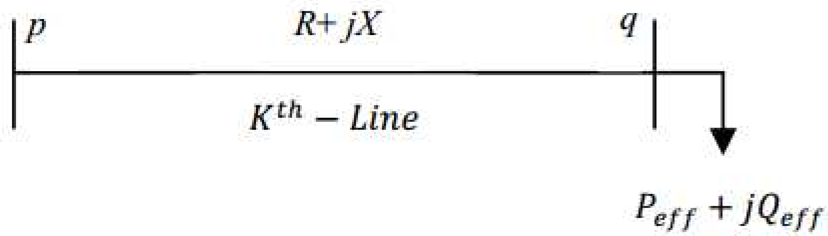
Section 2: Decreasing sensitivity coefficient and selection of candidate Buses

The reduction coefficient indicates which Bus will have the largest loss reduction in the system when a capacitor is installed on it. Therefore, sensitive Buses can be selected as candidate Buses for capacitors. Estimating these candidate buses helps to narrow the search space in the optimization problem. Since a small number of Buses are selected as candidate Bus to compensate for reactive power, the cost of installing capacitors is reduced accordingly.

$$P_{line\_loss}[k] = (P_{eff}^2[q] + Q_{eff}^2[q]) * [R_k] / (V^2[q])$$

Active power losses on the k line are obtained from the equation $R_k.I_k^2$, which can be expressed as follows.

Where we show the current passing through the line with the power passing through it (Figure 2).



Similarly, the reactive power losses in the k line are calculated from the following equation.

$$Q_{line\_loss}[\mathrm{k}] = (\mathrm{P}_{eff}^2[\mathrm{q}] + \mathrm{Q}_{eff}^2[\mathrm{q}]) * [X_k] / (\mathrm{V}^2[\mathrm{q}])$$

Sensitivity coefficients are obtained by deriving the ratio of power losses in the line to reactive power.

$$\partial P_{line\_loss}[\mathrm{k}] / \partial Q_{eff}[\mathrm{q}] = (2\mathrm{Q}_{eff}[\mathrm{q}]\mathrm{R}_k) / \mathrm{V}^2[\mathrm{q}] \qquad (7)$$

Selection of candidate Buses using reduction sensitivity coefficients

The reduction sensitivity coefficients are obtained from Equation (7) and the load distribution results that give us the injected P and Q to the buses. We arrange these coefficients in descending order in a vector, and in the same order, we place the Bus number corresponding to each sensitivity coefficient inside the vector called bpos[i]. The descending order of the sensitivity coefficient elements of the bpos vector will determine which buses are suitable for compensation. Then we normalize the voltage ranges of the buses in the order in which they are placed in bpos, using the following equation.

$$norm[i] = V[\mathrm{i}] / 0.95 \qquad (8)$$

The norm vector [i] and the sensitivity coefficient decide which buses need reactive power compensation and which buses do not need compensation.

In this paper, the 6 buses that have the highest sensitivity and the norm value [i] for them is less than 1.01, are selected as candidate Buses for capacitor installation. In other words, in order for a boss to be selected as a candidate, that boss must have these two conditions together. norm [i] less than 0.95 indicates that the low voltage Bus is close to 0.95 and needs to be compensated.

The following steps show the algorithm for finding candidate Buses for capacitors.

Step 1: Calculate the reduction sensitivity coefficients for distribution system buses using Equation (7)

Step 2: Set the sensitivity coefficients in descending order in a vector and store the number of Buses corresponding to each sensitivity coefficient in the same order in the Bus location vector (bpos [i])

Step 3: Calculate the value of the normalized voltage for each Bus in the order of the bpos vector using the equation (8) and the formation of the norm [i] vector Step 4: Sensitive buses whose norm [i] is less than 1.01, as buses Candidates are selected.

