Optimal Distributed Generation Placement in a Restructured Environment via a Multi-Objective Optimization Approach

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***Abstract*--The increasing use of electrical energy in nowadays modern societies and industries has brought about a sharp need for more efficient means of electricity generation. It seems rather logical to increase the electricity production proportional to the increasing rate of the demand. Distributed Generation (DG) has been recently accepted to be one of the most efficient means of electricity generation, particularly near to the load centers. The DG has been also considered in the generation expansion planning of power systems. In this paper, three main factors associated with the DGs placement procedure is scrutinized through a multi-objective optimization approach. One of the main factors considered in this paper is the network loss. The costs associated with the investment, operation, and maintenance of the DGs, together with the reliability worth and customer interruption cost are the other two criteria to be investigated in this paper. A multi-objective optimization approach is then proposed and the Non-dominated Sorting Genetic Algorithm II (NSGAII) as a convenient tool to deal with such a problem is utilized. The methodology well proves its applicability and efficiency by being applied to a real electric power distribution system.**

***Index Terms*--Multi-Objective, Optimization, Distributed Generation (DG), Distribution Network, Placement.**

I. INTRODUCTION

RECENT advances in science and technology, particularly in power industry, accompanied by the restrictions imposed environmentally, geographically, and economically have lead to major changes and challenges in power system structures. Increasing power system stability and security problems together with the ever-increasing demand growth have deteriorated the situation. On the other hand, power system restructuring necessitates the economical aspects of the power industry to be essentially contributed and customer satisfaction and power quality have become as the main objectives in the distribution companies [1]. Consequently, distribution operators do their best to increase quality of the delivered power quality using some strategies, i.e., new feeder installation, protection improvements, and moving toward smart distribution systems. Amongst, distributed generation has extensively found its place in power system planning to help the company meet both reliability cost and worth requirements. The most important and challenging work toward their usage is their placement procedure. Decision making process and the effective criteria incorporating in the final decision seem to play an important role.

In this respect, this paper proposes a comprehensive multi-objective optimization approach by which the placement procedure of DGs is scrutinized. The entire attempt is to include all the essential factors associated with the problem and hence, reach the optimized solution.

The rest of the paper is organized as follows. Section 2 deals with the DGs definition and its impacts on power system technical and economical aspects. Section 3 discusses the placement procedure to be followed in this paper. DGs effects on network losses and system reliability are thoroughly scrutinized in Section 3 as the main objectives of the proposed method to be met. Multi-objective optimization process and the Genetic Algorithm (GA) are then discussed in Section 4. Section 5 investigates the simulations done on a test electric power distribution system and well discusses the results, while the conclusion comes in Section 6.

II. DISTRIBUTED GENERATION AND ITS IMPACTS ON POWER SYSTEM OPERATION

In the literature, distributed generation refers to a variety of diminutive power generating technologies or sometimes storage systems which are frequently located at or near the load centers. Distributed generations are of different technologies. Biomass-based generators, combustion turbines, concentrating solar power and photovoltaic systems, fuel cells, wind turbines, and micro turbines are among the main means of power generation. Distributed generations are relatively small generating units, typically less than 30 MW, penetrated at or near consumer sites in electric power distribution systems to meet both the economical operation of the existing electric power distribution grid and service reliability [1]. In the era of both increasing power interruptions and rising demand for first-class power, and since cost is placed as an important attribute in power system expansion planning, the planner's essential aim is finding an

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effective strategy by which the overall cost minimization within the technical constraints is well guaranteed. Some other objectives are of great importance by having DGs incorporated in the network such as power quality, customer satisfaction indices, and environmental effects [2]-[4].

III. DG PLACEMENT PROCEDURE

Generally speaking, DGs are frequently installed near the load centers in power distribution networks. This is primarily done in accordance with the load point consumption rates [5]. In the past, the aim going to be followed by DGs installation was mainly and solely devoted to the technical indices and performances of power systems, such as voltage profile, network losses, and power system reliability while having faced with the power system restructuring trend and privatization process, economical factors have received as much importance as the technical ones. The main target is to decrease the total cost associated with the DGs investment, operation, maintenance, and so on. This kind of approach which solely considers the technical parameters and economical factors independently, may sometimes lead to a deep weakness in the performance of the system. Moreover, in many studies, the reliability worth and value of lost load are neglected as important factors in placement process and hence, eventuate in a non-optimal placement solution [4]. Therefore, it is essentially required to perform the planning process of power system expansion by considering reliability worth effects and interruption costs associated with all kinds of loads as a main and indisputable criterion to have the goal of placement accomplished.

