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Optimal Placement of Distributed Generations with Modified P-V Modal Analysis

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Abstract**—Optimal allocation of DGs is currently one of the major challenges for power system engineers. Determination of the proper location of DG units is imperative to maximize their benefits. This research investigates optimal placement of multiple DG units to obtain the most stable system. The proposed method is based on an advanced voltage stability analysis method: the new modified Voltage-Active Power Modal Analysis (VPMA). The modified VPMA assesses voltage stability by considering the incremental relationship between voltage and active power instead of between voltage and reactive power. The VPMA method involves eigenvalue techniques and the associated eigenvectors of the reduced Jacobian matrix. The eigenvectors of the reduced Jacobian matrix are calculated to determine the Voltage-Active Power Modal Participation Factor (VPMPF). VPMPF provides an indication of the weakest bus in the system. Furthermore, an objective function based on loss reduction and eigenvalue is formulated to determine the most appropriate bus location for DG placement. The proposed VPMA method is tested on the IEEE 34-bus distribution network and the results show the robustness of the method. Further relevant findings are also discussed in this paper.**

Keywords-Distributed generations (DG), eigenvalue, eigenvector, modal analysis, modal participation factor, voltage stability.

I. INTRODUCTION

DGs have grown rapidly as a clean renewable energy for alternative generation in the electricity industry due to their fast technological development as well as their advantages in economic and environmental advantages regarding the exhaustion of fossil fuels caused by conventional electricity generations that lead to global warming problems [1-3]. The integration of DGs into the electric power system has brought many benefits. Because DGs are installed within the local distribution system network or at a customer's site, they deliver power directly to the local distribution network. They can improve the voltage profile by reducing power flow inside the transmission system, decrease power losses at the distribution system by delivering power for some load demand at the distribution, enhance system reliability by providing additional system generating capacity at the distribution network for uninterrupted power supply and back-up supply, reduce bottlenecks in the transmission and distribution system, and improve preservation of the power system and restoration operations by supplying temporary back-up power supply.

. In this study, a new method to determine an optimal distributed generation allocation is presented. This method is based on the Voltage-Active Power Modal Analysis (VPMA) method. VPMA involves eigenvalue techniques and the associated eigenvectors of reduced Jacobian matrix. In VPMA, eigenvectors are used to calculate bus Voltage-Active Power Modal Participation Factor (VPMPF). VPMPF indicates the contribution of particular buses to the voltage instability of the corresponding system. VPMPF can directly provide information about the weakest bus in the system. Therefore, the load bus with the highest VPMPF will be selected as the location for DG unit placement. After the placement of distributed generations, the voltage stability of the system will be re-evaluated to validate the efficiency in improving voltage profile and system eigenvalues. To verify the effectiveness of the proposed method, the IEEE 34-bus distribution network is used in this study. While the integration of DGs into an existing network can result in several benefits, this work only focuses on voltage stability enhancement. The proposed method is robust, straightforward and its computation is timely efficient. More interesting results are presented in this paper.

The structure of this paper is as follows. Section 2 describes about distributed generations. Section 3 explains about the modified V-P Modal Analysis method that focusing on the relationship between active power and voltage, and then the VPMPF calculation for the determination of DG location. Section 4 presents the proposed methodology, objective function, system constraints and evaluation parameters. Results and analysis are presented in Section 5. Section 6 concludes the main findings of the research.

II. THE EMERGENCE OF DISTRIBUTED GENERATIONS

In the literature, various terminologies and definitions are used on the subject of distributed generation (DG). "Embedded generation" is frequently employed in Anglo-American countries; "dispersed generation" is utilized in North America while Europe and a few countries in Asia apply "decentralized generation". In addition to various terminologies for distributed generation, several definitions for DG are also applicable. Ackermann et al. [4] propose a general definition for DG as "an electric power source connected directly to the distribution network or on the customer site of the meter". Similar definition is also given in Ochoa et al. [5], where DG is defined as "the development of a set of sources of electric power connected to the distribution network or the customer side of the meter". A study by El-Khattam and Salama [6] gives classification of DGs based on their technologies, which are: traditional generators (combustion engines) and non-traditional generators. Traditional generators are micro turbine whereas the non-traditional generators are fuel cells, batteries, flywheels, photovoltaic and wind turbine can be seen in Figure 1. In addition, Haiyan et al. [7] provides

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classification of DG units based on their capacities and interfaces as in Table 1.

