Journal of
Electrical & Electronic Systems

Abul'Wafa, J Electr Electron Syst 2017, 6:1
DOI: 10.4172/2332-0796.1000213

Research Article Open Access

Novel Loss-Voltage Sensitivity Factor for Capacitor Placement in Radial Distribution System Using Analytical Approach

Ahmed R. Abul'Wafa*

Ain-Shams University, Electric Power and Machines, Cairo, Egypt

Abstract

An analytical technique is proposed for allocation of shunt capacitor bank in radial distribution system. The objective is formulated to determine the size, number and location of capacitor bank for real and reactive power loss reduction, voltage profile enhancement and annual cost saving. A novel Loss-Voltage Sensitivity Factor (LVSF), has been incorporated in the technique. The value of LVSF decides the candidate bus location.

The achievability of the proposed method (PM) has been demonstrated on IEEE-69 bus test system allowing comparing results with latest optimization techniques in literature. Further application of PM on 130 bus relatively large distribution system shows the effectiveness and robustness of the proposed technique.

Capacitors allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. This development is essential when allocated capacitors in nominal and heavy loading simulations do not include nodes of fixed capacitors.

Keywords: Shunt fixed and switchable capacitor bank; Analytical approach; Distribution system; LVSF; Load flow

Introduction

Placement of capacitor of optimal sizes and at optimal locations not only reduces the power losses, but also improves the voltage stability of the electric power systems. Several meta-heuristic techniques have been used by scientists and researchers over the years to address the problems of capacitor placements. They are very effective and powerful in comparison with conventional methods in solving complex nonlinear constrained optimization problems. Authors [1], used Differential Evolution algorithm, Direct Search Algorithm [2], Artificial bee colony algorithm (ABC) [3], Flower Pollination Algorithm [4], Bacteria Foraging (BF) [5], Ant Colony Search Algorithm (ACO) [6], Cuckoo Search Algorithm (CSA) [7], Harmony Search (HS) [8], Plant Growth Simulation Algorithm (PGSA) [9], Teaching Learning Based Optimization (TLBO) [10], Firefly Algorithm (FA) [11], shark smell optimization algorithm [12], Particle Swarm Optimization (PSO) [13,14], Heuristic Algorithm [15], Fuzzy–GA method [16], Simulated Annealing (SA) [17], Genetic Algorithm (GA) [18], Nonlinear Programming [19]. Carpinelli et al. [20] solved the problem of shunt capacitor placement and sizing by approximate power flow method. S Mandal et al. [21] used a new hybrid particle swarm optimization algorithm to determine the best location and size of capacitor units in radial distribution system. The cost of real power losses and cost of capacitors were included in the objective function. However, one of the major difficulties for these methods is the premature convergence.

In this paper a new analytical method has been presented to solve the capacitor allocation problem in distribution system. The objective was formulated to minimize real power loss to its minimum value. A new Loss-Voltage Sensitivity Factor (LVSF), has been proposed here. LVSF incorporated real power loss and voltage of the system. The proposed technique gives best location and size of capacitor banks simultaneously. The efficacy of the proposed methodology has been tested on IEEE 69 bus distribution system. Three loading conditions (Light, Nominal and Heavy) are also considered here.

A further development of the proposed technique, capacitors allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. This development is when allocated capacitors in nominal and heavy loading simulations do not include nodes of fixed capacitors.

The results of proposed technique applied on IEEE 69 bus distribution system are compared with various algorithms to check its supremacy. Further the proposed technique was applied on relatively large 130 bus real distribution system insuring the effectiveness and robustness of the proposed technique.

Paper Contributions

The main contributions of this paper can be defined as

- Proposal of a new technique to solve capacitor location problem especially for large scale system.
- Proposal of a new Loss-Voltage Sensitivity Factor (LVSF), has been incorporated in the technique to decide the candidate bus location.
- The proposed technique outlasts other algorithms in solving the optimal locations and sizing of capacitors in distribution systems. Moreover, it provides a promising and preferable performance over other algorithms in terms of voltage profiles, active and reactive power losses, total cost and net saving.
- Capacitor allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. Capacitors determined

***Corresponding author:** Ahmed R. Abul'Wafa, Ain-Shams University, Electric Power and Machines, Cairo, Egypt, Tel: +20226831474; E-mail: Ahmedlaila.nelly.ola@gmail.com

Received January 21, 2016; **Accepted** February 20, 2017; **Published** February 27, 2017

Citation: Abul'Wafa AR (2017) Novel Loss-Voltage Sensitivity Factor for Capacitor Placement in Radial Distribution System Using Analytical Approach. J Electr Electron Syst 6: 213. doi:10.4172/2332-0796.1000213

in nominal and heavy loading simulations are switchable capacitors.