Section 3: Cost Calculation (Object Function)

The cost consists of two main parts: the cost of energy and the cost of capacitors

The cost of energy

If I_i is the current flowing through line i during time T, the energy losses are obtained from the following equation.

$$EL_i = R_i I_i^2 T$$

$$EL = \sum_{i=1}^{m} EL_i$$

$$ELC = C_e . EL \qquad (9)$$

Total energy losses are obtained from the total energy losses of the lines (feeders).

Cost of energy losses (ELC) (also obtained by multiplying EL by energy rate (C_e) in $ / KWh

Capacitor replacement cost

Capacitor cost is divided into two parts: fixed installation cost and a variable cost that varies according to the capacitor specifications, in other words, the variable cost is the same as the cost of buying a capacitor. All these costs are calculated for one year. Therefore, the cost of the capacitor is expressed as follows.

$$CC = C_{ci} + (C_{cv} * Q_{ck}) \qquad (10)$$

Where C_{ci} is the fixed cost of installing the capacitor, C_{cv} is the cost of the capacitor per KVar (cost per kilowatt of capacitor) and Q_{ck} is the reactive power of the capacitor installed at the k bus.

$$\min \rightarrow OF = C_e . \sum_{i=1}^{m} EL_i + \sum (C_{ci} + (C_{cv} * Q_{ck}))$$

The cost function is obtained by combining two relations (9) and (10). This cost function is considered as the objective function of the problem, which must be minimized using the PSO algorithm.

Section 4: Particle Swarm Optimization Algorithm (PSO)

PSO is an iteration-based optimization technique based on the social behavior of particles or birds. In PSO, the set of answers that the candidate answers to the problem is called "particles”. These particles search the problem space using a simple mathematical relation. The PSO method was first proposed by Eberhart and Kennedy and was originally intended to simulate human community behaviors similar to those of a group of birds or a community of fish. But after a while it was used to optimize many mathematical problems in various fields of engineering [11-14].

The algorithm works in two steps, in the first step it uses a simple equation to determine the particle velocity and in the second step it uses this speed to determine the new particle location. Therefore, short computation time and memory required are short. In this algorithm, each particle of the population (each bird in the bird collection) shares the best location it has found with the whole group, thus guiding the population to the best answer.

Description of PSO algorithm [3]

Step 1: Each particle of the population is assigned a random location in the problem search space.

Step 2: The objective function is calculated for each particle.

Step 3: The value of the objective function for each particle in each iteration is compared with the value of the objective function of the particle in the previous iteration, and the best place found by each particle is obtained from the following equation. [15-17]

$$Pbest_j^k = \begin{cases} X_j^k \rightarrow if\ (\mathrm{OF}_j^k \le \mathrm{OF}(\mathrm{Pbest}_j^{k-1})) \\ Pbest_j^{K-1} \rightarrow if\ (\mathrm{OF}_j^k > \mathrm{OF}(\mathrm{Pbest}_j^{k-1})) \end{cases}$$

Where $Pbest_j^k$ is the best location found by the j particle in the k-iteration, X_j^k is the location of the j-particle in the k-iteration, and OF_j^k is the value of the objective function attributed to the j-particle in the k-iteration.

$$Gbest^k = \begin{cases} Gbest^k \rightarrow if\ (\mathrm{OF}(\mathrm{Gbest}^k) \le \mathrm{OF}(\mathrm{Gbest}^{k-1})) \\ Gbest^{k-1} \rightarrow if\ (\mathrm{OF}(\mathrm{Gbest}^k) > \mathrm{OF}(\mathrm{Gbest}^{k-1})) \end{cases}$$

Step 4: In each iteration k, from all Pbests, the best place found by the whole group is determined ($Gbest^k$). Then this value is compared with the best place found by the group in the previous iteration and using the following equation The best location is found by the whole group until k is repeated.

$$V_j^{k+1} = \omega V_j^k + c_1 rand_1 * (\mathrm{Pbest}_j^k - \mathrm{X}_j^k) + \mathrm{c}_2\, rand_2 * (\mathrm{Gbest}^k - \mathrm{X}_j^k)$$

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{k_{\max}} k$$

Where Gbestk is the best place found by the whole group up to k.

