Capacitor Placement In Distribution Systems Using Artificial Intelligent Techniques

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Abstract

This paper undertakes the problem of optimal capacitor placement in a distribution system. The problem is how to optimally determine the locations to install capacitors, the types and sizes of capacitors to be installed and, during each load level, the control settings of these capacitors in order that a desired objective function is minimized while the load constraints, network constraints and operational constraints (e.g. voltage profile) at different load levels are satisfied. The problem is formulated as a combinatorial optimization problem with a non-differentiable objective function. Four solution mythologies based on simulating annealing (SA), genetic algorithms (GA), tabu search (TS), and hybrid GA-SA algorithms are presented. The solution methodologies are preceded by a sensitivity analysis to select the candidate capacitor installation locations. The effect of non-linear loads on the optimal solution is studied. The solution algorithms have been implemented into and tested on a 69-bus power system.

Keywords: capacitor placement, simulated annealing, genetic algorithm, tabu search combinatorial optimization, non-linear loads, artificial intelligence

I. INTRODUCTION

The application of shunt capacitors in distribution systems has always been an important subject to distribution engineers [1]. The general capacitor placement problem, (CPP), consists of determining the number, location, type, size and control settings at different load levels of the capacitors to be installed. The objective is to minimize energy losses while considering capacitor installation costs. The subject of optimal capacitor placement is a well-researched topic, which has been addressed by many authors [1-8]. Different problem formulations and solution methodologies have been proposed. Analytical methods, gradient search techniques, sensitivity-based methods, dynamic programming and various heuristic techniques have all been applied to solve the capacitor placement problem, resulting in different features and shortcomings . Nowadays, because of the widespread use of power electronics and solid-state devices, the non-linear portion of distribution loads has increased, which can cause a significant amount of harmonic distortion in voltage and current. If not properly sized and placed, capacitors may amplify harmonic currents and voltages due to possible resonance. This may lead to additional stress on equipment insulation, an increased rate of capacitor failure, and interference with communication systems [7].

This paper reports on a solution of the CPP by means of general-purpose heuristic optimization techniques. The objective function is minimized subject to power flow constraints, minimum and maximum allowable operating voltages, load variation, use of both fixed and switched capacitors, maximum number of capacitors to be installed at a particular bus, and maximum allowable total harmonic distortion caused by the non-linear loads.

The paper also studies the impact of non-linear loads on the optimal solution.

II. PROBLEM FORMULATION

In this section, a formulation of the CPP is presented. By taking the non-linear loads into consideration, this new formulation is an extension of the problem formulation proposed by many researchers.

A. Assumptions

The following assumptions are considered while formulating the problem [7].

1. The system is balanced.
2. Loads vary in a conforming manner.
3. The forecasted active and reactive powers provided by the load duration curve represent fundamental frequency powers. Additional powers at harmonic frequencies are negligible.
4. Loads at bus 'j' are partitioned into w_j nonlinear loads and ($1- w_j$) linear loads.
5. Both clusters of linear and nonlinear loads at bus 'j' have the same displacement factor, i.e., power factor at fundamental frequency.

B. Objective Function

The objective of the capacitor placement problem is to reduce the total energy losses of the system during all load levels while striving to minimize the cost of the capacitors installed in the system . The objective function consists of two terms. The first is the cost of capacitor placement and the second is the cost of the total energy losses.

The cost associated with capacitor placement is composed of a fixed installation cost and a purchase cost. The cost function described in this way is a step-like function rather than a continuously differentiable function since capacitors in practice are grouped in banks of standard discrete capacities. The second term in the objective function represents the total cost of the energy losses. This term is obtained by summing up the real power losses for each load level multiplied by the corresponding duration.

