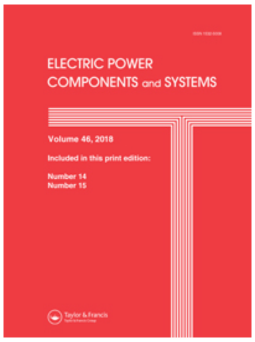

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CONTENTS

Abstract——In this paper, a novel voltage sensitivity analysis method is proposed. It presents a complementary formulation of the direct sensitivity analysis approach which has been previously developed based on the topological structure of the network. The proposed method named improved direct sensitivity analysis (IDSA) incorporates variations of power losses in the system branches due to the nodal power changes and their eventual impacts on the node voltages. Effectiveness of the IDSA in voltage estimation is investigated and compared with the voltage results obtained by the direct, Jacobian-based, as well as the perturb-and-observe sensitivity analysis methods. To this end, firstly, the introduced sensitivity analysis methods are tested when active or reactive power is changed at the selected nodes of the studied test systems. Accuracy of voltage responses obtained by each of the considered sensitivity analysis methods is evaluated with respect to the exact voltage value obtained from the load flow study. Moreover, performance of the introduced sensitivity analysis methods is examined when they are separately embedded in a multi-step voltage control algorithm which manages active and reactive powers of distributed generation units in order to keep the system voltages within the permitted voltage limits. Simulation results confirm that when the power losses impact is considerable, the IDSA outperforms the direct, perturb-and-observe, and Jacobian-based sensitivity analysis methods in terms of accuracy of the voltage estimation.

Keywords: MV distribution systems, voltage sensitivity analysis, voltage control, generation curtailment, reactive power control
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1. INTRODUCTION

Massive integration of distributed generation (DG) units has created voltage violation issues in the electric distribution systems. To manage the voltage control problem, DG powers should be controlled actively. In this context, it is useful to have dependencies between system voltages and DG powers. Voltage sensitivity analysis (VSA) gives us impacts of changing the nodal powers on the system voltages. Information provided by the VSA can be employed in a voltage control algorithm (VCA) in order to linearize the voltage-power relationships and to eventually simplify the corresponding formulation of the VCA, as it has been done in [1–10]. The proposed sensitivity-based voltage control approaches in the literature can be classified into the distributed [1–4] or centralized algorithm [4–10] that employs the transformer tap changer [4–6], active and reactive powers control of DGs [2–10] and energy storage device [1].

Sensitivity of system voltages with respect to the active and reactive powers is conventionally obtained from the inverse of Jacobian matrix in the Newton-Raphson Load Flow (NRLF) study. The NRLF method has been basically developed for the load flow study in the transmission systems that have different characteristics compared to the distribution systems, particularly, regarding the resistance to reactance (R/X) ratio of their lines. Distribution networks by having the lines with wide range of lengths, high R/X ratio and the radial structure fall into the category of ill-conditioned systems for the NRLF algorithm [11, 12]. As a result, application of the Jacobian-based sensitivity analysis (JBSA) approach in the distribution systems may encounter serious problems including inaccuracy or convergence failure [13–15]. Moreover, when the NRLF method is not used for the load flow calculation, the Jacobian matrix would not be available in order to derive the sensitivity coefficients. Also, the JBSA approach cannot give us sensitivity of power losses and branch currents with respect to the nodal power changes. To tackle these shortcomings of the JBSA method, some research has been carried out in the literature aiming at proposing new VSA approaches that are tailored for the distribution systems.

An analytical sensitivity analysis method has been proposed in [13] in order to calculate the sensitivity of nodal voltages and currents with respect to the active and reactive power variations for the 3-phase unbalanced distribution system. In this method, it is assumed that the phasors of all system voltages are known through a state estimation tool. Also, a new VSA approach based on the Gauss-Seidel load flow method and Z-bus matrix has been introduced in [14] in order to derive the voltage and loss sensitivity factors. It is shown that with this proposed VSA method, some results similar to the ones using JBSA approach can be obtained. In [15], voltage and loss sensitivity coefficients with respect to the node powers are obtained by running an initial load flow calculation and forming a matrix based on the topological structure of the system. The drawback of this method is that all DG-connected buses should be modeled as the voltage-controlled (PV) nodes with fixed voltage magnitudes. A VSA method for the radial medium-voltage (MV) distribution system considering the constant current models for loads and generators is developed in [16]. However, it is known that all types of DG units cannot be modeled with the constant current model as it is shown in [17]. A software toolkit is implemented in [18] based on the perturb-and-observe sensitivity analysis (POSA) approach in order to determine the relations between system voltages and nodal powers in MV distribution systems. Application of the Tellegen's theorem for calculating sensitivity indices based on the adjoint network is studied in [19–21] for the transmission and distribution levels. Also, a direct sensitivity analysis (DSA) method is presented in [22] in order to define dependencies between system voltages and nodal powers directly from the topological structure of the network. The DSA has advantage that the voltage sensitivity coefficients are independent of the network working point. On the other hand, its simple formulation can lead to inaccurate voltage estimation as shown in [7].

In the current paper, an attempt is made in order to cover the drawback of the DSA method by proposing a more accurate VSA approach. It is known basically that by supposing the system loads and generations independent of the voltage, the power losses make the voltage-power relationships nonlinear. Therefore, in order to have a more accurate VSA, the power losses should be taken into account, especially, in the case that the initial working point of the network is needed to be greatly moved. In this regard, in the current paper, a new VSA approach named improved direct sensitivity analysis (IDSA) is proposed. It presents a complementary formulation of the DSA method. Compared to the DSA and other approaches presented in [13–16] and [18–21], the IDSA considers variations in power losses of the system lines due to nodal power changes and their eventual impacts on the system voltages. Effectiveness of the IDSA in the voltage estimation is firstly tested by the numerical simulations when active and reactive powers at the selected system nodes are changed. It is compared with the results obtained by the DSA, JBSA, and POSA methods. Then, the introduced VSA methods are separately embedded in a multi-step VCA that modifies active and reactive powers of DGs to manage the system voltages. Performance of the introduced VSA methods is tested in a centralized voltage control application. The main contribution of this paper is to demonstrate the importance of incorporating the power losses in the VSA formulation by proposing the IDSA method and through comparative study of the IDSA with the DSA, POSA, and JBSA approaches, which has been conducted in different working points of the studied test systems.