Step 6: In this step, the velocity of the particles is obtained using the following equation for the next iteration.

$$X_j^{k+1} = X_j^k + V_j^{k+1}$$

Where V_j^k is the velocity of the particle j in the repetition of k, ω are the weighting coefficient of inertia and C_1 and C_2 are the acceleration coefficients that can change in the interval [4-0], and in this case we set them to a fixed number 2. $Rand_1$ and $rand_2$ are also random numbers between zero and one.

The weighting factor ω is used to control the convergence of PSO during the optimization process and is obtained from the following equation.

Where kmax is the maximum number of simulation iterations and k is the current iteration number.

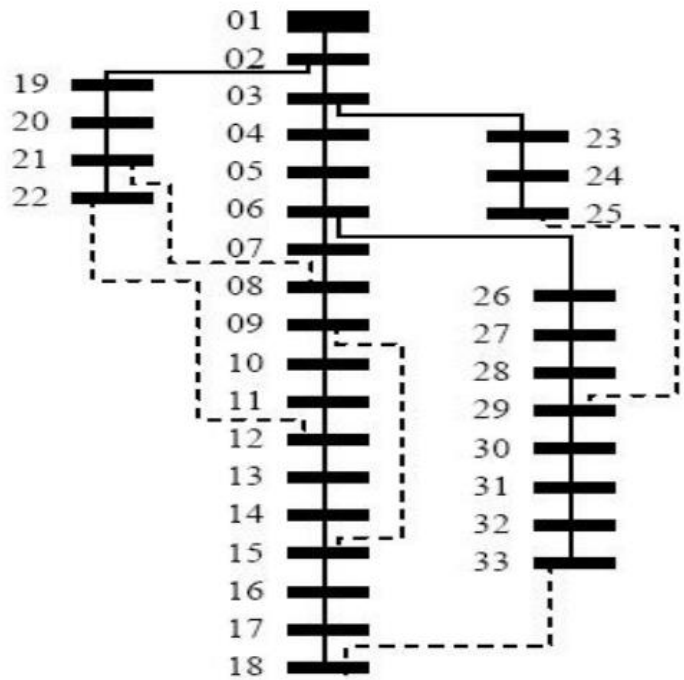
Step 6: The particle location for the next iteration (k + 1) is determined from the following equation.

Step 7: The convergence criterion is examir $k = k_{\max}$ و یا $V_j^{k+1} - V_j^k < \varepsilon$ the program ends and otherwise we return to the second step.

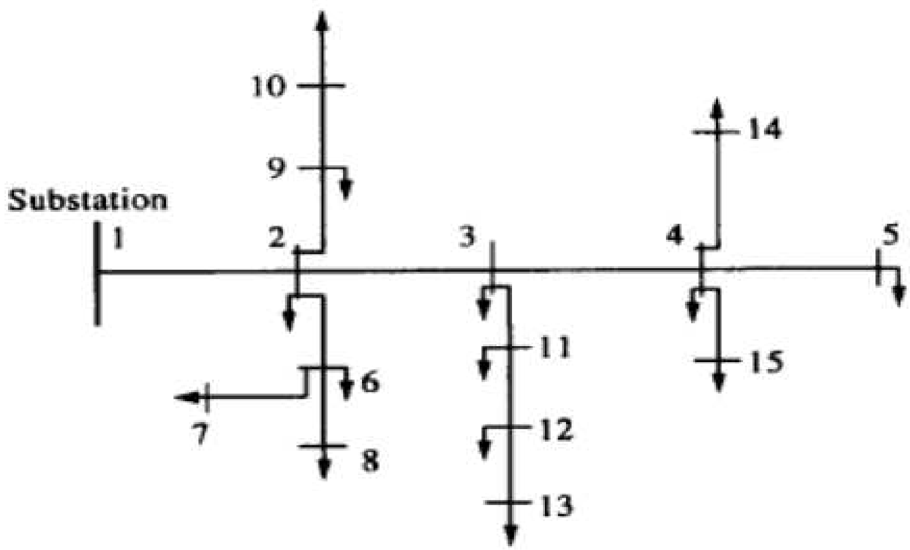
Section 5: Data required for simulation and test network

Unfortunately, the text of the article did not mention the data used for the test or reference networks. This data has been extracted from the following references and has been used in this project. Some results are not the same as the output of the article, which may be different from the test network data. However, the outputs obtained for the tested networks show the efficiency of the proposed method.

