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A comprehensive review: Optimal capacitor placement and sizing in a distribution system

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Abstract: In the last few years, electricity demand increased globally, as a result, losses are also increased in the power system. Capacitors are used in the power system at shunt state to minimize these power losses. Several analytical, heuristic and their combinational approaches have been proposed in the literature for the optimal capacitor placement problem. In this paper, the analytical, heuristic-based methods, and their combinational approaches are considered, reported in the literature for the optimal capacitor placement, and the objective is to provide a comprehensive review while considering the objective functions (minimization of power losses, and capacitor cost and maximization of net saving). To express each review effectively, details are tabulated in the form of load flow process, system constraints, analytical methods, Type of capacitors and loads, system considered (IEEE, Local), outcomes in terms of minimization and maximization.

Keywords: Optimal capacitor placement, Distribution system, Analytical techniques, Heuristic techniques, Objective functions,

1.0 INTRODUCTION

In early years, capacitors were placed at shunt state near to the power system i-e (secondary distribution level). It benefits the power system in the form of enhancement in power factor and stabilizing the voltage, along with the reduction in power losses. To acquire the maximum advantage in terms of voltage, and power factor capacitors were placed near to the secondary distribution level. But with the passage of time trend has been changed, and now capacitors are also placed at the primary distribution side as well[1]. To form a capacitor bank series, and a parallel combination of capacitors are used. Capacitance reduces when capacitors are used in series, and inversely capacitance increases when capacitors are placed in parallel. A simple rule is needed to remember here, that a single capacitor should not produce an overvoltage more than 110 percent when connected in a parallel or in a series group. Capacitor reactance and the voltage applied decides the magnitude of reactive power which can be expressed as:

$$Q_c = \frac{V^2}{X_c} \quad (1)$$

The reactive power support in the distribution system may give benefits in the form of, enhancing the efficiency of the distribution system (enhancement of voltage profile, and power factor along with the reduction in power losses), and management of reactive power in the deregulated power industry as well. In the literature, several methods (analytical, numerical programming, heuristic) are reported in the last few decades for reactive power compensation in a distribution system. In this paper analytical, heuristic-based methods and their combinational approaches are considered, and the objective is to provide a comprehensive review while considering the objective functions (minimization of cost of power losses, and capacitor, and maximization of net saving) as reported in the literature.

In this paper, an inclusive review of heuristic techniques, which have been reported in the past by different researchers for the OCP[1] problem is presented. This review includes the fuzzy, artificial intelligence, evolutionary computation heuristic techniques, and their combinational technique with analytical based techniques. OCP and its sizing, fixed or switched capacitors under (unbalance or time-varying system, bus voltage, maximum number of

[1] Optimal Capacitor Placement

capacitors, line capacity, total reactive power compensated, overall power factor) constraints, outcomes in the form of net savings, total cost minimization, system power losses minimization, and enhancement in voltage profile are considered. Whereas systems stability, harmonics, and reliability are not considered may be taken as advantages and drawback of this paper.

2.0 PROBLEM FORMULATION

Capacitor placement is required in the power system to minimize the losses and maximize the voltage profile, and power factor within the limitations. The main aim is to optimally place and sizing the capacitors in the distribution system to achieve power losses, and total cost minimization along with maximization in net savings. The problem is to decide the potential candidate buses for the capacitor placement, and sizing of capacitors in the distribution system and minimize the total cost acquired by system power losses and capacitor installation and maintenance cost. To formulate the optimal capacitor placement, and sizing problem following objective functions are reported in the literature:

$$P_{T,loss} = \sum_{i=0}^{n-1} I_r^2 R_i \tag{2}$$

$$C_{min} = K_p \sum_{i=0}^{n} P_{loss}^i + \sum_{k=1}^{n} K_c C_k \tag{3}$$

$$C_{min} = K_p \sum_{i=0}^{n} T_i P_{loss}^i + \sum_{k=1}^{n} (Kd_k + K_c C_k) \tag{4}$$

$$C_{min} = K_p \sum_{i=0}^{n} T_i P_{loss}^i + \sum_{k=1}^{n} K_c C_k \tag{5}$$

$$S_{max} = K_p LP + K_e LE - K_c C \tag{6}$$

$$C_{min} = K_p \sum_{i=0}^{n} T_i P_{loss}^i + p \sum_{k=1}^{n} (Kd_k + K_c C_k) + K_r \sum_{i=0}^{n} T_i P_{loss}^{i,max} \tag{7}$$

$$C_{min} = K_p \sum_{i=0}^{n} T_i P_{loss}^i + \sum_{k=1}^{n} K_c C_k + (K_{ci} + K_{co}) N_c \tag{8}$$

