DG Allocation in Distribution Networks with Considering of Voltage Stability Improvement and Loss Reduction

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Abstract. *The improvement of the line Load-ability (LL) for voltage stability establishes the main criterion for distribution networks. The Distributed Generation (DG) resources play an important role in the supply of active and reactive power loads, bus voltage profiles, and voltage stability in distribution systems. In this paper, a new technique has been proposed for optimization of the location placement and sizing of DGs, considering the Generalized voltage Stability Index (GSI) to determine the maximum load-ability. Also, an analytical method has been applied to infer the effects of DGs on the distribution systems' characteristics. The study also considers three types of DG modes, which are voltage control mode (PV mode), constant power mode (PQ mode), and also voltage control mode with reactive power constraint (PV mode with VAR constraint). The proposed method is applied to 12-bus, modified 12-bus, 69-bus and 94-bus radial distribution systems.*

Keywords

Distributed Generator, Generalized voltage Stability Index, Loadability margin, Radial Distribution Networks.

1. Introduction

Voltage stability studies practically express the maximum loadability of a power system. In this respect, different voltage stability indices have been developed with the aim of assessment of the boundary limits of the voltage stability [1], [2] and [3]. Furthermore, specific optimization approaches have been suggested for the location of the installation of auxiliary equipment in accordance with given indices and are used for improving voltage stability in Radial Distribution networks (RDS). Recently, several solutions have been discussed/proposed that rectify the passiveness of RDS by embedding electrical sources with small capacities to improve system reliability and voltage regulation [4]. Such embedded generation in the distribution systems is called dispersed generation or Distributed Generation (DG), which is expected to play an increasing role in emerging electrical power systems. It is understood that optimum planning of DG units for employing in existing distribution systems will have both economic and technical benefits with the prevention of problems on the reliability and operation of the system [5].

According to a report by Electric Power Institute, a DG is defined as a power generation unit producing powers spanned from "a few kilowatts up to 50 MW" [6]. Several adopted technologies of DG are microturbines, small gas or hydro turbines, fuel cells, the wind, and solar energy. Studies predict that DG will constitute a significant percentage of the new generations on the lines being installed [5], [6] and [7]. The significant technical benefits of the installation DG are reduced line losses, voltage profile improvement, increased overall energy efficiency, improved power quality, enhanced system reliability, and security. In order to achieve the aforementioned benefits, the DG's size and location have been optimized using different approaches such as analytical approaches [8], [9] and [10], heuristic [11], [12] and [13], artificial intelligence, Genetic Algorithm (GA) and fuzzy methods [14], [15], [16] and [17].

DG units are mostly connected at the distribution level due to their locally available resources and small scale. Therefore, the penetration level of distributed generation units in distribution systems is increased. Accordingly, connections of DGs to the power system are notably improved on the power systems' stability issues (i.e., angle, frequency, and voltage stability) [18] and [19].

A dynamic programming algorithm in [8] is proposed to locate the optimal sites with the maximum profits attained in the objective function. The authors in [9] present the analytical approach for the optimal location of the best type of DG that can enhance the voltage stability of distribution systems. They demonstrated that using the voltage sensitivity index and bus participation factors derived from continuation power flow and Modal Analysis could optimize DG units. Hedayati et al. [10] based their approach via an objective function installed on the DG units, with a certain capacity in these buses. They explained that the impact of DG technologies on static voltage stability and analysis tools for studying voltage stability is necessary.

Tabu search technique for discovering the optimal site and size of the DG unit with loss minimization as its objective function is proposed in [11]. A metaheuristic approach using Backtracking Search Algorithm (BSA) is proposed for optimal siting and sizing of DG unit in order to reduce power loss and improve the voltage profile in [12]. The author selected a number of nominated crisis buses based on the power loss index to reduce time consumption. In [13], a meta-heuristic method based on Symbiotic Organism Search (SOS) is presented to determine the optimal number, location and size of DG units in distribution systems. Using a loss sensitivity factor method to determine the optimal location of DGs, they have used the SOS method to calculate the optimum size. A methodology of combination utilizing the GA method with other techniques for optimal DG planning is described in [14]. They also utilize electrical network losses and the acceptable reliability level in the objective function. In general, [15] explained the linear programming method on the GA-based optimization procedures in order to be able to allocate and dimension DGs, taking into account the different objective functions. Also, the combination of GA and PSO is presented for optimal location and capacity of DG by taking into account multi-objective constraints, such as voltage stability and power losses [16]. In [17], a multi-objective optimization method is used to maximize voltage stability, improve voltage profile, and reduce losses in the radial distribution system. The authors performed the optimization program to achieve optimal results, using the bat algorithm based on the weight sum method and a fuzzy algorithm technique.

However, most analyses have been performed based on constant power mode (PQ mode), and the other modes of DG have been neglected. The author in [20] was considering these three modes of DG for analyzing DG sizing by reconfiguration technique to improve the voltage profile and reduce power losses using a simplified artificial bee colony. Also, by using BSA optimization and a multi-objective allocation, the optimal placement of multi-type DG units is established in radial distribution networks [21] and [22]. In order to identify the initial DG's locations, a set of fuzzy expert rules by considering loss sensitivity factors and bus voltages is taken into account. It is shown by suggestion of DG type that capability to supply reactive power in the network, the power factor, voltage profile and static voltage stability are certainly improved.

