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AN MINLP APPROACH FOR OPTIMAL DG UNIT'S ALLOCATION IN RADIAL/MESH DISTRIBUTION SYSTEMS TAKE INTO ACCOUNT VOLTAGE STABILITY INDEX*

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Abstract– Application of distributed generation (DG) units in distribution networks has increased in recent years. Sizing and sitting of DG units are two important factors which should be considered, especially for reduction of power losses in distribution system. This paper presents a new approach for DG placement in distribution systems using the mixed integer nonlinear programming (MINLP). This approach determines the optimal number, sitting and sizing of DG units in both radial and meshed distribution networks with the objectives of reducing the power losses, as well as minimizing the investment and operation costs of DG units, and the monetary value of voltage stability index improvement. The performance of the proposed method is compared with the genetic algorithm (GA), particle swarm optimization (PSO), combined GA and PSO, and combined loss sensitivity factor and simulated annealing (LSFSA). Compared with the conventional methods, the proposed scheme can be applied in the meshed distribution networks as well. A 33-bus radial network and CIVANLAR meshed distribution system have been used for simulation studies. The obtained results approve the efficiency of proposed method for sitting and sizing of DG units in distribution networks.

Keywords– DG allocation, MINLP approach, radial and mesh distribution systems, voltage stability index

1. INTRODUCTION

Application of DG units provides a wide range of advantages including economic, environmental and technical benefits. The economic advantages are reduction of transmission and distribution costs and electricity prices, as well as fuel saving. The last case can be considered as an environmental benefit, as well. Technical advantages consist of power loss reduction, peak shaving, increased system voltage profile and hence increased power quality. Therefore, optimal sitting and sizing of DG units has significant effect on decreasing network losses, voltage profile enhancement and also reliability improvement. Optimal placement of DG units has been widely investigated in the literature, as follows.

a) Literature review

Many approaches have been proposed to solve the DG placement problem. For instance, in [1], a new framework including distribution feeder reconfiguration in the presence of distributed generation has been studied. Distribution system planning integration of distributed generation, interruptible load and voltage regulator devices are studied in [2]. In [3], a multistage model for distribution expansion planning with distributed generation is proposed in a deregulated electricity market. In [4, 5], a loss sensitivity factor is presented for distribution systems, based on the equivalent current injection. The formulated sensitivity factor is employed for determination of the optimum size and location of DG units so that the total power

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loss is minimized by an analytical method. A visual optimization approach is introduced in [6] for optimal sitting and sizing of DG units. In this approach, the system deficiencies are considered by applying appropriate weight factors in the optimization process. In [7], the nodal pricing technique is used for optimal allocation of DG units in order to increase the profit, reduce the power losses, and improve the voltage profile. In [8], optimal sitting of DG units is determined by sensitivity analysis of the power flow equations. The sizing problem is formulated as a security-constrained optimization problem considering the loading condition, generation penetration level and power factor. A value-based method to find the best tradeoff between the costs and benefits of DG placement is proposed in [9] to find the optimal types of DG units and their corresponding locations and capacities. In [10], an iterative search technique using the Newton-Raphson method for load flow studies is implemented. In [11], the appropriate DG sites are determined in distribution systems considering the advantages gained from the correct DG placement. In [12], the optimal locations of DG units in distribution systems are determined using a multi-objective function to minimize the system power losses, enhance the reliability, and improve the voltage profile. A combined genetic algorithm (GA) and particle swarm optimization (PSO) approach is presented in [13] for optimal sitting and sizing of DG units in distribution systems. In [14], the reliability, the power losses, and the power quality of a distribution network in the presence of DG resources are studied using the CYMEDIST software. A new method to obtain the optimal size of DG units in distribution systems, considering the time-dependent evolution of generation and load is presented in [15]. In [16], a new algorithm for DG placement and sizing in distribution systems is proposed based on a novel index. This index is developed considering the stable node voltages and introduced as the power stability index. The cuckoo search algorithm is utilized in [17] for optimal DG allocation, voltage profile improvement and power loss reduction in distribution networks. In [18], an efficient technique is presented for optimal placement and sizing of DG units in a large-scale radial distribution system. The main objective is minimizing the network power losses and improving the voltage stability. A multi-objective methodology for optimal DG allocation and sizing in distribution systems is proposed in [19]. In [20], a new method based on the shuffled frog leaping algorithm (SFLA) is proposed for optimal placement of DG units in radial distribution systems. Moreover, the real power losses and the cost of DG units are decreased in this method. In [21], an improved group search optimization (GSO) approach is presented to compute the optimal location and capacity of DG units in distribution systems. A multi-objective model for the placement of DG units in distribution networks is presented in [22] considering the load uncertainty. In [23], a method is presented for placement of DG units in distribution networks based on the analysis of power flow continuation and determination of the buses which are more sensitive to voltage collapse. A heuristic curve-fitted technique is proposed in [24] to find the optimal location and size of the DG units and minimize the total system power loss in radial distribution systems. In [25] a new technique is presented for optimal placement and sizing of DG units in a radial distribution system. The main objective is to minimize the network power losses. This technique consists of two parts. In the first part, the optimal sitting is acquired by applying the power loss sensitivity factor (LSF). Then, in the second part, the Simulated Annealing (SA) algorithm is used to calculate the optimal size of DG units.

