

Optimal Placement of PV-Distributed Generation units in radial distribution system based on sensitivity approaches

Sirine Essallah, Adel Bouallegue and Adel Khedher

Advanced Systems in Electrical Engineering Laboratory SAGE, ENISO, University of Sousse, Tunisia

BP 264, 4023 Riadh City, Sousse, Tunisia

sirinesallah@gmail.com adelbouallegue@gmail.com adel_kheder@yahoo.fr

Abstract—Power utilities are facing major challenges as the demand of power system is growing exponentially. Therefore, the main attention is focused on Distributed Generation (DG) as they are providing many opportunities for the existing distribution system and becoming one of the key drivers of dealing with its issues. Voltage profile improvement, system loss reduction, reliability enhancement and electricity providing during peak load are the main challenges facing distribution systems. Thereby, the integration of renewable DGs such as Photovoltaic panels can be a good alternative to deal with these challenges. However, DGs integration benefits depend greatly on their placement and control strategy in the network. This work aims at selecting the most sensitive buses of the distribution network for DG units' allocation by means of three different sensitivity methods based on system losses reduction, voltage stability and voltage profile improvement. Advantages of integrating distributed generation are examined using voltage collapse index (L-index), loss sensitivity factor (LSF) and voltage performance index (VPI). These methods were executed on a typical IEEE-39 bus test distribution system using MATLAB tool box PSAT and the results were comparatively analyzed and discussed.

Keywords— Distributed generation (DG), Optimum location, Power loss reduction, Sensitivity.

I. INTRODUCTION

The main interest of power system is to insure the balance between energy supply and demand in the network with maximum reliability and low cost.

In recent years, considerable attention has been focused on distribution system' planning [1], to reduce the power, energy losses, capital investment involved and to provide better quality supply to consumers have been widely studied. Therefore, a healthy power system should be stable at any time while satisfying various operating criteria. Recently, the main challenge of the power system is the load demand increasing in various sectors such as residential, commercial and industrial [2] [3]. Thereby, the voltage stability and collapse problem caused by this increase in load demand has gained a lot of interest given the fact that major blackouts nowadays are caused by this phenomena [4]. Moreover, the active power loss can directly affect the network's performance [5]. Thus, the loss reduction has become the major concern of power utilities recently.

Therefore, DG has emerged as an immediate solution because of its promises to supply eco-friendly, reliable and cost effective electricity to the customer. It offers a prospective alternative to many of these new challenges and has the ability to decrease power losses, to enhance voltage profile, to improve stability, to decrease congestion in feeders and to improve reliability and security of the network [6] [7]. However, studies have proved that the integration of DGs at non-optimal locations can create a reverse flow of power towards distribution substation. This will results in an increase in system losses and overload conditions may occur in the system [8] [9]. System loss reduction, voltage stability and voltage profile improvement are the most significant factors in enhancing the performance of power transmission in distribution systems. Within this context, many researches have been focused on presenting new strategies of DG placement in recent years. In [10], a new analytical approach based on a novel power stability index has been presented for DG allocation. In [11], the DG units were placed at the weakest buses of the system for voltage stability improvement. The most sensitive buses of the network were selected based on a new voltage stability index [12]. A multi-objective problem for power loss reduction, reliability increasing and voltage profile improvement has been introduced in [13] to determine the most significant locations for DG units placement. In [14], the best locations and power capacity of DGs has been determined by means of loss sensitivity factor method. In [15], the authors have presented a voltage stability criterion for DG placement and an optimization technique based on loss reduction for DG power capacity. In [16], the power loss sensitivity technique was used to identify the optimal power capacity and placement of DGs.

In this work, we have attempted to identify the optimal bus location for DG placement considering power loss and system voltage sensitivity. Three different sensitivity methods were presented; the voltage collapse index (L-index), the loss sensitivity factor (LSF) and the voltage performance index (VPI) approaches. DG integration impact on voltage stability, system loss and voltage profile has been analyzed and efficiency of DG allocation based on these methods has been shown on an IEEE39-bus standard test system.

This paper is subdivided in five main sections. In the next section, three different sensitivity methods for DG placement are presented. Section III describes the test distribution system chosen for analysis. In section IV, the simulations are carried

out and discussed to test the performance of the presented methods. At the end, conclusions are summarized.

