Optimal Study of Distributed Generation Impact on Electrical Distribution Networks using GA and Generalized Reduced Gradient

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Abstract—This paper presents the effect of Distributed Generators (DG) existence in the electrical power distribution networks taking IEEE 14 and IEEE 30 bus test feeders as proposed systems. The analysis is done to examine the effect on the overall system losses and voltage profile. The aim behind this study is to obtain the optimum location and penetration level of the added DG unit in order to decrease the losses and enhance the voltage profile. The optimization is done using two different optimization techniques, generalized reduced gradient (GRG) and genetic algorithm (GA). The power system dynamic program MATLAB is used for this study. The simulation results are analyzed to show the effectiveness of GA over the GRG algorithm.

Index distributed generator (DG), genetic algorithms (GA), generalized reduced gradient (GRG), IEEE 14 bus system, IEEE 30 bus system and optimization.

I. INTRODUCTION

In the last few years the electrical power networks experiences tremendous increase in power demand from the local customers connected to the network. This is due to either increase in the number of the connected customers and/or due to increase in the social welfare. So the network has to meet this demand increase and secure sufficient power for all the customers. This is done either by increasing the power network capabilities (i.e. implementing more power units) which means deferring of cable sizes, medium voltage switchgear, protection devices settings, ...etc.; or by installing small generators in the distribution network, connected to the customer side of the meter. Hence the term distributed generator (DG) was introduced. The last solution leads to increase of the deregulation of the networks and also has many proponents whom claim that implementing DG units leads to the decrease in power losses, enhance voltage profile, decrease the generation cost and - last but not least – delay the deferring the of the existed substations [1], [3] and [6].

One of the most important factors affecting the choice of DG type is the technology used in producing electric power from the DG unit. It may be from photovoltaics, wind turbines or CHP units (combined heat and power) [1]. Also another factor affecting the decision of choosing of the DG is the penetration percentage of DG in the distributed system [1], [5] and [6]. In [2] the authors presented a comparison between the implementation of DG units to the distribution network or expanding the generation capabilities of the already existing substations - in order to meet the increase in power demand - and their results show that implementing DG's is the most optimal solution, as the total costs of the DG investment are minimized. Also the power purchasing cost from the grid has reduced to minimum. The real challenge that faced the system planners and operators was the choice of the correct place to install a DG unit in the distribution network, so, in [4] the authors proposed the using of genetic algorithms as an optimization technique to find the best location to install DG unit and the number of the units that should be used, because the wrong placement will lead to lose all the advantages of adding the DG unit.

This paper studies the performance of the IEEE 14-bus system and IEEE 30-bus system when implementing a DG unit on the buses that do not have generators. The main concerns are the following issues: optimal location, size and type of the installed DG unit in order to decrease the overall system losses, and the effect of the installed DG unit on the voltage profile. Finally the effect on the overall generation cost. All the above mentioned issues form the objective function. In this research the DG units are classified into two types, one which generates active power only (storage batteries and photovoltaics), the other type generates both active and reactive power (rotating generators).

The optimization is done by two optimization techniques which are genetic algorithm (GA) and generalized reduced gradient (GRG). Both optimization techniques are built by Matlab software. Thus a comparison is made between both optimization techniques to find the best location, size and type of the installed DG unit. This is based on a common objective function.

II. OPTIMIZATION APPROACH

Optimization is the art of choosing the best solution(s) from a set of different alternative that maximize the benefits and
decrease the losses in the problem under study. The optimum solution is not always the least point - on the curve describing the problem - it may be the maximum; it depends on the nature of the problem. There are many optimization techniques developed to find the best solution to the problem under study. They are divided into two categories: 1) conventional methods like generalized reduced gradient (GRG), 2) artificial intelligence methods that are inspired by biological systems like genetic algorithm (GA). Both methods are used in the present study to find the optimal solution for the proposed objective function previously mentioned.

A. Generalized Reduced Gradient
This optimization technique is used in the non-linear constrained problems, as it converts the constrained problem to an unconstrained one using direct substitution. It belongs to a family of techniques called the reduced gradient methods. The idea behind this technique is to build derivative matrix contains the derivatives of the function with respect to each variable. Also it uses dummy variables to represent the constraints thus the algorithm have original variables (basic) and the dummy variables (non-basic). After the first iteration, the algorithm modifies the values of the initial guess, as the optimization process goes on the variable values are updated after each iteration, until the algorithm reaches a satisfactory value (from the point of view of the operator) or the error reaches its pre-defined limit. One of the defects in this technique is the necessity of getting the function derivative and its calculation which may be, in some problems, hard to be found or calculated. Also the problem might have large number of variables which adds to the problem difficulty due to the large dimension of the derivative matrix [11].

