Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Optimal Sizing and Siting of Distributed Generation in Radial Distribution Network: Comparison of Unidirectional and Bidirectional Power Flow scenario

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Abstract**-- The introduction of Distributed Generation (DG) into distribution networks has a significant effect on losses. This effect can be detrimental or beneficial depending on where DG units are allocated and which sizes they have. This paper deals with optimal siting and sizing of DG units for minimizing the total power losses in a radial distribution network under bidirectional and unidirectional power flow scenario. An Enhanced Genetic Algorithm (EGA) is used for effectively explore the problem search space. Moreover, a simple and straightforward penalty function is presented in which the normalization of the violations is not needed. The method is implemented and tested on a typical 16-bus distribution network. Simulation results indicate that unidirectional flow constraint may restricts the ability of DG units to minimizing the network losses.**

Keywords**--Distributed Generation, Genetic Algorithm, Siting, Sizing.**

I. INTRODUCTION

IN general, Distribution Companies (DisCos) have an economic incentive to reduce losses in their networks. Usually, this incentive is the cost difference between real and standard losses, that is, if real losses are higher than standard ones, the DisCos are economically penalized, or, if the opposite happens, they obtain a profit [1]. Previously, losses could only be ameliorated by uprating overhead lines or other equipment. However, at present, DG is known as a tool which can affect the power losses in the wide range. These effects can be detrimental or beneficial depending on where DG units are allocated and which sizes they have. The proper placement of DG units will reduce losses and will free available capacity for transmission of power. Moreover, cost savings can be expected by deferring distribution system upgrading. While, improper placement of DG units will increase losses significantly [2-3]. Besides, finding the optimal size for DG may impede the over investment for it.

According to literature, two groups of studies are performed about the power losses of distribution network considering DG. In the first group, the optimal placement of DG is not taken into consideration; however, the aim is the study of the effects of DG on the power losses. Authors of [4] derive a parametric formula to calculate the amount of loss reduction of a distribution feeder with a lumped load due to adding DG. The work of [4] is developed for a distribution network which contains both distributed and lump load by the authors of [5].

Authors of [6] examined the loss reduction problem in a real network by using DG and considering two scenarios, open loop and close loop network. Authors of [7], by focusing on the electrical losses, investigated what effect the DG has on the technical performance of a reticulation network.

In the second group of relevant publications, the aim is the optimal allocation of DG for loss minimization. In [8], a Lagrangian based approach is used to determine optimal locations for placing DG, considering both economic and stability limits. Recently, evolutionary optimization techniques are being widely taken into consideration to combinatorial optimization problems in power systems. Authors in [2] employ Particle Swarm Optimization (PSO) technique to minimize the real losses in a typical distribution network using DGs. Moreover they considered two cases in which DG buses can be PV or PQ model. In [9], a GA based DG allocation method is presented where the power losses in an existing network is minimized. The voltage profile and short circuit level are imposed during the optimization process. In [10] the optimization process is solved by the combination of Genetic Algorithms (GA) techniques with methods to evaluate DG impacts in system reliability, losses and voltage profile. Their authors aim to optimize the siting and sizing of DG in order to minimize the losses of distribution network and to guarantee acceptable reliability level and voltage profile.

This work was supported in part by the Electrical Engineering Department of K. N. Toosi University of Technology, Tehran, 16315-1355, Iran.

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In brief, the authors in the aforementioned publications try to take some technical aspects of the operation of the network into account. However, they are only considered unidirectional power flow scenario in their studies, while, DG may lead to bidirectional power flow in the distribution network. Moreover, some technical and legislative constraints were ignored in their studies.

The aim of this paper is to find the optimal site and size of DG units in a radial distribution network with spot loads for loss minimization. Two possible scenarios are considered, unidirectional and bidirectional power flow. A full attention is paid to involve constraints in the solution methodology. To solve the problem, an enhanced GA is used that effectively explore the problem search space. A simple and straightforward penalizing strategy is used to handle the infeasible solution.