The main contribution of this paper is the introduction of a Generalized voltage Stability Index (GSI) as a new index to optimize the location and sizing of DG in order to achieve loss reduction and maximum loadability in practical networks. The method in this paper is based on the analysis of sweep backward/forward power-flow in distribution systems and the determination of the most sensitive buses to the voltage collapse. By installing DG units in critical buses via an iterative algorithm and an objective function, the capacity of the DG is calculated to find its optimum location. The proposed method is applied on a 12-bus modified system, 69-bus and a real 94-bus distribution system, such that to optimize the sizing of DGs in order to reduce the total system power loss and increase load-ability of the corresponding bus.

This paper is organized as follows: in Sec. 2. , the DG placement method based on introducing a generalized voltage stability index is presented to identify the critical buses in the distribution; the impact of distributed generator placement on voltage profile, reduction of system losses, and voltage stability improvement is described in Sec. 3. , the proposed algorithm for optimal sizing and sitting of DG is elaborated upon in Sec. 4. In Sec. 5. , the results and discussions are compared with previous work. Finally, the conclusion is given in Sec. 6. .

2. Voltage Stability Review

Voltage stability has been defined by the System Dynamic Performance Subcommittee of the IEEE Power System Engineering Committee as [23]:

"Voltage stability is the ability of a system to maintain voltage so that when load admittance is increased load power will increase and so that both power and voltage are controllable".

To study the voltage stability, there are theoretical explorations of a simple system combined of two buses, as shown in Fig. 1. The system under investigation has been modeled simply by a Thevenin impedance and an electric source, represented by Z_s and V_s, respectively; [24]. This equivalent circuit can provide clearer voltage stability analysis for detection of critical buses in a real distribution system and is helpful for computational time [25]. The voltage for each receiving distribution bus can be written as:

$$\vec{V}_{r,i} = \vec{V}_{s,i} - \vec{Z}_{s,i} \cdot \vec{I}_{r,i}, \quad i = 2, \ldots, n, \tag{1}$$

where Z_s is the Thevenin impedance of the terminated line of each bus from the main substation, and it can be calculated by the following equations:

$$\vec{S_s} - \vec{S_r} = \vec{Z_s} \cdot \left|\vec{I_s}\right|^2, \tag{2}$$

$$\vec{I_s} = \left(\frac{P_s + jQ_s}{V_s \angle \delta_s}\right)^*, \tag{3}$$

where S_s and S_r are the transferring apparent power from the main substation and delivery apparent power to each bus, respectively. n is number of buses. From Eq. (2) and Eq. (3), the equivalent impedance can be obtained.

$$\vec{Z_s} = \frac{(S_s - S_r) \cdot |V_s|^2}{(P_s^2 + Q_s^2)}. \tag{4}$$

In this model, with increasing load demands, the load impedance (Z_r) decreases and I_r increases; this, in turn, leads to a further drop of voltage on the receiving side of electric power. By calculating I_r as:

$$\vec{I_r} = \frac{V_s \angle \delta_s}{Z_s \angle \theta + Z_r \angle \phi} = \frac{\dfrac{V_s}{Z_s} \angle (\delta_s - \theta)}{1 + \dfrac{Z_r}{Z_s} \angle (\phi - \theta)}, \tag{5}$$

where,

$$\left|\vec{I_r}\right| = \frac{\left|\dfrac{V_s}{Z_s}\right|}{\sqrt{1 + \left|\dfrac{Z_r}{Z_s}\right|^2 + 2\left|\dfrac{Z_r}{Z_s}\right| \cos(0 - (\phi - \theta))}}. \tag{6}$$

Voltage V_r and apparent power S_r can be described as:

$$|V_r| = |Z_r| \cdot |I_r|, \tag{7}$$

$$|S_r| = |V_r| \cdot |I_r{}^*|, \tag{8}$$

Then by replacing Eq. (6) into Eq. (7) and Eq. (8), we derived:

$$V_r = \frac{Z_r}{Z_s} \frac{V_s}{\left[1 + \left(\dfrac{Z_r}{Z_s}\right)^2 + 2\left(\dfrac{Z_r}{Z_s}\right)^2 \cos(\beta)\right]^{0.5}}, \tag{9}$$

$$S_r = \frac{Z_r}{Z_s} \frac{\dfrac{(V_s)^2}{Z_s}}{\left[1 + \left(\dfrac{Z_r}{Z_s}\right)^2 + 2\left(\dfrac{Z_r}{Z_s}\right)^2 \cos(\beta)\right]}, \tag{10}$$

where $\beta = \theta - \phi$. And θ and ϕ are phase angles of impedance and Z_s, Z_r respectively.

Figure 2 and Fig. 3 show these equations in a graphical form for the resistive and capacitive loads. For general representation, V_s and Z_s, both are assumed to be one per unit. By this assumption, results have implied that the maximum transmitted appearance powers to loads will be achieved when the ratio $\frac{Z_r}{Z_s}$ equals one, as shown in Fig. 3. Therefore, this ratio has been considered mostly as a critical point for the determination of the voltage collapses. In conclusion, the $\frac{Z_r}{Z_s}$ ratio must be greater than one. This means that any arbitrary increase in Z_s or decrease in Z_r must not lead to voltage instability of the system. Because, in order to avoid the failure of the motor loads, values of V_r must be always larger than one; thus, any ratios of $\frac{Z_r}{Z_s}$ less than one would be undesirable [24].

