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# Optimal Allocation of Capacitor Bank in Radial Distribution System using Analytical Approach

**Sarfaraz Nawaz[1], M.P. Sharma[2], Abhishek Gupta[3]**
[1]Poornima University, Jaipur, India
[2]RVPNL Jaipur, India
[3]Swami Keshvanand Institute of Technology Management & Gramothan, Jaipur, India

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**ABSTRACT**

In this paper, a novel analytical technique is proposed for optimal allocation of shunt capacitor bank in radial distribution system. An objective function is formulated to determine the optimal size, number and location of capacitor bank for real & reactive power loss reduction, voltage profile enhancement and annual cost saving. A new constant, Power Voltage Sensitivity Constant (PVSC), has been proposed here. The value of PVSC constant decides the candidate bus location and size. The achievability of the proposed method has been demonstrated on IEEE-69 bus and real distribution system of Jamawaramgarh, Jaipur city. The obtained results are compared with latest optimization techniques to show the effectiveness and robustness of the proposed technique.



***Corresponding Author:***

Sarfaraz Nawaz,
Poornima University,
Jaipur, Rajasthan, India.
Email: eesarfaraz1983@gmail.com

## 1. INTRODUCTION

Complexity of the modern power system is increased due to stressed conditions in a distribution networks, exponential increment in population and high ongoing demands on power grids are major concern of the design engineers with every passing day. As per Indian scenario significant part of the system losses (around 21%) are distribution losses. The power losses can be divided into two parts i.e. active power loss and reactive power loss. Reactive power loss can be compensated by installation of shunt capacitor units. Allocation of shunt capacitor units at appropriate location and of optimal size reduces the real power loss and improves the voltage profile of the system. The researchers suggested many optimization techniques to solve the problem of optimal allocation of capacitor units in radial distribution system. In [1], Prakash et.al.used Particle Swarm Optimization algorithm to determine the best location and size of capacitor units in radial distribution system. Carpinelliet al. [2] solved the problem of shunt capacitor placement and sizing by approximate power flow method. The cost of real power losses and cost of capacitors were included in the objective function. Nonlinear Programming [3], Genetic Algorithm (GA) [4], Simulated Annealing (SA) [5], Cuckoo Search Algorithm [6], Heuristic Algorithm [7], Particle Swarm Optimization (PSO) [8-9], Artificial Bee Colony(ABC) [10], Firefly Algorithm (FA) [11], Teaching Learning Based Optimization (TLBO) [12], Plant Growth Simulation Algorithm (PGSA) [13], Harmony Search (HS) [14] Cuckoo Search Algorithm (CSA) [15], Ant Colony Search Algorithm (ACO) [16], Bacteria Foraging (BF) [17], Flower Pollination Algorithm[18, 23], Direct Search Algorithm [21], *Differential Evolution algorithm* [22] are developed to solve optimal allocation of capacitor problem. However, no author tested their algorithm on real power distribution system.

In this paper a new analytical method has been presented to solve the capacitor allocation problem in distribution system. The objective function was formulated to minimize real power loss to its minimum value. A new constant, Power Voltage Sensitivity Constant (PVSC), has been proposed here. This constant is incorporated with real power loss and voltage of the system. In other optimization algorithm the location of shunt capacitors are determined by loss sensitivity factor (LSF). But, the proposed PVSC gives optimal location and optimal size of capacitor banks simultaneously. The efficacy of the proposed methodology has been tested on standard 69 bus and real distribution system of Jamawaramgarh, Jaipur city. Three loading conditions (Light, Nominal and Heavy) are also considered here. The results of proposed technique are compared with various algorithms to check its supremacy.

## 2. OBJECTIVE FUNCTION

The objective function of capacitor allocation problem is to minimize the total cost due to energy loss and reactive power compensation under certain operating constraints.
Mathematically the problem can be written as:

Min. f= Energy loss cost + Reactive power compensation cost

$$\text{Min. } f = K_p * P_{loss} * t + K_i * C_B + K_C * \sum_i^{CB} Q_{ci} \quad (1)$$

where the constants are taken as [19].

The operating constraints are:

1. The voltage of each bus must be maintained between specified limits. $V_{min} \leq V \leq V_{max}$
2. The total reactive power injected is not to exceed the total reactive power demand in radial distribution system.
3. The reactive power injection at each candidate bus is given by its minimum and maximum compensation limit.

## 3. PROPOSED METHODOLOGY

An analytical approach has been presented for capacitor placement problem. The Power Voltage Sensitivity Constant (PVSC) is proposed to determine the size and location of capacitor units. This constant takes active power loss and voltage limits of individual buses in account and suggest the optimal location of the capacitor.

$$PVSC = \frac{V_{max}}{V_{min}} + \frac{Pcaploss}{Prealloss} \quad (2)$$

where,
$P_{realloss}$: base case real power loss.
$P_{caploss}$ : active power loss after capacitor placement at $i^{th}$ bus.
$V_{max}$ is maximum bus voltage in pu after capacitor placement at $i^{th}$ bus.
$V_{min}$ is minimum bus voltage in pu after capacitor placement at $i^{th}$bus.
For optimal placement of capacitor bank the value of PVSC should be minimum.