Where (I^2) is the current passing through conductor, (R) is the resistance of the conductor, (K_p) is power loss annual cost per unit($/kW-year) and ($P_{loss}$) is the power loss varies according to the system under test, (T_i) is the load varying time duration, and K_c is the capacitor installation cost ($/year) for the proposed size of the capacitor (C_k), for capacitor bus (k) kd_k is the fixed cost, S is saving in ($/year), LP and LE are the peak power loss and energy loss reduction, (K_e) is energy losses, CC is total capacitors cost, p is the fixed rate of annuity payment, (K_{ci}) and (K_{co}) are the installation and operation cost at (N_c) buses as reported in the literature.

3.0 CONSTRAINTS

To achieve the stated above objective functions with heuristic, analytical and their combinational techniques, constraints are considered in the literature in the form of bus voltage, available capacitor sizes, maximum reactive power compensation, line capacity, overall power factor.

3.1 BUS VOLTAGE

The operating bus voltages of the system must be in the considered limitations.

$$V_{min} \leq |V_i| \geq V_{max} \tag{9}$$

Where V_{min}, V_{max} is the upper, lower constraints and V_i is the rated bus voltage.

3.2 AVAILABLE CAPACITOR SIZE

Capacitors have size limitations as they are available in the discrete form.

$$Q_c \leq LQ_o \tag{10}$$

Where L is the integer, and Q_o is the smallest capacitor available size.

3.3 LINE CAPACITY

Each feeder has a specific rating for the flow of power so power flow in the line must be lower than its maximum rating.

$$S_i \leq S_{i,max} \tag{11}$$

3.4 MAXIMUM REACTIVE COMPENSATION

Total reactive power injected must be less than the reactive power demand of the system.

$$\sum_{i=1}^{nc} Q_{ci} \leq Q_{demand} \tag{12}$$

3.5 OVERALL POWER FACTOR

While placing the capacitor in shunt place in the system overall power factor should be within the limits.

$$PF_{min} \leq PF_{overall} \geq PF_{max} \tag{13}$$

Several techniques adopted by researchers reported below, they all used the above-stated power loss, cost minimization and Net savings functions with system constraints for the capacitor placement problem.

4.0 HEURISTIC METHODS

H Mori, Y Ogita[2], considered PTB[2] algorithm for the capacitor placement in the distribution system with power flow, bus voltage, and capacitor size. Equation 3 is used as a problem function and to show the effectiveness of the technique, IEEE 9 bus, and 27 bus radial distribution system considered as a test system, and results are compared with SA[3], GA[4] and TB[5] techniques. In[3], KH Kim, SK You used equation 4 as an objective function for the capacitor placement and sizing problem. A time-varying load is considered and apply GA algorithm on 10 bus and 25 bus system with load flow, bus voltage, and capacitor size constraints. GA and SA technique combination are proposed in[4]. IEEE 9 and 69 bus system is used while considering bus voltage limitations and equation 5 was their objective function. JC Carlisle, AA El-Keib[5], presented a graph search algorithm for the fixed and switched capacitor placement and sizing. They used four feeder example to express the ability of the presented technique for a time-varying system using equation 5 as an objective function. In[6], equation 6 is used as an objective function and to get maximum savings fuzzy expert system is applied on the IEEE 34 bus system along with voltage constraints. CT Su, GR Lii, CC Tsai, suggested combinational approach fuzzy reasoning and genetic algorithm[7] for objective function minimization stated in equation 2 and 3. Gauss-Seidel method for load flow and heuristic technique is adopted for the capacitor placement problem with bus voltage, the number of capacitors and maximum compensation constraints. R Annaluru, S Das, A Pahwa[8], presented a capacitor placement problem using AC[6] technique. To show the effectiveness of the algorithm they test their technique on radial 30 bus system and validate their results by comparing with the GA algorithm. Equation 5 is used as a cost minimization objective function. MLO[7]technique is applied with the objective function stated in equation 5, to minimize the cost function for capacitor placement problem[9]. Fixed and switched capacitors with time-varying load are used, with voltage and capacitor sizes constraints. In[10], researchers considered IEEE 9,33,66 and 132 bus system to demonstrate the robustness of the HDE[8]. Equation 3 is used as a cost minimization objective function with voltage, maximum capacitor size, and total reactive power constraints. AI[9] technique is used in[11], to demonstrate the capacitor placement problem. Equation 4 is taken as an objective function with voltage and varying load constraints. IEEE 9,69 and 135 bus system are considered to test the algorithm. R Sirjani, A Mohamed, H Shareef[12], demonstrated a capacitor placement problem with equation 3 as cost minimization objective function. IEEE 9 and 34 bus system are considered, to show the strength of the HS[10] algorithm. BIBC[11] method is used for the load flow with bus voltage and capacitor size constraints. CBO[12] technique is reported in[13] for capacitor placement problem. BFS[13] method is used for load flow with time-varying load, and equation 7 as an objective function with bus voltage, maximum capacitor size, and line capacity. S Nojavan, M Jalali, K Zare suggested MINP[14] approach for capacitor placement problem[14]. Equations 3 is taken as an objective function with bus voltage, total compensation, available capacitor size.