In this paper, the problem of optimal sitting and sizing of DG units is developed using the mixed integer nonlinear programming (MINLP). The proposed method is able to determine the optimal number, sitting and sizing of DG units in both radial and meshed distribution systems. The proposed objective function minimizes the cost of power loss, as well as the investment and operation costs of DG units. Moreover, the monetary value of voltage stability index improvement is minimized, as well. The simulation studies are implemented in the GAMS Software. The efficiency of the proposed method is compared with other methods such as GA [13], PSO [13], combined GA/PSO [13] and combined LSF/SA

[25]. The obtained numerical results prove the better performance of the proposed MINLP-based method in comparison with the mentioned methods.

b) Contribution

Most of the previous techniques are limited to radial distribution systems. This paper formulates the optimal DG placement problem for both radial and meshed distribution systems as an MINLP problem. The proposed problem can be solved using the DICOPT solver of GAMS software. The highlighted features of this paper are listed as follows:

1- The proposed method can be handled on both radial and meshed distribution systems.
2- The monetary value of voltage stability index improvement, as well as total cost of investment, operation and losses, is considered in the objective function.
3- Various-scale systems are used to compare the performance of proposed method with GA, PSO, combined GA/PSO, and combined LSF/SA.

c) Paper organization

The remainder of this paper is organized as follows. Section 2 describes the voltage stability index. Section 3 presents the proposed formulation and solution of DG placement problem as an MINLP problem. Section 4 includes the obtained simulation results in different case studies, as well as comparison with other methods. Finally, section 5 includes the conclusion of this paper.

2. VOLTAGE STABILITY INDEX

Voltage stability is the ability of a power system to maintain the voltage in an acceptable level so that if the system nominal load increases, the active power delivered to the load increases as well, and both active power and voltage are controllable. To increase the voltage stability at the network buses, the monetary value of voltage stability index will be considered in the proposed objective function. Therefore, the placement of DG units will increase the voltage stability of the network. When the DG units are applied in distribution networks, the node voltage will increase and the voltage security will enhance. Therefore, DG units can improve the voltage stability margin. The voltage stability improvement can be measured by the method introduced in [26]. For this purpose, the voltage stability index (VSI) is defined for each bus as:

$$VSI_m = |V_n|^4 - 4\left[P_{Load,m}X_{n,m} - Q_{Load,m}R_{n,m}\right]^2 - \left\{4|V_n|^2 \times \left(P_{Load,m}R_{n,m} - Q_{Load,m}X_{n,m}\right)\right\} \qquad (1)$$

3. PROBLEM FORMULATION AND SIMULATION METHOD

The problem of optimal sitting and sizing of DG units can be formulated as an MINLP problem. The objective function encompasses the total cost of power loss, the investment and operation costs of DG units, and the monetary value of voltage stability index. This objective function is constrained by some equality and inequality constraints which are explained as follows.