II. PROBLEM FORMULATION

In open markets the network owners and power producers are usually different companies with different objectives and responsibilities. In one hand, the network owner (DisCo) is responsible for preserving an acceptable level of reliability and power quality in the system. Besides, the cost of network losses and unsupplied energy are imposed to the DisCo. However, the DisCo usually could not invest in DG (in some market structures or due to budget limitation) to improve its both technically and financially operation and/or overcome supply insufficiency in the system. Thus, the role of DisCo may be restricted to finding the locations and the sizes of DGs that are more beneficial for network operation and then incentivize the investors to invest at those locations. On the other hand, the investors are willing to invest at locations that can be more cost-effective for installing and operation of DGs. However, it hard to be justified, if they don't follow the locations that DisCo introduces. Even DisCo may preclude the investors to connect their DGs to the network, if the reliability and power quality of the network are degraded. Nonetheless, the locations that DisCo introduces may yield to low level of profitability, that is, there is a lack of incentive to invest at those locations.

How can DisCo incentivize the investor to accompany with DisCo is an open question and is out of the scope of this paper. However, some researchers propose that investors would receive incentives in the form of capital deferral credit from the DisCo for replacing a distribution facility requirement [11]. In addition, the DisCo can negotiate with the investors to find out theirs economic perspective and then incentivizes them based on the amount of benefit that may technically and financially be received.

Irrespective of the type of the incentive, in this paper we assume that the investors invest at locations that DisCo suggests. Also, we assume that power producers commit the operation of their DG units to DisCo and, in addition, they gain based on hourly nodal prices at the point of connection to the transmission system and their generation. Thus, without investment, the DisCo can benefit technically and financially from DG units based on optimal dispatch of DG units. For example, the DisCo can technically improves the voltage profile through the feeders, reduces the amount of power losses in the network and financially saves the cost of this reduction, etc.

In this context, regarding the DisCo's technical perspective, this paper addresses the optimal sizing and siting of DGs. Some literatures deal with this problem deploying different objectives. This paper focuses only on the losses minimization. The mathematical formulation for DG siting and sizing problem is done from the perspective of DisCo. This problem is to be handled as a constrained optimization problem, where both the objective function and the constraints are nonlinear [12]. The objective function to be minimized is the radial distribution system real power losses, while the nonlinear constraints include equality, inequality and boundary constraints.

A. Objective Function

The problem addressed here is DG expansion planning with the objective of minimizing distribution feeder losses at the pre determined peak load condition of planning horizon. The proposed objective function (1) aims to minimize the amount of real losses, not the momentary value of it:

$$f = real\left(\sum_{i=1}^{M}\sum_{j=1}^{M}\left\{\frac{(|V_i|-|V_j|)^2}{|Z_{ij}|}\right\}\right) \tag{1}$$

Where, M is the number of buses in the network, V_i is the voltage of bus i and Z_{ij} is the impedance of the branch between bus i and bus j.

The objective function (1) is minimized subject to various constraints, including technical operational constraints on both network and DGs as well as national (legislative) constraints. These constraints are discussed as follows.

B. Constraints

Several constraints can be considered in a DG expansion planning, including: network and DG technical and operational constraints (including reliability aspects), national constraints (legislation and environmental constraints), as well as economical constraints (constraints on investment resources and economical efficiency). Some researchers were focused only on a few constraints, usually technical [11]. However, in the real world applications all constraints should be considered because they reduce the feasible space wherein solutions to the problem can be found.

Network technical constraints:

1). Total load-supply balancing constraint: The algebraic sum of all produced power (incoming and outgoing) over the DisCo feeders (taking into account feeder losses) and the power generated from DG should be equal to the total demand at the all buses minus the unserved power.

$$P_S + \sum_{i=1}^{NDG} P_{DG_i} = \sum_{j=1}^{M} P_{d_j} + P_{loss} - \sum_{j=1}^{M} P_{us_j} \tag{2}$$

Where P_S is the power served by upstream network, P_{DG_i} is the active power generated by DG number i, P_{d_j} is the demand at bus j, P_{loss} is the network losses, P_{us_j} is the un-served power at bus j and NDG is the number of DG units. Generally, in the expansion planning problems, the load serving is considered as a hard constraint. Consequently, the expansion is done on the assumption of $\sum P_{us} = 0$, be addressed in security-based planning. The similar constrain is valid on reactive power.

