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Multiple distributed generations placement and sizing based on voltage stability index and power loss minimization

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Abstract: This paper proposes a rapid analytical method to determine the locations and sizes of multiple distributed generations (DGs) inside a distribution network. DGs' locations are chosen with the aim of enhancing voltage stability and their sizes are picked so as to minimize system power losses. To evaluate the effect of the DG's nature on the system's performance, the proposed DG allocation method is tested for all DG types and the impact of the combination of different types of DGs is equally investigated, which offers a guide to designing an optimal hybrid network.

Key words: Distributed generation, optimal distributed generation allocation, voltage stability, power loss reduction, voltage profile improvement

1. Introduction

In traditional structures, electrical energy is transported from power plants to consumers through a hierarchical network dropping from the very high voltage HVB (>50 kV) to the medium voltage HVA (1 kV < Un <50 kV) and then to the low voltage LV (<1 kV). HVB transmission networks are meshed to ensure the reliability and availability of energy in the case of structural defects. In contrast, MV and LV distribution networks are mostly passive with a configuration operating in a radial structure (a single path to the upstream network). This topology of the system makes the flow of electrical energy unidirectional, namely from production to consumption. Such a power system structure allows better energy efficiency of generators, a reduction of operating costs, and a decrease of the risk of failures among other plus points [1]. However, to meet the growing demand, the development of the network involves the installation of new, larger power plants and the construction of HVB and HVA lines. These constructions are becoming more difficult because of such major drawbacks as their high cost, the lack of available installation space, and the growing public opposition to these new facilities [2, 3]. For all these reasons combined, the development of new, unconventional power generation units is urgently needed.

These new devices are called distributed generation (DG) and they are being developed in most countries based on cogeneration, renewable energy, or traditional production units. The energy yielded by these new means is produced locally (closer to consumption centers) and can range from a few kilowatts to a few megawatts [4]. It is, therefore, not intended to be transported over long distances. Consequently, the integration of this energy is usually performed at the level of the distribution networks [5]. Such a way of supplying strongly influences the power flow, leading to significant effects. These impacts can be positive or negative, depending on the

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characteristics of the DG. A measured DG allocation has the potential to allow better infrastructure security and grid reinforcement as it permits reduced power losses, enhanced voltage profile, and improved stability [6]. On the other hand, inappropriate DG integration could bring about adverse effects in the operation of the distribution network [7, 8]. Thus, to guarantee the achievement of beneficial effects, DG allocation has to be optimized in terms of integration location and size.

Over the past few years, different methods have been proposed to determine optimal DG placement and size. These methods apply either analytical approaches or optimization algorithms and discuss various issues. For example, Hedayati et al. [9] suggested power flow continuation analysis as the basis for an analytical method to locate a single DG in distribution networks with the objective of supporting the most loading area and minimizing power losses. This study does not take heed of the optimal DG size, however. Another study [10] offered a solution to both placement and sizing problems in an attempt to reduce the total active loss. However, the developed method requires a large number of load flow computations, which makes it slow. A faster method was suggested in a third study [11] based on an index to place the DG in the bus most sensitive to voltage instability. The authors took the minimization of active power loss as the main criterion to determine DG size.

All the works cited above were interested in locating and/or sizing only a single DG. Nevertheless, it is more rewarding to develop algorithms that deal with multiple DGs' penetration. Multiple-DG settings have attracted the interest of a number of researchers. The multiobjective particle swarm optimization (MOPSO) technique was applied in [12] to determine optimal sites and sizes of shunt capacitor banks and DGs considering three goals: reducing active power loss, improving voltage stability, and balancing the current of the different sections. In [13], an iterative process was described to find locations and sizes of DGs with a primary purpose of minimizing power losses. Although this method yields acceptable results in relation to the issue of power loss reduction, it is computationally demanding. Moreover, the authors of the last two studies [12, 13] took the DG to be a conventional generator and did not consider renewable energy sources. As the integration of nonconventional resources is highly encouraged in many parts of the world [14], it is deemed crucial here to take renewable sources into account throughout the formulation of the DG allocation solution.