a) Objective function

The objective function can be defined as minimizing a cost function which includes the mentioned costs. This cost function is given by:

$$TC = K_p \times 8760 \times P_{Loss} + 8760 \times \sum_{n=1}^{N}(b \times P_{DG,n} \times U_{DG,n}) + \sum_{n=1}^{N}(Inv_{DG} \times U_{DG,n}) + of_{VSI} \qquad (2)$$

$$\mathrm{P_{Loss}} = \sum_{n=1}^{N}\sum_{m=1}^{N}\left|I_{n,m}\right|^2 R_{n,m} \tag{3}$$

where TC is the total cost ($), K_p is the equivalent annual cost per unit of power loss ($/kWh), and $ is a fictional monetary unit, *b* is the operation cost of DG unit ($/kWh), Inv_{DG} is the DG investment cost, and $U_{DG,n}$ is a binary variable, which is equal to 1 if DG is selected at bus n, and otherwise, it is 0. Moreover, n = 1, 2, . . . , N is the index of the bus which is selected for compensation.

The second and third terms of (2) are the equivalent operation and investment costs of DG units, respectively. Meanwhile, the fourth term is the monetary value of VSI improvement which is described in the following subsection.

1. VSI cost: To consider the impact of DG units on VSI, the bus with minimum VSI is determined.

Afterwards, the monetary value of VSI for this bus is calculated according to [26]. It should be mentioned that the maximum cost of VSI for each curve is obtained by (2).

$$\mathrm{Cost}\,VSI = K_{ACB}^{vsi} \times P_{load}^{\min VSI} \times T_{peak\ load}^{vsi} \tag{4}$$

where $T_{peak\ load}^{vsi}$ and K_{ACB}^{vsi} are the duration of peak load (hour) and the average cost of a blackout ($/MW), respectively. Moreover, $P_{load}^{\min VSI}$ is the active power load corresponding to the bus with minimum VSI. According to the above equation, the saved value of the improved VSI can be written as follows.

$$of_{VSI} = \mathrm{cost\,VSI}^{without\,dg} - \mathrm{cost\,VSI}^{with\,dg} \tag{5}$$

where $\mathrm{cost\,VSI}^{without\,dg}$ and $\mathrm{cost\,VSI}^{with\,dg}$ are the costs of voltage stability for the bus which has the least VSI value before and after DG installation, respectively.

b) Constraints

The proposed objective function is accompanied by the equality and inequality constraints. These constraints should be satisfied during the optimization process.

1. Load flow equations: These equations are given by the Kirchhoff's laws, and determine the active and reactive power flows in the network:

$$P_{sys} + P_{DG,n} \times U_{DG,n} - P_{Load,n} - \sum_{m=1}^{N} V_n.V_m.Y_{nm}.\cos(\theta_{nm} + \delta_m - \delta_n) = 0; \forall\, n = 1,..., N \tag{6}$$

$$Q_{sys} - Q_{Load,n} + \sum_{m=1}^{N} V_n.V_m.Y_{nm}.\sin(\theta_{nm} + \delta_m - \delta_n) = 0 \qquad \forall\, n = 1,..., N \tag{7}$$

which are the active and reactive powers, respectively, *n* is the bus number, and N is the number of buses in the network.

2. Voltage limits: Voltage limits refer to the requirement for the system bus voltages to remain within a narrow range of levels. Since voltages are affected primarily by reactive power flows, the marginal cost of reactive power at each bus is directly dependent on the voltage level requirement at that bus. Voltage limits can be expressed by the following constraints:

$$\mathrm{V_{min}} \le V_n \le \mathrm{V_{max}} \qquad \forall\, n = 1,..., N \tag{8}$$

where $V_{n,\min}$ and $V_{n,\max}$ are the minimum and maximum voltage levels, respectively, that are acceptable at bus n, for all $n \in N$. Whenever necessary, reactive power sources are used in the system to keep the voltages within the required limits.