Computation Algorithm

Following pseudo code summaries the computational process for proposed analytical technique:

While $P_{loss_{wCap}}$ continue decreasing.

Do until a capacitor is allocated

a) Set any size (5 kVAr) of capacitor unit at a bus and run load flow program [22].

Calculate the $P_{loss_{wCap}}$ of the system and LVSF values for each bus.

b) Increment the size of capacitor in 5 kVAr steps and repeat 'i' and 'ii'.

Store the size of capacitor which gives least amount $P_{loss_{wCap}}$ of the system.

Store the bus, which has least LVSF value, will be the best location of capacitor unit.

Repeat steps 'd' to 'e' to find more locations and sizes of capacitors as multi-capacitor compensation.

End do.

Print best capacitor placement.

Print $P_{loss_{wCap}}$, $Q_{loss_{wCap}}$, power loss reduction % , and annual $ Saving.

Apply this process for Light loading condition to determine best location and size of fixed capacitors. Next apply this process with allocated fixed capacitors, for nominal and peak loading conditions to determine best location and size of switched capacitors.

Algorithm Variables

The variables in the computation algorithm are defined mathematically as follows:

$$\$\ \text{saving} = K_p \Delta P_{loss} + K_p \Delta P_{loss} T_{loss} - \left(K_i C_B + K_c \sum_{i}^{C_B} Q_{c_i} \right) \times CRF \quad (1)$$

Where

$K_p \Delta P_{loss}$ – Power Loss reduction cost ,

$K_e \Delta P_{loss} T_{loss}$ – Energy loss reduction cost ,

$K_i C_B + K_c \sum_{i}^{C_B} Q_{c_i}$ – Reactive power compensation cost ,

C_B and Q_{c_i} - Optimum number and rating of capacitors,

CRF - Capital return factor

$$CRF = \frac{\left(r(1+r)^t \right)}{\left(\left((1+r)^t \right) - 1 \right)} \quad (2)$$

Operational Constraints

The operating constraints are:

- The voltage of each bus must be maintained between specified limits.

$$V_{min} \le V_i \le V_{max} \quad (3)$$

- The total reactive power injected is not to exceed the total reactive power demand in radial distribution system.
- The reactive power injection at each candidate bus is given by its minimum and maximum compensation limit.

Loss-Voltage Sensitivity Factor (LVSF)

The analytical method incorporating a Loss-Voltage Sensitivity Factor (LVSF), has been proposed to determine the size and location of capacitor units. The LVSF takes the system active power loss with and without capacitors and voltage limits of individual buses with capacitors in account and suggest the best location of the capacitor. The LVSF includes main objectives (power loss reduction and voltage profile enhancement).

$$LVSF = \frac{V_{max_{wCap}}}{V_{min_{wCap}}} + \frac{P_{loss_{wCap}}}{P_{loss_{base}}} \quad (4)$$

where,

$P_{loss_{base}}$ Base case real power loss (kW)

$P_{loss_{wCap}}$ Real power loss after capacitor placement at a bus (kW)

$V_{max_{wCap}}$ Per unit maximum bus voltage after capacitor placement at a bus

$V_{min_{wCap}}$ Per unit minimum bus voltage after capacitor placement at a bus

Test Results

In proposed analytical approach, capacitor units are placed to minimize real power loss and to enhance voltage profile. The technique is employed on the IEEE 69 bus distribution system and on relatively large 130 bus real distribution system.

The implementation of proposed method for the best capacitor placement problem was done using version (9.0.0) R2016 a of MATLAB language on an Intel Core i7 processor running at 2.20 GHz with 7.95 GB RAM.

The values of various constant used in equation (1 to 2) are: Cost of power loss (K_p) = \$0.06/kwh, Cost of energy loss (K_e) = \$0.06/kWh , capacitor installation cost for single unit (K_i) = \$1000, Cost of per kVAr capacitor bank (K_c) = \$5, maximum loss hours = 1500, discount rate (r) = 0.08, and economic life of investment (years) = 10.

