Voltage Stability-Based DG Placement in Distribution Networks

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***Abstract*—Due to high penetration of distributed generation (DG) in distribution networks, transmission networks are no longer responsible solely for security issues in low-voltage distribution networks. DG units may also participate in security as well as power generation depending on their locations. In this paper, a DG placement problem is solved based on voltage stability analysis as a security measure. Modal analysis and continuous power flow are used in a hierarchal placement algorithm. Also, a modified equivalent reactive compensation method is proposed to provide a priority list of DG locations for compensating reactive power during occasions of reactive power shortage. Simulations are carried out on the well-known 33-bus radial distribution network. The results show the effectiveness of the placement algorithm and the ranking method.**

***Index Terms*—Continuous power flow (CPF), distributed-generation (DG) placement, modal analysis, radial distribution networks, voltage stability.**

I. Introduction

DISTRIBUTED generation (DG) is going to play a major role in power systems worldwide [1], [2]. The importance of DGs in future smart grids increases considering the fact that DGs will have a role in system security, reliability, efficiency, and quality as well [3]. Active management of distribution networks (i.e., integrated control of generators dispatch, transformers taps, and voltage regulators) as a lower level system may act similar to a catalyzer, speeding up the formation of smart grids [4]. As a key function in active management, DGs must be able to face the contingency conditions, while playing a remedial role in the system security. But current standards and practical experiences force DGs to be disconnected in the case of contingency. Also, DG units "shall not actively regulate the voltage at the point of common coupling" [5]. This policy is hard to implement at this growth rate of DGs in the power systems, as a disruption of a large amount of DGs for a small-scale contingency will result in a bigger one. DGs capability can be used to clear voltage stability problems, as a cause of the most recent blackouts. Considering that most DGs are located at the distribution level, determination of the best locations for installing DGs to maximize their benefits is very important in system design and expansion.

The problem of voltage stability in distribution networks and the analysis of DG units from this point of view are rather new concepts with few reported works. A new voltage-stability index is introduced by simplified load-flow equations to seek the most sensitive buses to voltage collapse in radial networks [6]. However, no DGs are modeled. An equivalent two-bus system of a distribution network is used for the analysis of voltage stability [7], [8]. The reconfiguration of radial distribution networks for voltage-stability enhancement is introduced with no DG penetration [9]. Bus indices for considering the effect of aggregated DGs into the voltage security of a transmission grid are developed with neglecting the behavior of radial distribution networks [10].

A new method for DG placement in radial distribution networks is introduced which uses CPF to identify the most sensitive bus to voltage collapse. Then, the effect of DG placement on the bus on voltage security margin (VSM) enhancement and loss reduction are also shown [11]. But the method does not always result in the best choices. It is also shown that a voltage magnitude is not a suitable indicator for the proximity to voltage collapse [12], [13].

In this paper, a DG placement problem is solved by using voltage stability techniques (i.e., modal analysis and continuous power flow, while the objective is to maximize the VSM and simultaneously minimize the losses. Also, a ranking method is introduced to provide a priority list of DG locations for compensating reactive power in the case of a reactive power shortage. The next section briefly reviews two techniques for identifying the voltage-stability problem. Section III elaborates on a new algorithm for DG placement which seeks reduced losses and enhanced VSM. The ranking method and its corresponding index are presented in Section IV. Simulation runs are carried out on the well-known 33-bus radial distribution network in Section V. Finally, Section VI concludes this paper.

II. Voltage-Stability Problem in Distribution Networks

A. Problem Identification

Voltage collapse usually occurs in heavily loaded systems that do not have sufficient local reactive power sources and consequently cannot provide secure voltage profile for the system. This reactive power shortage may lead to wide-area blackouts

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and voltage-stability problems as has occurred in many countries [14], [15]. The shortage can be alleviated by an increased share of DGs in low-voltage (LV) distribution systems to improve voltage stability [11]. These days, most DG technologies, such as synchronous machines, power-electronic interface devices (e.g., photovoltaic cells and micro turbines), and even new induction generators [e.g., doubly fed induction generators (DFIGs)], are capable of providing a fast, dynamic reactive power response. This capability can be used by the system operators to enhance system security and stability. Since a generator location affects the system voltage stability, it is important to identify the most effective buses to install a DG.