2). Distribution Substation Capacity Constraint: The total apparent power delivered by the substation over the outgoing distribution feeders from that bus must be within the substation capacity limit.

$$\sum_{j=1}^{N_f} S_j \le S_S^{\max} \tag{3}$$

Where S_j, is the apparent power flow of feeder j, $S_S^{\max}$ is the maximum capacity of the substation and N_f is the number of outgoing feeders from the substation.

3). Distribution Feeder Capacity Constraint: Power flow through any distribution feeder must comply with the thermal capacity limit of the feeder.

$$P_{ij} \le P_{ij}^{\max} \quad \forall \text{i, j} \quad \text{for each branch} \tag{4}$$

Where P_{ij} and $P_{ij}^{\max}$ are the power flow and maximum power flow of the branch between bus i and bus j, respectively.

4) Voltage Limits Constraints: The voltages should be preserved in permissible bands, provided by the DisCo.

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{5}$$

Where $V_i^{\min}$ and $V_i^{\max}$ are the lower and upper voltage magnitude limits of bus i, respectively.

5) Short Circuit Level Constraints: Connecting DGs into the network causes some changes in Thevenin impedances in viewpoint of the network buses. Hence, in short circuit condition, it may violate max short circuit level capacities of some buses. Actually, DGs particularly those using synchronous generators can increase the amount of fault current flowing through utility breakers, reclosers, and fuses.

$$S_{SC_i} \le S_{SC_i}^{\max} \tag{6}$$

Where S_{SC_i} and $S_{SC_i}^{\max}$ are the calculated short circuit at bus i and its maximum value, respectively.

6) Back Flow (Unidirectional) Constraints: At present, DisCos may preclude bidirectional power flows in their network branches due to the protection difficulties.

DG technical constraints:

7) Constraints on DG Operation: The apparent power generated from DG must be less than the DG capacity.

$$S_{DG_i} \le S_{DG_i}^{CAP} \tag{7}$$

Where, S_{DG_i} is the generated apparent power of DG i and $S_{DG_i}^{CAP}$ is the capacity of DG i. This constraint could be subdivided into detailed small constraints based on supply capability curve for synchronous type generators. However, such accuracy is unnecessary. Besides, each generator has to operate within the range of acceptable power factors as set by the DSO (e.g. 0.85-1 lagging).

$$DG_i^{PF} \ge \min DG^{PF} \tag{8}$$

Where, DG_i^{PF} is the power factor of DG i at operating point and DG^{PF} is the minimum power factor of DGs that is specified by DSO.

National (legislative) constraint:

8) Constraints on DG Penetration: DG penetration (DGP) is defined as the ratio of the amount of DG energy injected into the network to the feeder capacity. Now a day, some utilities apply this constraint on exploitation of DGs. The amount of this constraint can vary in every country and gradually be removed.

$$\sum_{i=1}^{NDG} P_{DG_i} \le DG_{penetration} \times P_d \tag{9}$$

Where $DG_{penetration}$ is the allowed penetration level of DGs and P_d is the sum of load demands.

9) Constraints on the amount of Pollution: in case of using renewable energy based generators, like winds and solar based generators, it will be produced low environmental pollution emission. However, the amount of pollution emission in fuel based DGs depend on the DG technology and are proportional to the amount of fuel consumption, that varies at every loading condition. This constraint is ignored here.

Economical constraint:

10) Constraint on Investment Resources: The DisCo often has to carry out investment planning decision making while considering its financial constraints. This constraint imposes a limit on how much capacity the DisCo can invest in.

$$\sum_{i=1}^{NDG} (C_{f_i} \times P_{DG_i}^{CAP}) \le BUDGETLIMIT \tag{10}$$

Where C_{f_i} is the investment cost that is considered for DG i. This constraint also will be ignored here.