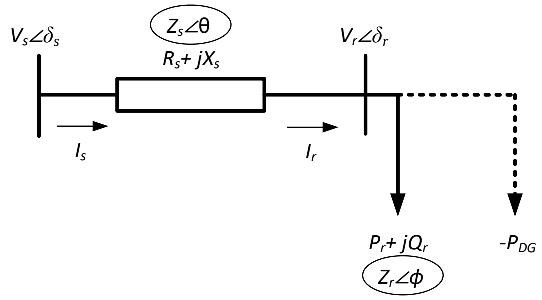


Fig. 1: Single-line diagram of a reduced system.

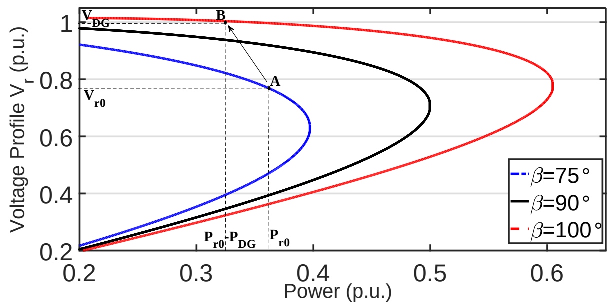


Fig. 2: Voltage-power relation in the equivalent circuit.

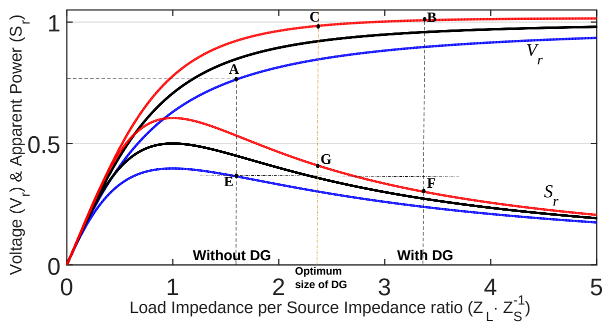


Fig. 3: Voltage and apparent power versus the load to the source impedance ratio.

From Fig. 2, it will be proved with injection PDG the voltage profile is improved from point A to B, but

$$\text{GSI} = \frac{2\left[R_s\left(P_r - P_{DG}\right) + X_s Q_r\right] + 2\sqrt{\left({R_s}^2 + {X_s}^2\right)\left[\left(P_r - P_{DG}\right)^2 + {Q_r}^2\right]}}{\left|V_s\right|^2}. \tag{11}$$

one question arises; what would be the appropriate size for installing DG?

Returning to Fig. 3, we can observe the load-ability and voltage stability (ratios of $\frac{Z_r}{Z_s}$) in the system decrease from point G to F by putting the inappropriate size of DG. As shown in Fig. 3, the optimal sizing of DG, when no reduction is has occurred in the transmission power, is around the point of G over the transmission appearance power curve. It is observed that the load-ability of the system is improved, and the voltage profile also reformed rather than point A. This, consequently, is an equivalent point of C for the system voltage. Hence, it shows the best size of DG exactly related to both the voltage stability index and power losses in the systems.

2.1. Generalized Voltage Stability Index (GSI)

Referring to Fig. 1, $V_s\angle\delta_s$ and $V_r\angle\delta_r$ are, respectively sending and receiving end voltages and $Z_s\angle\delta = R_s + jX_s$, the line impedance between the two buses.

The $Z_s\angle\phi$ is the corresponding load impedance, with $\phi \tan^{-1}\left(\frac{Q_r}{P_r}\right)$. By Substituting $\vec{I}_r = \left(\frac{P_r + jQ_r}{V_r\angle\delta_r}\right)$ in Eq. (1) and the separate this into two real and imaginary parts [26], therefore:

$$V_s V_r \cos(\delta) = \left|V_r\right|^2 + \left[R_s\left(P_r - P_{DG}\right) + X_s Q_r\right], \tag{12}$$

$$V_s V_r \sin(\delta) = \left[X_s\left(P_r - P_{DG}\right) - R_s Q_r\right], \tag{13}$$

where $(\delta = \delta_s - \delta_r)$ is the difference in the angle between the voltages of the sending bus (V_s) and the receiving bus (V_r). The values of P_r, Q_r are the total active and reactive power demands by the receiving bus in the distribution system, and determined from conventional power flow calculations.