C. Mathematical Representation

The capacitor placement problem is expressed mathematically as shown below:

$$\text{minimize} \sum_{k=1}^{n_c} C_k(u_k^o) + k_e \sum_{i=1}^{n_t} T_i P_{loss,i}(x^i, u^i) \qquad (1)$$

subject to:

1. $u_k^o = l_k * u_s$ where l_k is a non-negative integer, $k \in N_C$
2. u_k^i = discrete variable, $i \in N_T, k \in N_C$
3. power flow constraints $P_{flow}(x^i, u^i) = 0 \quad i \in N_T$
4. operational constraints $V_{\min} \le |V_{ik}| \le V_{\max}$
5. for $k \in C_1$ = fixed cap $u_k^i = u_k^j \le u_k^o$ for $i, j \in N_T$
6. for $k \in C_2$ = Switched cap. $0 \le u_k^i \le u_k^o$ for $i \in N_T$
7. $THD_{ik} \le THD_{\max}$
8. $l_k \le (l_k)_{\max}$

where:

$\sum_{k=1}^{n_c} C_k(u_k^o)$ represents the installation cost of capacitors;

$k_e \sum_{i=1}^{n_t} T_i P_{loss,i}(x^i, u^i)$ represents the cost of the total energy losses;

The variables are defined as follows:

i : load level
k : location(bus)
x^i: a vector of state variables
u^i : a vector of control variables (capacitor placement scheme
n_c : possible locations to install capacitors;
u_k^o : kVar value of the capacitor at the peak load;
k_e : energy cost per unit;
n_t : number of load levels;
T_i : duration for load level I;
u_s : standard size of capacitor bank;
N_c : set of possible locations to install capacitors;
N_t : set of different load levels;
$|V_{ik}|$: total rms voltage at the k-th bus during the i-th load level;
$V_{\min}$: minimum allowable operating voltage;
$V_{\max}$: maximum allowable operating voltage;
C_1 : set of fixed capacitors;
C_2 : set of switched capacitors;
THD_{ik} : total harmonic distortion at the k-th bus during the i-th load level;
$THD_{\max}$: maximum allowable total harmonic distortion;
$(l_k)_{\max}$: maximum number of capacitor banks to be installed at bus(k);

III. SOLUTION ALGORITHMS

Combinatorial optimization problems can be solved either by exact or by approximate methods. In exact methods, all the feasible solutions are evaluated and the best one is selected as the optimal solution. However, exact methods are impractical when a real-life problem is to be solved. This is due to the large number of feasible solutions to be evaluated. This paper reports on the application of simulated annealing (SA), genetic algorithm (GA), and the tabu search (TS) for the solution of the CPP problem. The methods are well documented in the literature and will not be reviewed here [9-11].

A. Application of SA to the Capacitor Placement Problem

The following steps summarize the procedure of an SA-based solution algorithm:

1. Input system and network data, integer seed, cost of capacitors and parameters of the annealing algorithm.
2. Calculate the system voltages, power losses during each load level and the total harmonic distortion for the case of nonlinear loads prior to capacitor placement.
3. Generate an initial feasible solution and calculate the associated cost function.
4. Obtain neighboring solutions by executing different types of moves based on their pre-specified percentages.
5. Check the feasibility of the new configuration. If not feasible go to 4, otherwise proceed to 6.
6. Design a proper cooling schedule. At each temperature, perform a number of moves. For any move do step (7) and step (8). Otherwise, proceed to step (9).
7. Generate a new feasible configuration.
8. Update the system configuration.
9. Check the stopping criterion. If not satisfied, go to (6); otherwise proceed to the next step.
10. Print out the optimal configuration.

B. Application of GA to the Capacitor Placement Problem

The algorithm procedure can be summarized as follows:

1. Read system and network data. Input the cost of capacitors, minimum and maximum allowable operating voltages. Input algorithm parameters, i.e. population size, crossover and mutation rates.
2. Calculate system power losses during each load level, total energy losses, bus voltages and total harmonic distortion at each bus for the case of nonlinear loads prior to capacitor installation.
3. Generate a set of initial feasible solution(s), forming the initial population, randomly.
4. Calculate the associated fitness value of each solution.
5. Calculate the average fitness value of the population. Also, calculate the probability selection of each individual.

6. Transfer all individuals whose fitness values are less than the calculated average fitness value to the next generation without change.
7. Select one parent. Choose the other parent randomly. Apply crossover and mutation operators to generate new offspring.
8. If the offspring is not feasible go to 7, else go to 9.
9. Calculate the fitness value of the offspring.
10. Generate an individual in the new population to replace an individual whose fitness value is greater than the calculated average fitness value.
11. Repeat steps (7) to (10) to find all remaining individuals.
12. Repeat steps (5) to (11) if the stopping criterion is not satisfied. Otherwise go to (13).

