A Novel Analytical Technique for Optimal Allocation of Capacitors in Radial Distribution Systems

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Abstract. In this paper, a novel analytical technique is proposed to determine the optimal size and location of shunt capacitor units in radial distribution systems. An objective function is formulated to reduce real power loss, to improve the voltage profile and to increase annual cost savings. A new constant, the Loss Sensitivity Constant (LSC), is proposed here. The value of LSC decides the location and size of candidate buses. The technique is demonstrated on an IEEE-33 bus system at different load levels and the 130-bus distribution system of Jamawa Ramgarh village, Jaipur city. The obtained results are compared with the latest optimization techniques to show the effectiveness and robustness of the proposed technique.

Keywords*:* *annual cost saving; capacitors; Jamawa Ramgarh; LSC; radial distribution system; real power loss.*

1 Introduction

The complexity of modern power systems is increasing due to stressed conditions in distribution networks, exponential increments in population and high ongoing demands on power grids. This is becoming a more pressing concern for design engineers with every passing day. As per the Indian scenario, a significant part of system losses are distribution losses (around 20-25%). The power losses can be divided into two kinds, 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 the appropriate locations and of optimal size reduces the real power loss and improves the voltage profile of the system. Several researchers have suggested optimization techniques to solve the problem of optimal allocation of capacitor units in radial distribution systems. In [1], Prakash, *et al.* used the Particle Swarm Optimization algorithm to determine the best location and size of capacitor units in a radial distribution system. Carpinelli, *et al.* [2] solved the problem of shunt capacitor placement and sizing using an approximate power flow method. The cost of real power losses and the cost of the capacitors were included in the objective function. Nonlinear programming [3], a genetic algorithm (GA) [4], simulated annealing (SA) [5], the cuckoo search algorithm [6], a heuristic algorithm [7], particle

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swarm optimization (PSO) [8-9], artificial bee colony (ABC) [10], the firefly algorithm (FA) [11], teaching-learning based optimization (TLBO) [12], the plant growth simulation algorithm (PGSA) [13], Harmony Search (HS) [14], the cuckoo search algorithm (CSA) [15], the ant colony search algorithm (ACO) [16], bacteria foraging (BF) [17], the flower pollination algorithm [18], the direct search algorithm [19], and the differential evolution algorithm [20] have been used to solve the optimal capacitor allocation problem. However, few authors have tested their algorithm on a real power distribution system.

In this paper, a new analytical method is presented to solve the capacitor allocation problem in a radial distribution system. The objective function was formulated to minimize annual cost (including energy loss cost and reactive power compensation cost). A new constant, the Loss Sensitivity Constant (LSC), is proposed. This constant incorporates real power loss and the voltage of the system. In other optimization algorithms the location of the shunt capacitors is determined by the loss sensitivity factor (LSF). However, the proposed LSC gives the optimal location and optimal size for the capacitor banks simultaneously. The efficacy of the proposed methodology was tested on a standard 33-bus system at different load levels and the 130-bus real distribution system of Jamawa Ramgarh village, Jaipur city. Three loading conditions (Light, Nominal and Heavy) were considered. The performance of the proposed technique was compared with various other algorithms.

2 Objective Function

The objective function of the capacitor allocation problem is designed to minimize the total cost due to energy loss and reactive power compensation under certain operating constraints.

Mathematically, the problem can be written as in Eq. (1)[21]:

Min. f = energy loss cost + reactive power compensation cost

$$\text{Min. } f = K_p * P_{loss} * t + K_i * C_B + K_C * \sum_{i}^{CB} Q_{ci} \tag{1}$$

where the constants are taken as in [21].

