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FEASIBLE METHOD FOR OPTIMAL CAPACITOR PLACEMENT IN A DISTRIBUTED SYSTEM BY USING GAME THEORY

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Abstract- The utilities are interested on economic and optimal projects which improve their services to customers. These projects should increase the utilities' profit as well. Reactive power compensation as a useful and practical approach has been studied very much. One way of reactive power injection is installation of constant capacitors that result in voltage profile improvement, power losses and cost decrease. The present paper's goal is to offer new flexible designs using Game Theory concepts. Power loss is first objective while capacitor and power loss cost are considered as second objective. The optimization algorithm, Strength Pareto Evolutionary Algorithm (SPEA), proposes some optimum plans for supplying system reactive power. In order to show the suggested method's capabilities, the results are compared with GA which proves the superiority of SPEA.

Keywords: Optimal Capacitor Placement, Game Theory, Distributed System.

I. INTRODUCTION

Capacitors have been commonly used to provide reactive power in distribution systems. The capacitor placement problem consists of determining the optimal numbers, types, locations and sizes of capacitor banks such that minimum yearly cost due to power/energy losses and cost of capacitors is achieved. Also in the distribution system, achieving the flat and standard voltage profile is so important. These techniques have been studied in many papers containing classic methods such as nonlinear programming [1] and modern algorithm such as genetic algorithm [2, 3], simulated annealing [4, 5], tabu search [6, 7], neural network [8, 13], fuzzy theory [9], and PSO algorithm [12].

Application of Game Theory concepts to solve high complex problems in power system is a new procedure that has not been used much in electrical engineering. In this paper the Strength Pareto Evolutionary Algorithms (SPEA) is applied for capacitor placement optimization. To inspect the advantages of this method the result of optimization is compared with the result of genetic algorithm.

II. LOAD FLOW AND LOSS CALCULATION

Common load flow procedures like Newton-Raphson (NR) and Gauss-Seidel have less accuracy and take much time to reach convergence in distribution network, because the ratio of X/R is small in respect of the transmission network. So to analysis of DG effect on the network and calculating the active power loss of the grid, backward-forward load flow method for distribution system [10] is considered. Backward-forward load flow is based on KVL and KCL laws. This method determines the current of any line and the voltage of any bus in four following stages:

A. Node Injection Currents

Whereas the loads data are available, we can calculate the injected current of each node by (1):

$$I_i^k = \frac{S_i^*}{(V_i^{k-1})^*} \tag{1}$$

S_i : Given apparent load of the ith node

I_i : The current of ith node in iteration k

V_i^{k-1} : The voltage of ith node in iteration $k-1$

In the first iteration all nodes voltages are assumed to be one pu.

B. Backward Sweep

In this step the current of all branches are calculated from the end-customer nodes towards the root node by (2).

$$J_L^k = I_i^k + \sum \text{branches derived from node } k \tag{2}$$

where,

L : Branch index

J_L^k : Current of Lth branch in iteration k

C. Forward Sweep

Update the voltage magnitude of all nodes by calculated current in step 2 by (3).

$$V_i^k = V_j^k - Z_L J_L^k \tag{3}$$

where V_i^k and V_j^k are the voltages of two nodes that are connected via a branch with impedance equal to Z_L.

D. Convergence Indexes

Calculate the apparent power of any load with new earned voltage and active and reactive power mismatch using these equations:

$$S_i^k = V_i^k (I_i^k)^* \tag{4}$$

$$\Delta P_i^k = \text{Real}\{S_i^k - S_i\} \tag{5}$$

$$\Delta Q_i^k = \text{Imagiary}\{S_i^k - S_i\} \tag{6}$$

ΔP_i^k : Active power mismatch in iteration k

ΔQ_i^k : Reactive power mismatch in iteration k

Repeat steps 1, 2, and 3 until results satisfies the convergence indexes. Load flow program will stop when ΔP_i^k and ΔQ_i^k enter into initially defined boundary.

III. DISTRIBUTED SYSTEM MODEL

The test system used in this paper is a 28-bus distribution system that some changes exist upon active power and reactive power and the length of lines. Figure 1 illustrates the system.