The rest of this paper is organized as follows. The proposed VSA approach is introduced in Section 2. Then, in Section 3, the studied cases are described and in Section 4, the investigated test system is presented. It is followed by the numerical validation of the studied VSA methods in

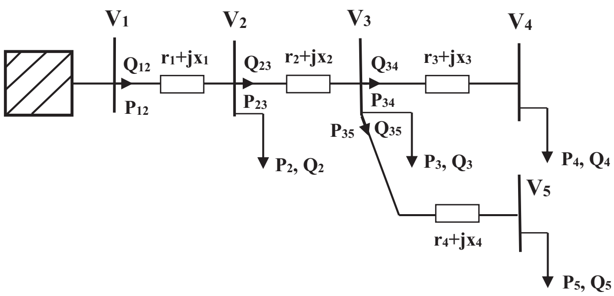

FIGURE 1. 5-bus radial distribution system.

Section 5. The comparative study of the VSA methods embedded in the VCA is done in Section 6. Finally, discussion on the results and the conclusion are reported in Sections 7 and 8, respectively.

2. THE PROPOSED VOLTAGE SENSITIVITY ANALYSIS METHOD

The IDSA method is developed based on the direct load flow approach which has been formulated for the distribution systems in [23]. According to the expression (1), voltage variation in a 2-bus distribution system is given by [7, 10, 22, 24–26]:

$$\Delta V_{12} = r_1 P_{12} + x_1 Q_{12} \tag{1}$$

where P_{12} and Q_{12} are the active and reactive powers that flow between nodes 1 and 2. Also, r_1 and x_1 are resistance and reactance of the line between nodes 1 and 2. From (1), it can be observed that the active power that flows in the line is coupled with the resistance of the line and the reactive power that flows in the line is coupled with the reactance of that line. In order to present the IDSA method, let consider the simple 5-bus radial distribution system shown in Figure 1.

In the distribution systems, voltage angle differences between two adjacent buses are small so that imaginary part of voltage variation vectors can be neglected (similar to (1)). Supposing that the system voltages are close to 1 pu, (1) can be recursively applied to the 5-bus system as below.

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} = \begin{bmatrix} r_1 & 0 & 0 & 0 \\ r_1 & r_2 & 0 & 0 \\ r_1 & r_2 & r_3 & 0 \\ r_1 & r_2 & 0 & r_4 \end{bmatrix} \begin{bmatrix} P_{12} \\ P_{23} \\ P_{34} \\ P_{35} \end{bmatrix} + \begin{bmatrix} x_1 & 0 & 0 & 0 \\ x_1 & x_2 & 0 & 0 \\ x_1 & x_2 & x_3 & 0 \\ x_1 & x_2 & 0 & x_4 \end{bmatrix} \begin{bmatrix} Q_{12} \\ Q_{23} \\ Q_{34} \\ Q_{35} \end{bmatrix} \tag{2}$$

where $V_1, V_2, \ldots, V_5$ denote the voltages of the 5-bus system. The relations between the nodal active powers and the active power losses in the system branches with the active power flows in the branches are obtained through bus-injection to branch-current (BIBC) matrix as below. The BIBC matrix introduced in the direct load flow approach in [23] presents the topological structure of the network. As it can be seen in (3), the BIBC matrix contains 1 and 0 elements to show whether the nodal powers and power losses in the branches are linked to the branch power flows, or not, respectively.

$$\begin{bmatrix} P_{12} \\ P_{23} \\ P_{34} \\ P_{35} \end{bmatrix} = [BIBC] \begin{bmatrix} P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} + [BIBC] \begin{bmatrix} P_{Loss1} \\ P_{Loss2} \\ P_{Loss3} \\ P_{Loss4} \end{bmatrix} = [BIBC] \begin{bmatrix} P_2 + P_{Loss1} \\ P_3 + P_{Loss2} \\ P_4 + P_{Loss3} \\ P_5 + P_{Loss4} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_2 + P_{Loss1} \\ P_3 + P_{Loss2} \\ P_4 + P_{Loss3} \\ P_5 + P_{Loss4} \end{bmatrix} \tag{3}$$

In (3), P_2, P_3, P_4, and P_5 denote the net active powers of the buses 2, 3, 4 and 5, respectively. Also, P_{Loss1}, P_{Loss2}, P_{Loss3}, and P_{Loss4} are the active power losses in the system branches that correspond to the resistances r_1, r_2, r_3, and r_4, respectively. The same manner is used to build the matrix giving the relations between reactive power flows in the system branches with nodal reactive powers and reactive power losses in the system lines. Using (2), (3) and its counterpart for reactive powers, we can obtain the sensitivity of system voltages with respect to the nodal active and reactive powers as follows.

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} = \begin{bmatrix} r_1 & r_1 & r_1 & r_1 \\ r_1 & r_1+r_2 & r_1+r_2 & r_1+r_2 \\ r_1 & r_1+r_2 & r_1+r_2+r_3 & r_1+r_2 \\ r_1 & r_1+r_2 & r_1+r_2 & r_1+r_2+r_4 \end{bmatrix} \begin{bmatrix} P_2 + P_{Loss1} \\ P_3 + P_{Loss2} \\ P_4 + P_{Loss3} \\ P_5 + P_{Loss4} \end{bmatrix} + \begin{bmatrix} x_1 & x_1 & x_1 & x_1 \\ x_1 & x_1+x_2 & x_1+x_2 & x_1+x_2 \\ x_1 & x_1+x_2 & x_1+x_2+x_3 & x_1+x_2 \\ x_1 & x_1+x_2 & x_1+x_2 & x_1+x_2+x_4 \end{bmatrix} \begin{bmatrix} Q_2 + Q_{Loss1} \\ Q_3 + Q_{Loss2} \\ Q_4 + Q_{Loss3} \\ Q_5 + Q_{Loss4} \end{bmatrix} \tag{4}$$

In a general form, (4) is rewritten as:

$$[V_1]-[V_k]=[R][P+P_{Loss}]+[X][Q+Q_{Loss}] \quad (5)$$
$$k=2,3,4,\ldots,nbus$$

where $[R]$ and $[X]$ are matrices that include the system resistances and reactances, respectively, according to (4). Also, *nbus* gives the total number of the system buses. Considering bus 1 as the slack node, the sensitivity of voltage at bus k with respect to active or reactive power at bus n ($n=2,\ 3,\ 4,\ \ldots,\ nbus$) is obtained by the following rules.