5.0 COMBINATIONAL METHODS

5.1 LSF WITH HEURISTIC TECHNIQUE

Loss sensitivity factor is taken as reported in the literature to nominate the candidate buses for the optimal location of capacitors in the distribution system. LSF can be presented as:

$$\frac{\partial P_{loss}}{\partial Q_{eff}} = \frac{\left(2 * Q_{eff}[q] * R[k]\right)}{(V[q])^2} \tag{14}$$

K Prakash, M Sydulu[15], demonstrated a capacitor placement problem with equation 2 power losses minimization objective function. IEEE 10,15,34,69 and 85 bus system are used, to make evident the effectiveness of the particle swarm technique. Vector-based load flow method with sparsity approach is considered, to get load flow data. Loss sensitivity factor method is used to decide candidate busses for capacitor placement and pso for power losses minimization objective function. Artificial bee colony algorithm referred in[16] for the capacitor placement. Equation 4 is taken as an objective function with bus voltage, capacitor size, and total compensation power. Loss sensitivity factor method is used, to find out potential buses for capacitor placement and 69 bus system is used to validate the performance of the algorithm. Equation 4 is taken as an objective function in[17], with bus voltage, available capacitor size, maximum reactive power compensation. Base case load flow and loss sensitivity methods are adopted to nominate buses for capacitor placement. Plant growth simulation algorithm is proposed to

[2] Parallel Tabu Search
[3] Simulated Annealing,
[4] Genetic Algorithm
[5] Tabu Search Algorithm
[6] Ant Colony Algorithm
[7] Mixed Linear Optimization
[8] Hybrid Differential Evaluation Algorithm
[9] Artificial Immune
[10] Harmony Search
[11] Branch Injection Branch Current
[12] Clustering Based Optimization
[13] Backward Forward Sweep
[14] Mixed Integer Nonlinear Programming

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get cost minimization function and tested on IEEE 10,34 and 85 bus radial systems. A. Elsheikh, Y. Helmy, Y. Abouelseoud[18], utilized equation 3 as their objective function while considering bus voltage, available capacitor size, and line capacity. Base case load flow is performed to calculate loss sensitivity factor for capacitor location evaluation, and discrete particle swarm optimization for sizing of capacitors. They tested their algorithm on IEEE 15 and 34 bus system with cost minimization and net saving functions.

5.2 VSI WITH HEURISTIC TECHNIQUE

VSI also used for nominating the buses to optimally place the capacitors in the distribution system as reported in the literature. Than any technique is optimization technique is applied for the capacitor sizing. VSI method can be express as :

$$L_m = V_k^4 - 4(P_m x_m - Q_m r_m)^2 - 4(P_m x_m - Q_m r_m)V_k^2 \quad (15)$$

In[19], researchers perform BIBC and BCBV[15] load method to support VSI method for capacitor placement, as an alternate the also used fuzzy expert system for capacitor placement and fuzzy real coded GA for sizing of the capacitor for IEEE 33 bus system. Equation 6 is used as an objective function with bus voltage and maximum capacitor size constraints. Equation 3 is adopted as objective function in[20]. IEEE 13 bus system is used and load flow is done with the BFS method. Than capacitor placement is done with the help of VSI, and EP[16] technique with bus voltage, available capacitor size, and maximum reactive power compensation limitations. KR Devabalaji, K Ravi, DP Kothari[21], used BIBC for load flow, and LSF[17] and VSI[18] method for allocating the buses for capacitor placement and BFO[19] algorithm for capacitor sizing with voltage, capacitor sizing constraints and time-varying load constraints. IEEE 34 and 85 bus system with equation 2 is considered as an objective function.

