Optimal Capacitor Placement for Loss Reduction

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Abstract— **This paper presents an approach for optimal placement of capacitor banks in a real power network for the purpose of economic minimization of loss and enhancement of voltage. The objective function includes the cost of power losses and capacitors. Constraint includes voltage limit. The optimization problem is solved by the use of MATLAB and Digsilent in conjunction and by Genetic Algorithm. As a result the size and the place of capacitors are determined. By applying the proposed method, the economic costs and power losses are reduced to a considerable degree while enhancing the voltage profile. Simulation results are investigated on Zanjan's power network.**

Keywords- Loss Reduction, Optimization, Capacitor placement, Economic Cost, Genetic Algorithm

I. INTRODUCTION

The increase in power demand and high load density in the urban areas makes the operation of power systems complicated. To meet the load demand, the system is required to expand by increasing the substation capacity and the number of feeders. However, this may not be easily achieved for many utilities due to various constraints. Therefore, to provide more capacity margin for the substation to meet load demand, system loss minimization techniques are employed. Besides, the effect of electric power loss is that heat energy is dissipated which increases the temperature of the associated electric components and can result in insulation failure. By minimizing the power losses, the system may acquire longer life span and have greater reliability.

Because of the growing effort to reduce system losses, many papers have been published in recent years referring to optimal distribution planning. Various methods have been used to reduce power losses economically. Optimal selection of capacitors, optimal selection of conductors, and feeder reconfiguration are among different ways of decreasing losses.

Several papers have considered the problem of optimal capacitor placement using different optimization techniques. For example, reference [1] proposes a hybrid method drawn upon the Tabu Search approach, extended with features taken from other combinatorial approaches such as genetic algorithms and simulated annealing, and from practical heuristic approaches.

Some others have considered capacitor placement in power networks in the presence of harmonics [2]-[4]. In [5, 6] the problem of capacitor placement has been solved in unbalanced distribution networks.

In this paper, capacitor placement method is employed to a real network (power system of Zanjan). The objective function is to reduce the power loss within minimum costs. The constraint is voltage limits. To solve this optimization problem, Genetic Algorithm (GA) method is used. GA method is a powerful optimization technique analogous to the natural genetic process in biology. In this paper, the objective function should be changed and the constraint is considered in the objective function. The new objective function minimizes the loss of a power network by considering optimal capacitor placement. In this optimization problem, the cost of capacitor placement, the cost of power losses, and the bus voltage profiles are considered. The proposed method is tested on the real power network of Zanjan. In the proposed method, for the sake of time and increasing the rate of calculation, the Digsilent software and MATLAB has been linked. Firstly, the calculations related to genetic algorithm are being run in MATLAB and then the results are exported to Digsilent for conducting optimization problem. The results of optimum capacitor places and sizes are available in MATLAB. The simulation results show a considerable improvement in active and reactive power losses and voltage profile as well.

II. PROBLEM FORMULATION

Power flow evaluation includes the calculation of bus voltages and line flows of a network. A single-phase representation is adequate because power systems are usually balanced. Associated with each bus, there are four quantities to be determined: the real and reactive power, the voltage magnitude and phase angle.

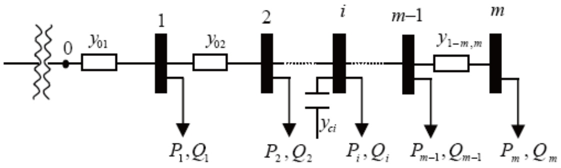

Figure 1. One-line diagram of radial network feeder

Figure 1 shows an m-bus radial power system where bus i has a load and shunt capacitor [7].

Notation:

$y_{i,i+1} = 1/(R_{i,i+1} + jX_{i,i+1})$: admittance of the line section between buses i and i+1

$R_{i,i+1}, X_{i,i+1}$: resistance and reactance of the line connecting bus i and i+1

P_i, Q_i : load active and reactive powers at bus i.