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 the radial distribution system.
3. The reactive power injection at each candidate bus is given by its minimum and maximum compensation limits.
4. Line current constraints $I_m \leq I_{mrated}$

3 Loss Sensitivity Constant (LSC)

An analytical approach was chosen to solve the capacitor placement problem. The Loss Sensitivity Constant (LSC) is proposed to determine the size and location of the capacitor units. This constant takes the active power loss and the voltage limits of the individual buses into account and suggests the optimal location and size of the capacitor units.

$$LSC = \frac{V_{max}}{V_{min}} + \frac{Pdgloss}{Prealloss} \tag{2}$$

where,

$P_{realloss}$ = base case real power loss
P_{dgloss} = active power loss after capacitor placement at the ith bus
V_{max} = rated bus voltage in pu after capacitor placement at the ith bus
V_{min} = minimum bus voltage in pu after capacitor placement at the ith bus

For optimal placement of the capacitor bank, the LSC value should be minimum. A flow chart of the proposed analytical approach is shown in Figure 1.

4 Test Results

In the proposed analytical approach, the capacitor units are placed so as to minimize the real power loss and to enhance the voltage profile. The proposed technique is implemented in a standard system of 33 buses and the 130-bus real distribution system of Jamawa Ramgarh village, Jaipur city. The complete scheme is developed with the MATLAB software. The values of the various constants used in Equation (1) are: cost of energy loss (Kp) = \$ 0.06/kwh, capacitor installation cost for one single unit (Ki) = \$ 1000, cost per kVAr capacitor bank (Kc) = \$ 3.

4.1 Case I: 33-bus System

The 33-bus test system had 12.66 kV and a 100 MVA base value [22]. The real and reactive power load of the system was 3.715 MW and 2.30 MVAr. To check the effectiveness of the proposed method, three different loading levels were used, i.e. light load (50% decrement in load), nominal load, and heavy load (60% increment in load).

The base network power loss was 202.6762 kW.

