Abstract: The optimal shunt capacitor allocation problem is the determination of the location and sizes of the capacitor to be placed in distribution networks in an optimal manner to reduce the energy losses and peak power losses of the networks. This paper shows the capability of Genetic Algorithm (GA) technique in solving such problem. It includes a study done in a real distribution networks in Muscat, Sultanate of Oman, and shows the effectiveness of GA technique in such application. Finally, a brief financial comparison of the optimal capacitor placement is presented to compare between the obtained results using GA technique and the ordinary standard used in Oman.

Keywords
Genetic Algorithm, Electrical Distribution Network, Optimal Capacitors Placement

1. INTRODUCTION

Capacitors have been commonly used to provide reactive power compensation in distribution systems. They are provided to minimize power and energy losses, maintain best voltage regulations for load buses and improve system security. The amount of compensation provided is very much linked to the compensation provided is very much linked to the placement of capacitors in the distribution system which is essentially determination of the location, size, number and type of capacitors to be placed in the system [1]. A large variety of research work has been done on capacitor placement problem in the past [2], [3]. All the approaches differ from each other by the way of their problem formulation and the problem solution method employed. Some of the early works have not considered capacitor cost in the formulation. In some approaches the objective function considered is to control the voltage. In some techniques, only fixed capacitors are considered and load changes which are very important in capacitor placement have not been considered. Other techniques have considered load changes only in three different levels. A few proposals were schemes for determining the optimal design and control of switched capacitors with non-simultaneous switching [4]. It is also very important to consider the real cost of the capacitors found in the market. Different problem solution methods have been employed to solve the capacitor placement problem, such as, gradient search optimization, local variation method, optimization of equal area criteria method for fixed capacitors and dynamic programs [4], [5], [6]. Although these techniques have solved the problem, most of early works used analytical methods with some kind of heuristics. In doing so, the problem formulation was oversimplified with certain assumption, which lacked generality. There is also the problem of local minimal in some of these methods. Furthermore, since the capacitor banks are non continuous variables, taking them as continuous compensation, by some authors, can cause very high inaccuracy with the obtained results. Genetic Algorithms (GA) have been applied in various power system problems [7], [8]. GA is a very well known and capable method for optimization problems. It is capable of determining near global solution with lesser computational burden. In this respect, it is very suitable to solve the capacitor placement problem.

In the present work GA is applied to determine the optimal capacitors location for Zone3 in Muscat distribution network. The network model and analysis of the Zone3 have been performed using Electrical Transient Analyzer Program (ETAP) [9]. The design variables are the capacitor sizes and the capacitor locations for fixed and switched capacitors used in the network. Load model of different levels, load flow study, and the cost of capacitors are also considered in the system simulation.

2. GENETIC ALGORITHM

The theoretical foundations for genetic algorithms were first described by John Holland [10] and then presented tutorially by David Goldberg [11]. Genetic algorithms are search algorithms based on the process of biological evolution.

GA uses a “Chromosomal” representation which requires the solution to be coded as a finite length string. The basic structure of GA used in this paper is as follows: First, a randomly constructed initial population of solutions is generated. Within this population new solutions are obtained during the genetic cycle using crossover and mutation operators. Crossover produces a new solution from a randomly selected pair of parent solutions providing the inheritance of some basic properties of the parents in the new solution. Mutation results in slight changes in the new solution structure and maintains diversity of solutions. Each new solution is decoded and its objective function “fitness” values are estimated. These values are a measure of the quality which is used to compare different solutions. The comparison is done by a selection procedure that decides which solution is better: the newly obtained one.
or the worst solution in the population. The better solution joins the population and the worse one is discarded. After several repetitions of the crossover-selection sequence, new randomly constructed solutions are generated to refill the shrunken population, and a new genetic cycle is started. The iterative loop is executed until the termination condition is satisfied. The degree of change in the quality of the individuals within the population over successive generations can serve as a measure for convergence. Before the algorithm finally terminates, the best individual of the last generation is returned as the solution of the optimization. Figure 1 presents the flow chart of a typical genetic algorithm.

