Optimal Sizing and Placement of DG Units in Radial Distribution System

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Abstract- The continuous growth of electricity demand has presented a new challenge for power system utilities in preserving the system efficiency. Thus, Distributed Generation (DG) has attracted a lot of interest since it provides clean, reliable and cost-effective power supply. However, DG type, location and size should be properly chosen. To this end, this paper presents a DG placement and sizing method regarding system losses reduction, voltage magnitude and stability enhancement. The system weakest buses were selected for DG allocation in the basis of sensitivity methods and optimal DG size of a single DG unit has been determined by means of the quadratic curve-fitting technique. Multiple DG units' placement has been performed using loss improvement and loss reduction indices. Proposed approach has been applied to the 33- bus distribution system. Power system modeling and simulations have been performed using MATLAB\PSAT toolbox. Simulation results have shown accurate and satisfactory results in enhancing the steady-state voltage profile and decreasing total power losses.

Keywords- Distributed generation; optimal capacity; Sensitivity.

1. Introduction

Over the last years, the main concerns of industry and research sectors have been concentrated on developing new strategies for distribution system scheduling with reference to system efficiency enhancement. Thereby, two main competitive strategies may be employed to overcome this problem; network expansion and DG allocation within the existing distribution system [1][2]. Given the fact that power system is operating nearby its boundary where the expansion is limited owing to several reasons like high costs and environmental problems, DG units based strategy has been considered as the most appropriate solution [3][4].

Otherwise, renewable DG units have gained a lot of attraction for their ability to enhance the distribution system efficiency [5, 6, 7]. However, studies have shown that the most critical issues in DG applications are optimal location, type and size selection. In fact, in accordance with recent researches, inaccurate use of DG units may reverse the feeders' power flow. This may lead to a decrease in voltage magnitude and to an increase in system power losses [8][9]. Therefore, DG parameters have to be appropriately chosen in order to improve the system efficiency.

In this regard, many approaches were presented in recent works in the field of DG allocation and sizing [10-14]. Sensitivity based approaches and optimization based methods are the most common. In [15,16], researchers have focused on developing methodologies for DG allocation and sizing to reduce distribution network power loss based on several sensitivity indexes.

Furthermore, since voltage stability improvement is a substantial issue that should be examined for DG units scheduling and operation, different studies have determined system weakest buses based on voltage stability index [17].

The optimal sizing and sitting of DGs have been simultaneously examined in [10, 18]. In [19], Distributed Generation allocation and sizing problem has been solved by means of Analytic Hierarchy Process (AHP) and Particle Swarm Optimization method. The selected approach generates best location, and power capacity of DGs based on power losses reduction, voltage magnitude improvement and investment cost saving.

In [20], the authors have proposed a new rapid and sturdy power flow formulation for DG placement and sizing that overcome convergence problems related to systems with large R/X branch ratios. A nonlinear programming technique for DG siting and sizing has been presented in [21]. The Objective function aims to reduce DGs number and to increase voltage stability margin (VSM). An analytical approach for optimal DGs sitting for power loss reduction has been suggested in [22]. In [23], candidate buses for DG placement have been determined by means of dynamic programming search method. Objective function includes minimizing the power losses and maximizing the VSM.

Likewise, different techniques based on artificial intelligence have been suggested [24]. The genetic algorithm based approach has been widely employed in solving multi-objective problems such as DG placement and sizing [25, 26]. In [27], Simultaneous placement problem of Capacitor banks and DGs has been solved considering DG units random behavior. Hybrid (GA–TS) method has been used to solve the suggested model. Wanxing Sheng et al. have developed in [28] an (INSGA-II) based method for optimal scheduling of multiple DGs. In [29], authors have presented a multi-objective optimization method for system costs saving.

Attempts have been constantly made to improve distribution system's efficiency and reliability. However, it is still estimated that a comprehensive study on the DG placement and sizing in power system is required.

Within this context, the present paper propose a multi-objective approach for DG allocation and sizing for voltage profile and stability improvement and system power loss reduction. Single DG allocation and sizing have been determined in the basis of sensitivity indices and quadratic curve fitting technique. However, a loss improvement index and a power loss reduction index have been presented for the placement of multiple DGs. The Performance of the developed approach is checked in the 33-bus distribution system.

Simulation results have demonstrated accuracy and effectiveness of the proposed approach in voltage magnitude enhancement, losses reduction and maximum loading and VSM increasing.

The layout of this paper works as follows: an overview of the distributed generation and their various types are put under scrutiny in the second section. Then, the third section describes the single DG allocation and sizing method. The following part is meant to discuss the placement of multiple DG units. Throughout section five, simulations results are summarized and the developed method performance is evaluated. Finally, the last section recapitulates the previous parts and spells out the final overall findings the paper has established.

2. Distributed Generation

DG units are on-site electricity production that refers to small generating units. The main purpose of installing them is to cover new load areas, to handle power transmission variations and to satisfy consumers demand. They have the ability to enhance voltage magnitude, to minimize power losses and to maintain transient stability.

