FEEDER RECONFIGURATION AND CAPACITOR SETTINGS ON DISTRIBUTION SYSTEMS: AN APPROACH FOR SIMULTANEOUS SOLUTION USING A GENETIC ALGORITHM

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Abstract – This paper presents an effective approach to simultaneous solution of capacitor setting and feeder reconfiguration for power-energy loss reduction and voltage profile enhancement in radial distribution systems. An optimization method using a Genetic Algorithm is proposed to determine the optimal selection size, location, type and number of fixed or switched capacitors as well as the open/closed states of the sectionalizing and tie switches for each load level. The proposed method has been tested in a range of networks and results show that taking into account feeder reconfiguration and capacitor setting simultaneously, losses can be minimized more efficiently than by considering them separately. Simulations results are presented for a 16 bus IEEE system and for a 733 bus practical distribution network.

Keywords: Distribution systems, genetic algorithm, system optimization, losses reduction.

1. INTRODUCTION

The pressure to improve overall efficiency has forced utilities to seek greater efficiency in distributions systems; communication and computing technology allow remote supervisory and control of capacitor and reconfiguration switches. In turn, this allows cost-effective solutions to loss minimization without any violations of operational conditions (voltage limits, maximum currents, radial configuration).

The problem of loss minimization can be obtained by an optimal setting of capacitors and feeder reconfiguration.

Capacitor setting is the process to determine capacitor types, sizes, locations and control schemes; and is the most widely accepted mean of improving voltage profile, power factor correction and loss reduction in distribution networks, but other operational parameters are also improved, like the peak current flows on network branches and the total peak MVA of the system.

Feeder reconfiguration is the process to determine a radial topological structures of distribution feeder by changing the open/closed states of the sectionalizing and tie switches in order to reduce losses, increase system security and enhance power quality.

The difficulty to solve the presented problems makes them to be resolved in an independent way. For this reason most of the studies handled capacitor setting without considering feeder reconfiguration or handled reconfiguration problems without considering the capacitor addition.

Optimal capacitor setting has been investigated since the 60’s. Early approaches were based on heuristic techniques applied to relaxed versions of the problem. In the 80’s, Grainger et. al. [1] formulated a more rigorous approach based on a non linear programming model solved by gradient search, Baran-Wu[2] proposed a solution by Benders decomposition. In the 90’s evolutionary computation were proposed as means of solving the capacitor setting problem; Sundhararajan [3] et. al. used genetic algorithm (GA) to select capacitor for radial distribution system, Chiang et. al.[4] proposed Simulated Annealing (SA), Huang et. al. [5] used tabu search, Lai [6] and Lee [7] used evolutionary programming to solve optimal reactive power planning problem. In the 00’s Gallego [8]et. al. proposed a hybrid method draw upon the tabu search, extended with features taken from GA and SA.

Feeder reconfiguration has been relatively recently tackled, due to advanced computing and control capabilities required for its study. One of the first works reported was presented by Merlin and Back [9]. It presents an integer-mixed non-linear optimisation model that is solved through the discrete branch and bound method. Due to the combinatorial nature of the problem, it requires checking a great number of configurations for a real-sized system.

In the 80’s Civanlar [10] et al. used a heuristic method for the estimation of the loss reduction obtained by a particular switching option (Switch exchange method), Shirzamhamdi et. al. [11] used other heuristic method based on the switches having the lowest current flow (sequential switch opening method). In the 90’s evolutionary computation is also proposed to solving the feeder reconfiguration problem. Nara et. al. [12] present an implementation using GA, Cheng et. al. [13] used a SA approach and Hsiao [14] et. al. used evolutionary programming.

Only a few papers on loss minimization for simultaneous feeder reconfiguration and capacitor setting had been presented. In the 90’s, Peponis et. al. [15] used a two steps heuristic procedure, one for obtain a feeder reconfiguration and other for determine fixed capacitor size and location, this procedure is repeated until the two steps produce the same configuration and capacitor arrangements; Jiang et. al. [16] used a two steps procedure too, the first one employed SA to optimise the switch configuration and the second one a discrete optimisation algorithm to optimal capacitor control. In the 90’s Su and Lee [17] presented an first approach for feeder reconfiguration and capacitor setting simultaneously using SA, but they do not consider energy losses neither capacitors costs.

This paper presents a Genetic Algorithm for optimal loss minimization of distribution systems under jointly optimal capacitor setting and feeder reconfiguration. The proposed methodology has the following characteristics:

- It solves a multi-objective optimization problem for...
capacitor setting and feeder reconfiguration simultaneously, considering operating and engineering constraints.