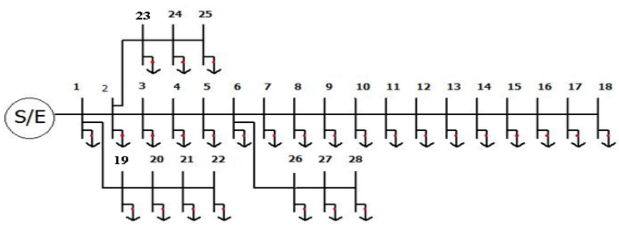

Figure 1. 28-bus distributed system test case

IV. PROBLEM FORMULATION

In this paper assumptions and simplification are as follow:

1. Capacitor banks are as constant reactive power generator.
2. All loads are balanced.
3. Capacitor placement in any bus is possible.

A. Constraints

The RMS voltage should be in the specific range. The allowable rated voltage is considered according to the standard of IEEE-519.

$$\begin{aligned} &V_{\min} \le V_{rms} \le V_{\max} \\ &\text{IEEE-519 standard} \quad 0.95 \le V_{rms} \le 1.05 \end{aligned} \tag{7}$$

B. Objective Functions

In this paper the two objective functions are defined as power system losses reduction and cost reduction of capacitor placement equipments. Common optimization methods like genetic algorithm utilize the weighted combination of objective functions. In this paper as a new method the two objective functions will be optimized by SPEA separately.

To evaluation the results of proposed method, these results are compared with the genetic algorithm results. The objective function of genetic algorithm is annual cost that includes of the annual losses cost and the capacitor placement equipments cost which is illustrated in (8).

$$\text{minimize } F_1 = \text{cost of } P_{loss} + \text{cost of CP} \tag{8}$$

where, the losses cost in distribution system is total fixed cost of demand and variable cost of energy which is derived from (9).

$$\text{cost of } P_{loss} = \text{P\_loss} \times (\text{demand\_price} + \text{energy\_price}) \tag{9}$$

The prices are given in appendix. Also the capacitor placement equipments cost is illustrated in Table 1.

Table 1. The cost of allowable capacitor bank

Capacitor bank (KVAR)	30	75	120	900
Installation cost ($)	90	150	210	4500

In genetic algorithm only the first objective function (9) will optimize while the second objective function for SPEA is power losses of distributed system which is shown in (10).

$$\text{minimize } F_2 = P_{loss} \tag{10}$$

V. GAME THEORY

A multi-objective optimization problem can be generally described as follow:

minimize $f_i(x), \ i = 1, \ldots, m$

where $f(x)$ is vector of target functions and $x = (x_1, x_2, \ldots x_n)$ is the decision vector.

A solution x_1 in the decision space is non-dominated if there exist no other x_2 such that for all i values, $f_i(x_2) \le f_i(x_1)$ and at least for one i, $f_i(x_2) < f_i(x_1)$.

The set of all non-dominated solutions is called Pareto Optimal Set (POS) and the set of the corresponding values of the objective functions is called Pareto Optimal Front (POF) or simply Pareto Front.

Evolutionary algorithms (EA's) are suitable approaches to solve the multi-objective optimization problems because they process a set of solutions in parallel. In the recent decades, there has been a growing interest in solving multi-criteria optimization problems using evolutionary approaches. Now, several multi-objective EA's are available that are capable of searching for multiple Pareto optimal solutions alongside in a single run. Niched Pareto Genetic Algorithm (NPGA), Hajela's and Lin's Genetic Algorithm (HLGA), Vector Evaluated Genetic Algorithm (VEGA), Non-dominated Sorting Genetic Algorithm (NSGA) and Strength Pareto Evolutionary Algorithm (SPEA) are some advanced methods [11]. In the present paper, the SPEA is used. Figure (2), presents its flowchart. More details are given in [11].

A. Chromosome Structure

In this paper, each chromosome consists of 28 genes; each gene is assigned to one bus of the system. Each gene demonstrates an integer from 0 to 4. Each integer illustrates one of the allowable and available capacitor banks that results the injected reactive power in each bus. Also zero represents no need for the capacitor in defined bus. Available capacitor banks values are 30, 75, 120 and 900 KVAR. Proposed chromosome structure is shown in Figure 3. Due to this structure capacitor placement is possible in any bus. Non time consuming in calculation and more performance are the most advantage of this structure.