Considering their ability to deliver active and reactive power DG resources may be subdivided into [30]:

- Active power producers like PV arrays, micro turbines…,
- Reactive power producers like synchronous compensators,
- Active and reactive power producers as synchronous generators,
- Active power producers and reactive power consumers like fixed speed wind turbines.

The third type is the only one to be considered in this study. Accordingly, the DG model adopted in this paper is a negative load model with constant P and Q generation.

3. Test System Description

The base configuration of the 33-bus distribution system used in simulation is depicted in Fig.1. The load and branch data are given in Table 1. The system voltage is 12.66 kV and the total system loads are 3715 KW and 2300KVAr. The active power losses at the base case are 197 KW. All analytical studies were performed using PSAT Matlab.

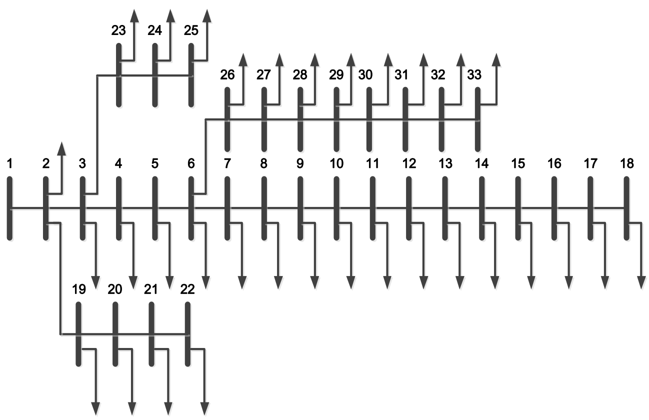


Fig. 1. IEEE 33-bus radial distribution network

Table 1. System data and parameters for the IEEE 33-bus distribution network

Branch Number	From Bus	To Bus	R (p.u)	X (p.u)	Active power injected (MW)	Reactive power injected (MVar)
1	1	2	0.575	0.293	0.1	0.06
2	2	3	0.03076	0.01567	0.09	0.04
3	3	4	0.02284	0.01163	0.12	0.08
4	4	5	0.02378	0.01211	0.06	0.03
5	5	6	0.0511	0.04411	0.06	0.02
6	6	7	0.01168	0.03861	0.2	0.1
7	7	8	0.04439	0.01467	0.2	0.1
8	8	9	0.06426	0.04617	0.06	0.02
9	9	10	0.06514	0.04617	0.06	0.02
10	10	11	0.01227	0.00406	0.045	0.03
11	11	12	0.02336	0.772	0.06	0.035
12	12	13	0.09159	0.07206	0.06	0.035
13	13	14	0.03379	0.04448	0.12	0.08
14	14	15	0.03687	0.03282	0.06	0.01
15	15	16	0.0456	0.034	0.06	0.02
16	16	17	0.08042	0.10738	0.06	0.02
17	17	18	0.04567	0.03581	0.09	0.04
18	2	19	0.01023	0.976	0.09	0.04
19	19	20	0.09385	0.08457	0.09	0.04
20	20	21	0.02555	0.02985	0.09	0.04
21	21	22	0.04423	0.05848	0.09	0.04
22	3	23	0.02815	0.01924	0.09	0.05
23	23	24	0.05603	0.04424	0.42	0.2
24	24	25	0.0559	0.04374	0.42	0.2
25	6	26	0.01267	0.645	0.06	0.025
26	26	27	0.01773	0.0.093	0.06	0.025
27	27	28	0.06607	0.05826	0.06	0.02
28	28	29	0.05018	0.04371	0.120	0.07
29	29	30	0.03166	0.01613	0.2	0.6
30	30	31	0.068	0.0608	0.15	0.07
31	31	32	0.01937	0.02258	0.21	0.1
32	32	33	0.02128	0.03319	0.06	0.04

4. Proposed Method for DG units' Allocation

The selection of appropriate locations for DG integration is crucial since utilities cannot tolerate issues related to non-optimal DG placement like system losses increasing and lower voltage magnitude. Within this context, we present in this paper three DG allocation approaches founded on voltage magnitude enhancement and power loss minimization. These approaches are:

- Voltage stability improvement approach, L-index.
- Voltage profile enhancement method, VPI.
- Loss reduction, LSF.

4.1. The L-index method

Different voltage stability methods have been presented in literature in order to identify the system's sensitive buses [31]. Thus, the L-index method presented in [32] has attracted a lot of interest owing to its computational simplicity and pertinent results.

The primary goal of L-index method is to estimate the range between system actual state and stability boundary. Thus, the weakest bus refers to the one that generates a minimum voltage and which is mostly affected by the changes in load demands. The L-index can be computed as follows:

$$L_j = \max_{j\in\alpha_L}\left\{L_j\right\} = \max_{j\in\alpha_L}\left|1-\frac{\sum_{i\in\alpha_G} F_{ji}\bar{V}_i}{\bar{V}_j}\right| \quad (1)$$

Where, L_j is the L-index,

α_L, α_G :are the consumer and generator nodes respectively,

V_j, V_i : are the voltage in the load node j and generator node i

F_{ji} : is the load participation factor.