Computational process for proposed analytical technique is explained below:
*Step 1: Run the base case load flow program and calculate real power loss $P_{realloss}$.*
*Step 2: Set any size of capacitor unit and run load flow program.*
*Step 3: Calculate the real power loss of the system and "PVSC" values for each bus using eq. 2.*
*Step 4: Now vary the size of capacitor in minute step (10 kVAR) and compute real power loss by running load flow program.*
*Step 5: Store the size of capacitor which gives least amount of real power loss.*
*Step 6: The bus, which has least "PVSC" value, will be the optimal location of capacitor unit.*
*Step 7: Repeat Steps 4 to 6 to find more location of capacitors.*

## 4. TEST RESULTS AND DISCUSSION

In proposed analytical approach, capacitor units are placed to minimize real power loss and to enhance voltage profile. A standard system of 69 bus and a real 130 bus distribution system of Jamwaramgarh, Jaipur are employed to implement the proposed technique. This complete scheme is developed in MATLAB software. The values of various constant used in equation (1) are: Cost of energy loss (Kp)= $0.06/kwh, capacitor's installation cost for single unit (Ki)= $1000, Cost of per kVAr capacitor bank (Kc)=$3.

**Case I: 69 bus system**

The standard system of 69 bus has 12.66 kV and 100 MVA base value. The base case real power loss and minimum bus voltage are 225 kW and 0.9092 pu [20]. To check the effectiveness of proposed method, three different loading levels i.e. light load (50% decrement in load), nominal load & heavy load (60% increment in load) are used. The first three candidate buses with optimal size have been determined by PVSC. The results for three different loading conditions are shown in Table 1. The real power loss at nominal load level (without compensation) is 225 kW and is reduced to 147 kW after installation of capacitor of total size 1470 kVAr. The minimum bus voltage is also improved from 0.909 pu to 0.931 pu. The results at light and heavy loading condition are also given in Table 1.

Table 1. Results for 69 bus system after capacitor installation

| | | Light Load (50%) | Nominal Load (100%) | Heavy Load (160%) |
|---|---|---|---|---|
| Before Capacitor Placement | Power Loss in kW | 53.31 | 225 | 643 |
| | Min. bus voltage | 0.956 | 0.909 | 0.845 |
| After Capacitor Placement | Capacitor Size in kVAr and location | 410 (61)<br>80 (21)<br>170 (64) | 750 (61)<br>270 (21)<br>400 (64) | 1500 (61)<br>240 (21)<br>600 (64) |
| | Total kVAr | 660 | 1420 | 2340 |
| | Power Loss (kW) | 36 | 147 | 408 |
| | Min. bus voltage | 0.966 | 0.931 | 0.887 |
| | % Loss reduction | 32.4 | 34.66 | 36.54 |

The results of proposed method is compared with latest optimization technique like Direct Search Algorithm [21], *Differential Evolution algorithm* [22], Flower Pollination Algorithm[23].The comparative analysis is shown in Table 2. It is noticed from table that the proposed approach give maximum loss reduction on lesser size of capacitor bank and percentage saving in cost is also maximum than other technique.

Table 2. Comparison of annual loss saving for various techniques at nominal load for 69 bus system

| Item | Without Capacitor | DSA [21] (2012) | DE [22] (2103) | FPA [23] (2016) | Proposed |
|---|---|---|---|---|---|
| Total Loss | 225 | 147 | 151.37 | 152 | 147 |
| % Loss Reduction | - | 34.66 | 32.7 | 32.44 | 34.66 |
| Min. Voltage | 0.909 | 0.93 | 0.931 | 0.93 | 0.931 |
| Optimal Size (Location) in kVAr | - | 900 (61)<br>450 (15)<br>450 (60) | 150 (57)<br>50 (58)<br>1000 (61)<br>150 (60)<br>100 (59) | 1350 (61) | 750 (61)<br>270 (21)<br>400 (64) |
| Total kVAr | - | 1800 | 1450 | 1350 | 1420 |
| Annual Cost ($/year) | 118260 | 85322 | 88910 | 84941 | 84523 |
| Net Saving ($/year) | - | 32938 | 29350 | 33319 | 33737 |
| % Saving | - | 27.8% | 24.8% | 28.17% | 28.52% |

The bus voltage profile of 69 bus system is also improved due to proposed approach. The improved voltage profile before and after compensation is shown in Figure 1.

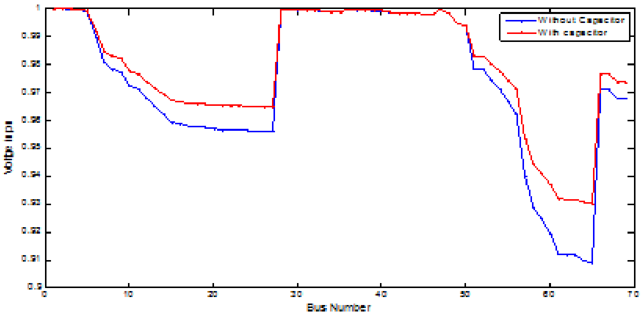


Figure 1. Voltage profile before and after capacitor placement for 69 bus system

Case II: 130 bus Jamwaramgarh (Jaipur) system

The system under consideration, as shown in figure 2, is 11 kV, 130 bus radial distribution system of Jamwaramgarh area, Jaipur city. The system load is 1878 kW and 1415 kVAr. The line and load data are given in appendix. The real power loss of the system is 335 kW and minimum bus voltage is 0.825 pu without compensation. The proposed approach is applied to determine the optimal location and size of capacitor bank. According to PVSC value, first five candidate buses are selected for allocation of capacitor units. Table 3 shows the result of jamwaramgarh system after compensation.