In this issue, we use a 33-Bus network to evaluate the performance of the proposed method, the data of which are given in [4] and [6]. The network topology is as follows (Figure 3).



15-Bus network data is also given in [5].



The values used for the objective function are as follows.

Parameter	Value	Dimension
C_e	0.0547	$\$/KWh$
C_{ci}	100	$\$/year$

C_{cv}	4	$\$/KVar$

The values used for the PSO algorithm are as follows.

Parameter	Value
$\omega_{\max}$	0.9
$\omega_{\min}$	0.04
c_1	2
c_2	2

Section 6: Simulation Results

This simulation includes M-files 3 called Load Flow, Data and Main. Information about the network as well as the code for forming the BCBV, BIBC and DLF matrices are given in the Data file.

The Load-Flow subprogram is also used to capture load from the network based on the algorithm described in Section 1.

The output of this program is Bus voltage, Bus injection current and line current.

The main program is Main, in which the selection of candidate Buses and the PSO algorithm are implemented.

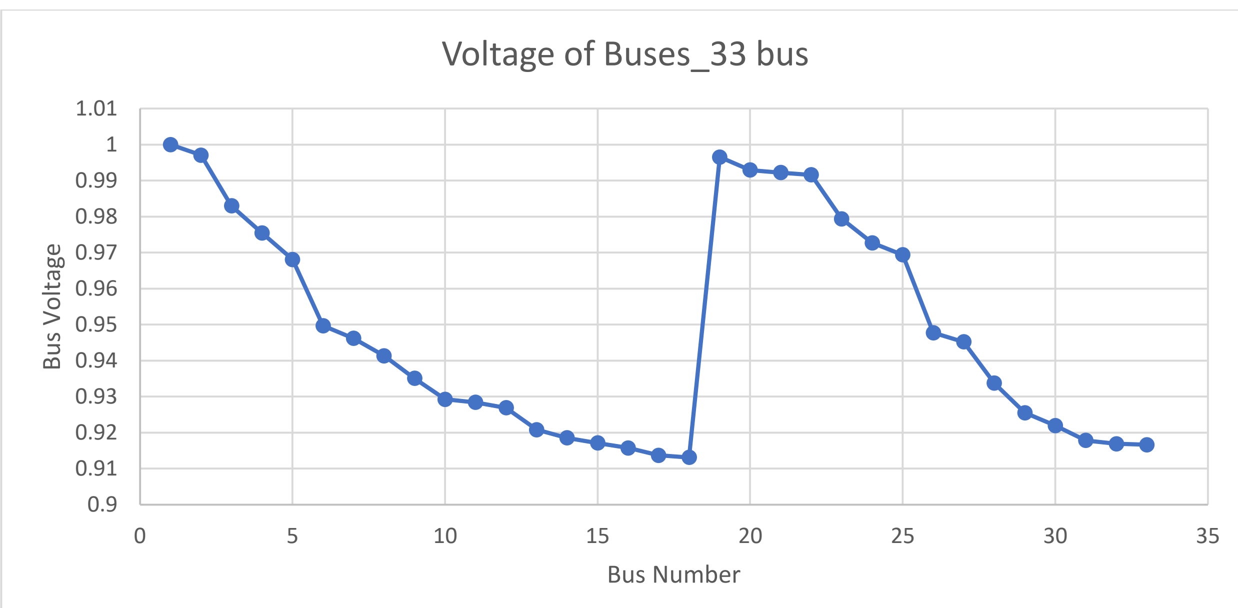
33-Bus network simulation results:

Before performing any operation, during the load distribution from the network, the Bus voltage was as follows.