With the limitations of the already published solutions identified above in mind, the present paper is a contribution that proposes an easily implemented method for the simultaneous placement and sizing of multiple DGs inside a distribution network. DGs are placed in such a manner as to reinforce the areas most sensitive to voltage instability based on an index that is both simple in form and characterized by its sensibility to both active and reactive loadabilities. DG sizing is performed with the main objective of reducing active power losses. All DG types (i.e. conventional and nonconventional) are to be addressed below; the effect of every type as well as the impact of the association of different DG types on the system performance are analyzed with the aim of providing a guide to design an optimal hybrid distribution network. Detailed simulations are carried out on the 33-bus IEEE network considering ten different cases of study and a comparative analysis is conducted with various optimization approaches.

The rest of this paper is organized as follows: first, the principles of DG placement and sizing are introduced in the second section. The third section includes the explanation and implementation of the suggested multiple-DG integration method. Additionally, the results of the proposed algorithm are reported, discussed, and compared to previous results in the literature that are obtained through algorithms based on the 33-bus IEEE network as a test system. Finally, some concluding remarks are provided in the fourth and final section of the article.

2. Principles of DG allocation

2.1. DG placement

Due to the heavy loading levels of power systems, today's distribution networks are operating close to their voltage stability limits [15]. As a result, it is necessary to consider this issue when dealing with the issue of DG integration [16]. An insufficient power supply represents the major cause of voltage instability [17]. However, supporting the system by a source of power close to the consumption point(s) can significantly reinforce the network potential to supply the requested amount of power, which contributes to a higher voltage stability margin. On the other hand, it is not possible, technically or economically, to reinforce every bus of the network by a DG [11]. To achieve high benefits, therefore, DG units should be installed into the most sensitive buses, namely those candidates most susceptible to voltage instability.

Voltage stability indices (VSIs) have been identified as the most useful tools to decide on the critical line to voltage instability [18–20], allowing the determination of the weakest bus (or buses) in a network. Indices that are currently discussed in a plethora of published works on the topic and employed by system planners are LQP, LVSI, Lmn, and FVSI [21]. Considering a sending bus (Bus S) and a receiving bus (Bus R), as shown in Figure 1, connected by a line characterized by impedance Z, the above mentioned VSIs can be expressed as in Table 1. The formulae of all these indices are derived from the load flow calculation. However, only the LQP index is directly related to both active and reactive powers' evolutions, thus allowing a better sensitivity to voltage instability. For this reason, this index is proven in the literature as one of the most accurate voltage stability indices [21]. In addition, the LQP index is expressed as a function of an input datum (X) and direct results of load flow computation (Vs, Pi, and Qj), which makes it a simple-in-form and easy-to-implement index. As a result, the LQP index is employed in the present paper when addressing the voltage stability issue so as to select the optimal DG locations.

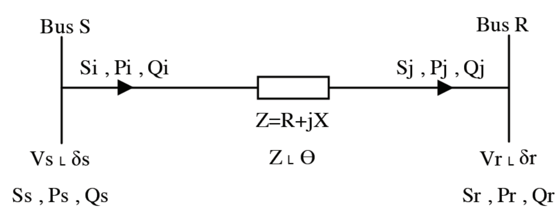

Figure 1. Model representation of two connected buses.

Table 1. Voltage stability indices' formulae.

Index	LQP[22]	LVSI[23]	Lmn[24]	FVSI[25]
Formulae	$4(\frac{X}{V_s^2})(\frac{X}{V_s^2}P_i^2+Q_j)$	$\frac{4P_iR}{[V_s cos(\theta-\delta)]^2}$	$\frac{4Q_iX}{[V_s sin(\theta-\delta)]^2}$	$\frac{4Z^2Q_i}{V_s^2X}$
Critical value	1	1	1	1

Here, $V_i\angle\delta_i$ is the complex voltage at the ith bus. $R_{ij}+jX_{ij}=Z_{ij}$ is the ijth element of the [Zbus] impedance matrix. P_i and P_j are active power injections at the ith and jth buses. Q_i and Q_j are reactive power injections at the ith and jth buses.