Having formulated all the effective aforementioned technical and economical parameters interconnected with the procedure, the robust method referred to as Non-dominated Sorting Genetic Algorithm II (NSGAII) is well utilized to deal with the problem. This method can well evaluate all the parameters which may behave such contradictorily that the decision is not going to be easily and accurately made.

Although distributed generations can have a considerable effect of 53% decrease in electric power distribution system losses, due to the different choices of placement [6], they may considerably aggravate the total loss of distribution network. To have a comprehensive knowledge of the network, the optimal placement should be performed by having the network configuration, candidate locations, and capacity and type of available DGs into consideration. The recent research done on the network configuration and DGs indicates that compensating 10 to 20 percent of the feeder load capacity via distributed generations can have a significant decrease in the network losses [7]. It is of great importance to note that many placement procedures and algorithms have been proposed in accordance with the sole power system losses. So, it is assumed to be one of the technical targets going to be covered by this paper.

The loss amount of an electric power distribution system is mainly dependent to the line resistance and the passing current magnitude of the lines. As the line resistance remains constant, the network loss amount solely varies with the change in the current passing through the line which depends to the network topology and DG locations in the system, and finally the loads and their behaviors. To investigate the network losses, power flow study can be performed.

$$P_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \cos(\delta_i - \delta_j - \gamma_{ij}) \tag{1}$$

$$Q_i = V_i \sum_{j=1}^{n} Y_{ij} V_j \sin(\delta_i - \delta_j - \gamma_{ij}) \tag{2}$$

where, P_i and Q_i are respectively active and reactive power of the *i*-th bus, V is the bus voltage, Y_{ij} is the system admittance matrix element, δ is the bus voltage angle, and γ is the angle of system admittance matrix element. Generally, by loss decrease due to DGs incorporation in the network, we mean the real power which is introduced as in (3).

$$P_{loss} = \sum_{i=1}^{n} P_{G_i} - \sum_{i=1}^{n} P_{D_i} \tag{3}$$

where, P_G is the bus generated power and P_D represents the total load connected to that load point and P_{loss} stands for the real power losses. Also, P_{loss} and its incremental values are expressed as in (4) and (5), respectively.

$$P_{loss} = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j + \sum_{i=1}^{n} P_i B_{i0} + B_{00} \tag{4}$$

$$\frac{\delta P_{loss}}{\delta P_i} = 2B_{ij} P_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} B_{ij} P_i + B_{i0} \tag{5}$$

The above equations obviously clarify the fact that the variation in load capacities can lead to the total network losses being effectively decreased. To have the DGs optimally placed, the load flow is performed and the candidates associated with the lowest amount of system losses will be obtained [8]. Consequently, the candidates are prioritized according to the network losses and the expansion procedure via the addition of new units is continued till the losses remain constant or stop increasing.

As in many distribution systems, DGs penetration as the supporting generation for the loads of high interruption costs, e.g., commercial and industrial, the required level of power reliability can be easily met and even increased [9]. DGs are consequently able to be considered as the compensations for the demand growth in different power systems and accordingly their penetration in power systems lead to lower energy not served and higher reliability level.

IV. MULTI-OBJECTIVE OPTIMIZATION AND GENETIC ALGORITHM

Simultaneous optimization of several objective functions is of great interest in many practical problems. Generally speaking, some of these objectives may behave in such a conflicting manner which make the decision making process more labor some. Moreover, this leads to some more sets of optimal solutions instead of a single optimal solution. These optimal solutions are usually referred to as Pareto-optimal solutions.

A general multi objective optimization problem is regularly associated with a set of equality and inequality constraints that can be formulated as in (6):

$$\min[f_i(x)] \qquad i = 1,2,\dots,m \tag{6}$$

Having the bellow constraints into consideration:

$$g_j(x) = 0 \qquad j = 1,2,\dots,p \tag{7}$$

$$h_k(x) \le 0 \qquad k = 1,2,\dots,q \tag{8}$$

In which, m is the number of objective functions, x is the random variable vector, p represents the number of equality constraints, and q is the number of inequality constraints.