The estimated value of L-index is varying from 0 to 1 [32]. Thus, the VSM can be identified. A voltage collapse may occur when the estimated value converges to 1 else, the system operates at normal condition. Accordingly, the highest L-index value correspond to the most vulnerable bus in the network.

4.2. The VPI

DG units are able to inject active and reactive power and to absorb only the reactive one. They are able to enhance voltage magnitude for various power factors. The voltage magnitude variation versus DG size is given by Fig.2.

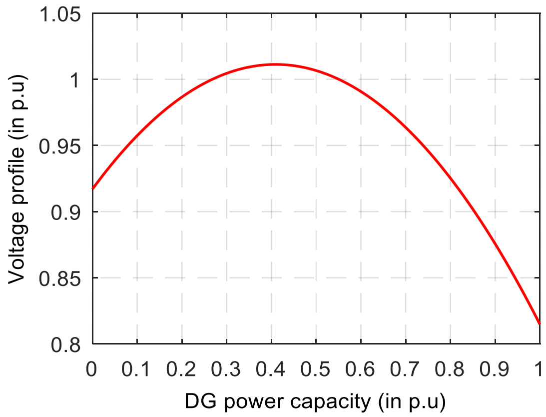


Fig. 2. Impact of DG power capacity on voltage profile

System sensitive buses are determined by computing a voltage performance index (VPI) given by the following expression [33]:

$$(VPI)^{(i)} = \sum_{j=1}^{N} \frac{w_j}{2n} \left(\frac{\Delta V_j^{(i)}}{\Delta V_j^{lim}} \right)^{2n} \quad (2)$$

$$\Delta V_j^{(i)} = V_j^{(i)} - V_j^{lim} \quad (3)$$

$$V_j^{lim} = V_j^{max}, \forall\, V_j^{(i)} \geq 1.0 \quad (4)$$

$$V_j^{lim} = V_j^{min}, \forall\, V_j^{(i)} < 1.0 \quad (5)$$

$$V_j^{(i)} = V_j^{max}, \forall\, V_j^{(i)} > V_{max} \quad (6)$$

$$V_j^{(i)} = V_j^{min}, \forall\, V_j^{(i)} < V_{min} \quad (7)$$

$$\Delta V_j^{lim} = \frac{V_j^{max} - V_j^{min}}{2} \quad (8)$$

Where, N is the number of system buses, w_j is the weighing factor of bus j, 2n represents the performance index order, is the voltage $v_j^{(i)}$ at bus j with increment change in DG capacity at i^{th} bus.

A smaller VPI value is obtained if the voltage magnitude of all buses is in its permissible range, whereas it has a high value in the opposite case. This approach selects the DG's optimal locations to keep the voltage around its nominal value. The best site to place DG unit based on voltage magnitude improvement correspond to the bus having higher VPI value.

4.3. The LSF method

In power system, the transmission of the produced power to consumers with highest reliability is very crucial. Moreover, researches [1] have denoted that inappropriate DG placement and sizing can lead to a rise in system losses. Therefore, the determination of optimum placement of DG units can ensure the losses reduction.

Loss Sensitivity Factor (LSF) approach is broadly employed in capacitor placement but it's still recent in the field of DG placement [34]. This method aims to select suitable locations for DG sitting based on losses reduction. The loss sensitivity factor may be defined by the following expression:

$$LSF(i) = \frac{\Delta P_{loss}}{\Delta P(i)} = \frac{P_{Loss}(i) - P_{loss}^{b}}{P_{DG}^{inc}(i)} \quad (9)$$

Where, $P_{Loss}(i)$ are the losses after DG placement, P_{loss}^{b} are the initial power losses, $P_{DG}^{inc}(i)$ is the DG size increase of bus i.

If the LSF value is strictly negative, the system losses are reduced, else, the DG integration has the effect of increasing system losses. Therefore, the buses having lowest LSF values are selected for DG placement.

5. Identifying Optimal Number and Size of DGs

5.1. Constraints

For a safe operation of the distribution system, DG planning must be subjected to the following constraints:

The DG power capacity is subjected to:

$$\begin{cases} P_{DG} \leq P_{Load} \\ Q_{DG} \leq Q_{Load} \end{cases} \quad (10)$$

The bus voltage is considered as follows:

$$V_{min} \leq V_i \leq V_{max}\, , i = 1, \ldots, N \quad (11)$$

Where N is the total number of the buses; V_{min}, V_{max} are minimum and maximum acceptable bus voltages: (0.9 and 1.05 p.u) ± 6% respectively.

5.2. Optimal capacity of DG units

The DG size is computed based on loss power minimization. Indeed, the power loss variation versus DG power capacity can be approximated to a quadratic function as it is shown in Fig.3. The total system loss is reduced by increasing DG power capacity in that location until reaching a minimum value. Therefore, the optimum DG size is obtained when the total system loss is at the minimum point.