At bus i, we have:

$$P_i - jQ_i = V_i^* I_i \quad \text{i=1, 2,..., m} \tag{1}$$

Where Ii is positive when it flows into the system and m is the number of buses in the feeder. The bus voltage and line losses can be solved by the Gauss-Seidel iterative method employing the following formula [2]:

$$V_i^{(k+1)} = \frac{1}{Y_{ii}}\left(\frac{P_{bi} - jQ_{bi}}{V_i^{*(k)}} - \sum_{\substack{n=1 \\ n\neq i}}^{m} Y_{im} V_m\right) \tag{2}$$

Where

- $V_i^{(k)}$: voltage of bus i at the K th iteration
- P_{bi}, Q_{bi} : active and reactive bus power of bus i
- $Y_{im} = y_{i,m} \qquad i \neq m$
- $Y_{ii} = y_{i,m-1} + y_{i,m+1} + y_{ci} \quad i = m$

At the power frequency, the power loss in the line section between buses i and i+1 can be computed by:

$$P_{loss(i,i+1)} = R_{i,i+1} \cdot \left[\left|V_{i+1} - V_i\right| \cdot \left|y_{i,i+1}\right|\right]^2 \tag{3}$$

The purpose of placing compensating capacitors is to obtain the lower the total power loss and bring the bus voltages within their specified while minimizing the total cost. The total power loss is given by Eq. (4) [2].

$$P_{loss} = \sum_{i=0}^{m} P_{loss(i,i+1)} \tag{4}$$

Considering shunt capacitors, there exists a finite number of standard sizes which are integer multiple of the smallest size Q_o^c. Besides, the cost per KVAR varies from one size to another. In general, larger-size capacitors have lower unit prices. The available capacitor size is usually limited to:

$$Q_{\max}^c = DQ_o^c \tag{5}$$

Where D is an integer. Therefore for each installation location, there are D capacitor sizes $\left[Q_o^c, 2Q_o^c, ..., DQ_o^c\right]$ available. Let the corresponding equivalent annual cost per KVAR for the D capacitor sizes, $\left[K_1^c, K_2^c, ..., K_D^c\right]$ be given; then the equivalent annual capacitor installation cost for each compensation bus can be determined.

III. Objective Function

In each optimization problem, objective function should be defined. Eq. (6) illustrates the proposed objective function in this paper. This objective function aims at minimizing the total annual cost due to capacitor placement, and power losses with constraints that include limits on voltage Eq. (7) and size of installed capacitors. These constraints are added as penalty functions to the objective function.

$$F = K_p P_{loss} + \sum_{j=1}^{J} k_j^c Q_j^c + \sum_{i=1}^{m}\left\{\max(0, V_{\min} - V_i)^2 + \max(0, V_i - V_{\max})^2\right\} \tag{6}$$

$$V_{\min} \leq \left|V_i\right| \leq V_{\max} \tag{7}$$

Where:

K_p : annual cost per unit of power losses

J : the buses in which the capacitors is installed

m : the number of buses

K_j^c : the capacitor annual cost per kvar

Q_j^c : the shunt capacitor size placed at bus

$V_{\min}, V_{\max}$: minimum and maximum permissible bus voltages

The objective function Eq. (6) includes three statements which are described as follows:

Statement 1: the cost of power losses,

Statement 2: the cost of the installed capacitor, Statement 3: the constraints of voltage limit,

IV. PROPOSED COMPUTATIONAL ALGORITHM

The genetic algorithm is a global search technique for solving optimization problems, which is essentially based on the theory of natural selection, the process that drives biological evolution [8]. Following are the important terminology in connection with the genetic algorithm:

- Individual: an individual is any point to which objective function can be applied. It is basically the set of values of all the variables for which function is going to be optimized. The value of the objective function for an individual is called its score. An individual is sometimes referred to as a genome and the vector entries of it as genes.
- Population: it is any array of individuals. For example, if the size of the population is 100 and the number of variables in the objective function is 3, population can be represented by a 100-by-3 matrix in which each row correspond to an individual.
- Generation: at each iteration, the genetic algorithm performs a series of computations on the current population to produce a new population by applying genetic operators. Each successive population is called new generation.
- Parents and children: to create the next generation, the genetic algorithm selects certain individuals in the current population, called parents, and uses them to create individuals in the next generation, called children.