Non dominated solutions of multi objective solutions which are at the aim points of the decision maker can be obtained through a range of mathematical or evolutionary algorithms proposed. Amongst, is GA whose capability in handling almost all kinds of nonlinear, no convex, and mixed integer optimization problems are well appreciated [10]. As its procedure, it starts with a randomly-selected initial population as its initial solution within the feasible area. Consequently, fitness assignment and accordingly ranking is done for each solution and the final optimal solution is then reached through some operations such as crossover, mutation, or reproduction. The distinguished usefulness of GA in coping with the multi-objective non-convex optimization problems in comparison with the other approaches calls for a method of indisputable robustness to thoroughly solve this kinds of optimization problems. The method is called as "Elitist Non dominated Sorting Genetic Algorithm" (NSGA II) [11]. The main idea here is the procedure of the selection following the ranking process. The ranking process deals with the identification of non dominated individuals in the population, constitution of the first non dominated front of a large dummy fitness value to make the individuals, and assigning the same fitness value to all the individuals. This well helps the non dominated solutions in the population to be determined at each generation. The non dominated fronts are formed by them and the usual process of selection, crossover, and mutation are performed [12]. The next step is to apply a sharing method to maintain the population diversity in the population. The first front individuals are then ignored and the loop is closed and repeatedly returns to identify the second non dominated front.

The process continues till the non dominated fronts are all classified in the whole population. References [12] and [13] elaborate on concepts of the method and its applications.

Having emphasized the non dominated points, NSGA favors the schematic representation of the Pareto-optimum regions. Non dominance definition is applied over the population to accomplish the goal of ranking procedure. Also, exploiting a niche formation technique leads to a non dominated uniform distribution to be guaranteed. Having determined the non dominated set, it is time to find a realistic and favorable solution which is able to compromise the different objectives [14].

Among all the methods of finding the best reliable solution, the fuzzy approach is conducted due to its simplicity and similarity to the human beings' interpretation. Membership functions are framed to define the fuzzy sets. In fuzzy satisfying method, and for each objective, a rigorously monotonically declining and continuous membership function is assigned which is 1 at the minimum and 0 at the maximum of the objective function [15]. To put it clear, the value of the membership function deals with the fact that to what extent a solution is fulfilling the objective function.

Defining the membership function for each objective function, and in accordance with the favorable surface previously defined by the decision maker, (μ_{di}), the final solution is reached solving the bellow optimization problem.

$$\min_{X \in Solutionset} \sum_{i=1}^{3} \left|\mu_{di} - \mu_{f_i}(X)\right|^n \qquad n \in [1,\infty) \tag{9}$$

As can be easily traced, this relation can minimize the membership function deviation of X in comparison with the favorable surface. This nuance in larger values of n would lead to a less sensitivity to the desirable surface.

V. SIMULATION RESULTS

According to what has been investigated in the face of DG placement procedure and what has just been discussed in the previous sections, three main objectives are thoroughly going to be investigated. Since the main expenditures and costs associated with DGs investment, operation, and maintenance are of great importance in the utility perspective, these fixed and variable costs of DGs are aimed to be as minimal as possible and to meet the maximum profitability for the distribution companies. The variation in network losses in the presence of DGs is going to be scrutinized, and their considerable influences on the reliability level of electric power distribution systems is of the other interests in this paper.

The assumption made in this paper is that all the available DGs are of 2.5 MW capacities. The investment cost associated with each DG is assumed to be 1373570 $ [16]. The variable costs consist of maintenance and operation costs which are given by (10) and (11), respectively [7], [8].

$$Main - Cost = 87{,}731 \ \$ / yr \tag{10}$$

$$Opr - Cost = 0.062P^2 + 15P \ \$ / hr \tag{11}$$

where, *Main-Cost* is representative of DGs annual maintenance costs and *Opr-Cost* deals with the operation cost function to produce P megawatt power via the distributed generation.

Since we are going to minimize the total fixed and variable costs of a utility in the first step, it is required to change all the costs into the annual costs to be comparable. In this way, the planning study period is assumed to be 10 years and the interest rate is considered as 10%. So, the annual investment cost can be obtained through (12):

$$Ann - InvCost = InvCost \times (1+i)^n \left[\frac{i}{(1+i)^n - 1}\right] \tag{12}$$

In which n represents the planning period and i is the interest rate. Having considered the load curves for network different load buses and approximating them as peace wise linear segments (into 12 parts, each part represents the peak load value for each month of the year), the operation studies for each load level will be done, and eventually the annual operation costs can be reached. The procedure is finalized as shown in (13):

$$\underline{f_1} = \min \sum_{i=1}^{n} \begin{pmatrix} Main-Cost_i + Annual-InvCost_i \\ +Annual-OprCost_i \end{pmatrix} \quad (13)$$