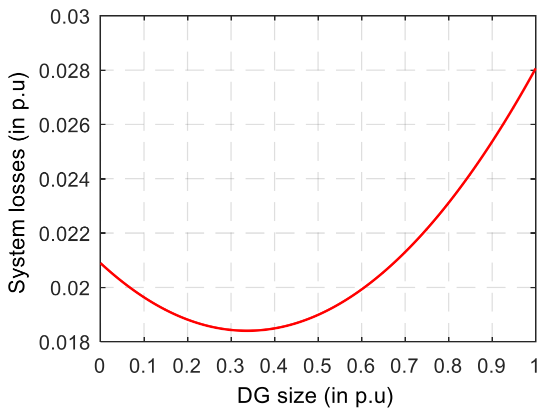


Fig. 3. DG size impact on system losses

The procedure of DG sizing is performed by means of the algorithm illustrated by Fig.4.

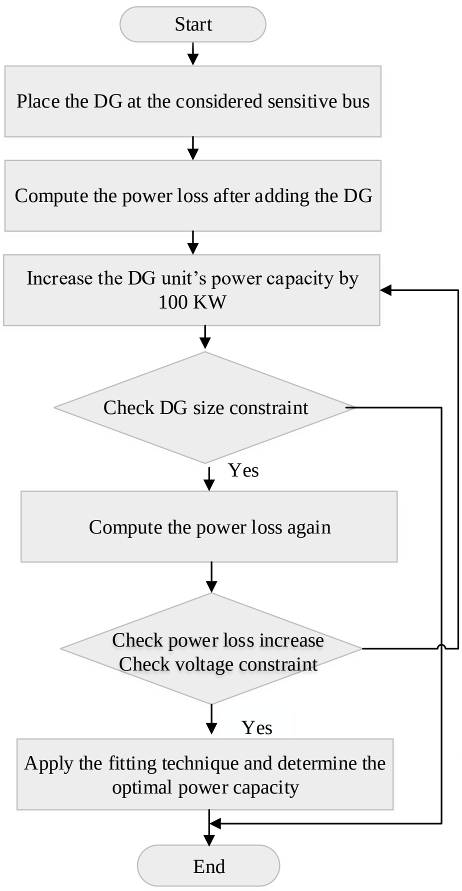


Fig. 4. Optimal DG power capacity computing

5.3. Determination of the optimal number of DG units

A loss improvement index (LI) and a loss reduction index (LR) have been adopted for multiple DG allocation. The LI index is computed by:

$$LI = \frac{PL^{BC} - PL^{DG}}{\text{new DG capacity}} \qquad (12)$$

Where, PL^{BC} and PL^{DG} are the system losses at the base case and after DG integration respectively.

The system losses' decrease after DG unit placement is translated by a positive LI value. However, negative value of LI denotes that additional generation would not give any improvement in losses reduction compared to the base case.

The LR index is expressed by:

$$LR = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}} * 100\% \qquad (13)$$

Where P_{loss} the initial system is power loss and P_{Loss}^{DG} is the system losses after adding DGs.

Based in these indices, the allocation process is given by Fig.5. The optimal number of DGs that can be allocated in the system is obtained for the highest values of LI and LR.

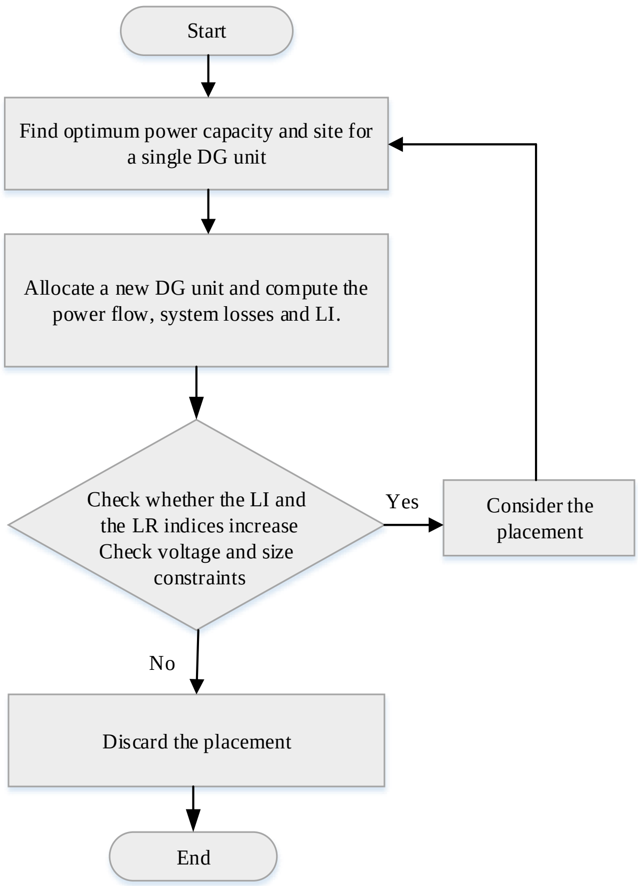


Fig. 5. Multiple DG allocation algorithms

6. Simulation Results and Discussion

6.1. Results of DG placement

The system load has been modified linearly by 5% steps until reaching 45% of the nominal value. Then, the values of the local index Lj have been computed. Based on simulation results of Fig.6, buses 30, 14, 29, 32 and 25 exhibits the highest Lj index. Therefore, they are the most vulnerable ones to voltage drop in load increase case. Accordingly, these buses were chosen as appropriate locations for DG units with reference to voltage stability enhancement.

