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A New Sensitivity Approach for Preventive Control Selection in Real-time Voltage Stability Assessment

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Abstract: Voltage instability is one of the serious problems in power networks due to the growing demand. Sensitivity analysis has been widely hailed as an effective method for voltage stability prediction and control. However, the common loading margin sensitivity approaches are not appropriate for real-time applications. This is because those approaches are based on continuation power flow or the singularity of the Jacobian matrix to find the maximum loading point. In this study, a new sensitivity method is developed for choosing the most effective control variables for voltage instability prevention in power systems. The sensitivity analysis is performed on a voltage stability index, namely Thevenin-Based Voltage Stability Margin (TVSM), derived from the coupled single-port circuit concept to capture the changes in power system operation. The sensitivity approach is computed via the derivation of nodal voltages (magnitudes and angles) with respect to preventive controls. The proposed sensitivity approach is tested on the IEEE 39 bus network and the IEEE 118 bus network to verify their accuracy.

Keywords: Preventive Control; Sensitivity Analysis; Voltage Stability; Loading Margin; Real-time Applications.

1. Introduction

Voltage instability is one of the main challenges in large-scale power networks. Many blackouts have occurred worldwide due to voltage collapse [1]. Network operators are required to keep a sufficient loading margin for network stability and reliability. Therefore, preventive or corrective control is often developed to perform appropriate control actions.

Optimization-based methods are part of the preventive/corrective controls and are created to minimize the cost of control measures while keeping the system operation within security constraints. The method proposed in [2] is an example for this type of optimization methods. The interior point method was performed for voltage instability prevention/ correction. The preventive control methods used in [3]-[8] are also optimization-based methods with no restrictions on the number of control variables. However, optimization approaches are impractical since enormous options of preventive controls are available in power systems and all of them must be implemented into the optimization model. This means that most, if not all preventive controls, have to be activated to obtain the optimal solution.

To reduce the number of preventive controls, many sensitivity methods have been employed to choose the most effective control variables for the optimization or control space [9]-[18]. A loading margin sensitivity obtained by a continuation power flow (CPF) and oriented for load shedding purposes is developed in [9]. In [10], a load margin sensitivity based on the optimal multiplier power flow is presented for load shedding in AC/DC system after severe contingencies. The authors in [13] used linear and quadratic approximation to find out how system parameters or controls can vary the loading margin. This method needs the calculation of eigenvalue of the Jacobian matrix at the critical point. The comprehensive approach proposed in [14] for voltage instability preventive and corrective used a sensitivity analysis to identify the most effective control actions. This method accurately models the main characteristics of network components and finds the critical point during the equilibrium tracing process. In [15], a sensitivity computation is coupled with CPF method for voltage stability analysis to deal with unstable or low voltage situations caused by contingences. In [16], tangent vector concept is used for tracing PV or PQ curves. In [17], a method combining linear sensitivities and eigenvalue analysis was proposed for voltage contingency ranking.

However, the aforementioned sensitivity approaches suffer from some problems. They are based on CPF or the singularity of the Jacobian matrix to find the maximum loading point (MLP) [19]. Such methods require a significant computational effort that makes them not suitable to be implemented in real-time applications of modern power systems. Indeed, fast response equipments, in particular FACTS and decentralized generation (DG), can often change the state of operation of modern power grids [20]. Thus, a fast sensitivity method is required to meet the requirements of modern power networks. Although the authors in [21]-[22] have developed a fast sensitivity method based on Look-Ahead technique via the quadratic estimation of the PV curve, the MLP identified by using the quadratic estimation was inaccurate.

Development of a measurement-based sensitivity method can mitigate the computation efforts associated with the conventional sensitivity methods and thus make it suitable for online applications. In the literature, many measurement-based techniques have been proposed for real time voltage stability monitoring [23]-[40]: L- index [23]-[24], Tellegen's theorem [25], decision tree [26], Voltage Collapse Proximity Indicator [27], based on two consecutive measurements of voltage [28], VSI-index [29], Corsi Identification Algorithm [30], Voltage Instability Predictor VIP [32], a hybrid method which combines model-based and measurement-based techniques [35], an index based on analyzing local measurements [37], coupled single-port circuit concept [40]. Since the latter method can capture the dynamic nonlinear behavior of power networks, it is considered the most accurate approach for voltage stability monitoring. However, this work has a shortage in the information regarding the decisions of preventive control. It did not perform sensitivity analysis on the voltage stability margin. The information of which preventive controls to activate when the instability is approached is equally as important as the assessment of the voltage stability itself. Although the authors in [41] have performed the sensitivity analysis on L-index derived from coupled single-port circuit concept, they neglect the effects of the line resistances and the angle differences. This makes the obtained sensitivities inaccurate. The sensitivities of this method are also derived with respect to only power injections, without taking into account the different types of preventive controls. The loading margin sensitivity proposed in [42] also depends on the coupled single-port circuit concept, but it was derived with respect only to reactive power injection without fully explanation.