In which n represents the number of DGs. One of the main goals, where distribution utilities are going toward, is to draw the generations near to the load points and consequently let the network losses to be minimized.

$$P_{loss} = \sum_{i=1}^{n} P_{G_i} - \sum_{i=1}^{n} P_{D_i} \quad (14)$$

Hence, loss minimization is of great importance and is among the crucial objectives in this paper.

$$\underline{f_2} = \min P_{loss} \quad (15)$$

The introduced algorithm is studied on a test feeder which is illustrated in Fig. 1. The test feeder is constructed of 27 buses and 24 load points. The lines and loads data are given in Tables I and II, respectively. The network reliability data and the customers' interruption data are supplied in Tables III and IV, respectively.

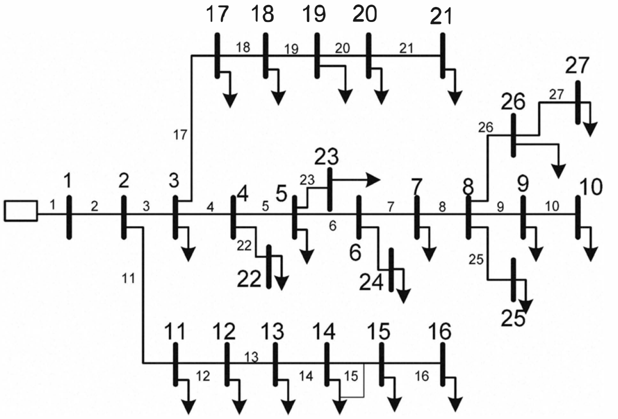

Fig. 1. The test system.

To accomplish the placement study of DGs, as the first step, 7 candidate points, which seem to be of critical role in the test system, are selected. These candidates are found via sensitivity analysis of different load buses in accordance with the variations in the network losses and voltage profile. The studies are done using the MATPOWER in the MATLAB environment. The candidate points are illustrated in Fig. 2.

The placement procedure is simulated with a population size of 200 and 100 iterations of NSGAII. The results of simulations on the test system are shown in Fig. 3 and Fig. 4.

TABLE I
NETWORK LINE DATA

R(Ω/Km)	X(Ω/Km)
0.1233	0.4127

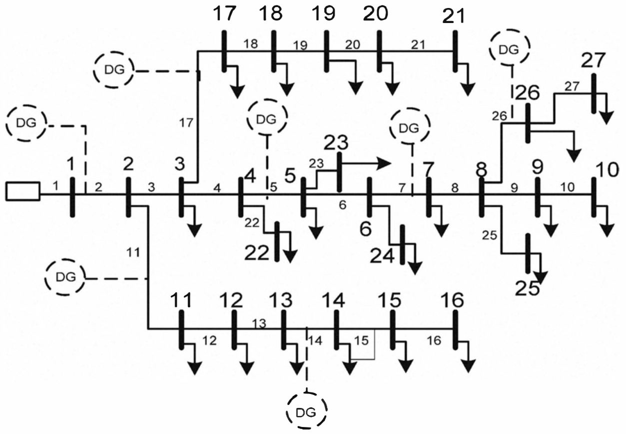

Fig. 2. Candidate locations for DGs.

TABLE II
LINES AND LOADS DATA

Line No	From	To	Line Length	Load (KVA)	Power Factor
1	0	1	-	0	-
2	1	2	2.5	0	-
3	2	3	4.7354	1350	0.8
4	3	4	2.5712	0	-
5	4	5	7.3123	1300	0.95
6	5	6	3.3381	0	-
7	6	7	4.5219	1250	0.9
8	7	8	10.5507	0	-
9	8	9	11.7567	1000	0.9
10	9	10	4.7354	1313	0.8
11	2	11	2.5712	1100	0.95
12	11	12	7.3123	400	0.75
13	12	13	3.3381	1350	0.85
14	13	14	4.5219	1225	0.82
15	14	15	10.5507	1125	0.93
16	15	16	11.7567	1300	0.75
17	3	17	4.7354	300	0.9
18	17	18	2.5712	1150	0.8
19	18	19	7.3123	350	0.85
20	19	20	3.3381	400	0.8
21	20	21	4.5219	1100	0.8
22	4	22	10.5507	125	0.93
23	5	23	11.7567	965	0.89
24	6	24	4.7354	982	0.88
25	8	25	2.5712	1300	0.9
26	8	26	7.3123	875	0.75
27	26	27	3.3381	200	0.9