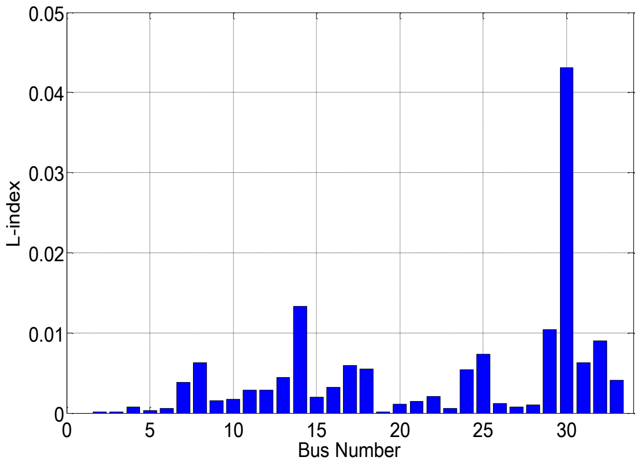


Fig. 6. IEEE 33-bus L-index for voltage stability limit

For the voltage improvement sensitivity method, the VPI is computed for different DG size. The obtained values are ranked in decreased order as presented in Table 2. Based in the results of Table 2, it can be figured out that bus 19 has the highest VPI value and hence, it present a suitable location for DG placement. Fig.7 shows the VPI plots versus DG power capacity for the 4 first sensitive buses having the highest values.

Table 2. VPI values and buses' ranking

Bus No.	VPI	Rank	Bus No.	VPI	Rank
2	0.4769	5	18	0.3562	24
3	0.4763	6	19	0.6242	1
4	0.4615	7	20	0.4410	9
5	0.4515	8	21	0.3851	20
6	0.4009	19	22	0.3754	21
7	0.4179	13	23	0.4799	4
8	0.3545	25	24	0.4850	3
9	0.3564	23	25	0.5336	2
10	0.3490	32	26	0.4184	10
11	0.3501	31	27	0.4155	15
12	0.3532	26	28	0.4180	12
13	0.3518	29	29	0.4181	11
14	0.3532	27	30	0.4165	14
15	0.3502	30	31	0.4140	18
16	0.3529	28	32	0.4145	17
17	0.3568	22	33	0.4150	16

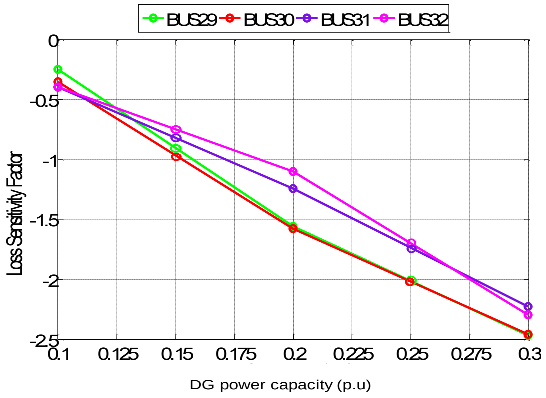


Fig. 7. VPI as a function of DG size

For the third method, the LSF is calculated for various DG capacity. A suitable DG location is obtained for a minimum value of LSF. Table 3 summarize the ranking of different buses with reference to LSF values. The LSF plots of the 4 first buses with minimum values versus DG size are illustrated in Fig.8.

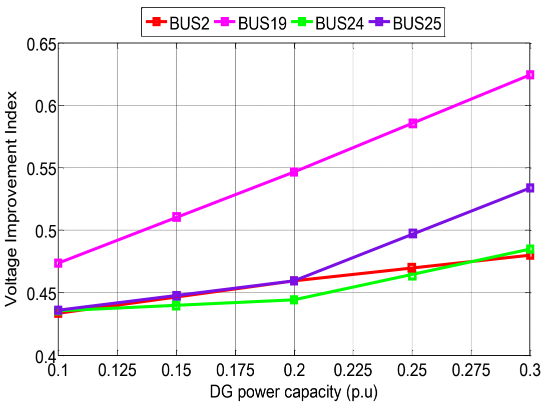


Fig. 8. LSF as a function of distributed generation power capacity

Table 3. LSF values and buses' ranking for DG placement

Bus No.	LSF	Rank	Bus No.	LSF	Rank
2	-0.0089	18	18	0.5824	31
3	-0.5309	12	19	-0.1469	17
4	-0.3922	14	20	0.0138	19
5	-0.5811	10	21	0.0595	20
6	-0.8446	9	22	0.4225	26
7	-0.5346	11	23	-0.4352	13
8	0.6384	32	24	-0.2445	16
9	0.1343	21	25	-0.3069	15
10	0.5239	29	26	-1.0219	7
11	0.4265	27	27	-1.017	8
12	0.1781	22	28	-1.7832	6
13	0.3359	24	29	-2.4693	1
14	0.2705	23	30	-2.458	2
15	0.5775	30	31	-2.225	4
16	0.4857	28	32	-2.296	3
17	0.3813	25	33	-2.053	5

6.2. *Results of single DG sizing*

After finding the optimum locations for the most sensitive buses in the distribution system regarding system losses minimization, voltage stability and voltage magnitude enhancement, the quadratic curve fitting technique is applied on the total system power loss versus DG power capacity curve. Then, the power flow is computed. Power loss variation versus DG size for various sensitive buses of the IEEE-33 distribution system is given by Fig.9.