In this regard, a new sensitivity approach for selecting the most effective preventive controls is proposed in this work. The proposed method uses a voltage stability margin, namely TVSM, derived from nodal measurements of voltages and currents and based on the concept of Thevenin's impedance match. The sensitivity of TVSM is then derived by evaluating the sensitivity of the load and the equivalent impedances of a load bus to preventive controls. This can be investigated via the derivation of nodal voltages (magnitudes and angles) with respect to preventive controls. The controls are then ranked based on their sensitivities and the most effective ones can be chosen for the optimization or control space.

The proposed technique requires less computational effort and therefore it has the potential to be implemented in real-time applications. The sensitivities can be updated to consider the continuous changes in power system operation. The sensitivities can also provide an analysis of not only how the controls affect the system loading margin but also how they can affect the voltage stability of each bus. The sensitivities and the ranking obtained via the proposed method coincide with the ones calculated using other methods, with the advantage of reducing the computational cost.

The key contributions of this work are:

1. Development of a new approach for loading margin sensitivity. The sensitivity analysis is presented for the first time in order to derive the sensitivity of TVSM by evaluating the load and the equivalent impedances of load buses to preventive controls. This can be investigated via the derivation of nodal voltages (magnitudes and angles) with respect to preventive controls.
2. Unlike the common sensitivity methods, the proposed method does not require complex calculations to compute the MLP via CPF or the singularity of the Jacobian matrix. The required computing time is smaller than the common methods.
3. Compared with the common loading margin sensitivity techniques, the proposed method is not limited to unstable voltage conditions near the critical point, but also stable (normal) voltage conditions. Since the wide-area measurements can capture the continuous changes of power system operation, the proposed method is highly applicable for any operating condition.
4. Application of the proposed sensitivity method to rank the most effective preventive controls of power networks.

The rest of this work is organized as follows: Section 2 describes the loading impedance margin for voltage stability analysis based on the nodal measurements. Section 3 describes TVSM-based sensitivity analysis. Simulation results are presented in section 4 while the conclusions and the future works are stated in section 5.

2. Loading Impedance Margin

With the development of phasor measurement units (PMUs), designing a model for online voltage stability prediction has been raised. The method developed in [40] for voltage stability prediction depends on the equivalent nodal analysis and aims to simplify the external grid seen by a load node to a Thevenin equivalent impedance. Thus, PMUs are required to be installed at the load nodes to monitor the nodal voltages and currents and SCADA system to collect the data of network topology.

2.1 Equivalent Nodal Analysis of Multi-Bus Network

In general, the system buses can be divided into generator buses G, load buses L and tie buses T. According to [40], the nodal current equation can be expressed as:

$$\begin{bmatrix} I_G \\ -I_L \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} & Y_{GT} \\ Y_{LG} & Y_{LL} & Y_{LT} \\ Y_{TG} & Y_{TL} & Y_{TT} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \\ V_T \end{bmatrix} \tag{1}$$

Where $\boldsymbol{I}$ and $\boldsymbol{V}$ denote the voltage and current vectors, and $\boldsymbol{Y}$ represents a submatrix of the network admittance matrix. By eliminating the tie buses, we obtain:

$$\begin{bmatrix} I_G \\ -I_L \end{bmatrix} = \begin{bmatrix} Y'_{GG} & Y'_{GL} \\ Y'_{LG} & Y'_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{2}$$

Where :

$$Y'_{GG} = Y_{GG} - Y_{GT} Y_{TT}{}^{-1} Y_{TG}$$
$$Y'_{GL} = Y_{GL} - Y_{GT} Y_{TT}{}^{-1} Y_{TL}$$
$$Y'_{LG} = Y_{LG} - Y_{LT} Y_{TT}{}^{-1} Y_{TG}$$
$$Y'_{LL} = Y_{LL} - Y_{LT} Y_{TT}{}^{-1} Y_{TL}$$