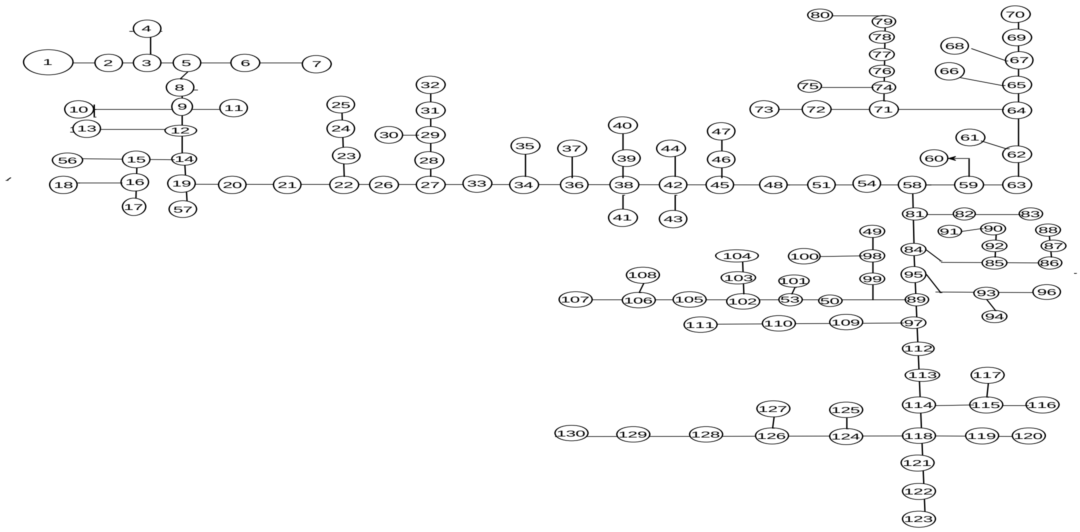

Figure 2. 130 bus Radial Distribution system, Jamwaramgarh, Jaipur

Table 3. Results of Jamwaramgarh (Jaipur) system

| Item | Without Capacitor | With capacitor |
|---|---|---|
| Total Loss | 335 | 208 |
| % Loss Reduction | - | 38% |
| Min. bus Voltage | 0.825 | 0.872 |
| Optimal Size (Location) in kVAr | - | 290 (53)<br>140 (77)<br>140 (114)<br>150 (120)<br>210 (126) |
| Total kVAr | - | 930 |
| Annual Cost ($/year) | 175550 | 117110 |
| Net Saving ($/year) | - | 58440 |
| % Saving | - | 33.3 % |

The real power loss is reduced to 208 kW after installation of capacitor of total size 930 kVAr. The minimum bus voltage is also enhanced from 0.825 pu to 0.872 pu after compensation. There will be 33.3 % saving in annual cost after shunt compensation. The improved voltage profile after shunt compensation is shown in Figure 2.

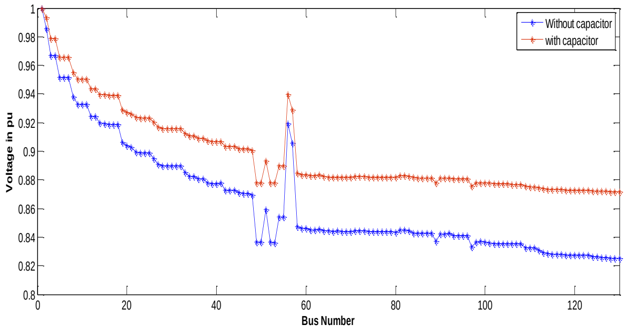


Figure 3. Voltage profile before and after capacitor placement for Jamwaramgarh, Jaipur

## 5. CONCLUSION

In this paper, the optimal allocation of shunt capacitor in radial distribution system is modeled to solve the objective of real power loss minimization, voltage profile improvement & energy cost saving. A power voltage sensitivity constant (PVSC) has been proposed to solve the problem. The effectiveness of proposed approach has been experienced on 69 bus test system and real distribution system of Jamawaramgarh village, Jaipur city. The obtained results of 69 bus system are compared with latest approaches and found superior in terms of percentage loss reduction, voltage profile improvement and annual cost saving. The proposed approach is also successfully implemented on Jmawaramgarh distribution system. The annual installation cost of capacitor bank is $117110 whereas the annual cost saving due to energy loss is $ 58440. Therefore, the cost of shunt capacitor bank will be recovered in 3months of installation.

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