In this case, the amount of network losses is equal to 202KW (in [8] is exactly the same figure) and the annual cost of these losses is 97117$. MATLAB program outputs show these numbers (is the loss output in watts.)

V1	**1**
V2	0.997032
V3	0.982938
V4	0.975456
V5	0.968059
V6	0.949658
V7	0.946172
V8	0.941328
V9	0.935059
V10	0.929244
V11	0.928384
V12	0.926875
V13	0.920761
V14	0.918495
V15	0.917082
V16	0.915714
V17	0.913687
V18	00.91308
V19	0.996504
V20	0.992926

V21	0.992222
V22	0.991584
V23	0.979352
V24	0.972681
V25	0.969356
V26	0.947729
V27	0.945165
V28	0.933725
V29	0.925507
V30	00.92195
V31	0.917789
V32	0.916874
V33	00.91659



Candidate buses for capacitors were selected by the program as follows.

After capacitor placement using PSO algorithm, the required capacitance on each candidate Bus (Gbest) was obtained as follows.

```
==========================================================================
         Value of System Variables BEFORE Capacitor Placement
==========================================================================

P_loss_BEFORE_Cap_Placement =

  2.0268e+005


Annual_Costs_of_Losses =

  9.7117e+004
==========================================================================
                             Candidate Buses
==========================================================================

Candidate_Buses =

     6     28     29     30      9     13
```

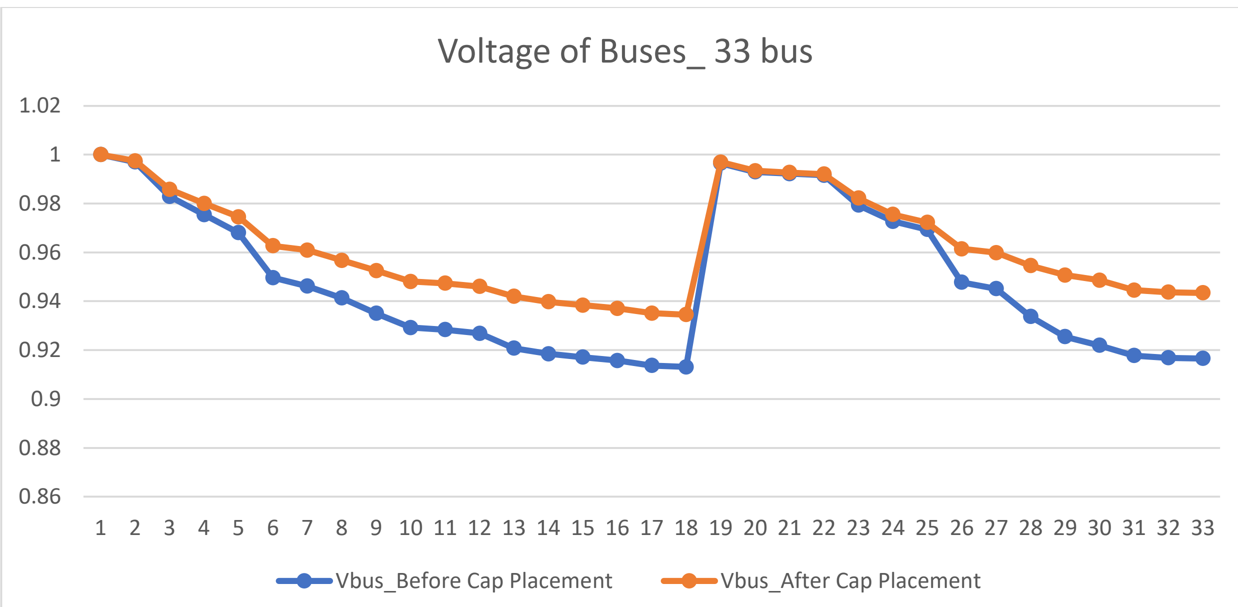
With this amount of capacitance, system losses were reduced to 135KW and the total cost of energy losses and capacitance was 73190$. As a result, we make a profit of 97117-73190=23927$ with this annual capacitance.

```
==========================================================================
         Value of System Variables AFTER Capacitor Placement
==========================================================================

Gbest =

           0        50000       100000       800000       150000       250000


P_loss_Gbest =

  1.3584e+005


Annual_Cost_AFTER_Cap_Placement =

  7.3190e+004
```