The best solution in the new population is the optimal solution.

C. Application of TS to the Capacitor Placement Problem

The TS solution method has been implemented to the CPP. The algorithm procedure is summarized as follows:

1. Input system and network data, capacitor cost, allowable operating voltage limits, and tabu search parameters including number of moves per iteration and tabu list size.
2. Calculate bus voltages, power losses, and total energy losses during all load levels and total harmonic distortion at each bus for the case of nonlinear loads.
3. Begin the TS algorithm with some initial solution, from the solution space. If not feasible, generate another solution at random. The initial solution is the current best solution.
4. Go through a sample set of candidate moves to generate neighborhood solutions from the neighborhood structure of the current solution.
5. Evaluate the current move. If the move produces a higher evaluation than any other so far found admissible, go to (6). Otherwise, go to (9).
6. Check tabu status. If the candidate move is tabu, go to (7). Otherwise, go to (8).
7. Check aspiration criterion. If the move passes the aspiration criterion, go to (8). Otherwise, go to (9).
8. Check if the move is admissible. Store as new current best move..
9. Check sampling criteria, if another move in the list is to be examined, go to (5).
10. Make the chosen best move.
11. If the stopping criterion is not satisfied, update the tabu list, tabu status and aspiration level. Otherwise, go to (4).
12. Print out the best solution found so far.

D. Application of a Hybrid SA-GA to the CPP

The heuristic techniques that have been discussed above may be combined with each other to form a hybrid having advantages from each one of these heuristics. The efficiency of the new hybrid algorithm is expected to increase [19].

One way to form a hybrid algorithm is to start with a heuristic to give a fairly good feasible solution rather than starting completely at random. This solution will be considered as the initial solution from which the other heuristic, following the first one, will start the search for the optimal solution. In the paper, combining both GA and SA forms a hybrid algorithm. The algorithm is referred to as GA-SA hybrid algorithm. The GA is applied first to provide a good initial solution. Then, SA begins the search from this solution to find the optimal one.

IV. NUMERICAL RESULTS

The solution algorithms have been implemented into software packages using FORTRAN-77. Several numerical results are presented to illustrate the performance of the solution algorithms. The test system is a 69-bus distribution system with one main branch and seven laterals. The schematic diagram and load and network data are given in [6]. Table 1 shows the cost, operating data and the operating constraints. The peak, medium, and light load durations are considered 1000 hrs, 6760 hrs and 1000 hrs respectively. The medium and light loads are assumed to be 0.8 and 0.5 of the peak value respectively.

Table 1 System Cost and Related Data

N	V_{min}	V_{max}	THD_{max} (%)	$(I_k)_{max}$ (bank)	K_e ($/kWh)	Inst. Cost($)	Cost ($) bank	Size kVar
11	0.93	1.05	5	4	0.06	1000	900	300

Three different cases have been studied as described below:

Case-I: With fixed capacitors only and all loads are linear.

Case-II: With fixed and switched capacitors and all loads are linear.

Case-III: With both fixed and switched capacitors and with both linear and non-linear loads.

In the case of non-linear loads, buses # 5,14,20,30,39,50,61 and 64 are assumed to have nonlinear loads with a percentage of 20,10,10,20,30,40,30, and 50% respectively.

A. System Conditions Without Capacitors

Prior to capacitor placement, system conditions have been calculated. Minimum bus voltage (V_{min}), maximum bus voltage (V_{max}), real power losses (P_{loss}), cost of energy losses during each load level (E_{loss}) and the total cost of energy losses for the case with all the loads linear are shown in Table 2. Table 3 shows the same for the case of the combined linear and nonlinear loads. Maximum total harmonic distortion (THD_{max}) during each load level is calculated for this case.