The load voltage vector V_L can be written as a function of V_G and I_L as:

$$V_L = (- {Y'_{LL}}^{-1} Y'_{LG})V_G - Z_{LL} I_L \quad (3)$$

Where $Z_{LL} = {Y'_{LL}}^{-1}$. For a load bus i, the bus voltage can be obtained as:

$$V_{L,i} = [(- {Y'_{LL}}^{-1} Y'_{LG})V_G]_i - Z_{LL,ii} I_{L,i} - \sum_{j\neq i} Z_{LL,ij} I_{L,j} \quad (4)$$

where $I_{L,i}$ and $I_{L,j}$ are the injection currents at the load bus i and j respectively; $Z_{LL,ii}$ represents the self-impedance of load bus i; $Z_{LL,ij}$ represents the mutual impedance between the two buses i and j. Since the voltage $V_{L,i}$ can be expressed as $V_{eq,i} - Z_{eq,i} I_{L,i}$, we can conclude from (4) that:

$$Z_{eq,i} = Z_{LL,ii} + \sum_{\substack{j \in L \\ i \neq j}} Z_{LL,ij} \frac{I_{L,j}}{I_{L,i}} \quad (5)$$

Where $V_{eq,i}$, $Z_{eq,i}$ represent the Thevenin's equivalent voltage and impedance referred to the load bus i, respectively. As we can see from (5) that the equivalent impedance varies according to the dynamic behavior of loads.

2.2 Thevenin-Based Voltage Stability Margin (TVSM)

According to the equivalent impedance obtained in section (2.1) and based on the concept of Thevenin's impedance match, the maximum power transfer is identified when load impedance equals the Thevenin's impedance of the network (i.e. $|Z_{eq}| = |Z_L|$). The ratio between the two impedances $|Z_{eq}| / |Z_L|$ can be considered as an indicator for voltage stability margin [43]. Accordingly, a voltage stability margin *TVSM* can be found as:

$$TVSM_{\text{i}} = \frac{|Z_{L,i}| - |Z_{eq,i}|}{|Z_{L,i}|} \quad (6)$$

Where $Z_{L,i}$ represents the impedance of load bus i and can be obtained as:

$$Z_{L,i} = \frac{V_{L,i}}{I_{L,i}} \quad (7)$$

Where $\boldsymbol{V_{L,i}}$ and $\boldsymbol{I_{L,i}}$ represent the measured voltage and current at load bus i, respectively. Based on other similar indices [42], the value of *TVSM* varies from 0 to 1, and the instability condition occurs when $\boldsymbol{TVSM_i}$= 0.

It is clear from (5)-(7), that the TVSM depends on the system admittance Y and the nodal measurements of load buses.

For large networks, the smallest value among the *TVSMs* can be used to identify the loading margin of the network as [40]:

$$\text{TVSM} = \min(\text{TVSM}_1, \text{TVSM}_2, \ldots, \text{TVSM}_i) \quad (8)$$

To consider the limits violation of generator reactive power, the previous index TVSM can be extended by incorporating internal model for generators based on their dynamic models and nodal measurements. Based on [44], synchronous generators can be represented by an internal voltage E_G in series with an impedance Z_G. For the 4th order generator, the internal impedance and voltage can be obtained as [44]:

$$Z_G = \frac{[(r_a i_d - (x'_q - x_l) i_q) + j(r_a i_q - (x'_d - x_l) i_d)]}{i_d + j i_q} \quad (9)$$

$$E_G = V_G + I_G Z_G \quad (10)$$

Where $r_a, x_l, x'_q, x'_d, i_d$ *and* i_q are armature resistance, leakage reactance, q-axis transient reactance, d-axis transient reactance, d-axis current and q-axis current, respectively. Since generator parameters are known and V_G and I_G are obtained from PMUs, equivalent parameters E_G and Z_G can be calculated. after adding the generator internal model to the nodal current equation illustrated in (1), we obtain:

$$\begin{bmatrix} 0 \\ -I_L \\ 0 \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{GG} + Y_n & Y_{GL} & Y_{GT} & -Y_n \\ Y_{LG} & Y_{LL} & Y_{LT} & 0 \\ Y_{TG} & Y_{TL} & Y_{TT} & 0 \\ -Y_n & 0 & 0 & Y_n \end{bmatrix} \begin{bmatrix} V_G \\ V_L \\ V_T \\ E_G \end{bmatrix} \quad (11)$$

