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Abstract	Distributed energy resource (DER) has become an effective attempt in promoting use of renewable energy resources for electricity generation. The core intention of this study is to expand an approach for optimally placing several DER units to attain the most stable performance of the system and the greatest power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new modified modal analysis (MMA) and the continuation power flow (CPF) or MMA–CPF methods. The MMA evaluates voltage stability by considering incremental connection relating voltage and active power, which includes the eigenvalue and the related eigenvectors computed from the reduced modified Jacobian matrix. Furthermore, an active participation factor (APF) is computed from the eigenvectors of the reduced modified Jacobian matrix. The CPF method uses a predictor–corrector stepping pattern to reach the solution track and compute the tangent vector sensitivity (TVS). Both APF and TVS indicate each load bus sensitivity in the network. In addition, an objective function regarding losses decrease and eigenvalue is

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expressed to calculate the best bus position for DER allocation. The proposed MMA–CPF technique has been assessed on a 34-bus RDN and the outcomes demonstrate the effectiveness of the proposed scheme.

Keywords continuation power flow; distributed energy resource; distributed generation; eigenvalue; eigenvector; modal analysis; network losses; renewable energy resources; voltage stability

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5 December 2022

Dear Editor-in-Chief of Energies,

I wish to submit an original research article entitled “**Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement**” for consideration by Energies. I confirm that this work is original and has not been published elsewhere, nor is currently under consideration for publication elsewhere.

This paper reports on a novel approach for optimally placing several distributed energy resources (DER) units to attain the most stable performance of the system and the most power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new Modified Modal Analysis (MMA) and the Continuation Power Flow (CPF) or MMA-CPF methods. We believe that this manuscript is appropriate for publication by Energies because it reports innovation in DER optimal placement in distributed systems. Especially since DER is an effective attempt in promoting the use of renewable energy resources for electricity generation.

I wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Please address all correspondence concerning this manuscript to me at ardiaty@eng.unhas.ac.id.

Thank you for your consideration of this manuscript.

Sincerely yours,

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Article

Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement

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Abstract: Distributed energy resource (DER) has become an effective attempt in promoting the use of renewable energy resources for electricity generation. The core intention of this study is to expand an approach for optimally placing several DER units to attain the most stable performance of the system and the most power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new Modified Modal Analysis (MMA) and the Continuation Power Flow (CPF) or MMA-CPF methods. The MMA evaluates voltage stability by taking into account the incremental connection relating voltage and active power that includes the eigenvalue and the related eigenvectors computed from the reduced modified Jacobian matrix. Furthermore, an Active Participation Factor (APF) is computed from the eigenvectors of the reduced modified Jacobian matrix. The CPF method, uses a predictor-corrector stepping pattern to reach the solution track and compute the Tangent Vector Sensitivity (TVS). Both APF and TVS indicate each load bus sensitivity in the network. In addition, an objective function regarding losses decrease and eigenvalues is expressed to calculate the best bus position for DER allocation. The proposed MMA-CPF technique has been assessed on a 34-bus RDN and the outcomes demonstrate the effectiveness of the proposed scheme.

Keywords: continuation power flow; distributed energy resource; distributed generation; eigenvalue; eigenvector; modal analysis; network losses; renewable energy resources; voltage stability.

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1. Introduction

Due to rapid technological advances also the economic and environmental benefits of a distributed energy resource (DER), DER has become a global unpolluted renewable energy source for alternative generations. Nowadays, DERs are more developed in the grid worldwide because of their advantages compare to the conventional fossil fuel power generations that drive the issue of global warming. DERs can be divided into four main categories based on their ability to supply active and reactive power, which are [1]:

- Type 1 DER unit (pf_{DERi} = 1, unity power factor): The type 1 DER can only supply active power to the system. Examples of Type 1 DER are photovoltaic (PV) [2, 3], micro-turbines (MT), and fuel cells (FC). These DERs are connected to the main network using converters/inverters;
- Type 2 DER unit (pf_{DERi} = 0). The type 2 DER can only provide reactive power to the network. For example, static power compensators such as capacitor, static VAr compensator (SVC), static synchronous compensator (STATCOM), etc. [4, 5];
- Type 3 DER unit (0 < pf_{DERi} < 1 with lagging power factor). The type 3 DERs can provide active power and reactive power to the network. Examples of type 3 DER are a synchronous generator operated in cogeneration and gas-fired DER;

- Type 4 DER unit ($0 < pf_{DERi} < 1$ with leading power factor). This type of DER provides active power to the system but attracts reactive power. An example of type 4 DER is primarily an induction generator in a wind farm, such as doubly-fed induction generators (DFIG)[6].

The connection of DERs into the grid has resulted in several gains. Because the DERs are located inside the local grid or at the customer's site, DERs provide electrical energy directly to the customers or the local distribution grid. DERs tend to decrease the flow of power in the transmission system, which can enhance the voltage profile in the distribution system. DERs assist to lessen losses in the distribution network by supplying locally to the load demand. DERs also enhance system reliability by delivering supplementary system generation capacity for power distribution networks for non-disruptive power supplies and backup power supplies, and providing temporary emergency power [7]. However, these benefits are highly dependent on the proper placement and capacity of the DERs. Proper placement of the DERs will greatly improve the system stability and reduce distribution grid losses [8]. Optimum DER allocation is one of the main challenges for DER integrations [9]. Studying the most appropriate placements of DERs was essential to take full advantage of DER's operating advantages. Power system engineers and researchers have recommended various methodologies to determine the optimal placement of DERs. A comprehensive review on DG placement is provided by [10].

Many analytical techniques have been proposed for solving DER placement. The authors in [11] proposed $Q - PQV$ bus pair considering load demand seasonal changes biomass DER placement. In [12], bifurcation analysis and dynamic programming were used. The authors of [13] have established a power stability index (PSI) that determines a stable node voltage for the placement and sizing of DERs. Work in [14] defined an objective function by employing the maximum power stability index (MPSI) for finding the DER location. An integer nonlinear programming was implemented in [15] to choose sensitive nodes to increase voltage profiles. Article [16] suggested a technique for determining the optimal position of DERs considering network losses and using the Kalman filter algorithm to compute the optimal size of DER. Nonetheless, no standard criteria for the determination of the optimal number of DERs. The author of [17] recommended analytical power losses equations for calculating the optimal size and position of DER to reduce network losses. Nevertheless, the big size and difficulty of the distribution system can affect how the robustness is not satisfied. From [18], a “2/3 rule” which was firstly used for capacitor placement in the distribution network was assumed to determine the position of DERs. This method is very easy, but cannot be directly applied to a meshed network. Furthermore, the capacitors supply only reactive power while the DER produces active power. Consequently, this rule cannot be used effectually to locate the DERs. The authors of [19] offered a Continuation Power Flow (CPF) based settlement of DER units and indicated the most sensitive bus to voltage breakdown. The DER units were placed on the chosen buses via the iterative algorithm and objective function. Yet, this technique does not always offer the ideal solution.

Moreover, many meta-heuristic methodologies have been proposed for optimal DER placement. A sensitivity analysis and harmony search algorithm (HAS) was used to decide the most appropriate DER place [20]. A differential evolution algorithm is proposed in [21] for DER integration. Genetic algorithm (GA) and AC-OPF were proposed by authors in [22] for placement and size of DER. GA is a suitable technique for solving multi-objective difficulties and can provide effectual solutions, but it is time-consuming in its computation. Chaotic bat algorithm (CBA) was developed in [23] for optimal locations and DERs’ sizes. A fuzzy-embedded multi-objective particle swarm optimization (FMOPSO) method was used in [24]. Nevertheless, the shortcoming of PSO is it obtains solutions to local solutions quickly or prematurely converges. Ant colony system (ACS) was occupied in [25] for DER placement. However, a few obstacles to the ACS approach may additionally reduce its effectiveness. ACS relies upon preliminary points and necessitates a longer computational time to discover the most efficient arrangement. Authors in [26] developed a fireworks algorithm for network reconfiguration and finding the most suitable allocation of DER in a distribution system. In [27], the authors developed DER placement based on a modified teaching-learning-based optimization (MTLBO) algorithm. Meta-heuristics techniques are widely known utilized for optimal DER allocation, nonetheless, their severe drawbacks are the divergence possibility, they require a long period to acquire the best solution, and they cannot often warranty to obtain the best result, but a sensible result that is near to a perfect result.

Hence, we proposed an original hybrid analytical method in this article with Modified Modal Analysis (MMA) and Continuation Power Flow (CPF) to resolve the DER deployment with the objective of maximizing voltage stability and minimizing active power losses. Gao et al. [28] developed modal analysis and it has been implemented to resolve several power systems issues. This method includes the eigenvalue method and the related eigenvectors computed from the reduced voltage-reactive power Jacobian matrix. The reduced voltage-reactive power Jacobian matrix emphasizes the relationship between system voltage and reactive power. However, in order to meet the aim of this study, the reduced Jacobian matrix was adapted where its focus was on voltage and active power properties, rather than reactive power. This method is appropriate for DER Type 1 because the MMA and CPF give information about the correlation between voltage magnitude and active power at each load bus.

Placement of DER units at the appropriate place will substantially lessen system losses and considerably enhance the stability of the system. Hence, the key contributions of this manuscript are:

- developing a new hybrid scheme to compute the optimal DER placement. This technique is a hybrid approach: the Modified Modal Analysis (MMA) and Continuation Power Flow (CPF) or MMA-CPF method. This approach combines the key feature of both techniques. The MMA incorporates the eigenvalue computation and the correlated eigenvectors of the reduced modified voltage-active power Jacobian matrix. MMA uses eigenvectors to compute the bus Active Participation Factor (APF). The APF provides an indication of the participation of a certain bus in solving the instability problem of the network. On the other hand, the CPF reformulates the equation of the power flow by using a prediction-correction stepping algorithm to reach the solution track and computes the Tangent Vector Sensitivity (TVS). Both APF and TVS give indications about the bus that has the biggest influence in improving the system stability directly. Thus, the load bus that has the biggest APF/TVS is chosen as the place for the DER unit;
- delivering a complete evaluation of the impact of DER allocation on system losses and assessment of voltage stability, which in this case, are the smallest eigenvalues for the system, as they are a common indicator for assessing the performance of system stability;
- enhancing the objective functions based on the power losses as well as eigenvalues to conclude the most suitable DER site when the difference between APF and TVS happens. The formulation of this objective function provides a calculation of which bus will give the least losses and the most stable system.

After determining the DER placement, this work re-evaluates the voltage stability of the system to confirm the efficiency of the proposed placement in enhancing voltage profile, eigenvalues of the system, and reduction in power losses. The proposed technique was simulated on a 34-bus RDN to clarify the efficacy of the recommended scheme. Even though the integration of DERs into a present distribution network can offer several paybacks, this research only emphasizes the improvement of voltage stability and reduction of network losses. This work computed the network losses, voltage magnitude, and system smallest eigenvalue. The developed scheme is simple, straightforward, robust, and its time calculation is effectual because it uses a non-iterative procedure in calculating DER placement based on the APF/TVS. Further interesting outcomes are elaborated in this manuscript.

2. Modified Modal Analysis

The modal analysis technique was proposed by [28]. This technique has been implemented in many areas of power systems to resolve different stability problems. This approach forms a reduced Jacobian matrix that provides a direct correlation between variations in reactive power and system voltage. The modal analysis presents *proximity* and *mechanism. Proximity* provides information about the security of the system voltage that gives details on the stability level of the system which is indicated by the eigenvalues (ε_i). The ε_i indicates if the system is stable or not stable at a particular operational state. The *mechanism* provides identification of areas likely to instability problems which is helpful to preclude system instability. The information on the instability *mechanism* is given by the eigenvectors. Their computation states critical voltage instability areas and signifies components that are imperative in the instability occurrence.

The linearized equation of a static steady-state power system is given by,

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

Nevertheless, in the modal analysis by [28], the evaluation of voltage stability is regarding the correlation between reactive power (Q) and voltage (V). Yet, in the placement of the Type-1 DER, the assessment should emphasize the active power supplied by DERs. Therefore, in this manuscript, the initial modal analysis is adjusted to assess the stability of the system by taking into account the incremental correlation between active power (P) and voltage (V), thus reactive power (Q) is considered the same.

If ΔQ in Eq. 1 is kept constant, then the reduced modified Jacobian Matrix can be written as

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

$$\Delta P = \left[J_{PV} - J_{P\theta} \, J_{QV} \, {J_{Q\theta}}^{-1} \right] \Delta V = J_R^* \, \Delta V \tag{3}$$

$$\Delta V = J_R^{*-1} \, \Delta P \tag{4}$$

$$J_R^* = \left[J_{PV} - J_{P\theta} \, J_{QV} \, {J_{Q\theta}}^{-1} \right] \tag{5}$$

The reduced modified Jacobian matrix is marked as J_R^* to differentiate it from the initial Jacobian matrix, which correlates directly with variations between active power and the magnitude of the bus voltage. Hence we can reformulate the eigenvalues and eigenvectors as follow:

$$J_R^* = \Re^* \, \Phi^* \, \Upsilon^* \tag{6}$$

$$J_R^{*-1} = \Re^* \, \Phi^{*-1} \, \Upsilon^* \tag{7}$$

By substituting Eq. 7 into Eq. 4, the direct correlation between the incremental variations of active power and the system voltage can be obtained as follow:

$$\Delta V = \Re^* \, \Phi^{*-1} \, \Upsilon^* \; \Delta P \tag{8}$$

Or,

$$\Delta V = \sum_i \frac{\zeta_i^* \, \varrho_i^*}{\varepsilon_i^*} \Delta P \tag{9}$$

Therefore the APF becomes:

$$APF_{ki} = \zeta_{ki}^{*}\, \varrho_{ik}^{*} \tag{10}$$

APF_{ki} signifies the participation of bus i to the voltage-active power sensitivity at bus k. The bigger the APF_{ki} value, the more significant bus i effect in deciding voltage-active power sensitivity at bus k [29].

3. The Continuation Power Flow (CPF)

The intention of the CPF scheme is to attain a different power flow results for a particular load variation situation. The CPF scheme concisely delivered in this manuscript is according to the method explained by [30].

Initially, we define a load parameter (ϖ) as:

$$0 \leq \varpi \leq \varpi_{critical}$$

where ϖ = 0 relates to the system base-load and $\varpi = \varpi_{critical}$ indicates the critical load. Then ϖ is then included in the power equations of both active and reactive to acquire:

$$0 = P_{Gi0}(1 + \varpi k_{Gi}) - P_{Li0} - \varpi\,(k_{Li}\, S_{\Delta base} \cos\theta_i) - P_{Ti} \tag{11}$$

$$0 = Q_{Gi0} - Q_{Li0} - \varpi\,(k_{Li}\, S_{\Delta base} \sin\theta_i) - Q_{Ti} \tag{12}$$

A continuance procedure is implemented at the remodeled power flow calculations, hence Eqs. 11-12 are adjusted in a simple formula:

$$F\left(\bar{\delta}, \bar{V}, \varpi\right) = 0 \tag{13}$$

The continuation power flow technique exploits a prediction-correction system to attain a result track of remodeled power flow formulas. A tangent vector is computed in the prediction phase by considering the derivation of both power flow equations sides, hence:

$$[F_{\bar{\delta}} \quad F_{\bar{V}} \quad F_{\varpi}] \begin{bmatrix} d\bar{\delta} \\ d\bar{V} \\ d\varpi \end{bmatrix} = 0 \tag{14}$$

A revision is done in the prediction stage by parameterization enlargement to recognize every result alongside the trajectory being tracked. The tangent vector specifies sensitivity analysis to resolve the most sensitive buses in addition to the way of the solution route. A sensitive bus in CPF is the bus with a big ratio of voltage differential variation to load differential variation, which is provided by the tangent vector [31]. Hence, the formula for Tangent Vector Sensitivity (TVS) at bus j can be written as:

$$TVS_j = \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd\varpi}\right| = \max\left[\left|\frac{dV_1}{Cd\varpi}\right|, \left|\frac{dV_2}{Cd\varpi}\right|, \dots \left|\frac{dV_n}{Cd\varpi}\right|\right] \tag{15}$$

4. Proposed Methodology, System Constraints, Objective Function, and Evaluation Parameters

4.1 Proposed Hybrid MMA-CPF Technique

The load bus that has the biggest APF/TVS value signifies the most sensitive bus in the network thus having a prevalent impact on enhancing the system stability. Hence, the DER placement position is recommended according to the bus with the largest APF/TVS value. Additionally, this work develops a new formulation for objective function based on the APF/TVS outcomes to resolve the most appropriate bus for DER placement that would result in the most stable system and the lowest system losses. The APF computation is provided in Eq. 10 while the TVS calculation can be obtained in Eq. 15. Figure 1 provides the proposed MMA-CPF technique flowchart.

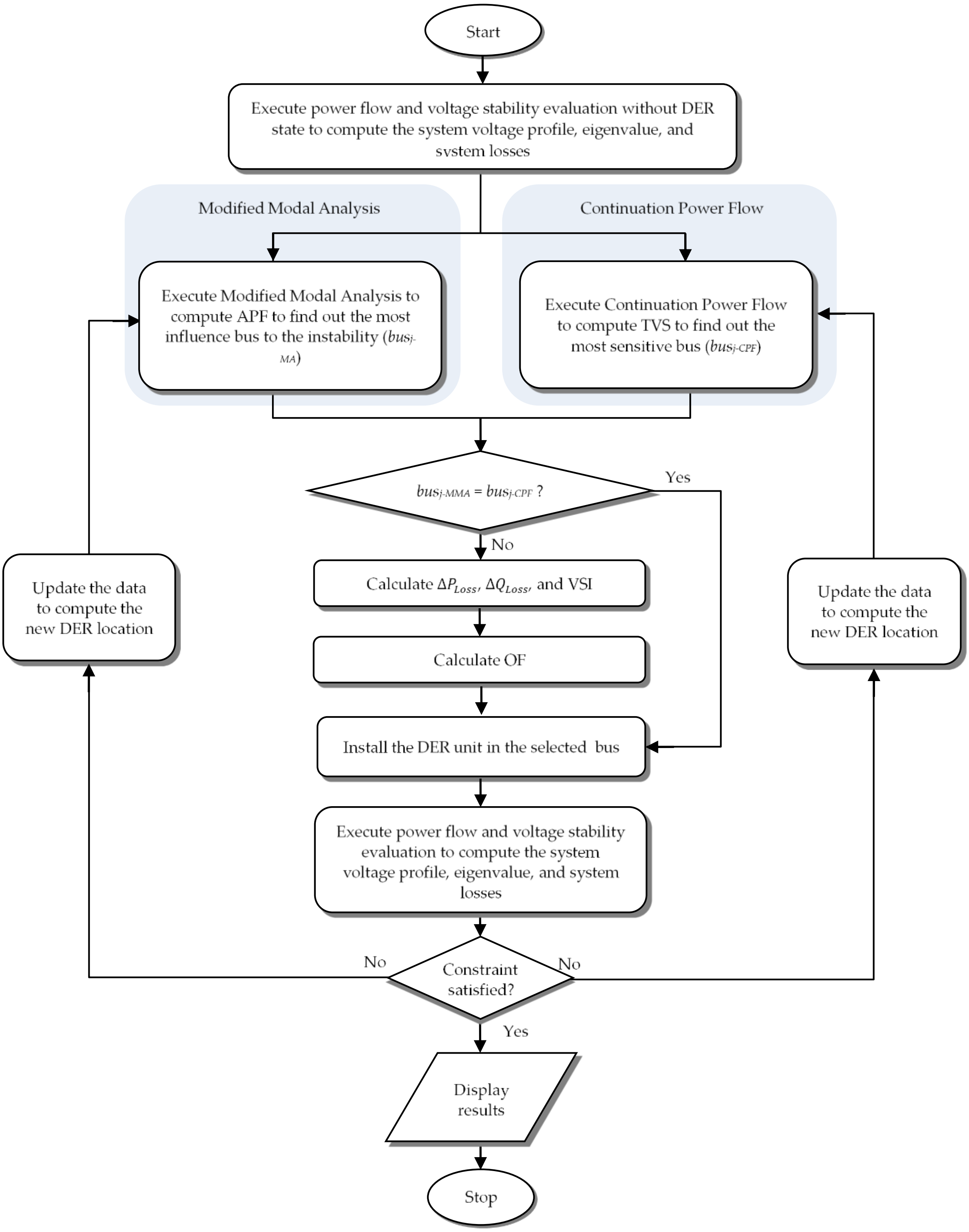

Figure 1. The hybrid MMA-CPF DER allocation approach flowchart

The detailed computational process for DER allocation according to the hybrid MMA-CPF technique is described as:

Step 1 Input the system data.