Taken together with the two sides of the square Eq. (12) and Eq. (13) and eliminate δ, can reach to:

$$\begin{gathered}\left|V_r\right|^4 + \left\{2\left[R_s\left(P_r - P_{DG}\right) + X_s Q_r\right] - \left|V_s\right|^2\right\}\left|V_r\right|^2 + \\ + \left\{\left({R_s}^2 + {X_s}^2\right)\left[\left(P_r - P_{DG}\right)^2 + {Q_r}^2\right]\right\} = 0,\end{gathered} \tag{14}$$

Therefore,

$$\left|V_r\right|^2 = \frac{\left\{\left|V_s\right|^2 - 2\left[R_s\left(P_r - P_{DG}\right) + X_s Q_r\right]\right\} \pm \sqrt{\Delta}}{2}, \tag{15}$$

$$\begin{gathered}\Delta = \left\{2\left[R_s\left(P_r - P_{DG}\right) + X_s Q_r\right] - \left|V_s\right|^2\right\}^2 + \\ -4\left\{\left({R_s}^2 + {X_s}^2\right)\left[\left(P_r - P_{DG}\right)^2 + {Q_r}^2\right]\right\}\end{gathered}, \tag{16}$$

As a result, to have a real answer, it must be $\Delta \geq 0$. In [26], Chakroverty and Das are derived from the voltage stability index as SI from the Eq. (14), Eq. (15) and Eq. (16). Based on this index, the buses with lower voltage amplitude always are close to voltage instability than other buses.

According to Eq. (15), four answers can be obtained or the values of V_r which only one of them is acceptable.

$$\begin{gathered}2\left[R_s\left(P_r - P_{DG}\right) + X_s Q_r\right] - \left|V_s\right|^2 \leq \\ \leq -2\sqrt{\left({R_s}^2 + {X_s}^2\right)\left[\left(P_r - P_{DG}\right)^2 + {Q_r}^2\right]}.\end{gathered} \tag{17}$$

So, by rearranging the inequality of Eq. (17), we obtain a generalized voltage stability index with the presence of DG as follows in the Eq. (11).

In Eq. (11), all characteristics of the active and reactive power consumption affect the limits of voltage stability. The studied distribution system will be stable when the value of a defined index for each bus is less than one (0≤ GSI<1). This voltage stability indicator is dimensionless, and as a result, both actual and per-unit values can be used.

3. Impact of Distributed Generation (DG)

Most of the equipment in distribution systems is arranged based on the assumption that the electric power flows from the main substation to the loads. Thus, due to output fluctuations or a reverse flow from distributed generation units, some issues affect distribution systems like power losses, voltage profile, and reliability [5] and [27].

3.1. Voltage Profile and Voltage Stability

To regulate the voltage and reduce the voltage drop in distribution systems, the capacitors on the feeders can be used. Moreover, the use of tap changing at substation transformers or voltage regulators is also useful. This form of voltage control assumes that the power flows from the substation to the loads, but DG inserts reversed power flows, which may create interference with these traditional regulation methods [15] and [17]. Therefore, unsuitable DG allocation can cause over-voltages in the system. On the other hand, inappropriate DG planning can influence voltage stability and load-ability margin as well. Equation (1) indicates that the reduction of $Z_s \cdot I_r$ component is an important factor to improve the voltage at the receiving end by providing active power support locally using distributed resources Fig. 1.

3.2. Power Losses

One of the important benefits of DG utilization is their improvements on the active power flow as well as reactive power flow. DG has a positive impact on line losses due to its proximity to load centers and should be positioned in locations where they result in maximum reduction of losses.

Thus, it is important to select the location of the DG that will result in a minimum loss as well as improving the voltage profile. Once that size and locations of DG are determined, there is a need to check the entire system again to make sure those stability constraints are not violated.

4. Optimal DG Placement Methodology

In order to achieve the maximum benefits of DG, such as improving reliability and voltage stability, the optimal locations and optimum sizes of DG units are necessary for the distribution networks. Fig. 4 shows the proposed algorithm as a flowchart with programming in MATLAB environment.

4.1. Placement Algorithm for DG

According to Fig. 4, the location of the DG units in the Radial Distribution System (RDS) is implemented based on the execution of an iteration algorithm. For finding the most suitable location for the placement of DG, the GSI index is used to determine the most critical buses in the system. Then, the optimum size of DG is determined based on the proposed method of the next section and placed at critical buses one at a time. In each case, GSI is calculated again to determine the lowest value of GSI on respective buses. The bus connected with DG and the lower value of GSI indicates the optimum location of the DG.

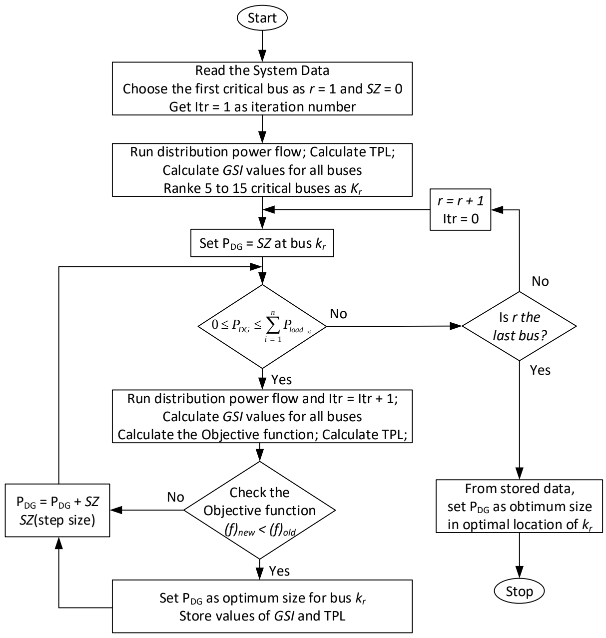


Fig. 4: Flowchart of the proposed method.