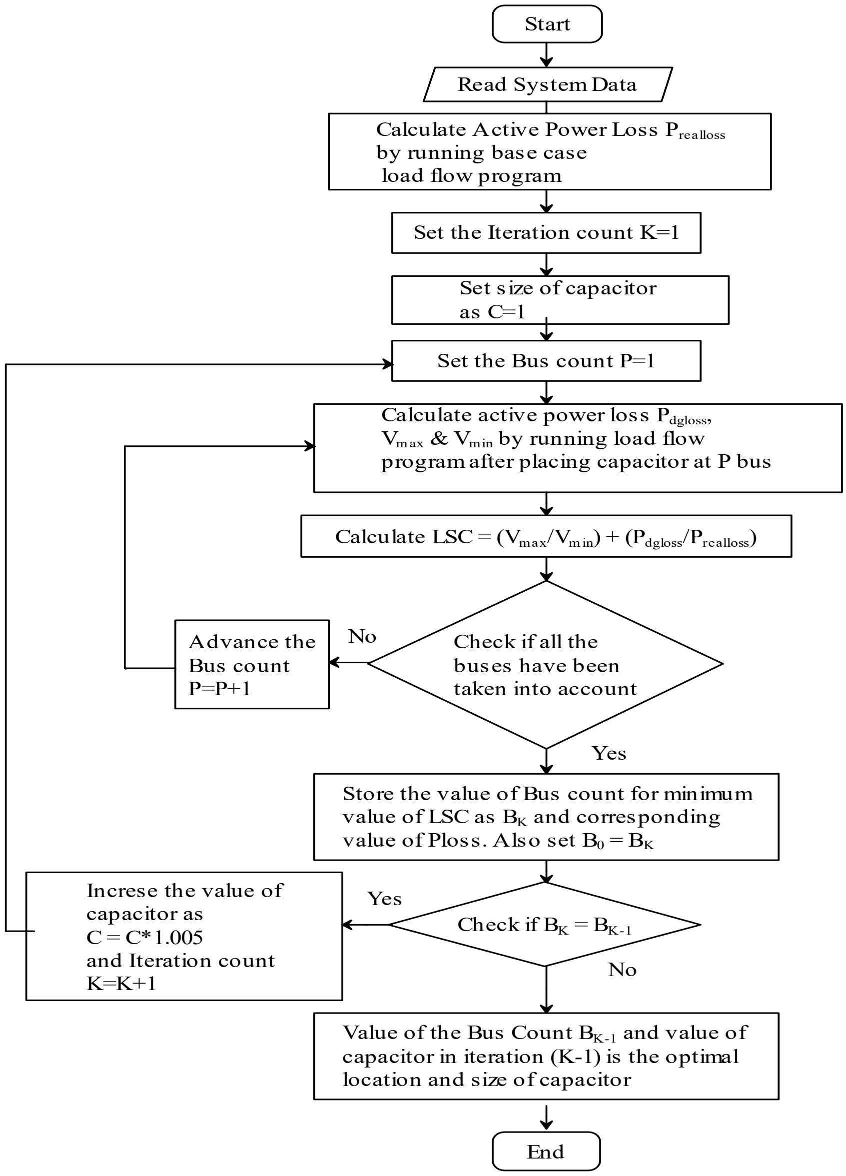

Figure 1 Flow chart of proposed analytical method.

Table 1 Results for 33-bus test system after capacitor installation.

		Light load (50%)	**Nominal load (100%)**	**Heavy load (160%)**
Before capacitor placement	Power loss in kW	47	202.7	575.36
	Min. bus voltage	0.9583	0.9131	0.853
After capacitor placement	Capacitor size in kVAr and location	300 (14) 250 (30) 170 (32)	550 (14) 480 (30) 330 (32)	840 (14) 650 (30) 520 (32)
	Total kVAr	720	1360	2010
	power loss (kW)	33.04	138.72	384
	Min. bus voltage	0.9734	0.9428	0.90
	% loss reduction	29.8	31.5	33.21

The results of the proposed method were compared with the two latest optimization techniques, i.e. simulated annealing (SA) [23] and the interior point algorithm (IP) [23], respectively. A comparative analysis is shown in Table 2. It can be seen from the table that the proposed approach resulted in a higher loss reduction with a smaller size of capacitor bank than other techniques and the annual cost saving is also higher.

Table 2 Comparison of annual loss saving for various techniques at nominal load for 33-bus test system.

Item	**Without capacitor**	**SA [23] (2015)**	**IP [23] (2015)**	**Proposed**
Total loss	202.7	151.7	171.8	138.77
% loss reduction		25.12	15.24	31.5%
Min. voltage	0.9131	0.959	0.95	0.944
Optimal size (location) in kVAr		450 (10) 900 (14) 350 (30)	450 (9) 800 (29) 900 (30)	550 (14) 480 (30) 330 (32)
Total size in kVAr	-	1700	2150	1360
Annual cost ($/year)	106540	87860	99738	79991
Net saving ($/year)	-	**18680**	**6802**	**26550**
% saving	-	17.53%	6.3%	25%

The bus voltage profile of the 33-bus system was also improved due to the proposed approach. The improved voltage profile before and after compensation is shown in Figure 2.

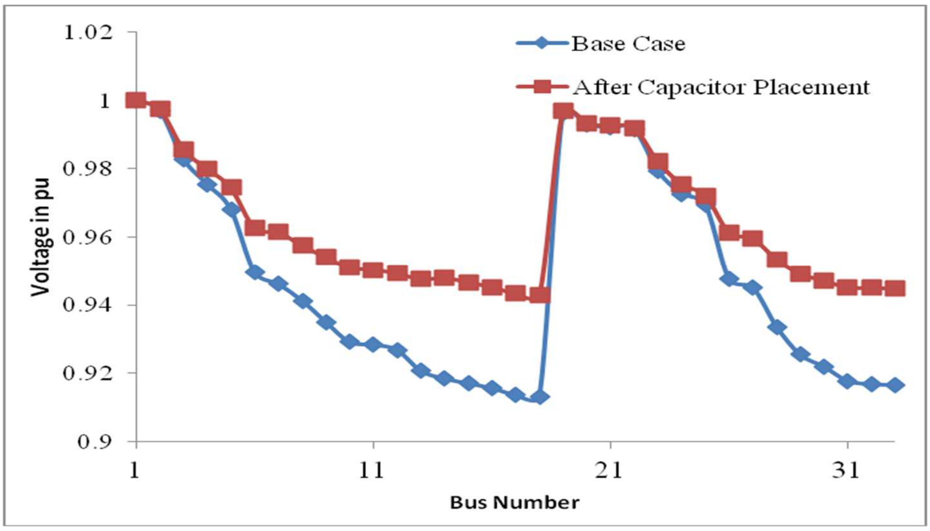

Figure 2 Comparison of voltages before and after compensation at nominal load for 33-bus system.