B. Modal Analysis

The voltage-stability problem has a dynamic nature in general, but static analysis techniques are promising tools for predicting the problem characteristics [16]. A modal analysis, as a static approach, can discover the instability characteristics and can be used to find the best sites for reactive power compensation, generator redispatch, and load-shedding programs. This is accomplished by solving the linearized power-flow equations

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}. \tag{1}$$

Considering $\Delta P = 0$, the reduced Jacobian matrix is obtained as [17]:

$$J_R = J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \tag{2}$$

and

$$\Delta Q = J_R \Delta V \tag{3}$$

$$\Delta V = J_R^{-1} \Delta Q \tag{4}$$

let

$$J_R = \xi \Lambda \eta \tag{5}$$

where

- ξ right eigenvector matrix of J_R;
- η left eigenvector matrix of J_R;
- Λ diagonal eigenvalue matrix of J_R.

Then, inverting (5) yields

$$J_R^{-1} = \xi \Lambda^{-1} \eta \tag{6}$$

and substituting (6) in (4) results in

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \tag{7}$$

or

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \tag{8}$$

where η_i is the ith row of the left eigenvector of J_R, and ξ_i is the ith column of the right eigenvector. The ith mode of the Q-V response is defined by the ith eigenvalue λ_i, and the corresponding right and left eigenvectors ξ_i and η_i. Since $\xi_i^{-1} = \eta_i$, (7) may be written as

$$\eta \Delta V = \Lambda^{-1} \eta \Delta Q. \tag{9}$$

By defining $v = \eta \Delta V$ as the vector of modal voltage variation and $q = \eta \Delta Q$ as the vector of modal reactive power variation, one can write uncoupled first-order equations as

$$v = \Lambda^{-1} q. \tag{10}$$

Thus, for the ith mode, we have

$$v_i = \frac{1}{\lambda_i} q_i. \tag{11}$$

If $\lambda_i > 0$, the ith modal voltage and the ith modal reactive power variations move in the same direction, indicating voltage stability of the system; whereas $\lambda_i < 0$ refers to instability of the system. The magnitude of λ_i indicates a relative degree of instability of the ith modal voltage. The smaller the magnitude of a positive λ_i, the closer the ith modal voltage is to being unstable. The voltage collapses when $\lambda_i = 0$, because any change in the modal reactive power causes an infinite change in the modal voltage.

The relative contribution of the power at bus k in mode i is given by the bus participation factor

$$P_{ki} = \xi_{ki} \eta_{ki}. \tag{12}$$

Participation factors determine the most critical areas which lead the system to instability. Usually, the higher the magnitude of the participation factor of a bus in a specific mode, the better the remedial action on that bus in stabilizing the mode.

C. Continuous Power-Flow Methodology

The determination of maximum loading is one of the most important problems in voltage-stability analysis that cannot be calculated directly by modal analysis. Considering a loading scenario, a continuous power flow uses a successive solution to compute the voltage profile up to a collapse point (i.e., where the Jacobian matrix in (1) becomes singular, to determine the voltage security margin (VSM) [18], [19]. The VSM is known as the distance from an operating point to a voltage collapse point [20]. In the successive procedure, the power at the loads increases continuously by a scaling factor δ as

$$P_L = \delta P_{L0} \tag{13}$$

$$Q_L = \delta Q_{L0} \tag{14}$$

where P_{L0} and Q_{L0} are the base-case load active and reactive powers. The generated power at each generator can be freely scaled by a scaling factor or may be limited by its boundary conditions.

III. DG Placement Algorithm

A. DG Placement Process

The DG placement problem can be formulated by many objective functions, including loss minimization, voltage profile