In this simulation, capacitors with 50KVar step are used and the total installed capacitor is equal to 1350KVar.

Candidate bus	Installed Capacitance on the candidate bus(kVAR)
6	0
28	50
29	100
30	800
9	150
13	250

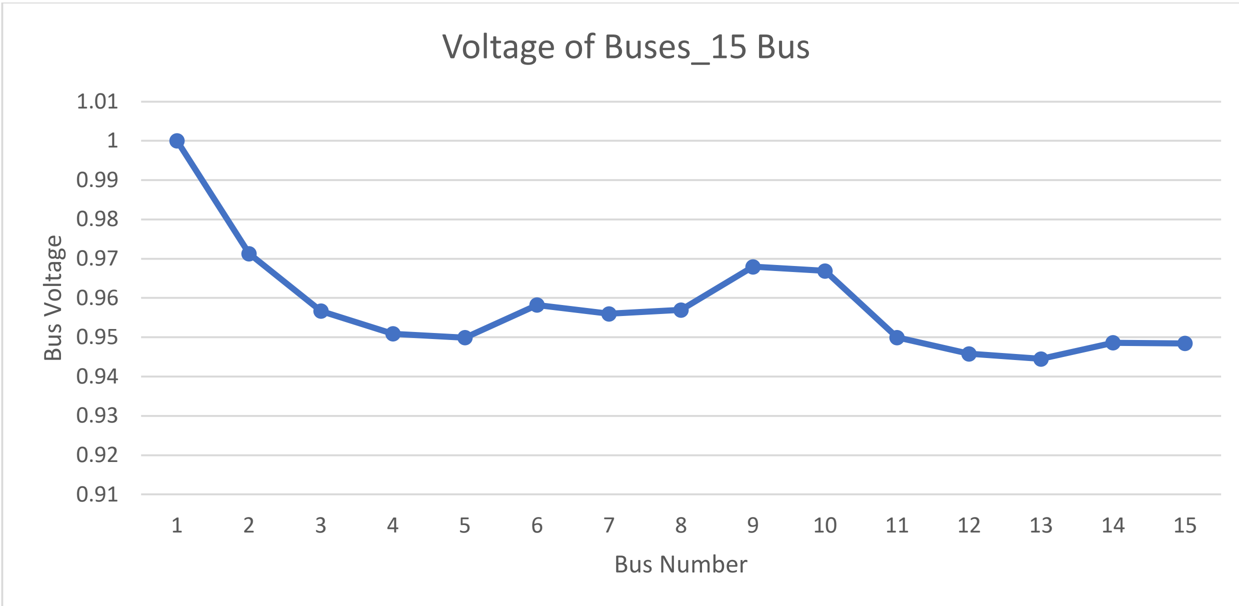
The voltage profile also changed as follows after capacitor.



It is observed that by capacitor placement the voltage profile in different busbars (red diagram)

15-Bus network simulation results:

The different Bus voltages are as follows before capacitor.