Step 2 Execute power flow with Eq. 1 and evaluate voltage stability for the original state (no DER unit) to compute voltage profile, system losses, and eigenvalue

Step 3 (a) Execute MMA to compute APF at each load bus to define the most influential bus ($bus_{j\text{-}MMA}$), and

(b) Execute CPF to compute TVS at each load bus to define the most sensitive bus ($bus_{j\text{-}CPF}$).

Step 4 Compare the outcomes of MMA and CPF. If $bus_{j\text{-}MMA} \neq bus_{j\text{-}CPF}$, go to *Step 5*, else go to *Step 7.*

Step 5 Compute ΔP_{Loss}, ΔQ_{Loss}, and VSI.

Step 6 Compute the OF. The bus that has the highest objective function is recommended as the DER location.

Step 7 Set up DER in the designated bus.

Step 8 Execute power flow and evaluate voltage stability assessment to compute voltage profile, system losses, and eigenvalue

Step 9 Assess the performance of the system as to if all the voltages are within the voltage limit constraints.

Step 10 If the bus voltage magnitudes are not fulfilled, then adjust the system data to acquire a new DER place and go back to *Step 3.*

Step 11 Once the voltage stability constraints are fulfilled, the program is terminated.

4.2 Voltage Stability Constraints

The voltage threshold stability limit utilized in this study is as follows:

$$V_{min} \leq V_i \leq V_{max} \longrightarrow 0.95 \leq V_i \leq 1.05 \text{ p.u}$$

4.3 The Eigenvalue Evaluation

The eigenvalue is one of the popular parameters for assessing voltage stability and has been confirmed its usefulness in evaluating voltage stability. In this manuscript, the smallest system eigenvalue ε_{min} is calculated and implemented to assess the level of the system voltage stability. It is also considered a voltage stability indicator. Therefore, we can expand Eq. 6 into:

$$J_R^* = \begin{bmatrix} \zeta_{11} & \zeta_{12} & \cdots & \zeta_{1n} \\ \zeta_{21} & \zeta_{22} & \cdots & \zeta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \zeta_{n1} & \zeta_{n2} & \cdots & \zeta_{nn} \end{bmatrix} \begin{bmatrix} \mathcal{E}_1 & 0 & \cdots & 0 \\ 0 & \mathcal{E}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \mathcal{E}_n \end{bmatrix} \begin{bmatrix} \varrho_{11} & \varrho_{12} & \cdots & \varrho_{1n} \\ \varrho_{21} & \varrho_{22} & \cdots & \varrho_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \varrho_{n1} & \varrho_{n2} & \cdots & \varrho_{nn} \end{bmatrix} \tag{16}$$

The ε_i magnitude defines the bus i^{th} modal voltage's degree of stability.

4.4 Network Power Losses

The following formulations represent the total active and reactive power losses [32]:

$$P_{Loss} + jQ_{Loss} = \sum_{i=1}^{N} S_i = \sum_{i=1}^{N} V_i I_i^* \tag{17}$$

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_i.P_j + Q_i.Q_j\right) + \beta_{ij}\left(Q_i.P_j - P_i.Q_j\right)\right] \tag{18}$$

$$Q_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\gamma_{ij}\left(P_i.P_j + Q_i.Q_j\right) + \delta_{ij}\left(Q_i.P_j - P_i.Q_j\right)\right] \tag{19}$$

Where,

$$\alpha_{ij} = \frac{R_{ij}}{|V_i||V_j|}\cos(\theta_i - \theta_j), \quad \beta_{ij} = \frac{R_{ij}}{|V_i||V_j|}\sin(\theta_i - \theta_j)$$

$$\gamma_{ij} = \frac{X_{ij}}{|V_i||V_j|}\cos(\theta_i - \theta_j), \quad \delta_{ij} = \frac{X_{ij}}{|V_i||V_j|}\sin(\theta_i - \theta_j)$$

These following formulas are used to assess the DER unit placement effect on reduction of power losses:

$$\%\Delta P_{Loss} = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}} * 100\% \tag{20}$$

$$\%\Delta Q_{Loss} = \frac{Q_{Loss} - Q_{Loss}^{DG}}{Q_{Loss}} * 100\% \tag{21}$$

4.5 Objective Function

To determine the DER unit's placement in the distribution system, the objective function deliberated in this work is minimizing the network losses (maximum losses reduction) and maximizing the system eigenvalue (system stability). Hence, the objective function (OF) is formulated as follows:

$$\mathrm{OF} = \Delta P_{Loss} + \Delta Q_{Loss} + VSI \tag{22}$$

$$\Delta P_{Loss} = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}}, \quad \Delta Q_{Loss} = \frac{Q_{Loss} - Q_{Loss}^{DG}}{Q_{Loss}}, \quad VSI = \frac{\varepsilon_{min}^{DG} - \varepsilon_{min}}{\varepsilon_{min}}$$

The bus with the largest objective function is chosen as the place for DER installment as locating the DER unit in this bus, the aim is to get the lowest losses and the highest stability index will be achieved.

5. Test Results and Analysis

This paper developed a novel hybrid approach to resolve the integration of DER based on objective function computed from APF and TVS. Both the APF and TVS give info about the most sensitive bus in the network or the bus that has the biggest influence on improving stability. If APF and TVS indicate different most sensitive buses, an objective function that measures minimum losses and maximum stability index is calculated. The bus that has the biggest objective function is chosen as the location for DER since by assigning DER in this bus, network losses can be minimum whereas the index of stability can be maximum. To assess the proposed method's performance, tests were conducted on the 34-bus RDN.

5.1 APF and TVS Computation for DER Location

The outcomes APF and TVS computation at each load bus to find out the appropriate location for the 1st DER allocation are shown in Figure 2. As can be seen from Figure 2, bus 26 has the biggest APF value (0.1774) and TVS value (0.124), as indicated by the big black marks, therefore bus 26 has the biggest influence on improving stability and is confirmed as the most efficient bus for the location of DER. Nonetheless, after DER integration at bus 26, the system is not stable yet, hence a second DER is required. Regarding Figure 3, bus 33 then has the biggest APF and TVS values of 0.1698 and 0.115 respectively, hence it is becoming the most sensitive bus to instability for the second computation. However since the system constraints have not been satisfied yet, the third DER is needed. The APF and TVS outcomes for the third DER can be perceived in Figure 4 where bus 11 has the biggest APF (0.1393), but bus 17 has the biggest TVS (0.113). Due to this difference, the objective function needs to be computed to resolve the most effective bus for the third DER unit. The result of the objective function calculation is shown in Figure 5 where bus 11 is shown to have the highest objective function value (0.8926), hence bus 11 is chosen as the site for the third DER unit. With 3 DERs positioned at buses 26, 33, and 11, the voltages at all buses system have recovered above the stability constraints thus the procedure is completed.

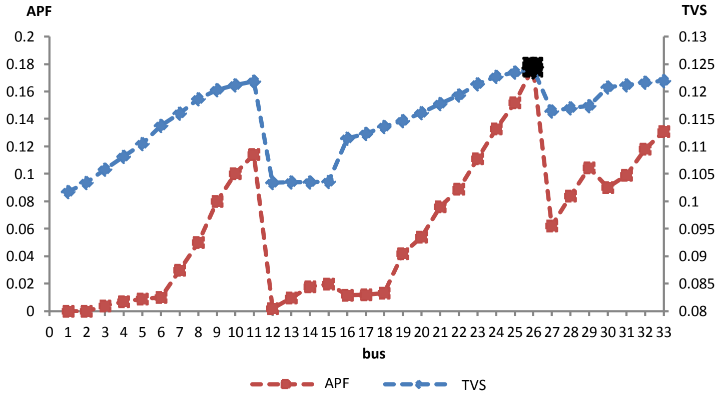

Figure 2. The APF and TVS for determining first the DER location

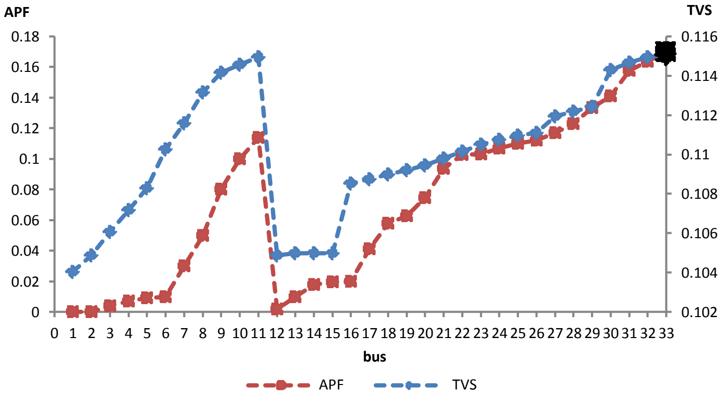

Figure 3. The APF and TVS for determining the second DER location

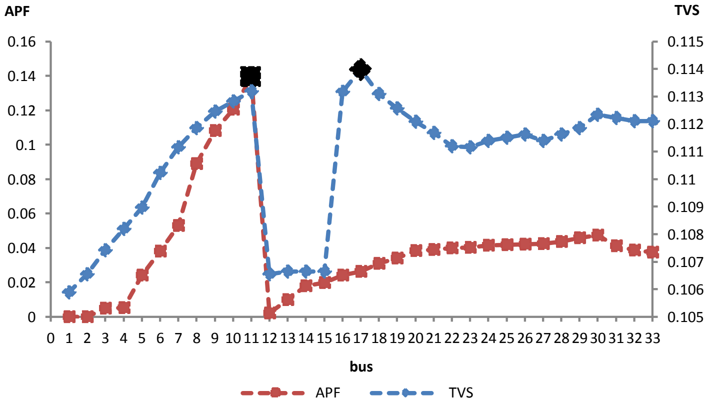

Figure 4. The APF and TVS for determining the third DER location

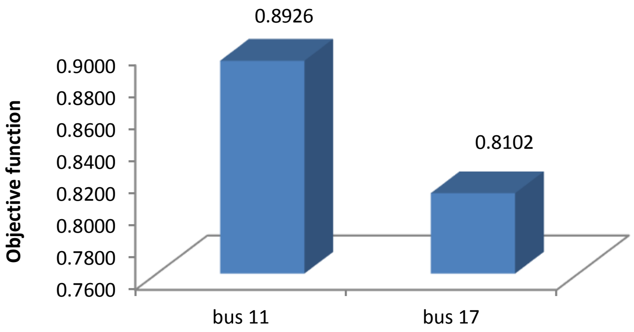

Figure 5. Objective function (OF) to determine the third DER location

5.2 Voltage Profile Enhancement

Figure 6 shows the voltage profile of the system for several scenarios. To verify the effectiveness of the developed hybrid MMA-CPF scheme, we also simulate the system stability if 3 DER units are placed at the least sensitive buses that have small APF and TVS. By seeing Figures 2-4, buses 1, 2, and 12 have small APF/TVS. We also evaluate the system performance if the DERs are placed at average APF/TVS values buses, for example at buses 5, 15, and 29.

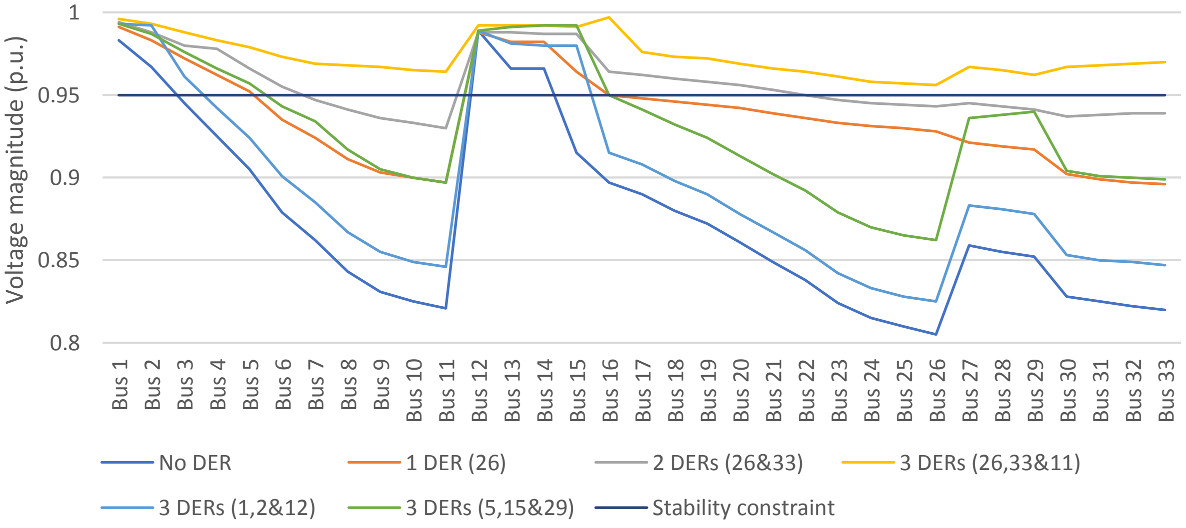

Figure 6. Voltage profile improvement with DER units placement

The line in blue color shows the system voltage profile of all buses at the original state before DER integration. It obviously indicates that voltages at the majority of the system are beneath the stability constraint (black line). The system voltage magnitude increases after one DER is integrated at bus 26 (red line). After the second DER is connected at bus 33, the system voltage profile improves again (green line). Then the system voltage profile with 3 DERs connected at buses 26, 33, and 11 is shown by the dark purple graph. These 3 locations are the placements according to the proposed hybrid MMA-CPF approach.

Different scenarios are evaluated in this manuscript. This work also investigates the system voltage profile if 3 DERs are integrated at buses with low APF/TVS values (1, 2, and 12) and buses with average APF/TVS values (5, 15, and 29) as assigned with the light blue and orange lines, respectively. Apparently, the voltage profile of the system does not increase substantially in both conditions. Interestingly, the system voltage with only one DER integrated at the most appropriate bus or high APF/TVS value bus (26) is better. Nevertheless, for a more comprehensive stability assessment of the system, the following section delivers an evaluation of the system performance by using the eigenvalue computation analysis.

5.3 The System Smallest Eigenvalue ($\boldsymbol{\varepsilon_{min}}$)

The eigenvalue assessment is one of the most powerful techniques for assessing the power system stability. The smallest eigenvalue (ε_{min}) informs the *proximity* of the system stability which is the voltage stability level indication.

Figure 7 illustrates the system smallest eigenvalue for different scenarios. At the original state, no DER, the ε_{min} is 1.572. If one DER is connected at bus 26, the ε_{min} increases to 1.598 and then to 1.607 after the addition of another DER placement at bus 33. Then with the third DER positioned at bus 11, the final ε_{min} for 3 DER units becomes 1.625. However, if 3 DERs with the same capacity are sited at the least sensitive buses or buses with small APF/TVS values (buses 1, 2, 12), the ε_{min} is just 1.579. This ε_{min} value is even below the ε_{min} for a single DER at bus 26 (1.598). Similar outcomes apply to the average APF/TVS values buses (5, 15, 29); the ε_{min} is only 1.589 and also below the ε_{min} for a DER at bus 26. Even though with simply a single DER at the proper location, in this case, bus 26 with a size of 50 MW, it provides a more stable system compare to 3 DERs total of 150 MW at buses with small and average APF/TVS values. Briefly, a single DER at the appropriate bus can ensue in an improved system voltage and greater eigenvalue ε_{min}, therefore the system is in a better and more stable state.

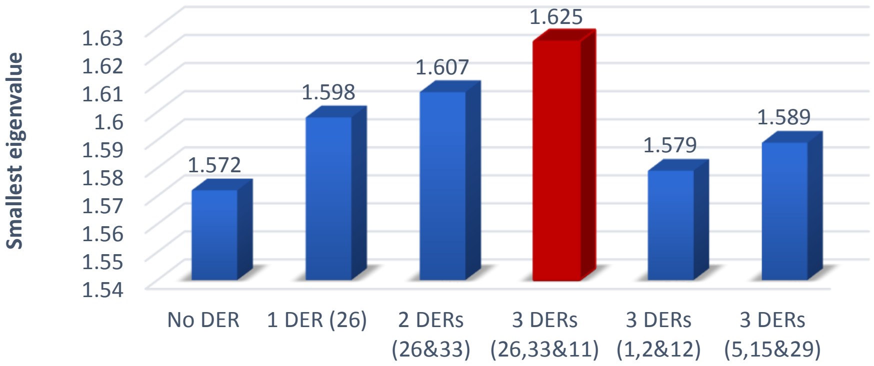

Figure 7. The system's smallest eigenvalue comparison

5.4 Network Power Losses

The network power losses both active and reactive were calculated for each state and are presented in Figure 8. If the first DER is placed at bus 26, the network losses are (0.391+j0.095) p.u. Then if another DER is placed at bus 33, the losses decrease to (0.187+j0.046) p.u. With another DER at bus 11, the losses further reduce to (0.074+j0.016) p.u, hence the percentage of losses reduction are $\%\Delta P_{Loss}$ is 42.25% and $\%\Delta Q_{Loss}$ is 44.59%. If 3 DERs are located at the least sensitive buses, buses with low APF/TVS values, buses 1, 2, and 12, the power losses are relatively significant, even bigger than the system losses for one DER at bus 26. The losses only reduce to (0.434+j0.125) p.u. with $\%\Delta P_{Loss}$ 4.44% and $\%\Delta Q_{Loss}$ 8.88%. Likewise, when 3 DER units are sited at buses with average values of APF/TVS, bus 1, 15, and 29, the system losses are also relatively large, which is (0.409+j0.109), $\%\Delta P_{Loss}$ of 7.06% and $\%\Delta Q_{Loss}$ of 14.27%.

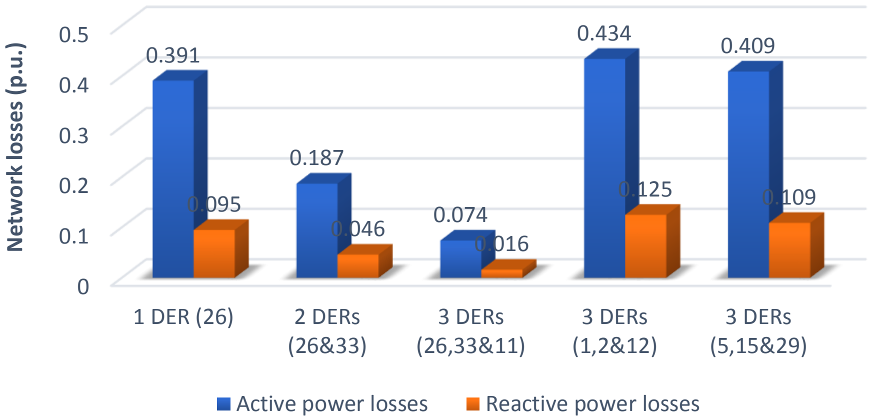

Figure 8. Comparison of system losses after DER units placement

The outcomes of this examination from the location of DER, the system's smallest eigenvalue, and the losses reduction with the proposed hybrid MMA-CPF approach with DER locations at buses with small and average values of APF/TVS are summarized in Table 1. Integrating the same size of DERs at buses with small and average APF/TVS values cannot assist to increase the voltage stability considerably and lessen the losses in significant quantity. Hence, it is certainly not suggested to locate DER units at the buses with small and average APF/TVS values from the perspective of voltage stability and system losses.

Table 1. Results comparison in terms of system smallest eigenvalue, and network losses reduction percentage

	High values of APF/TVS (Recommended)	Small values of APF/TVS	Average values of APF/TVS
DER Locations	26, 33 and 11	1, 2 and 12	5,15 and 29
ε_{min}	1.625	1.579	1.589
$\%\Delta P_{Loss}$	42.25	4.44	7.06
$\%\Delta Q_{Loss}$	44.59	8.88	14.27

The further interesting outcome obtained is that the operation of the system operating with only 1 DER integrated at bus 26 is superior to 3 DERs at small APF/TVS values buses (1, 2, 12) or average APF/TVS values (5, 15, 29), in terms of voltage profile of the system, eigenvalue assessment, and power losses reduction. The voltage profile performance at the majority of the system, if DER is located at bus 26 is higher than if 3 DERs are located at small or average APF/TVS values buses as can be seen in Figure 9. Furthermore, Figure 10 informs the results from an eigenvalue viewpoint and displays related results. Eigenvalue or ε_{min} for 1 DER unit located at bus 26 is greater than ε_{min} for 3 DER units at small or average APF/TVS values buses. Similarly, the system losses if DER is positioned in bus 26 are marginally lesser than losses if 3 DERs at small or average APF/TVS values buses as can be perceived in Figure 11.