II. IDENTIFYING OPTIMAL NUMBER AND LOCATION OF DG UNITS USING SENSITIVITY METHODS

Since distribution system are facing many problems in recent years, further problems such as system loss increasing and lower voltage magnitude owing to non-optimal placement of DG units cannot be tolerated. Thus, it is crucial to identify the best location for DG integration in distribution system. In this regard, three different methods based on voltage improvement profile and power loss reduction have been presented for DGs' allocation. These methods are respectively:

- Voltage stability enhancement sensitivity method: voltage collapse index, L-index.
- Voltage profile improvement sensitivity method: voltage performance index, VPI.
- Loss reduction sensitivity method: loss sensitivity factor, LSF.

The ranking of various locations for optimal DG placement have been determined for each one of those methods where higher values of L-index and VPI correspond to an appropriate location for DG placement. However, a lesser value of LSF indicates the same assertion.

A. Voltage stability enhancement sensitivity method

In power systems voltage instability problems are caused by the heavily loaded operating situation and contingencies [17]. In this field, many studies were carried out to find out efficient index for voltage stability in order to expect voltage collapse when the distribution system is exposed to a sudden load increasing or face some incidents [18] [19]. To have an idea about the most sensitive buses in the network, a voltage collapse index is used to get a feel on the best locations of DGs in distribution system in the case of overload conditions and contingencies. Therefore, different predictive strategies for voltage stability and voltage collapse have been studied in many researches. However, the L-index method proposed in [20] has gained the main interest due to its simplified numerical calculations and its expressive results [21] [22].

The main objective of L-index method developed by Kessel et al. in [20] is to find a quantitative measure for the estimation of the distance from actual state of the system to the stability limit. The aim of computing the L-index is to select the weakest bus of the system regarding voltage sensibility. This means that the node having the lower voltage value in comparison with other nodes is identified as the most sensitive bus in the system which is the most one that may be affected by the load demand increasing.

The L index is given by the following equation:

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

Where, α_L is the set of consumer nodes and α_G is the set of generator nodes, V_j is the complex voltage for load node j , V_i complex voltage for generator node i , F_{ji} is the load participation factor.

L_j is a local indicator that determinates the busbar from where collapse may originate. The L-index margin of the calculated value varies from 0 to 1. Considering this value, the voltage stability margin can be estimated. If the calculated value is close to 1 then the system is subjected to a voltage collapse whereas the estimated value approaches to 0 then we have a no-load condition. Otherwise the system is under normal operating condition. Thereby, the bus having the most important value of L-index will be considered as the most sensitive one in the network.

B. Voltage profile improvement sensitivity method

Distributed generation units are able of injecting and absorbing both active and reactive power in the distribution network. They have the ability to maintain and to improve voltage profile at different power factor [23]. The variation of the bus voltage versus DG power capacity is illustrated by Fig.1.

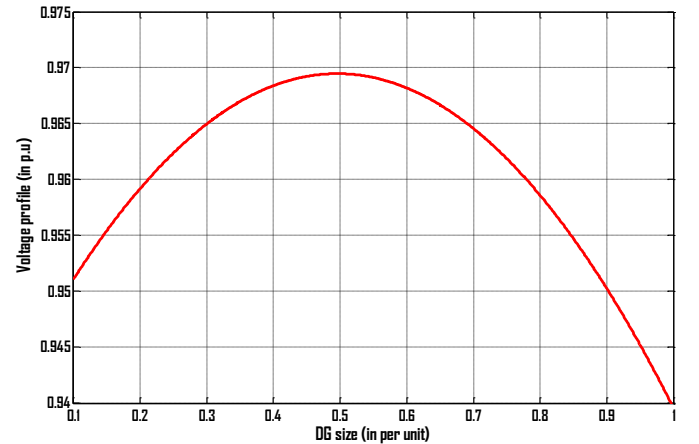


Figure 1. DG size effect on bus voltage magnitude

The ranking and selection of load buses is obtained with reference to contingency selection by computing a severity index known as performance index. There are several types of performance index in literature [24] but in our study we were restricted to the following voltage performance index (VPI) expressed as follows [24]:

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

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

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

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

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

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

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

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

The VPI index has a small value when all line flows are within their limits and a high value when there are lines overloaded. This approach selects the best locations for DG to sustain the voltage close to its nominal magnitude. The best locations for installing DG with reference to voltage improvement profile are in the buses having higher VPI value.