2.2. DG sizing

The integration of a DG into a power system can exacerbate power loss [6]. Thus, the determination of a DG unit's size will be based on the need to minimize the total active losses while considering technical and electrical limitations of the network. The "exact loss formula" is used to compute the system's active losses and it is defined as follows [26]:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)]. \tag{1}$$

The constraints considered in this work are:

(a) Voltage magnitude constraint: the voltage magnitude at each bus must be within the [90%–105%] interval of the nominal voltage:

$$0.9 \leq V_i \leq 1.05. \tag{2}$$

(b) System power balance constraint: the balance between the generated power and the demanded power must be established:

$$P_G + \sum_{k=1}^{NDG} P_{DG} = \sum_{i=1}^{N} P_{Di} + P_L, \tag{3}$$

$$Q_G + \sum_{k=1}^{NDG} Q_{DG} = \sum_{i=1}^{N} Q_{Di} + Q_L, \tag{4}$$

where P_G and Q_G are the active and reactive power of the generator at the slack bus. P_{DG} and Q_{DG} are the active and reactive power of the DG. P_{Di} and Q_{Di} are the active and reactive power demand at bus i. P_L and Q_L are the total active and reactive power losses. N is the number of buses. NDG is the number of DGs.

3. Case study

3.1. DG model and types

DG units can be represented either with a PV node, i.e. constant terminal voltage control, or with a PQ node, i.e. constant power factor control [27]. Usually, in load flow calculation problems, the DGs are described by means of both the supplied active power and the magnitude of the voltage at the connection node. The reactive power of a given DG is calculated by the resolution algorithm. Nevertheless, in the context of the present research project, the objective is to directly drive the reactive power production of each DG. Consequently, in order to be able to control the reactive power of the DGs, they are modeled as PQ nodes [15]. In that sense, DG units can be classified into four types based on their capacity to produce active and reactive powers:

(i) First type: produces active power only, such as a photovoltaic unit.

(ii) Second type: produces active and reactive power, like diesel generators.

(iii) Third type: produces active power and consumes reactive power, like a fixed-speed wind turbine.

(iv) Fourth type: produces reactive power producer, like a synchronous compensator, for example.

3.2. Proposed algorithm

The proposed algorithm (Figure 2) as an optimization technique is formulated around two major components. The first component consists of selecting the optimal DG location(s) using the LQP index. The DG will be connected to the end bus of the line with the highest LQP value.

After installing the DG into the appropriate bus, the second defining component, i.e. DG size, is started. The main objective of this component is to determine the DG size providing minimal active power losses. First, losses are calculated without DG integration, using (1). Then the DG size will be increased linearly, and for every step, the losses' value is updated and compared with the last one. This procedure ends when the losses reach a higher value than the previous one, considering the limitations spelled out in equations (2), (3), and (4). Thus, the DG size is fixed to the size obtained before that at which the losses climb up again. Once the placement and the size of the first DG are defined, the process returns to the beginning to execute the load flow program considering the installed DG and then the same steps are redone to determine the location and size parameters for the next DG.

3.3. Presentation of the test system

Simulations are to be performed on an IEEE distribution system. As shown in Figure 3, the network has 32 branches and 33 buses: one slack bus (bus 1) and 32 PQ buses with a total load of 3.715 MW and 2.3 MVAR. The base apparent power and the base voltage are 10 MVA and 12.66 kV, respectively.

3.4. Results and discussion

3.4.1. The case of one DG

To begin with, the efficiency of the proposed method is to be examined in the case of a single DG. As explained above, the first step in the proposed algorithm consists in placing the DG at the bus most affected by voltage instability. To do so, line and load data of the 33-bus network were fed into the algorithm, and then the load flow program was executed using the Newton–Raphson method and LQP values were calculated for each line. The obtained values are presented in Figure 4. It is clear from this figure that, in the base case (i.e. with no DGs), the 5th line has the highest LQP value, which makes it the closest line to voltage instability. Hence, the DG will be connected to the 6th bus. After attaching the DG at this bus, the DG sizing process is performed. It is found that, for the four DG types, active power loss variations versus DG size augmentation have parabolic curves (Figure 5) and achieve their minima with DG sizes of 2.6 MW, 2.8 MW, 2 MW, and 1.8 MVAR for the 1st, 2nd, 3rd, and 4th DG types, respectively.