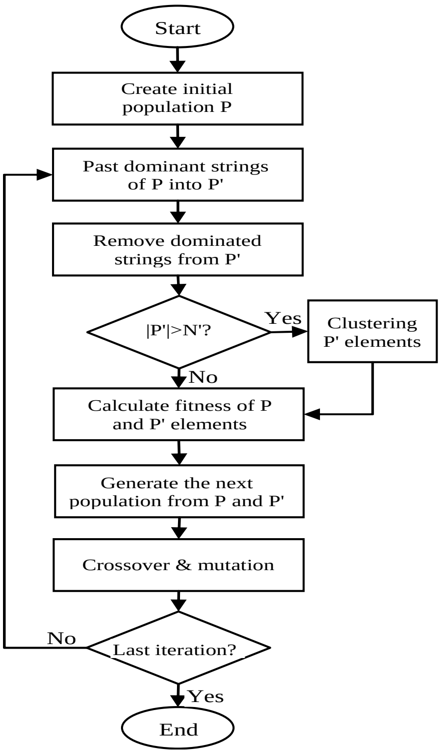

Figure 2. SPEA Flowchart

1:30	2:75	…..	4:900
bus 1	bus 2	…..	bus *n*

Figure 3. Proposed Chromosome Structure

B. Proposed Fitness Function

As the genetic algorithm and game theory which are used in this paper could find the maximum amount of the function, the fitness function is considered as inverse of sum of the weighted terms. These terms are applied to considering the objective function and constraints which are shown in (11) as follows:

$$F_{fit1} = \frac{1}{F_C + F_V} \tag{11}$$

where, F_C and F_V are the terms for objective functions and rated voltage constraint, respectively according to Equations (12) and (13).

$$F_C = \text{cost of } P_{loss} + \text{cost of } CP/K_1 \tag{12}$$

$$F_V = \prod_{i=1}^{n} F_{V,i}$$

$$F_{V,i} = \begin{cases} 1 & \text{if } V_{\min} \le V_{rms} \le V_{\max} \\ V_{rms,i} & \text{if } V_{rms} > V_{\max} \\ 2 - V_{rms,i} & \text{if } V_{rms} < V_{\min} \end{cases} \tag{13}$$

The second fitness function that should be maximized is the inverse of system power losses (14).

$$F_{fit2} = 1/P_{loss} \tag{14}$$

Roulette wheel is used as selection operator and one-point crossover is applied to the problem. Convergence index is run of 100 iterations, and each population is consists of 72 chromosomes.

VI. SIMULATION RESULTS

In this paper the genetic algorithm and SPEA are two optimization approaches which were carried out with MATLAB to find the best place and size of capacitor bank. Figure 4 shows the results of SPEA simulation. 20 optimum answers are concluded from SPEA. In this illustration, vertical axis indicates the system's losses and the horizontal axis shows the price of capacitor placement. According to each of two factors the power loss and costs; user is allowed to choose each of suggested optimum point with SPEA. Furthermore the comparison of genetic algorithm output with SPEA results shows the SPEA method has more capability. Results determine that after capacitor placement, in all answers the voltage profile has been improved and it will be in considered range. Also the power losses will decrease. The results of one of these points (illustrated in Figure 4) and the results of genetic algorithm are shown in Table 2. The maximum and minimum of the buses voltage before compensation are in bus 1 and bus 18 with the value of 1 V(pu) and 0.9429 V(pu) respectively and these quantities after capacitor placement with genetic algorithm are in bus 1 and bus 18 with the value of 1 V(pu) and 0.951 V(pu), respectively (Figure 5). Also these quantities after capacitor placement with SPEA are in bus 1 and bus 18 with the value of 1 V(pu) and 0.951 V(pu) respectively. The system power losses before capacitor placement is 1.4108 MW and this quantity after compensation with GA and SPEA will be 1.0337 and 1.0268 MW respectively which show a considerable decrease in power losses (Table 3).

VII. CONCLUSIONS

Since the electric consumption is increasing and the structure of power system is changing, supplying energy and decreasing the losses are important problems. Among losses reduction method and improving the voltage level one way is use of capacitor banks in distribution system. In this study optimum capacitor placement (magnitude and location) with SPEA was done. In order to improve the voltage profile and reduce losses, the purpose has been chosen of minimizing cost in a distribution 28-bus system. Simulation was carried out with MATLAB. SPEA algorithm is a game theory-based optimization method which has the ability to optimize the multi objective problems. The result of this algorithm is some of optimum answers which are completely optimum. To inspect the advantages of this method the result of optimization is compared with the result of genetic algorithm. Simulation results show that by using the proposed method the voltage profile improves and power losses are decreased more than genetic algorithm method.