C. Loss reduction sensitivity method

The main objective of transmission subsystem is to transmit the generated power to load centers with the greatest possible efficiency. However, power loss in transmission lines is rising continuously owing to various factors. The most of power systems are strained to use better their available transmission lines before installing new ones. Therefore, power loss is not avoidable, but can be reduced to an optimum level due to DGs. Otherwise, researches[25] [26] have indicated that improperly DG allocation and power capacity identification can lead to an increase in system power loss. Hence, it is crucial to find out the best location of DGs in order to reduce system power loss. The variation of the power losses versus DG power capacity is illustrated by Fig.2.

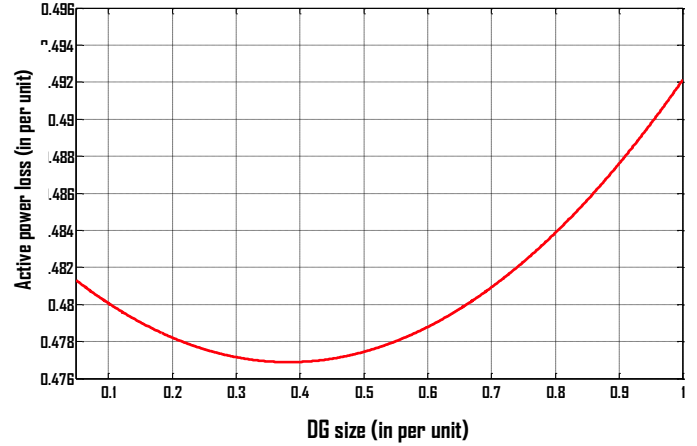


Figure 2. DG size effect on total system power loss

Loss Sensitivity Factor (LSF) method has been broadly widespread in the field of capacitor placement [27]. The application of this method in DG allocation is recent and has been reported in [28]. The main objective of this method is to identify the best locations for DG integration in distribution system based on power loss minimization. The LSF owing to injection by DG at i^{th} bus can be determined as follows:

$$LSF_i = \frac{\Delta P_{\text{loss}}}{\Delta P_i} = \frac{P_{\text{loss}}^i - P_{\text{loss}}^b}{P_{DG,i}^{\text{inc}}} \quad (9)$$

where, P_{loss}^i is the system loss with increment in DG capacity at i^{th} load bus, P_{loss}^b is the total system loss for base case, $P_{DG,i}^{\text{inc}}$ is the increment in DG capacity at i^{th} bus.

If this index have a strictly positive value the DG injection has the impact of increasing system loss, else, if this index has a strictly negative value the loss system is reduced, otherwise, the DG integration has no effect. Based on (9), a lower LSF value refers to a suitable DG location considering power loss minimization.

D. Identifying the optimal number of DGs to be added to the network

The optimal DGs' number to be added to the network is determined considering the system's power loss. Usually, the power loss is minimized by the integration of DGs in the network. Therefore, if the number of added DG units rise up, then the active power loss is minimized significantly. Thus, the best number of DGs is determined by the following procedure. In the beginning, we compute the active power loss of the distribution system after adding one PV-DG unit. Next, in every iteration a new DG unit is added at the system and system power loss is computed again. When increasing the number of DGs, the total power loss is checked regularly. If it has a lower value than the previous loss, then we increase the DG's number. This procedure is repeated until we reach a

higher value than the preceding one. The number of DGs integrated into the distribution system before the total power loss increase again refers to the optimum DG number to be integrated to the network.

III. TEST SYSTEM DESCRIPTION

Fig.3 shows the radial 39-bus distribution system used in simulations. The base configuration of the system consists of

39 buses with 10 generators. The system has 12 transformers, 34 transmission lines and 19 load points. The total real power for base configuration is 6145.97 MW and 1363.41 Mvar.

The IEEE-39 bus system is given by Fig.3.

The studies were carried out using PSAT Matlab based Simulink & Simulation tool used for Power System Analysis [29]. Power flow by Newton-Raphson method and Continuation Power Flow (CPF) method [30] of MATLAB tool box PSAT are used.