3.4.1.1. Voltage profile discussion To examine the effect of the different DG types on the overall voltage profile, Figure 6 presents the voltage profiles, with and without the DG, for the four DG types. What is worth remarking is that, whatever the type of the integrated DG, the overall voltage profile is improved as compared to the base case (i.e. without a DG unit), which provides to the end consumer higher energy quality and ensures the betterment of voltage security.

3.4.1.2. Losses discussion The obtained results, for all the DG types, are summarized in Table 2. From this table, it is obvious that the addition of any DG type into the network leads to the decrease of the power loss and the enhancement of the minimum bus voltage, allowing considerable cost reduction and more reliable network operation. More specifically, it can be noticed that the 2nd DG type, i.e. the DG resource with the

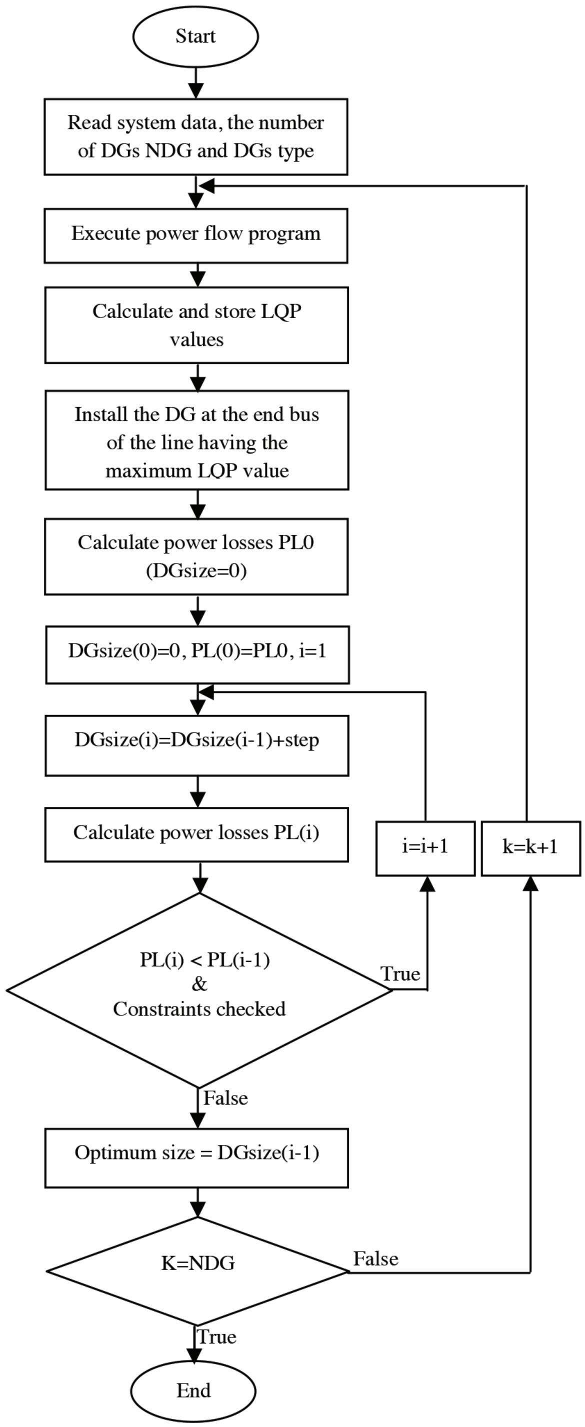

Figure 2. Flow chart of the proposed method

ability to supply both active and reactive powers, produces the best results in terms of both loss reduction and minimum voltage improvement. As a result, the addition of such a DG type with a size of 2.8 MW provides a reduction of 69% in the active power losses and improves the lowest bus voltage from 0.9131 pu to 0.9702 pu.