B. Genetic Algorithms
This optimization technique was inspired from the evolution theory postulated by Charles Darwin (1809-1882) which stated the famous concept "survival of the fittest". The algorithm codes the possible solutions for the problem in a form of bit strings of equal length (the size is assigned by the user), each bit string called chromosome or individual and the bits forming the string called genes. Then the algorithm forms mating pool which contains all the strings and applies three operators in order to optimize the function, these operators are: selection, crossover and mutation [8], [9] and [10].

Selection
This operator is used by the algorithm to choose the best individuals or chromosomes in the mating pool based on their fitness values (as the fitness of the individual increase it becomes more likely to be selected) to form the initial population. The method that was used is stochastic uniform selection due to its ability to provide zero bias and minimum spread in the selection of the individuals forming the mating pool [8], [9] and [10].

Elitism
It is considered as one of the selection methods and it is used to ensure the survival of the "super individuals" (individuals with the highest fitness value). The selected individuals are called elite children; the aim from this method is to prevent the loss of potential solutions, as the selection methods might discard this power full solution from the mating pool. And the individuals pass to the next generation directly (i.e. without passing by the stage of crossover and mutation) [8],[9] and [10].

Crossover
This operator is used by the algorithm to enhance the fitness value of the individuals. In this operator, two randomly selected individuals (called parents) exchange some of their genes together in order to get two new two individuals are called offspring. And the method that was used is crossover probability with a probability value equals to 0.8 which means that crossover operator will be applied on 80% of the individuals in the current population. This technique was chosen due its superiority among the other crossover techniques as it ensures the transportation of the best traits in the current generation to next one [8], [9] and [10].

Mutation
This operator prevents the algorithm from being trapped in local minima as it helps in the recovering of the lost traits due to the crossover operator. It also helps in the exploration of the search space thus adding more diversity to the population. The technique used in this research was the mutation probability in which the algorithm flips certain number of bits (from zero to one or vice versa) in each of the selected individuals to be mutated. The value was low comparably with the crossover ratio in order to keep the exploitation/exploration balance [8], [9] and [10].

The GA will not run endless as it has many stopping criteria's among which, it should produce certain number of generations (populations), or to run for several preset time, or the difference in the fitness value does not change for several preset number of generations.

Fig.1 shows a flow chart describes how GA works to reach the optimum solution.

![Flow chart showing how GA operates](image-url)
The function that is used in the optimization of the systems can be formulated as a polynomial function or a piece-wise linear function contains the sum of all the operating costs of each generator in the each system. The function used to express the overall operating cost was:

\[
\sum_{j=1}^{N_g} (a_j + b_j \times P_{gi} + c_j \times P_{gi}^2) + (a_{DG} + b_{DG} \times P_{DG} + c_{DG} \times P_{DG}^2)
\]

(1)

Where \(a, b, c\) are cost factors for each generator

\(P_{gi}\): the output power from the \((i)th\) generator

\(N_g\): the number of the generator, for IEEE 14; \(N_g = 6\), and for IEEE 30; \(N_g = 7\).

\(P_{DG}\): the output power from the installed DG unit

III. MODELING

A. Network Model

The two systems under study are shown in fig. 2 and fig. 3 respectively. Fig. 2 shows IEEE-14 bus test feeder which consists from 5 generators with different capacities located at buses 1,2,3,6 and 8, also, fig. 3 shows IEEE-30 bus test feeder which contains 6 generators with different capacities located at buses 1,2,5,8,11 and 13. The buses are connected in loop thus it is considered as a power system that operates under 11kV level.

<table>
<thead>
<tr>
<th>#</th>
<th>Point of comparison</th>
<th>IEEE 14 bus</th>
<th>IEEE 30 bus</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Slack Bus</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>PV Buses</td>
<td>2,3,6,8</td>
<td>2,5,8,11,13</td>
</tr>
<tr>
<td>3</td>
<td>PQ Buses</td>
<td>4,5,7,9,10,11,12,13,14</td>
<td>3,4,6,7,9,10,12,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30</td>
</tr>
<tr>
<td>4</td>
<td>Number of Loads</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>Number of Branches</td>
<td>20</td>
<td>41</td>
</tr>
</tbody>
</table>

B. DG Approach

The aim from this study was to implement generators—with different penetration levels—on the PQ buses, in order to study the impact of the DG implementation on the distribution network. The goal is to optimize the network operation and this is by minimizing both network losses and generation fuel cost. The DG capacity (i.e. generator size) was chosen according to the following equation:

\[
DG\ capacity = capacity\ factor \times Overall\ system\ capacity
\]

(2)

DG capacity: it is the size of the chosen DG unit regardless the technology it uses to generate electrical power either from renewable or non renewable resources.

The capacity factor: is a factor chosen by the operator. It was chosen to range from 0.01 to 0.2 with 0.01 step.

Overall system capacity: the capacity of the system is the sum of the maximum capacities of the already existed units.