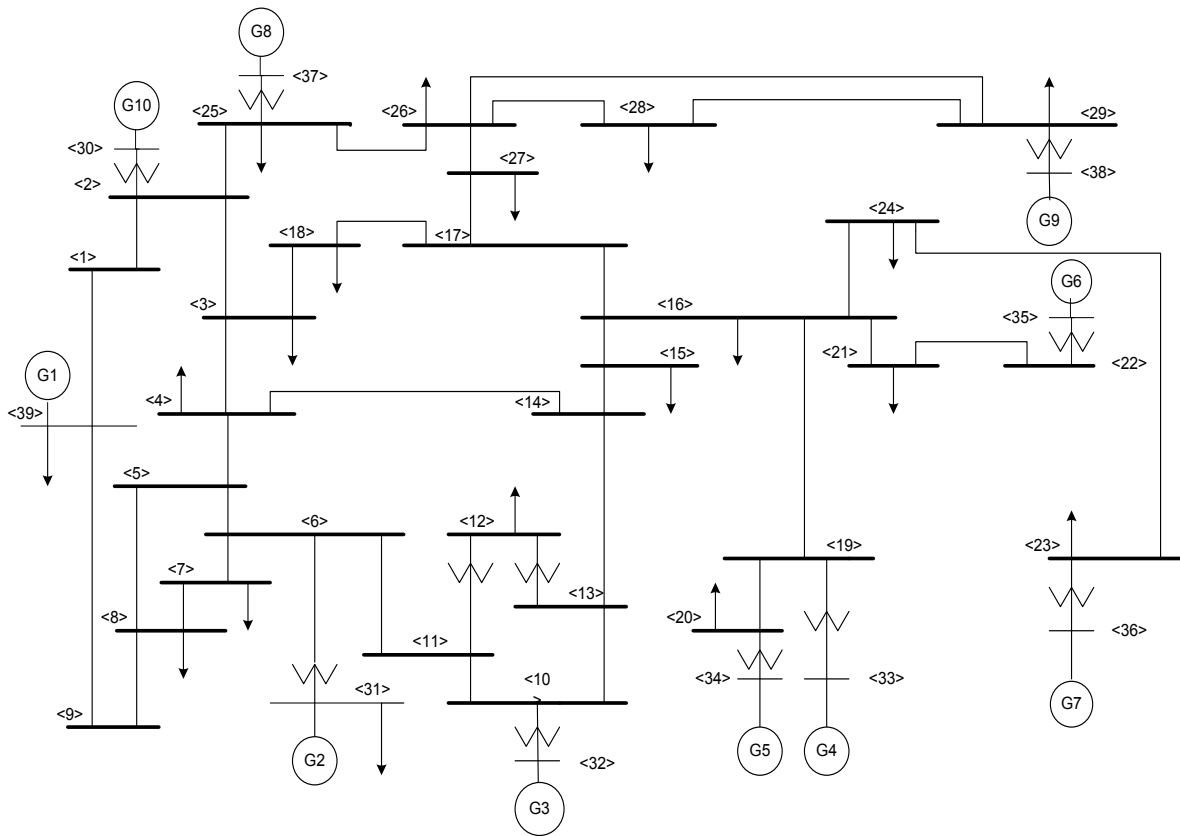


Figure 3. The base configuration of the 39-bus radial distribution system

IV. RESULTS AND ANALYSIS

A. DG allocation results by means of L-index method

Firstly, the IEEE-39 bus system was modeled on PSAT using standard test data and before adding DGs to the distribution system, the feeders' loads were varied linearly from 5% to 45% of the initial case. A power flow study was performed by means of Newton-Raphson method for every changing of the load values and results were recorded.

Based on the observation of power flow results it is difficult to determine the defected areas in the network.

Thereby, we have proceeded to the 2D and 3D voltage magnitude contour plot of the power flow analysis provided by PSAT Toolbox in order to identify which area is subjected to voltage stability problem. Low voltages are generally displayed in red, Valleys are easily recognized as "depressed" regions and hills possibly indicate congestion. As depicted in Fig.4, we can see that the voltage magnitude of bus 4, 5, 6, 7, 8, 10, 11, 12, 13 and 14 are the lowest ones in the network for both cases; load increase or decrease. Their voltage levels continue to decrease when varying the system load. This continuous fall in voltage magnitude may result on system voltage collapse.

