

Optimal Multi-Objective Planning of Distribution System with Distributed Generation

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Abstract:

This paper presents a multi-objective formulation for optimal siting and sizing of distributed generation (DG) resources in distribution systems in order to minimize the cost of power losses and energy not supplied. The implemented technique is based on a genetic algorithm (GA) and weight method that employed to obtain the best compromise between these costs. Simulation results on 33-bus distribution test system are presented to demonstrate the effectiveness of the proposed procedure.

Keywords: Distributed Generation, Distribution networks, Genetic algorithm, Reliability, Weight method

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1. Introduction

For many years, the distribution system has been planned, built and operated always in the same way. But in the last decade, the first signs of changes have appeared due to the liberalization of the electricity market, the governmental drive to reduce number and duration of long interruption and the growing presence of DG. In particular, if DG penetration reaches a high level, as predicted by many authors, distribution utilities will probably have to dismiss the traditional radial network operation, adopting a more flexible meshed structure. If DG is properly planned and operated, it may provide benefits to distribution networks (e.g., reduction of power losses, capacity saving, reliability and power quality improvement). The effect of adding DG on network indices will vary depending on its type and position and (forecast) load at the connection point. Consequently, one or more sites on a given network may be optimal.

There are many methods available for DG planning. Most of them have been considered only one objective function. In [1] an algorithm to determine the near optimal, with respect to system losses, placement of these units on the power grid has been presented. Further, the impacts of dispersed generation at the distribution level are performed with an emphasis on resistive losses, and capacity savings.

Moreover in [2] a strategic DG placement method has been proposed to enhance the reliability and obtain the benefits for DG placement. In [3] a methodology has been formulated for the optimal sitting of distributed generators and reclosers. Optimal sitting is determined by sensitivity analysis of the power flow equations. The sizing method for a set of loading conditions, generation penetration level and power factor is formulated as a security constrained optimization problem.

The cost of active and reactive power generation based on GA and optimal power flow calculations, has been minimized in [4]. Furthermore in [5] a technique has been presented for assisting network planners to determine the optimum rating and position of dispersed generators in an established distribution network, considering practical objectives and constraints over a number of planning years. The objectives considered were: the minimization of system losses, the minimization of disruption to the existing network, the minimization of costs and the maximization of the rating of the dispersed generators. The tool exploits conventional techniques in assessing the constraints imposed by the network, subsequently using Genetic Algorithms to provide an optimization of the decision making process.

In this paper, a genetic algorithm based multi-objective (MO) formulation is proposed to optimize cost of power losses and energy not supplied simultaneously. Then, a global non-inferior solution for MO problem is achieved by means of Genetic Algorithm. In a next stage, by using weight method, a set of non-inferior solutions can be

produced with an iterative procedure in order to find the most compromised solution.

2. Multi-Objective Programming

Recently, the liberalization of electric energy markets has brought important changes in the economic and technical aspects of power system planning and operation; the grids have to be managed according to new principles but taking into account the technical constraints. Therefore, it is necessary to change the methodologies and the algorithms used for the power system optimization. In particular, new tools that allow managing the system, complying with the rules of the electric market, must be available. The new scenario forces a change in the duties and objectives of the traditional planning and it compels to take into account several objectives that are likely to be in mutual conflict. The MO methodologies give a different solution that obtained by standard optimization methods. First of all, their intermediate results are not unique, but provide an infinite set of optimal solutions called Pareto set. Each point belonging to the Pareto set has an important characteristic: The improvement in one of the objectives results in the worsening of at least another objective. The general formulation of a MO problem is expressed by:

$$\begin{aligned} \min & [f_1(x), f_2(x), \dots, f_m(x)]^T \\ & x \in \Omega \\ & g_j(x) = 0 \quad j = 1, \dots, n \\ & h_k(x) \leq 0 \quad k = 1, \dots, p \end{aligned} \quad (1)$$

Where x represents a decision vector, f_i is the i_{th} objective function, Ω is the domain of solutions, g_j and h_k are the equality and inequality constraints, respectively.