III. SOLUTION METHODOLOGY

A. Optimization Technique

In this paper, a GA optimization technique has been used for finding the solutions of the optimization algorithm. The main feature of GA is it does not require any prior knowledge, space limitations, or special properties of the function to be optimized, such as smoothness, convexity, or existence of derivatives. It only requires the evaluation of the so-called *fitness function (FF)* to assign a quality value to every solution produced. The second feature is it's a population based evolutionary optimization technique, which allows the GA to explore several areas of the search space simultaneously, reducing the probability of finding local optima.

Each population members, individuals, carries phonotype (genotype in binary coding) control parameters to be optimized. The real value of a control parameter is called an *allele* [13]. In phonotype coding, the genes (containing alleles) are concatenated consecutively to form an individual (chromosome).

In this paper, 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 number, size and location of DG units. For this reason each candidate solution can be constructed by using a vector, whose size is depend on the number of DG units to be found, in which each segments, including 3 allele (phonotype) for each DG units, contains the information on the location and both active and reactive production of a DG unit, as shown in Fig. 1. Integer and real coding is exploited for genes, indicating DG sites (locations) and DG sizes, respectively.

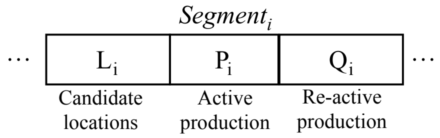

Fig. 1. Control variables for each DG unit.

To determine the DG sizes additional mechanisms are used. The sizing of each DG unit is base on its apparent power production regarding its operating limits. Therefore, a prefixed number of generator sizes (candidate DGs) have been assumed and a DG size is selected from a list of candidate based on each active and reactive power production.

Assuming an initial random population produced and evaluated, genetic evolution takes place by means of three basic genetic operators:

1) Parent selection
2) Crossover
3) Mutation

Until now, many *selection*, *crossover* and *mutation* schemes, have been proposed in some literature. In brief, Irrespective of their deferent types, *selection* is the procedure whereby two chromosomes are selected randomly and base on their fitness values to form the parent. The higher the fitness value, the higher the chance to select. *Crossover* is the operator which is responsible for the structure recombination (information exchange between mating chromosomes). While it is the main genetic operator exploiting the information included in the current generation, it does not produce new information. On the other hand, *Mutation* is the operator responsible for the injection of new information. In a binary string it flips random selected bits from 0 to 1 and vise versa and gives new characteristics that do not exist in the parent population [13]. However, it could not be used in integer and real coding. To solve this difficulty we use normal mutation, in which new information generated by a normal function is replaced (is embedded into the chromosome), instead of the random selected allele.

Beside these well-known genetic operators, a set of advanced, powerful and problem-specific genetic operators including : Gene Swap Operator (GSO), Gene Cross-Swap Operator (GCSO), Gene Copy Operator (GCO), Gene Inverse Operator (GIO) and Gene Max-Min Operator (GMMO), firstly introduced in [14], are used to effectively explore the problem search space. Some modifications were applied to conform GCO and GIO with our non-binary coding as well as with the specification of DG expansion problem. The GCO operator randomly selects one gene (allele) in a chromosome and with the equal probability copies its value into the same control type. In this work it restricted to acts only on active and reactive genes not on the genes indicating DG's locations, due to the redundancy of DGs on a bus (problem specification). The GIO operator in [14], with binary coding, randomly selects one gene in a chromosome and inverse its bit-values from 0 to 1 and vise versa. However if it generates an unacceptable (not infeasible) solution which is inconsistent with true discernment, the problem will be failed. For example, assume a 10 bus network which needs at least 4 bits to be distinguished. Now, if GIO operator applied on bus number 1, 2, 3, 4, and 5, it generates bus numbers 15, 14, 13, 12 and 11, respectively, where they do not exist. To remove this difficulty, we modify the GIO operator to generate a semi-complement value of any randomly selected gene according to its max range, and call it Gene Semi-Complement Operator (GSCO). If the GSCO operator will be applied on the previous example, it generates bus numbers 10, 9, 8, 7, and 6. For other control parameters it is possible to use both GIO and GSCO operator, while we use the GSCO. To handle the phonotype genes by GIO, at first an equivalent binary string for any selected allele is created. Next, all its bit-values are inversed. Then, the real value of the inversed binary string is calculated. The main feature of both GIO and GSCO is to retain the diversity of the population. The flowchart is like that's use in [14].