4.2. Proposed Algorithm

The main objective in this work is to optimize the size of the DG by minimizing the Total Power Losses (TPL) per per-unit, enhancing the voltage stability and improving the voltage profiling in the given RDS. The simple objective function is formulated as:

$$f = \min \left\{ \frac{\left(\sum_{i=1}^{b} |I_i|^2 R_i \right)}{TPL_{Normal-Load}} + \text{GSI} \right\}. \tag{18}$$

Subjected to maximize generation and voltage constraints:

$$0 \leq P_{DG} \leq \sum_{i=1}^{n} P_{load,i}, \tag{19}$$

$$V_{i,\min} \leq V_i \leq V_{i,\max}, \quad i = 1, 2, \ldots, n. \tag{20}$$

In each iteration, $TPL = \left(\sum_{i=1}^{b} |I_i|^2 R_i \right)$ and maximum value of GSI calculate by considering DG selection. Also, n is the number of nodes; b the number of branches; P_{load}, i is the connected load in each node i; P_{DG} the distributed generation power; and the acceptable range of voltage at each node of the RDS should not exceed within 0.9 p.u. to 1.05 p.u.

Generally, the following steps are performed to determine the optimal size of DG:

- By putting DG with the minimum value at the first node, the total losses and GSI index is calculated.

Tab. 1: Performance of the proposed algorithm on radial distribution systems after DG installation in PQ mode.

Bus system	Main substation bus	Proposed algorithm			Golden section search algorithm [29]	
		Bus no.	Optimum size (MW)	Max. GSI value	Bus no.	Optimum size (MW)
12	1.00	9th	0.2388	0.9954	9th	0.2354
Modified 12	1.00	8th	1.3942	0.9953	9th	1.1912
69	1.00	61st	1.8259	0.9906	61st	1.8727

- By assumption of the constant power factor, the DG size is varied from a minimum value to an amount equal to the total power load demands in constant Step Sizes (SZ) for each bus in the iteration loop. For each iteration, the system losses with the value of GSI are calculated to found their minimum values.
- The results in minimum losses and minimum voltage stability index are taken as DG size optimum for each bus.
- Comparing the results, the lowest outcome from all optimum DG sizing in each bus is selected as the optimal location.

5. Results and Discussion

The proposed method for optimal placement and the sizing of DG is implemented in MATLAB programming and tested for several radial distribution networks. In this case, it is assumed that one DG is appropriate to install at selective case study. The rating active power of the distributed generation unit is limited to the total active power load, and the power factor is unity. The sweep backward/forward power flow method is applied to accomplish an efficient load flow and a small number of iteration for solving the distribution system states. The test system of 12-bus, 69-bus and 94-bus radial distribution test systems are shown in Fig. 5, Fig. 9 and Fig. 12, respectively.

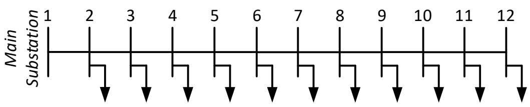


Fig. 5: Schematic diagram of 12-bus radial distribution network.

5.1. Modified 12-bus and 12-bus Test System

To better express the effectiveness of the proposed algorithm, a modified 12-bus system is used. In this case, the all active power loads of 12-bus test system multiply to five. So, the modified 12-bus system is a radial 11 kV, the system with a total load of 2.175 MW, 0.405 MVar, and 11 branches, as shown in Fig. 5. The total real power loss in the system is 434.112 kW, while the total reactive power loss is at 166.836 kVar when calculated using the load flow method [28]. Figure 6 illustrates the total power losses of the modified 12 bus test system when the corresponding optimum DG size for each bus calculate. It shows that the minimum active and reactive losses occur by the installation of DG on bus 8.

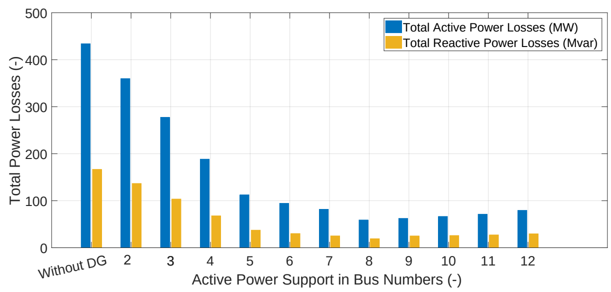


Fig. 6: System losses profile of the modified 12-bus with corresponding optimum DG size at each bus.

The results for the best location and optimum sizing problems of DG, based on the flowchart and proposed objective function, are described in Tab. 1. The proposed algorithm is also compared with the Golden Section Search (GSS) method [29], implemented using the VS&OP power tool. The results clearly show the advantages of the proposed technique for optimal location and sizing of DG in all three test systems with the loss reduction and improvement in voltage stability margin, which will be discussed further. Table 1 demonstrates the best size and location of DG are 0.2388 MW, at bus 9, which improves GSI values in the entire system. It obtains that the results of the proposed algorithm are very close to the GSS method.