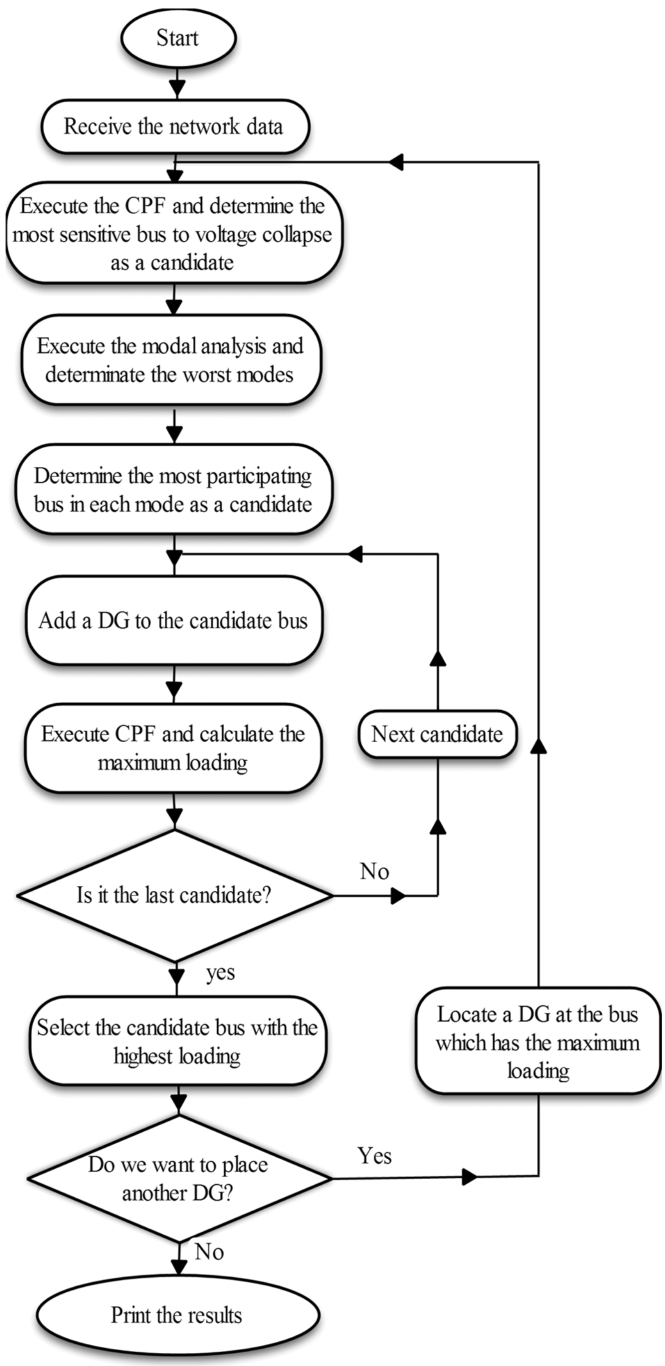

Fig. 1. Flowchart of the placement algorithm.

improvement, economical revenue, environmental impact reduction, improvement on reliability aspects, etc. [21]–[24]. In this section, the problem is formulated and solved by using modal analysis and the CPF method by an objective of voltage security margin enhancement and loss reduction, while the results are compared with the results of the proposed method in [11, Sec. IV] . The CPF can be used for the determination of the VSM and the bus voltages at collapse points. However, it cannot identify the voltage instability characteristics. Therefore, the modal analysis is used concurrently to determine the critical modes and their associated buses. This is especially attractive since the complexity of large-scale power systems does not exist in small radial distribution networks. The candidate buses for DG placement are obtained by the methods, through a voltage stability-based algorithm as shown in Fig. 1. According to the proposed algorithm, a CPF is executed on the system under study, and the bus with a minimum voltage at the collapse point is defined as the most sensitive bus to voltage collapse [11]. This bus is selected as a candidate for DG placement. The modal analysis is then executed and some critical modes and their participating buses are determined. The number of modes that must be studied is determined according to the size, topology, and other conditions of the considered system. The higher the number of eigenvalues, the more comprehensive and optimized the results. The bus which has the biggest participation factor in each mode is selected as another candidate for DG placement. Then, a DG is installed at one of the candidates and a new CPF is carried out on the system with the installed DG to determine the system maximum loading. This procedure is repeated for all candidates. The bus which has the biggest loading factor is selected as the best bus for DG placement. If more DGs are allowed to be installed, the procedure will be repeated, taking into account the already installed DG/DGs.

TABLE I
DG PLACEMENT EVALUATION INDICES

Index	Formula
DG Penetration Level	$PL = \frac{S_{DG}}{S_{load}} \times 100\ \%$
Voltage Security Margin	$VSM = \delta_k^{\max} - \delta_k$
Active Loss Reduction	$ALR = \frac{\mathrm{Re}\{losses_0\} - \mathrm{Re}\{losses_1\}}{\mathrm{Re}\{losses_0\}} \times 100\%$
Reactive Loss Reduction	$RLR = \frac{\mathrm{Im}\{losses_0\} - \mathrm{Im}\{losses_1\}}{\mathrm{Im}\{losses_0\}} \times 100\%$
Voltage Index	$VI = \sum_{i=1}^{n} (V_{i,0} - V_{i,1})^2$

B. DG Placement Evaluation Indices

To clarify the effect of DG units on the performance of power systems, some indices are used as shown in Table I. The penetration level of DG units is defined by PL, where $S_{\rm DG}$ and $S_{\rm load}$ are the apparent power of DG/DGs and the total apparent load of the network, respectively. The stability margin of the system is shown by VSM, where $\delta_k^{\max}$ is the maximum loading and δ_k is the reference loading which is considered to be 0 in this paper $(\delta_k = 0)$ [16]. The higher the VSM, the more secure the system.