$$\frac{\partial(V_1-V_k)}{\partial P_n}=\frac{-\partial V_k}{\partial P_n}=R_{k-1,n-1}+\sum_{J=1}^{nbr}R_{k-1,J}\frac{\partial P_{LossJ}}{\partial P_n}+\sum_{J=1}^{nbr}X_{k-1,J}\frac{\partial Q_{LossJ}}{\partial P_n} \quad (6)$$

$$\frac{\partial(V_1-V_k)}{\partial Q_n}=\frac{-\partial V_k}{\partial Q_n}=X_{k-1,n-1}+\sum_{J=1}^{nbr}R_{k-1,J}\frac{\partial P_{LossJ}}{\partial Q_n}+\sum_{J=1}^{nbr}X_{k-1,J}\frac{\partial Q_{LossJ}}{\partial Q_n} \quad (7)$$

where *nbr* is the total number of the system branches. In (6) and (7), the first term is a constant value that comes from the topology of grid (array $k-1$, $n-1$ of $[R]$ or $[X]$). However, the second and third terms are in function of the network operating point and incorporate the variations of power losses in the system branches due to nodal power changes and their eventual impacts on the system voltages.

In [27], problem of the optimal placement and sizing of DG is addressed. An analytical method has been presented in order to obtain the sensitivity of total power losses with respect to the active power injection at a system node. According to [27], active power losses in the Jth branch of the system as a function of the real and imaginary parts of the nodal currents using BIBC matrix is written as:

$$P_{LossJ}=r_J\left[\left(\sum_{k=2}^{nbus}BIBC_{J,k-1}\mathrm{Re}_{(I_k)}\right)^2+\left(\sum_{k=2}^{nbus}BIBC_{J,k-1}\mathrm{Im}_{(I_k)}\right)^2\right] \quad (8)$$

where r_J is the resistance of the Jth branch. In (8), the first and second parentheses give the real and imaginary parts of the current in branch J, respectively. Also, I_k is the complex value of the current at bus k. Its real and imaginary parts are given by:

$$\mathrm{Re}_{(I_k)}=\frac{P_k\cos\theta_{Vk}+Q_k\sin\theta_{Vk}}{V_k} \quad (9)$$

$$\mathrm{Im}_{(I_k)}=\frac{P_k\sin\theta_{Vk}-Q_k\cos\theta_{Vk}}{V_k} \quad (10)$$

where V_k, θ_{Vk}, P_k and Q_k are the voltage magnitude, voltage angle, active, and reactive powers at the bus k, respectively. The sensitivity of active power losses in the branch J with respect to the active power at node n is obtained using (8)–(10) as:

$$\frac{\partial P_{LossJ}}{\partial P_n}=2r_J\left(\sum_{k=2}^{nbus}BIBC_{J,k-1}\mathrm{Re}_{(I_k)}\right)\times BIBC_{J,n-1}\frac{\cos\theta_{Vn}}{V_n}+2r_J\left(\sum_{k=2}^{nbus}BIBC_{J,k-1}\mathrm{Im}_{(I_k)}\right)\times BIBC_{J,n-1}\frac{\sin\theta_{Vn}}{V_n} \quad (11)$$

If the power at bus n does not pass through the branch J, the term $BIBC_{J,n-1}$ in (11) is equal to zero and eventually, the sensitivity of power losses of branch J with respect to power changes at node n will be null. A similar procedure as presented in (8)–(11) is followed to obtain all partial derivative coefficients of the active and reactive power losses in the system lines with respect to the nodal active and reactive powers which are needed in (6) and (7).

3. THE STUDIED CASES

In this paper, the IDSA method is validated through the numerical simulations by changing active and reactive powers at the selected buses of the studied systems. Moreover, performance of the IDSA is tested when it is embedded in a VCA that manages active and reactive powers of DGs in order to keep the system voltages within the permitted limits. The IDSA results are compared with the responses obtained from the DSA, JBSA, and POSA methods. The DSA, JBSA, and POSA are briefly described in the following subsections.

3.1. The Direct Sensitivity Analysis Method

The DSA approach has been introduced in [22]. It is a simplified version of the IDSA method by neglecting the power losses in the system branches. Therefore, in (3)–(5), the terms corresponding to the active and reactive power losses in the system branches are disregarded. As a result, the sensitivity coefficients are directly obtained through the matrices $[R]$ and $[X]$ based on the topological structure of the network. In other words, in the DSA method, the

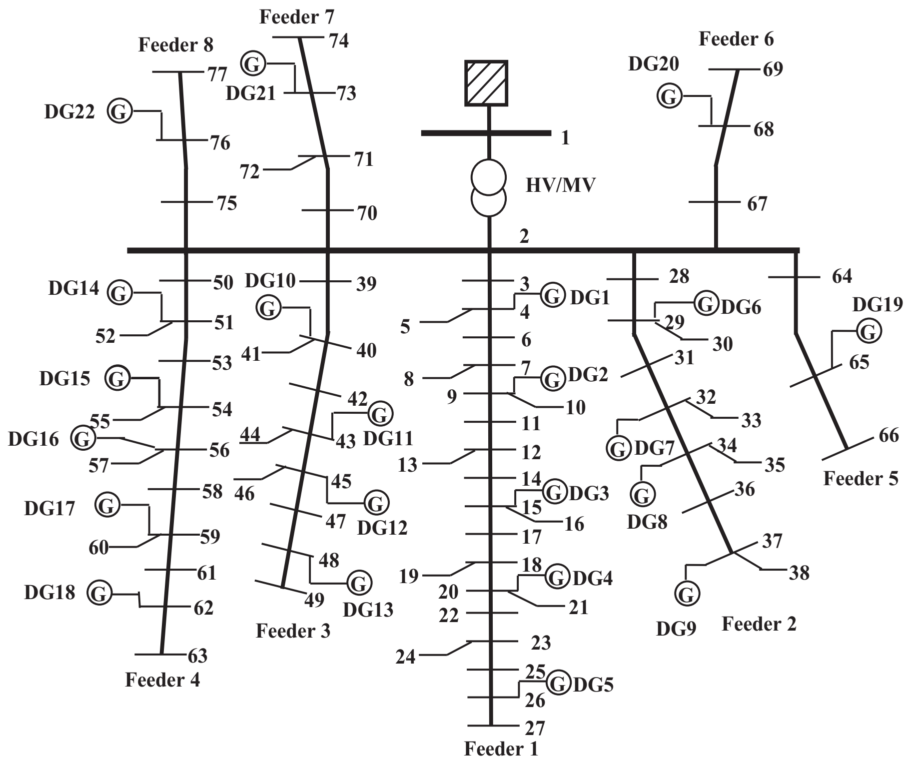

FIGURE 2. 77-bus, 11 kV United Kingdom generic distribution system.

sensitivity coefficients are obtained by (6) and (7) while their second and third terms are neglected.