B. Penalty Function

In order to applying GA to constrained optimization problems, constraint handling strategies are needed to be employed [16]. These strategies are: 1) Rejecting strategy (ignoring infeasible solutions), 2) Repairing strategies, 3) Preserving feasibility methods, and 4) Penalizing strategy. Merit and demerit of these methods are found in [15], [16].

In strategies (1) and (3), only the feasible space (region) are explored and infeasible solutions are rejected or not at all could be generate. Strategies (2) allow the individuals (chromosomes) to go out of the feasible space, but by applying special operators or actions to infeasible solutions they will be came back into the feasible space. All these three methods only explore the feasible space. But it is believed that if the search space be include feasible and infeasible spaces, we may have better final solution (solutions in multi objective cases), specially for the highly constrained optimization problems, such as expansion planning problems in all sectors of the power system particularly in presence of power market.

The penalizing strategies are the methods that consider infeasible space in their exploring. These methods add a second function, $\lambda.p(\bar{x},t)$, so called penalty function (term), to the original objective function $f(\bar{x})$ to penalize the infeasible solutions. Different penalty functions can be founded in some literatures. The most popular penalty function is mainly consisted of weighted sum of all the amount of normalized constraint violations. However, in this paper a simple and straightforward method for penalty function calculation, which releases the normalization process of each violation, is used.

The idea is that the penalty function is calculated based on the number of violations for each solution not based on the amount of them. Consequently, at first, the number of violations of any constraint is counted, (eg. for a solution it leads to 3 branch current violations, 2 bus voltage violations and substation capacity limit violation). Secondly, they are added up together considering a weighted vector, which defines the relative importance of violations in viewpoint of the DisCo, in which the weighted vector is calculated based on the analytical hierarchy process (AHP).

Besides, constraints can be hard or soft [16]. A constraint is considered hard if it must be satisfied in order to make a solution acceptable. In this paper such hard constraint is load-supply balance, hard equality constraint; the others could be unidirectional flow constraint, hard inequality constraint, if it is important, and rigid emergency capacity limits. A soft constraint, on the other hand, can be relax to some extent in order to accept a solution, if no solution could be founded to satisfy all constraint. e.g. normal capacity limit violation of some feeders in peak hours, where due to engineering design margins, the system can operate successfully in the range between normal and emergency limits.

We reject the infeasible solutions that violate the hard limits (rejecting strategy) and penalize the other infeasible solutions.

IV. RESULTS AND DISCUSSION

A. Primary Distribution System under Study

A typical distribution system under study is shown in Fig. 2. It comprises of a 63/12.4 KV, 50 MVA substation serving loads at 16 nodes during normal operation. The branch's impedances are also shown in TABLE I. Each branch is specified by the right side's end bus number. The DisCo plans to minimize the losses at predetermined peak load condition, 57.4MW+j34.4MVAr, shown for each node in TABLE I employing DG capacities.

B. DG Options

A set of candidate DGs, from 0 MVA (no DG) to 40 MVA, is predetermined as it is shown in TABLE I. This candidate list, specially the greatest candidate DG, allows the candidate solution to move towards the feasible space boundaries at every proper location (node), if the distribution network demands more generation from any DG units to minimize the electric losses. The DisCo forced each DG to operate in power factor between 0.85-1 lagged. Choosing the DG from the candidate list is based on its active and reactive power operating point in the chromosome (as mentioned in section II.A).

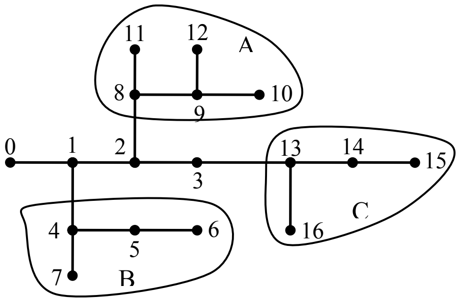

Fig. 2. Typical distribution system under study and its three load sections.