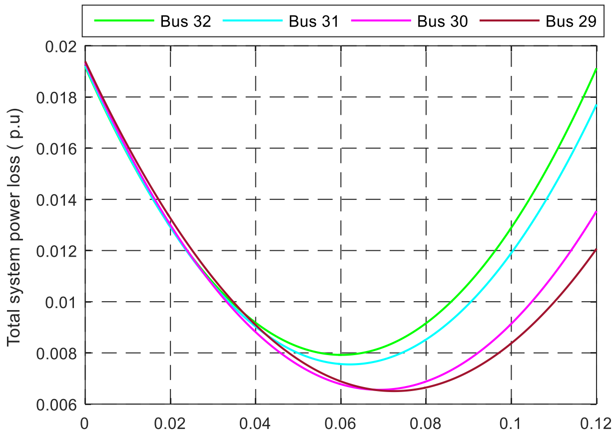


Fig. 9. Total power losses versus DG power capacity and location

Based on the results given by Fig.9, the optimum power capacity of DG units for several locations is outlined in Table 4. The most significant loss reduction is obtained for the sensitive buses determined by LSF method. In addition, the maximum loss reduction is reached for Bus 29 where the LR is about 65.43%.

Table 4. Optimal power capacity of single DG unit

Optimum location	Optimum power capacity (MVA)	LR (Power Loss Reduction) (%)
Bus 14	1.5299	48.33
Bus 19	1.949	3.1
Bus 25	1.533	20.31
Bus 29	2.076	65.43
Bus 30	1.984	65.08

6.3. *Results of multiple DG placement*

Table 5 summarizes the results of multiple DG allocation. Here, the DG number considering losses reduction and loss improvement index has been given. Results have shown that the optimal DG number that can be integrated into the distribution network vary depending on the sensitivity method. For instance, the optimal DG units' number that can be allocated in the network is 2, 1 and 2 for L-index, LSF and VPI methods respectively. Accordingly, by installing two DG units, the active power loss will be reduced compared to the initial case by 65.13% and 21.52% for the L-index and VPI methods respectively. However, for the LSF method the system losses have decreased by 65.43% with the integration of a single DG unit.

Moreover, by adding a new DG unit to the system after reaching the optimal number, the LR is reduced as for the case of the LSF. For some cases, it attains negative values since the active power losses increase continuously and exceeds those obtained for the basic case. These results show that the benefits of additional DG power capacity are decreasing gradually. Table 6 summarize the power demand and the generated output power before and after DG installation for the case of 0.85 power factor.

Table 5. Results for 33 bus distribution network with multiple DGs

	DG number	L-index	LSF	VPI
LI	1	0.0743	0.0714	0.0036
	2	0.0964	0.0084	0.0318
LR (%)	1	65.08	65.43	3.1
	2	65.13	7.36	21.52

6.4. *Impact of DG allocation on maximum loadability and Voltage Stability*

Fig.10 shows the impact of DG units on maximum loadability (λ) and voltage stability margin expressed by:

$$VSM = \frac{\lambda_m - \lambda_{op}}{\lambda_m} \tag{14}$$

Table 6. Summary of power demand and generated power before and after DG integration

Item	Base case	1 DG unit			2 DG units	
		L-index	LSF	VPI	L-index	VPI
Power demand (KW/KVar)	3715 2300	2215 1371.2	2015 1247.4	2115 1309.3	1115 690.1	815 504.3
Generated output power (KW/KVar)	3912 2145.4	2283.3 116.8	2082.2 991.6	2305.9 1151.5	1160.2 398.5	969.7 323.5
Generated output power from DG (KVA)	0 0	1764.3	1999.5	1881.9	3058.1	3410.9
Loading parameter (λ)	3.4	4.08	3.9	3.42	5.81	3.5

The power-voltage (P-V) curve characteristic represented in Fig.10 refers to the voltage stability of a load bus before and after DG integration.