where Y_n is a diagonal matrix with ($1/Z_{G1}$, $1/Z_{G2}$,…,$1/Z_{Gm}$) values. It is clear from (11) that additional buses are added to the nodal power flow equation. These additional buses act as tie buses. Thus, (11) can be simplified as:

$$\begin{bmatrix} -I_L \\ 0 \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & \hat{Y}_{LT} & 0 \\ \hat{Y}_{TL} & \hat{Y}_{TT} & \hat{Y}_{TG} \\ 0 & \hat{Y}_{GT} & Y_n \end{bmatrix} \begin{bmatrix} V_L \\ \hat{V}_T \\ E_G \end{bmatrix} \quad (12)$$

Where $\hat{x}$ denotes for the new submatrices or vectors. By eliminating the tie buses and obtaining the load voltage vector V_L, we obtain:

$$\begin{bmatrix} I_G \\ -I_L \end{bmatrix} = \begin{bmatrix} Y''_{GG} & Y''_{GL} \\ Y''_{LG} & Y''_{LL} \end{bmatrix} \begin{bmatrix} E_G \\ V_L \end{bmatrix} \quad (13)$$

Where :

$$Y''_{GG} = Y_n - \hat{Y}_{GT} {\hat{Y}_{TT}}^{-1} \hat{Y}_{TG}$$
$$Y''_{GL} = 0 - \hat{Y}_{GT} {\hat{Y}_{TT}}^{-1} \hat{Y}_{TL}$$
$$Y''_{LG} = 0 - \hat{Y}_{LT} {\hat{Y}_{TT}}^{-1} \hat{Y}_{TG}$$
$$Y''_{LL} = Y_{LL} - \hat{Y}_{LT} {\hat{Y}_{TT}}^{-1} \hat{Y}_{TL}$$

The voltage V_L can then be obtained as:

$$V_L = (- {Y''_{LL}}^{-1} Y''_{LG})V_G - Z^{new}_{LL} I_L \quad (14)$$

Where $Z^{new}_{LL,ij} = {Y''_{LL}}^{-1}$. Similar to (5), the new Thevenin's equivalent impedance $Z^{new}_{eq,i}$ can be calculated as:

$$Z^{new}_{eq,i} = Z^{new}_{LL,ii} + \sum_{\substack{j \in L \\ i \neq j}} Z^{new}_{LL,ij} \frac{I_{L,j}}{I_{L,i}} \quad (15)$$

By comparing (15) with (5), we conclude that the effect of the generators' reactive power limits can be modelled as additional impedance Z_a embedded in the new Z^{new}_{eq} as:

$$Z^{new}_{eq,i} = Z_{eq,i} + Z_{a,i}$$

Since the index TVSM depends on the Thevenin's equivalent impedance, the additional impedance Z_a can affect TVSM. The new TVSM can be expressed as:

$$TVSM_i^{new} = \frac{|Z_{L,i}| - |Z_{eq,i}^{new}|}{|Z_{L,i}|} \quad (16)$$

For simplicity, the terms Z_{eq} and Z_{LL}in the next sections denotes for the new impedances $Z_{eq,i}^{new}$ and $Z_{LL,ii}^{new}$.

Remark 1: the parameters of synchronous generators may change due to factors such as magnetic saturation, temperature, and aging. The change in generator parameters could affect the value of the additional impedance Z_a. By taking the advantages of using PMUs at generator buses, an online estimation of generator parameters can effectively be obtained. This issue is not part of this work and will be studied in our future works.

3. TVSM-Based Sensitivity Analysis

According to (16), the voltage stability of each load bus can be obtained. However, an information can be provided to help the system operators to guide the decisions of control. Loading margin sensitivity is often used to refer to the sensitivity of the voltage stability margin to system disturbances (i.e. change in system topology or nodal power injection). In this work, sensitivity analysis is performed on *TVSM* to obtain the impact of the change of preventive controls on voltage stability. With the proposed sensitivity, the contributions of the control variables to the improvement of the *TVSM* can be accurately obtained.