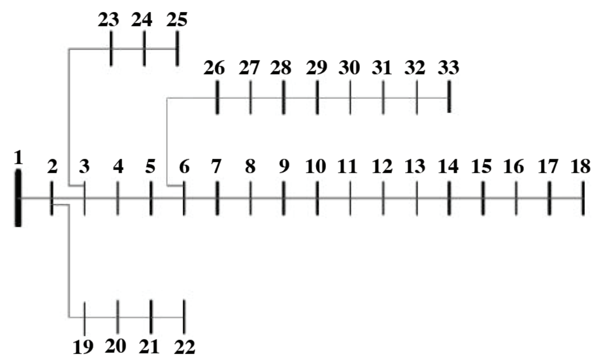

Figure 3. The 33-bus IEEE network.

In contrast, the 1st, 3rd, and 4th DG types yield a real power loss decrease of 49%, 27%, and 24%, respectively, and the minimum bus voltage achieves 0.9514 pu in the case of the 1st DG type, 0.9364 pu in the case of the 3rd DG type, and 0.9304 pu with the 4th DG type. This is due to the fact that the 2nd DG type provides not only active power support but also reactive power support. Supporting the reactive power production brings about a reduction of the reactive import from the substation and hence the associated total losses and voltage magnitude are improved significantly.

3.4.1.3. Voltage stability discussion To evaluate the voltage stability after connecting the different DG units, the LQP index is computed for each line of the network as well as for each DG type. It can be noticed from the results illustrated in Figure 4 that all the DG types permit a decrease of LQP values, translated as an improvement in voltage stability, except for the 3rd DG type, which causes stability decline of the first five lines. This is due to the nature of this DG type since it presents a supplementary reactive load to the network, thus causing an increase in the lines' loadability. This loadability augmentation in turn incurs a decline in stability [26].

3.4.1.4. Comparative study To validate the obtained results, a comparison is carried out with four other methods, which are the hybrid gray wolf optimizer method [28], the fast approach ELF [10], one analytical method [27], and the PSO technique [29]. As represented in Table 2, all methods point to the same DG location (bus 6), except for the PSO technique in the case of the 4th DG type that yields bus 30. Concerning the DG units' size parameter, the five compared methods indicate different DG sizes. These similarities as well as differences tend to cause disparities in the power loss, voltage level, and voltage stability results. The comparison of these results, with reference to Table 2, proves that the proposed method is the most efficient one among all the methods considered. For example, in the case of the 1st DG type, the proposed method presents an extra loss reduction of 4%, 2%, and 6% as compared to the hybrid gray wolf optimizer method, the analytical method, and the PSO technique, respectively. Similarly, the minimum bus voltage achieved by means of the method developed in the present work (0.9514 pu) is higher than that of the three other methods (0.94 pu for both the hybrid gray wolf optimizer and the analytical methods, and 0.95 pu for the PSO technique).

3.4.2. The case of multiple DG units

The objective of this part is not only to evaluate the validity of the proposed method for multiple DGs, but also to analyze the effect of the combination of different DG types on the network performance so as to provide

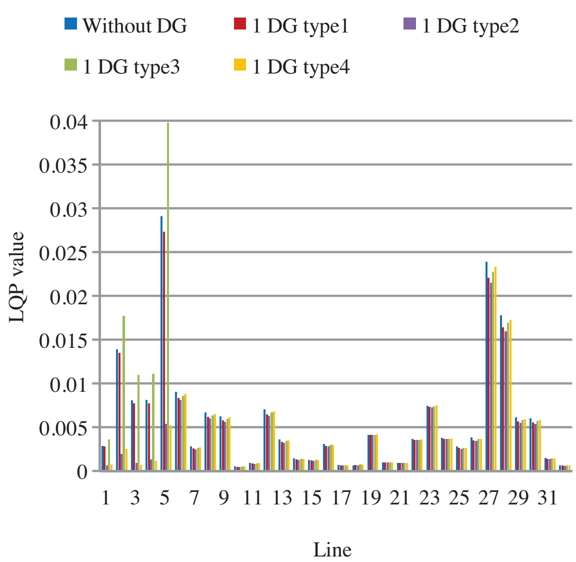

Figure 4. Voltage stability examination of different cases.