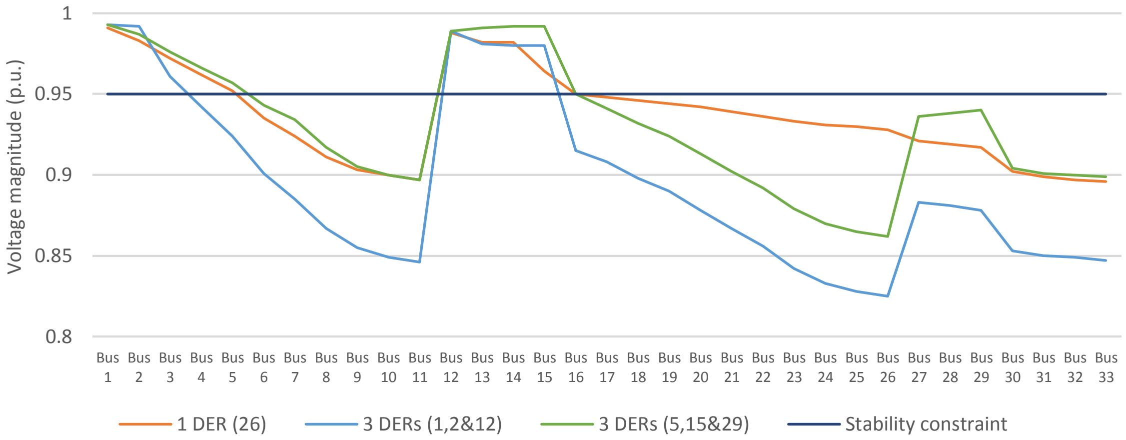

Figure 9. Comparison of voltage profile

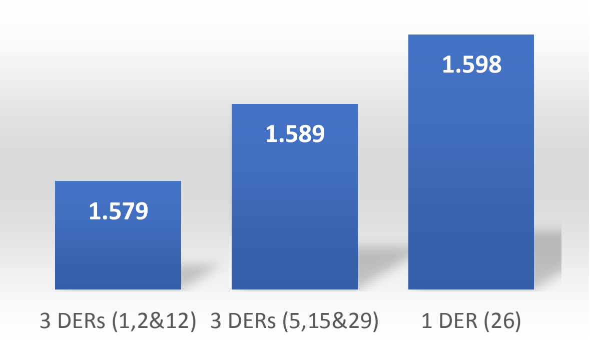

Figure 10. System eigenvalue comparison

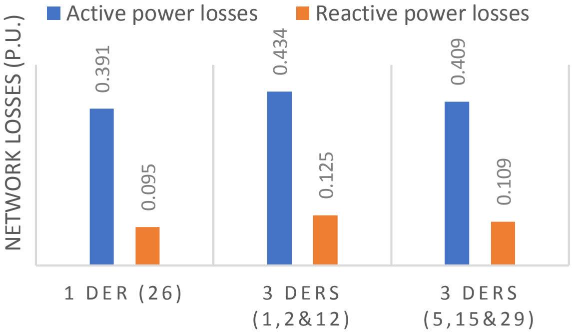

Figure 11. Losses comparison

Additionally, in this manuscript, the proposed hybrid approach was compared with the CPF method by [19] to confirm the efficiency of the proposed hybrid approach. Table 2 informs the DER location based on our proposed hybrid approach and the CPF technique while Figure 12 displays the enhancement of voltage profile after DERs are placed according to both techniques.

Table 2. DER Locations

Iteration	CPF Method [19]	Proposed Method Hybrid MMA-CPF
1	26	26
2	33	33
3	17	11

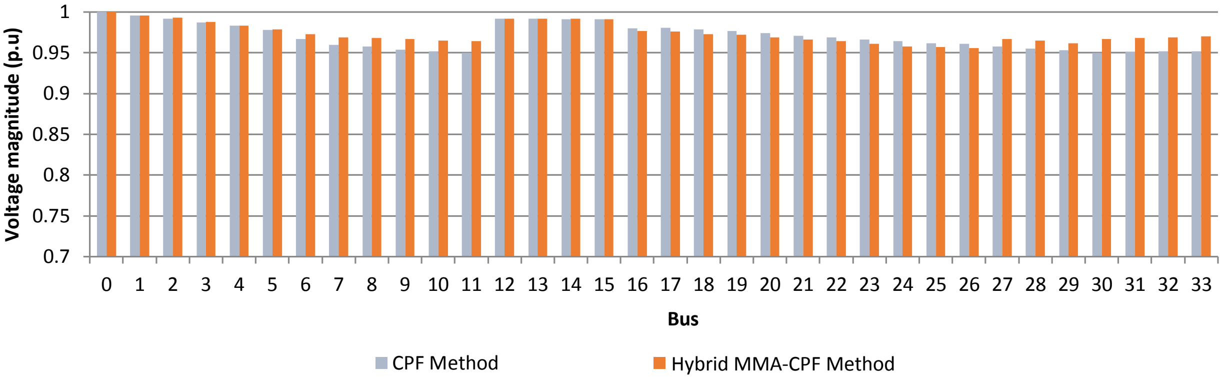

Figure 12. Voltage magnitude after DER integration with the CPF method and the proposed hybrid method

As the eigenvalue assessment (ε_{min}) is one of the most efficient techniques to evaluate the static voltage stability analysis, hence the ε_{min} is utilized to make the efficient comparison of DER location attained by the proposed hybrid method and the CPF. As can be perceived in Figure 14, the ε_{min} of the system with the CPF is only 1.610, whereas the ε_{min} with the proposed hybrid method is 1.618 which is larger than the CPF method eigenvalue. This informs that the proposed hybrid approach is rather more efficient than the CPF technique in resolving the placement of DER.

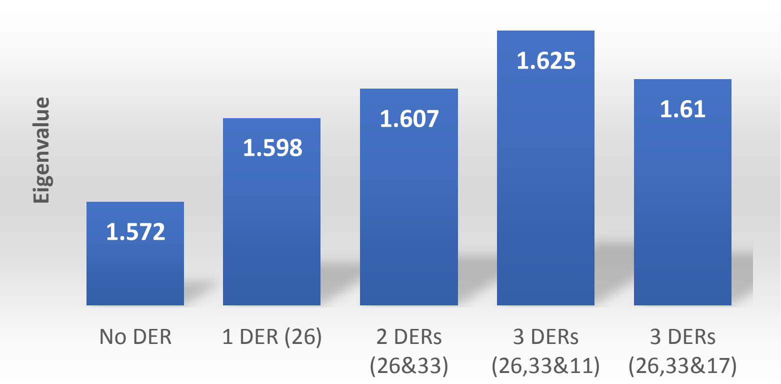

Figure 13. System eigenvalues with the CPF approach and the proposed method

Moreover, DER placement based on the proposed hybrid technique results in the largest losses reduction with 42.25% and 44.59% for $\%\Delta P_{Loss}$ and $\%\Delta Q_{Loss}$, respectively. Though, by using the CPF approach, with 3 DERs at buses 26, 33, and 17, the reduction of losses is not as much as the losses reduction if DERs at buses 26, 33, and 11, where the 3rd DER is placed at bus 17, the losses decline a little below the network losses reduction for the proposed approach. The $\%\Delta P_{Loss}$ with CPF is 36.36% and $\%\Delta Q_{Loss}$ is 41.29%. Table 3 clarifies the $\%\Delta P_{Loss}$ and $\%\Delta Q_{Loss}$ if DERs are placed at particular locations.

Table 3 Results Comparison

DER Placement	Approach	ε_{min}	$\%\Delta P_{Loss}$	$\%\Delta Q_{Loss}$	VSI (%)	OF
26, 33 and 17	CPF [19]	1.610	36.36	41.29	2.430335	80.08033
26, 33 and 11	MMA-CPF	1.618	42.25	44.59	2.939305	89.77931
26 and 33	Both	1.6067	30.34	35.33	2.220384	67.89038
26	Both	1.5988	8.87	18.97	1.717776	29.55778

6. Conclusions

The appropriate allocation of DERs is essential to exploit the DER advantages. This manuscript recommends a novel technique based on two analytical voltage stability analysis approaches, the Modified Modal Analysis and Continuation Power Flow (MMA-CPF). The aim of this work is to attain the most stable system, the lowest losses, and the highest system eigenvalue. To assess the efficiency of the developed technique, this work also examines the performance of the system if DER units are sited at the least sensitive and the average APF/TVS values buses.

The outcomes of implementing this approach to the modified 34-bus RDN elucidate the efficiency of this technique in the optimum allocation of DERs. The outcomes demonstrate the robustness of the APF/TVS in deciding the optimum placement for DER to improve the voltage stability, reduce the losses, and also increase the eigenvalue. It was proven in this paper that an appropriate DER site is very crucial to maximize DERs' advantages. The proper DER allocation can enhance voltage profile substantially and reduce network losses significantly.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

APF	Active Participation Factor
TVS	Tangent Vector Sensitivity
RDN	Radial Distribution Network
DG	Distributed Generation
DER	Distributed Energy Resources
MMA	Modified Modal Analysis
CPF	Continuation Power Flow
MMA-CPF	Modified Modal Analysis - Continuation Power Flow
OF	Objective Function
ΔP	Active power variations
ΔQ	Reactive power variations
$\Delta \theta$	Voltage angle variations
ΔV	Voltage magnitude variations
J	Jacobian Matrix
J_R^*	Reduced Modified Jacoban Matrix
$\mathfrak{R}^*$	Right eigenvector matrix of J_R^*
υ^*	Left eigenvector matrix of J_R^*

φ^*	Diagonal eigenvalue matrix of J_R^*
ε_i^*	i^{th} eigenvalue of J_R^*
ζ_i^*	i^{th} column right eigenvector of J_R^*
ϱ_i^*	i^{th} row left eigenvector of J_R^*
ϖ	Load parameter
P_{Gi0}	Base case active power generation at bus *i*
P_{Li0}	Initial active power load at bus *i*
P_{Ti}	Injected active power at bus *i*
Q_{Gi0}	Base case reactive power generation at bus *i*
Q_{Li0}	Initial reactive power load at bus *i*
Q_{Ti}	Injected reactive power at bus i.
$S_{\Delta base}$	A specified amount of complex power which is selected to offer suitable ϖ scaling
k_{Gi}	Constant assigned for the degree of generation variation at bus *i* as ϖ varies
k_{Li}	Constant assigned for the degree of load variation at bus *i* as ϖ varies
θ_i	Power angle changes at bus *i*
$\bar{\delta}$	Vector of generator angle
$\bar{V}$	Vector of the bus voltage magnitude vector
$V_i\angle\delta_i$	Complex voltages at bus *i*
$V_j\angle\delta_j$	Complex voltages at bus *j*
$R_{ij}+jX_{ij}=Z_{ij}$	*ij*th component of Z_{bus} impedance matrix
P_i	Active power generation at bus *i*
P_j	Active power generation at bus *j*
Q_i	Reactive power injection at bus *i*
Q_j	Reactive power injection at bus *j*
P_{Loss}	Active power losses at initial conditions without DER integration
P_{Loss}^{DG}	Active power losses after integration of DER
Q_{Loss}	Reactive power losses at initial conditions without DER integration
Q_{Loss}^{DG}	Reactive power losses after integration of DER
ΔP_{Loss}	Reduction of active power losses
ΔQ_{Loss}	Reduction of reactive power losses
$\%\Delta P_{Loss}$	Reduction percentage of active power losses
$\%\Delta Q_{Loss}$	Reduction percentage of reactive power losses
VSI	Voltage stability index, indicating the voltage stability improvement after DER placement
ε_{min}^{DG}	The smallest eigenvalue with DER unit(s)
ε_{min}	The smallest eigenvalue without any DER unit

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Journal	Energies (https://www.mdpi.com/journal/energies) (ISSN 1996-1073)
Manuscript ID	energies-2110246
Type	Article
Title	Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement (https://www.mdpi.com/1996-1073/16/4/1698)
Authors	Ardiaty Arief * , Muhammad Bachtiar Nappu
Section	A: Sustainable Energy (https://www.mdpi.com/journal/energies/sections/sustainable_energy)
Special Issue	Planning, Modelling, Operation and Assessment of Renewable Energy Power Systems (https://www.mdpi.com/journal/energies/special_issues/Renewable_Energy_Power_Systems)
Abstract	Distributed energy resource (DER) has become an effective attempt in promoting the use of renewable energy resources for electricity generation. The core intention of this study is to expand an approach for optimally placing several DER units to attain the most stable performance of the system and the most power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new Modified Modal Analysis (MMA) and the Continuation Power Flow (CPF) or MMA-CPF methods. The MMA evaluates voltage stability by taking into account the incremental connection relating voltage and active power that includes the eigenvalue and the related eigenvectors computed from the reduced modified Jacobian matrix. Furthermore, an Active Participation Factor (APF) is computed from the eigenvectors of the reduced modified Jacobian matrix. The CPF method, uses a predictor-corrector stepping pattern to reach the solution track and compute the Tangent Vector Sensitivity (TVS). Both APF and TVS indicate each load bus sensitivity in the network. In addition, an objective function regarding losses decrease and eigenvalues is expressed to calculate the best bus position for DER allocation. The proposed MMA-CPF technique has been assessed on a 34-bus RDN and the outcomes demonstrate the effectiveness of the proposed scheme.

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Authors' Responses to Reviewer's Comments (Reviewer 1)

Author's We would like to thank you for your valuable comments and

Notes	suggestions. All the comments have been incorporated in the paper appropriately and the response to the reviewers' comments are attached.
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Quality of English Language	( ) English very difficult to understand/incomprehensible ( ) Extensive editing of English language and style required ( ) Moderate English changes required (x) English language and style are fine/minor spell check required ( ) I am not qualified to assess the quality of English in this paper

	Yes	Can be improved	Must be improved	Not applicable
Does the introduction provide sufficient background and include all relevant references?	(x)	( )	( )	( )
Are all the cited references relevant to the research?	(x)	( )	( )	( )
Is the research design appropriate?	(x)	( )	( )	( )
Are the methods adequately described?	(x)	( )	( )	( )
Are the results clearly presented?	(x)	( )	( )	( )
Are the conclusions supported by the results?	( )	(x)	( )	( )

Comments and Suggestions for Authors

The Paper proposes a very interesting novel methodology to optimize DER units (Distributed Energy resource) typically used in renewable energy sources dedicated to electricity generation in order to produce a more stable performance and reduce power losses. This goal is achieved combining a Modified Modal Analysis (MMA) and Continuation Power Flow (CPF) techniques enabling via the calculation of Active Participation Factor (APF) and the Tangent Vector Sensitivity (TVS) to know precisely

the load bus sensitivity in the network.

The paper is very well written and explained requiring almost no changes before it can be published. Few suggestions for a deeper reflection:

1) Line 281-282

It is important to explain that and if $\Delta PLoss$ and $\Delta QLoss$ are minimized at the same time or not and if not which becomes more important. I think it really depends on the application, but this should be clarified.

2) Figure 2 / Line 322

It is not clear from the explanation provided of Figure 2 and then 3 (lines 304 -320) if the fact that both maxima (for APF and TVS in Figure 2) are “by chance” both corresponding to bus 26 and above all if this is ALWAYS the case. In other words, what happens if the maximum of APF is for example bus 10 and maximum of TVS is bus 26? How then a decision is made? It would seem a second DER is needed and then a third. So when does the process stop?

If not, it would help explaining why mathematically the two solutions are effectively “always” converging or at least put a clear reference to paragraph 5.3 where the eigenvalues are compared. While Figure 5 explains that the total objective function is reduced, it does not show that is “absolutely” reduced, meaning it is the absolute minimum. It seems that the results of figure 6 are needed to explain or confirm the ones of Figure 5. Please, elaborate further and more clearly.

3) Figure 9-10 / Line 422-424

It is not clear what is the significance of Figure 9 and Figure 10 as differences in results are quite small if not negligible. What conclusion can be inferred from these plots? Please elaborate further.

4) Conclusions

While the idea is well explained, I would suggest providing in the conclusions a percentage number (15%? 27%?) of possible maximum reduced losses achieved with this new methodology similarly to what summarized in TABLE 3 and maybe TABLE 1. This would help illustrate better the clear advantages put in evidence in this study.

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Submission Date	05 December 2022
Date of this review	30 Dec 2022 17:20:38

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Journal	Energies (https://www.mdpi.com/journal/energies) (ISSN 1996-1073)
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Type	Article
Title	Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement (https://www.mdpi.com/1996-1073/16/4/1698)
Authors	Ardiaty Arief * , Muhammad Bachtiar Nappu
Section	A: Sustainable Energy (https://www.mdpi.com/journal/energies/sections/sustainable_energy)
Special Issue	Planning, Modelling, Operation and Assessment of Renewable Energy Power Systems (https://www.mdpi.com/journal/energies/special_issues/Renewable_Energy_Power_Systems)
Abstract	Distributed energy resource (DER) has become an effective attempt in promoting the use of renewable energy resources for electricity generation. The core intention of this study is to expand an approach for optimally placing several DER units to attain the most stable performance of the system and the most power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new Modified Modal Analysis (MMA) and the Continuation Power Flow (CPF) or MMA-CPF methods. The MMA evaluates voltage stability by taking into account the incremental connection relating voltage and active power that includes the eigenvalue and the related eigenvectors computed from the reduced modified Jacobian matrix. Furthermore, an Active Participation Factor (APF) is computed from the eigenvectors of the reduced modified Jacobian matrix. The CPF method, uses a predictor-corrector stepping pattern to reach the solution track and compute the Tangent Vector Sensitivity (TVS). Both APF and TVS indicate each load bus sensitivity in the network. In addition, an objective function regarding losses decrease and eigenvalues is expressed to calculate the best bus position for DER allocation. The proposed MMA-CPF technique has been assessed on a 34-bus RDN and the outcomes demonstrate the effectiveness of the proposed scheme.

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Authors' Responses to Reviewer's Comments (Reviewer 2)

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Notes	suggestions. All the comments have been incorporated in the paper appropriately and the response to the reviewers' comments are attached.
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Are the results clearly presented?	( )	(x)	( )	( )
Are the conclusions supported by the results?	( )	(x)	( )	( )

Comments and Suggestions for Authors	The paper is well written and timely, my only suggestion is to provide larger case studies and provide a computational analysis on the scalability of the proposed addproach
Submission Date	05 December 2022
Date of this review	22 Dec 2022 12:14:41

25 January 2023

Dear Editor-in-Chief of Energies,

We wish to resubmit the revised version of our research article entitled "**Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement**" for consideration by Energies. I confirm that this work is original and has not been published elsewhere, nor is currently under consideration for publication elsewhere. We have made appropriate changes and revisions according to the reviewers' comments. The English language in this paper has been re-checked several times and edited for improvement.

I wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Please address all correspondence concerning this manuscript to me at ardiaty@eng.unhas.ac.id.

Thank you for your consideration of this manuscript.

Sincerely yours,

Ardiaty Arief, Ph.D.
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Article

Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement

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Abstract: Distributed energy resource (DER) has become an effective attempt in promoting the use of renewable energy resources for electricity generation. The core intention of this study is to expand an approach for optimally placing several DER units to attain the most stable performance of the system and the most power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new Modified Modal Analysis (MMA) and the Continuation Power Flow (CPF) or MMA-CPF methods. The MMA evaluates voltage stability by taking into account the incremental connection relating voltage and active power that includes the eigenvalue and the related eigenvectors computed from the reduced modified Jacobian matrix. Furthermore, an Active Participation Factor (APF) is computed from the eigenvectors of the reduced modified Jacobian matrix. The CPF method~~,~~ uses a predictor-corrector stepping pattern to reach the solution track and compute the Tangent Vector Sensitivity (TVS). Both APF and TVS indicate each load bus sensitivity in the network. In addition, an objective function regarding losses decrease and eigenvalue~~s~~ is expressed to calculate the best bus position for DER allocation. The proposed MMA-CPF technique has been assessed on a 34-bus RDN and the outcomes demonstrate the effectiveness of the proposed scheme.

Keywords: continuation power flow; distributed energy resource; distributed generation; eigenvalue; eigenvector; modal analysis; network losses; renewable energy resources; voltage stability.