From simulation results, it is learned that capacitor locations during light loading condition simulation may not repeated in nominal and heavy loading simulations. Therefore, in this paper capacitor allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. Capacitors determined in nominal and heavy loading simulations are switchable capacitors. To the author knowledge this approach was not tackled in previous publications. This approach shall be detailed in the following section.

Case 1: 69 bus system

The IEEE 69 bus has 12.66 kV and 100 MVA base values. The base case real power loss and minimum bus voltage are 224.7893 kW and 0.9092 pu [23].

Generally Capacitor bank size, location and control are determined based on reactive load curve usually approximated by a steps ladder function. In this work, three steps functions are used. Thus, calculation of energy losses requires power losses in peak (160 % of nominal load), nominal and light (50% decrement in load) load levels.

Simulation results for the three operating conditions are summarized in Table 1. The voltage profile after compensation compared to base case is shown in Figure 1 for nominal operating condition and in Figure 2 for heavy operating condition.

Meaning beside (175/17+260/50 kVAr/node) fixed capacitors, (1267/61+303/50 kVAr/node) switched capacitors are required at nominal load operating condition and additional (844/61+54/50 kVAr/node) switched capacitors are required at heavy load operating condition.

The results of proposed method are compared with latest optimization technique like Fuzzy-GA [16], Direct Search Algorithm [2], PSO [13], Heuristic [15], and Flower Pollination Algorithm [24]. 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 exceeds those in other technique. The bus voltage profile of 69 bus system is also improved due to proposed approach. DE [2] and FPA [24] searched lesser size

		Light Load (50%)	Nominal Load (100%)	Heavy Load (160%)
Before Capacitor Placement	Power Loss (kW)	51.6150	224.7893	651.9646
	Min. bus voltage (pu)	0.9567	0.9092	0.8445
After Capacitor Placement	Capacitor Size in kVAr and location	175/17 260/50	1267/61 303/50	2111/61 357/50
	Total kVAr	435	1570	2468
	Power Loss (kW)	34.6352	145.9182	410.1286
	Min. bus voltage (pu)	0.9680	0.9316	0.8854
	% Loss reduction	32.8969	35.0867	37.0934

Table 1: Simulation results for 69 bus system after capacitor installation.

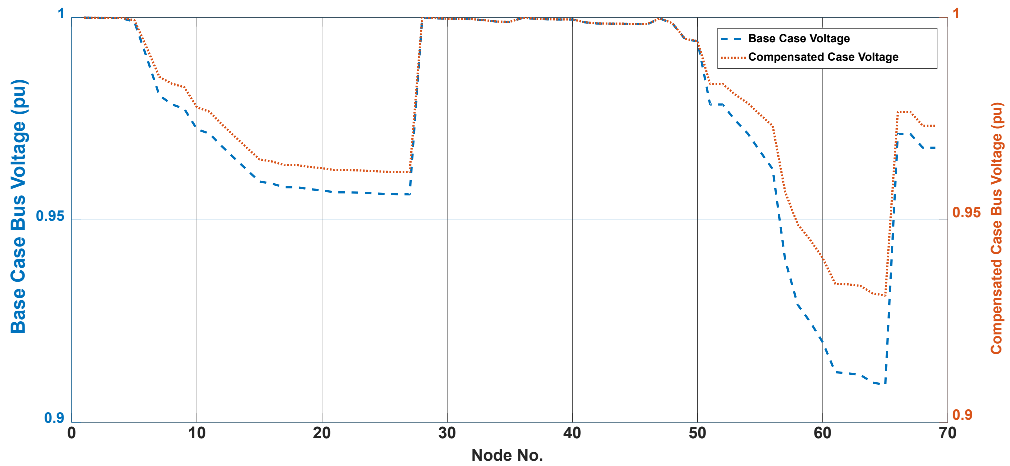

Figure 1: Voltage profile before and after capacitor placement for 69 bus system in nominal loading condition.