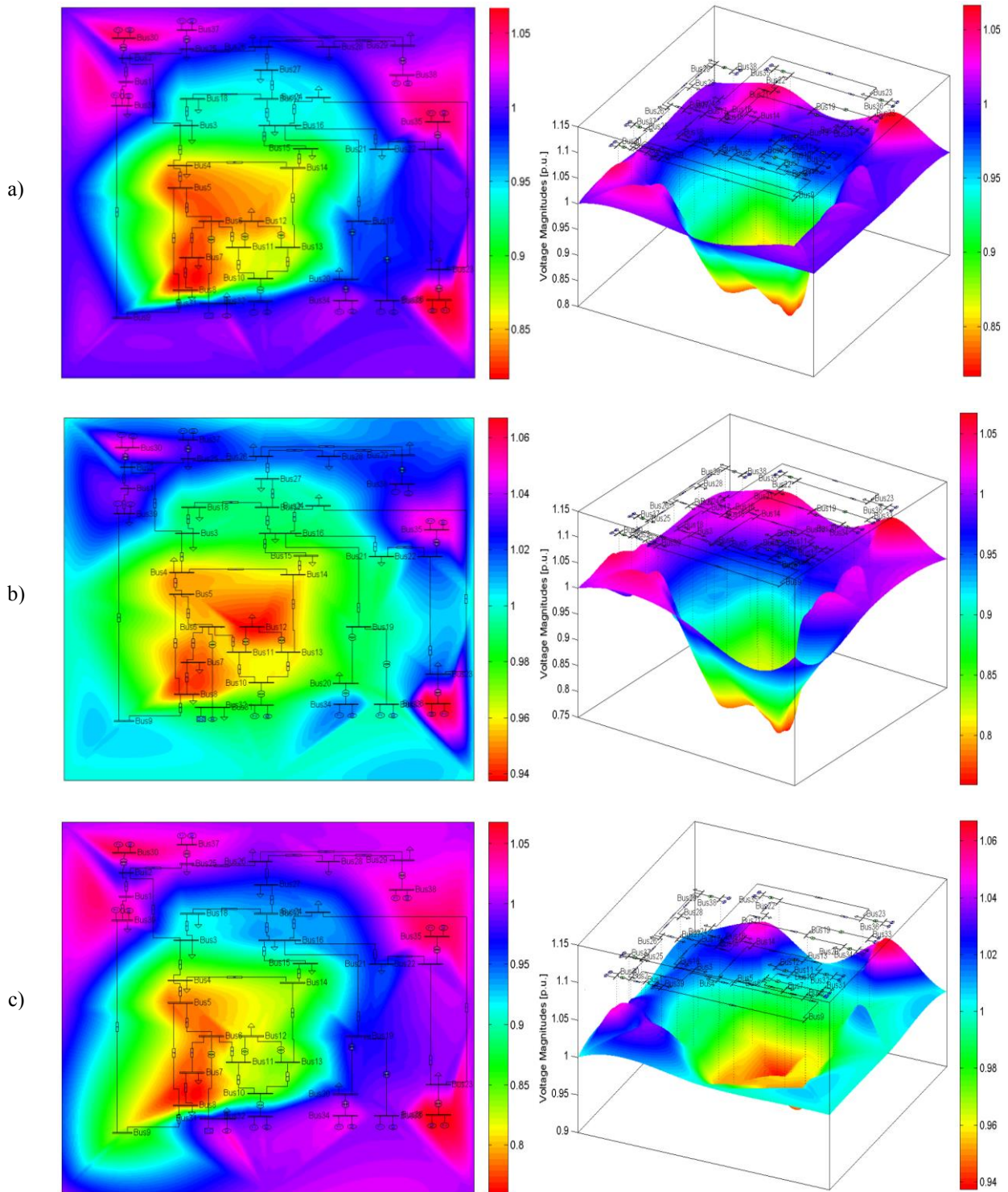


Fig.4. 2D and 3D voltage magnitude contour plot of the IEEE-39 bus test system for: (a: the base case), (b: a load increasing of 45%) and (c: a load decreasing of 45%)