- It is applicable to large-scale distribution systems with comprehensive modelling of diverse distribution components; including loads represented by diverse voltage depend models, fixed and switched capacitor, sectionalising and tie switches, transformer losses.
- It considers power losses and energy losses as well as capacitors costs.
- It considers a non-iterative power flow method for losses estimation.
- It attains a higher quality solution than classical methods for loss reduction in distribution systems.

2. PROBLEM FORMULATION

Given a balanced radial distribution network with a known topological structure, the problem consists of finding, for each load level, an optimal capacitor setting and a radial network among all possible radial networks generated with the switch condition changes (reconfiguration) and all possible capacitors types considered (capacitor placement), that minimizes the power and energy losses and that does not infringe the networks load flows and operational constraints. This is a combinatorial, non differentiable and a mixed integer non-linear optimization problem.

The simultaneous solution of the optimal reconfiguration and capacitor setting problem determines which network switches should be open and which closed as well as capacitor types, sizes, control and locations in order to reduce losses, to improve voltage profile and, in a more limited way, to increase feeder capacity, under different load curves conditions and satisfying equipment and operation constraints.

In this paper the objective function is formulated as minimization of costs and investments (C) over a time period T, including power losses and energy losses, then the objective is to reduce the energy losses and peak power losses (P_{pmax}) on the system while striving to minimize the cost of capacitor in the system (C_c). The cost of a switch state condition change are not considered. The mathematical formulation is described in eq. (1).

\[
\min C = CE_p(T) + CP_p(T) + C_C
\]

\[
st: \quad V_{min} \leq V_i(t) \leq V_{max} \quad i = 1, 2, ..., n, \quad 0 < t < T
\]

\[
I_j(t) \leq I_{max j} \quad j = 1, 2, ..., (n-1), \quad 0 < t < T
\]

\[
Q_{C_k}^-(t) \leq Q_{C_{max}} \quad k = 1, 2, ..., N_{cond}, \quad 0 < t < T
\]

\[
Q_{C_k}^+(t) = Q_{C_{disp m}} \quad m = 1, 2, ..., N_{disp}
\]

\[
N_{cond} \leq N_c
\]

No feeder section can be left out of service and radial network structure must be retained.

The energy (CE_p) and active power (CP_p) losses costs associated to a particular network configuration are evaluated with the equation (2), (3), where Ke is the energy cost factor and Kp is the active power cost factor. To calculate the energy losses in the system, the load variations for a given period of time T are taken into account, Fig. 1. A simplified calculation method has been named "Simplified Power Summation Method" is use for losses estimation (P_p), [18].

\[
CE_p(T) = Ke \sum_{j=1}^{N_{niv}} P_p(j) \cdot \Delta T_j
\]

\[
CP_p(T) = Kp \cdot P_{p_{max}}
\]

The formulation considers fixes (Q_{CF}) and switches capacitors (Q_{CV}) with a cost function such as Fig. 2 shows.

3. GENETIC ALGORITHM

From Fig. 2, the total cost for new capacitor allocation (C_C) is given by eq. (4).

\[
C_C = \sum_{i=1}^{n_{cf}} C(Q_{CV_i}) + \sum_{i=1}^{n_{cv}} C(Q_{CV_i})
\]
A genetic algorithm (GA) is proposed, the most popular form of Evolutionary Algorithms, inspired by the principle of evolution and, in essence, consists on a population of strings transformed by three genetic operators: selection, crossover and mutation. Each string (chromosome) represents a possible solution to the problem being optimized and each part of the string (sub string) represents a value for some variable of the problem (gene). These solutions are classified by an evaluation function, giving better values, or fitness, to better solutions. Each solution must be evaluated by the fitness function (having the role of environment) to produce a value. The pair (chromosome, fitness) represents an individual. The GA algorithm proposed in this paper has the following characteristics, [19].

3.1 Coding

Each possible radial distribution system with some switches states and capacitor setting is an individual in the population represented by a four sub string such as Table 1 shows. The sub string are as follows:
- An integer coded exists for the reactive power for fixed and switched capacitor for each load level.
- An integer coded exists to designate the bus capacitor location.
- A binary multi-parameter coded exists for the switches states for each load level. If the binary value is zero the switch is open and it is one the switch is closed.
- An integer multi-parameter coded exists for the topological system configuration for each load label based on a predecessor vector [19]; this representation indicates for each node its predecessor, in other words, the nearer node from which receives the feeding.