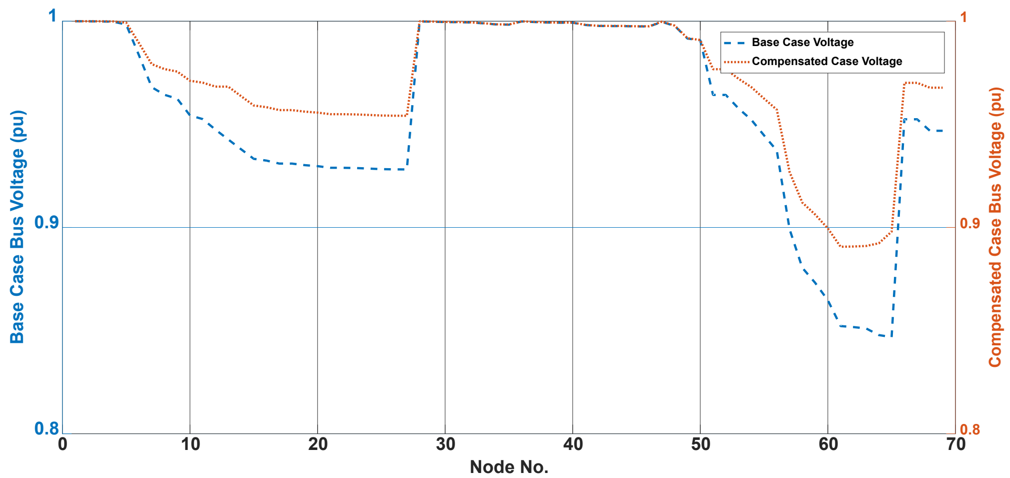

Figure 2: Voltage profile before and after capacitor placement for 69 bus system in heavy loading condition.