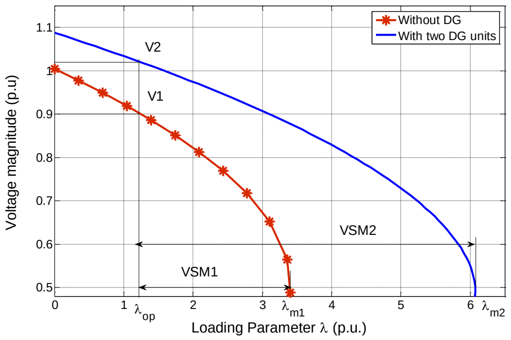


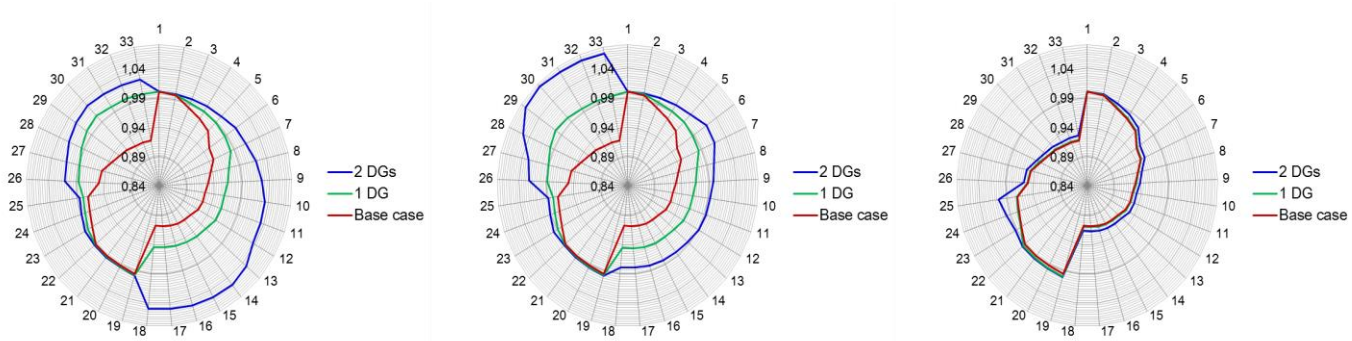
Fig. 10. DG placement impact on maximum loading and VSM for the L-index method

As illustrated in Fig.10, by adding 2 DGs at the optimal locations, the maximum loading parameter and the voltage magnitude moves from $\lambda_{m1} = 3.402$ p.u and $V_1 = 0,95$ p.u to $\lambda_{m2} = 6.074$ p.u and $V_2 = 1.018$ p.u. Thus, the VSM has improved to 82.78%. Table 7 summarizes the results of maximum loading parameter and stability margin for several sensitivity methods.

The voltage profile of the test distribution network is illustrated by Fig.11. Results obviously show that when DG number increases, system voltage profile becomes better.

Table 7. Maximum loading parameter and voltage stability for the sensitivity methods

	L-index	LSF	VPI
λ_m	6.074	4.5261	3.5056
VSM (%)	82.78	77.11	70.16



(a) (b) (c)

Fig.11. Voltage profile of the distribution network for the various sensitivity methods in presence of DG units: (a). L-index , (b). LSF and (c) VPI

6.5. Impact of DG allocation on total system power loss

Table 8 summarizes the influence of DG allocation on system losses. Indeed, the total active power loss is around 197KW at the base case. By adding 2 DGs, the system power loss is reduced to 68.8 KW and 154.6 KW for the L-index and VPI sensitivity methods respectively.

However, for the LSF method, the best losses' reduction was for the case of 1 DG unit with an amount of 68.1 KW. Therefore, the LSF method has shown better results in term of losses reduction than the L-index and the VPI methods. Thus, the system power loss depends greatly on the choice of DG units' location. The DG impact on total system loss is depicted in Fig.12.

Table 8. Total system power loss in KW for the different sensitivity methods

No of DG	L-index	LSF	VPI
0	197	197	197
1	68.8	68.1	190.9
2	68.7	182.5	154.6

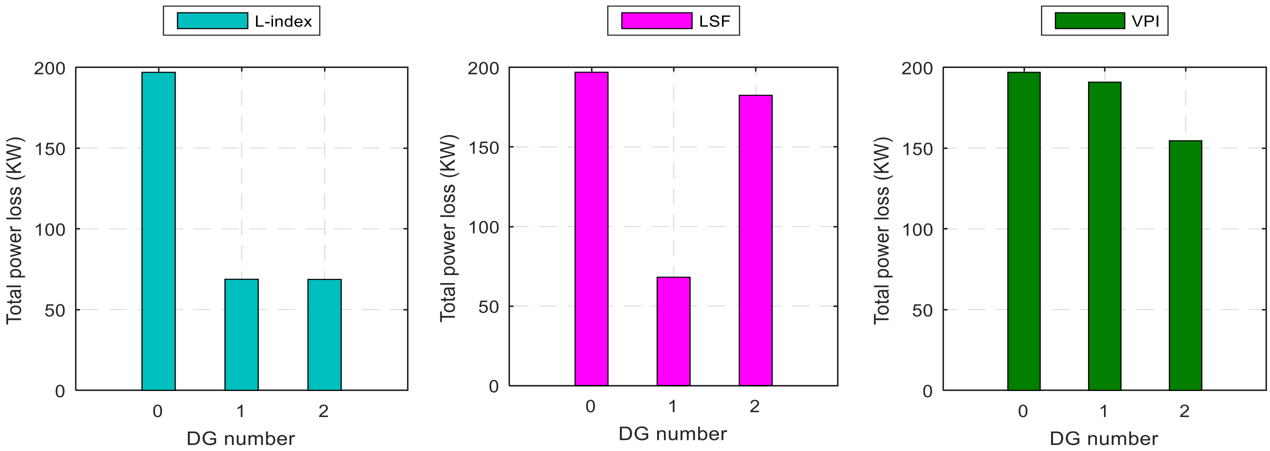


Fig. 12. Impact of DG integration on total system power loss for different sensitivity method