4.2 Case II: 130-bus Jamwa Ramgarh System

The real system under consideration, as shown in Figure 3, was the 11 kV, 130-bus radial distribution system of Jamwa Ramgarh village, Jaipur city. The system load was 1878 kW and 1415 kVAr. The real power loss of the system was 335 kW and minimum bus voltage was 0.825 pu without compensation.

The proposed approach was applied to the real distribution system in order to determine the optimal location and size of the capacitor bank. First, five candidate buses were selected according to the value of LSC for allocation of the capacitor units. Table 3 shows the result for the Jamwa Ramgarh system after shunt compensation.

The real power loss was reduced to 208 kW after installation of capacitors with a total size of 930 kVAr. The minimum bus voltage will also enhanced, from 0.825 pu to 0.872 pu after compensation. There will be a 33.3% saving in annual costs after shunt compensation. The cost of the capacitor bank will be recovered within 3 months of installation. The improved voltage profile after shunt compensation is shown in Figure 4.

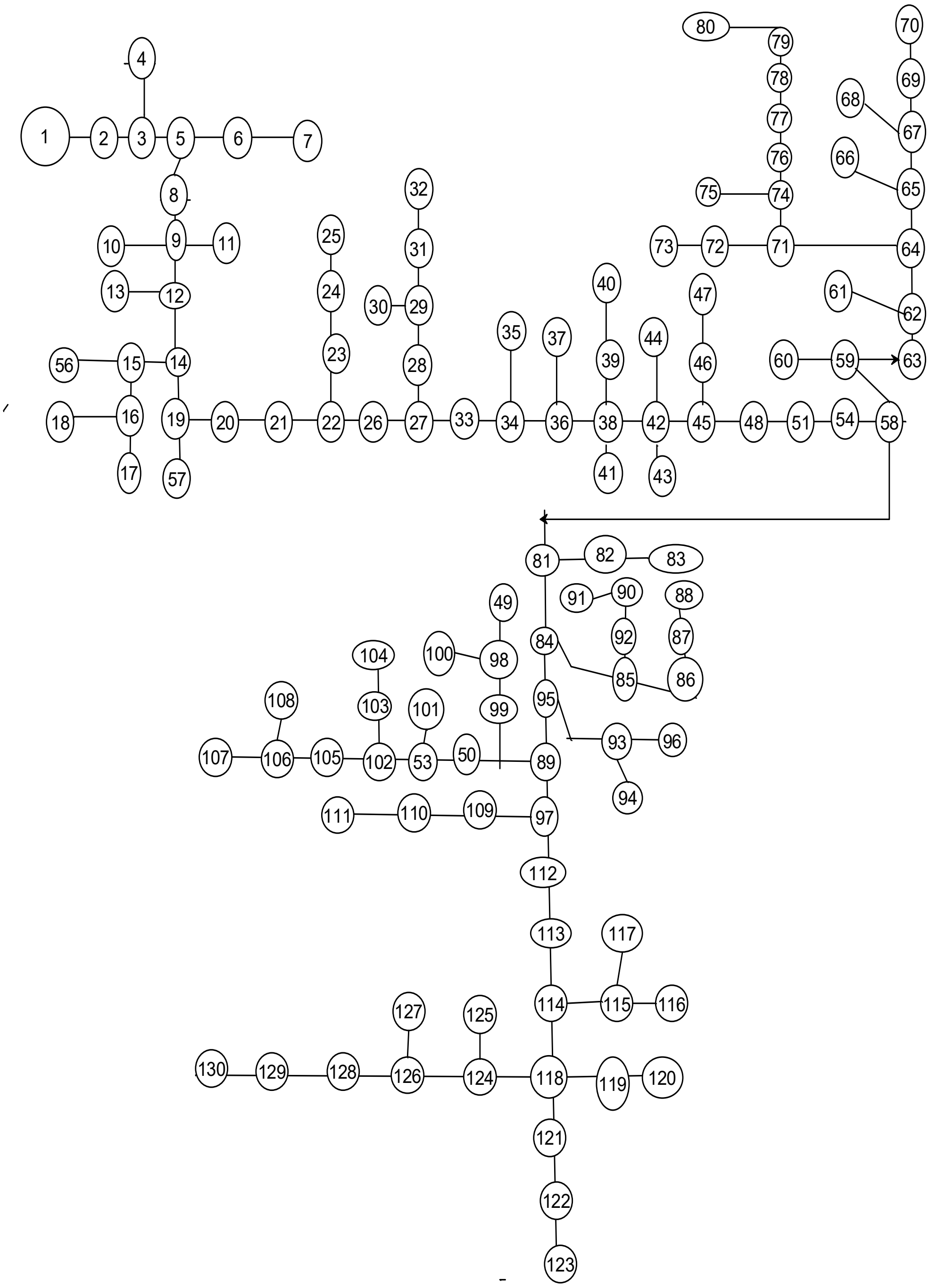

Figure 3 130-bus radial distribution system, Jamwa Ramgarh, Jaipur.

Table 3 Results of 130-bus Jamwa Ramgarh system.

Item	Without capacitor	With capacitor
Total real power loss in kW	335	208
% loss reduction	-	38%
Min. bus voltage	0.825	0.872