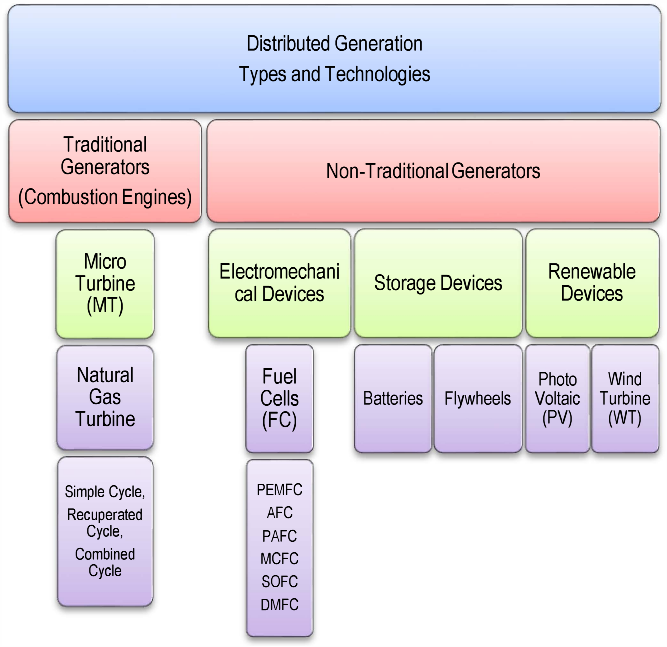

Figure 1. Types of DG and technologies [6]

TABLE I. DG CAPACITIES AND SYSTEM INTERFACE [7]

Technology	Capacity Ranges	System Interface
Solar, Photovoltaic	A few W to several hundred kW	DC/AC converter
Wind	A few hundred W to a few MW	Asynchronous generator
Geothermal	A few hundred kW to a few MW	Synchronous generator
Ocean	A few hundred kW to a few MW	Synchronous generator
Microturbine	A few tens of kW to a few MW	AC/AC converter
Fuel cell	A few tens of kW to a few tens of MW	DC/AC converter

The integration of distributed generations into electric power system has brought many benefits. It has positive effects on the voltage profile at the distribution system as well as power quality. However, these benefits depend on the location and the size of distributed generations. The appropriate location of DGs installation significantly improves voltage stability. Currently, the optimal placement of DG units is one of the major challenges for power system engineers [8]. Therefore, investigation on the DGs' optimal allocation becomes important to maximize their operation benefits.

III. THE PROPOSED METHOD: V-P MODAL ANALYSIS

The voltage stability analysis for a given system state considers two aspects [9]: *proximity* that verifies the voltage security and determines the closeness of the system to instability and *mechanism* that identifies areas prone to voltage instability issues and offers solution information useful to forestall instability

Modal analysis developed by Gao et al. [9] has been applied to solve various power system problems. This method involves eigenvalue techniques and the associated eigenvectors of the reduced Jacobian matrix. The focus of using the reduced Jacobian matrix instead of system state matrix is on voltage and reactive power characteristics. It provides an accurate estimation of *proximity* and *mechanism* to voltage instability. In modal analysis, the *proximity* is measured by the magnitude of eigenvalues. The eigenvalues sign indicates whether the system is stable or not at the given operating circumstance. The information of *mechanism* of voltage instability is provided by the eigenvectors. The eigenvector-based participation factors clearly define crucial areas of voltage instability and indicate elements which are important in the instability phenomenon.

The linearized model of steady-state power system is given by,

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V}\end{bmatrix}\begin{bmatrix}\Delta \theta\\ \Delta V\end{bmatrix} = J\begin{bmatrix}\Delta \theta\\ \Delta V\end{bmatrix} \qquad (1)$$

where,
ΔP is the bus real power incremental change
ΔQ is the bus reactive power injection incremental change
$\Delta \theta$ is the bus voltage angle incremental change
ΔV is the bus voltage magnitude incremental change
J is the Jacobian matrix of partial derivatives

However, in the original modal analysis, voltage stability is assessed with respect to the relationship between V and Q. Nevertheless, in the DG placement study, the research should focus on the active power delivered by DGs to the distribution system. Therefore, we modified the modal analysis that evaluates the system voltage stability by considering the incremental relationship between V and P, hence in this case, Q is kept constant at each operating point.