IV. SIMULATION RESULTS

The following results, represented by the following graphs, are samples from the obtained results due to the analysis that was applied on both systems under study using the GRG algorithm. Fig.4 shows that implementing DG unit to some buses leads to noticeable decrease in the overall system losses without any constraint on the penetration level. On the other hand fig.5 shows that implementing DG unit to some other buses leads to major increase in the losses even with small penetration level. Fig.6 shows that at low penetration levels of
DG the losses are high, while at higher level of penetration the losses start to decrease. While Fig.7, shows the opposite of Fig.6, as the losses were low at low penetration level and losses went higher as the penetration level increases. The last two curves show that implementing the DG unit does not always cause "continuous" decrease or increase in the losses, but it depends on the penetration level. This means that there is optimal location, optimal penetration percentage level (i.e. DG size) and this is applicable to both systems under study.

The reason behind the behavior shown on Fig.4 refers to that the amount of power generated from the DG unit meets only the local load. On the contrary, in Fig.5 the DG generated power was more than the local load thus the remaining power will spread in the system, hence the overall system losses starts to increase. But in both figures 6, 7 the curves show that there is a certain penetration level after which the losses start to decrease (Fig.6) or increase (Fig.7). Another advantage of DG implementation was the enhancement in system's voltage profile (for both systems under study) as the penetration percentage increase the voltage profile becomes better, this is shown in Fig.8 and Fig.9. The limits of permissible deviation from nominal value are taken +/- 6%.

In Fig.10 and Fig.11 the effect of implementing DG unit to the cost are shown. When the target was to minimize the fuel
cost, the algorithms always depend on the cheapest generator, that has the lowest operating coefficients only regardless the position of this generator, to produce as much power as its limit permits thus the overall cost decrease. And this was done by decreasing the dependency on the expensive generators (shutting them down partially) and increase the dependency on more cheap generators.

Fig. 10. Effect of DG unit implementation on overall fuel costs (IEEE 14 bus "bus 5")

Fig.11. Effect of DG unit implementation on overall fuel costs (IEEE 30 bus "bus 3")

All the above figures were obtained using the GRG optimization method. Similar curves are obtained using GA. Further analysis was done on the two systems under study using GA algorithm. The GA obtained more optimum values when applied on the same objective function (with the same constraints), than the GRG obtained. The GA got less overall losses value and enhanced the voltage profile but the cost increased by a small amount and the reason was. Table II shows the optimum penetration values of the added DG unit on the PQ buses for both the 14 and 30 bus systems.

Table II

<table>
<thead>
<tr>
<th>#</th>
<th>Penetration Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 14 Bus System</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>5,14</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>4,7</td>
</tr>
</tbody>
</table>

Fig.12, fig.13 and fig.14 shows comparison between the most optimum overall system values obtained concerning the losses, voltage profile and the overall fuel cost respectively for the IEEE 14 bus system, by GRG and GA after implementing DG unit (with certain penetration value), to the buses without generators, on the overall system losses. Also Fig.15, fig.16, fig.17 shows the same concerning the IEEE 30 bus system. The reason behind the slight increase in cost value obtained by the GA than the GRG is that the GA found that the cheap generators are distant from the load centers which lead to the spreading of the generated power in the network thus increasing the losses and decreasing the cost (fig.12, fig.14, fig.15 and fig.17). So the GA shuts down the distant generators (cheap one) and uses the near generators, which sometimes be more expensive thus leading to a considerable decrease in the overall power losses and slight increase in cost.

Fig. 12. Overall losses values (IEEE 14 bus)

Fig.13. Voltage profile values (IEEE 14 bus)
This paper discussed the effect of implementing DG unit to the buses without generators in the IEEE 14 bus and the IEEE 30 bus test feeders and the effect of the penetration level of the added DG unit (DG size) on losses, voltage profile and the fuel cost. The analysis is done by using the two optimization techniques on is conventional which is GRG and the other technique was an artificial intelligence one which is GA. In this analysis, the GA has been proved to be more effective than conventional optimization methods. The analysis has shown that there are three sets of busses which are: 1) Set one: implementing of the DG unit to those busses will lead to continuous decrease in the overall system losses. 2) Set two: implementing of the DG unit to those busses will lead to continuous increase in the overall system losses. 3) Set three: implementing of DG unit will lead to a "fluctuating" behavior which means that the overall losses value will depend on the penetration level (DG unit size). Another interesting thing that is shown in this analysis which is, the losses increases as soon as the power generated spreads in the network, which happens due to the far distance between the loads and the substations. So the new installed DG units should be installed beside/to the load centers to prevent the spreading in power (i.e. decrease the overall system losses).

This will lead to a result which is, the location and the penetration level of the DG unit should be chosen carefully by the network operator in order to prevent the increase of the overall system losses, which prevents the network operator from taking on the advantages of installing DG.

VI. REFERENCES