Therefore, to solve a MO problem it is necessary to follow these steps: a) define the useful objectives; b) find the Pareto set and c) choose a solution from Pareto set. Step c) is the most important, because the final solution depends on the point of view of the decision maker who has to take into account the relative importance of the conflicting objectives. There are various techniques for generating non-inferior solutions (Non-inferiority means that improvements in one objective are attained only at the cost of some sacrifice in the other objective functions). The method presented and used in this paper is the Weight Method. It transforms the MO optimization problem into a traditional problem: the different objective functions are weighted and added to form a single objective function to be optimized. The optimization problem can be defined as follows:

$$\min \sum_{i=1}^k w_i f_i(\bar{x}) \quad (2)$$

Where $w_i \geq 0$ are the weighting coefficients representing the relative importance of the objectives. It is usually assumed that

$$\sum_{i=1}^k w_i = 1 \quad (3)$$

The main strength of this method is its efficiency (computationally speaking) and its suitability to generate a strongly non-dominated solution that can be used as an initial solution for other techniques [6].

3. Problem Formulation

The main goal of this paper is to determine optimal locations and sizes for new generators by minimizing the cost of energy losses and cost of energy not supplied subject to bus voltages limits, DG power limit, short circuit currents and network power flow equations.

In the following, each cost function is described in detail under the assumption of a linear load growth during the whole planning period.

3.1. Cost of Energy Losses (C_L)

The losses of distribution system depend on the line resistance and currents and are usually referred to as thermal losses. While the line resistances are fixed, the currents are a complex function of the system topology and the location of generation and load.

In this work, only the real power injections as they relate to distribution losses are of concern. The system losses at the beginning of the planning period can be expressed as

$$P_{0L} = \sum_{i=1}^n P_{G_i} - \sum_{i=1}^n P_{D_i} \quad (4)$$

Where P_{0L} is the real power loss, P_{G_i} is the real power generated at the i_{th} bus, P_{D_i} is the real power required at the i_{th} bus. All of the above parameters are calculated by power flow program. The net present value of the power losses cost in the whole planning period can be calculated as follows:

$$C_L = 8760 \times U_E \times \sum_{h=1}^{N_y} B^h \cdot P_{0L} \cdot (1 + \gamma)^h$$

$$B = \frac{1 + f}{1 + \mu} \quad (5)$$

Where B is a economic factor for converting costs to present value, f and μ are inflation and interest rate respectively, γ is a load growth rate per year, U_E is cost of energy(\$/kWh) and N_y is planning period. In eq. (5) it has been assumed that DG units operate 24 h/day at their rated power. That's why coefficient of $24 \times 365 = 8760$ h/year has been used.

3.2. Cost of Energy Not Supplied (C_{ENS})

In order to calculate the cost of energy not supplied the duration of a branch fault is usually divided into two phases: fault location and fault repair. Automatic sectionalizers and reclosers can restrict the area of influence of a fault, reducing the number of customers affected by long-term interruptions during the fault location phase. In this stage, intentional islanding may be used to supply unfaulted portions of the network automatically separated from the faulted section. The repair stage consists of the time required to isolate the faulted branch, connect any emergency ties and repair the fault. DG, enabling power to be restored to the nodes downstream the sectionalized branch, can lead to significant reliability improvements. Load flow studies should be performed to check that voltages and currents are within their operative ranges and that DG units have a sufficient probability to pick up the loads in the islanded network. Equation (6) gives the cost of energy not supplied of the j_{th} network branch.

$$C_{0a_j} = 8760 \times U_E \lambda_j L_j \times \left(\sum_{i=1}^{N_{loc}} P_{0i} \cdot t_{loc} + \sum_{i=1}^{N_{rep}} P_{0i} \cdot t_{rep} \right) \quad (6)$$

Where λ_j is the branch fault rate (number of faults per year and km of feeder), L_j is the branch length (km), N_{loc} and N_{rep} are the number of nodes isolated during the fault location and repair stages, respectively, P_{0i} is the node power (kW) at the beginning of the planning period, and t_{loc} and t_{rep} are the durations of the fault location and repair stages (h), respectively.

The net present value of the cost of energy not supplied due to a fault in the j_{th} branch during the planning period is calculated with the following expression:



$$C_{ENSj} = \sum_{h=1}^{N_y} C_{0aj} \times (1 + \gamma)^h \times B^h \quad (7)$$

The cost of energy not supplied (C_{ENS}) is then obtained as the sum of the C_{ENSj} for each branch in the whole planning period.