Three following genetic operators are applied on parents to form children for next generation:

- Reproduction: selects the fittest individuals in the current population to be used in generating the next population. The children are called Elite children.
- Crossover: causes pairs of individuals to exchange genetic information with one another. The children are called Crossover children.
- Mutation: causes individual genetic representations to be changed according to some probabilistic rule. The children in this case are called Mutation children.

In this paper for the purpose of minimization of the objective function, Genetic Algorithm technique has been applied. The main computational procedures of the proposed method may be stated using a flowchart shown in Fig. 2.

As can be seen from Fig. 2, first of all the Genetic Algorithm in MATLAB is being run. Then, the first produced generation, which is in fact the proposed places of capacitor banks and their sizes, is sent to Digsilent for power flow operation and calculation of objective function. The results will be returned to MATLAB again. This iterative procedure will continue until the optimum places and sizes of capacitor banks are being determined.

V. STUDY CASE

In this paper, simulations have been done on transmission and sub-transmission Zanjan's network. For simulation purpose 2 general cases have been considered. In the first case, power flow calculations have been conducted on the network with its capacitors present. In the other case, the network's capacitors have been eliminated and power flow operations have been carried out on the network without any capacitor. For each case, the amounts of active and reactive losses as well as transformers' and substations' losses have been calculated. The results are present in table 1.

After that, for each of stated cases, optimization problem has been solved and the optimal places for capacitors and their sizes have been determined.

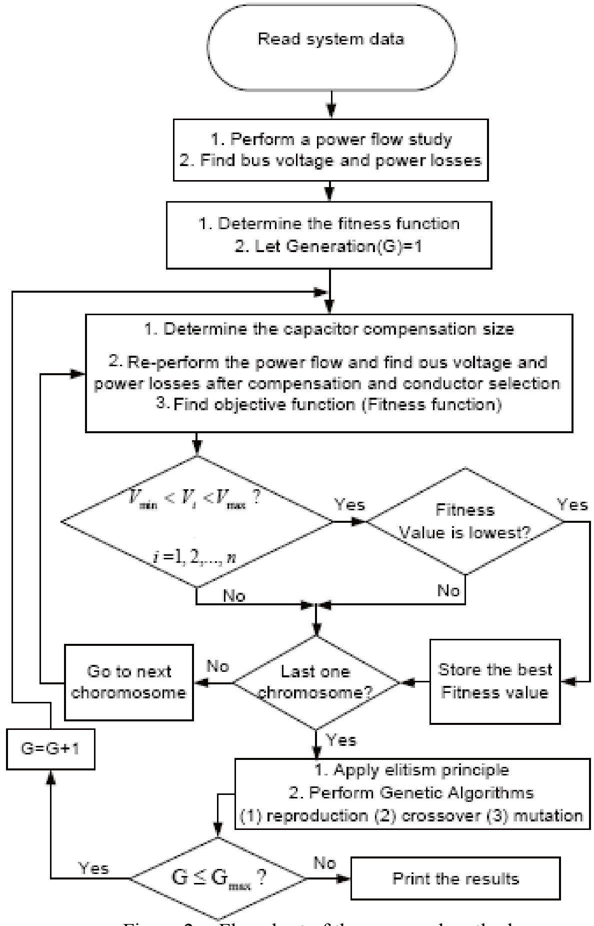

Figure 2. Flowchart of the proposed method

The power flow results after capacitor placement for the first case and the second one are shown in table (2) and table (3) respectively.