2.1 Fitness Evaluation

The fitness evaluation is provided by the objective functions. A fitness function design for optimal allocation of static shunt VAR for distribution network is described next.

2.2 Control Parameters

The values of the control parameters influence the performance of genetic algorithms. For example, the number of generations required by the optimization depends on the values of the control parameters. The following quantities are referred to as control parameters:

- The population size \( n_p \)
- The chromosome length \( l_c \)
- The crossover probability \( P_c \)
- The mutation probability \( P_m \)

Test runs of genetic algorithms have indicated that a high crossover rate and a low mutation rate are normally required to obtain good results. Typical values for \( P_c \) lie within the range of \([0.6,0.95]\) and typical values for \( P_m \) lie within the range of \([0.01,0.1]\). High \( P_c \) values which are close to the upper limit force convergence, while high mutation rates promote diversity among the population.

The population size must be large enough to supply sufficient genetic structures so that a wide variety of genetic material to work upon is present. The population size should depend on the chromosome length. The larger the chromosome length, the larger the solution space covered, and therefore, the larger the population size should be.

The given proposals for the settings of the parameters can only serve as guidelines. Appropriate settings may vary significantly for different kinds of problems for which the genetic algorithm is used. It is therefore advisable to run several tests with different settings and compare the performance of the genetic algorithm.

3. GA IMPLEMENTATION

The representation and implementation of the GA for the optimal capacitor banks location and size is proposed in this section. Each capacitor is represented by a string \( C \) of a number of binary bits. The first bit represents the state of the capacitor (1 for on, 0 for off). The remaining bits represent the capacity level of the capacitor. As an example, the string \( C = [10000] \) represents a capacitor working at minimum MVAR; \( C = [00000] \) represents a capacitor which is not operating (or not existing); the string \( C = [11111] \) represents a capacitor working at full capacity. In order to represent the type of each capacitor, a new string \( T \) is defined as consisting of the concatenation of 2 strings \( C \) (thus \( T \) contains 10 bits). Therefore, let \( T = C1C2 \), where \( C1 \) represents type A of capacitor. For example, at a given node the string \( T = [1111100000] \) represents the situation where only one capacitor should be placed on that node, and this capacitor should be a type A working at full capacity. It is assumed, based on this representation, that a maximum of one capacitor of each type can be placed on any given node. As each string \( T \) represents the capacitor (and size) to be placed at a given node, the representation of the general location of the capacitor over the network is straightforward. A string \( S \) is defined as consisting of the concatenations of 20 \( T \) strings. This sequence \( S \) contains 20 (nodes) × 10

![Figure 1: Genetic Algorithm Flow Chart.](image-url)
(bits per node) = 200 bits. As any string S describes a valid placement and size configuration of capacitors over the network, therefore the string S is the chromosome used within the GA. The implementation of GA consists of a number of individuals (each one a different string S). The fitness of each individual is given by the objective function, and it also considers a penalization if the voltage or Power Factor (PF) goes outside the allowed range, plus another penalization if the number of capacitors exceeds 10.

The Optimal Capacitor Placement toolbox in ETAP requires an objective function and the encoding techniques for voltage regulation and power factor correction. The methodology of the capacitor design in distribution system is as follows:

1) Input the distribution system branch impedance values and the bus real and reactive power data.

2) Run the power flow calculation without any capacitor in different load levels.

3) Determine the losses without capacitor compensation.

4) Form a random initial chromosomes population (number of chromosomes population is usually set to 2-2.5 times the number of nodes in the network).

5) For each chromosomes population set in the previous stage, place one capacitor in the distribution system and repeat the load flow calculation. Then, determine the losses for each chromosome. If any of the load flow results is out of the specified ranges of power factor or voltage constraints then the proposed solution is not considered as a candidate solution.

6) For each chromosome, evaluate the objective function and the fitness value. The objective function is determined according to the difference of annual savings made from placement of the capacitors in the distribution system with the cost of capacitor placement in one year or during the planning years.