Optimal size (location) in kVAr	-	290 (53) 140 (77) 140 (114) 150 (120) 210 (126)
Total kVAr	-	930
Annual cost ($/year)	175550	117110
Net saving ($/year)	-	58440
% annual cost saving	-	33.3 %

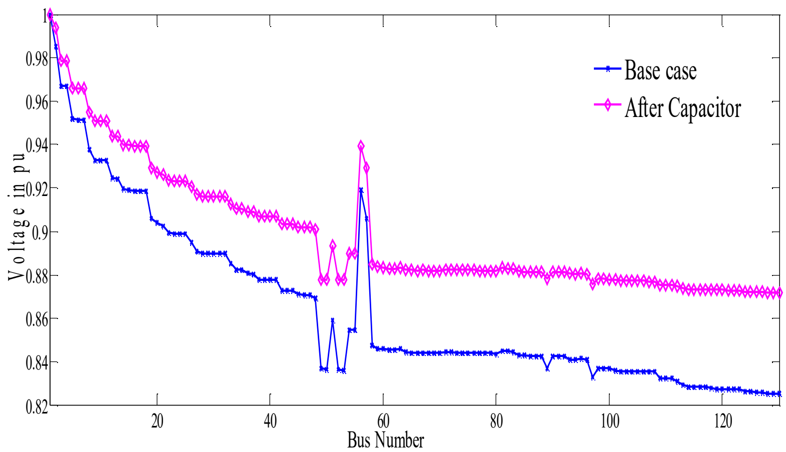

Figure 4 Voltage profile before and after capacitor placement for Jamwa Ramgarh distribution system, Jaipur.

5 Conclusion

In this study, optimal allocation of shunt capacitors in a radial distribution system was modeled to solve the objective of real power loss minimization, voltage profile improvement, and energy cost saving. The Loss Sensitivity Constant (LSC) was proposed to solve the problem. The effectiveness of the proposed approach was tested on a 33-bus test system and the 130-bus real distribution system of Jamawa Ramgarh village, Jaipur city. The obtained results of the 33-bus test system were compared with the latest approaches and found superior in terms of percentage loss reduction, voltage profile improvement, and annual cost savings. The proposed approach was also successfully implemented on the real 130-bus Jamwa Ramgarh distribution system. The annual installation cost of the capacitor bank is $ 117,110, whereas the annual cost savings due to energy loss minimization is $ 58,440. Therefore, the cost of the shunt capacitor bank will be recovered in 3 months after installation.

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