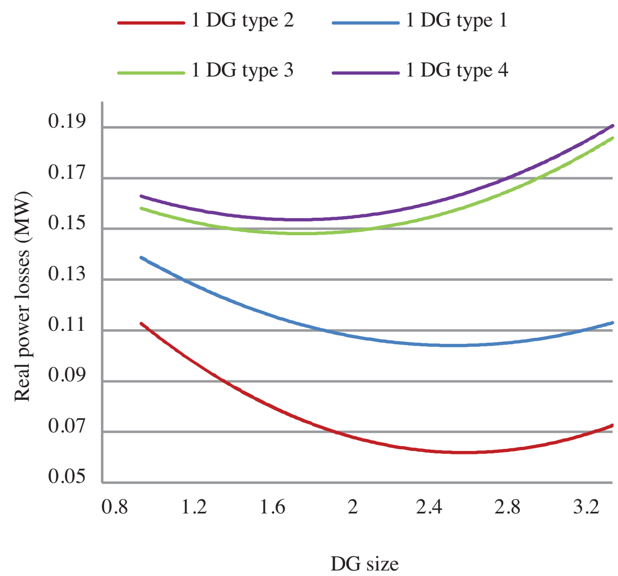

Figure 5. Effect of DG size variation on active power losses.

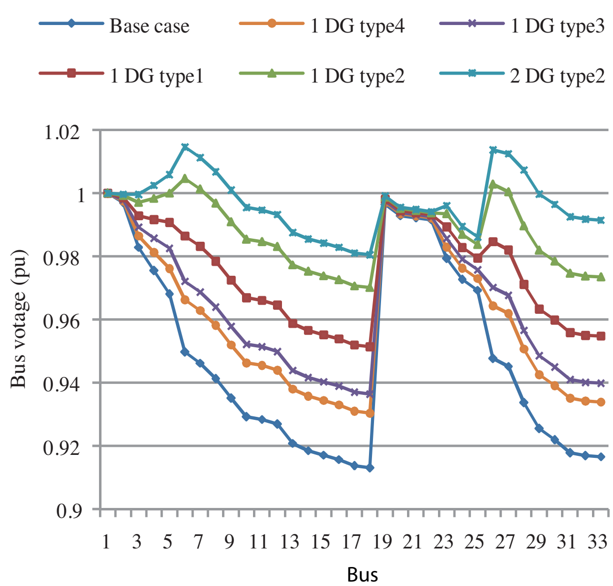

Figure 6. Voltage profiles of different cases

a blueprint for the optimal design of a hybrid network. Since the 2nd DG type is the one that generates the best results in the case of a single generator, the effect of the addition of two 2nd type DGs is first examined and then the impact of the combination of different DG types.

3.4.2.1. Placement and sizing of the two 2nd type DGs In this case, we will evaluate the validity of the proposed method for more than one DG. To this end, the primary move to be made is to identify the location of the additional DG. After executing the algorithm, results reveal that the 27th line has the highest LQP value, thereby attaching the second DG unit to the 28th bus as it is the candidate bus most affected by voltage instability. Then the optimal DG size resulting in the lowest power losses is calculated and it is found

Table 2. Comparison of the obtained results with other existing methods.

		1st type	2nd type	3rd type	4th type
Base case	Real power losses (MW)	0.203	0.203	0.203	0.203
	Minimum bus voltage (pu)	0.9131	0.9131	0.9131	0.9131
Proposed method	DG size	2.6 MW	(2.8 MW; -1.735 MVAR)	(2MW; 0.657MVAR)	-1.8 MVAR
	DG location	Bus 6	Bus 6	Bus 6	Bus 6
	Real power losses (MW)	0.104	0.062	0.148	0.154
	Loss reduction %	49	69	27	24
	Minimum bus voltage (pu)	0.9514	0.9702	0.9364	0.9304
	Voltage stability improvement%	6	33	1	29
Hybrid gray wolf optimizer[28]	DG size	2.601MW	-	-	-
	DG location	Bus 6	-	-	-
	Real power losses (MW)	0.111	-	-	-
	Loss reduction %	45	-	-	-
	Minimum bus voltage (pu)	0.9425	-	-	-
Fast approach (ELF) [10]	DG size	-	(2.635 MW; -1.633 MVAR)	-	-
	DG location	-	Bus 6	-	-
	Real power losses (MW)	-	0.0682	-	-
	Loss reduction %	-	66	-	-
	Minimum bus voltage (pu)	-	0.957	-	-
Analytical method [27]	DG size	2.497MW	(2.505 MW; -1.724MVAR)	-	-
	DG location	Bus 6	Bus 6	-	-
	Real power losses (MW)	0.111	0.068	-	-
	Loss reduction %	45	66	-	-
	Minimum bus voltage (pu)	0.9423	0.9582	-	-
PSO technique [29]	DG size	3.15 MW	(2.476MW; -1.729MVAR)	-	-1.23 MVAR
	DG location	Bus 6	Bus 6	-	Bus 30
	Real power losses (MW)	0.115	0.0677	-	0.151
	Loss reduction %	43	66	-	26
	Minimum bus voltage (pu)	0.9502	0.957	-	0.92