3.3. Problem Constraints

Two above objectives were subject to the following constraints:

1. The network voltage levels should be held within specified limits.
2. The short circuit limitations of network plant needed to be respected.
3. DG real and reactive power capabilities needed to be respected.

These are represented by the following equations:

$$\begin{aligned} V_{\min} &\leq V_i^n \leq V_{\max} \quad n = 1, \dots, N \\ S_{\min}^b &\leq S_i^b \leq S_{\max}^b \quad b = 1, \dots, B \\ P_{DG \min}^k &\leq P_{DGi}^k \leq P_{DG \max}^k \quad k = 1, \dots, K \\ Q_{DG \min}^k &\leq Q_{DGi}^k \leq Q_{DG \max}^k \quad k = 1, \dots, K \end{aligned} \quad (8)$$

Where N is the number of nodes in the network, K is the number of DG units and B is the number of branches (transformers and lines), V_i is the node voltage in year i , P_{gi}^k and Q_{gi}^k are real and reactive power generated by generator k in year i respectively and S_i^b is the apparent power flowing in branch b in year i .

4. GA Implementation

In this paper, a GA optimization technique has been used for finding the non-inferior solutions of the MO optimization algorithm. The key steps in the implementation of GA involve formulation of the fitness function for the problem, choice of representation and coding techniques for the solution, evaluation the fitness of each candidate solution and application of the genetic operators, namely reproduction, crossover and mutation iteratively to evolve the solutions until a desirable solution is obtained [7].

If the network structure is fixed, all the branches between nodes are known, and the evaluation of the objective functions described above depend only on the size and location of DG units. For this reason two control variables were identified for each solution vector. These were the position and size of DG units. A node chosen for installation of a generator was treated as a PV bus,

thus the node active power and voltage values had to be specified within their specified limits.

There are different coding techniques to code the solution of GA optimization problems. But the most important ones are binary and real coding methods. In many optimization problems using GA, binary coding was used. But if the number of decision variables increase, binary coding will be complicated and the length of solution vector increased. In addition, the size of DG units is real values and it is easier to represent it with real coding. That's why in this paper real coded GA was used.

The fitness function was derived from the objective function by transforming it so that the minimization problem became a maximization problem. The following transformation was used:

$$\begin{aligned} \text{Max Fitness} &= \frac{1}{C} \\ C &= w_1 C_L + w_2 C_{ENS} \end{aligned} \quad (9)$$

Where C is weighted sum of C_L and C_{ENS} .