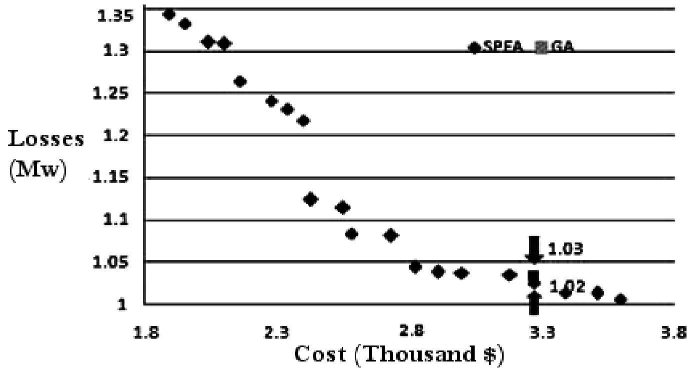

Figure 4. Simulation results

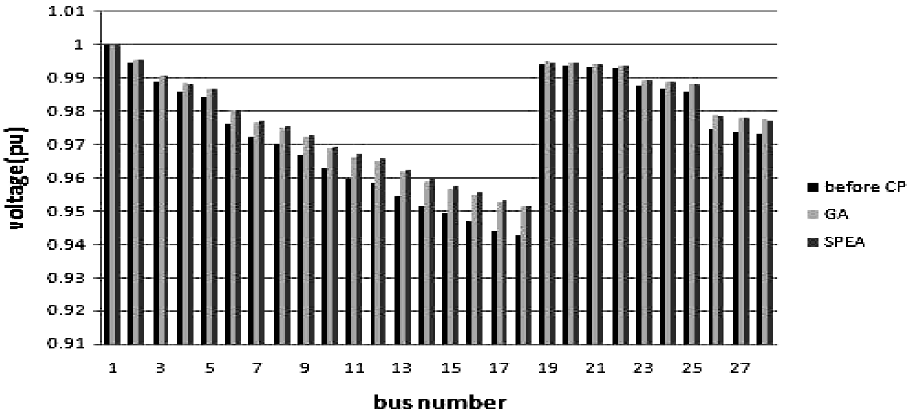

Figure 5. Voltage profile before and after capacitor placement

Table 2. Active and reactive load and bus voltage

Bus number	Reactive load before CP	Reactive load after CP	Reactive load after CP (SPEA)	Voltage (pu) before CP	Voltage (pu) after CP(GA)	Voltage (pu) after CP (SPEA)
1	19.5	0	0	1	1	1
2	13	30	90	0.994	0.995	0.995
3	26	75	90	0.989	0.990	0.990
4	65	120	0	0.986	0.988	0.988
5	45.5	30	360	0.984	0.986	0.986
6	39	0	360	0.976	0.980	0.980
7	130	75	90	0.972	0.977	0.977
8	117	120	0	0.970	0.975	0.975
9	162.5	0	2700	0.967	0.972	0.973
10	26	30	360	0.962	0.968	0.969
11	78	0	90	0.960	0.966	0.967
12	110.5	75	90	0.958	0.965	0.965
13	130	0	0	0.954	0.962	0.962
14	6.5	30	90	0.951	0.959	0.959
15	97.5	30	90	0.949	0.957	0.957
16	26	30	0	0.947	0.955	0.955
17	188.5	75	2700	0.944	0.953	0.95
18	1027	900	0	0.942	0.951	0.951
19	65	75	0	0.994	0.995	0.994
20	52	0	0	0.993	0.994	0.994
21	39	75	0	0.993	0.994	0.994
22	130	30	0	0.992	0.993	0.993
23	26	0	225	0.987	0.989	0.989
24	162.5	30	0	0.987	0.988	0.988
25	195	30	360	0.986	0.988	0.988
26	32.5	75	225	0.974	0.979	0.978
27	195	30	225	0.974	0.978	0.978
28	650	900	0	0.973	0.978	0.977

Table 3. Power losses (MW) comparison

(SPEA) Power losses after compensation	(GA) Power losses after compensation	Power losses before compensation
1.0267	1.0337	1.4708

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