7) If chromosomes population has converged, then print the capacitor results for each bus, otherwise go to the next stage.

8) Select the new population based on reproduction mechanism.

9) Apply the crossover and mutation on the new population.

10) Define a new population and go to step 5.

The objective of optimal capacitor placement is to minimize the cost of the system. The cost includes four parts:

- Fixed capacitor installation cost
- Capacitor purchase cost
- Capacitor bank operating cost (maintenance and depreciation)
- Cost of real power losses

The cost can be represented mathematically as:

$$\sum_{i=1}^{N_{bus}} (x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T + C_2 \sum_{l=1}^{N_{load}} T_l P_{L}^i) \quad (1)$$

Where:
- $N_{bus}$ Number of bus candidates
- $x_i$ 0/1, 0 means no capacitor installed in bus 1
- $C_{0i}$ Installation cost
- $C_{1i}$ Per kVar cost of capacitor bank
- $Q_{ci}$ Capacitor bank size in kVar
- $B_i$ Number of capacitor bank
- $C_{2i}$ Operating cost per bank per year
- $T$ Planning period (Year)
- $C_2$ Cost of each kWh loss
- $N_{load}$ Load levels (Maximum, Minimum, and Average)
- $T_l$ Time duration of load level l
- $P_{L}^i$ Total system loss at load level l

The main constraints for capacitor placement have to comply with the load flow constraints. In addition, all voltage magnitudes of load (PQ) buses should be within the lower and upper limits. Power Factor (PF) should be greater than the minimum. There may be a maximum power factor limit. The constraints can be represented mathematically as:

- $V_{min} \leq V \leq V_{max}$ and $PF_{min} \leq PF \leq PF_{max}$ for all PQ buses.

The GA algorithm can handle large low voltage (LV) distribution networks and medium voltage (MV) networks. In case of significant variations in daily load curve, fixed and switched capacitors will be applied [12]. If the switched capacitor banks considered, the GA codification and cost objective function have to be adapted.

### 3.1 Discrete Load Variation

Plotting the discrete load variation curve of the power distribution network under evaluation is an important task to solve the optimal capacitor problem. In this study the discrete load variation curve was assumed based on the average data collected from the power system operators. The result of this assumption is presented in Table 1 and Figure 2.
Table 1 Load Duration Average Data

<table>
<thead>
<tr>
<th>Months</th>
<th>No of Months</th>
<th>% of Months</th>
<th>Peak Load Time %</th>
<th>Average Load Time %</th>
<th>Off Peak Load %</th>
</tr>
</thead>
<tbody>
<tr>
<td>January to March</td>
<td>3</td>
<td>25%</td>
<td>0%</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>April to May</td>
<td>2</td>
<td>16.67%</td>
<td>5%</td>
<td>75%</td>
<td>20%</td>
</tr>
<tr>
<td>June to August</td>
<td>3</td>
<td>25%</td>
<td>20%</td>
<td>75%</td>
<td>5%</td>
</tr>
<tr>
<td>September to December</td>
<td>4</td>
<td>33.33%</td>
<td>5%</td>
<td>65%</td>
<td>30%</td>
</tr>
<tr>
<td>Average</td>
<td>8%</td>
<td>67%</td>
<td>25%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Discrete Load Duration

4. CASE STUDY & RESULTS

Muscat electricity network is divided into 3 main zones, as shown in Figure 3. The zones are representative of geographical areas in Muscat region. Zone 3 shown in Figure 5, is selected to implement the proposed methodology. The existing total capacitors in use are 130MVar which are located in the 11kV side at different primary substations. The existing shunt capacitors at 11kV side are capacitor banks with one MVAR per step. First, the network is implemented in ETAP software. Then, the GA is used to find out the optimal location and size of the capacitors according to the given objective function. Figure 4, shows the GA fitness function values during the optimization process. The solution showed that the actual needed capacitors in the system are 63MVar located in different locations in the network. Some of the locations are the same as the existing ones and some are not. Table 2 shows the difference between the existing capacitor and the one proposed by GA at each grid point.