C. Scenarios under Study

Two possible scenarios, unidirectional and bidirectional power flow are investigated in this section. Besides, some DGPLs are considered in each scenario.

As mentioned earlier, the size and location of DG units can beneficially or detrimentally affect on the amount of feeder losses. Then a good sizing and siting tool is needed to achieve the beneficial effects of DG units on losses reduction; hence, in this paper an enhanced GA with penalty strategy is used to solve the problem. For all scenarios the following assumptions are used.

TABLE I
BRANCH'S IMPEDANCES, PREDETERMINED PEAK LOAD AND DG UNIT'S CANDIDATE LIST.

Branch physical characteristics			Forecasted peak load			DG Candidate List	
Branch #	R (Ohm)	X (Ohm)	Node #	Pd (MW)	Qd (MVAr)	DG Sizes (MVA)	X (pu.)
1	—	—	1	0	0	0	0.8
2	0	0	2	0	0	0.5	0.8
3	0	0	3	0	0	1.5	0.8
4	.075	0.1	4	4	3	2	0.8
5	0.09	0.18	5	4	1.6	3	0.8
6	0.04	0.04	6	3	2.4	4	0.8
7	0.08	0.11	7	6	3	5	0.8
8	0.11	0.11	8	8	5.4	7	0.8
9	0.08	0.11	9	10	6	10	0.8
10	0.08	0.11	10	9	4	12	0.8
11	0.11	0.11	11	2	1.8	15	0.8
12	0.11	0.11	12	1.2	0.2	20	0.8
13	0.11	0.11	13	2	1.8	25	0.8
14	0.08	0.11	14	2	1.8	30	0.8
15	0.04	0.04	15	4.2	2	35	0.8
16	0.09	0.12	16	2	1.4	40	0.8

Population size: 150
Pcross: 0.6 (Probability of crossover operator)
Pmut: 0.5 (Probability of mutation operator)

Pgso: 0.2 (Probability of Gene Swap Operator)
Pgcso: 0.2
Pgco: 0.05
Pgsco: 0.3
Pgmmo: 0.05

Besides, the number of exploited DG units also influences on the extracted results. This will be taken into account by using 2, 3 and 4 DG unit options in the network.

1) Unidirectional Power Flow Scenario: Total loads at peak hours are 67 MVA, which is greater than the substation capacity limits, 50 MVA. In case ignoring this limitation, the substation should be served 69.458 MVA, considering network losses. Active and reactive power losses in this base case are 1.751 MW and 2.01 MVAr, respectively. Due to substation capacity limitation, the DisCo has decided to exploit DG units to serve the peak load condition with the objective of minimizing the imposed active power losses at peak hours.

At present, legislatives and some technical constraints (including power quality, protections and etc. constraints) restrict the high penetration of DG units in the network. While, other incentives like deferment of network upgrading costs, peak shaving capability, voltage support as well as Kyoto protocol for the renewable based generations encourage or obligate the parties to increase the exploitation of DG units. Due to this some DGPLs are takes into account, low penetration: 40%, high penetration: 70%, and no limitation.

a) *Low DG Penetration level:* In low penetration level the optimization is carried out to obtain the optimal DG sizing and siting that minimize the network losses in three cases (for 2, 3, and 4 DG units in turn). The results for three cases are presented in TABLE II.

In case sizing and siting two DG units, the optimal locations: node numbers 5 and 9, and optimal sizes 7 MVA and 25 MVA were found. Having explored in a few last generations, it was found that the nodes in section A, shown in Fig. 1, suggest the suitable locations for installing a DG unit. This is because loads in section A are higher than those in both other sections and all the network branch's physical characteristics (r and x) are approximately the same. By more exploring, it also was found that the most candidate solutions with a better in fitness value than the mean of all fitness values in the same population suggest one candidate location (bus number) in section A and the other one in section either B or C. This issue implies that the nodes in both section B and section C can be a suitable location for installing DG units. Hence, in the next stage the number of DG units was increased by one.