ALR and RLR show active and reactive loss reduction after installing DG/DGs, where 0 represents the base case and 1, the case after DG installation [11]. Higher values of ALR and RLR indicate better performance of DGs in loss reduction.

The VI index is a good indicator for the determination of deviation from bus voltage targets, where $V_{i,0}$ is the desired voltage at bus i (usually 1 p.u.) and $V_{i,1}$ is the bus voltage when DG is presented in the network, both in per unit The lower the VI, the better the performance of DG units.

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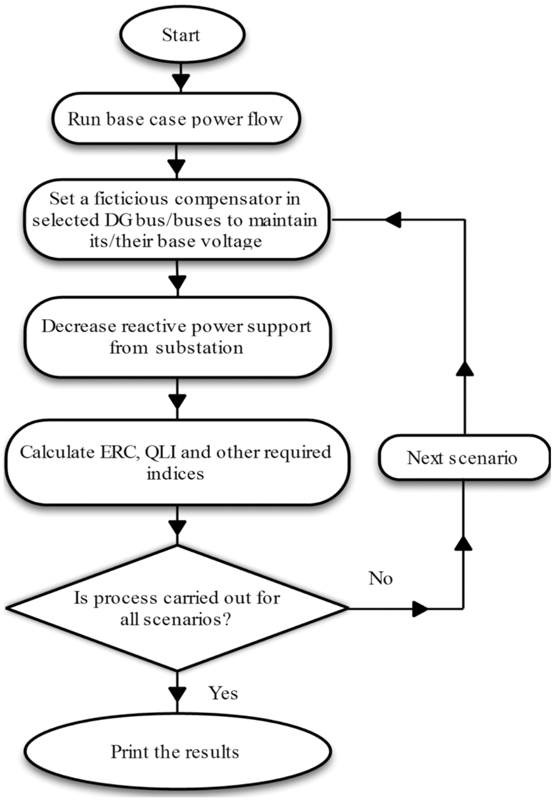

Fig. 2. Flowchart of the ranking algorithm.

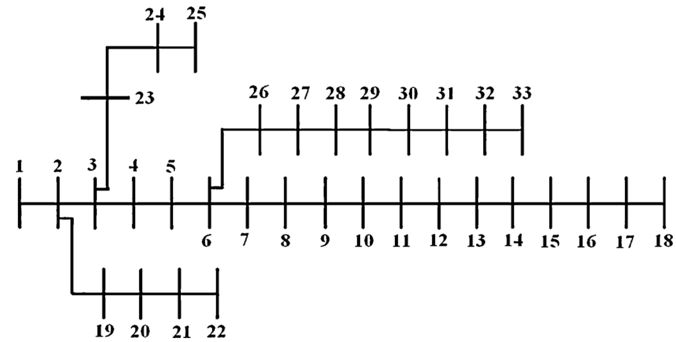

Fig. 3. Single-line diagram of the 33-bus radial distribution network.

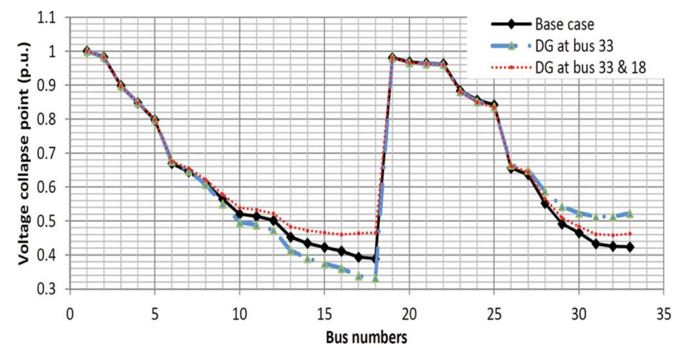

Fig. 4. Bus voltages at the collapse point for different placement scenarios (PL = 40%).

IV. Short-Term Reactive Power Ranking

Since reactive power cannot travel over long distances, system operators/dispatchers should provide it locally. DG units are good local reactive power sources, but economic issues are an obstacle against their reactive power production in normal operations. However, in the case of contingency, it would be beneficial to use the DGs VAr capability to maintain system security. But due to the structure of distribution networks and the different DG locations, reactive power compensated by each DG differs from the others, both in terms of the amount of reactive power compensated, and the remedial effects on the network voltage (i.e., the worth of the reactive power for the network). Therefore, providing a priority list to rank the DGs from the viewpoint of their reactive power effect on the network will help the operators find the best scenario, producing lower reactive power and causing a better voltage profile in the case of a reactive power shortage. In this section, a modified equivalent reactive compensation method (MERC) is proposed (Fig. 2), which uses a qualified load index (QLI) to determine a priority list of DGs to compensate reactive power shortages in any arbitrary conditions. The MERC will not seek the maximum VSM, but it only ranks the DG locations from the viewpoint of reactive power production in the case of a reactive power shortage in the network.