to be equal to 0.5 MW.

After the insertion of the second DG unit with the aforementioned characteristics, the active and reactive losses achieve 0.059 MW and 0.047 MVAr, respectively, and the minimum bus voltage increases to 0.9805 pu. Furthermore, as represented in Figure 6, the overall voltage profile has improved. As a result, it can be concluded that the additional DG unit has enabled a higher power loss diminution and a more improved voltage magnitude in regard to both the base case and the case of one DG unit integration.

The reinforcement of the network with 2 DGs also allows the reduction of the amount of power generated by the conventional generator in the slack bus. Indeed, the active and reactive powers produced by the substation decrease to 0.474 MW and 0.237 MVAR, respectively. The power injected by the main feeder becomes very small, which means that the addition of another DG unit could engender a power flow reverse through the slack bus [1, 30]. For this reason, the number of integrated DGs is limited to two.

To validate these results, a comparison was conducted with another analytical method that deals with the same network [13]. As indicated in Table 3, the two methods provide different DG locations and sizes. In fact, based on the analytical method, optimal DG placements are in 6th and 14th buses with sizes of 1.12 MW and 0.775 MW, respectively, which permits a loss reduction of 33.55% and a minimum bus voltage of 0.9584 pu. Conversely, using the algorithm developed in the present study, power losses decline to 0.059 MW, or 70.93%, and the minimum bus voltage rises to 0.9805 pu.

Table 3. Comparison of the obtained results in the case of the installation of two type 2 DGs with another method.

Method	Proposed method	Analytical method [13]
DG locations	Bus 6 Bus 28	Bus 6 Bus 14
DG sizes	(2.8MW; -1,735MVAR) (0.5MW; -0.375MVAR)	(1.12MW; -1.053MVAR) (0.775MW; -0.37MVAR)
Min bus voltage (pu)	0.9805 (Bus 18)	0.9584 (Bus 33)
Max bus voltage (pu)	1.0146 (Bus 6)	1 (Bus 1)
Active power loss (MW)	0.059	0.134
Loss reduction%	71	34
Voltage stability improvement%	37	-

3.4.2.2. Placement and sizing of DGs of different types Table 4 summarizes the results of attaching DGs of different types. It is worth noting that the combination of various DG types provides a significant reduction in power losses as well as an enhancement in both voltage magnitudes and stability. In comparison with the PSO technique [29] (Table 5) in the case of 1st and 4th type DG placement and sizing, the outcome is very similar. While the PSO technique's power loss reduction is higher by 3 kW, the proposed algorithm permits a higher minimum voltage. Furthermore, results of the 2nd and 4th type DG association are compared with those of the MOPSO method [12] (Table 5). It can be noticed that although the minimum bus voltage is the same for the two compared methods, the proposed method yields better performance in both power loss reduction and voltage stability enhancement.

It was shown in the last section that the insertion of a 3rd type DG causes the decline of some line stability. Therefore, in order to examine the effect of the combination of the 3rd type DG with one of the 4th type, the voltage stability index is computed for each line and the registered values are illustrated in Figure 7. What can be noted is that this combination permitted the improvement of the voltage stability as compared to the base case and also the case of the 3rd type DG integration.

Thus, the proposed optimization method is applicable in the case of placement and sizing of multiple DG units for it yields better results in terms of voltage stability improvement, losses reduction, and voltage profile enhancement as compared to the various methods suggested in the corresponding literature on DG allocation.