By increasing DG unit numbers into three units, as expected, the many solutions with a relatively better (lower) fitness values than the others allocate one DG units to the nodes in each section, although, the best founded solution were located in only sections A and B. Moreover, the maximum allowable production, due to DGP limits, was approximately met by DG units. This implies that using more DG production (the expansion in DG penetration limit) may lead into more reducing in network losses.

In case using four DG units, the results no improved significantly.

b) *High DG penetration level:* In this case, when two DGs were placed, flow direction in line 9 (from bus 8 to bus 9) were restricted the more exploitation of DGs. While, in case

TABLE II
RESULT OF SITING AND SIZING DG UNITS IN A TYPICAL DISTRIBUTION NETWORK. TWO POSSIBLE SCENARIOS WITH AND WITHOUT POWER FLOW DIRECTION CONSTRAINTS WERE INVOLVED. IN EACH SCENARIO THREE PENETRATION LEVELS WERE CONSIDERED. FURTHER AT EACH PENETRATION LEVEL DIFFERENT NUMBERS OF GD UNITS WERE PLACED.

Flow directions	Penetration level	NDG	DG's Locations	Network Loss(pu.)	Optimal DG's operating points (MW, MVAr)	Optimal DG's sizes (MVA)
Base case	—	—	—	1.751		
Unidirectional	Low	2	5,9	0.484	(4.19, 1.64) , (19.22, 11.26)	7, 25
		3	5,9,10	0.432	(4.2,2),(12,5.4),(7.8,4.4)	5, 15, 10
		4	6,9,10,15	0.425	(2.4,1.28),(12.5,6.55),(7.5,3.62), (1.75,0)	3, 15, 10, 2
	High	2	4,9	0.366	(16.61,10.51),(20.25,13.84)	20, 25
		3	4,9,14	0.278	(13.2,8.18),(20.08,11,68), (5.98,2.08)	20, 25, 7
		4	4,8,9,14	0.234	(10.34,4.4),(5.43,3,75),(19.85,10.08),(4.95,3.03)	12, 7, 25, 7
	Not limited	2	4, 8	0.556	(16.93,10.18), (30,18.23)	20, 40
		3	4, 9, 13	0.264	(17,10.5), (20.1,12.2), (8.8,5.2)	20, 25, 12
		4	4, 8, 9 15	0.233	(16.61,8.2), (13,7), (16.75,10.3), (2.5,0)	20, 15, 20, 3
Bidirectional	Low	2	9,10	0.483	(13.49,9.37),(9.71,3.95)	20, 12
		3	5,9,10	0.431	(4.21,1.98),(9.8,5.43),(9.86,4.6)	5, 12, 12
		4	6,9,10,15	0.425	(2.4,1.28),(12.5,6.55),(7.5,3.62), (1.75,0)	3, 15, 10, 2
	High	2	5,9	0.329	(11,5.3),(24.3,13.41)	15, 30
		3	5,9,15	0.208	(10.8,3.7),(23.7,13.9),(6.8,4.5)	12, 30, 10
		4	5,9,10,15	0.161	(11,4.5),(17,10.1),(6.4,3.34), (7.35,3.2)	12, 20, 10, 10
	Not limited	2	5, 9	0.32	(11.8, 6.4), (26.2, 14.52)	15, 30
		3	5, 9, 15	0.188	(11.9,7.32), (26.52,14.66), (7.64,4.2)	15, 35, 10
		4	5, 7, 9, 15	0.157	(7.3,4.4), (6.9,0.8), (26,16), (8,4.6)	10, 7, 30, 10

of using three/four DG units, the full penetration limit is utilized. On the other word, the more increasing in DGP, the more decreasing in network losses, until the unidirectional flow limits or DGP limit, were met.

c) *Unlimited DG penetration level:* In case no limitation on DGP was imposed, the technical constraint of network as well as DG units restricts the full ability of DG units to minimize the electrical losses in the network. Any small increase in DGPL (0.9558, 0.9358, and 0.9602 for two, three, and four DG units, respectively) leads into violation in at least one technical constraint. Comparing the cases in which two and three DG units used indicates that using more DG units do not conduce needing more DGPL to attain more reduction in network losses. On the other hand, when the number of DGs in the network is increased, more reduction in network power losses can be achieved in lower DGP.