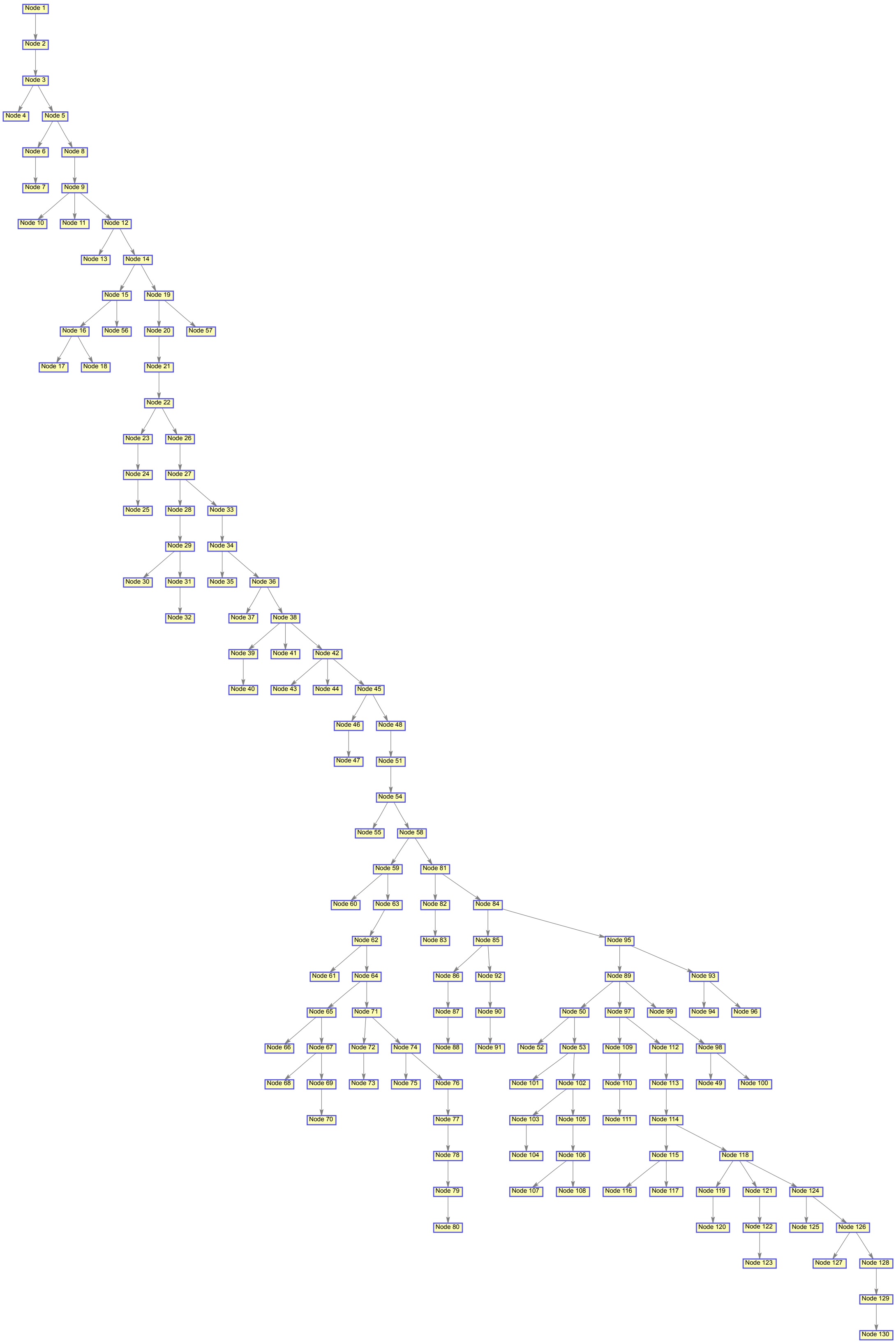

Figure 3: Tree graph of 130 bus radial distribution system.

Citation: Abul'Wafa AR (2017) Novel Loss-Voltage Sensitivity Factor for Capacitor Placement in Radial Distribution System Using Analytical Approach. J Electr Electron Syst 6: 213. doi:10.4172/2332-0796.1000213

of capacitor bank, however resulting in lower loss reduction and percentage saving.

Case 2: 130 bus system

The system under consideration is 11 kV, 130 bus radial distribution system. The system load is 1911.6 kW and 1423.8 kVAr. The line and load data are given in Appendix and the tree graph of the feeder is shown in Figure 3. The real power loss of the system is 365.1864 kW and minimum bus voltage is 0.9243 pu without compensation. The procedure of proposed approach, as detailed for IEEE 69 bus system is

Items	Un-compensated	Compensated					
		Fuzzy-GA [16]	DE [2]	PSO [13]	Heuristic [15]	FPA [24]	Proposed Method
Total losses (kW)	224.8949	156.62	151.3763	152.48	148.48	150.28	145.9182 (Base kW losses 224.7893)
Loss reduction (%)		30.4	32.7	32.2	34 35.2	33.20	35.0867
Minimum voltage	0.9092	0.9369	0.9311		0.9305	0.9323	0.9316
Optimal location and size in kVAr (Node/kVAr)		59/100 61/700 64 800	57/150 58/50 61/1000 60/150 59/100	46/241 47/365 50/1015	8/600 58/150 60/1050	61/1350	61/1267 50/303
Total kVAr		1600	1450	1621	1800	1350	1570
Annual cost ($/year)	118,204.8	90119.5	88913.4	88006.5	86441.1	85356.7	
Net saving ($/year)		28085.3	29291.4	30198.3	31763.7	32848.1	39327.5791 (Base Annual cost=128130 $/yr.)
% saving		23.8	24.8	25.6	26.9	27.8	30.69

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

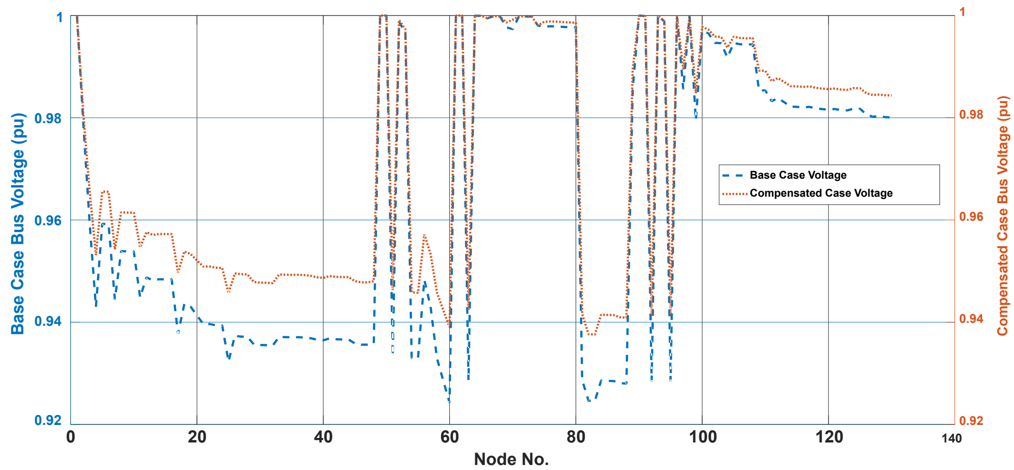

Figure 4: Voltage profile before and after capacitor placement for 130 bus system in nominal loading condition.