3. The penetration limits of DG units: The maximum capacity and number of DG units are constrained as

$$0 \leq P_{DG,n} \leq P_{DG,\max} \times U_{DG,n} \qquad \forall\, n = 1,...,N \tag{9}$$

$$\sum_{n=1}^{N} U_{DG,n} \leq \hat{N}_{DG} \tag{10}$$

where $\hat{N}_{DG}$ is the maximum number of installed DG units.

c) Simulation method

For general optimization problems, one of the favorite choices is the general algebraic modeling system (GAMS) software [27]. GAMS is a high-level modeling system for mathematical optimization problems. It consists of a proprietary language compiler and a variety of integrated high-performance solvers. GAMS is specifically designed for large and complex problems, and allows creating and maintaining models for a wide variety of applications and disciplines [27]. GAMS is able to formulate models in many different types of problem classes, such as linear programming (LP), nonlinear programming (NLP), mixed-integer linear programming (MIP), mixed-integer nonlinear programming (MINLP) and dynamic nonlinear programming (DNLP). It makes this framework a problem-independent framework. Required changes in the objective function, such as adding or deleting an item or variable, can be applied only by the change of the type of solver. For example, by adding an integer variable in an NLP problem, the solver should be changed to another one which is able to solve MINLP problems. Therefore, the objective function can be changed easily according to decision makers and available planning options without the worry of whole framework changing.

In this paper, the optimal DG placement model is formulated as an MINLP problem, and solved by the GAMS software using the DICOPT solver [28]. The proposed method is implemented on a standard desktop hardware with objective of minimizing (2), and subject to the constraints (3) to (10).

4. CASE STUDY

The proposed DG placement has been tested on a 33-bus radial distribution system and the CIVANLAR meshes network. Performance of the proposed method is compared with other methods such as GA [13], PSO [13], combined GA/PSO [13] and combined LSF/SA [25]. The obtained results are presented as follows.

a) 33- bus radial distribution system

The new MINLP formulation for optimal DG placement has been applied to a 33-bus distribution system. The proposed method is implemented on a Pentium IV, 2-GHz personal computer with 0.99 GB RAM. The single-line diagram of the 12.66 kV, 33-bus system is shown in Fig. 1. The line and load data are presented in Table 1.

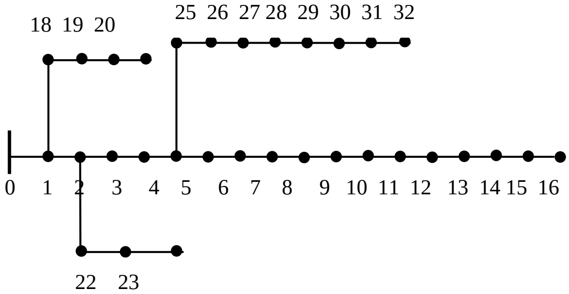

Fig. 1. Single line diagram of 33-bus radial distribution system

Table 1. 33-bus distribution system data

Nomber of Branch	Sending Node	Receiving Node	R(ohm)	X(ohm)	Active Power Injected(KW)	Reactive Power Injected(KVar)
1	0	1	0.0922	0.0470	100	60
2	1	2	0.4930	0.2511	90	40
3	2	3	0.3660	0.01864	120	80
4	3	4	0.3811	0.1941	60	30
5	4	5	0.8190	0.7070	60	20
6	5	6	0.1872	0.6188	200	100
7	6	7	0.7114	0.2351	200	100
8	7	8	1.03	0.74	60	20
9	8	9	1.044	0.74	60	20
10	9	10	0.1966	0.0650	45	30
11	10	11	0.3744	0.1238	60	35
12	11	12	1.4680	1.1550	60	35
13	12	13	0.5416	0.7129	120	80
14	13	14	0.5910	0.5260	60	10
15	14	15	0.7463	0.5450	60	20
16	15	16	1.2890	1.7210	60	20
17	16	17	0.7320	0.5740	90	40
18	1	18	0.1640	0.1565	90	40
19	18	19	1.5042	1.3554	90	40
20	19	20	0.4095	0.4784	90	40
21	20	21	0.7089	0.9373	90	40
22	2	22	0.4512	0.3083	90	50
23	22	23	0.8980	0.7091	420	200
24	23	24	0.8960	0.7011	420	200
25	5	23	0.2030	0.1034	60	25
26	25	26	0.2842	0.1447	60	25
27	26	27	1.0590	0.9337	60	20
28	27	28	0.8042	0.7006	120	70
29	28	29	0.5075	0.2585	200	600
30	29	30	0.9744	0.9630	150	70
31	30	31	0.3105	0.3619	210	100
32	31	32	0.5032	0.5302	60	40

In order to compare the proposed method with other methods, the prevalent objective function which is used in [13, 25] is considered, as well. This objective function includes only the power loss. Then, the introduced objective function is used for the evaluation of proposed method.