3.1 Derivation of The Proposed TVSM- Based Sensitivity

The derivation of the index TVSM of a load bus i with respect to the control variable u_n is achieved by taking the derivation of (16) as:

$$\frac{dTVSM_i}{du_n} = \frac{d\left\{\frac{|Z_{L,i}| - |Z_{eq,i}|}{|Z_{L,i}|}\right\}}{du_n}$$

$$= \frac{|Z_{L,i}|\frac{d\{|Z_{L,i}| - |Z_{eq,i}|\}}{du_n} - (|Z_{L,i}| - |Z_{eq,i}|)\frac{d|Z_{L,i}|}{du_n}}{|Z_{L,i}|^2} \quad (17)$$

For any load impedance $Z_{L,i} = X_{L,i} + j\ Y_{L,i}$, the partial derivative of $d|Z_{L,i}|/du_n$ can be expressed as:

$$\frac{d|Z_{L,i}|}{du_n} = \frac{1}{|Z_{L,i}|}\left(X_{L,i}\frac{d(X_{L,i})}{du_n} + Y_{L,i}\frac{d(Y_{L,i})}{du_n}\right) \quad (18)$$

Similarly, for any equivalent impedance $Z_{eq,i} = X_{eq,i} + j\ Y_{eq,i}$, the partial derivative of $|Z_{eq,i}|/du_n$ can be expressed as:

$$\frac{d|Z_{eq,i}|}{du_n} = \frac{1}{|Z_{eqi}|}\left(X_{eq,i}\frac{d(X_{eq,i})}{du_n} + Y_{eq,i}\frac{d(Y_{eq,i})}{du_n}\right) \quad (19)$$

By substituting (18) and (19) into (17), the sensitivity of the index $TVSM_i$ to control variable u_n can be written as:

$$\frac{dTVSM_i}{du_n} = \frac{1}{|Z_{L,i}|^2}\left(\frac{|Z_{eq,i}|}{|Z_{L,i}|}\left(X_{L,i}\frac{d(X_{L,i})}{du_n} + Y_{L,i}\frac{d(Y_{L,i})}{du_n}\right) - \frac{|Z_{L,i}|}{|Z_{eq,i}|}\left(X_{eq,i}\frac{d(X_{eq,i})}{du_n} + Y_{eq,i}\frac{d(Y_{eqi})}{du_n}\right)\right) \quad (20)$$

For real power networks, calculating the sensitivity of all loading margins for each preventive control is impractical. Since the voltage collapse of one node represents the collapse of the entire system, the smallest margin among all the system can be used to represent the system margin. This coincides with [45] which discusses the smallest minimum singular value of power flow Jacobian matrix for voltage stability analysis. Thus, the TVSM of pilot bus indicated by eq. (8) is used for TVSM-sensitivity analysis.

The computations of the sensitivities are explained in the next subsection.

3.2 Computations of Sensitivities

The sensitivities $dX_{L,i}/du_n$ and $dY_{L,i}/du_n$ can be obtained by taking the derivation of (7) with respect to control variable u_n. Thus, we obtain:

$$\frac{dZ_{L,i}}{du_n} = \frac{d\left\{\frac{V_{L,i}}{I_{L,i}}\right\}}{du_n} = \frac{I_{L,i}\frac{dV_{L,i}}{du_n} - V_{L,i}\frac{dI_{L,i}}{du_n}}{{I_{L,i}}^2}$$

$$= \frac{d(X_{L,i})}{du_n} + j\frac{d(Y_{L,i})}{du_n} \quad (21)$$

Similarly, sensitivities $dX_{eq,i}/du_n$ and $dY_{eq,i}/du_n$ can be obtained by taking the derivation of (15) with respect to control variable u_n. Thus, we obtain:

$$\frac{dZ_{eq,i}}{du_n} = \sum_{\substack{j \in L \\ i \neq j}} Z_{ij}\ \frac{I_{L,i}\frac{dI_{L,j}}{du_n} - I_{L,j}\frac{dI_{L,i}}{du_n}}{{I_{L,i}}^2}$$

$$= \frac{d(X_{eq,i})}{du_n} + j\frac{d(Y_{eq,i})}{du_n} \quad (22)$$

Where dI_L/du_n and dV_L/du_n represent the sensitivity of the load current and voltage to control variable u_n, respectively. Since the load current $I_{L,i}$ can be written in terms of complex power S and the load voltage as ${S_{L,i}}^*/{V_{L,i}}^*$, $dI_{L,i}/du_n$ is calculated as:

$$\frac{dI_{L,i}}{du_n} = \frac{d\left\{\frac{{S_{L,i}}^*}{{V_{L,i}}^*}\right\}}{du_n} = \frac{{V_{L,i}}^*\frac{d{S_{L,i}}^*}{du_n} - {S_{L,i}}^*\frac{d{V_{L,i}}^*}{du_n}}{{V_{L,i}}^{*2}} \quad (23)$$