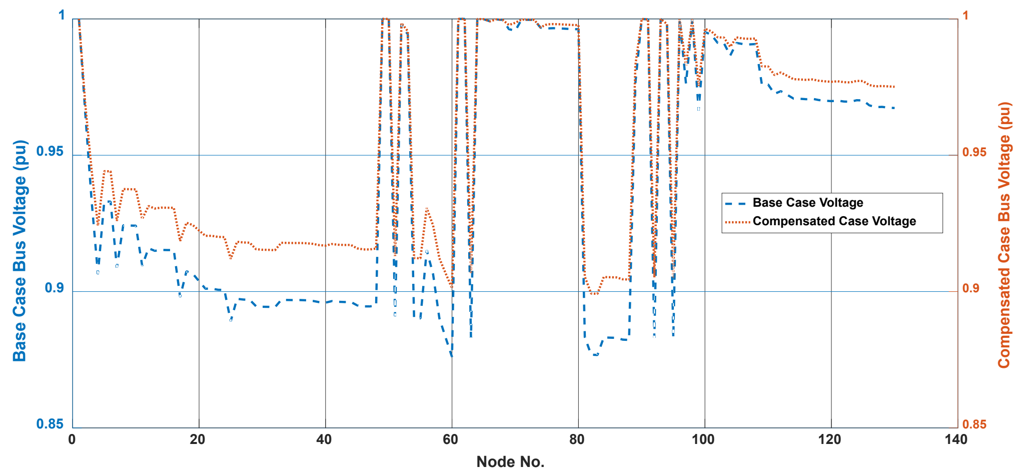

Figure 5: Voltage profile before and after capacitor placement for 130 bus system in heavy loading condition.

		Light Load (50%)	Nominal Load (100%)	Heavy Load (160%)
Before Capacitor Placement	Power Loss (kW)	185.4599	365.9583	979.0706
	Min. bus voltage (pu)	0.9562	0.9242	0.8760
After Capacitor Placement	Capacitor Size in kVAr and location	10/5	1085/89 340/20 45/129 40/6	1670/89 660/19 115/128 65/3
	Total kVAr	10	1510	2510
	Power Loss (kW)	64.0474	241.8028	633.9606
	Min. bus voltage (pu)	0.9682	0.9376	0.8992
	% Loss reduction	65.4656	33.9261	35.3367

Table 3: Simulation results of the 130 bus distribution system.

repeated for this relatively large system to determine the best location and size of capacitor bank.

Simulation results for the three operating conditions are summarized in Table 3. The voltage profile after compensation compared to base case is shown in Figure 4 for nominal operating condition and in Figure 5 for heavy operating condition.

Meaning beside (10/5 kVAr/node) fixed capacitors, (1085/89+115/128+65/3 kVAr/node) switched capacitors are required at nominal load operating condition and additional (585/89+320/20+25/6 kVAr/node) switched capacitors are required at heavy load operating condition.

Conclusion

In this paper, an analytical technique is proposed for allocation of shunt capacitor bank in radial distribution system for real and reactive power loss reduction, voltage profile enhancement and annual cost saving. A new Loss-Voltage Sensitivity Factor (LVSF), has been incorporated in the technique to decide the candidate bus location.

Capacitors allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. This development is when allocated capacitors in nominal and heavy loading simulations do not include nodes of fixed capacitors.

A large scale and small scale distribution systems are used to demonstrate the performance of the new formulation. The proposed algorithm provides an efficient solution since it provides a promising and preferable performance over other algorithms in terms of voltage profiles, active and reactive power losses, total cost and net saving.