The role of DG in reducing the losses and improving the voltage profile for a modified 12-bus system is shown in Fig. 7 and Fig. 8, respectively. In this case, the total active and reactive losses are illustrated by separately putting the optimal size on each bus. It can be observed that the suitable location of DG, in terms of objective function minimizing, is at bus 8. Figure 8

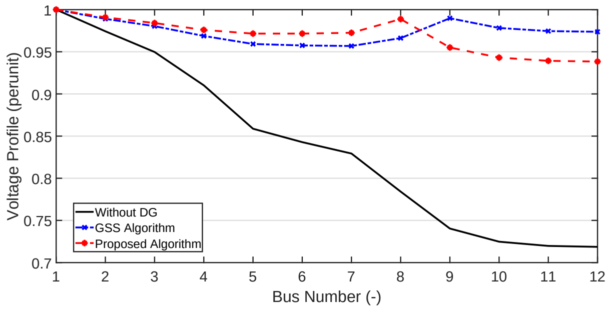


Fig. 7: Effect of DG on Voltage profile of the modified 12-bus system.

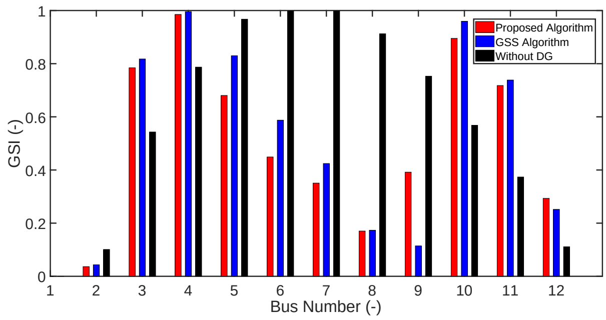


Fig. 8: Schematic GSI value for each node in a modified 12-bus system in three cases.

proves this outcome by installing the amount of DG equal to 1.1912 MW at bus 9 [29], it can be seen that the other buses will go to the collapse point (bus number 4 is closed to collapse point); but by putting the value equal 1.3942 MW at bus 8, it will not only decrease the power losses but also improve the voltage stability margin in the system. The reason for changing the location of the critical node is non-optimal DG installing and variation of $\frac{Z_r}{Z_s}$ ratio, described in Sec. 2. .

5.2. The 69-bus Radial Distribution System

The second test case is a 69-bus radial distribution system on 12.66 kV, with seven lateral lines and a total load of 3.804 MW and 2.693 MVar, which is presented in Fig. 9 The proposed algorithm is tested on the second case study for comparison with previous works. The voltage profile and effect of optimization methods on the GSI index are illustrated in Fig. 10 and Fig. 11. Figure 10 demonstrates that the voltage magnitude of bus-65 has a lower voltage level without DG installation, which after optimum DG significantly improves.

Results show that stability indices for the whole system improved after installing the optimally planned DG; while the buses critical to voltage instability are more than nine buses far from substation without any

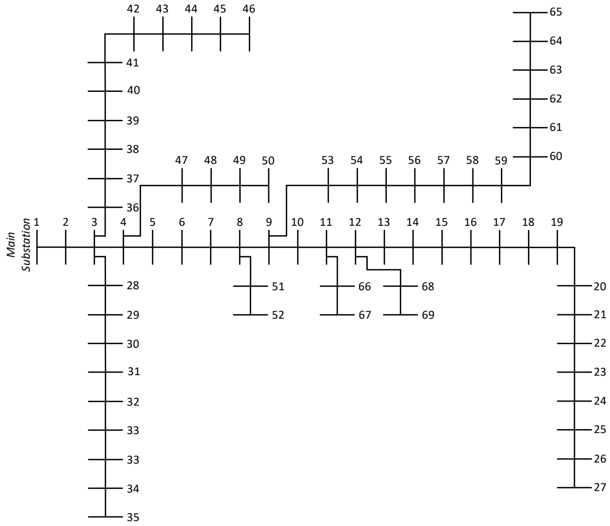


Fig. 9: Schematic diagram of 69-bus radial distribution.

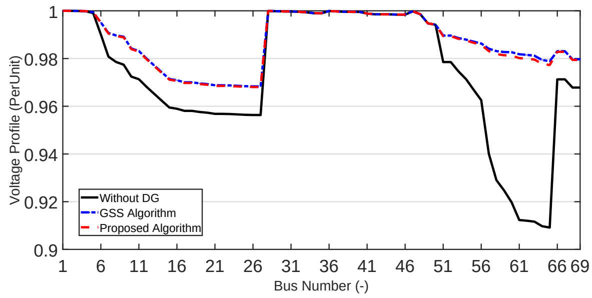
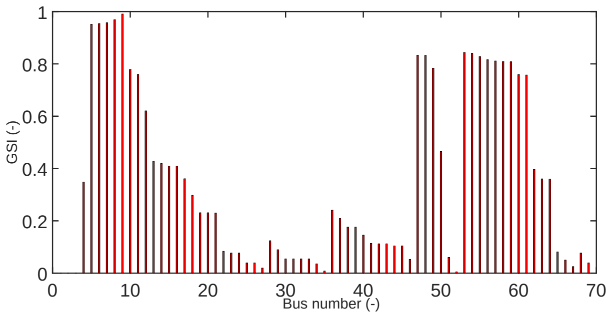
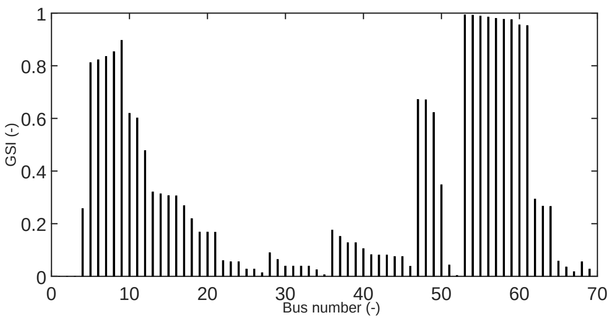


Fig. 10: Effect of DG on voltage profile of 69-bus test system.