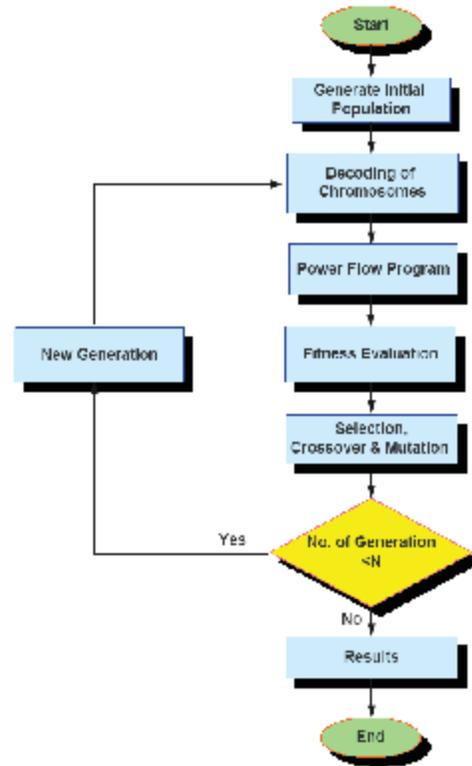


Fig. 1: Optimization process block diagram in sizing and placement of DG units

The implemented GA starts by randomly generating an initial population of possible solutions. For each solution a value of DG penetration is chosen between 0 and a maximum limit, fixed by the planner on the ground of economical and technical justifications; then, a number of DG units of different sizes is randomly chosen until the total amount of power installed reaches the DG penetration level assigned. At this point, the DG units are randomly located among the network nodes and the objective function is evaluated verifying all the technical constraints. Regarding the population size, the best results have been found assuming it equal to the number of network nodes. Once the initial population is formed, the genetic operators are repeatedly applied in order to produce the new solutions. In particular, a “roulette wheel” scheme has been applied for the selection operator and a “two cut-point crossover” has been chosen by which each vector’s element is swapped with probability 0.7. For the mutation operator, all the vector elements are mutated, with a small mutation probability of 0.05. Finally, according to the GA “steady-state” typology, the new population is formed comparing old and new solutions and choosing the best among them. The algorithm stops when the maximum number of generations is reached or when the difference between the objective function value of the best and the worst individuals becomes smaller than a specified value. The block diagram of the described MO optimization algorithm is depicted in Figure 1.

5. Results and Discussion

In order to show the capability of the proposed algorithm to solve the problem of the optimal DG allocation, a 33 bus distribution test system has been considered. A fast decoupled power flow program for radial distribution systems has been developed and used for simulation of proposed method [8].

The period taken into consideration for the planning study is 10 years long, with all nodes existing at the beginning of the period. For each node a constant power demand growth rate of 5% per year has been assumed. The inflation and interest rate has been considered 7% and 10% respectively. The cost of energy has been assumed 4.2 ¢/kWh.

The total cost of the network during the assigned study period is equal to k\$486.5 (see Table 1.) without any operating DG. Such a high generalized network cost is due to the significant growth rate of the demand, which requires the enforcement of a large number of branches. The attempt to minimize the global cost has led to a solution with many lines operate close to their maximum capacity and for this reason the cost of the energy losses counts for a significant percentage of the generalized cost of the network. The use of DG as an electric supply option can reduce both costs.

Very often the planner needs more alternatives to evaluate and sometimes he can prefer to reduce the cost of losses instead of improving service quality, depending on strategic decisions, regulatory directives regarding the electric service, and budget restrictions. As showed in the following examples, the proposed MO optimization process permits of finding out alternative configurations, characterized by different costs for each single function constituent of the global cost. In each optimization stage the MO algorithm looks for alternative solutions according to weighting coefficient of objective functions. Three cases with different weighting coefficients have been investigated. In the first case study (see Table 2. and 3.), the power losses cost has been regarded and a larger weighting coefficient has been given to it. The value assumed by the cost of the power losses in the initial network configuration is equal to k\$227.4. Three consecutive steps of iteration have been run. In the first iteration, the power losses cost and energy not supplied cost reduced in percentage of the 23% and 5.3% respectively. The total cost also reduced 13.6%. This cost reduction is obtained resorting to a DG penetration level (DG% is the ratio between the DG capacity and the power of load) of 15.98%. In the second iteration, the cost of C_L decreases from the value of k\$175.1 to the value of k\$152.5. The penetration level of DG increases from the value of the 15.98% to the value of 26.67%. Finally, in the third iteration a new optimal solution has been achieved and C_L decreases to k\$138.7 with DG penetration level of 37.34%. In the second case study, the cost of service interruptions C_{ENS} has been regarded with larger weighting coefficient. In this case the planner aims at reducing the number and the duration of service interruptions by positioning DG in suited locations. Even though many standards and almost all the distributors do not generally allow resorting to “intentional islanding” operation, in order to emphasize the effect of DG it has been hypothesized that this practice can take place. In the proposed example, the capability of optimizing the location of DG has been advantageously used to find a network arrangement able to give the customers a much more reliable service avoiding the construction of new emergency ties. The starting network configuration is equal to the previous case study, where the C_{ENS} cost has the value of k\$259.1. With the first optimization step this value is reduced to k\$198.6 (see Table 4.). A further optimization permits reducing C_{ENS} up to k\$169.3 thanks to a new allocation of DG. It is worth noticing that in this case generators are located at the end of long and heavy loaded lateral edges to serve as back up energy sources during upstream faults. Global benefits on energy not supplied and cost of not supplied energy are clearly recognizable, but benefits are much more significant for those customers that suffer for poor quality due to their position in the network.