Table 2: System Conditions (linear loads only)

	Load Case		
	Light	Medium	Peak
V_{min}(p.u.)	0.9569	0.9290	0.9094
V_{max}(p.u.)	1.0000	1.0000	1.0000
P_{loss} (kW)	50.4991	137.1431	222.5266
E_{loss} Cost	3029.947	55625.23	13351.59
Total Cost of Energy Losses =US$72006.770			

Table 3: System Conditions (linear & non-linear loads)

	Load Case		
	Light	Medium	Peak
V_{min}(p.u.)	0.9573	0.9295	0.9099
V_{max}(p.u.)	1.0005	1.0006	1.0006
THD_{max}(%)	3.419	3.792	3.884
P_{loss} (kW)	50.6559	138.2789	223.8575
E_{loss} Cost	3039.355	56085.93	13431.45
Total Cost of Energy Losses = US$72556.73			

B. Design Parameters of the Solution Algorithms

B.1 Design Parameters for the SA

The parameters for the SA algorithm are given in Table 4 for the three study cases, (T) represents the initial temperature, (AR) is the initial acceptance ratio, (M) is number of moves in each iteration, (CF) is the cooling factor and SC represents the number of consecutive iterations, during which no improvement is encountered in the optimal solution, executed before the algorithm is terminated.

Table 4: SA Design Parameters

Parameter	T	AR	M	CF	SC
Case-I	13000	0.8	5	0.85	15
Case – II	33000	1.0	7	0.85	15
Case - III	100	0.53	15	0.88	8

B.2 Design Parameters for the GA

Table 5 shows the design parameters of the GA algorithm applied to the CPP. The parameters are the population size, (P_s), mutation rate, (M_r), crossover rate, C_r, and the number of generations before the algorithm is terminated, (G).

Table 5 GA Design Parameters

Parameter	P_s	M_r	G	C_r
Case -I	30	0.1	20	1.0
Case- II	32	0.08	20	1.0
Case – III	20	0.2	15	1.0

B. 3 Design Parameters for the TS

Table 6 shows the design parameter for the TS algorithm as applied to the CPP. The parameters are the tabu list,(T_s), number of moves in each iteration,(V), and the number of consecutive iterations during which no improvement is achieved.

Table 6 TS Design Parameters

Parameter	T_s	V	I_t
Case -I	16	3	40
Case -II	13	7	10
Case -III	13	4	40

B.4 Design Parameters for the GA-SA Hybrid

Finally, a hybrid algorithm has been designed by combining both the GA and SA. The algorithm is referred to as GA-SA algorithm. In this hybrid algorithm, the GA is applied first to obtain a fairly good feasible solution. This solution is used as the initial solution for the SA algorithm in its search for the optimal solution. The design parameters of the GA-SA algorithm are given in Table 7.

Table 7- Test System-1: GA-SA Design Parameters

Parameter	T_o	A_{ro}	M	C_f	S_c	Ps	M_r	G	C_r
Case -I	1000	0.83	6	0.90	15	6	0.15	2	1.0
Case –II	3000	1.0	5	0.92	30	6	0.10	3	1.0
Case -III	3000	0.57	7	0.90	20	20	0.2	5	1.0

C. System Solution for Study Case I

Table 8 shows the results of the simulation for the study case–I . This case assumes that the system has linear loads and that only fixed capacitors can be used. The data in Table 8 shows the capacitor location and size for different load levels when the various solution algorithms are used. Table 8 also shows the cost of system losses, cost of the capacitor installations, and the system savings. The savings result from the reduction of system losses. The solution calls for the installation of 300 kVar and 1200 kVar capacitors at buses 21 and 61 respectively. The solution algorithms produce the same results with system savings of US$17028.40.

Table 8 Comparison of the results for Case-I

	Solution Method							
	SA		GA		TS		GA-SA	
(Bus)	21	61	21	61	21	61	21	61
Cap (kVar) light load	300	1200	300	1200	300	1200	300	1200
Cap (kVar) mdeium load	300	1200	300	1200	300	1200	300	1200
Cap (kVar) lpeak load	300	1200	300	1200	300	1200	300	1200
Cost of Losses (US$)	48478.33		48478.33		48478.33		48478.33	
Installation Cost (US$)	6500		6500		6500		6500	
Total System Cost (US$)	54978.33		54978.33		54978.33		54978.33	
Savings (US$)	17028.44		17028.44		17028.44		17028.44	