Then we have computed the L-index values L_j of the IEEE-39busbar test system in order to confirm the conclusions made from the analysis of voltage magnitude contour plot. From the summarized results of Fig.5, it can be seen that bus 4, 5, 6, 7, 8, 10, 11, 12, 13 and 14 exhibits the most important L_j index, which denotes that they are the weakest buses on the network and which may cause voltage collapse when increasing the loading parameters. Therefore, these selected buses present the most suitable locations of DGs regarding voltage stability. However, the optimum number of DG units to be integrated in the distribution system in the basis of the process described in section II is four. The buses having the highest L_j index and which are 5, 6, 7 and 8 are considered.

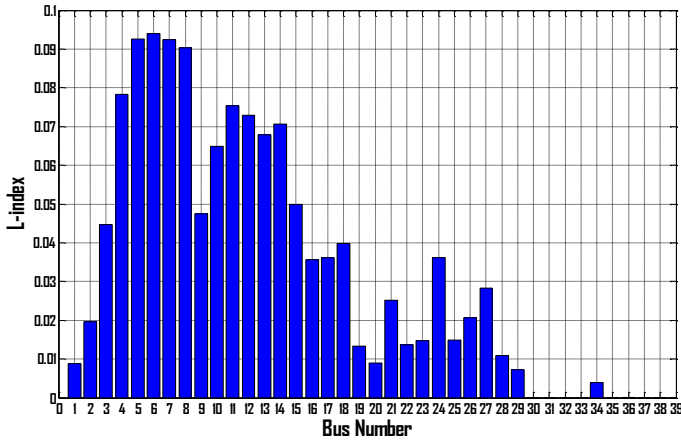


Figure 5. IEEE 39-bus L-index for different buses

Fig. 6 shows the influence of DG units on voltage stability margin (VSM) and maximum loading parameter defined as: λ is the loading parameter which corresponds to load increase rates and VSM is expressed by the following equation:

$$VSM = \frac{\lambda_{max} - \lambda_{op}}{\lambda_{max}} \quad (10)$$

The PV curve represented by Fig.6 refers to the voltage stability at bus 6 with and without DG integration. As it can be seen by adding four DG units at weakest buses of the system, the maximum loading parameter λ_{max} moves from $\lambda_{max1} = 1.14 p.u$ to $\lambda_{max2} = 1.19 p.u$ and the voltage moves from $V_1 = 0,9508 p.u$ to $V_2 = 0,9597 p.u$. Thus, the voltage stability margin has improved to 15.97%.

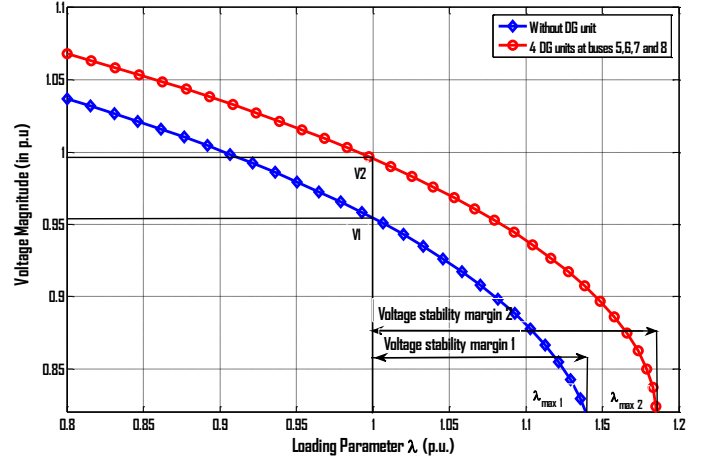


Figure 6. DG placement effect on full loading and VSM

B. Results for DG allocation by means of voltage performance index method

The VPI is computed at every load bus for various DG capacities. The obtained values are ranked in decreased order. The ranking order is strongly linked to the loading condition of the system which means that a bus can have different rank depending on the injected power capacity of DG. The highest VPI value denotes the best locations for DGs' placement regarding the voltage magnitude improvement. Table I summarize the VPI values and the rank of the various load buses. Here, the optimal number of DGs to be added to the network is also four. Load buses 5, 7, 12 and 13 have been chosen as optimal locations for DG integration. Fig.6 shows the VPI plots of the selected buses.