In the third case, the weighting coefficient for both of costs has been considered the same and equal to 0.5. The results of optimization process were represented in Table 6. and 7.



Table 1: Cost of Distribution Network before DG Installation

| C_L (k\$) | C_{ENS} (k\$) | C_{TOT} (k\$) |
|-------------|-----------------|-----------------|
| 227.4 | 259.1 | 486.5 |

Table 2: Cost Progression in MO Iterative Procedure (Case1)

| $W_1=0.75, W_2=0.25$ | | | |
|----------------------|-------------|-----------------|-----------------|
| Iteration No. | C_L (k\$) | C_{ENS} (k\$) | C_{TOT} (k\$) |
| 1 | 175.1 | 245.2 | 420.3 |
| 2 | 152.5 | 230.4 | 382.9 |
| 3 | 138.7 | 221.5 | 360.2 |

Table 3: DG Location and DG % (Case 1)

| Iteration No. | DG Location (Bus No.) | DG (%) |
|---------------|-----------------------|--------|
| 1 | 8,31 | 15.98 |
| 2 | 24,25 | 26.67 |
| 3 | 8,24,31 | 37.34 |

Table 4: Cost Progression in MO Iterative Procedure (Case2)

| $W_1=0.25, W_2=0.75$ | | | |
|----------------------|-------------|-----------------|-----------------|
| Iteration No. | C_L (k\$) | C_{ENS} (k\$) | C_{TOT} (k\$) |
| 1 | 220.8 | 198.6 | 419.4 |
| 2 | 205.5 | 180.2 | 385.7 |
| 3 | 198.2 | 169.3 | 367.5 |

Table 5: DG Location and DG % (Case 2)

| Iteration No. | DG Location (Bus No.) | DG (%) |
|---------------|-----------------------|--------|
| 1 | 8,14 | 24.89 |
| 2 | 8,30,32 | 30.23 |
| 3 | 7,8,30,32 | 40.9 |

| | | |
|---|-----------|-------|
| 1 | 8,14 | 24.89 |
| 2 | 8,30,32 | 30.23 |
| 3 | 7,8,30,32 | 40.9 |

Table 6: Cost Progression in MO Iterative Procedure (Case3)

| $W_1=0.5, W_2=0.5$ | | | |
|--------------------|-------------|-----------------|-----------------|
| Iteration No. | C_L (k\$) | C_{ENS} (k\$) | C_{TOT} (k\$) |
| 1 | 208.3 | 240.7 | 449 |
| 2 | 194.9 | 230.6 | 425.5 |
| 3 | 183.9 | 213.2 | 397.1 |

Table 7: DG Location and DG % (Case 3)

| Iteration No. | DG Location (Bus No.) | DG (%) |
|---------------|-----------------------|--------|
| 1 | 8,32 | 14.22 |
| 2 | 8,25 | 24.89 |
| 3 | 8,24,25 | 33.78 |

6. Conclusion

The values of Distributed Generation are very dependent on its type, size and location as it was installed in distribution feeders. Hence, a genetic multi-objective optimization for siting and sizing of distributed generation resources in distribution systems has been performed in order to minimize the cost of power losses and energy not supplied. Simulation results on 33-bus distribution test system have been presented for three case studies. The results show 25.96%, 24.46% and 18.37% reduction on total cost for case1, case2 and case3, respectively.

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Appendix:

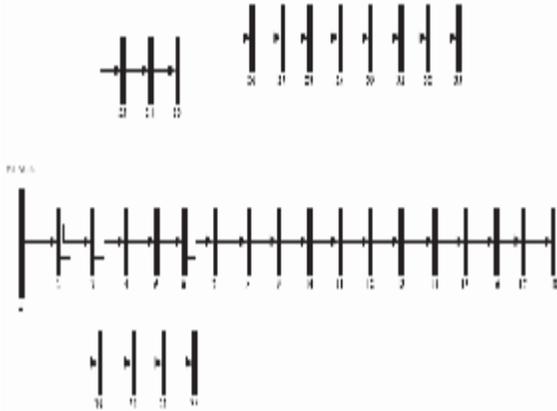


Fig. A-1: The 33-bus radial distribution test system diagram

Table 8: Line Length for 33-bus Test System

| Line No. | Length (km) | Line No. | Length (km) | Line No. | Length (km) |
|----------|-------------|----------|-------------|----------|-------------|
| 1 | 0.103 | 12 | 0.125 | 23 | 0.650 |
| 2 | 0.350 | 13 | 0.427 | 24 | 0.641 |
| 3 | 0.335 | 14 | 0.452 | 25 | 0.270 |
| 4 | 0.279 | 15 | 0.457 | 26 | 0.390 |
| 5 | 0.134 | 16 | 0.245 | 27 | 0.194 |
| 6 | 0.560 | 17 | 0.300 | 28 | 0.449 |
| 7 | 0.540 | 18 | 0.120 | 29 | 0.304 |
| 8 | 0.453 | 19 | 0.224 | 30 | 0.496 |
| 9 | 0.510 | 20 | 0.512 | 31 | 0.187 |
| 10 | 0.306 | 21 | 0.423 | 32 | 0.192 |
| 11 | 0.200 | 22 | 0.198 | - | - |

Table 9: Data used for Reliability Calculation

| Parameter | Overhead Lines |
|-----------|------------------------------|
| λ | $1.2 \text{ (year.km)}^{-1}$ |
| t_{loc} | 2 h |
| t_{rep} | 6 h |



Table 10: Load and Line Data for Test System before DG Installation

| Sending Bus | Receiving Bus | R (Ω) | X (Ω) | Load at Receiving Bus | |
|-------------|---------------|----------------|----------------|-----------------------|----------|
| | | | | P (kW) | Q (kVAr) |
| 1 | 2 | 0.0922 | 0.0477 | 100 | 60 |
| 2 | 3 | 0.4930 | 0.2511 | 90 | 40 |
| 3 | 4 | 0.3660 | 0.1864 | 120 | 80 |
| 4 | 5 | 0.3811 | 0.1941 | 60 | 30 |
| 5 | 6 | 0.8190 | 0.7070 | 60 | 20 |
| 6 | 7 | 0.1872 | 0.6188 | 200 | 100 |
| 7 | 8 | 1.7114 | 1.2351 | 200 | 100 |
| 8 | 9 | 1.0300 | 0.7400 | 60 | 20 |
| 9 | 10 | 1.0400 | 0.7400 | 60 | 20 |
| 10 | 11 | 0.1966 | 0.0650 | 45 | 30 |
| 11 | 12 | 0.3744 | 0.1238 | 60 | 35 |
| 12 | 13 | 1.4680 | 1.1550 | 60 | 35 |
| 13 | 14 | 0.5416 | 0.7129 | 120 | 80 |
| 14 | 15 | 0.5910 | 0.5260 | 60 | 10 |
| 15 | 16 | 0.7463 | 0.5450 | 60 | 20 |
| 16 | 17 | 1.2890 | 1.7210 | 60 | 20 |
| 17 | 18 | 0.7320 | 0.5740 | 90 | 40 |
| 2 | 19 | 0.1640 | 0.1565 | 90 | 40 |
| 19 | 20 | 1.5042 | 1.3554 | 90 | 40 |
| 20 | 21 | 0.4095 | 0.4784 | 90 | 40 |
| 21 | 22 | 0.7089 | 0.9373 | 90 | 40 |
| 3 | 23 | 0.4512 | 0.3083 | 90 | 50 |
| 23 | 24 | 0.8980 | 0.7091 | 520 | 200 |
| 24 | 25 | 0.6960 | 0.7011 | 320 | 200 |
| 6 | 26 | 0.2030 | 0.1034 | 60 | 25 |
| 26 | 27 | 0.2842 | 0.1447 | 60 | 25 |
| 27 | 28 | 1.0590 | 0.9337 | 60 | 20 |
| 28 | 29 | 0.8042 | 0.7006 | 120 | 70 |
| 29 | 30 | 0.5075 | 0.2585 | 200 | 600 |
| 30 | 31 | 0.9744 | 0.9630 | 250 | 70 |
| 31 | 32 | 0.3105 | 0.3619 | 210 | 100 |
| 32 | 33 | 0.3410 | 0.5302 | 60 | 40 |