A. Qualified Load Index (QLI)

In the reactive power shortage conditions, it may not be applicable to maintain all bus voltages at their desired values. So it would be desirable to maintain as high amount of load as possible at the desired voltage level. Table I shows the evaluation indices which are used in the placement process. The VI is the only index that considers the bus voltage levels, but it cannot distinguish between heavily loaded and lightly loaded buses. Therefore, the following index is proposed to take into account the voltage level and the power consumed by the load at each bus as a weighting factor

$$\mathrm{QLI} = \sum_{i=1}^{n} V_i \times P_{Li} \tag{15}$$

where V_i and P_{Li} are the voltage and the active load at the load buses in per unit. The most important objective of this index is to maintain as high amount of loads as possible at higher voltages.

B. Ranking Process

The main idea behind the MERC is as follows: when the main substation reduces its reactive output, the network voltage profile will change and each DG unit should produce some reactive power to maintain its basic bus voltage. As the reactive power extraction form the main substation becomes zero, the total amount of reactive power compensated by DGs is referred to as equivalent reactive compensation (ERC) [25]. The QLI and the ERC are basic components in the evaluation algorithm of Fig. 2. The algorithm ranks the DG locations from the viewpoint of providing VAr in the shortage cases, under the premise that the DG placement has been performed using any arbitrary objective function. At the beginning, the base-case power flow is solved with the system condition of interest, neglecting any

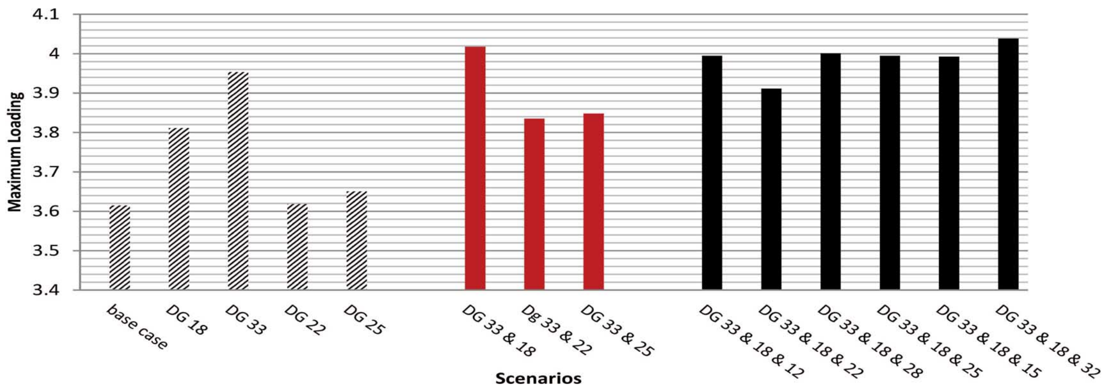

Fig. 5. Maximum loading ($\delta_k^{\max}$) for different placement scenarios ($\mathrm{PL} = 40\%$).

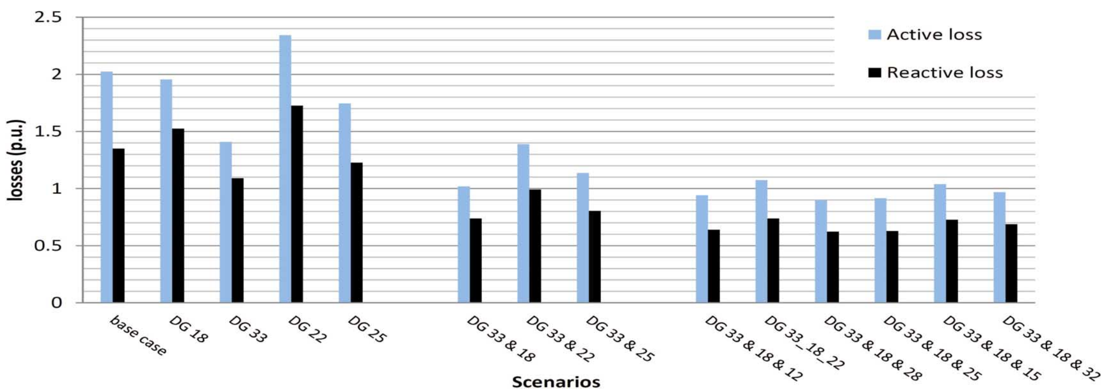

Fig. 6. System active and reactive losses for different placement scenarios when DGs active power is limited to 0.4 total load and no voltage regulation is performed by DGs.