Before capacitor placement in the network, the amount of power losses is equal to 61KW and the annual cost of these losses is 29610$. Matlab program outputs show these results.

```
==========================================================================
         Value of System Variables BEFORE Capacitor Placement
==========================================================================

P_loss_BEFORE_Cap_Placement =

  6.1794e+004


Annual_Costs_of_Losses =

  2.9610e+004
```

Candidate buses for capacitors are: 7,12,4,11,6,3

After capacitor placement using PSO algorithm, the amount of capacitor obtained for each Bus (Gbest), with minimizing costs, was calculated as follows.

```
================================================================================
                              Candidate Buses
================================================================================

Candidate_Buses =

     3      6     11      4     12      7
```

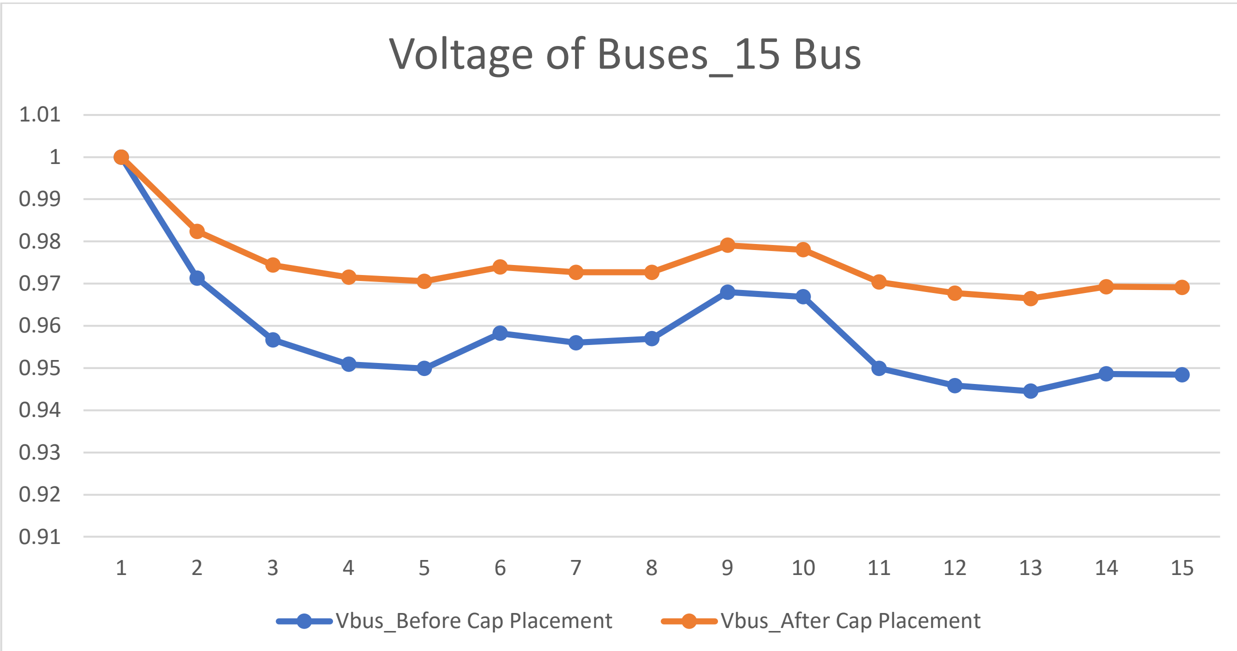
With this amount of capacitance, system losses were reduced to 31KW and the total cost of energy losses and capacitance was 20400$. As a result, we make an annual profit of 29610-20400=9210$

```
================================================================================
         Value of System Variables AFTER Capacitor Placement
================================================================================

Gbest =

           0       150000       150000       400000       100000       150000


P_loss_Gbest =

  3.1096e+004


Annual_Cost_AFTER_Cap_Placement =

  2.0400e+004
```

The total capacitor installed on the buses is 950KVar.

Candidate bus	Installed Capacitor on Candidate bus
3	0
6	150
11	150
4	400
12	100
7	150

The voltage profile after capacitor is as follows.



Here, too, as can be seen, the voltage profile has been greatly improved.

Therefore, in this project, we observed that with proper capacitance in the radial distribution system, energy losses and consequently operating costs in the system can be reduced. Also, as the simulation results show, the voltage profile is well improved by capacitor placement.

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