References

1. Elfergany A (2013) Optimal capacitor allocations using evolutionary algorithm. IET Proc Gener Transm Distribution 7: 593-601.
2. Raju M, Murthy K, Avindra K (2012) Direct search algorithm for capacitive compensation in radial distribution systems. Int J Electr Power Energy System 42: 24-30.
3. El-Fergany AA, Abdelaziz AY (2014) Artificial bee colony algorithm to allocate fixed and switched static shunt capacitors in radial distribution networks. Electric Power Comp Syst 42: 427-438.
4. Tamilselvan V, Jayabarathi T (2016) Multi objective Flower Pollination Algorithm for solving capacitor placement in radial distribution system using data structure load flow analysis. Archives of Electrical Engineering 65: 203-220.
5. Tabatabaei SM, Vahidi B (2011) Bacterial foraging solution based fuzzy logic decision for optimal capacitor allocation in radial distribution system. Int J Electric Power Syst Res 81: 1045-1050.
6. Chang CF (2008) Reconfiguration and capacitor placement for loss reduction of distribution systems by ant colony search algorithm. IEEE Trans. Power Syst 23: 1747-1755.
7. El-Fergany AA, Abdelaziz AY (2014) Capacitor allocations in radial distribution networks using cuckoo search algorithm. IET Generation Transm. Distrib 8: 223-232.
8. Sirjani R, Mohamed A, Shareef H (2010) Optimal capacitor placement in a radial distribution systems using harmony search algorithm. J Appl Sci 10: 2998-3006.
9. Rao RS, Narasimham SVL, Ramakingaraju M (2011) Optimal capacitor placement in a radial distribution system using plant growth simulation algorithm. Int J Electr Power Energy Syst 33: 1133-1139.
10. Sultana S, Roy PK (2014) Optimal capacitor placement in radial distribution systems using teaching learning based optimization. Int J Electr Power Energy Syst 54: 387-398.
11. Das P, Banerjee S (2014) Optimal sizing and placement of capacitor in a radial distribution system using loss sensitivity factor and firefly algorithm. Int J Eng Comput Sci 3: 5346-5352.
12. Gnanasekaran N, Chandramohan S, Sathish Kumar P, Mohamed Imran A (2016) Optimal placement of capacitors in radial distribution system using shark smell optimization algorithm. Ain Shams Engineering Journal 7: 907-916.
13. Prakash K, Sydulu M (2007) Particle swarm optimization based capacitor placement on radial distribution systems. Proc IEEE power engineering society general meeting pp: 1-5.
14. Amanifar O, Golshan MEH (2011) Optimal distributed generation placement and sizing for loss and THD reduction and voltage profile improvement in distribution systems using particle swarm optimization and sensitivity analysis. Int J Tech Phys Probl Eng 3: 47-53.
15. Hamouda A, Sayah S (2013) Optimal capacitors sizing in distribution feeders using heuristics search based node stability indices. Int J Electr Power Energy Syst 46: 56-64.
16. Das D (2008) Optimal placement of capacitors in radial distribution system using a Fuzzy-GA method. Int J Electr Power Energy Syst 30: 361-367.
17. Subrahmanyam JBV (2009) Optimal Capacitor Placement in Unbalanced Radial Distribution Networks. Journal of Theoretical and Applied Information Technology 6: 106-115.
18. Jovica Vuletic, Mirko Todorovski (2016) Optimal capacitor placement in distorted distribution networks with different load models using Penalty Free Genetic Algorithm. Electrical Power and Energy Systems 78: 174-182.
19. Nojavan S, Jalali M, Zare K (2014) Optimal allocation of capacitors in radial/mesh distribution systems using mixed integer nonlinear programming approach. Int J Electric Power Syst Res 107: 119-124.
20. Carpinelli G, Varilone P, Di Vito V, Abur A (2005) Capacitor placement in three-phase distribution systems with nonlinear and unbalanced loads. Proc Inst Elect Eng Gen Transm Distrib 152: 47-52.
21. Mandal S, Mandal KK, Tudu B (2016) A new hybrid particle swarm optimization technique for optimal capacitor placement in radial distribution systems. Proc 2nd Int Conf on Control, Instrumentation, Energy and Communication (CIEC) pp: 536-540.
22. Ahmed R Abul'Wafa (2012) A network-topology-based load flow for radial distribution networks with composite and exponential load. Electric Power Systems Research 91: 37-43.

23. Ahmed R Abul'Wafa (2013) Optimal capacitor allocation in radial distribution systems for loss reduction: A two stage method. Electric Power Systems Research 95: 168-174.

24. Abdelaziz AY, Ali ES, Abd Elazim SM (2016) Flower Pollination Algorithm and Loss Sensitivity Factors for optimal sizing and placement of capacitors in radial distribution systems. Int J of Electrical Power and Energy Systems 78: 207-214.