6.6. Efficiency of the proposed methodology

In order to illustrate the effectiveness of the proposed methodology in this paper, the obtained results for the examined IEEE 33-bus system are compared with other approaches from published literature that deal with the same distribution network. In [35], a new approach for optimum allocation and sizing of DG units for system loadability maximization has been presented. Hybrid particle swarm optimization (HPSO) algorithm is proposed to solve the single objective and multi-constraints problem. In [36], authors have proposed a novel analytical method for optimal placement and sizing of DGs. This approach is tested on two different distribution system consisting of 15 and 33-buses. In [37], a novel nature-inspired Whale Optimization Algorithm (WOA) is used to determine the optimal DG size. Objectives taken in consideration are system power losses reduction and voltage profile improvement.

The comparison summary of the obtained results of the proposed methodology with approaches in [35-37] is shown in table 9.

As it can be seen from table 9, the proposed approach present better performance in terms of system losses reduction compared to other approaches for different power factors and DG number. The best result in terms of losses reduction and maximum loadability is obtained for the case of L-index with 2 DG units at 0.8502 power factor. In this case, the loss reduction percentage is 77.06% and the maximum loadability is 5.85 p.u. For the case of single DG unit, the LSF method has shown better performance with a loss reduction percentage of 65.88% and a maximum loadability of 3.9 p.u. This indicates that the proposed algorithm efficiently with high accuracy predicts the optimal location and size of DGs with the maximum power loss reduction percentage and improved voltage stability.

Furthermore, it can be concluded that when the DG unit produce both active and reactive power, the system losses are reduced considerably compared to the case where only active power is injected into the grid. Thus, with respect to the results comparison provided in table 9, it can be said that the proposed approach in this paper has shown better performance and efficiency compared to other techniques.

Table 9. Comparaison of simulations results for the 33-bus distribution system

Item	1 DG				2 DGs		
	Proposed			HPSO [35]	Proposed		HPSO [35]
	L-index	LSF	VPI		L-index	VPI	
Location	30	29	19	8	30 14	30 19 25	16 22
DG power capacity (KVA)	1764.3	1999.5	1881.9	3623.9	3058.1	3410.9	3526.2
PLoss before DG (KW)	197	197	197	210.99	197	197	210.99
PLoss after DG (KW)	68.3	67.2	190.9	131.85	45.2	154.7	87.65
Loss reduction %	65.33	65.88	3.096	37.51	77.06	21.47	58.46
λ max (p.u)	4.08	3.9	3.42	4.31	5.81	3.5	5
Power factor	0.8502	0.8502	0.8502	0.8502	0.8502	0.8502	0.8502

Item	1 DG				2 DGs		
	Proposed			Analytical approach [36]	Proposed		Analytical approach [36]
	L-index	LSF	VPI		L-index	VPI	
Location	30	29	19	6	30 14	19 25	6 14
DG power capacity (KVA)	1579	1789.5	1684.2	2968.46	3021.9	3571.4	2396.9
PLoss before DG (KW)	197	197	197	197.94	197	197	197.94
PLoss after DG (KW)	80.7	78.2	191.1	139.16	60.8	160.3	131.53
Loss reduction %	59.04	60.30	2.99	29.69	69.14	18.63	33.55
λ max (p.u)	4.04	3.84	3.42	-	5.85	3.51	-
Power factor	0.95	0.95	0.95	0.95	0.728	0.728	0.728

Item	1 DG							
	Proposed			WOA [37]	Proposed			WOA [37]
	L-index	LSF	VPI		L-index	LSF	VPI	
Location	30	29	19	15	30	29	19	15
DG power capacity (KW/KVA)	1500	1700	1600	1061	1666.7	1888.9	1777.8	1255.89
PLoss before DG (KW)	197	197	197	210.9974	197	197	197	210.9974
PLoss after DG (KW)	111.1	109.2	192.2	133.503	72.5	70.5	190.9	108.406
Loss reduction %	43.6	44.57	2.44	36.73	63.2	64.2	3.1	48.62
λ max (p.u)	3.76	3.98	3.41	-	4.07	3.88	3.41	-
Power factor	1	1	1	1	0.9	0.9	0.9	0.9

7. Conclusion

In the present paper, the impact of DG units on power network was studied considering losses reduction and voltage profile and stability improvement. Analyses were carried out on the 33 bus distribution system using MATLAB/PSAT toolbox. The suitable buses' locations of DG units were selected by means of L-index, VPI and LSF methods. The best DG units' locations correspond to the buses having maximum L-index and VPI values and minimum values of LSF. Based on the selected locations the optimal power capacity of single DG unit was determined using the quadratic curve fitting technique. A loss improvement index and a power loss reduction index based algorithm has been proposed for multiple DG allocation. Results have shown significant enhancement of the distribution system efficiency while using proposed algorithms.

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