TABLE II
MODAL ANALYSIS RESULTS FOR THE 33-BUS RADIAL SYSTEM IN DIFFERENT PLACEMENT SCENARIOS

Eigenvalue	M.P, Base Case	M.P, DG at Bus 33	M.P, DG at Bus 33 & 18
λ_1	18	18	12
λ_2	33	18	22
λ_3	18	22	28
λ_4	22	18	25
λ_5	25	25	15

M.P: The most participating bus.

reactive power injection by DGs to the system in normal operation. Then, fictitious compensators are placed in a selected DG bus/buses. Voltage setpoints of these compensators are set to a base voltage which is obtained from the base-case power flow. The reactive power injection from the substation decreases step by step, and ERC and QLI and other required indices are recorded at each step. This procedure will be repeated for each desired scenario.

V. CASE STUDY

A. Application of the Placement Algorithm

Application of the placement method and the corresponding indices are examined on the well-known 33-bus radial distribution network of Fig. 3 [26]. The system total apparent load is 4.3694 MVA and DG penetration in all cases is considered to be 40% (i.e., 1.7477 MVA). The voltage instability often occurs in heavily loaded systems with insufficient reactive power support, and DGs are going to participate in reactive power production in such conditions; so the peak loading condition is of interest in this paper.. Also, different load models (i.e., constant power, constant current, and constant impedance) will not influence the results, because the modal analysis uses the reduced Jacobian matrix of power-flow equations in the operating point, so it is not dependent on load models. On the other hand, CPF determines the static stability margin with the use of PV curves which can be obtained only by PQ load models.

Almost all readily available DG technologies [except squirrel-cage induction generators (SCIGs)] can participate in providing fast, dynamic reactive power compensation activities. Also, similar to conventional synchronous generators, these DGs have a capability curve showing the direct relationship between their active and reactive power output [27]–[29]. The distribution system operator can provide reactive power from DGs based on their capability curve; but to avoid deviation from the main problem, the control strategy (capability curve) of each technology is neglected in this paper. In CPF and modal studies, DGs are modeled as synchronous compensators with their default voltages obtained from a base power flow. Since the reactive power extraction from DGs is not economical in normal operation, the DGs are supposed to be working in the

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TABLE III
SUMMARY OF THE PLACEMENT ALGORITHM RESULTS FOR DIFFERENT PENETRATION LEVELS

DGs Penetration Level	Placement Iteration	Candidate Bus by CPF	Candidate Buses by Modal Analysis	Selected bus	VSM	ALR	RLR	VI	QLI
Base case (0%)		--	--	--	3.6146	--	--	0.1168	0.0353
20%	Iter. 1	18	18,33,22,25	33	3.833	33.28	31.01	0.0660	0.0357
	Iter. 2	18	18,22,25	18	3.8444	40.67	40.91	0.0528	0.0358
	Iter. 3	18	12,22,28,25,15	--	--	--	--	--	--
40%	Iter. 1	18	18,33,22,25	33	3.9533	30.42	19.28	0.0363	0.0362
	Iter. 2	18	18,22,25	18	4.0176	49.68	45.31	0.0187	0.0363
	Iter. 3	32	12,22,28,25,15	32	4.0379	52.11	49.05	0.0222	0.0362
60%	Iter. 1	18	18,33,22,25	33	4.0546	-1.60	-26.98	0.0221	0.0366
	Iter. 2	18	18,22,25	18	4.1297	32.64	19.68	0.0047	0.0367
	Iter. 3	16	12,22,28,25,15	28	4.1503	50.11	44.23	0.0046	0.0366