<table>
<thead>
<tr>
<th>Sub string</th>
<th>Coding</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor reactive power (Qc)</td>
<td>Integer</td>
<td>Vector with ((nCV \times Nniv + nCF)) elements that designate the Qc for each load level.</td>
</tr>
<tr>
<td>Capacitor allocation</td>
<td>Integer</td>
<td>Vector with ((nCV + nCF)) elements that designate the bus number for the capacitor</td>
</tr>
<tr>
<td>Switches states</td>
<td>Binary</td>
<td>(Nniv) vectors with the (Nllav) switches states for each load level</td>
</tr>
<tr>
<td>Network configuration</td>
<td>Integer</td>
<td>(Nniv) predecessor vectors that designate the network topologic for each load level.</td>
</tr>
</tbody>
</table>

\(nCV\) : Number of switched capacitor  
\(nCF\) : Number of fixed capacitor  
\(Nniv\) : Number of load levels  
\(Nllav\) : Number of switches

3.2 Initialization

A random initial population is considered. Parameters of GA must be initialized such as generation size, population size, crossover probability and mutation probability for capacitor addition and feeder reconfiguration.

3.3 Fitness Evaluation

All individual are evaluated with the same fitness function. The fitness function incorporates the objective function, i.e., the total cost of associated to power losses, energy losses and capacitors costs eq.(1) with cost penalties if a individual violates any of the constraint. The fitness function, \(f_k\), can be expressed as follows:

\[
f_k = C_k + \alpha \cdot \Delta V_k + \beta \cdot \Delta I_k \tag{5}
\]

where \(C_k\) is the total cost of individual \(k\) (eq. 1), \(\alpha, \beta\) are the penalty functions associated with the voltage \(\Delta V_k\) and currents \(\Delta I_k\) constraints.

3.4 Reproduction operation

In this operation, the matting pool needs to be formed by the population in proportion to their elitism. Elite ones will copy more to the matting pool. The roulette wheel selection was used to guarantee the occupancy of an area equal to the individual’s share of the total fitness.

3.5 Crossover

Given a switched and capacitor crossover probability, a crossover is performed considering one or more crossover point.

3.6 Mutation

Given a switched and capacitor crossover probability, random alteration of genes in a individual may occur. A switches mutation represents a simple bit change, a capacitor mutation represents a change in bus number to any valid location or the reactive power setting.

4. TEST RESULTS

The proposed method was implemented in the C programming language on a Pentium III 550MHz, to demonstrate its performance two system benchmarks was considered for this paper: a 16 bus IEEE system used to validate the proposed GA methodology and a 733 bus real distribution system used to test the algorithm efficiency on a large network.
4.1 16 bus IEEE test system.

This is a frequently studied IEEE distribution system obtained from [10] and displayed in Fig. 3. The system consists of 16 buses, three feeders, 13 sectionalizing switches and three tie switches. This system is used in this paper with two purposes, in the first place to validate the proposed method and in second place to show the advantage of the proposed GA method.

4.1.1 16 bus IEEE system, case 1.

Simulation results are presented for the 16 bus IEEE system and compared to the feeder reconfiguration and capacitor setting obtained from [17], which use simulated annealing (SA) to solve the problem, both feeder reconfiguration and setting of capacitor are taken into account together, but only power losses reduction is considered. The system load is assumed to be constant and buses 4, 8 and 13 are selected to set up capacitor banks for feeder 1, 2 and 3 respectively. Practical size available for the capacitor banks are 300, 600, 900, 1200, 1500 and 1800 KVAr. In order to compare results, this paper has considered the same four cases presented by Su [17]. These four cases are the following:

Case a: Only feeder reconfiguration is considered
Case b: Only capacitor addition is considered
Case c: Both capacitor addition and feeder reconfiguration are considered; however, capacitor addition is carried out before feeder reconfiguration.
Case d: Both capacitor addition and feeder reconfiguration are considering and are taken into account simultaneously.

The genetic parameters setting considered for all simulation cases are show in table 2, the final system configuration for the four cases studied are depicted in Fig. 3 and summarized in table 3.

The obtained results are the same as [17] presents and validate the proposed methodology. Table 3 show that case d) can reduce power loss the most among these four cases.
To show some of the advantages and simulation alternatives of the proposed approach the 16 bus IEEE system was studied with the following considerations:

- Three load level were considered with the load duration data for the system presented in table 4.

To show some of the advantages and simulation alternatives of the proposed approach the 16 bus IEEE system was studied with the following considerations:

- Voltage and current constraints were considered:
  \[ V_{\text{max}} = 1.1 \text{ pu.}, \quad V_{\text{min}} = 0.9 \text{ pu.}, \quad I_{\text{max}} = 0.18 \text{ pu.} \]

- Instead of minimizing only power losses, the costs of capacitor and power-energy losses were considered too. The cost constants assumed for this problem according to eq. (2), (3) are the following: \( K_p = 300 \text{ US$/KW/year} \), \( K_e = 0.1 \text{ US$/KWh} \) and \( K_c = 5 \text{ US$/KVAr} \).

- The same switched and capacitor from the case 1 were considered, but now they can be located in any bus of the system.