3.2. The Jacobian-Based Sensitivity Analysis Method

The JBSA is obtained from the inverse of Jacobian matrix in the NRLF study. The Jacobian matrix is basically composed through expanding the equations of nodal active and reactive powers by the Taylor series while neglecting all the terms higher than the first order. The inverse of Jacobian matrix (denoted by J^{-1}) gives us the linearized relationships between small changes in the real and reactive powers and small changes in nodal voltage angles and magnitudes as below.

$$\begin{bmatrix} \Delta\theta_V \\ \Delta V \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \dfrac{\partial\theta_V}{\partial P} & \dfrac{\partial\theta_V}{\partial Q} \\ \dfrac{\partial V}{\partial P} & \dfrac{\partial V}{\partial Q} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{12}$$

where $\Delta\theta_V$, ΔV, ΔP, and ΔQ are the vectors of small variations in voltage angles, voltage magnitudes, active, and reactive powers at the load (PQ) buses, respectively. Based on the Taylor series theorem, an analytical function can be represented as an infinite sum of terms that are calculated from the values of the function's derivatives at a single point. Therefore, the linearized relationships extracted from the Taylor series are valid for a single point. As a result, the sensitivity analysis obtained from the Jacobian matrix is also valid for a single point and the sensitivity coefficients need to be updated for other network operating points.

In this work, the JBSA is obtained based on the generic formulation of the Jacobian matrix that can be found in [28] according to which, elements of the Jacobian matrix are partial derivatives of nodal active and reactive powers with respect to node voltage amplitudes and angles. Therefore, the JBSA does not take the line losses into account. Once the NRLF algorithm is converged, the lower half-part of the square matrix J^{-1} is used to derive the so-called Jacobian-based voltage sensitivity coefficients with respect to nodal active and reactive powers.

3.3. The Perturb-and-Observe Sensitivity Analysis Method

Sensitivity of system voltages with respect to nodal powers can be obtained based on the perturb-and-observe concept. In this technique, two load flow calculations are performed, once considering the initial network operating point and once more taking into account a small power variation at the perturbation point. The voltage variation at the observed point (ΔV_{obs}) due to the power change applied to the perturbation point (ΔP_{pert}) is measured in order to derive the sensitivity of voltage at the observed node with respect to the power at the perturbation node using the following equation.

$$\frac{\partial V_{obs}}{\partial P_{pert}} = \frac{\Delta V_{obs}}{\Delta P_{pert}} \tag{13}$$

In case of applying reactive power change, ΔP_{pert} and P_{pert} in (13) are replaced by ΔQ_{pert} and Q_{pert}, respectively. In this study, the initial network operating point is perturbed by 1 kW (or 1 kvar) active (or reactive) power variation in order to calculate the needed voltage sensitivity coefficients. As it can be noticed, the drawback of this method is that the perturb-and-observe procedure should be repeated for each single node of the system.

4. THE INVESTIGATED TEST SYSTEM

In order to test effectiveness of the introduced VSA methods, the 77-bus, 11 kV radial distribution system shown in Figure 2 is considered [6, 7]. It is the so-called ''HVUG'' test case of the United Kingdom Generic Distribution System (UKGDS). In the investigated network, bus number 1 is considered as the slack node while all other buses are of PQ (load) type. The substation transformer located between nodes 1 and 2 is modeled with a pure reactance equal to 12.5% pu in the transformer base power (80 MVA) [29]. The studied network feeds 75 loads which have total active and reactive powers equal to 24.27 MW and 4.85 Mvar, respectively. The line and load data are presented in [30]. In the studied network, loads are considered with the constant power model and lines are modeled with the series impedances similar to the most of the practical cases in the distribution systems [6, 7, 16, 22–27, 30–35]. As reported in [36, 37], impacts of voltage dependency of load powers and shunt admittances of lines on the node voltages are not considerable in the studied UKGDS. The average resistance to reactance ratio of the system lines is equal to 1.765. The UKGDS also hosts 22 DG units which are identical with the rated powers equal to 3.5 MW. The capability curves of DGs are obtained from the points given in [22]. The DG active power is modeled as a negative load.

5. NUMERICAL VALIDATION OF THE STUDIED VOLTAGE SENSITIVITY ANALYSIS METHODS

In this section, performance of the introduced VSA methods is tested in response to the power changes at a system node. To do so, active or reactive power at a unique system bus is gradually changed while all other parameters are kept constant. For each point of the power variations, voltage value at bus k (V_k) subject to the power changes at bus k (ΔP_k) is calculated according to the following equation.

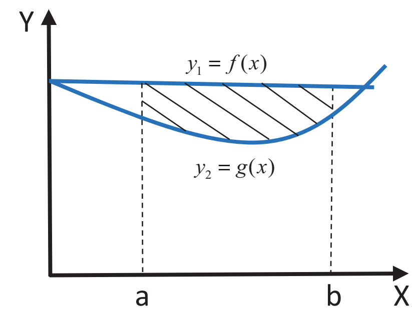

FIGURE 3. The area between $y_1(x)$ and $y_2(x)$.

$$V_k = V_k^{init} - \left|\frac{\partial V_k}{\partial P_k}\right| \Delta P_k \tag{14}$$

where V_k^{init} is the initial voltage value of bus k in the starting point of the power variations (with power changes equal to zero). In case of reactive power changes, ΔP_k (and P_k) in (14) is replaced by ΔQ_k (and Q_k). In the starting point with the power changes at bus k equal to zero, the voltage sensitivity at bus k with respect to the power at that bus is calculated using each of the four introduced VSA methods. The sensitivity coefficient corresponding to the starting point is kept constant and used to calculate the voltage at bus k when active or reactive power is changed, according to (14). Also, the load flow calculation is done for each single point of the power variations. Therefore, the load flow results give us the exact voltage values while using the VSA method according to (14) or its reactive power counterpart, the estimated voltage values are obtained.