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1. Introduction

Due to rapid technological advances also the economic and environmental benefits of a distributed energy resource (DER), DER has become a global unpolluted renewable energy source for alternative generations. Nowadays, DERs are more developed in the grid worldwide because of their advantages compare to the conventional fossil fuel power generations that drive the issue of global warming. DERs can be divided into four main categories based on their ability to supply active and reactive power, which are [1]:

- Type 1 DER unit ($pf_{DERi} = 1$, unity power factor): The type 1 DER can only supply active power to the system. Examples of t~~T~~ype 1 DER are photovoltaic (PV) [2, 3], micro-turbines (MT), and fuel cells (FC). These DERs are connected to the main network using converters/inverters;
- Type 2 DER unit ($pf_{DERi} = 0$). The type 2 DER can only provide reactive power to the network. For example, static power compensators such as capacitors, static VAr compensators (SVC), static synchronous compensators (STATCOM), etc. [4, 5];
- Type 3 DER unit ($0 < pf_{DERi} < 1$ with lagging power factor). The type 3 DERs can provide active power and reactive power to the network. Examples of type 3 DER are a synchronous generator operated in cogeneration and gas-fired DER;

- Type 4 DER unit (0 < pf_{DERi} < 1 with leading power factor). This type of DER provides active power to the system but attracts reactive power. An example of type 4 DER is primarily an induction generator in a wind farm, such as doubly-fed induction generators (DFIG) [6].

The connection of DERs into the grid has resulted in several gains. Because the DERs are located inside the local grid or at the customer's site, DERs provide electrical energy directly to the customers or the local distribution grid. DERs tend to decrease the flow of power in the transmission system, which can enhance the voltage profile in the distribution system. DERs assist to lessen losses in the distribution network by supplying locally to the load demand. DERs also enhance system reliability by delivering supplementary system generation capacity for power distribution networks for non-disruptive power supplies and backup power supplies, and providing temporary emergency power [7]. However, these benefits are highly dependent on the proper placement and capacity of the DERs. Proper placement of the DERs will greatly improve the system stability and reduce distribution grid losses [8]. Optimum DER allocation is one of the main challenges for DER integrations [9]. Studying the most appropriate placements of DERs was essential to take full advantage of DER's operating advantages. Power system engineers and researchers have recommended various methodologies to determine the optimal placement of DERs. A comprehensive review of~~n~~ DG placement is provided by [10].

Many analytical techniques have been proposed for solving DER placement. The authors in [11] proposed $Q-PQV$ bus pair considering load demand seasonal changes biomass DER placement. In [12], bifurcation analysis and dynamic programming were used. The authors of [13] have established a power stability index (PSI) that determines a stable node voltage for the placement and sizing of DERs. Work in [14] defined an objective function by employing the maximum power stability index (MPSI) for finding the DER location. An integer nonlinear programming was implemented in [15] to choose sensitive nodes to increase voltage profiles. Article [16] suggested a technique for determining the optimal position of DERs considering network losses and using the Kalman filter algorithm to compute the optimal size of DER. Nonetheless, no standard criteria for the determination of the optimal number of DERs. The author of [17] recommended analytical power loss~~es~~ equations for calculating the optimal size and position of DER to reduce network losses. Nevertheless, the big size and difficulty of the distribution system can affect how the robustness is not satisfied. From [18], a "2/3 rule" which was first~~ly~~ used for capacitor placement in the distribution network was assumed to determine the position of DERs. This method is very easy, but cannot be directly applied to a meshed network. Furthermore, the capacitors supply only reactive power while the DER produces active power. Consequently, this rule cannot be used effectually to locate the DERs. The authors of [19] offered a Continuation Power Flow (CPF) based settlement of DER units and indicated the most sensitive bus to voltage breakdown. The DER units were placed on the chosen buses via the iterative algorithm and objective function. Yet, this technique does not always offer the ideal solution.

Moreover, many meta-heuristic methodologies have been proposed for optimal DER placement. A sensitivity analysis and harmony search algorithm (HAS) was used to decide the most appropriate DER place [20]. A differential evolution algorithm is proposed in [21] for DER integration. Genetic algorithm (GA) and AC-OPF were proposed by authors in [22] for the placement and size of DER. GA is a suitable technique for solving multi-objective difficulties and can provide effectual solutions, but it is time-consuming in its computation. A c~~C~~haotic bat algorithm (CBA) was developed in [23] for optimal locations and DERs' sizes. A fuzzy-embedded multi-objective particle swarm optimization (FMOPSO) method was used in [24]. Nevertheless, the shortcoming of PSO is it obtains solutions to local solutions quickly or prematurely converges. Ant colony system (ACS) was occupied in [25] for DER placement. However, a few obstacles to the ACS approach may additionally reduce its effectiveness. ACS relies upon preliminary points and necessitates a longer computational time to discover the most efficient arrangement. Authors in [26] developed a fireworks algorithm for network reconfiguration and finding the most suitable allocation of DER in a distribution system. In [27], the authors developed DER placement based on a modified teaching-learning-based optimization (MTLBO) algorithm. Meta-heuristics techniques are widely known and utilized for optimal DER allocation, nonetheless, their severe drawbacks are the divergence possibility, they require a long period to acquire the best solution, and they cannot often warranty to obtain the best result, but a sensible result that is near to a perfect result.

Hence, we proposed an original hybrid analytical method in this article with Modified Modal Analysis (MMA) and Continuation Power Flow (CPF) to resolve the DER deployment with the objective of maximizing voltage stability and minimizing active power losses. Gao et al. [28] developed a modal analysis and it has been implemented to resolve several power systems issues. This method includes the eigenvalue method and the related eigenvectors computed from the reduced voltage-reactive power Jacobian matrix. The reduced voltage-reactive power Jacobian matrix emphasizes the relationship between system voltage and reactive power. However, in order to meet the aim of this study, the reduced Jacobian matrix was adapted where its focus was on voltage and active power properties, rather than reactive power. This method is appropriate for DER Type 1 because the MMA and CPF give information about the correlation between voltage magnitude and active power at each load bus.

Placement of DER units at the appropriate place will substantially lessen system losses and considerably enhance the stability of the system. Hence, the key contributions of this manuscript are:

- developing a new hybrid scheme to compute the optimal DER placement. This technique is a hybrid approach: the Modified Modal Analysis (MMA) and Continuation Power Flow (CPF) or MMA-CPF method. This approach combines the key feature of both techniques. The MMA incorporates the eigenvalue computation and the correlated eigenvectors of the reduced modified voltage-active power Jacobian matrix. MMA uses eigenvectors to compute the bus Active Participation Factor (APF). The APF provides an indication of the participation of a certain bus in solving the instability problem of the network. On the other hand, the CPF reformulates the equation of the power flow by using a prediction-correction stepping algorithm to reach the solution track and computes the Tangent Vector Sensitivity (TVS). Both APF and TVS give indications about the bus that has the biggest influence in improving the system stability directly. Thus, the load bus that has the biggest APF/TVS is chosen as the place for the DER unit;
- delivering a complete evaluation of the impact of DER allocation on system losses and assessment of voltage stability, which in this case, are the smallest eigenvalues for the system, as they are a common indicator for assessing the performance of system stability;
- enhancing the objective functions based on the power losses as well as eigenvalues to conclude the most suitable DER site when the difference between APF and TVS happens. The formulation of this objective function provides a calculation of which bus will give the least losses and the most stable system.

After determining the DER placement, this work re-evaluates the voltage stability of the system to confirm the efficiency of the proposed placement in enhancing the voltage profile, eigenvalues of the system, and reduction in power losses. The proposed technique was simulated on a 34-bus RDN to clarify the efficacy of the recommended scheme. Even though the integration of DERs into a present distribution network can offer several paybacks, this research only emphasizes the improvement of voltage stability and reduction of network losses. This work computed the network losses, voltage magnitude, and system's smallest eigenvalue. The developed scheme is simple, straightforward, robust, and its time calculation is effectual because it uses a non-iterative procedure in calculating

DER placement based on the APF/TVS. Further interesting outcomes are elaborated in this manuscript.

2. Modified Modal Analysis

The modal analysis technique was proposed by [28]. This technique has been implemented in many areas of power systems to resolve different stability problems. This approach forms a reduced Jacobian matrix that provides a direct correlation between variations in reactive power and system voltage. The modal analysis presents *proximity* and *mechanism. Proximity* provides information about the security of the system voltage that gives details on the stability level of the system which is indicated by the eigenvalues (ε_i). The ε_i indicates if the system is stable or not stable at a particular operational state. The *mechanism* provides identification of areas likely to instability problems which is helpful to preclude system instability. The information on the instability *mechanism* is given by the eigenvectors. Their computation states critical voltage instability areas and signifies components that are imperative in the instability occurrence.

The linearized equation of a static steady-state power system is given by,

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

Nevertheless, in the modal analysis by [28], the evaluation of voltage stability is regarding the correlation between reactive power (Q) and voltage (V). Yet, in the placement of the Type-1 DER, the assessment should emphasize the active power supplied by DERs. Therefore, in this manuscript, the initial modal analysis is adjusted to assess the stability of the system by taking into account the incremental correlation between active power (P) and voltage (V), thus reactive power (Q) is considered the same.

If ΔQ in Eq. 1 is kept constant, then the reduced modified Jacobian Matrix can be written as

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

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

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

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

The reduced modified Jacobian matrix is marked as J_R^* to differentiate it from the initial Jacobian matrix, which correlates directly with variations between active power and the magnitude of the bus voltage. Hence we can reformulate the eigenvalues and eigenvectors as follow:

$$J_R^* = \Re^*\, \Phi^*\, \Upsilon^* \quad (6)$$

$$ {J_R^*}^{-1} = \Re^*\, {\Phi^*}^{-1}\, \Upsilon^* \quad (7)$$

By substituting Eq. 7 into Eq. 4, the direct correlation between the incremental variations of active power and the system voltage can be obtained as follow:

$$\Delta V = \Re^*\, {\Phi^*}^{-1}\, \Upsilon^*\, \Delta P \quad (8)$$

Or,

$$\Delta V = \sum_i \frac{\zeta_i^*\, \varrho_i^*}{\varepsilon_i^*} \Delta P \quad (9)$$

Therefore the APF becomes:

$$APF_{ki} = \zeta_{ki}^{*}\, \varrho_{ik}^{*} \tag{10}$$

APF_{ki} signifies the participation of bus *i* to the voltage-active power sensitivity at bus *k*. The bigger the APF_{ki} value, the more significant bus *i* effect in deciding voltage-active power sensitivity at bus *k* [29].

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3. The Continuation Power Flow (CPF)

The intention of the CPF scheme is to attain ~~a~~ different power flow results for a particular load variation situation. The CPF scheme concisely delivered in this manuscript is according to the method explained by [30].

Initially, we define a load parameter (ϖ) as:

$$0 \le \varpi \le \varpi_{critical}$$

where $\varpi = 0$ relates to the system base ~~-~~load and $\varpi = \varpi_{critical}$ indicates the critical load. Then ϖ is then included in the power equations of both active and reactive to acquire:

$$0 = P_{Gi0}(1 + \varpi k_{Gi}) - P_{Li0} - \varpi\,(k_{Li}\, S_{\Delta base} \cos\theta_i) - P_{Ti} \tag{11}$$

$$0 = Q_{Gi0} - Q_{Li0} - \varpi\,(k_{Li}\, S_{\Delta base} \sin\theta_i) - Q_{Ti} \tag{12}$$

A continuance procedure is implemented at the remodeled power flow calculations, hence Eqs. 11-12 are adjusted in a simple formula:

$$F\left(\bar{\delta}, \bar{V}, \varpi\right) = 0 \tag{13}$$

The continuation power flow technique exploits a prediction-correction system to attain a result track of remodeled power flow formulas. A tangent vector is computed in the prediction phase by considering the derivation of both power flow equations sides, hence:

$$\begin{bmatrix} F_{\bar{\delta}} & F_{\bar{V}} & F_{\varpi} \end{bmatrix} \begin{bmatrix} d\bar{\delta} \\ d\bar{V} \\ d\varpi \end{bmatrix} = 0 \tag{14}$$

A revision is done in the prediction stage by parameterization enlargement to recognize every result alongside the trajectory being tracked. The tangent vector specifies sensitivity analysis to resolve the most sensitive buses in addition to the way of the solution route. A sensitive bus in CPF is a~~the~~ bus with a big ratio of voltage differential variation to load differential variation, which is provided by the tangent vector [31]. Hence, the formula for Tangent Vector Sensitivity (TVS) at bus *j* can be written as:

$$TVS_j = \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd\varpi}\right| = \max\left[\left|\frac{dV_1}{Cd\varpi}\right|, \left|\frac{dV_2}{Cd\varpi}\right|, \ldots \left|\frac{dV_n}{Cd\varpi}\right|\right] \tag{15}$$

4. Proposed Methodology, System Constraints, Objective Function, and Evaluation Parameters

4.1 Proposed Hybrid MMA-CPF Technique

The load bus that has the biggest APF/TVS value signifies the most sensitive bus in the network thus having a prevalent impact on enhancing the system stability. Hence, the DER placement position is recommended according to the bus with the largest APF/TVS value. Additionally, this work develops a new formulation for objective function based on the APF/TVS outcomes to resolve the most appropriate bus for DER placement that would result in the most stable system and the lowest system losses. The APF computation is provided in Eq. 10 while the TVS calculation can be obtained in Eq. 15. Figure 1 provides the proposed MMA-CPF technique flowchart.

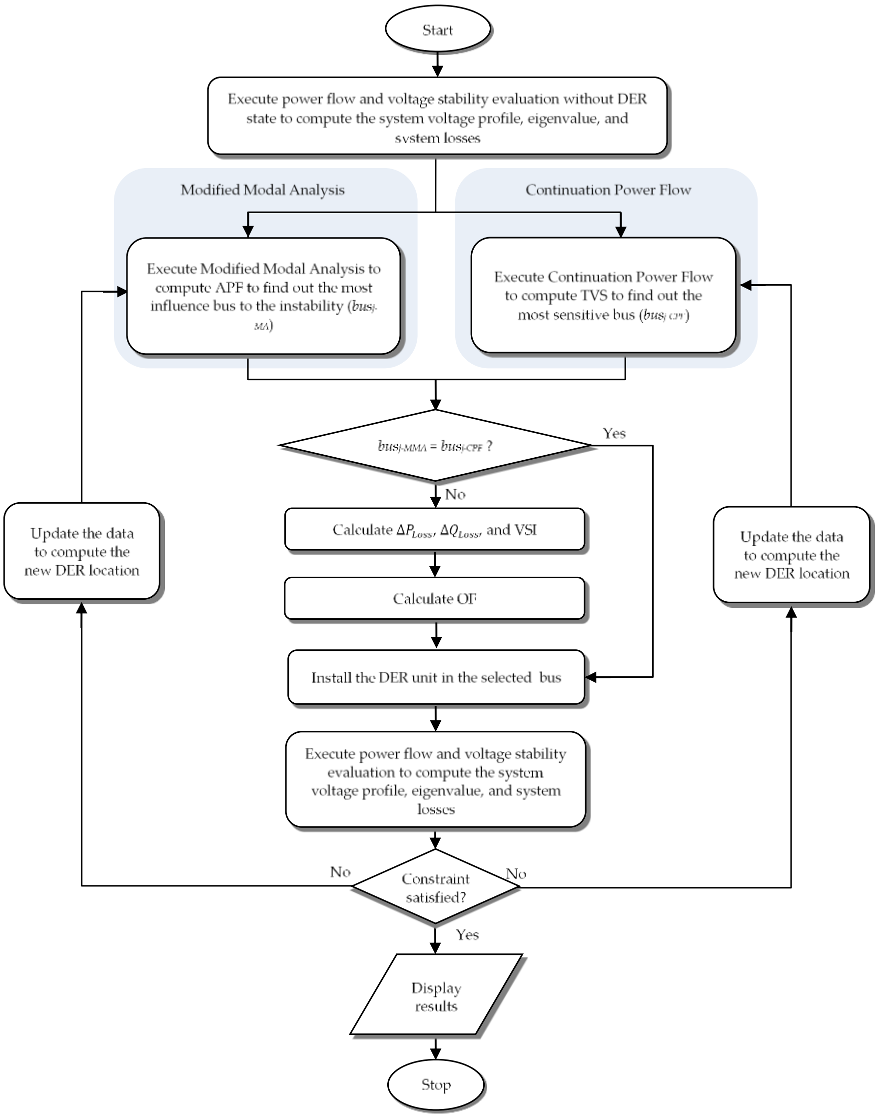

Figure 1. The hybrid MMA-CPF DER allocation approach flowchart

The detailed computational process for DER allocation according to the hybrid MMA-CPF technique is described as:

Step 1 Input the system data.
Step 2 Execute power flow with Eq. 1 and evaluate voltage stability for the original state (no DER unit) to compute voltage profile, system losses, and eigenvalue
Step 3 (a) Execute MMA to compute APF at each load bus to define the most influential bus ($bus_{j\text{-}MMA}$), and
(b) Execute CPF to compute TVS at each load bus to define the most sensitive bus ($bus_{j\text{-}CPF}$).
Step 4 Compare the outcomes of MMA and CPF. If $bus_{j\text{-}MMA} \neq bus_{j\text{-}CPF}$, go to *Step 5*, else go to *Step 7*.
Step 5 Compute ΔP_{Loss}, ΔQ_{Loss}, and VSI.
Step 6 Compute the OF. The bus that has the highest objective function is recommended as the DER location.
Step 7 Set up DER in the designated bus.
Step 8 Execute power flow and evaluate voltage stability assessment to compute voltage profile, system losses, and eigenvalue
Step 9 Assess the performance of the system as to if all the voltages are within the voltage limit constraints.
Step 10 If the bus voltage magnitudes are not fulfilled, then adjust the system data to acquire a new DER place and go back to *Step 3*.
Step 11 Once the voltage stability constraints are fulfilled, the program is terminated.

4.2 Voltage Stability Constraints

The voltage threshold stability limit utilized in this study is as follows:

$$V_{min} \leq V_i \leq V_{max} \dashrightarrow 0.95 \leq V_i \leq 1.05\ \mathrm{p.u}$$

4.3 The Eigenvalue Evaluation

The eigenvalue is one of the popular parameters for assessing voltage stability and has been confirmed its usefulness in evaluating voltage stability. In this manuscript, the smallest system eigenvalue ε_{min} is calculated and implemented to assess the level of the system voltage stability. It is also considered a voltage stability indicator. Therefore, we can expand Eq. 6 into:

$$J_R^* = \begin{bmatrix} \zeta_{11} & \zeta_{12} & \cdots & \zeta_{1n} \\ \zeta_{21} & \zeta_{22} & \cdots & \zeta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \zeta_{n1} & \zeta_{n2} & \cdots & \zeta_{nn} \end{bmatrix} \begin{bmatrix} \mathcal{E}_1 & 0 & \cdots & 0 \\ 0 & \mathcal{E}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \mathcal{E}_n \end{bmatrix} \begin{bmatrix} \varrho_{11} & \varrho_{12} & \cdots & \varrho_{1n} \\ \varrho_{21} & \varrho_{22} & \cdots & \varrho_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \varrho_{n1} & \varrho_{n2} & \cdots & \varrho_{nn} \end{bmatrix} \tag{16}$$

The ε_i magnitude defines the bus i^{th} modal voltage's degree of stability.

4.4 Network Power Losses

The following formulations represent the total active and reactive power losses [32]:

$$P_{Loss} + jQ_{Loss} = \sum_{i=1}^{N} S_i = \sum_{i=1}^{N} V_i I_i^* \tag{17}$$

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_i.P_j + Q_i.Q_j\right) + \beta_{ij}\left(Q_i.P_j - P_i.Q_j\right)\right] \tag{18}$$

$$Q_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\gamma_{ij}\left(P_i.P_j + Q_i.Q_j\right) + \delta_{ij}\left(Q_i.P_j - P_i.Q_j\right)\right] \tag{19}$$

Where,

$$\alpha_{ij} = \frac{R_{ij}}{|V_i||V_j|}\cos(\theta_i - \theta_j), \quad \beta_{ij} = \frac{R_{ij}}{|V_i||V_j|}\sin(\theta_i - \theta_j)$$

$$\gamma_{ij} = \frac{X_{ij}}{|V_i||V_j|}\cos(\theta_i - \theta_j), \quad \delta_{ij} = \frac{X_{ij}}{|V_i||V_j|}\sin(\theta_i - \theta_j)$$

The~~se~~ following formulas are used to assess the DER unit placement effect on the reduction of power losses:

$$\%\Delta P_{Loss} = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}} * 100\% \quad (20)$$

$$\%\Delta Q_{Loss} = \frac{Q_{Loss} - Q_{Loss}^{DG}}{Q_{Loss}} * 100\% \quad (21)$$

4.5 Objective Function

To determine the DER unit's placement in the distribution system, the objective function deliberated in this work is minimizing the network losses (maximum losses reduction) and maximizing the system eigenvalue (system stability). Hence, the objective function (OF) is formulated as follows:

$$\text{OF} = \Delta P_{Loss} + \Delta Q_{Loss} + VSI \quad (22)$$

$$\Delta P_{Loss} = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}} \quad , \quad \Delta Q_{Loss} = \frac{Q_{Loss} - Q_{Loss}^{DG}}{Q_{Loss}} \quad , \quad VSI = \frac{\varepsilon_{min}^{DG} - \varepsilon_{min}}{\varepsilon_{min}}$$

The bus with the largest objective function is chosen as the place for DER installment as locating the DER unit in this bus, the aim is to get the lowest losses and the highest stability index will be achieved.