Table 2 Existing Capacitor and GA Results

<table>
<thead>
<tr>
<th>Grid Point</th>
<th>Existing</th>
<th>GA Proposal</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mawaleh</td>
<td>60MVAR</td>
<td>24MVAR</td>
<td>40%</td>
</tr>
<tr>
<td>Rusail</td>
<td>10MVAR</td>
<td>12MVAR</td>
<td>120%</td>
</tr>
<tr>
<td>Seeb</td>
<td>30MVAR</td>
<td>8MVAR</td>
<td>27%</td>
</tr>
<tr>
<td>Barka</td>
<td>30MVAR</td>
<td>19MVAR</td>
<td>63%</td>
</tr>
</tbody>
</table>

Financially, the cost of the capacitor may be recovered within 1 to 2 years only. The calculated actual revenue collected in 5 planning years is around 660,000 Omani Rial (1,716,000 $) in this part of Muscat distribution network only. This amount is calculated after subtracting the capital cost of initial capacitor purchase and installation cost. Load growth was not considered in this case study. Load growth can be considered if required, but this needs longer time and much more effort to calculate the capacitor required for the future use.
Table 3 Mawaleh Capacitor Comparison

<table>
<thead>
<tr>
<th>Primary Name</th>
<th>Existing</th>
<th>Optimal Capacitor Placement (GA)</th>
<th>Capacitor Cost R.O.</th>
<th>Capacitor Cost R.O.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hail</td>
<td>10 MVAR</td>
<td>0 MVAR</td>
<td>20,000</td>
<td>0</td>
</tr>
<tr>
<td>Rusail B</td>
<td>0 MVAR</td>
<td>1 MVAR</td>
<td>2,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Khoudh</td>
<td>10 MVAR</td>
<td>9 MVAR</td>
<td>20,000</td>
<td>18,000</td>
</tr>
<tr>
<td>Royal Flight</td>
<td>0 MVAR</td>
<td>1 MVAR</td>
<td>20,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Mawaleh</td>
<td>10 MVAR</td>
<td>0 MVAR</td>
<td>20,000</td>
<td>0</td>
</tr>
<tr>
<td>Mawaleh A</td>
<td>10 MVAR</td>
<td>0 MVAR</td>
<td>20,000</td>
<td>0</td>
</tr>
<tr>
<td>Mawaleh B</td>
<td>10 MVAR</td>
<td>3 MVAR</td>
<td>20,000</td>
<td>6,000</td>
</tr>
<tr>
<td>City Center</td>
<td>0 MVAR</td>
<td>0 MVAR</td>
<td>20,000</td>
<td>0</td>
</tr>
<tr>
<td>Sultan School</td>
<td>10 MVAR</td>
<td>10 MVAR</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>TOTAL</td>
<td>60 MVAR</td>
<td>24 MVAR</td>
<td>120,000</td>
<td>48,000</td>
</tr>
<tr>
<td>% Difference</td>
<td></td>
<td></td>
<td></td>
<td>40%</td>
</tr>
</tbody>
</table>

5. CONCLUSION

The presented results in this paper have shown that the exiting shunt capacitor banks are over used in the studied distribution network. In addition to that, many of shunt capacitors are not correctly placed or not used. As an example, 40% only of the capacitors used in primaries connected to Mawaleh network are needed. The 60% of installed capacitors are not used or malfunctioned. In the other hand, few primaries need some shunt capacitor. The optimal placement and Mvar rating of shunt capacitor banks have been determined for the studied distribution networks using the proposed GA. The determined optimal location has reduced the system energy loss and consequently minimizes the cost of the capacitors in the system.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Sultan Qaboos University, to Qatar University and to Muscat Electricity Distribution Company for their support.

REFERENCES


[8] Electrical Transient Analyzer Program (ETAP), www.etap.com