If ΔQ in Eq. 1 is kept constant, then the V-P reduced Jacobian Matrix becomes:

$$\begin{bmatrix}\Delta P\\ 0\end{bmatrix} = \begin{bmatrix}J_{P\theta} & J_{PV}\\ J_{Q\theta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta \theta\\ \Delta V\end{bmatrix} \qquad (2)$$

$$\Delta P = \left[J_{PV} - J_{P\theta}\, J_{QV}\, {J_{Q\theta}}^{-1}\right]\Delta V = J_R^{VP}\, \Delta V \qquad (3)$$

And,

$$\Delta V = {J_R^{VP}}^{-1}\, \Delta P \qquad (4)$$

$$J_R^{VP} = \left[J_{PV} - J_{P\theta}\, J_{QV}\, {J_{Q\theta}}^{-1}\right] \qquad (5)$$

The reduced V-P Jacobian matrix is labelled as J_R^{VP} which directly relates the bus voltage magnitude and the bus active power supply. For the next description, the superscript VP is used to indicate and differentiate from the original V-Q Modal Analysis. Therefore the eigenvalues and eigenvectors of the V-P reduced Jacobian matrix can be obtained from:

$$J_R^{VP} = \xi^{VP}\, \Lambda^{VP}\, \eta^{VP} \qquad (6)$$

Where,

ξ^{VP} is the right V-P eigenvector matrix of J_R^{VP}
η^{VP} is the left V-P eigenvector matrix of J_R^{VP}
Λ^{VP} is the diagonal V-P eigenvalue matrix of J_R^{VP}

$${J_R^{VP}}^{-1} = \xi^{VP}\, {\Lambda^{VP}}^{-1}\, \eta^{VP} \qquad (7)$$

Then we get the direct relation between incremental changes in active power and voltage, hence:

$$\Delta V = \xi^{VP} {\Lambda^{VP}}^{-1} \eta^{VP} \ \Delta P \tag{8}$$

Or,

$$\Delta V = \sum_i \frac{\xi_i^{VP} \eta_i^{VP}}{\lambda_i^{VP}} \Delta P \tag{9}$$

Where,
λ_i^{VP} is the ith eigenvalue of J_R^{VP}
ξ_i^{VP} is the ith column right eigenvector of J_R^{VP}
η_i^{VP} is the ith row left eigenvector of J_R^{VP}.

Hence the VPMPF can be written as:

$$MPF_{ki}^{VP} = \xi_{ki}^{VP} \eta_{ik}^{VP} \tag{10}$$

MPF_{ki}^{VP} indicates the participation of λ_i to the V-P sensitivity at bus k. The bigger the value of MPF_{ki}^{VP}, the more influence of λ_i in determining V-P sensitivity at bus k.

IV. METHODOLOGY

A. Proposed VPMA Methodology

Load bus with the highest VPMPF is the weakest bus in the system and hence has the biggest influence on the instability of the system. Therefore, the location for DG placement is based on the bus with the highest VPMPF. The VPMPF calculation is given Eq. 10. The flowchart of the proposed VPMA method can be seen in Figure 2.

B. Voltage Stability Limit and DG Capacity

In this study this following voltage threshold stability constraint is used:

$$V_{min} \le V_i \le V_{max} \ \longrightarrow \ 0.95 \le V_i \le 1.05$$

The DG capacity unit is set at 50 MW by referring to various definitions in [4].

C. The system smallest eigenvalue (λ_{min})

The eigenvalue analysis method has been validated to be useful in assessing the steady-state voltage stability of a system. It is one of the most popular voltage stability assessment parameters. The smallest system eigenvalue λ_{min} is applied to measure the voltage stability of the system. It also becomes an index for voltage stability measurement.

Eq. 6 can be extended into:

$$J_R^{VP} = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{n1} & \xi_{n2} & \cdots & \xi_{nn} \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \lambda_n \end{bmatrix} \begin{bmatrix} \eta_{11} & \eta_{12} & \cdots & \eta_{1n} \\ \eta_{21} & \eta_{22} & \cdots & \eta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \eta_{n1} & \eta_{n2} & \cdots & \eta_{nn} \end{bmatrix} \tag{11}$$

The magnitude of λ_i determines the degree of stability of the ith modal voltage.

V. TEST RESULTS AND ANALYSIS

In this paper, a new method to determine DG placement based on VPMPF is presented. The VPMPF provides information about the weakest bus in the system. The bus with the highest VPMPF is selected as the DG placement location because by placing DG in this bus, the voltage magnitude will be the most stable. To evaluate the performance of the proposed method, tests have been carried out on the IEEE 34-bus distribution network as can be seen in Figure 3.