(a) Proposed algorithm: DG size = 1.8259 MW at Bus 61.



(b) Proposed algorithm: without DG.

Fig. 11: GSI value for each node in the 69-bus system.

Tab. 2: Effect of DG installation on power losses in the 69-bus system.

Main substation voltage	DG size (MW)		Total losses		
			P (kW)	Q (kVar)	Max. GSI
1.00	**Without DG**	–	225.072	102.240	0.9933
	Bus 61	1.8259	83.289	40.644	0.9906
1.05	Bus 61	1.8221	83.302	40.656	0.9815

Tab. 3: Effect of main substation voltage on GSI.

Bus system	Main substation voltage (p.u.)	Proposed algorithm		
		Bus no.	Optimum size (MW)	Max. GSI value
12	1.00	-	**Without DG**	0.9987
		9th	0.2388	0.9954
	1.05	-	**Without DG**	0.9985
		9th	0.2384	0.9946
Modified 12	1.00	8th	1.3942	0.9953
	1.05	8th	1.3898	0.9935
69	1.00	61st	1.8259	0.9906
	1.05	61st	1.8221	0.9815

Tab. 4: Optimal location and size of DG in different modes.

Case study	12 Buses				Modified 12 Buses				69 Buses			
	DG location	P (MW)	PF	Power losses (kW)	DG location	P (MW)	PF	Power losses (kW)	DG location	P (MW)	PF	Power losses (kW)
PQ mode	9	0.2388	1.0	10.776	8	1.3942	1.0	59.091	61	1.8259	1.0	83.289
PV mode with Var Constraint	9	0.2793	0.95	5.937	8	1.2615	0.95	55.078	61	2.0617	0.95	38.397
PV mode	8	0.2832	0.8	3.505	9	0.9374	0.8	98.922	61	1.8068	0.8	23.282

DG installation that is demonstrated in Fig. 11(b). It is shown that the critical nodes shifted to some primary buses that can be supported by increasing the voltage magnitude of the main substation.

In Tab. 2, the effects of DG installation on power losses in 69-bus test system illustrate that the optimal size value is 1.8259 MW at bus 61. It shows that the total active and reactive losses reach 83.289 kW and 40.644 kVAr, respectively. Also, by increasing the main substation voltage to 1.05 p.u., the voltage stability index improves in the whole system. Table 3 shows the effect of DG installation on GSI as the variation in the main substation voltage. Table 3 proves that the substation voltage helps improve voltage stability. The results show that an increase of main substation voltage leads to finding the minimum size of DG by enhancing GSI values.

Table 4 shows the optimal DG results for three different modes on all test systems. It can be seen when DG operates in PV mode; the lowest power loss value is obtained. It is because of the reactive power injection into the network by the DG unit when operating in PV mode. Moreover, the voltage profile improves, and the impact $|I|^2 \cdot R$ of reduces but the voltage stability index in the system has become to stress status. Conversely, by operating of DG in PQ mode, the DG is modeled as a negative load and supplied the real power to some of the loads in the system. Therefore, due to the lack of reactive power injection, the power loss in PQ mode is higher than PV mode in all test systems.

The second case relates to the PV mode of DG with lead power factor equal to 0.95 (i.e. injection reactive power by DG). It can be observed that the power losses decrease in all systems. Also, in the case of PV mode with 0.8 leading Power Factor (PF = 0.8), the DG sizing reduces to 0.9374 MW, specifically in the modified 12-bus test system.

5.3. The 94-bus Radial Distribution System

The third test case is an actual Portuguese radial distribution system on 15.00 kV, with 94-bus and 22 lateral lines and a total load of 4.797 MW and 2.324 MVar, which is presented in Fig. 12. All data of the system are addressed in [21]. The voltage profile and effect of optimization methods on the power losses reduction are illustrated in Fig. 13 and Tab. 5.