Table 4. Achieved results of the proposed method in the case of different types of DGs' integration.

DG types	Type 1 & Type 4	Type 2 & Type 4	Type 3 & Type 4	Type 1 & Type 2 & Type 4
DG locations	Bus 6 & Bus 6	Bus 6 & Bus 28	Bus 6 & Bus 6	Bus 6 & Bus 28 & Bus 6
DG sizes	2.6 MW -1.8 MVAR	(2.8MW; -1,735MVAR) -0.4 MVAR	(2MW; 0.657MVAR) -2.3 MVAR	2.6 MW (0.4MW ; -0.3 MVAR) -1.8 MVAR
Min bus voltage (pu)	0.968 (Bus 18)	0.9738 (Bus 18)	0.958 (Bus 18)	0.9763 (Bus 18)
Max bus voltage (pu)	1.0025 (Bus 6)	1.0081 (Bus 6)	1 (Bus 1)	1.0105 (Bus 6)
Active power loss (MW)	0.061	0.058	0.066	0.056
Loss reduction%	70	71	67	73
Voltage stability improvement%	34	38	34	36

Table 5. Results of the PSO and the MOPSO methods in the case of different types of DGs' integration.

Method	PSO technique [29]	MOPSO method [12]
DG locations	Bus 6 Bus 30	Bus9, Bus 23, Bus 30 Bus 10, Bus 21
DG sizes	2.5 MW -1.2 MVAR	(0.911 MW ; -0.175 MVAR) (0.669 MW ; -0.488 MVAR) (1.423 MW ; -1.067 MVAR) -1.05 MVAR -1.2 MVAR
Min bus voltage (pu)	0.957 (Bus 18)	0.98 (Bus 25)
Max bus voltage (pu)	1.0002 (Bus 6)	1.02 (Bus 9)
Active power loss (MW)	0.058	0.081
Loss reduction%	71	60
Voltage stability improvement%	-	34

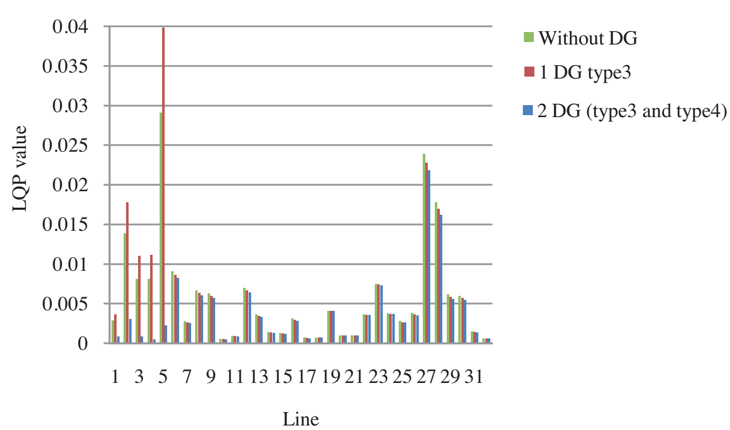

Figure 7. Effect of the association of the 3rd type with the 4th type of DG units on voltage stability.

4. Conclusion

This paper deals with an easy-to-implement method for improving power system performance. The method consists in the placing and sizing of multiple DG units inside a distribution network. DGs are placed to reinforce the areas most affected by voltage instability and sized with the main objective of minimizing power losses. The aim of this work is twofold: (i) to develop an algorithm for optimal DG integration and (ii) to analyze the impact of different DG types on system performance. With a view to realizing this, all DG types are considered, which are modeled as PQ buses, i.e. operating in constant power factor control mode. After this DG selection phase, detailed simulations are carried out on the 33-bus IEEE distribution network. The suggested method is first evaluated in the case of a single DG insertion. It is found that the attachment of any DG type leads to an improvement of voltage stability, an enhancement of the system's overall voltage profile, and a significant reduction in power losses, with the exception of the DG representing a reactive power consumer, which causes a decline in some line voltage stability. After that, the association of more than one DG type is explored and the results reveal that the combination of different DG types contributes to an extra gain as compared to the base and single DG cases.

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