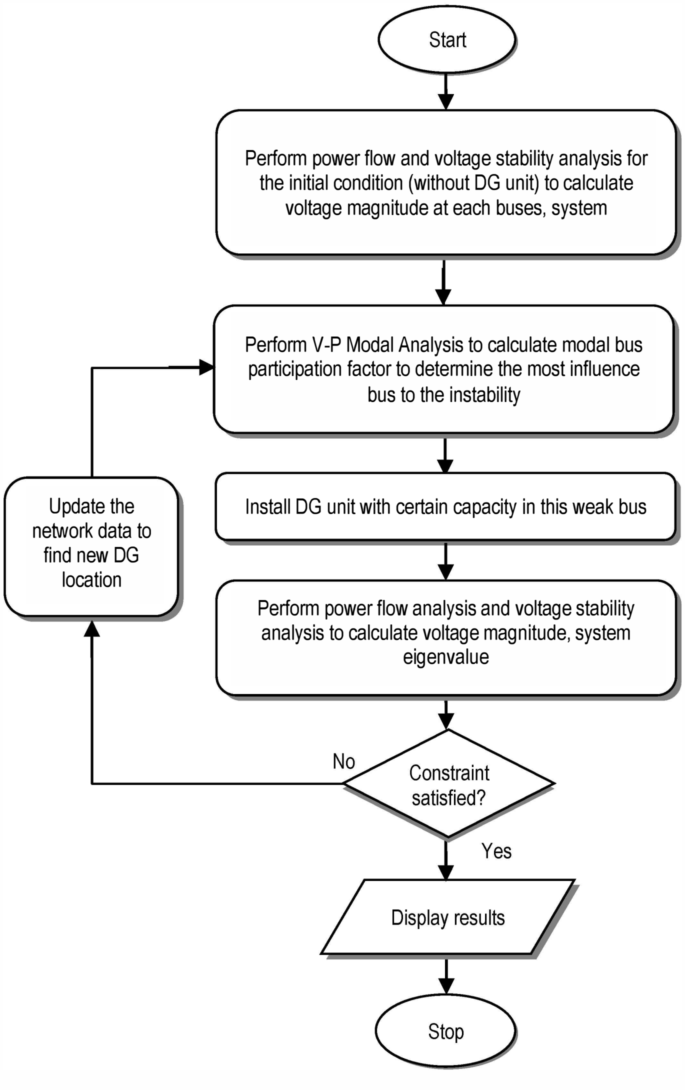

Figure 2. Flowchart of the proposed DG allocation methodology with VPMA

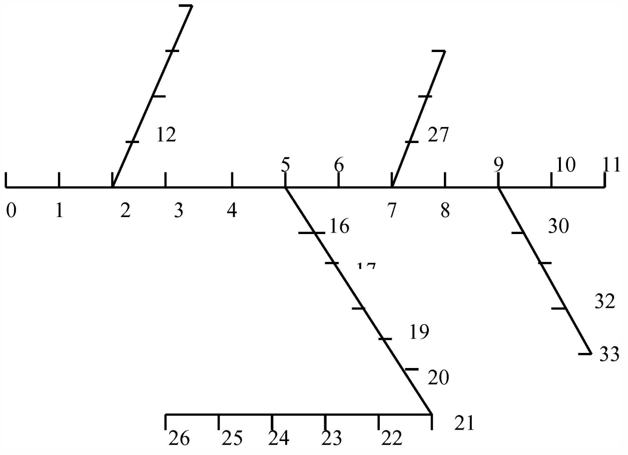

Figure 3. IEEE 34-bus distribution network test system

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A. VPMPF Calculation for DG Placement

Figure 4 shows the VPMPF at each load buses to determine the location for the 1st DG placement. As shown, bus 26 has the highest VPMPF (0.1774), hence bus 26 is declared as the most effective DG placement. However, after DG placement at bus 26, the voltage stability constraints are not yet satisfied, so a second DG unit needs to be placed. With reference to Figure 5, bus 33 becomes the most influential to instability with the highest VPMPF values of 0.1698. Again because the constraints have not yet been met, the third DG unit needs to be placed, hence the VPMPF for the third DG unit is calculated and the results can be seen in Figure 6 in which bus 11 has the highest MPF (0.1393). With 3 DG units placed at buses 26, 33 and 11, the stability constraints have been satisfied, and hence the process is stopped.