D. System Solution for Study Case II

Study case–II assumes linear loads but allows for the installation of switchable and fixed capacitors. Table 9 shows the results when the four solution algorithms are applied. As in case–I, capacitors are needed at buses 21 and 61. However, in this case the sizes vary, depending on the load levels. Column two indicates that a switchable capacitor of 300 kVar is required at bus 21. However, this capacitor should be switched on only during medium and peak load levels. The requirements at bus 61 are 900 kVar capacitors for both light and medium loads. At the peak load, the capacitor should be 1200 kVar. The other algorithms produced different solutions. The hybrid GA-SA shows similar results to the SA's for bus 21. The GA-SA solution requires the installation of 600 kVar, 900 kVar and 1200 kVar for light, medium and peak loads respectively. This algorithm also produced the highest savings of US$18033.0.

Table 9 Comparison of the Results for Case-II

	Solution Method							
	SA		GA		TS		GA-SA	
Location(Bus)	21	61	21	61	21	61	21	61
Cap(kVar) light load	0	900	600	600	300	900	0	600
Cap(kVar) mdeium load	300	900	600	900	300	1200	300	900
Cap(kVar) lpeak load	300	1200	600	1200	300	1200	300	1200
Cost of Energy Losses (US$)	47807.47		47449.47		47908.653		47472.95	
Installation Cost (US$)	6500		7400		6500		6500	
Total System Cost (US$)	54307.47		54849.47		54408.65		53972.95	
Savings (US$)	17699.3		17157.3		17598.12		18033.82	

C. System Solution for Study Case III

Case–III deals with a system of linear and nonlinear loads. Buses 5, 14, 20, 30, 39, 50, 61, and 64 contain linear and nonlinear loads with different percentages as indicated at the beginning of Section 5. The study also allows for the use of switchable and fixed capacitors. The inclusion of the nonlinear loads and harmonic constraints has produced substantial changes in the optimal solution as indicated in Table 10. The SA algorithm produces a solution that requires capacitors at buses 8, 21, 48, 49, 59, and 61. The capacitor sizes and modes are shown in column two. For example, a 1200 kVar has to be placed at bus 8. During the light load, only 600 kVar needs to be switched on. The GA and TS algorithms show that there is a need for capacitors at buses 8, 11, 12, 48, 49, 50, 59 and 61. Columns three and four show system losses and savings. Both methods produce very low savings. As in case –III, the hybrid GA-SA produced the highest savings when capacitors are placed at buses 8, 21, 48, 50, and 61. The savings are US$4591.95.

V. CONCLUSIONS

The following conclusions may be drawn :

- The energy losses of the system increase if nonlinear loads are considered.
- The installation of fixed capacitors has proven to be very economical as it reduces the overall system cost. Installation of switched capacitors is even more economical.
- The optimal solution is changed substantially when the nonlinear loads are taken into account, due to the possible resonance that may be caused by capacitors. If the resonance condition takes place, the distortion levels will be amplified. In this case, the algorithm will search for locations and sizes that do not violate the maximum THD constraint. This, however, will be at the expense of the overall savings of the system. Therefore, the effect of non-linear loads should be incorporated during the planning and design phases of the system.

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Table 10 Comparison of the results for Case-III

	Heuristic Method																				
	SA						GA					TS					GA-SA				
Location(Bus)	8	21	48	49	59	61	8	12	48	49	61	11	48	50	59	61	8	21	48	50	61
Cap(kVar) light load	600	0	900	300	0	900	900	600	300	0	600	300	600	900	600	900	600	300	1200	900	600
Cap(kVar) mdeium load	1200	300	1200	300	0	900	1200	600	900	900	900	300	900	900	600	900	600	300	1200	900	900
Cap(kVar) lpeak load	1200	300	1200	300	300	1200	1200	600	900	900	1200	900	900	1200	600	900	1200	300	1200	900	1200
Cost of Energy Losses	49469.7						51574.98					52702.2					48564.78				
Installation Cost of Capacitors	19500						19400					18500					19400				
Total System Cost	68969.70						70974.98					71202.20					**67964.78**				
Savings	3587.03						1581.75					1354.53					**4591.95**				