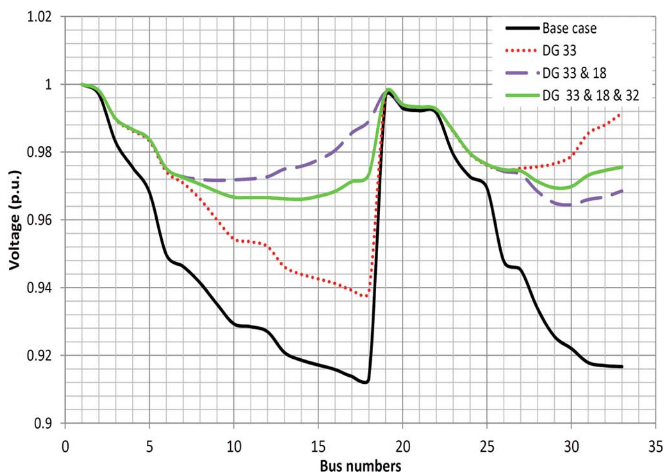

Fig. 7. Voltage profile for different placement scenarios ($\mathrm{PL} = 40\%$).

power-quality (PQ) mode and no voltage regulation is performed in normal conditions. But the system operator can force them to maintain their default voltages in case of contingency. In each DG placement iteration, as an optional index, five of the lowest eigenvalues are selected as critical modes.

CPF determines Bus 18 (Fig. 4) as the most sensitive bus to voltage collapse while modal analysis determines Buses 18, 33, 22, and 25 as critical buses as shown in Table II. Note that bus 18 is the critical bus for two modes. Hence, buses 18, 33, 22, and 25 are the DG placement candidates. Fig. 5 shows bus 33 as the best candidate for DG placement due to a higher VSM, despite a previous suboptional selection of Bus 18 (with use of the proposed method in [11]). Fig. 6 shows that an active power production by a settled DG at bus 33 reduces the system losses more than that of a DG at bus 18, providing a higher security margin.

In the second placement round with the same DG penetration, a CPF analysis introduces bus 18 as the most sensitive bus to voltage collapse while the modal analysis determines buses 18, 22, and 25 as in Table II. By investigating the effects of DG placements, Fig. 5 shows that the bigger loadability is provided when a DG is set at bus 18. Therefore, this bus is selected as the best location for the second DG. In the third placement round, with two DGs in buses 33 and 18, a CPF shows that the most sensitive bus to voltage collapse is Bus 32, when the modal analysis presents buses 12, 22, 28, 25, and 15 as critical buses (Table II). Maximum loadability and system losses after DG installation in each candidate bus are shown in Figs. 5 and 6, respectively. Finally, bus 32 is selected as the best place for the third DG. The effect of DG placement on the voltage profile is shown on Fig. 7.

The proposed placement algorithm is implementable in different DG penetration scenarios. For example, when DG penetration is 20%, buses 33 and 18 are selected as the first and the second DG buses, but locating the third DG will no longer increase the maximum loading. It means that adding two large DGs (each 10%) will improve maximum loading better than adding three small DGs (each 6.67%). Also, when DG penetration is 60%, buses 33, 18, and 28 are selected successively as DG locations. A summary of the placement algorithm results along with the evaluation indices for different DG penetration levels are shown in Table III.

Since in this study, the main substation bus is modelled as an infinite bus, DG penetration of the neighboring feeders in the same substation will have no effect on the feeder under study. In the case that the substation is not an infinite bus, the results would highly depend on the substation short-circuit power; the stronger the substation, the less effect of neighbor feeders on the feeder under study.

It is good to mention that due to the radial nature of distribution networks, the buses of each network branch, from the tail to the main feeder, usually have participation factors in a descending order for a specific mode (Fig. 8). Locating a DG at the most participating bus in a branch will reduce the participation of other buses in this branch as well (Fig. 9). For example, Bus 17 is the second most participating bus to the mode as shown in Fig. 8. However, after adding a DG at Bus 18, the participation of Bus 17 to the mode will be negligible (Fig. 9). If some buses contribute to several weak modes, they represent a weak area that should be prioritized in DG placement. Therefore, only the bus with highest participation factor in each mode is considered as a DG placement candidate. Also, it should be mentioned that

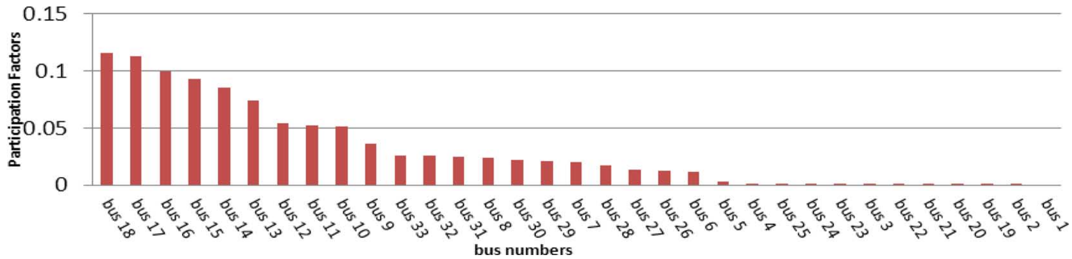

Fig. 8. The 33-bus radial networks participation factors for mode 1 in descending order in the base case.