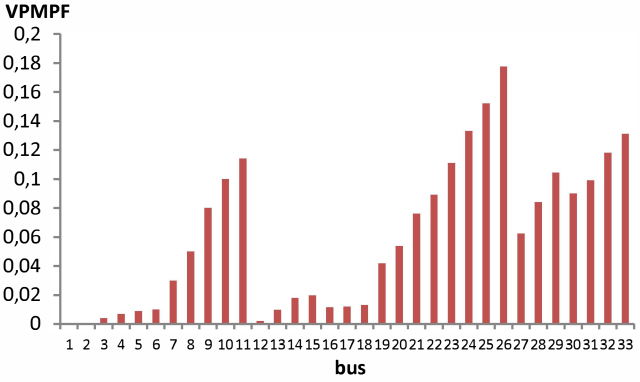

Figure 4. The VPMPF for determining first DG location

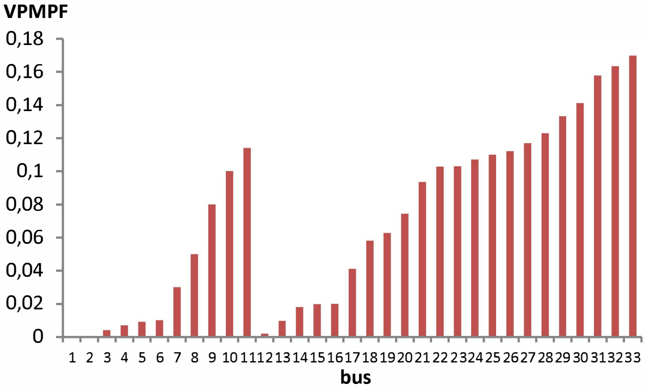

Figure 5. The VPMPF for determining second DG location

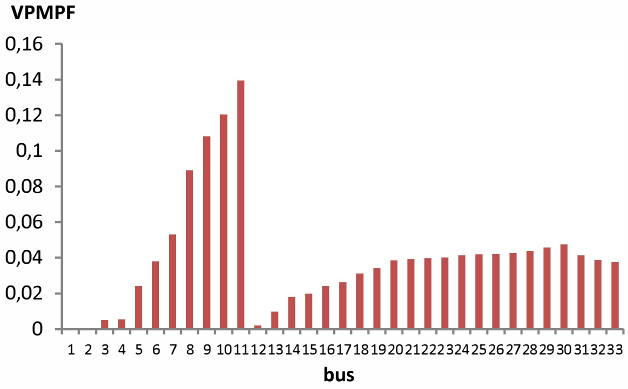

Figure 6. The VPMPF for determining third DG location

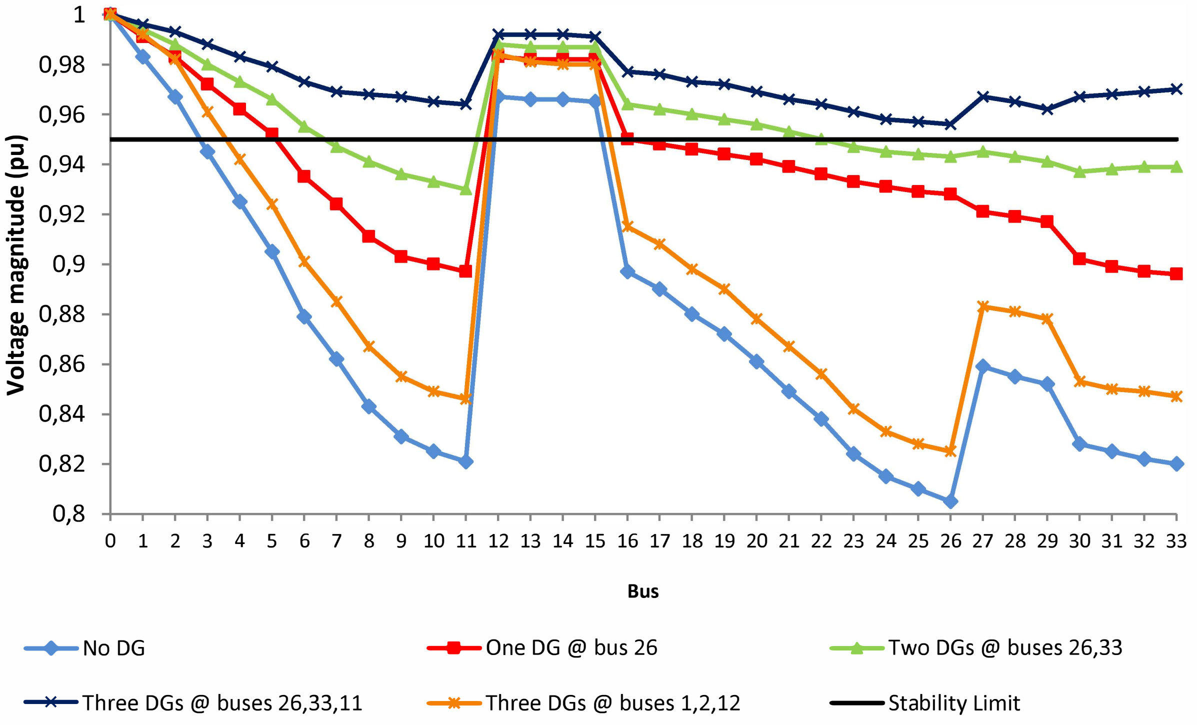

Figure 7. Voltage profile improvement with DG units placement

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B. System Voltage Profile Improvement

Figure 7 presents the voltage magnitude for each condition. To prove the robustness of the proposed method, we also observe the system performance when 3 DG units with a capacity of 50 MW each are installed at strong buses.

The light blue line represents the voltage profile of each bus at initial condition without any DG. It clearly shows that voltages at most buses are below the stability limit (black line). The voltage profile improves when a one DG unit is placed at bus 26 (the red line). The voltage magnitude increases again when the second DG is installed at bus 33 (the green line). The dark blue line represents the voltage magnitude with 3 DG units installed at buses 26, 33 and 11 based on the proposed VPMA method.

This study also observes the voltage magnitude when 3 DGs are placed in strong buses (1, 2 and 12) as indicated with the orange line. Evidently, the voltage magnitudes do not improve considerably. In fact, the voltage profile with only one DG placed at proper bus (26) is better. However, for a better indication of stability, the next section will review the system performance from the eigenvalue analysis.

Strong buses are indicated with small VPMPF values. By referring to Figures 4, 5, and 6, bus # 1, 2 and 12 all have small VPMPF values.

C. The System Smallest Eigenvalue (λ_{min})

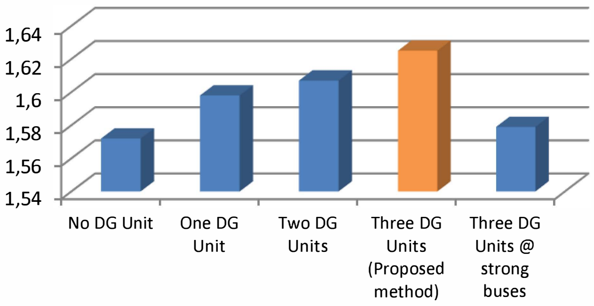

Figure 8. The system smallest eigenvalue