To evaluate accuracy of the voltage estimation, it is needed to plot the characteristics of the voltage at bus k subject to active (or reactive) power changes which are obtained by each of the VSA methods as well as the load flow study. However, these voltage-power characteristics are sometimes very close to each other such that it is not easy to distinguish them. In addition, it is aimed to validate the introduced VSA methods for different working points at the selected buses of the studied test systems. This means that we have to deal with many figures which would not be easily compared and analyzed. In this regard, an index based on the concept of the area between curves (ABC) is introduced that is described as follows.

	UKGDS		UKGDS-DUP	
	bus 26	bus 9	bus 26*	bus 9
ABC of LF and DSA	1.7816	0.7311	6.0664	0.9075
ABC of LF and IDSA	**1.0359**	0.4105	**3.602**	0.543
ABC of LF and JBSA	1.7648	0.2685	7.4724	0.2751
ABC of LF and POSA	1.7648	**0.2684**	7.4639	**0.2750**

TABLE 1. Simulation results in case 1.
The bold value shows the smallest error obtained by the studied VSA methods.

As known, the area between two curves shown in Figure 3 with the given functions $f(x)$ and $g(x)$ between the points a and b is obtained by:

$$ABC = \int_a^b f(x) - g(x)dx \tag{15}$$

In our application, the errors between the voltage values obtained by the VSA approach and the exact values calculated by the load flow study are needed. In this regard, if one of the curves shown in Figure 3 is considered to be obtained by the consecutive load flow calculations and another one to be defined by the sensitivity analysis, the area between these two curves gives us an indicator of the overall accuracy of the VSA method between the studied points a and b. Thus, if the ABC of the load flow and a VSA method is small, it is concluded that the voltage values obtained by that VSA method were close to the exact values obtained by the load flow study.

To implement this method, firstly, the gradual changes of active or reactive power at one of the system nodes are applied. The voltage responses subject to the power variations are calculated using the VSA according to (14) as well as the load flow study. This gives us two sets of points representing the voltage-power characteristics obtained by the VSA as well as the load flow. The area between these two characteristics is calculated by the trapezoidal method in MATLAB. For all introduced VSA methods, the same procedure is repeated separately, each time for the characteristics obtained by one of the VSA methods and the load flow study. It should be noted that if the characteristics obtained by the load flow study and a VSA method cross each other, relation (15) is applied to the subintervals during which, one function (voltage-power characteristic) is on the top of the another one. The total ABC will be consequently equal to the sum of the absolute values of the ABC in these subintervals.

The investigation is done on the test system shown in Figure 2 at the buses 26 and 9 in feeder 1 where DG5 and DG2 are located, respectively. Bus 26 situated at the end of the feeder 1 is selected since it is highly influenced by the power losses factor. In contrast, bus 9 is much less affected by variations in the power losses since it is closer to the slack node. Furthermore, in order to examine performance of the considered VSA methods over a larger scale distribution system, the original UKGDS shown in Figure 2 is duplicated from node 2. The new resultant network is named UKGDS-DUP that consists of 152 buses and 44 DG units. In order to comply with ampacity limits of the branches, maximum active power injection of each DG will be divided by two in the latter network. Similarly, in order to have realistic voltage drop violations, the nominal load powers in UKGDS-DUP are equal to 50% of their initial values in UKGDS. In the case of UKGDS-DUP, the ABC will be calculated at the buses 9 and 26*. While bus 9 is located in the first half of the network, bus 26* is located at the end of the feeder one of UKGDS-DUP (in the new added part). In other words, bus 26* corresponds to the duplication of bus 26 in UKGDS-DUP. In both studied networks, the gradual changes of active (or reactive) power are applied separately to the selected buses by step changes of 1 kW (or 1 kvar). Four cases as described in below are considered in order to evaluate performance of the introduced VSA methods using the ABC index.

5.1. Case 1

In the first case, it is assumed that DG active and reactive powers are equal to zero while the load powers are at 100% of their respective rated values. It is worth mentioning that the load powers are divided by two in UKGDS-DUP with respect to initial values of the original UKGDS. The reactive power variations from 0 to 3500 kvar towards the capacitive direction are applied at the selected buses in both studied networks. It simulates the case that the capacitive reactive power compensation of DGs manages the existing voltage drop problem of the network. Table 1 presents the results of calculating the ABC obtained by each of the introduced VSA methods and the Load Flow (LF) study in both studied networks.

In Table 1, it is clearly seen that in both studied networks and at all selected buses, the IDSA method outperforms the DSA approach in terms of the accuracy of the voltage estimation. It is explained by the fact that the IDSA method presents a complementary formulation of the DSA by taking into account the power loss variation impacts on the node voltages. Similarly, for the study at bus 26 of UKGDS and bus 26* of UKGDS-DUP, the IDSA leads to more accurate voltage results compared to

	UKGDS		UKGDS-DUP	
	bus 26	bus 9	bus 26*	bus 9
ABC of LF and DSA	4.4956	1.496	16.772	1.712
ABC of LF and IDSA	**0.7235**	**0.1087**	**4.0327**	**0.0714**
ABC of LF and JBSA	1.9789	0.241	9.5845	0.2458
ABC of LF and POSA	1.9662	0.2407	9.5678	0.2451

TABLE 2. Simulation results in case 2.
The bold value shows the smallest error obtained by the studied VSA methods.

	UKGDS		UKGDS-DUP	
	bus 26	bus 9	bus 26*	bus 9
ABC of LF and DSA	0.9750	0.8755	8.3362	2.3924
ABC of LF and IDSA	**0.4503**	0.260	**2.6516**	0.9768
ABC of LF and JBSA	1.4726	0.256	5.9092	**0.3036**
ABC of LF and POSA	1.4679	**0.2553**	5.9145	0.3045

TABLE 3. Simulation results in case 3.
The bold value shows the smallest error obtained by the studied VSA methods.

the ones obtained by the JBSA and POSA. As known, by getting distance from the slack bus, the series impedance between the slack bus and each single point of the system is increased. Therefore, it can be expected that the voltage-power relationship at bus 26 (or 26*) will be more influenced by the power losses than the one at bus 9. Due to the fact that the IDSA incorporates power loss variation impacts on node voltages, it shows a better performance for the study on bus 26 (or 26*) compared to the JBSA and POSA approaches. On the other hand, there is an approximation in the formulation of the IDSA method which neglects the imaginary part of the voltage variation vector (see Eq. (2)) since the voltage angles are expected to be small in the distribution systems. This assumption has an impact on the voltage estimation of the IDSA. Consequently, due to the introduced approximation of the IDSA, for the investigation on bus 9 where power loss impacts on the nodal voltages are not significant, the JBSA or POSA can show more accurate voltage results in comparison with the IDSA. In Table 1, it is seen also that the JBSA and POSA result in identical or very close ABC values in both studied networks.