In summary, the first step in determining the DER location is to calculate the APF and TVS values. In general, both tend to show the same results. However, if there is a difference, the value of the objective function (OF) as in Eq. 22 will be calculated, which in this OF calculation is to compute the summation of the ratio of changes in active power, changes in reactive power and changes in eigenvalue as an index of voltage stability of the electric power system. Hence from this OF calculation, it can be seen which bus has the greater influence on both the reduction of active power and reactive power. This process will be repeated until the voltage stability limits at all buses have been met as written in Section 4.2.

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5. Test Results and Analysis

This paper developed a novel hybrid approach to resolve the integration of DER based on objective function computed from APF and TVS. Both the APF and TVS give info about the most sensitive bus in the network or the bus that has the biggest influence on improving stability. If APF and TVS indicate different most sensitive buses, an objective function that measures minimum losses and maximum stability index is calculated. The bus that has the biggest objective function is chosen as the location for DER since by assigning DER in this bus, network losses can be minimum whereas the index of stability can be maximum. To assess the proposed method's performance, tests were conducted on the 34-bus RDN as can be seen in Figure 2.

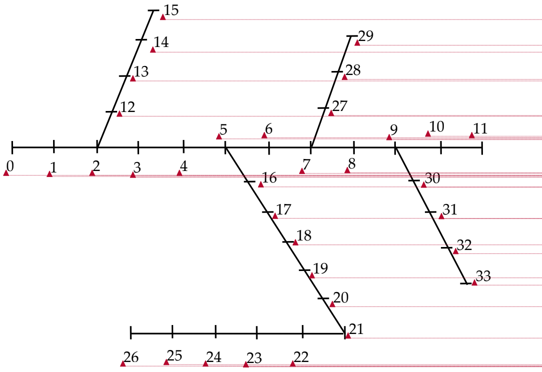

Figure 2. IEEE 34-bus distribution network test system [19].

5.1 APF and TVS Computation for DER Location

The outcomes APF and TVS computation at each load bus to find out the appropriate location for the 1st DER allocation are shown in Figure ~~2~~3. As can be seen from Figure ~~2~~3, bus 26 has the biggest APF value (0.1774) and TVS value (0.124), as indicated by the big black marks, therefore bus 26 has the biggest influence on improving stability and is confirmed as the most efficient bus for the location of DER. Nonetheless, after DER integration at bus 26, the system is not stable yet, hence a second DER is required. Regarding Figure ~~3~~4, bus 33 then has the biggest APF and TVS values of 0.1698 and 0.115 respectively, hence it is becoming the most sensitive bus to instability for the second computation. However since the system constraints have not been satisfied yet, the third DER is needed. The APF and TVS outcomes for the third DER can be perceived in Figure ~~4~~ 5 where bus 11 has the biggest APF (0.1393), but bus 17 has the biggest TVS (0.113). Due to this difference, the objective function (OF) needs to be computed to resolve the most effective bus for the third DER unit. The result of the objective function calculation is shown in Figure ~~5~~ 6 where bus 11 is shown to have the highest objective function value (0.8926), hence bus 11 is chosen as the site for the third DER unit. With 3 DERs positioned at buses 26, 33, and 11, the voltages at all buses system have recovered above the stability constraints $(0.95 \leq V_i \leq 1.05\ \mathrm{p.u})$ thus the procedure is completed.

Therefore for the first and second iterations, APF and TVS indicate the same bus for the best DER location, hence OF is not calculated. Nevertheless, in the third iteration, because the highest APF and TVS values were on different buses, OF is calculated to determine the DER location. Table 1 provides a summary of the results of the highest APF, TVS, and OF calculations to determine the DER location.

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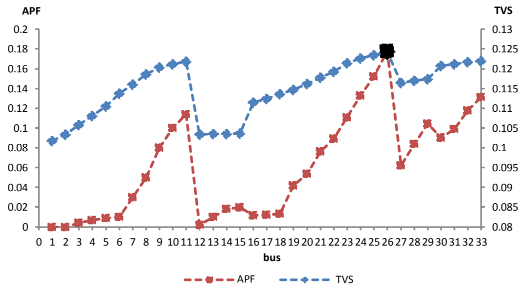

Figure 3~~2~~. The APF and TVS for determining first the DER location

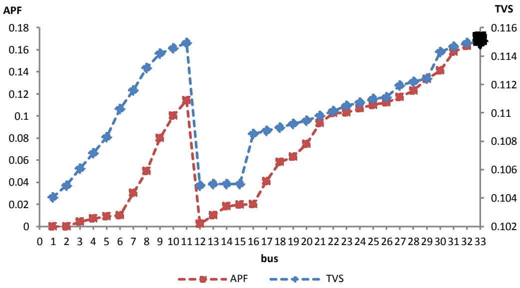

Figure 4~~3~~. The APF and TVS for determining the second DER location

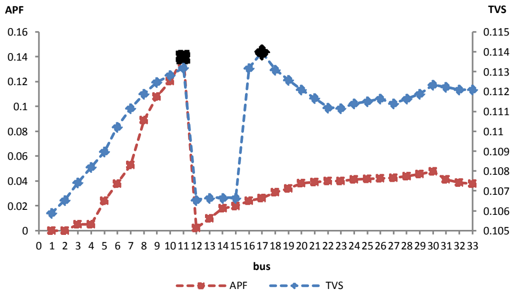

Figure 5~~4~~. The APF and TVS for determining the third DER location

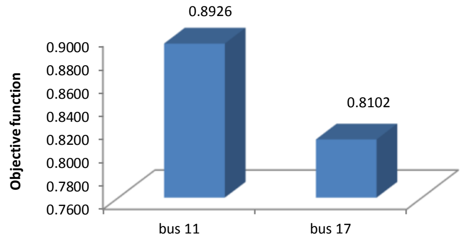

Figure 6~~5~~. Objective function (OF) to determine the third DER location

Table 1. Summary of the results of the highest APF, TVS, and OF calculations to determine the DER location

Iteration	Highest APF	Highest TVS	Highest OF	DER location
1	26	26	-	26
2	33	33	-	33
3	11	17	11	11

5.2 Voltage Profile Enhancement

Based on the results of APF, TVS, and OF calculations (Table 1), the DER locations proposed by the results of the proposed method are buses 26, 33, and 11. Figure ~~6~~ 7 shows the voltage profile of the system for several scenarios. To verify the effectiveness of the developed hybrid MMA-CPF scheme, we also simulate the system stability if 3 DER units are placed at the least sensitive buses that have small APF and TVS. By seeing Figures ~~2~~3-~~4~~5, buses 1, 2, and 12 have small APF/TVS. We also evaluate the system performance if the DERs are placed at average APF/TVS values buses, for example at buses 5, 15, and 29.

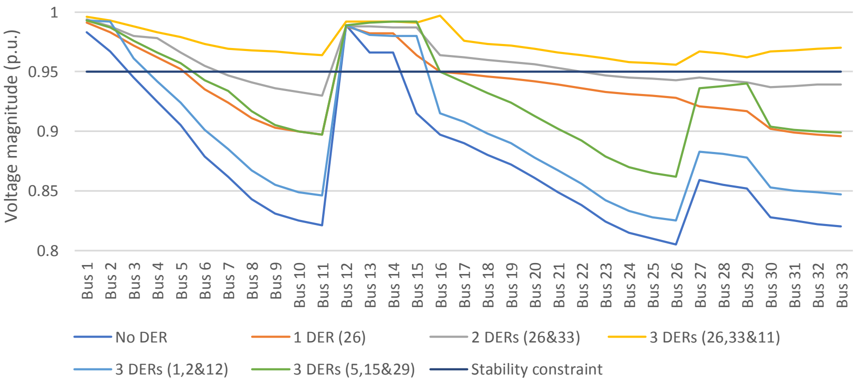

Figure 7~~6~~. Voltage profile improvement with DER units placement

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The line in blue color shows the system voltage profile of all buses at the original state before DER integration. It obviously indicates that voltages at the majority of the system are beneath the stability constraint (black line). The system voltage magnitude increases after one DER is integrated at bus 26 (red line). After the second DER is connected at bus 33, the system voltage profile improves again (green line). Then the system voltage profile with 3 DERs connected at buses 26, 33, and 11 is shown by the dark purple graph. These 3 locations are the placements according to the proposed hybrid MMA-CPF approach.

Different scenarios are evaluated in this manuscript. This work also investigates the system voltage profile if 3 DERs are integrated at buses with low APF/TVS values (1, 2, and 12) and buses with average APF/TVS values (5, 15, and 29) as assigned with the light blue and orange lines, respectively. Apparently, the voltage profile of the system does not increase substantially in both conditions. Interestingly, the system voltage with only one DER integrated at the most appropriate bus or high APF/TVS value bus (26) is better. Nevertheless, for a more comprehensive stability assessment of the system, the following section delivers an evaluation of the system's performance by using the eigenvalue computation analysis.

5.3 The System Smallest Eigenvalue ($\boldsymbol{\varepsilon_{min}}$)

The eigenvalue assessment is one of the most powerful techniques for assessing the power system stability. The smallest eigenvalue (ε_{min}) informs the *proximity* of the system stability which is the voltage stability level indication.

Figure 7 in Section 5.2 shows the system voltage profile for DER placement for various scenarios while Figure 8 illustrates the smallest system eigenvalue for various scenarios whose voltage profiles are shown in Figure 7. There is a close relationship between the voltage profile and the smallest eigenvalue. The higher the smallest eigenvalue indicates the better voltage profile or system voltage stability. It can be seen from Figures 7 and 8, the better the system voltage profile, the higher the eigenvalue.

~~Figure 7 illustrates the system smallest eigenvalue for different scenarios.~~ At the original state, no DER, the ε_{min} is 1.572. If one DER is connected at bus 26, the ε_{min} increases to 1.598 and then to 1.607 after the addition of another DER placement at bus 33. Then with the third DER positioned at bus 11, the final ε_{min} for 3 DER units becomes 1.625. However, if 3 DERs with the same capacity are sited at the least sensitive buses or buses with small APF/TVS values (buses 1, 2, 12), the ε_{min} is just 1.579. This ε_{min} value is even below the ε_{min} for a single DER at bus 26 (1.598). Similar outcomes apply to the average APF/TVS values buses (5, 15, 29); the ε_{min} is only 1.589 and also below the ε_{min} for a DER at bus 26. Even though with simply a single DER at the proper location, in this case, bus 26 with a size of 50 MW, it provides a more stable system compare to 3 DERs total of 150 MW at buses with small and average APF/TVS values. Briefly, a single DER at the appropriate bus can ensue in an improved system voltage and greater eigenvalue ε_{min}, therefore the system is in a better and more stable state.

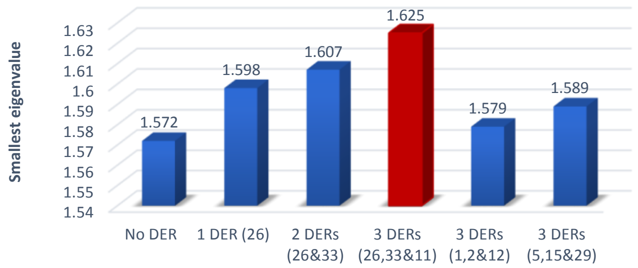

Figure 8~~7~~. The system's smallest eigenvalue comparison

5.4 Network Power Losses

The network power losses both active and reactive were calculated for each state and are presented in Figure ~~8~~9. If the first DER is placed at bus 26, the network losses are (0.391+j0.095) p.u. Then if another DER is placed at bus 33, the losses decrease to (0.187+j0.046) p.u. With another DER at bus 11, the losses further reduce to (0.074+j0.016) p.u, hence the percentage of losses reduction are $\%\Delta P_{Loss}$ is 42.25% and $\%\Delta Q_{Loss}$ is 44.59%. If 3 DERs are located at the least sensitive buses, buses with low APF/TVS values, buses 1, 2, and 12, the power losses are relatively significant, even bigger than the system losses for one DER at bus 26. The losses only reduce to (0.434+j0.125) p.u. with $\%\Delta P_{Loss}$ 4.44% and $\%\Delta Q_{Loss}$ 8.88%. Likewise, when 3 DER units are sited at buses with average values of APF/TVS, bus 1, 15, and 29, the system losses are also relatively large, which is (0.409+j0.109), $\%\Delta P_{Loss}$ of 7.06% and $\%\Delta Q_{Loss}$ of 14.27%.

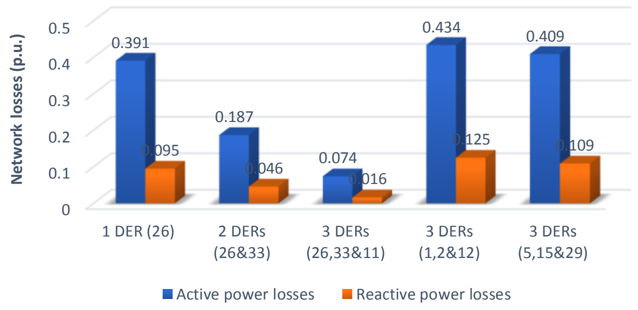

Figure 9~~8~~. Comparison of system losses after DER units placement

The outcomes of this examination from the location of DER, the system's smallest eigenvalue, and the loss~~es~~ reduction with the proposed hybrid MMA-CPF approach with DER locations at buses with small and average values of APF/TVS are summarized in Table ~~1~~2. Integrating the same size of DERs at buses with small and average APF/TVS values cannot assist to increase the voltage stability considerably and lessen the losses in significant quantity. Hence, it is certainly not suggested to locate DER units at the buses with small and average APF/TVS values from the perspective of voltage stability and system losses.

Table 2~~1~~. Results comparison in terms of the system smallest eigenvalue, and network losses reduction percentage

	High values of APF/TVS (Recommended)	Small values of APF/TVS	Average values of APF/TVS
DER Locations	26, 33 and 11	1, 2 and 12	5,15 and 29
$\varepsilon_{\min}$	1.625	1.579	1.589
$\%\Delta P_{Loss}$	42.25	4.44	7.06
$\%\Delta Q_{Loss}$	44.59	8.88	14.27

The further interesting outcome obtained is that the operation of the system operating with only 1 DER integrated at bus 26 is superior to 3 DERs at small APF/TVS values buses (1, 2, 12) or average APF/TVS values (5, 15, 29), in terms of voltage profile of the system, eigenvalue assessment, and power losses reduction. The voltage profile performance at the majority of the system, if DER is located at bus 26 is higher than if 3 DERs are located at small or average APF/TVS values buses as can be seen in Figure ~~9~~10. Furthermore, Figure 11~~0~~ informs the results from an eigenvalue viewpoint and displays related results. Eigenvalue or ε_{min} for 1 DER unit located at bus 26 is greater than ε_{min} for 3 DER units at small or average APF/TVS values buses. Similarly, the system losses if DER is positioned in bus 26 are marginally lesser than losses if 3 DERs at small or average APF/TVS values buses as can be perceived in Figure 12~~1~~.

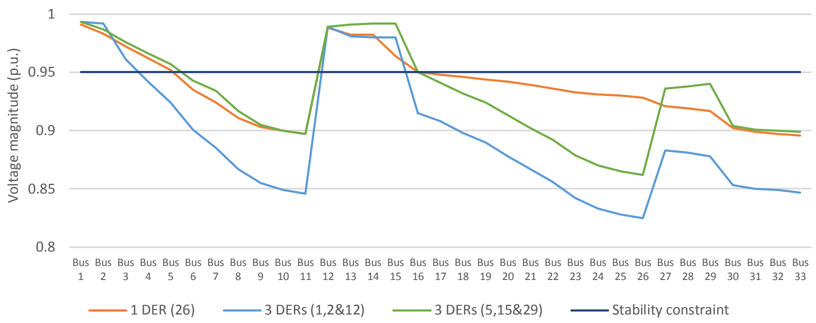

Figure 10~~9~~. Comparison of voltage profile

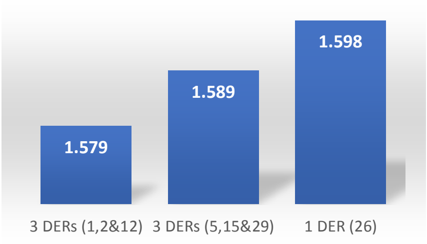

Figure 11~~10~~. System eigenvalue comparison

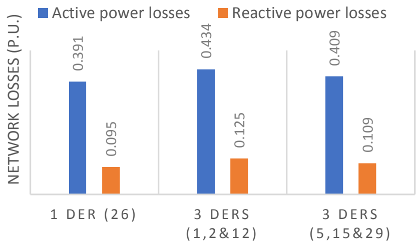

Figure 12~~11~~. Losses comparison

Additionally, in this manuscript, the proposed hybrid approach was compared with the CPF method by [19] to confirm the efficiency of the proposed hybrid approach. Table ~~2~~3 informs the DER location based on our proposed hybrid approach and the CPF technique while Figure 1~~2~~3 displays the enhancement of the voltage profile after DERs are placed according to both techniques.

Table 3~~2~~. DER Locations

Iteration	CPF Method [19]	Proposed Method Hybrid MMA-CPF
1	26	26
2	33	33
3	17	11

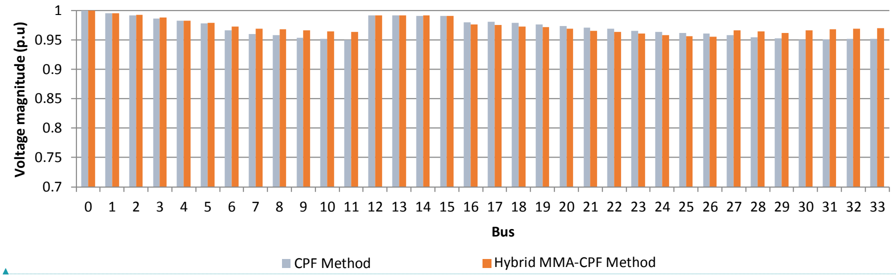

Figure 13~~12~~. Voltage magnitude after DER integration with the CPF method and the proposed hybrid method

As the eigenvalue assessment (ε_{min}) is one of the most efficient techniques to evaluate the static voltage stability analysis, hence the ε_{min} is utilized to make the efficient comparison of the DER location attained by the proposed hybrid method and the CPF. As can be perceived in Figure 14, the ε_{min} of the system with the CPF is only 1.610, whereas the ε_{min} with the proposed hybrid method is 1.618 which is larger than the CPF method

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eigenvalue. This informs that the proposed hybrid approach is rather more efficient than the CPF technique in resolving the placement of DER.

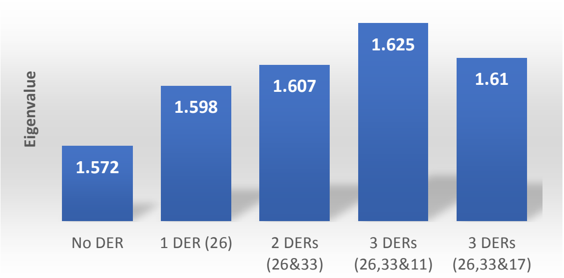

Figure 14~~13~~. System eigenvalues with the CPF approach and the proposed method

Moreover, DER placement based on the proposed hybrid technique results in the largest losses reduction with 42.25% and 44.59% for $\%\Delta P_{Loss}$ and $\%\Delta Q_{Loss}$, respectively. Though, by using the CPF approach, with 3 DERs at buses 26, 33, and 17, the reduction of losses is not as much as the losses reduction if DERs at buses 26, 33, and 11, where the 3rd DER is placed at bus 17, the losses decline a little below the network losses reduction for the proposed approach. The $\%\Delta P_{Loss}$ with CPF is 36.36% and $\%\Delta Q_{Loss}$ is 41.29%. Table ~~3~~ 4 clarifies the $\%\Delta P_{Loss}$ and $\%\Delta Q_{Loss}$ if DERs are placed at particular locations.