TABLE I. POWER FLOW RESULTS OF THE STUDY CASE BEFORE CAPACITOR PLACEMENT

	Active losses (MW)	Reactive losses (MVAR)	Active losses (%)	Reactive losses (%)	V_{max} (pu.)	V_{min} (pu.)
1st case	29.83	266.14	4.25	53	1.048	.849
2nd case	30.85	276.31	4.4	51	1.036	.831

As it can be seen from table 1, the power losses in transmission and sub-transmission network of Zanjan are considerable. So the necessity of loss reduction is apparent. As a result, we have conducted optimal capacitor placement on this network to obtain less active and reactive power losses. The simulation results are as follow:

TABLE II. POWER FLOW RESULTS OF THE STUDY CASE AFTER CAPACITOR PLACEMENT

	Active losses (MW)	Reactive losses (MVAR)	Active losses (%)	Reactive losses (%)	V_{max} (pu.)	V_{min} (pu.)
1st case	27.33	249.11	3.9	50.8	1.07	.88
2nd case	23.25	259.86	3.3	49.7	1.05	.887

We can conclude from table (1) and table (2) that the amounts of active and reactive power losses have been reduced when we place some capacitors in appropriate places in the network.

As can be obtained from the tables, by applying optimization method to the network, the active and reactive power losses have been reduced by 8.4% and 6.4% respectively. For the second case, in which the original capacitors of network have been removed and then optimum capacitor placing has been conducted, the amounts of reduction in active and reactive power are equal to 2.46% and 2.34% respectively. In addition to decreasing losses, the two tables show an improvement in voltage profile as well.

Finally, by applying the optimization method, the best places for capacitors and their sizes that lead to loss reduction can be determined as tabulated in table 3 and table 4. Table 2 shows the optimum capacitor places and sizes when optimum capacitor placement has being done in the presence of the network's original capacitors. Table 4 shows the optimum capacitor places and sizes when firstly the network's capacitors have been eliminated and after that the optimal capacitor placement method has been applied to the network.

TABLE III. OPTIMAL CAPACITOR PLACES AND SIZES WHEN THE NETWORK'S CAPACITORS ARE PRESENT

Station No.	Station Name	Capacitor Size (Mvar)
64	abgarm	2*2.4
88	sfarvarin	6*2.4
77	Razy	2*2.4
36	hidaj	2*2.4

TABLE IV. OPTIMAL CAPACITOR PLACES AND SIZES WHEN THE NETWORK'S CAPACITORS ARE ELIMINATED

Station No.	Station Name	Capacitor Size (Mvar)
46	garmab	1*2.4
103	gey1	1*2.4
88	sfarvarin	6*2.4
100	sayin	1*2.4
91	bavers	1*2.4
54	lia	2*2.4

At the end, the simulation results are summarized in table 5. In this table, a comparison between different states of capacitor placement in the network has been carried out.

TABLE V. MINIMUM AND MAXIMUM VOLTAGES AND ACTIVE AND REACTIVE LOSSES IN EACH STAGE

stage	Active losses (MW)	Reactive losses (MVAR)	V_{max} (pu.)	V_{min} (pu.)
Original network	29.83	266.14	1.048	0.849
Original network without its capacitors	30.85	276.31	1.03	0.831
Capacitor placement in original network with its capacitors present	27.33	249.11	1.07	0.88
Capacitor placement in original network with its capacitors eliminated	23.25	259.89	1.05	0.877

As it is obvious from table 5, optimization in the original network with its capacitors removed will lead to better results from loss reduction point of view.

VI. CONCLUSION

In this paper, a new method for optimal capacitor placement has been proposed. By making a new objective function and solving the optimization problem by GA method, the size and the place of capacitors have been determined. The method has been applied to a real network. The simulation results show a considerable improvement in active and reactive power losses and voltage profile as well.

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