TABLE III
NETWORK RELIABILITY DATA

r_{lines}(hrs)	λ_{lines}(f/yr/km)	$r_{breaker}$(hrs)	$\lambda_{breaker}$(f/yr/km)
10	0.025	4	0.006

TABLE IV
CUSTOMER INTERRUPTION DATA

	Load Types			
	Outage Duration	Residen.	Industr.	Commer.
Daily IEAR ($/kW)	$0 < h < 4$	49.5	1162.5	3485
	$4 < h < 8$	174.75	2215	6950
	$8 < h < 12$	312.25	2872.5	8980
	$12 < h < 16$	414.5	3460	10400
	$16 < h < 20$	488.75	4010	11465
	$20 < h < 24$	514.25	4530	12190

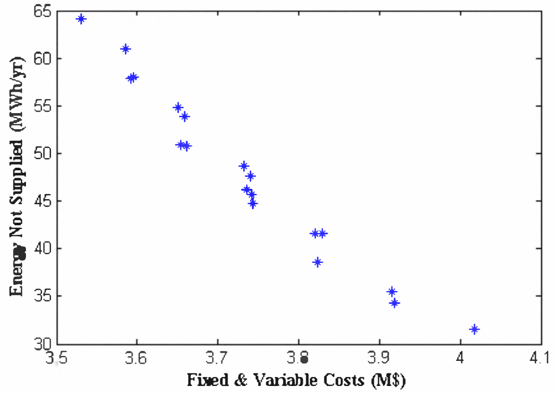

Fig. 3. Trade-off between the cost and reliability.

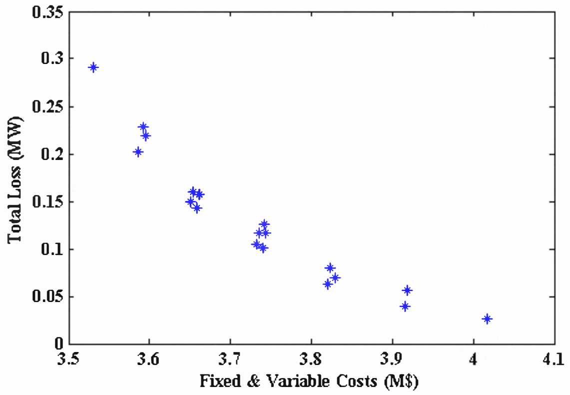

Fig. 4. Trade-off between the cost and loss.

The results in Fig. 3 show that the energy not served variations of the optimal solutions from 30 to 64 MWh/yr lead to the required investment costs of DGs to change in the range of 3.52 to 4.08 million dollars. For this range of variations in the reliability level and investment costs, and according to Fig. 4, the total network losses change from 0.02 MW to 0.29 MW. Hence, it can be concluded that different placement plans are prepared for the decision maker. Also, it is construed that the results are so robust that any decision with either the cost constraints or the other constraints of the objective functions would be feasible. According to the simulation outcome, Table V represents the results associated with the final and optimal placement scheme of DGs in the test system via fuzzy satisfaction method. As can be easily traced, this table well demonstrates the final optimal scheme variations in respect to the variations in the importance of the objective functions. In other words, this table performs a sensitivity analysis on the importance levels of the objectives in the current optimization problem.

TABLE V
FINDING THE OPTIMAL SCHEME THROUGH EXERTING THE DECISION VARIABLES

Satisfactory Level			Bus No - Line No						
μ_{d1}	μ_{d2}	μ_{d3}	2-3	2-11	13-14	3-17	4-5	4-7	8-26
0.9	0.9	0.55	0	0	1	1	0	1	0
0.6	0.9	0.55	0	1	0	1	1	1	0
0.9	0.55	0.55	0	1	0	0	0	1	0
0.9	0.8	0.95	0	0	1	1	1	1	0

VI. CONCLUSION

In this paper, the planning procedure of distributed generations in restructured electric power distribution systems was investigated. The main aim of the paper was to find the optimal location of DGs based on both technical and economical effective parameters. The procedure was done through a multi objective optimization problem and via a robust method of NSGAII. In this respect, and to have the new challenges of power systems in restructured environments into consideration, three main factors of total costs, total losses, and system reliability are conducted in the proposed algorithm. To have the proposed method under evaluation, the algorithm was applied to a distribution test system. The results demonstrated the proposed algorithm efficiency in the case of DG placement. Moreover, the results well depicted the compromising of the proposed objectives.

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