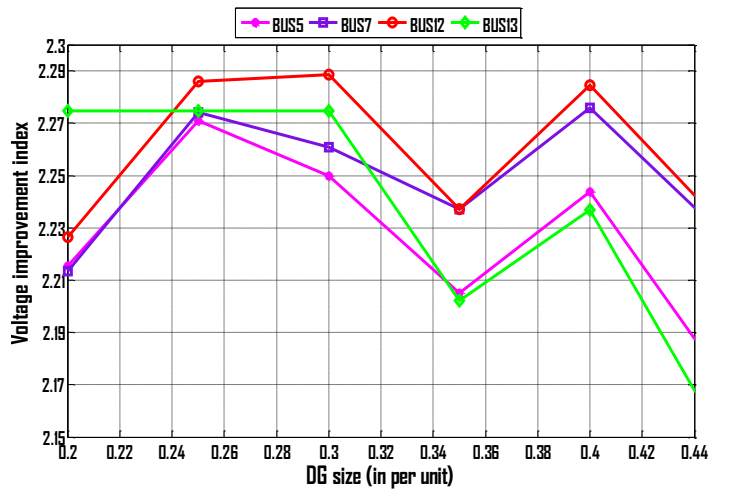


Figure 7. VPI versus DG power capacity

TABLE I: LOAD BUSES'S RANKING FOR DGs ALLOCATION REGARDING VPI

Bus. N°	VPI	Row	Bus. N°	VPI	Row
1	2.18611537	5	16	2.01249061	18
2	2.05429579	13	17	1.94142304	19
3	1.89912317	21	18	1.9246565	20
4	2.08509879	12	19	1.88142904	22
5	2.24375864	3	20	1.76255448	24
6	2.14652674	9	21	1.82562796	23
7	2.27588065	2	22	2.02016016	17
8	2.17430504	6	23	2.02669829	15
9	2.16897866	7	24	1.68768768	25
10	2.13839708	10	25	2.02753768	17
11	2.14820557	8	26	1.4573511	27
12	2.28442142	1	27	1.58061769	26
13	2.23697445	4	28	1.37292114	28
14	2.11231492	11	29	0.63257931	29
15	2.02137272	16			

In the aim to verify the influence of DG unit's integration on voltage profile, the voltage variation at the optimum locations with and without DG units is portrayed in Fig.8. The results demonstrate the considerable enhancement in voltage magnitude in the presence of DGs. In fact, as it can be seen in the figure below for the integration of the first DG unit at bus number 12 the voltage magnitude of the other buses has increased. The most important rise is in the load bus where the DG unit is located and the same assertion is to be made for other DG locations.

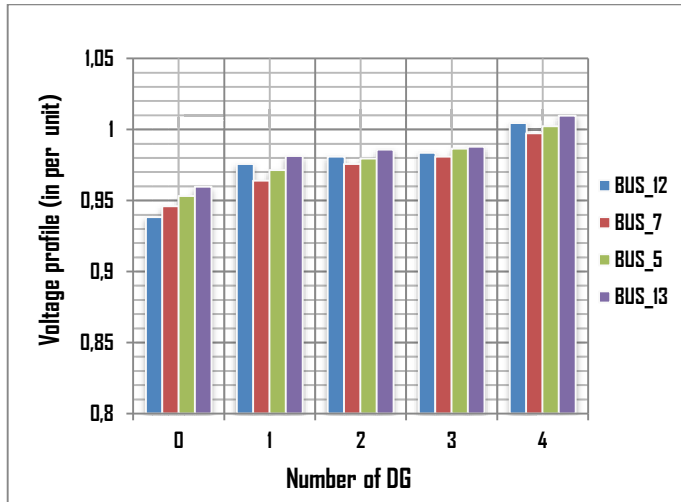


Figure 8. DG penetration effect on voltage magnitude

C. Results for DG allocation by means of LSF method

LSF is computed at every load bus for different DG size. The lowest LSF value refers to an appropriate location for DG unit. LSF values are ranked in ascending order for various load buses for a DG size of 0.4 p.u and results are summarized in table II. This ranking may vary when the DG capacity

increases. In this basis, the system operator can increase or decrease the operating DG capacity. Fig.9 shows the plots of LSF for the four first buses having the minimum values as a function of DG size.