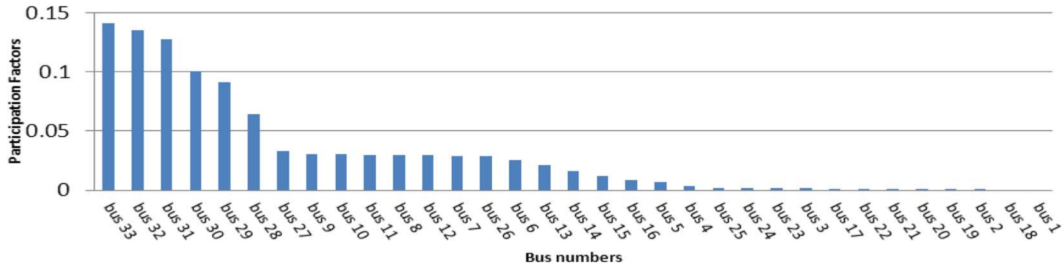

Fig. 9. The 33-bus radial networks participation factors for mode 1 in descending order when a DG is set at bus 18.

as opposed to transmission systems, more than one mode should be studied in distribution systems. Considering the most participating buses in several modes, will cover more weak areas in the system.

B. Application of the Ranking Method

Application of the ranking method is examined on all candidate buses obtained from the placement algorithm. As shown in Fig. 10, bus 28 is the best site for reactive power compensation in the case of shortage. When a settled DG at bus 28 is trying to maintain its basic voltage as the reactive power income from the substation becomes zero, a lower reactive power is compensated and simultaneously a better voltage profile is obtained. After that, buses 25, 22, 12, 32, 33, and 18 are the next choices. In this section, the ranking is implemented on the candidate buses which are obtained from voltage-stability-based algorithm. The method is not confined to these candidates and can evaluate and rank any arbitrary buses. It can even be used for capacitor placement programs and other VAr resource placement in radial distribution or high-voltage transmission networks. The ranking procedure can be repeated when more than one DG present on the network is a reactive compensator.

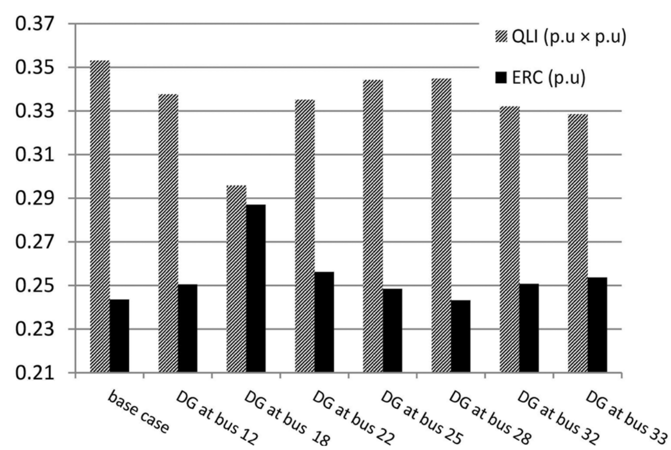

Fig. 10. Qualified load index (QLI) and equivalent reactive compensation (ERC) for different DG locations in the ranking method.

VI. Conclusion

In this paper, a voltage-stability-based algorithm for DG placement in radial distribution networks is presented. Modal analysis and CPF are used for determining DG placement candidates, while the loading parameter is the comparison index for selecting the best DG places. The places are ranked using an MERC method, which determines a priority list of DG locations for reactive power compensation during occasions of reactive power shortage.

The placement algorithm is executed on the well-known 33-bus radial distribution network, and the results show the remedial effect of DGs, both in loss reduction and voltage profile improvement in normal operation, and enhancement of the loading parameter in the case of voltage instability. The ranking method is executed over the obtained candidates to provide a priority list from the viewpoint of reactive power compensation in the case of shortage. The main objective is to serve a high amount of load as possible with a higher voltage when a shortage occurs, while the placement algorithm seeks the maximum VSM in the presence of a voltage-stability problem. The results show that the best candidate for DG placement is different from the best location for reactive power compensation. So the long-term DG placement problem can be solved by the proposed placement algorithm, while the short-term reactive power issues can be addressed by the ranking method.

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