Table 4~~3~~ Results Comparison

DER Placement	Approach	ε_{min}	$\%\Delta P_{Loss}$	$\%\Delta Q_{Loss}$	VSI (%)	OF
26, 33 and 17	CPF [19]	1.610	36.36	41.29	2.430335	80.08033
26, 33 and 11	MMA-CPF	1.618	42.25	44.59	2.939305	89.77931
26 and 33	Both	1.6067	30.34	35.33	2.220384	67.89038
26	Both	1.5988	8.87	18.97	1.717776	29.55778

6. Conclusions

The appropriate allocation of DERs is essential to exploit the DER advantages. This manuscript recommends a novel technique based on two analytical voltage stability analysis approaches, the Modified Modal Analysis and Continuation Power Flow (MMA-CPF). The aim of this work is to attain the most stable system, the lowest losses, and the highest system eigenvalue. To assess the efficiency of the developed technique, this work also examines the performance of the system if DER units are sited at the least sensitive and the average APF/TVS values buses.

The outcomes of implementing this approach to the modified 34-bus RDN elucidate the efficiency of this technique in the optimum allocation of DERs. ~~The outcomes demonstrate the robustness of the APF/TVS in deciding the optimum placement for DER to improve the voltage stability, reduce the losses, and also increase the eigenvalue.~~ When the DER units are placed according to the proposed hybrid technique (buses 26, 33, and 11), it resulted in the largest losses reduction with 42.25% for $\%\Delta P_{Loss}$ and 44.59% for $\%\Delta Q_{Loss}$. The reduction of losses with the comparative method, the CPF approach (buses 26, 22, and 17), is not as much as the losses reduction if DERs placement based on the proposed method, in which the $\%\Delta P_{Loss}$ with CPF is 36.36% and $\%\Delta Q_{Loss}$ is 41.29%. If 3

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DERs are located at buses with low APF/TVS values (buses 1, 2, and 12), the power losses reduction is very insignificant with $\%\Delta P_{Loss}$ of only 4.44% and $\%\Delta Q_{Loss}$ of 8.88%. Similarly, when 3 DER units are sited at buses with average values of APF/TVS (buses 1, 15, and 29), the losses reduction is quite low, with the $\%\Delta P_{Loss}$ is 7.06% and the $\%\Delta Q_{Loss}$ is 14.27%.

It was proven in this paper that an appropriate DER site is very crucial to maximize DERs' advantages. The proper DER allocation can enhance the voltage profile substantially and reduce network losses significantly. The outcomes demonstrate the robustness of the APF/TVS in deciding the optimum placement for DER to improve the voltage stability, reduce the losses, and also increase the eigenvalue.

Author Contributions: Conceptualization, A.A.; methodology, A.A.; software, A.A. and M.B.N.; validation, A.A. and M.B.N.; formal analysis, A.A. and M.B.N.; investigation, A.A.; resources, A.A. and M.B.N.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A. and M.B.N.; visualization, A.A.; supervision, M.B.N.; project administration, A.A.; funding acquisition, M.B.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

APF	Active Participation Factor
TVS	Tangent Vector Sensitivity
RDN	Radial Distribution Network
DG	Distributed Generation
DER	Distributed Energy Resources
MMA	Modified Modal Analysis
CPF	Continuation Power Flow
MMA-CPF	Modified Modal Analysis - Continuation Power Flow
OF	Objective Function
ΔP	Active power variations
ΔQ	Reactive power variations
$\Delta\theta$	Voltage angle variations
ΔV	Voltage magnitude variations
J	Jacobian Matrix
J_R^*	Reduced Modified Jacoban Matrix
$\mathfrak{R}^*$	Right eigenvector matrix of J_R^*
υ^*	Left eigenvector matrix of J_R^*
φ^*	Diagonal eigenvalue matrix of J_R^*
ε_i^*	i^{th} eigenvalue of J_R^*
ζ_i^*	i^{th} column right eigenvector of J_R^*
ϱ_i^*	i^{th} row left eigenvector of J_R^*
ϖ	Load parameter
P_{Gi0}	Base case active power generation at bus i
P_{Li0}	Initial active power load at bus i
P_{Ti}	Injected active power at bus i
Q_{Gi0}	Base case reactive power generation at bus i
Q_{Li0}	Initial reactive power load at bus i
Q_{Ti}	Injected reactive power at bus i.
$S_{\Delta base}$	A specified amount of complex power which is selected to offer suitable ϖ scaling
k_{Gi}	Constant assigned for the degree of generation variation at bus i as ϖ varies
k_{Li}	Constant assigned for the degree of load variation at bus i as ϖ varies
θ_i	Power angle changes at bus i

$\bar{\delta}$	Vector of generator angle
$\bar{V}$	Vector of the bus voltage magnitude vector
$V_i\angle\delta_i$	Complex voltages at bus *i*
$V_j\angle\delta_j$	Complex voltages at bus *j*
$R_{ij}+jX_{ij}=Z_{ij}$	*ij*th component of Z_{bus} impedance matrix
P_i	Active power generation at bus *i*
P_j	Active power generation at bus *j*
Q_i	Reactive power injection at bus *i*
Q_j	Reactive power injection at bus *j*
P_{Loss}	Active power losses at initial conditions without DER integration
P_{Loss}^{DG}	Active power losses after integration of DER
Q_{Loss}	Reactive power losses at initial conditions without DER integration
Q_{Loss}^{DG}	Reactive power losses after integration of DER
ΔP_{Loss}	Reduction of active power losses
ΔQ_{Loss}	Reduction of reactive power losses
$\%\Delta P_{Loss}$	Reduction percentage of active power losses
$\%\Delta Q_{Loss}$	Reduction percentage of reactive power losses
VSI	Voltage stability index, indicating the voltage stability improvement after DER placement
ε_{min}^{DG}	The smallest eigenvalue with DER unit(s)
ε_{min}	The smallest eigenvalue without any DER unit

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Response to Reviewer 1 Comments

The authors would like to thank the Editor and Reviewers. All the comments have been incorporated in the paper appropriately and below are the response to the reviewers' comments.

The paper proposes a very interesting novel methodology to optimize DER units (Distributed Energy resource) typically used in renewable energy sources dedicated to electricity generation in order to produce a more stable performance and reduce power losses. This goal is achieved combining a Modified Modal Analysis (MMA) and Continuation Power Flow (CPF) techniques enabling via the calculation of Active Participation Factor (APF) and the Tangent Vector Sensitivity (TVS) to know precisely the load bus sensitivity in the network.

The paper is very well written and explained requiring almost no changes before it can be published. Few suggestions for a deeper reflection:

1) Line 281-282

It is important to explain that and if $\Delta PLoss$ and $\Delta QLoss$ are minimized at the same time or not and if not which becomes more important. I think it really depends on the application, but this should be clarified.

Response 1: Thank you for your suggestions. We have added more explanation in Section 4.5

In summary, the first step in determining the DER location is to calculate the APF and TVS values. In general, both methods tend to show the same results. However, if there is a difference, the value of the Objective Function (OF) as in Eq. 22 will be calculated, which in this OF calculation is to compute the summation of the ratio of changes in active power, changes in reactive power and changes in eigenvalue as an index of voltage stability of the electric power system. Hence from this OF calculations, it can be seen which bus has the greater influence on both the reduction of active power and reactive power.

The detailed explanation about the proposed method can be seen in the flowchart and the step by step procedure as in Section 4.1.

2) Figure 2 / Line 322

It is not clear from the explanation provided of Figure 2 and then 3 (lines 304 -320) if the fact that both maxima (for APF and TVS in Figure 2) are "by chance" both corresponding to bus 26 and above all if this is ALWAYS the case. In other words, what happens if the maximum of APF is for example bus 10 and maximum of TVS is bus 26? How then a decision is made? It would seem a second DER is needed and then a third. So when does the process stop?

If not, it would help explaining why mathematically the two solutions are effectively "always" converging or at least put a clear reference to paragraph 5.3 where the eigenvalues are compared. While Figure 5 explains that the total objective function is reduced, it does not show that is “absolutely” reduced, meaning it is the absolute minimum. It seems that the results of figure 6 are needed to explain or confirm the ones of Figure 5. Please, elaborate further and more clearly.

Response 2:

The explanation of the first part for Comment 2 is the same as in Comment 1. We have added more explanation on Section 4.5 on how to decide the DER location if APF and TVS are different.

In summary, the first step in determining the DER location is to calculate the APF and TVS values. In general, both tend to show the same results. However, if there is a difference, the value of the Objective Function (OF) as in Eq. 22 will be calculated, which in this OF calculation is to compute the summation of the ratio of changes in active power, changes in reactive power and changes in eigenvalue as an index of voltage stability of the electric power system. Hence from this OF calculation, it can be seen which bus has the greater influence on both the reduction of active power and reactive power. This process will be repeated until the voltage stability limits at all buses have been met as written in Section 4.2.

We have added a picture of the 34 bus distribution system, hence Figure 2 changes to Figure 3. Figure 3 (previously Figure 2) shows the results of the APF and TVS calculations for the first iteration and the highest APF and TVS values are both bus 26, thus bus 26 is chosen as a candidate for DER placement in iteration 1. We have added a more complete explanation to the article as follows:

The outcomes APF and TVS computation at each load bus to find out the appropriate location for the 1st DER allocation are shown in Figure 3. As can be seen from Figure 3, bus 26 has the biggest APF value (0.1774) and TVS value (0.124), as indicated by the big black marks, therefore bus 26 has the biggest influence on improving stability and is confirmed as the most efficient bus for the location of DER. Nonetheless, after DER integration at bus 26, the system is not stable yet, hence a second DER is required. Regarding Figure 4, bus 33 then has the biggest APF and TVS values of 0.1698 and 0.115 respectively, hence it is becoming the most sensitive bus to instability for the second computation. However since the system constraints have not been satisfied yet, the third DER is needed. The APF and TVS outcomes for the third DER can be perceived in Figure 5 where bus 11 has the biggest APF (0.1393), but bus 17 has the biggest TVS (0.113). Due to this difference, the objective function (OF) needs to be computed to resolve the most effective bus for the third DER unit. The result of the objective function calculation is shown in Figure 6 where bus 11 is shown to have the highest objective function value (0.8926), hence bus 11 is chosen as the site for the third DER unit. With 3 DERs positioned at buses 26, 33, and 11, the voltages at all buses system have recovered above the stability constraints ($0.95 \leq V_i \leq 1.05$ p.u) thus the procedure is completed.

Therefore for the first and second iterations, APF and TVS indicate the same bus for the best DER location, hence OF is not calculated. Nevertheless, in the third iteration, because the highest APF and TVS values were on different buses, OF is calculated to determine the DER location. Table 1 provides a summary of the results of the highest APF, TVS and OF calculations to determine the DER location.

Table 1. Summary of the results of the highest APF, TVS and OF calculations to determine the DER location

Iteration	Highest APF	Highest TVS	Highest OF	DER location
1	26	26	-	26
2	33	33	-	33
3	11	17	11	11

From Figures 3-5, we can also see buses that have low or average APF and TVS values. Hence to evaluate the selected buses, we compare the magnitude of the voltage profile and the eigenvalues when the DERs are placed on buses with low or average APF/TVS values. The results of the voltage profile can be seen in Figure 7 and the eigenvalues can be seen in Figure 8. The eigenvalue is one of the stability indices in the analysis of voltage stability of power systems and the higher the eigenvalue shows that the system is more stable. It can be seen from Figures 7 and 8, the better the system voltage profile, the higher the eigenvalue.

Figure 7 in Section 5.2 shows the system voltage profile for DER placement for various scenarios while Figure 8 illustrates the smallest system eigenvalue for various scenarios whose voltage profiles are shown in Figure 7. There is a close relationship between the voltage profile and the smallest eigenvalue. The higher the smallest eigenvalue indicates the better voltage profile or system voltage stability.

3) Figure 9-10 / Line 422-424

It is not clear what is the significance of Figure 9 and Figure 10 as differences in results are quite small if not negligible. What conclusion can be inferred from these plots? Please elaborate further.

Response 3: In this section, we would like to point out that with only 1 DER at bus 26 results in better voltage profile, eigenvalue and lower losses compare to if 3 DERs are placed in improper buses. The results of voltage profile as in Figure 10 (previously Figure 9), eigenvalue as in Figure 11 (previously Figure 10), and losses in Figure 12. The differences are quite small because we compare only 1 DER at the proper location with 3 DERs at improper location. The explanation in the article are as follow:

The further interesting outcome obtained is that the operation of the system operating with only 1 DER integrated at bus 26 is superior to 3 DERs at small APF/TVS values buses (1, 2, 12) or average APF/TVS values (5, 15, 29), in terms of voltage profile of the system, eigenvalue assessment, and power losses reduction. The voltage profile performance at the majority of the system, if DER is located at bus 26 is higher than if 3 DERs are located at small or average APF/TVS values buses as can be seen in Figure 10. Furthermore, Figure 11 informs the results from an eigenvalue viewpoint and displays related results. Eigenvalue or ε_min for 1 DER unit located at bus 26 is greater than ε_min for 3 DER units at small or average APF/TVS values buses. Similarly, the system losses if DER is positioned in bus 26 are marginally lesser than losses if 3 DERs at small or average APF/TVS values buses as can be perceived in Figure 12.

4) Conclusions

While the idea is well explained, I would suggest providing in the conclusions a percentage number (15%? 27%?) of possible maximum reduced losses achieved with this new methodology similarly to what summarized in TABLE 3 and maybe TABLE 1. This would help illustrate better the clear advantages put in evidence in this study.

Response 4: We have added more explanation in the conclusion based on the suggestion above as follow:

The outcomes of implementing this approach to the modified 34-bus RDN elucidate the efficiency of this technique in the optimum allocation of DERs. When the DER units are placed according to the proposed hybrid technique (buses 26, 33 and 11), it resulted in the largest losses reduction with 42.25% for $\%\Delta P_{Loss}$ and 44.59% for $\%\Delta Q_{Loss}$. The reduction of losses with the comparative method, the CPF approach (buses 26, 22 and 17), is not as much as the losses reduction if DERs placement are based on the proposed method, which the $\%\Delta P_{Loss}$ with CPF is 36.36% and $\%\Delta Q_{Loss}$ is 41.29%. If 3 DERs are located at buses with low APF/TVS values (buses 1, 2, and 12), the power losses reduction is very insignificant with $\%\Delta P_{Loss}$ of only 4.44% and $\%\Delta Q_{Loss}$ of 8.88%. Similarly, when 3 DER units are sited at buses with average values of APF/TVS (buses 1, 15, and 29), the losses reduction is quite low, which the $\%\Delta P_{Loss}$ is 7.06% and the $\%\Delta Q_{Loss}$ is 14.27%.

Response to Reviewer 2 Comments

The authors would like to thank the Editor and Reviewers. All the comments have been incorporated in the paper appropriately and below are the response to the reviewers' comments.

The paper is well written and timely, my only suggestion is to provide larger case studies and provide a computational analysis on the scalability of the proposed addproach.

Response: We would like to thank for your suggestion. Unfortunately, it is a bit difficult to add new case study in this article considering the short time frame given for revising this paper. We actually have planned for our future works to improve the proposed method and expanding the proposed method also for larger case studies such as in the transmission network in addition to distribution network.

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Novel Hybrid Modified Modal Analysis and Continuation Power Flow Method for Unity Power Factor DER Placement

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Abstract: Distributed energy resource (DER) has become an effective attempt in promoting use of renewable energy resources for electricity generation. The core intention of this study is to expand an approach for optimally placing several DER units to attain the most stable performance of the system and the greatest power losses decrease. The recommended technique is established on two analytical methods for analyzing voltage stability: the new modified modal analysis (MMA) and the continuation power flow (CPF) or MMA–CPF methods. The MMA evaluates voltage stability by considering incremental connection relating voltage and active power, which includes the eigenvalue and the related eigenvectors computed from the reduced modified Jacobian matrix. Furthermore, an active participation factor (APF) is computed from the eigenvectors of the reduced modified Jacobian matrix. The CPF method uses a predictor–corrector stepping pattern to reach the solution track and compute the tangent vector sensitivity (TVS). Both APF and TVS indicate each load bus sensitivity in the network. In addition, an objective function regarding losses decrease and eigenvalue is expressed to calculate the best bus position for DER allocation. The proposed MMA–CPF technique has been assessed on a 34-bus RDN and the outcomes demonstrate the effectiveness of the proposed scheme.

Keywords: continuation power flow; distributed energy resource; distributed generation; eigenvalue; eigenvector; modal analysis; network losses; renewable energy resources; voltage stability

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1. Introduction

Due to rapid technological advances and the economic and environmental benefits of a distributed energy resource (DER), DER has become a global unpolluted renewable energy source for alternative generation. Nowadays, DERs are more developed in the grid worldwide because of their advantages compared to conventional fossil fuel power generation methods, which drive the issue of global warming. DERs can be divided into four main categories based on their ability to supply active and reactive power, which are [1]:

- Type 1 DER unit (pf_{DERi} = 1, unity power factor). Type 1 DER can only supply active power to the system. Examples of type 1 DER are photovoltaic (PV) [2,3], micro-turbines (MT), and fuel cells (FC). These DERs are connected to the main network using converters/inverters;
- Type 2 DER unit (pf_{DERi} = 0). The type 2 DER can only provide reactive power to the network. For example, static power compensators, such as capacitors, static VAr compensators (SVC), static synchronous compensators (STATCOM), etc. [4,5];
- Type 3 DER unit ($0 < pf_{DERi} < 1$ with lagging power factor). Type 3 DERs can provide active power and reactive power to the network. Examples of type 3 DER are a synchronous generator operated in cogeneration and gas-fired DER;

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- Type 4 DER unit ($0 < pf_{DERi} < 1$ with leading power factor). This type of DER provides active power to the system but attracts reactive power. An example of type 4 DER is primarily an induction generator in a wind farm, such as doubly fed induction generators (DFIG) [6].

Connection of DERs into the grid has resulted in several gains. Because the DERs are located inside the local grid or at the customer's site, DERs provide electrical energy directly to the customers or the local distribution grid. DERs tend to decrease the flow of power in the transmission system, which can enhance the voltage profile in the distribution system. DERs assist to lessen losses in the distribution network by supplying locally to the load demand. DERs also enhance system reliability by delivering supplementary system generation capacity for power distribution networks for non-disruptive power supplies and backup power supplies and provide temporary emergency power [7]. However, these benefits are highly dependent on proper placement and capacity of DERs. Proper placement of DERs will greatly improve a system stability and reduce distribution grid losses [8]. Optimum DER allocation is one of the main challenges for DER integration [9]. Studying the most appropriate placements of DERs was essential to take full advantage of DERs' operating advantages. Power system engineers and researchers have recommended various methodologies to determine optimal placement of DERs. A comprehensive review of DG placement is provided by [10].

Many analytical techniques have been proposed for solving DER placement. The authors in [11] proposed $Q - PQV$ bus pair considering load demand seasonal changes biomass DER placement. In [12], bifurcation analysis and dynamic programming were used. The authors of [13] have established a power stability index (PSI) that determines a stable node voltage for placement and sizing of DERs. Work in [14] defined an objective function by employing the maximum power stability index (MPSI) for finding the DER location. Integer nonlinear programming was implemented in [15] to choose sensitive nodes to increase voltage profiles. Further, [16] suggested a technique for determining the optimal position of DERs considering network losses and using the Kalman filter algorithm to compute the optimal DER size. Nonetheless, no standard criteria exist for determination of optimal number of DERs. The author of [17] recommended analytical power loss equations for calculating optimal size and position of DERs to reduce network losses. Nevertheless, the large size and difficulty of the distribution system can affect how robustness is not satisfied. From [18], a "2/3 rule" that was first used for capacitor placement in the distribution network was assumed to determine the position of DERs. This method is very easy but cannot be directly applied to a meshed network. Furthermore, capacitors supply only reactive power while the DER produces active power. Consequently, this rule cannot be used effectually to locate the DERs. The authors of [19] offered a continuation power flow (CPF)-based settlement of DER units and indicated the most sensitive bus to voltage breakdown. The DER units were placed on the chosen buses via the iterative algorithm and objective function. Yet, this technique does not always offer the ideal solution.