Figure 13 illustrates the voltage magnitude of the system without and with considering of DG optimal in two cases. The DG type in PV mode (PF = 0.853)

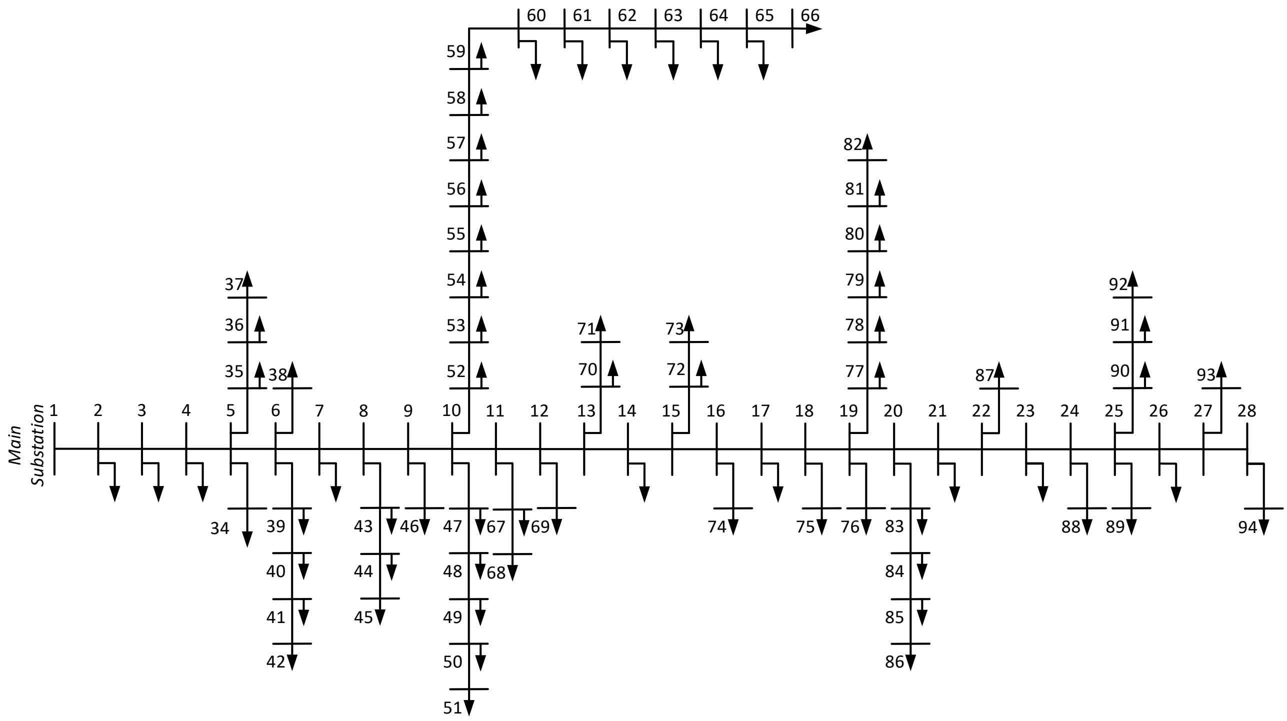


Fig. 12: Schematic diagram of 94-bus radial distribution system.

Tab. 5: Optimal location and size of DG in different modes in 94-bus test system.

Case study	Proposed algorithm					BSAO method [21]				
	DG location	P_{DG} (MW)	PF	Power losses		DG location	P_{DG} (MW)	PF	Power losses	
				P(kW)	Q(kVAr)				P(kW)	Q(kVAr)
PQ mode PV mode	19 (104s.)	2.6863	1	132.47	163.87	21 (118s.)	2.3985	1	153.86	177.46
with Var Constraint	19 (130s.)	2.4944	0.853	82.97	92.70	18 (234s.)	2.3985	0.853	85.13	97.18

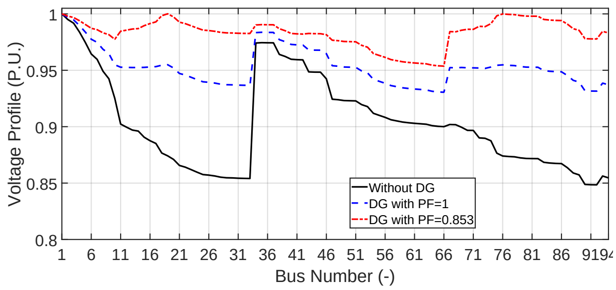


Fig. 13: Effect of DG on voltage profile of 94-bus test system.

compares with DG by PF = 1, and it shows that the DG in PV mode can significantly improve the magnitude of bus voltages. Table 4 describes the comparison between the proposed algorithm and meta-heuristic Brain Storm Optimization Algorithm (BSOA) technique. The results show that the values obtained from the proposed algorithm for the location and size of DG are very close to the results of the BSOA. By selecting critical buses nominated to voltage instability from GSI for DG location algorithm, the optimal size of DG could be rapidly calculated. In addition, 15 nominated buses in 94-bus distribution system are 11, 12, 13, 14, 15, 16, 17, 18, 19, 52, 10, 53, 9, 55, and 8.

6. Conclusion

This paper proposes a reliable technique for the determination of location and sizing of DGs. This new analytical approach is suitable for voltage stability analysis and can be applied to real systems. The performance of the general voltage stability indicator for finding the optimal placement and optimum sizing of DG is applied to achieve adequate results in all radial distribution systems. The critical buses for DG placement are selected by generalized voltage stability index. Three modes of DG (PQ mode, PV mode and PV mode with VAR constraint) are applied to the study of the effects of reactive power injection into the system, especially to the reduction of power losses and improvement of the voltage profile. The observed outcomes well justify usage of the algorithm for the purpose of improvement in voltage profile, voltage stability margin, and reduction of power losses.

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