5.2. Case 2

In the second studied case, DG active and reactive powers are equal to 0 and load powers are at 100% of their respective rated values similar to case 1. However, the active power

	UKGDS		UKGDS-DUP	
	bus 26	bus 9	bus 26*	bus 9
ABC of LF and DSA	7.0716	2.3752	5.4854	0.5271
ABC of LF and IDSA	**1.0843**	1.0415	**0.1685**	0.4708
ABC of LF and JBSA	1.2933	0.1673	0.512	0.2335
ABC of LF and POSA	1.1895	**0.1667**	0.509	**0.233**

TABLE 4. Simulation results in case 4.
The bold value shows the smallest error obtained by the studied VSA methods.

(injection) is changed here from 0 to 3500 kW. It corresponds to the case of solving voltage drop problem by injecting the active power (for instance, from an energy storage device). Table 2 gives the ABC results corresponding to the investigation on the selected buses.

In Table 2, it is again observed that the IDSA method clearly outperforms the DSA method at the selected buses of both studied networks. Furthermore, the IDSA method shows more accurate voltage results in comparison with the JBSA and POSA ones too; even at the bus 9 that is known to be less affected by the power losses. It is worth noting that the branch resistance between the transformer and bus 26* is 2 times bigger than the one from the transformer to bus 26. Consequently, bus 26* will be much more influenced by power losses than the case of bus 26. Therefore, in Table 2, it is seen that the IDSA method by a big difference (compared to other methods) provides the best result at bus 26*. From Table 2, it can be also noticed that the JBSA and POSA have led to very close voltage results like the previous studied case.

5.3. Case 3

In case 3, DG active powers are considered to be at their maximum values (*i.e.*, 3.5 MW for UKGDS and 1.75 MW for UKGDS-DUP) and DG reactive powers are equal to 0.5 Mvar (inductive). The load powers are also at 10% of their respective rated values. The reactive power changes are done from 0 to 3500 kvar towards the inductive direction at the selected buses in both studied networks. It corresponds to the case of solving voltage rise problem using the inductive reactive power compensation of DGs. Table 3 gives the ABC results corresponding to voltages obtained by the load flow calculations and ones found through each of the VSA methods.

In Table 3, the IDSA method leads to more accurate voltage results compared to the DSA ones at the selected buses of both studied networks. In comparison with the JBSA and POSA, the IDSA shows superior results for the study at bus 26* as well as bus 26 and almost similar results at bus 9 of UKGDS. However, at bus 9 of UKGDS-DUP, the JBSA approach gives the most accurate voltage estimation while the POSA performance remains in a very close agreement with the JBSA one.

5.4. Case 4

The same working point as the one in case 3 is considered here. However, in the current test case, the active power injection is changed from 3500 kW to 0 in UKGDS and from 1750 kW to 0 in UKGDS-DUP in order to simulate the situation in which the voltage rise problem is managed by the generation curtailment of DGs. Table 4 presents the ABC results in case 4.

Regarding the results reported in Table 4, it is seen that the IDSA clearly outperforms the DSA like all the previous cases. At buses 26 and 26*, the IDSA exhibits better performances compared to the JBSA and POSA ones too. Concerning the investigation on bus 9, however, the JBSA and POSA provide more accurate results compared to the IDSA ones. Therefore, it can be noticed that the JBSA and POSA methods with an acceptable accuracy estimate the voltage-power relationships at the buses which are close to the slack node. On the other hand, by getting distance from the slack bus, nodal voltage-power relationships will be more influenced by power loss variations (caused by the node power changes). As a consequence, the IDSA method can lead to more accurate voltage estimation for analysis of the buses which are relatively far from the slack node. These points can be verified considering the results reported in Tables 1–4 regarding both studied networks. It is worth noting that for a voltage regulation purpose, power variation at the buses which are located far from the slack node (like bus 26) will be mostly demanded as the voltage violations usually occur at the end of the system feeders.

6. COMPARATIVE STUDY OF THE INTRODUCED VSA METHODS EMBEDDED IN THE VCA

The VCA presented in [22] is used here in order to evaluate performance of the studied VSA methods in a centralized closed-loop voltage control application. The considered VCA manages active and reactive powers of DGs to bring back the violated voltages within the permitted voltage limits. The priority of voltage regulation is given to the bus with the biggest voltage violation such that in each iteration of the VCA, voltage at the bus with the biggest violation will be treated. The multi-step feature of the VCA has an advantage that the mutual impacts of DGs will be minimized since all violated voltages are not considered simultaneously. It is worth noting that the VSA linearizes the voltage-power relationship by assuming that all other parameters of system are kept constant. Therefore, when several DGs are employed in the VCA, the VSA coefficients would not be any more valid and accurate due to mutual impacts of DGs.

The VCA starts with running an initial load flow calculation. If the voltage violations are found in the system, the main iterative-based procedure of the VCA begins. In the first iteration ($\mathrm{I}=1$), the voltage at the bus with the biggest violation (denoted by $\mathrm{V_w}$) is selected and amount of the voltage violation at that bus (*i.e.*, bus w) from the permitted voltage limit is calculated. It gives us the required value of voltage modification ($\Delta \mathrm{V_w^{req}}$) in order to return that voltage inside the permitted voltage range. In the voltage rise case, considering the permitted upper voltage limit equal to 1.03 pu, we have:

$$\Delta V_w^{req} = 1.03 - V_w \tag{16}$$

The voltage control problem at $\mathrm{I}=1$ is formulated as an optimization problem given in below, which aims at minimizing the total weighted changes of DG active and reactive powers subject to the voltage constraint of the bus with the biggest violation as well as the DG power limits.