As can be seen in Figure 8, the system eigenvalue increases with the installation of more DG units. The λ_{min} for the system without any DG unit is 1.572. When one DG unit is installed at bus 26, the λ_{min} becomes 1.598, and then improves to 1.607 when two DG units are installed at buses 26 and 33. By using the proposed VPMA method, the third DG is placed at bus 11. The final eigenvalue with 3 DG units placed at buses 26, 33 and 11 becomes 1.61. If 3 DG units are placed at strong buses, i.e. bus # 1, 2 and 12, the λ_{min} is only 1.579, which is lower than λ_{min} for one DG unit placed at bus 26 (1.598). Yet there is only one DG unit at bus 26 with a capacity of 50 MW, and if we install DG units at these 3 strong or normal buses, the total DG capacity is 150 MW. However, one DG unit at the proper location will result in better voltage profile magnitude and higher λ_{min}, hence the system will be in a more stable condition.

VI. CONCLUSION

The proper placement of DG units is important to maximize the benefits of DG. This paper proposes a new method based on an advanced voltage stability analysis technique: the Voltage-Active Power Modal Analysis (VPMA). The objective of this study is to obtain the most stable system. To evaluate the robustness of the proposed method, this work also observes the system's performance when DG units are placed at strong buses.

The results of applying this method to the modified IEEE 34-bus distribution network clarify the robustness of this method in the optimal placement of DG units. The results show the efficiency of VPMPF in determining the optimal allocation for DG installation for the improvement of voltage profile and also to increase the system's eigenvalue compare to the existing approach. It was evident in this study that proper DG location is very critical to maximize their benefits.

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