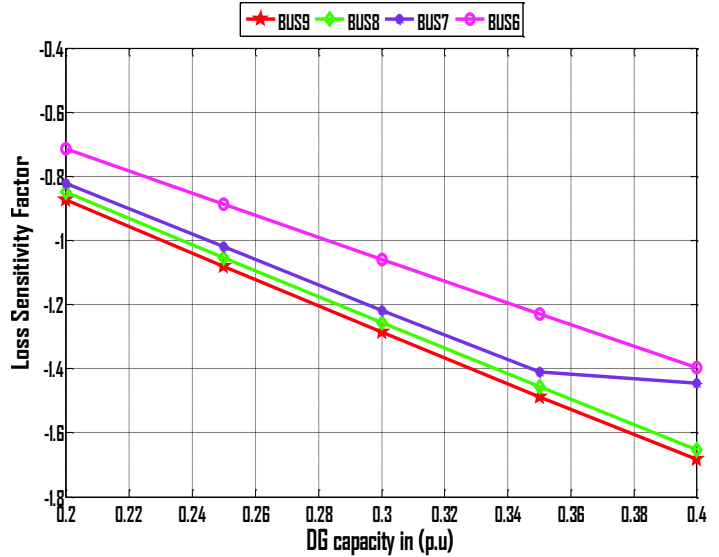


Figure 9. LSF versus DG size

TABLE II: LOAD BUSES RANKING FOR DGs ALLOCATION REGARDING LSF

Bus. N°	LSF	Row	Bus. N°	LSF	Row
1	-0.692	16	16	0.61	26
2	-0.842	14	17	0.528	25
3	-1.008	12	18	0.482	23
4	-1.286	6	19	-0.494	21
5	-1.292	5	20	-0.516	20
6	-1.398	4	21	-0.722	15
7	-1.444	3	22	-0.598	19
8	-1.652	2	23	-0.602	18
9	-1.684	1	24	-0.856	13
10	-1.146	9	25	-0.66	17
11	-1.24	7	26	0.664	27
12	-1.1	10	27	0.496	24
13	-1.046	11	28	0.814	28
14	-1.154	8	29	1.01	29
15	0.404	22			

As represented in Fig.10, the impact of DG units' integration in the network on the system power losses is clear. The total active power loss is around 0.49 p.u at the base case and which is reduced. The reduction depends on the position and the number added DGs.

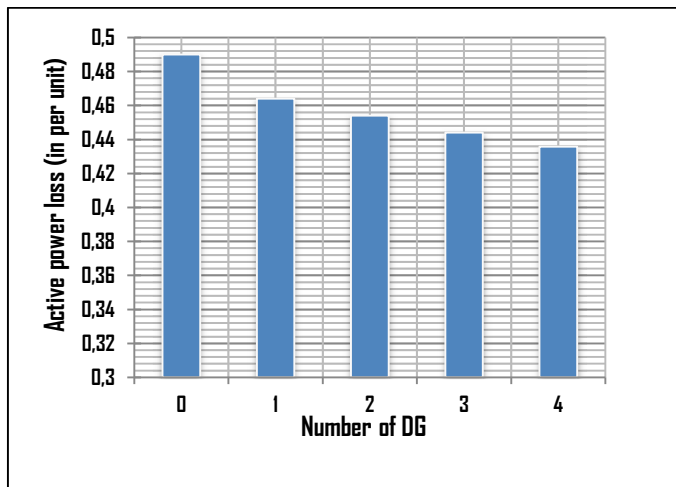


Figure 10. DG injection effect on total power loss

V. CONCLUSION

In this work, the DG's impact on distribution system has been examined regarding voltage stability enhancement, power loss minimization and voltage magnitude improvement. The suitable locations for DG placement were selected based on three sensitivity methods. The L-index, VPIs and LSFs have been evaluated for every load buses and best DGs' locations have been identified with reference to higher values of L-index and VPI unlike LSF where lower values refers to optimal locations. The results of these methods applied to the IEEE 39 bus system have shown the efficiency of these approaches in improving voltage magnitude, reducing power losses and increasing system loading capacity. Therefore, distributed generation can be a promising solution to deal with distribution system issues and improving power quality.

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