$$\textbf{Minimize:} \sum_{x=1}^{N} \left(C_Q |\Delta Q_{DGx}| + C_P \Delta P_{DGx} \right) \tag{17}$$

$$\sum_{x=1}^{N} \left(\frac{\partial V_w}{\partial Q_{DGx}} \Delta Q_{DGx} + \frac{\partial V_w}{\partial P_{DGx}} \Delta P_{DGx} \right) \le \Delta V_w^{req} \tag{18}$$

$$\Delta Q_{DGx}^{\min} \le \Delta Q_{DGx} \le \Delta Q_{DGx}^{\max} \tag{19}$$

$$0 \le \Delta P_{DGx} \le |P_{DGx}| \tag{20}$$

where N is the total number of DGs that contribute in the voltage control problem. ΔP_{DGx} and ΔQ_{DGx} are active and reactive power changes of the DG number x ($x = 1, 2, 3, \ldots, N$). Also, C_P and C_Q are weighting coefficients for DG active and reactive powers, respectively. Inequality constraint (18) presents the fact that the DG power changes should return the voltage of the bus with the biggest violation into the permitted voltage range. The left side of (18) is equal to the voltage variation at the worst bus due to DG power changes. Also, using (19), possible reactive power variations of DGx according to its capability curve are taken into consideration. Finally, inequality constraint (20) indicates that the curtailed active power of DGx (*i.e.*, ΔP_{DGx}) should be a nonnegative value, equal or less than the current active power of DGx (*i.e.*, P_{DGx}).

In the VCA, thanks to application of the VSA, effects of DG power changes on the system voltages are known.

	DSA		IDSA	
	I = 1	I = 2	I = 1	I = 2
ΔV_w^{req} (pu)	−0.0298	−0.0152	−0.0298	−0.0152
At bus	26	62	26	62
Err (%)	1.019	1.6	0.998	1.4
ΔQ_{DGx} (Mvar)	DG4 = 1.633	DG18 = 2.249	DG4 = 1.634	DG18 = 2.244
x = 1, 2, 3, …, N	DG5 = 2.31		DG5 = 2.31	

TABLE 5. VCA results regarding study on the reactive power control of DGs using DSA and IDSA.

Therefore, there is no need to run load flow calculation inside the optimization problem. The voltage sensitivity coefficients in (18) are known parameters obtained by each of the studied VSA methods. The required value of voltage modification for solving the voltage violation at the worst bus is also a known parameter, but ΔQ_{DGx} and ΔP_{DGx} are decision variables that must be optimally selected. The linear programing toolbox of MATLAB is used to solve the presented optimization problem. Once it is solved, the new set-point of DGs in order to remove the voltage violation at the worst bus in I = 1 is defined. Then, a new load flow calculation is done at the end of the iteration one to define whether the VCA must go to the next iteration or it can stop. If a new voltage violation is found, the iteration 2 (I = 2) starts, and a new optimization problem based on the one presented in (17)–(20) is composed to bring back the biggest voltage violation of the second iteration within the permitted voltage limits. Again, at the end of the I = 2, a new load flow calculation is performed to decide if the next iteration is needed or not. The iterative procedure of the VCA stops when there is no voltage violation greater than 0.001 pu in the system.

The studied VSA methods are separately embedded in the VCA. When the DSA, IDSA, and POSA methods are tested, the direct load flow approach [23] is used in the VCA. For the JBSA method, the NRLF method is employed. It should be noted that the voltage sensitivity coefficients obtained from the JBSA, POSA, and IDSA methods are updated at the end of each iteration of the VCA by the new load flow study while their counterparts in the DSA method are kept constant since they are independent of the network working point.

To evaluate accuracy of the studied VSA methods in the voltage regulation procedure, a new parameter is defined by the following equation.

$$\text{Err }(\%) = \left|\frac{1.03 - V_w^{cor}}{\Delta V_w^{req}}\right| \times 100 \qquad (21)$$

where V_w^{cor} is the corrected voltage of the worst bus. It is obtained by the load flow calculation that is done at the end of each iteration of the VCA (considering the corrective actions of DGs). The numerator of (21) gives the mismatch of the corrected voltage value at the worst bus with respect to the permitted 1.03 pu voltage limit. Its corresponding relative error with regard to the required voltage correction at bus w is obtained by (21). It should be noted that for the simplicity of the formulation, only the voltage rise problem is considered in the VCA.

The VCA including the studied VSA methods are coded in the MATLAB environment. Effectiveness of the studied VSA methods is examined in response to separate changes of DG active and reactive powers. The investigation is carried out on the UKGDS shown in Figure 2. An identical initial working point is considered in the studied cases. It is supposed that the load powers are at 10% of their respective nominal values, DG active powers are equal to 90% of their rated values ($0.9 \times 3.5 = 3.15$ MW) while the initial reactive powers of DGs are set to zero. In this situation, it is expected to deal with the voltage rise problem at the DG-connected buses.

6.1. Study on the Reactive Power Control of DGs

The first part of the study on the VCA is devoted to evaluate performance of the presented VSA methods in response to only reactive power changes of DGs. In this regard, the weighting coefficient for DG reactive power variations is set to one ($C_Q = 1$) while active power control of DG is penalized with a factor of 1000 ($C_P = 1000$) in order to eventually use only DG reactive powers. Table 5 presents the iterative procedure of the VCA for returning the existing voltage violations inside the permitted voltage range using the DSA and IDSA methods. Table 6 gives the VCA results when JBSA and POSA are used. It should be noted that hereafter the DGs which are employed by the VCA are mentioned in the tables and for the rest of DGs (which are not listed), power changes are equal to zero.

As it can be seen in Tables 5 and 6, in the first iteration (I = 1), the biggest voltage rise is found at bus 26. To remove this voltage violation, DG5 which has the biggest

	JBSA		POSA	
	I = 1	I = 2	I = 1	I = 2
ΔV_w^{req} (pu)	−0.0298	−0.0148	−0.0298	−0.0148
At bus	26	62	26	62
Err (%)	4.232	2.16	4.242	2.157
ΔQ_{DGx} (Mvar)	DG4 = 1.863	DG18 = 2.273	DG4 = 1.864	DG18 = 2.274
x = 1, 2, 3, …, N	DG5 = 2.31		DG5 = 2.31	

TABLE 6. VCA results regarding study on the reactive power control of DGs using JBSA and POSA.

impact on the voltage at bus 26 is used with its maximum available reactive power (2.31 Mvar). The rest of needed reactive power is provided by DG4. Then, in the second iteration, voltage rise at bus 62 (as the one with the biggest violation) is managed by the reactive power change of DG18. Using all studied VSA methods, within two iterations of the VCA, the system voltages are returned inside the permitted voltage range.