1. Prevalent objective function: To compare the proposed method with other methods, the objective function of (2) is decreased to minimize the total loss. The initial condition derived from power flow is shown in Table 2. The obtained results from the proposed method and the previous methods [13, 25] including GA, PSO, GA/PSO and LSFSA are given in Table 3.

As shown in Table 3, in the proposed method the DG units with the rating capacities of 0.753, 1.100 and 1.071 MW are placed at the optimal locations of 14, 24 and 30, respectively. The initial power loss is 210.9 kW and reduces to 71.54 kW after DG installation. It can be concluded from the presented results that the proposed method provides better solutions than the previous methods.

Table 2. 33-bus test network: initial conditions and results

System Load [kVA]	**3715+j2300**
Active Losses without capacitor [kw]	**210.9**
Reactive Losses without capacitor [kvar]	**134.829**
Minimum voltage [p.u.] (at node)	**0.903 (18)**
Maximum voltage [p.u.] (at node)	**1 (1)**

Table 3. Comparison results of the proposed method for 33-bus RDS

method	P loss (KW)		Minimum voltage no.bus/value(p.u)		Optimal location DG	Optimal size DG [MW]	Comparison of results		
	Without DG	With DG	Without DG	With DG			Total capacity of DG [MW]	Loss reduction [KW]	Payback period [yr]
GA [13]	210.9	106.3	18/0.903	25/0.98094	11 29 30	1.5000 0.4228 1.0714	2.9942	104.6	9.5309
PSO [13]		105.35		30/0.98063	8 13 32	1.1768 0.9816 0.8297	2.9881	105.55	9.4258
GA/PSO [13]		103.4		25/0.98083	11 16 32	0.9250 0.8630 1.2000	2.9880	107.5	9.2545
LSFSA [25]		82.03		14/0.9676	6 18 32	1.1124 0.4874 0.8679	2.4677	128.87	6.3756
Proposed method		73.229		33/0.969	14 25 30	0.7270 0.7100 1.0220	2.4590	137.671	5.9470

2. The proposed objective function: In this case, the introduced objective function of (2) is used for simulation studies. If the VSI cost is neglected in the problem of optimal DG placement, the system planners must pay additional costs to improve the voltage stability. However, considering the monetary value of VSI in the objective function makes the planners capable of improving the voltage stability, as well as the optimal placement of DG units. The following results demonstrate the impact of DG units on reduction of total costs and improvement of voltage stability.

For this test system, it is assumed that K_p =120 $/ Mwh, b =5$/MWh, INV_{DG}=350,000$/MW, K_{ACB}^{vsi} =70 $/kWh and $T_{peak\ load}^{vsi}$ =1825 h.

The results of optimal allocation of DG units considering the proposed objective function are shown in Table 4.

Table 4. Comparison results of DG allocation using the proposed objective function

Parameter	Without DG	With DG allocation
Optimal place and size of DG units (bus no/ MW)	------	14 /0.737 24/1.085 29/1.133
Total P loss (KW)	210.9	72.121
Loss reduction [%]	------	65.8
Minimum voltage (bus no./ value[p.u])	18/0.903	33/0.967
Minimum VSI (bus no. / value [p.u])	18/0.697	33/0.874
Saving of VSI [$]	0	2517.104
Cost of VSI [$]	3481.209	964.105
Total cost [M$]	212.96	75.948

b) CIVANLAR meshed distribution system

Most previous MINLP techniques are limited to radial distribution systems. However, the proposed method can be applied in the meshed distribution networks, as well. In this case, the proposed method is tested on CIVANLAR meshed distribution system. Line and load data are shown in Table 5. The single-line diagram of the 23 kV and 100 MVA, CIVANLAR mesh distribution system is shown in Fig. 2.