Moreover, many meta-heuristic methodologies have been proposed for optimal DER placement. A sensitivity analysis and harmony search algorithm (HAS) was used to decide the most appropriate DER placement [20]. A differential evolution algorithm is proposed in [21] for DER integration. Genetic algorithm (GA) and AC-OPF were proposed in [22] for placement and size of DERs. GA is a suitable technique for solving multi-objective difficulties and can provide effectual solutions, but it is time-consuming in its computation. A chaotic bat algorithm (CBA) was developed in [23] for optimal locations and DER sizes. A fuzzy-embedded multi-objective particle swarm optimization (FMOPSO) method was used in [24]. Nevertheless, the shortcoming of PSO is it obtains solutions to local solutions quickly or prematurely converges. Ant colony system (ACS) was used in [25] for DER placement. However, a few obstacles to the ACS approach may additionally reduce its effectiveness. ACS relies upon preliminary points and necessitates a longer computational time to discover the most efficient arrangement. The authors in [26] developed a fireworks algorithm for network reconfiguration and finding the most suitable allocation of DER in a distribution system. In [27], the authors developed DER placement based on a modified teaching–learning-based optimization (MTLBO) algorithm. Meta-heuristics techniques are widely known and utilized for optimal DER allocation; nonetheless, their severe drawbacks are the divergence possibility, they require a long period to acquire the best solution, and they cannot often guarantee to obtain the best result but a sensible result that is near to a perfect result.

Hence, we proposed an original hybrid analytical method in this article with modified modal analysis (MMA) and continuation power flow (CPF) to resolve DER deployment with the objective of maximizing voltage stability and minimizing active power losses. Gao et al. [28] developed a modal analysis and it has been implemented to resolve several power systems issues. This method includes the eigenvalue method and the related eigenvectors computed from the reduced voltage–reactive power Jacobian matrix. The reduced voltage–reactive power Jacobian matrix emphasizes the relationship between system voltage and reactive power. However, in order to meet the aim of this study, the reduced Jacobian matrix was adapted, where its focus was on voltage and active power properties rather than reactive power. This method is appropriate for DER type 1 because the MMA and CPF provide information about the correlation between voltage magnitude and active power at each load bus.

Appropriate placement of DER units will substantially lessen system losses and considerably enhance the stability of the system. Hence, the key contributions of this manuscript are:

- developing a new hybrid scheme to compute optimal DER placement. This technique is a hybrid approach between the modified modal analysis (MMA) and continuation power flow (CPF) or MMA–CPF method. This approach combines the key features of both techniques. The MMA incorporates eigenvalue computation and the correlated eigenvectors of the reduced modified voltage–active power Jacobian matrix. MMA uses eigenvectors to compute the bus active participation factor (APF). The APF provides an indication of the participation of a certain bus in solving the instability problem of the network. On the other hand, the CPF reformulates the equation of power flow by using a prediction–correction stepping algorithm to reach the solution track and computes the tangent vector sensitivity (TVS). Both APF and TVS provide indications about the bus that has the largest influence in improving the system stability directly. Thus, the load bus that has the largest APF/TVS is chosen as the place for the DER unit;
- delivering a complete evaluation of the impact of DER allocation on system losses and assessment of voltage stability, which, in this case, are the smallest eigenvalues for the system as they are a common indicator for assessing the performance of system stability;
- enhancing the objective functions based on the power losses and eigenvalues to conclude the most suitable DER site when a difference between APF and TVS occurs. Formulation of this objective function provides a calculation in which bus will provide the least losses and the most stable system.

After determining the DER placement, this work re-evaluates the voltage stability of the system to confirm the efficiency of the proposed placement in enhancing the voltage profile, eigenvalues of the system, and reduction in power losses. The proposed technique was simulated on a 34-bus RDN to clarify the efficacy of the recommended scheme. Even though integration of DERs into a present distribution network can offer several advantages, this research only emphasizes improvement in voltage stability and reduction in network losses. This work computed the network losses, voltage magnitude, and system's smallest eigenvalue. The developed scheme is simple, straightforward, robust, and its time calculation is effectual because it uses a non-iterative procedure in calculating DER placement based on the APF/TVS. Further interesting outcomes are elaborated in this manuscript.

2. Modified Modal Analysis

The modal analysis technique was proposed by [28]. This technique has been implemented in many areas of power systems to resolve different stability problems. This approach forms a reduced Jacobian matrix that provides a direct correlation between variations in reactive power and system voltage. The modal analysis presents *proximity* and *mechanism. Proximity* provides information about the security of the system voltage, which provides details on the stability level of the system, which is indicated by the eigenvalues (ε_i). The ε_i indicates if the system is stable or not stable at a particular operational state. The *mechanism* provides identification of areas likely vulnerable to instability problems, which is helpful to preclude system instability. The information on the instability *mechanism* is provided by the eigenvectors. Their computation states critical voltage instability areas and signifies components that are imperative in instability occurrence.

The linearized equation of a static steady-state power system is provided by,

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

Nevertheless, in the modal analysis by [28], evaluation of voltage stability is regarding the correlation between reactive power (Q) and voltage (V). Yet, in the placement of the type 1 DER, the assessment should emphasize the active power supplied by DERs. Therefore, in this manuscript, the initial modal analysis is adjusted to assess the stability of the system by considering the incremental correlation between active power (P) and voltage (V); thus, reactive power (Q) is considered the same.

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If ΔQ in Equation (1) is kept constant, then the reduced modified Jacobian matrix can be written as:

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

$$\Delta P = \left[J_{PV} - J_{P\theta}\, J_{QV}\, {J_{Q\theta}}^{-1}\right]\Delta V = J_R^*\,\Delta V \tag{3}$$

$$\Delta V = {J_R^*}^{-1}\,\Delta P \tag{4}$$

$$J_R^* = \left[J_{PV} - J_{P\theta}\, J_{QV}\, {J_{Q\theta}}^{-1}\right] \tag{5}$$

The reduced modified Jacobian matrix is marked as J_R^* to differentiate it from the initial Jacobian matrix, which correlates directly with variations between active power and magnitude of bus voltage. Hence, we can reformulate the eigenvalues and eigenvectors as follows:

$$J_R^* = \Re^*\,\Phi^*\,\Upsilon^* \tag{6}$$

$${J_R^*}^{-1} = \Re^*\,{\Phi^*}^{-1}\,\Upsilon^* \tag{7}$$

By substituting Equation (7) into Equation (4), the direct correlation between the incremental variations in active power and system voltage can be obtained as follows:

$$\Delta V = \Re^*\,{\Phi^*}^{-1}\,\Upsilon^*\,\Delta P \tag{8}$$

Or,

$$\Delta V = \sum_i \frac{\zeta_i^*\,\varrho_i^*}{\varepsilon_i^*}\Delta P \tag{9}$$

Therefore, the *APF* becomes:

$$APF_{ki} = \zeta_{ki}^*\,\varrho_{ik}^* \tag{10}$$

APF_{ki} signifies the participation of bus *i* in the voltage–active power sensitivity at bus *k*. The larger the APF_{ki} value, the more significant bus *i* effect in deciding voltage–active power sensitivity at bus *k* [29].

3. Continuation Power Flow (CPF)

The intention of the CPF scheme is to attain different power flow results for a particular load variation situation. The CPF scheme concisely delivered in this manuscript is according to the method explained by [30].

Initially, we define a load parameter (ϖ) as:

$$0 \leq \varpi \leq \varpi_{critical}$$

where ϖ = 0 relates to the system base load and $\varpi = \varpi_{critical}$ indicates the critical load. Then, ϖ is then included in the power equations of both active and reactive to acquire:

$$0 = P_{Gi0}(1 + \varpi k_{Gi}) - P_{Li0} - \varpi\,(k_{Li}\, S_{\Delta base} \cos\theta_i) - P_{Ti} \tag{11}$$

$$0 = Q_{Gi0} - Q_{Li0} - \varpi\,(k_{Li}\, S_{\Delta base} \sin\theta_i) - Q_{Ti} \tag{12}$$

A continuance procedure is implemented at the remodeled power flow calculations; hence, Equations (11) and (12) are adjusted in a simple formula:

$$F\left(\bar{\delta}, \bar{V}, \varpi\right) = 0 \tag{13}$$

The continuation power flow technique exploits a prediction–correction system to attain a result track of remodeled power flow formulas. A tangent vector is computed in the prediction phase by considering the derivation of both power flow equations sides; hence:

$$\begin{bmatrix} F_{\bar{\delta}} & F_{\bar{V}} & F_{\varpi} \end{bmatrix} \begin{bmatrix} d\bar{\delta} \\ d\bar{V} \\ d\varpi \end{bmatrix} = 0 \tag{14}$$

A revision is completed in the prediction stage by parameterization enlargement to recognize every result alongside the trajectory being tracked. The tangent vector specifies sensitivity analysis to resolve the most sensitive buses in addition to the manner of the solution route. A sensitive bus in CPF is a bus with a large ratio of voltage differential variation to load differential variation, which is provided by the tangent vector [31]. Hence, the formula for tangent vector sensitivity (TVS) at bus *j* can be written as:

$$TVS_j = \left|\frac{dV_j}{dP_{total}}\right| = \left|\frac{dV_j}{Cd\varpi}\right| = \max\left[\left|\frac{dV_1}{Cd\varpi}\right|, \left|\frac{dV_2}{Cd\varpi}\right|, \dots \left|\frac{dV_n}{Cd\varpi}\right|\right] \tag{15}$$

4. Proposed Methodology, System Constraints, Objective Function, and Evaluation Parameters

4.1. Proposed Hybrid MMA–CPF Technique

The load bus that has the largest APF/TVS value signifies the most sensitive bus in the network, thus having a prevalent impact on enhancing the system stability. Hence, the DER placement position is recommended according to the bus with the largest APF/TVS value. Additionally, this work develops a new formulation for objective function based on the APF/TVS outcomes to resolve the most appropriate bus for DER placement that would result in the most stable system and the lowest system losses. The APF computation is provided in Equation (10), while the TVS calculation can be obtained in Equation (15). Figure 1 provides the proposed MMA–CPF technique flowchart.

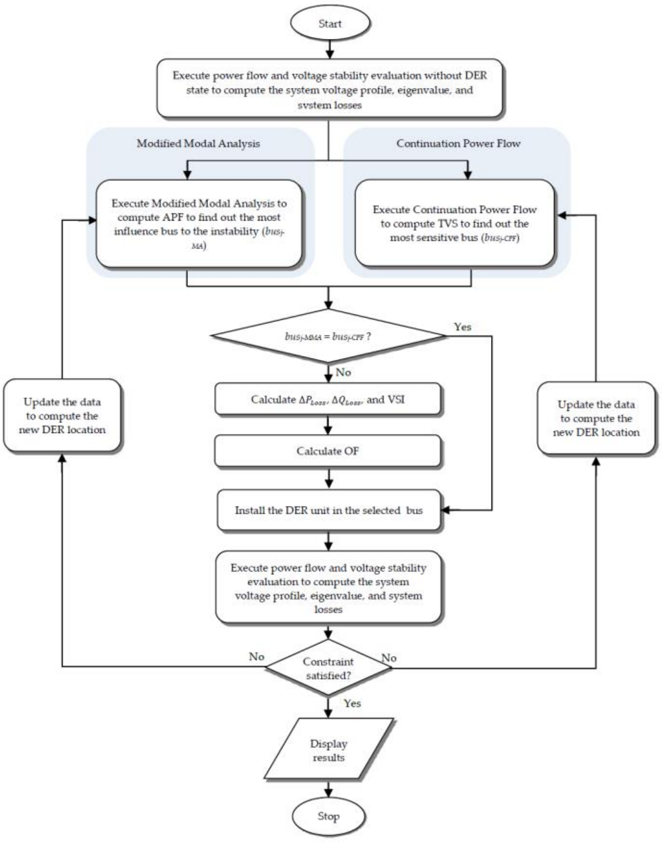

Figure 1. The hybrid MMA–CPF DER allocation approach flowchart.

The detailed computational process for DER allocation according to the hybrid MMA–CPF technique is described as:

Step 1 Input the system data.
Step 2 Execute power flow with Equation (1) and evaluate voltage stability for the original state (no DER unit) to compute voltage profile, system losses, and eigenvalue.
Step 3 (a) Execute MMA to compute APF at each load bus to define the most influential bus (bus_{j-MMA}), and
(b) execute CPF to compute TVS at each load bus to define the most sensitive bus (bus_{j-CPF}).
Step 4 Compare the outcomes of MMA and CPF. If $bus_{j-MMA} \neq bus_{j-CPF}$, go to Step 5; otherwise, go to Step 7.
Step 5 Compute ΔP_{Loss}, ΔQ_{Loss}, and VSI.
Step 6 Compute the OF. The bus that has the highest objective function is recommended as the DER location.
Step 7 Set up DER in the designated bus.
Step 8 Execute power flow and evaluate voltage stability assessment to compute voltage profile, system losses, and eigenvalue.

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Step 9 Assess the performance of the system as to if all the voltages are within the voltage limit constraints.

Step 10 If the bus voltage magnitudes are not fulfilled, then adjust the system data to acquire a new DER place and go back to Step 3.

Step 11 Once the voltage stability constraints are fulfilled, the program is terminated.

4.2. Voltage Stability Constraints

The voltage threshold stability limit utilized in this study is as follows:

$$V_{min} \leq V_i \leq V_{max} \rightarrow 0.95 \leq V_i \leq 1.05\ \mathrm{p.u}$$

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4.3. Eigenvalue Evaluation

The eigenvalue is one of the popular parameters for assessing voltage stability and has been confirmed for its usefulness in evaluating voltage stability. In this manuscript, the smallest system eigenvalue ε_{min} is calculated and implemented to assess the level of system voltage stability. It is also considered a voltage stability indicator. Therefore, we can expand Equation (6) into:

$$J_R^* = \begin{bmatrix} \zeta_{11} & \zeta_{12} & \cdots & \zeta_{1n} \\ \zeta_{21} & \zeta_{22} & \cdots & \zeta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \zeta_{n1} & \zeta_{n2} & \cdots & \zeta_{nn} \end{bmatrix} \begin{bmatrix} \mathcal{E}_1 & 0 & \cdots & 0 \\ 0 & \mathcal{E}_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \mathcal{E}_n \end{bmatrix} \begin{bmatrix} \varrho_{11} & \varrho_{12} & \cdots & \varrho_{1n} \\ \varrho_{21} & \varrho_{22} & \cdots & \varrho_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \varrho_{n1} & \varrho_{n2} & \cdots & \varrho_{nn} \end{bmatrix} \tag{16}$$

The ε_i magnitude defines the bus i^{th} modal voltage's degree of stability.

4.4. Network Power Losses

The following formulations represent the total active and reactive power losses [32]:

$$P_{Loss} + jQ_{Loss} = \sum_{i=1}^{N} S_i = \sum_{i=1}^{N} V_i I_i^* \tag{17}$$

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_i.P_j + Q_i.Q_j\right) + \beta_{ij}\left(Q_i.P_j - P_i.Q_j\right)\right] \tag{18}$$

$$Q_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\gamma_{ij}\left(P_i.P_j + Q_i.Q_j\right) + \delta_{ij}\left(Q_i.P_j - P_i.Q_j\right)\right] \tag{19}$$

where

$$\alpha_{ij} = \frac{R_{ij}}{|V_i||V_j|}\cos\left(\theta_i - \theta_j\right), \quad \beta_{ij} = \frac{R_{ij}}{|V_i||V_j|}\sin\left(\theta_i - \theta_j\right)$$

$$\gamma_{ij} = \frac{X_{ij}}{|V_i||V_j|}\cos\left(\theta_i - \theta_j\right), \quad \delta_{ij} = \frac{X_{ij}}{|V_i||V_j|}\sin\left(\theta_i - \theta_j\right)$$

The following formulas are used to assess the DER unit placement effect on reduction in power losses:

$$\%\Delta P_{Loss} = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}} * 100\% \tag{20}$$

$$\%\Delta Q_{Loss} = \frac{Q_{Loss} - Q_{Loss}^{DG}}{Q_{Loss}} * 100\% \tag{21}$$

4.5. Objective Function

To determine the DER unit’s placement in the distribution system, the objective function deliberated in this work is minimizing the network losses (maximum losses reduction) and maximizing the system eigenvalue (system stability). Hence, the objective function (OF) is formulated as follows:

$$\text{OF} = \Delta P_{Loss} + \Delta Q_{Loss} + VSI \tag{22}$$

$$\Delta P_{Loss} = \frac{P_{Loss} - P_{Loss}^{DG}}{P_{Loss}}, \Delta Q_{Loss} = \frac{Q_{Loss} - Q_{Loss}^{DG}}{Q_{Loss}}, VSI = \frac{\varepsilon_{min}^{DG} - \varepsilon_{min}}{\varepsilon_{min}}$$

The bus with the largest objective function is chosen as the place for DER installment as locating the DER unit in this bus; the aim is to obtain the lowest losses, and the highest stability index will be achieved.

In summary, the first step in determining DER location is to calculate the APF and TVS values. In general, both tend to show the same results. However, if there is a difference, the value of the objective function (OF) as in Equation (22) will be calculated, which, in this OF calculation, is to compute the summation of the ratio of changes in active power, changes in reactive power, and changes in eigenvalue as an index of voltage stability of the electric power system. Hence, from this OF calculation, it can be seen which bus has the greater influence on both reduction in active power and reactive power. This process will be repeated until the voltage stability limits at all buses have been met as written in Section 4.2.

5. Test Results and Analysis

This paper developed a novel hybrid approach to resolve integration of DER based on an objective function computed from APF and TVS. Both the APF and TVS provide info about the most sensitive bus in the network or the bus that has the largest influence on improving stability. If APF and TVS indicate different most sensitive buses, an objective function that measures minimum losses and maximum stability index is calculated. The bus that has the largest objective function is chosen as the location for DER since, by assigning DER in this bus, network losses can be minimized and the index of stability can be maximized. To assess the proposed method’s performance, tests were conducted on the 34-bus RDN, as shown in Figure 2.

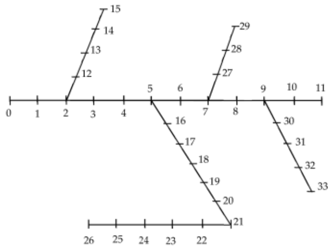

Figure 2. IEEE 34-bus distribution network test system [19].

5.1. APF and TVS Computation for DER Location

The outcomes of APF and TVS computation at each load bus to determine the appropriate location for the first DER allocation are shown in Figure 3. As can be seen from Figure 3, bus 26 has the largest APF value (0.1774) and TVS value (0.124), as indicated by the big black marks; therefore, bus 26 has the largest influence on improving stability and is confirmed as the most efficient bus for the location of DER. Nonetheless, after DER integration at bus 26, the system is not stable yet; hence, a second DER is required. Regarding Figure 4, bus 33 then has the largest APF and TVS values of 0.1698 and 0.115, respectively; hence, it is becoming the most sensitive bus to instability for the second computation. However, since the system constraints have not been satisfied yet, the third DER is needed. The APF and TVS outcomes for the third DER can be perceived in Figure 5, where bus 11 has the largest APF (0.1393) but bus 17 has the largest TVS (0.113). Due to this difference, the objective function (OF) needs to be computed to resolve the most effective bus for the third DER unit. The result of the objective function calculation is shown in Figure 6, where bus 11 is shown to have the highest objective function value (0.8926); hence, bus 11 is chosen as the site for the third DER unit. With three DERs positioned at buses 26, 33, and 11, all the voltages have recovered above the stability constraints ($0.95 \leq V_i \leq 1.05$ p. u); thus, the procedure is complete.

Therefore, for the first and second iterations, APF and TVS indicate the same bus for the best DER location; hence, OF is not calculated. Nevertheless, in the third iteration, because the highest APF and TVS values were on different buses, OF is calculated to determine the DER location. Table 1 provides a summary of the results of the highest APF, TVS, and OF calculations to determine the DER location.

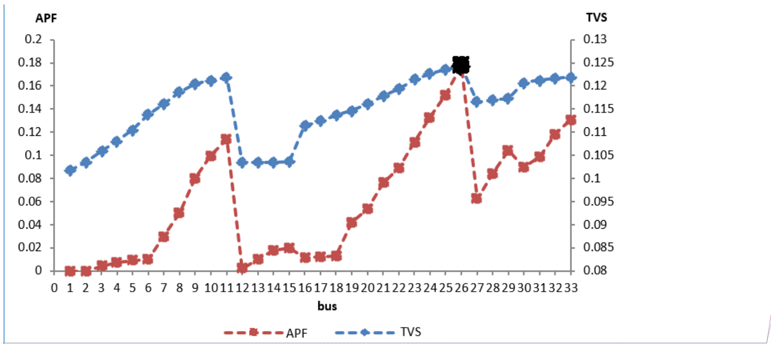

Figure 3. The APF and TVS for determining the first DER location.