### 4.1.2 16 bus IEEE system, case 2.

Under this conditions the same four cases (4.1.1) were analyzed. A costs comparison results are presented in table 5 and the detail for the case d is summarized in table 6.

From table 5 it can be observed that the best solution corresponded to case d), with both feeder reconfiguration and capacitor setting are taken into account simultaneously.

### 4.2 733 bus test system

The method has been applied to a practical 13.8 kV Distribution system with 733 buses and 118 switches. The system was studied considering an upper limit of 4 new switched capacitor, four load levels, voltage and currents constraints. For space reasons only the results of costs comparison are presented in table 7. Numerical results show that the proposed approach is efficient on large distributions system too.

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### TABLE 3: Summarize results for the four cases studied on the 16 bus IEEE system, case 1.

<table>
<thead>
<tr>
<th>Main items</th>
<th>Original configuration</th>
<th>Case a</th>
<th>Case b</th>
<th>Case c</th>
<th>Case d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switches status alternated</td>
<td></td>
<td>{15,19}, {21,17}</td>
<td>{15,19}, {21,17}</td>
<td>{15,19}, {21,17}</td>
<td>{15,19}, {21,17}</td>
</tr>
<tr>
<td>Maximum bus voltage</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Minimum bus voltage</td>
<td>0.96927</td>
<td>0.971575</td>
<td>0.97132</td>
<td>0.97362</td>
<td>0.97362</td>
</tr>
<tr>
<td>Capacitors added [Kvar]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus 4</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Bus 8</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Bus 13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Total power loss [MW]</td>
<td>0.5144</td>
<td>0.4691</td>
<td>0.4971</td>
<td>0.4552</td>
<td>0.4543</td>
</tr>
<tr>
<td>Power loss reduction [%]</td>
<td>8.81</td>
<td>4.6</td>
<td>5.5</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>CPU time [s]</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 4: Load duration data, Case 2

<table>
<thead>
<tr>
<th>Level 0</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load level (p.u.)</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Time interval (hours)</td>
<td>1000</td>
<td>6760</td>
</tr>
</tbody>
</table>

### TABLE 5: Costs comparison for a 16 bus IEEE system, case 2

<table>
<thead>
<tr>
<th>Main items</th>
<th>Initial configuration</th>
<th>Case a</th>
<th>Case b</th>
<th>Case c</th>
<th>Case d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max total power loss [MW]</td>
<td>0.6316</td>
<td>0.5988</td>
<td>0.5764</td>
<td>0.5574</td>
<td>0.5513</td>
</tr>
<tr>
<td>Total Cost loss [US$]</td>
<td>388427</td>
<td>377669</td>
<td>353230</td>
<td>354591</td>
<td>345352</td>
</tr>
<tr>
<td>Cost loss reduction [%]</td>
<td>2.8</td>
<td>9.1</td>
<td>8.7</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>CPU time [s]</td>
<td>--</td>
<td>1m 2s</td>
<td>1m 14s</td>
<td>2m 17s</td>
<td>5m 50s</td>
</tr>
</tbody>
</table>

### TABLE 6: Final results for the case d, 16 bus IEEE system, case 2

<table>
<thead>
<tr>
<th>Main items</th>
<th>Load level 0</th>
<th>Load level 1</th>
<th>Load level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switches status alternated</td>
<td>{17,21}</td>
<td>{17,21}</td>
<td>{14,26}</td>
</tr>
<tr>
<td>Maximum bus voltage</td>
<td>1.0</td>
<td>1.0</td>
<td>1.02</td>
</tr>
<tr>
<td>Minimum bus voltage</td>
<td>0.972</td>
<td>0.988</td>
<td>0.998</td>
</tr>
<tr>
<td>Capacitors added [Kvar]</td>
<td>Bus 8</td>
<td>1800</td>
<td>0</td>
</tr>
<tr>
<td>Bus 7</td>
<td>1500</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>Bus 9</td>
<td>1200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total power loss [MW]</td>
<td>0.5513</td>
<td>0.1700</td>
<td>0.0759</td>
</tr>
</tbody>
</table>
CONCLUSION

In this paper a Genetic Algorithm has been presented to solve both feeder reconfiguration and capacitor setting simultaneously. The approach has been tested in a range of networks and the test results lead to the following conclusions:

- Taken into account both capacitor setting and feeder reconfiguration simultaneously can generate more energy-power losses reduction than considering them separately.
- An efficient coding system was developed for applying GA to the target problem, it handles possible generation of strings with violation of operational constraints.
- As size of the network and the load levels considered increase, the simultaneous solution requires more computational time than the separately solution (only reconfiguration or only capacitor setting).
- The level of distribution modeling employed, include loads represented by diverse voltage depend models, fixed and switched capacitor, sectionaising and tie switches, transformer losses, capacitors costs.

REFERENCES