Due to the fact that in the considered working point, initial reactive powers of all DGs are zero, sensitivity of active and reactive power losses in the system branches with respect to nodal reactive power changes is small. Therefore, the second and third terms in (7) are small too. As a result, the direct and IDSA methods exhibit almost similar performances; although the IDSA results are slightly more accurate than the DSA ones. Regarding the JBSA method, it is noticed that it solves the voltage control problem with a higher global amount of DG reactive powers and bigger relative errors compared to the results of DSA and IDSA methods. The inaccuracy of JBSA is explained by the fact that in the VCA, the working point is greatly moved by power changes of DGs. It is worth noting that the values of DG power changes given in Tables 5 and 6 are considerably bigger than what normally exist in the NRLF study as the power residuals (vectors of ΔP and ΔQ in (12)). In Table 6, it is seen that the VCA results obtained by the POSA are almost identical to the ones of JBSA, similar to the performed analyses of Section 5 using the ABC index.

6.2. Study on the Active Power Curtailment of DGs

In the second part of this section, the introduced VSA methods are tested when only generation curtailment of DG active powers is applied in the VCA. To this end, weighing coefficient for active power curtailment of DGs (C_P) is set to 1 while reactive power variation of DGs is penalized by a factor of 1000 ($C_Q = 1000$). Since in the considered initial working point, active powers of all DGs are maximal, the nodal active power changes have considerable impacts on the active and reactive power losses in the system branches. Therefore, unlike study on the reactive power control of DGs in the previous case, in the following case, it is expected to see that the IDSA and DSA methods exhibit different performances. Table 7 shows the VCA results using the DSA method and Table 8 gives the ones found through the IDSA, JBSA, and POSA methods.

In the results given in Table 7, it is seen that the DSA method cannot estimate accurately the voltage response when active powers of DGs are curtailed. As a consequence, the VCA needs 4 iterations in order to bring back the violated voltages within the permitted voltage range. The relative error of voltage regulation at the worst bus using the DSA is considerably high in all iterations and reaches 12.427%. Considering the results shown in Table 8, it can be noticed that the IDSA, JBSA, and POSA exhibit smaller relative errors compared to the DSA ones. In the IDSA, the maximum relative error is 2.068% while in the JBSA and POSA, it increases to 4.241% and 4.233%, respectively, which confirms that the IDSA has led to the most accurate voltage estimation in this studied case. Moreover, the voltage control problem has been solved with a smaller global amount of active power curtailment using the IDSA method (8.093 MW) compared to the case of using JBSA or POSA approach (8.294 MW). It should be noted that the unnecessary active power curtailment or reactive power utilization of DGs will increase the system management costs. In other words, it can be stated that an accurate VSA can minimize the system operating costs.

7. DISCUSSION

Based on the results of the analyses performed on the studied networks using the ABC index, it is confirmed that the power losses factor has a direct impact on the accuracy of the VSA. Given that in the IDSA method, variations of power losses due to the nodal power changes and their eventual impacts on the system voltages are taken into consideration, it shows a better performance compared to the one of the DSA method. For the same reason, at the buses

	DSA			
	I = 1	I = 2	I = 3	I = 4
ΔV_w^{req} (pu)	−0.0298	−0.0219	−0.0047	−0.0029
At bus	26	62	20	59
Err (%)	12.427	12.032	10.424	10.927
ΔP_{DGx} (MW)	DG4 = 0.326	DG17 = 0.081	DG4 = 0.7167	DG17 = 0.552
x = 1, 2, 3, …, N	DG5 = 3.15	DG18 = 3.15		

TABLE 7. VCA results regarding study on the active power control of DGs using DSA.

	IDSA		JBSA		POSA	
	I = 1	I = 2	I = 1	I = 2	I = 1	I = 2
ΔV_w^{req} (pu)	−0.0298	−0.0221	−0.0298	−0.0221	−0.0298	−0.0221
At bus	26	62	26	62	26	62
Err (%)	1.479	2.068	4.241	3.292	4.233	3.287
ΔP_{DGx} (MW)	DG4 = 1.027	DG17 = 0.766	DG4 = 1.166	DG17 = 0.8284	DG4 = 1.1661	DG17 = 0.8285
x = 1, 2, 3, …, N	DG5 = 3.15	DG18 = 3.15	DG5 = 3.15	DG18 = 3.15	DG5 = 3.15	DG18 = 3.15

TABLE 8. VCA results regarding study on the active power control of DGs using IDSA, JBSA, and POSA.

which are far from the slack node (like bus 26), the IDSA method provides more accurate results than the JBSA ones too. Generally, it can be stated that the preference of the JBSA or IDSA method depends on the selected network working point, the selected network bus and the amount of moving system working point.

Moreover, in Sections 5 and 6, it is seen that the POSA and JBSA lead to almost identical performances. It is due to the fact that the voltage sensitivity coefficients in POSA and JBSA are derived based on the similar concepts. In the former, the sensitivity coefficients are obtained by extracting the slope of the voltage-power characteristic. In the latter, the sensitivity coefficients are found from inverse of the Jacobian matrix, which consists of the partial derivatives of nodal powers with respect to voltages.

Furthermore, comparative study of the VSA methods embedded in the VCA reveals that an inaccurate VSA leads to a higher amount of DG power changes and excessive number of the VCA iterations. In the VCA, the DGs that are located at the end of the feeders are used since they have greater impacts on the violated voltages. Consequently, it is seen that the VCA including the IDSA shows more accurate voltage estimation compared to the ones obtained through other methods.

8. CONCLUSION

In this paper, the IDSA method is developed which incorporates power loss variations in the system branches due to the nodal power changes and their eventual impacts on the system voltages. Effectiveness of the IDSA in voltage estimation is investigated and compared with the voltage results obtained by the direct, Jacobian-based, as well as the POSA methods. The studied VSA methods are firstly tested through gradual changes of active and reactive powers using the proposed index based on the area between two curves concept. Then, the introduced VSA methods are separately embedded in a VCA which manages DG active and reactive powers in order to bring back the system voltages inside the permitted voltage limits. Based on the simulation results, it can be concluded that the power losses have important impacts on the accuracy of the VSA. It is also confirmed that the IDSA method indeed exhibits an improved performance compared to the DSA method one. In the case that the system working point is greatly moved at the buses close to the slack node or when the power changes are applied at the buses which are relatively far from the slack node, impacts of power loss variations on node voltages will be considerable. Consequently, the IDSA method will have more accurate voltage estimation compared to that of the JBSA or POSA method.

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