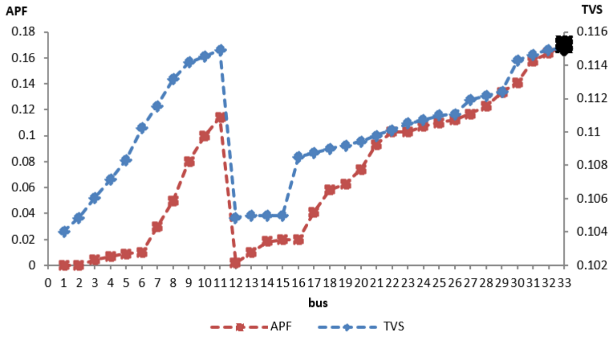

Figure 4. The APF and TVS for determining the second DER location.

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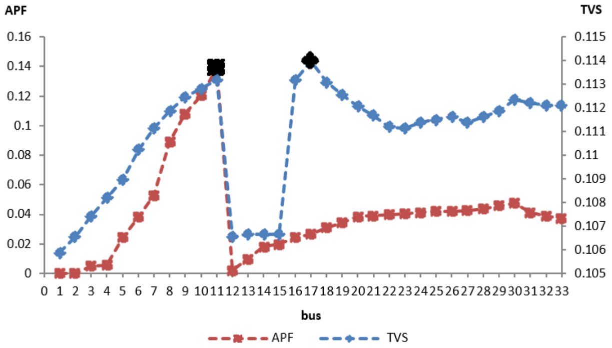

Figure 5. The APF and TVS for determining the third DER location.

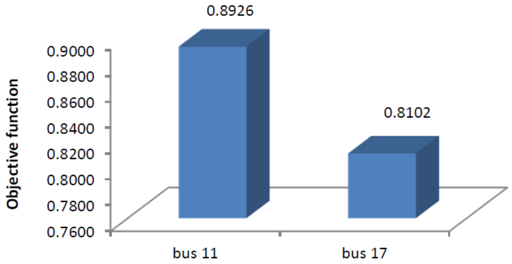

Figure 6. Objective function (OF) to determine the third DER location.

Table 1. Summary of the results of the highest APF, TVS, and OF calculations to determine the DER location.

Iteration	Highest APF	Highest TVS	Highest OF	DER Location
1	26	26	-	26
2	33	33	-	33
3	11	17	11	11

5.2. Voltage Profile Enhancement

Based on the results of APF, TVS, and OF calculations (Table 1), the DER locations proposed by the results of the proposed method are buses 26, 33, and 11. Figure 7 shows the voltage profile of the system for several scenarios. To verify the effectiveness of the developed hybrid MMA–CPF scheme, we also simulate system stability if three DER units are placed at the least sensitive buses that have small APF and TVS. Figures 3–5 indicate that buses 1, 2, and 12 have small APF/TVS. We also evaluate the system performance if the DERs are placed at average APF/TVS values buses, for example, at buses 5, 15, and 29.

The line in blue color shows the system voltage profile of all buses at the original state before DER integration. It obviously indicates that most voltages are beneath the stability constraint (black line). The system voltage magnitude increases after one DER is integrated at bus 26 (red line). After the second DER is connected at bus 33, the system voltage profile improves again (green line). Then, the system voltage profile with three DERs connected at buses 26, 33, and 11 is shown by the dark purple graph. These three locations are the placements according to the proposed hybrid MMA–CPF approach.

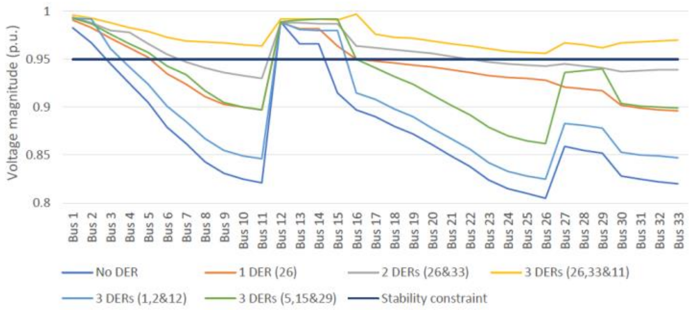

Figure 7. Voltage profile improvement with DER units placement.

Different scenarios are evaluated in this manuscript. This work also investigates the system voltage profile if three DERs are integrated at buses with low APF/TVS values (1, 2, and 12) and buses with average APF/TVS values (5, 15, and 29), as assigned with light blue and orange lines, respectively. Apparently, the voltage profile of the system does not increase substantially in both conditions. Interestingly, the system voltage with only one DER integrated at the most appropriate bus or high APF/TVS value bus (26) is better. Nevertheless, for a more comprehensive stability assessment of the system, the following section delivers an evaluation of the system's performance by using eigenvalue computation analysis.

5.3. *The System Smallest Eigenvalue* (ε_{min})

Eigenvalue assessment is one of the most powerful techniques for assessing power system stability. The smallest eigenvalue (ε_{min}) informs the *proximity* of the system stability, which is the voltage stability level indication.

Figure 7 in Section 5.2 shows the system voltage profile for DER placement for various scenarios, while Figure 8 illustrates the smallest system eigenvalue for various scenarios, whose voltage profiles are shown in Figure 7. There is a close relationship between voltage profile and smallest eigenvalue. The higher the smallest eigenvalue, the better the voltage profile or system voltage stability. It can be seen from Figures 7 and 8 that, the better the system voltage profile, the higher the eigenvalue. At the original state, no DER, the ε_{min} is 1.572. If one DER is connected at bus 26, the ε_{min} increases to 1.598 and then to 1.607 after addition of another DER placement at bus 33. Then, with the third DER positioned at bus 11, the final ε_{min} for three DER units becomes 1.625. However, if three DERs with the same capacity are sited at the least sensitive buses or buses with small APF/TVS values (buses 1, 2, 12), the ε_{min} is just 1.579. This ε_{min} value is even below the ε_{min} for a single DER at bus 26 (1.598). Similar outcomes apply to the average APF/TVS values buses (5, 15, 29); the ε_{min} is only 1.589 and also below the ε_{min} for a DER at bus 26. Even though, with simply a single DER at the proper location, in this case, bus 26 with a size of 50 MW, it provides a more stable system compared to three DERs total of 150 MW at buses with small and average APF/TVS values. Briefly, a single DER at the appropriate bus can result in improved system voltage and a greater eigenvalue ε_{min}; therefore, the system is in a better and more stable state.

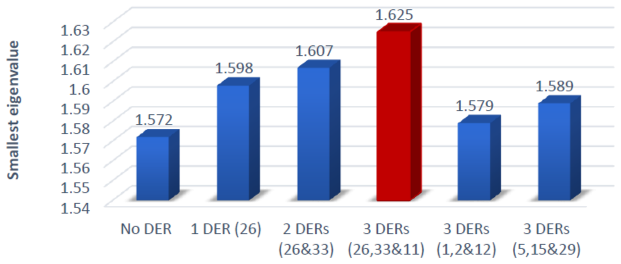

Figure 8. The system's smallest eigenvalue comparison.

5.4. Network Power Losses

The network power losses, both active and reactive, were calculated for each state and are presented in Figure 9. If the first DER is placed at bus 26, the network losses are (0.391 + j0.095) p.u. Then, if another DER is placed at bus 33, the losses decrease to (0.187 + j0.046) p.u. With another DER at bus 11, the losses further reduce to (0.074 + j0.016) p.u.; hence, the percentages of losses reduction are %ΔP_{Loss} is 42.25% and %ΔQ_{Loss} is 44.59%. If three DERs are located at the least sensitive buses, buses with low APF/TVS values, buses 1, 2, and 12, the power losses are relatively significant, even larger than the system losses for one DER at bus 26. The losses only reduce to (0.434 + j0.125) p.u. with %ΔP_{Loss} 4.44% and %ΔQ_{Loss} 8.88%. Likewise, when three DER units are sited at buses with average values of APF/TVS, bus 1, 15, and 29, the system losses are also relatively large, which is (0.409 + j0.109), %ΔP_{Loss} of 7.06% and %ΔQ_{Loss} of 14.27%.

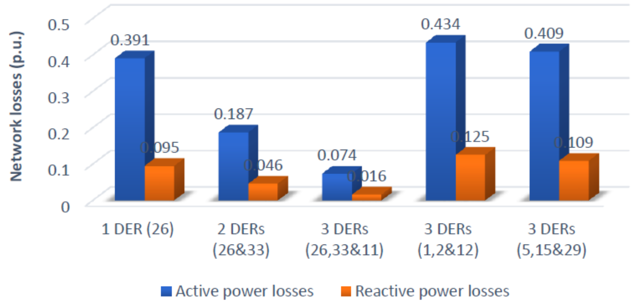

Figure 9. Comparison of system losses after DER units placement.

The outcomes of this examination from the location of DER, the system's smallest eigenvalue, and the loss reduction with the proposed hybrid MMA–CPF approach with DER locations at buses with small and average values of APF/TVS are summarized in Table 2. Integrating the same size of DERs at buses with small and average APF/TVS values cannot assist to increase the voltage stability considerably and lessen the losses in significant quantity. Hence, it is certainly not suggested to locate DER units at buses with small and average APF/TVS values from the perspective of voltage stability and system losses.

Table 2. Results comparison in terms of the system smallest eigenvalue, and network losses reduction percentage.

	High Values of APF/TVS (Recommended)	Small Values of APF/TVS	Average Values of APF/TVS
DER Locations	26, 33, and 11	1, 2, and 12	5, 15, and 29
$\varepsilon_{\min}$	1.625	1.579	1.589
$\%\Delta P_{Loss}$	42.25	4.44	7.06
$\%\Delta Q_{Loss}$	44.59	8.88	14.27

A further interesting outcome obtained is that the operation of the system operating with only one DER integrated at bus 26 is superior to three DERs at small APF/TVS values buses (1, 2, 12) or average APF/TVS values (5, 15, 29) in terms of voltage profile of the system, eigenvalue assessment, and power losses reduction. The voltage profile performance for the majority of the system if DER is located at bus 26 is higher than if three DERs are located at small or average APF/TVS values buses, as can be seen in Figure 10. Furthermore, Figure 11 informs the results from an eigenvalue viewpoint and displays related results. Eigenvalue or ε_{min} for one DER unit located at bus 26 is greater than ε_{min} for three DER units at small or average APF/TVS values buses. Similarly, the system losses if DER is positioned in bus 26 are marginally lesser than losses if three DERs at small or average APF/TVS values buses as can be perceived in Figure 12.

Additionally, in this manuscript, the proposed hybrid approach was compared with the CPF method by [19] to confirm the efficiency of the proposed hybrid approach. Table 3 informs the DER location based on our proposed hybrid approach and the CPF technique, while Figure 13 displays enhancement of the voltage profile after DERs are placed according to both techniques.

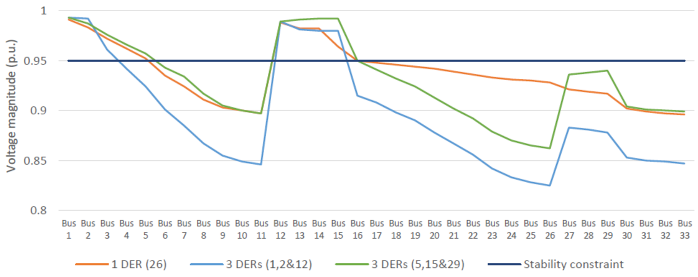

Figure 10. Comparison of voltage profile.

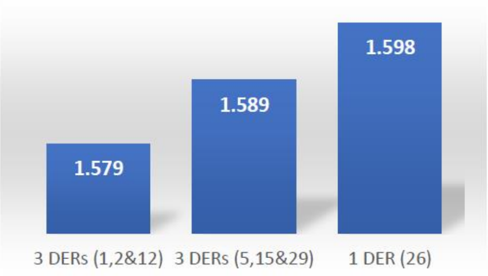

Figure 11. System eigenvalue comparison.

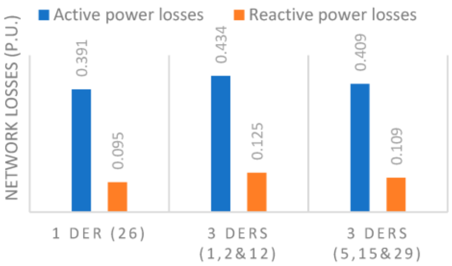

Figure 12. Losses comparison.

Table 3. DER locations.

Iteration	CPF Method [19]	Proposed Method Hybrid MMA–CPF
1	26	26
2	33	33
3	17	11

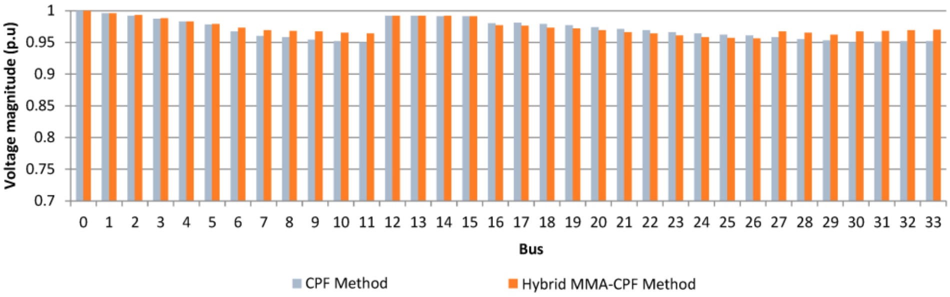

Figure 13. Voltage magnitude after DER integration with the CPF method and the proposed hybrid method.

As eigenvalue assessment (ε_{min}) is one of the most efficient techniques to evaluate static voltage stability analysis, ε_{min} is utilized to carry out efficient comparison of the DER location attained by the proposed hybrid method and the CPF. As can be perceived in Figure 14, the ε_{min} of the system with the CPF is only 1.610, whereas the ε_{min} with the proposed hybrid method is 1.618, which is larger than the CPF method eigenvalue. This informs that the proposed hybrid approach is rather more efficient than the CPF technique in resolving placement of DER.

Moreover, DER placement based on the proposed hybrid technique results in the largest losses reduction, with 42.25% and 44.59% for $\%\Delta P_{Loss}$ and $\%\Delta Q_{Loss}$, respectively. However, by using the CPF approach with three DERs at buses 26, 33, and 17, the reduction in losses is not as much as the losses reduction with DERs at buses 26, 33, and 11, where the third DER is placed at bus 17; the losses decline a little below the network losses reduction for the proposed approach. The $\%\Delta P_{Loss}$ with CPF is 36.36% and $\%\Delta Q_{Loss}$ is 41.29%. Table 4 clarifies the $\%\Delta P_{Loss}$ and $\%\Delta Q_{Loss}$ if DERs are placed at particular locations.

Figure 14. System eigenvalues with the CPF approach and the proposed method.

Table 4. Results comparison.

DER Placement	Approach	ε_{min}	$\%\Delta P_{Loss}$	$\%\Delta Q_{Loss}$	VSI (%)	OF
26, 33, and 17	CPF [19]	1.610	36.36	41.29	2.430335	80.08033
26, 33, and 11	MMA–CPF	1.618	42.25	44.59	2.939305	89.77931
26 and 33	Both	1.6067	30.34	35.33	2.220384	67.89038
26	Both	1.5988	8.87	18.97	1.717776	29.55778

6. Conclusions

Appropriate allocation of DERs is essential to exploit DER advantages. This manuscript recommends a novel technique based on two analytical voltage stability analysis approaches, modified modal analysis and continuation power flow (MMA–CPF). The aim of this work is to attain the most stable system, the lowest losses, and the highest system eigenvalue. To assess the efficiency of the developed technique, this work also examines the performance of the system if DER units are sited at the least sensitive and average APF/TVS values buses.

The outcomes of implementing this approach to the modified 34-bus RDN elucidate the efficiency of this technique regarding optimum allocation of DERs. When the DER units are placed according to the proposed hybrid technique (buses 26, 33, and 11), it resulted in the largest losses reduction, with 42.25% for $\%\Delta P_{Loss}$ and 44.59% for $\%\Delta Q_{Loss}$. The reduction in losses with the comparative method, the CPF approach (buses 26, 22, and 17), is not as much as the losses reduction for DERs placement based on the proposed method, in which the $\%\Delta P_{Loss}$ with CPF is 36.36% and $\%\Delta Q_{Loss}$ is 41.29%. If three DERs are located at buses with low APF/TVS values (buses 1, 2, and 12), the power losses reduction is very insignificant, with $\%\Delta P_{Loss}$ of only 4.44% and $\%\Delta Q_{Loss}$ of 8.88%. Similarly, when three DER units are sited at buses with average values of APF/TVS (buses 1, 15, and 29), the losses reduction is quite low, with the $\%\Delta P_{Loss}$ being 7.06% and the $\%\Delta Q_{Loss}$ 14.27%.

It was proven in this paper that an appropriate DER site is very crucial to maximize the advantages of DER. Proper DER allocation can enhance the voltage profile substantially and reduce network losses significantly. The outcomes demonstrate the robustness of the APF/TVS in deciding optimum placement for DER to improve voltage stability, reduce losses, and also increase the eigenvalue.

Author Contributions: Conceptualization, A.A.; methodology, A.A.; software, A.A. and M.B.N.; validation, A.A. and M.B.N.; formal analysis, A.A. and M.B.N.; investigation, A.A.; resources, A.A. and M.B.N.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A. and M.B.N.; visualization, A.A.; supervision, M.B.N.; project administration, A.A.; funding acquisition, M.B.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

APF	Active Participation Factor
TVS	Tangent Vector Sensitivity
RDN	Radial Distribution Network
DG	Distributed Generation
DER	Distributed Energy Resources
MMA	Modified Modal Analysis
CPF	Continuation Power Flow
MMA–CPF	Modified Modal Analysis–Continuation Power Flow
OF	Objective Function
ΔP	Active power variations
ΔQ	Reactive power variations
Δ◎	Voltage angle variations
Δ◎	Voltage magnitude variations
J	Jacobian Matrix
J_R^*	Reduced Modified Jacobian Matrix
$\mathfrak{R}^*$	Right eigenvector matrix of J_R^*
υ^*	Left eigenvector matrix of J_R^*
φ^*	Diagonal eigenvalue matrix of J_R^*
ε_i^*	*i*th eigenvalue of J_R^*
ζ_i^*	*i*th column right eigenvector of J_R^*
ϱ_i^*	*i*th row left eigenvector of J_R^*
ϖ	Load parameter
P_{Gi0}	Base case active power generation at bus *i*
P_{Li0}	Initial active power load at bus *i*
P_{Ti}	Injected active power at bus *i*
Q_{Gi0}	Base case reactive power generation at bus *i*
Q_{Li0}	Initial reactive power load at bus *i*
Q_{Ti}	Injected reactive power at bus *i*.
$S_{\Delta base}$	A specified amount of complex power that is selected to offer suitable ϖ scaling
k_{Gi}	Constant assigned for the degree of generation variation at bus *i* as ϖ varies
k_{Li}	Constant assigned for the degree of load variation at bus *i* as ϖ varies
θ_i	Power angle changes at bus *i*
$\bar{\delta}$	Vector of generator angle
$\bar{V}$	Vector of the bus voltage magnitude vector
$V_i\angle\delta_i$	Complex voltages at bus *i*
$V_j\angle\delta_j$	Complex voltages at bus *j*
$R_{ij} + jX_{ij} = Z_{ij}$	*ij*th component of Z_{bus} impedance matrix
P_i	Active power generation at bus *i*
P_j	Active power generation at bus *j*
Q_i	Reactive power injection at bus *i*
Q_j	Reactive power injection at bus *j*
P_{Loss}	Active power losses at initial conditions without DER integration
P_{Loss}^{DG}	Active power losses after integration of DER
Q_{Loss}	Reactive power losses at initial conditions without DER integration
Q_{Loss}^{DG}	Reactive power losses after integration of DER
ΔP_{Loss}	Reduction in active power losses
ΔQ_{Loss}	Reduction in reactive power losses
$\%\Delta P_{Loss}$	Reduction percentage of active power losses
$\%\Delta Q_{Loss}$	Reduction percentage of reactive power losses
VSI	Voltage stability index, indicating voltage stability improvement after DER placement
ε_{min}^{DG}	The smallest eigenvalue with DER unit(s)

ε_{min} The smallest eigenvalue without any DER unit

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Received: 5 December 2022
E-mails: ardiaty@eng.unhas.ac.id
Submitted to section: A: Sustainable Energy,
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