2) *Bidirectional Power Flow Scenario:* Some utilities may bring the bidirectional power flow scenario in their operating condition consideration aiming to keep islanding during the transmission system outages as well as to exported energy to the upstream network in a market environment, specially, when the amount of DGPL is increased. However, this paper focuses only on power losses in this scenario.

a) Low DG penetration level: For all three cases (deploying 2, 3, and 4 DG units) the maximum allowable production (maximum allowed DGP limit), was approximately met by DG units. The operating points and the candidate DG units were selected from a candidate list are shown in TABLE II. The results (optimal locations and sizes) are the same as those founded in low DGPL in subsection *C1-c* except for employing two DG units, in which unidirectional flow constraint had precluded full utilization of penetration level of DG units.

b) High DG penetration level: Similar results were found by increasing penetration level of DG. However, Different DG's locations and sizes were founded in comparison with those founded in subsection *C1-b*. The results show in one hand, if the flow direction constraint is removed, the network losses could be more reduced at the same DGPL. On the other hand, it yields different sites and sizes for installing DG units.

When using two DG units, the best solution was found at 0.6954 DGPL, i.e. maximum allowed DGP limit was approximately met by DG units. In case using three and four DG units, the full DGPL was met as well.

c) Unlimited DG penetration level: In case using two DG units, the best solution was found at 0.755 DGPL. Using more DGP, without violating any constraint, leads into increasing in network losses. When using three and four DG units, it was found that the minimum losses take place at 0.9224 and 0.9525 DGPL respectively. It is to be mentioned that, although, a small increase in generation of some DG units may reduce the losses in two later cases, it may violate some technical constraints. For example, in case using four DG units, 0.1 MVAr increase in generation of the generator where located on bus 5 may decreases 0.002 p.u. in network losses, however, it violates the DG power factor limit that sets by the DSO. Another example, increasing 0.4 MVAr or 0.1 MW in reactive or active power generated by the DG located on bus 7 violates the maximum permissible short circuit capacity level due to the fact that it leads into the greater size will be selected from the DG candidate list.

3) *Comparison Unidirectional and Bidirectional Power Flow Scenario:* As mentioned earlier, DG may cause bidirectional power flow in the distribution network. However, some researcher may take only unidirectional power flow scenario in their studies. In this paper the both scenarios were considered and reported in TABLE II. In general, considering bidirectional power flow may result in better operation of radial distribution network with regard to electrical loss minimization. In fact, in an identical DGPL the bidirectional flow scenario may lead to more decrease in the electrical power losses. This is due to the fact that removing unidirectional flow may expand the feasible space in some scenarios. The amount of losses that can be reduced in lower penetration levels are close to each other, however, at higher DGPL they may keep distance to each other. In both cases, even if the DGP limits were removed, either the other technical constraints or the objective function (e.g. in case *C2-c* with two GD units) may restrict the DGPL with respect to loss minimization below the 100%, although it is not a general case. In brief, the amount of losses that may be reduced is depending on DGPL, number of DG that used, network technical constraints, the system loading condition, etc.

V. CONCLUSION

In this paper, losses minimization on a redial distribution network using DG units was investigated. An enhanced GA technique was utilized to explore the highly constrained search space and to find the optimal sites and sizes of DG units. A simple constraints handling methods, where adds the number of constraint violations instead the amount of their violations, were presented and used. Two possible scenarios, unidirectional and bidirectional power flow cases as well as different DGPLs were investigated and compared. The result shown that if the flow direction constraints are removed, the network losses can be more reduced at the same DGPL.

The results show that in case the level of DGP is not limited, the minimum network losses can be achieved in both unidirectional and bidirectional scenarios. Moreover, in case of bidirectional power flow, the loss reduction is more than those in unidirectional case.

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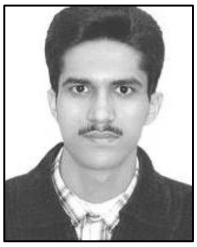
VII. BIOGRAPHIES



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