5.2 PLI WITH HEURISTIC TECHNIQUE

PLI[20] also considered for potential buses nomination for capacitor placement in the distribution system as listed in literature and couples with any heuristic technique which decides the sizing of capacitor for the nominated buses.

$$PLI(m) = \frac{LR(m) - LR_{min}}{LR_{max} - LR_{min}} \quad (16)$$

In[22], researchers used combinational method for the capacitor placement problem. PLI method is used for nominating the buses, and GA method to define the rating of the capacitors. Equation 5 is considered as an objective function with voltage constraints and tested their methodology on IEEE 13 and 34 bus system. AA El-Fergany, AY Abdelaziz[23], suggested CS[21] algorithm for capacitor placement problem using equation 8 as an objective function with bus voltage, line capacity, total reactive injection, overall system power factor. BIBC method is considered for load flow, and PLI method for the buses nomination in the system is used. Fuzzy logic with PLI method is reported in[24] for losses minimization in the distribution system. N-R method is used for load flow and equation 2 as an objective function with voltage and time-varying load constraints. In[25], HPSO[22] with PLI reported, to find capacitor location and sizing for losses reduction. They used BIBC and BCBV method for load flow and equation 7 as an objective function with voltage, available capacitor size, and line capacity constraints.

Table. 1 Gradual Assessment of Optimal Capacitor Placement Techniques

Literature References	Load Flow	Optimization Technique			System Constraints					Capacitor Type		Time-Varying Load	Test System		Outcomes		
		Analytical	Heuristic	Combination	Bus Voltage	Maximum Capacitor Sizes	Line Capacity	Total Reactive compensation	Overall System Power factor	Fixed	Switched		IEEE	Local	Voltage Profile	Total Cost	Net Savings
[2]			□		□	□	□			□			9	27		□	
[3]			□		□	□	□			□		□	10	25		□	
[4]			□		□					□			9,69			□	
[5]			□		□					□	□						□

[15] Branch Current Branch Voltage
[16] Evolutionary Programming
[17] Loss Sensitivity Factor
[18] Voltage Stability Index
[19] Bacterial Foraging Optimization
[20] Power Loss Index
[21] Cuckoo Search
[22] Hybrid Particle Swarm Optimization

[6]			□		□					□		□	34				□
[7]			□		□	□		□		□			9,30			□	
[8]			□		□					□				30		□	
[9]			□		□	□				□	□	□	9,70			□	
[10]			□		□	□		□		□			9,33	66,132		□	
[11]			□		□					□	□	□	9,69,135			□	
[12]	□		□		□	□				□			9,34		□	□	
[13]	□		□		□	□	□			□			69,85	22		□	
[14]			□		□	□		□		□			10,34, 85			□	□
[15]	□	LSF		□	□	□				□			10,15,34,69,85				
[16]	□	LSF		□	□	□		□		□			69			□	
[17]	□	LSF		□	□	□		□		□			10,34,85			□	□
[18]	□	LSF		□	□	□	□			□			15,34			□	□
[19]	□	VSI		□	□	□				□			33		□		□
[20]	□	VSI		□	□	□		□		□			13			□	□
[21]	□	VSI		□	□	□				□		□	34,85		□		□
[22]		PLI		□	□					□	□	□	13,34			□	
[23]	□	PLI		□	□		□	□	□	□	□		69,118		□		□
[24]	□	PLI		□						□	□	□	5,14,30		□		
[25]	□	PLI		□	□	□	□		□	□			34,85,94		□	□	

6.0 CONCLUSION

This paper provides a comprehensive review of one of the conventional method used to minimize the system power losses i-e optimal capacitor placement in the distribution system. This review based on research published in the last few decades. The literature itemized in this review delivers a typical example of modern methodological evaluation relating to the enhancement in the distribution system efficiency by attaining minimum total cost and maximum net saving through power losses minimization.

Heuristic-based and their combination with analytical methods are stated in this review, considered for optimal capacitor placement and sizing problem with multiple objectives and constraints. Method considered in this review paper for power losses minimization in the distribution system summaries in table .1, a conclusion can be extracted, optimal capacitor placement is a simple and effective technique, which is easy to implement for minimizing the power losses in the distribution system.

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