Table 5. Line and load data for CIVANLAR meshed distribution test system

From bus	To bus	R (pu)	X (pu)	P (MVA)	Q (MVA)
1	4	0.075	0.1	2	1.6
4	5	0.08	0.11	3	1.5
4	6	0.09	0.18	2	0.8
6	7	0.04	0.04	1.5	1.2
2	8	0.11	0.11	4	2.7
8	9	0.08	0.11	5	3
8	10	0.11	0.11	1	0.9
9	11	0.11	0.11	0.6	0.1
9	12	0.08	0.11	4.5	2
3	13	0.11	0.11	1	0.9
13	14	0.09	0.12	1	0.7
13	15	0.08	0.11	1	0.9
15	16	0.04	0.04	2.1	1
5	11	0.04	0.04		
10	14	0.04	0.04		
7	16	0.0.9	0.12		

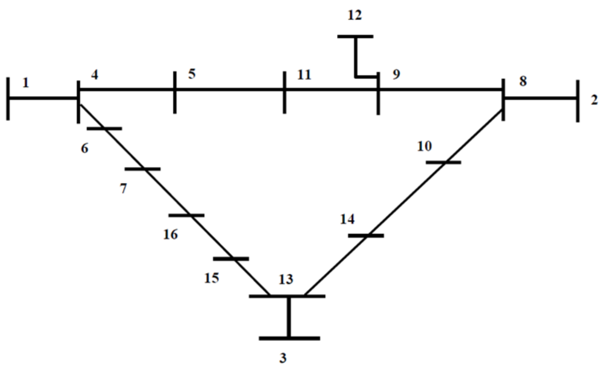

Fig. 2. Single line diagram of CIVANLAR meshed distribution system

As mentioned, the proposed objective function consists of the operation and installation costs of DG units, cost of total losses, and the monetary value of VSI improvement.

The obtained results of optimal sitting and sizing of DG units in CIVANLAR meshed distribution system, as well as initial conditions, are presented in Table 6. This table represents the total cost reduction, power loss reduction and voltage stability index improvement due to DG placement. Using the proposed method, the DG units with the rating capacities of 2, 2 and 2 MW are placed at the optimal locations of 9, 11 and 12, respectively. The initial power loss is 531.301 kW, which is decreased to 347.052 kW after DG placement.

Table 6. Comparison results of DG allocation in CIVANLAR meshed distribution system

Parameter	Without DG	With DG allocation
Optimal place and size of DG units (bus no/ MW)	------	9 /2 11/2 12/2
Total P loss (KW)	531.301	347.052
Loss reduction [%]	------	34.68
Minimum voltage (bus no./ value[p.u])	12/0.966	12/0.973
Minimum VSI (bus no. / value [p.u])	12/0.891	12/0.913
Saving of VSI [$]	0	14.282
Cost of VSI [$]	71030	56748
Total cost [M$]	558.57	365.23

5. CONCLUSION

This paper presents an MINLP-based approach for DG placement in distribution systems. The optimal number, sitting and sizing of DG units in both radial and meshed distribution systems are determined. The proposed method minimizes the cost of power loss, the investment and operation cost of DG units, and the monetary value of voltage stability index improvement. Two radial and meshed distribution systems have been used to evaluate the proposed MINLP-based approach. Performance of the proposed method is compared with the genetic algorithm (GA), particle swim optimization (PSO), combined GA/PSO, and combined loss sensitivity factor and simulated annealing (LSFSA). The obtained results approve the better performance of the proposed method in comparison with the previous methods. Moreover, the proposed method is applicable in the meshed distribution systems, as well.

NOMENCLATURE

Indices:

n, m index of buses

Constants:

N number of buses

$\hat{N}_{dg}$ maximum number of DG units

K_p annual cost per unit of the active power loss ($/kw.year)

$P_{DG,\max}$ maximum capacity of DG unit (kw)

$Q_{Load,n}$ reactive load power in bus n (kvar)

$P_{Load,n}$ active load power in bus n (kw)

Variables:

N_{DG} number of DG units

TC total Cost ($)

P_{Loss} total real power loss (Kw)

V_n voltage in bus n (p.u)

δ_n angle voltage in bus n (rad)

$P_{DG,n}$ active power injected by DG at bus n (Kw)

U_{DGn} binary variable, which is 1, if the DG is selected at bus n; otherwise, it is 0

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