Since ${S_{L,i}}^* = |V_{L,i}|^2/Z_{L,i}$, the term $d{S_{L,i}}^*/du_n$ can be obtained as:

$$\frac{d{S_{L,i}}^*}{du_n} = \frac{2\,V_{L,i}}{Z_{L,i}}\frac{dV_{L,i}}{du_n} \quad (24)$$

The term dV_L/du_n can be calculated as:

$$\frac{dV_{L,i}}{du_n} = e^{j\theta_i}\left(\frac{d|V_{L,i}|}{du_n} + j|V_{L,i}|\frac{d\theta_{L,i}}{du_n}\right) \quad (25)$$

Where $d|V_{L,i}|/du_n$ and $d\theta_{L,i}/du_n$ represent the sensitivities of the voltage magnitude and angle with respect to the control variable respectively, and (*) represents conjugate.

It is clear from (21)- (25) that all the sensitivities can be written in terms of $d|V_{L,i}|/du_n$ and $d\theta_{L,i}/du_n$. This means that the sensitivity of the index TVSM to control variables strongly depends on the sensitivities $d|V_{L,i}|/du_n$ and $d\theta_{L,i}/du_n$. Thus, the proposed sensitivity method can be considered as a good indicator of how the system voltage stability can be improved by changing the control variables. In other words, since the change in control variables causes a variation in real or reactive power injection, the robustness of the two sensitivities in identifying how the index TVSM is changed with changing the control variables can be understood using the PV or PQ curve. Let us consider the PV curve shown in Fig.1 with three operating points (A, B and C). It is assumed that point A represents the current operating state of the system with no control action (i.e. the state of the control variable is u_o). Point B represents an operating state with a positive increment in the control variable u (i.e. a positive increment in power injection, Δu >0) and point C represents an operating state with a negative increment in the control variable u (i.e. a negative increment in power injection, Δu < 0). It is clear that the slope of tangent at the point A occurs between the slope of secants, AB and AC. If the sensitivity $dTVSM_i/du_n$ is expressed in terms of $\Delta|V_{L,i}|/\Delta u_n$ and $\Delta\theta_{L,i}/\Delta u_n$ instead of $d|V_{L,i}|/du_n$ and $d\theta_{L,i}/du_n$, we can notice that the sensitivity of the index TVSM to the change in control variables is strongly connected to the slope of the secants AB or AC. As $\Delta u \rightarrow 0$, the sensitivity of TVSM corresponds to the slope of the tangent at point A (i.e. the voltage sensitivity at the current operating point).

If the control variables are considered to be the nodal real and reactive power injection, the two sensitivity terms can be found by taking the inverse of the Jacobian matrix $[J]^{-1}$. However, control variables of practical power systems are mainly generator terminal voltage, shunt capacitor, tap changer transformers and generators output power.

To consider all types of control variables in the sensitivity analysis, let us formulate the power flow equations of any power system as follows:

$$F(|V|, \theta, u, \lambda) = 0 \qquad (26.a)$$
$$G(|V|, \theta, u, \lambda) = 0 \qquad (26.b)$$

Where F is the set of equations for active power injected at all PV and PQ buses. G is the set of equations for reactive power injected at all PQ buses. $|V|$ and θ represent the vectors of bus voltage magnitudes and angles, respectively. u represents the vector of preventive controls. λ is the load parameter.

By taking the derivative of (26), we obtain:

$$F_{|V|}\, d|V| + F_\theta\, d\theta + F_u\, du + F_\lambda\, d\lambda = 0 \qquad (27.a)$$
$$G_{|V|}\, d|V| + G_\theta\, d\theta + G_u\, du + G_\lambda\, d\lambda = 0 \qquad (27.b)$$

Where $F_{|V|}, F_\theta, F_u$ *and* F_λ represent the partial derivatives of the injected active power with respect to the voltages, angles, control variables, and load parameter, respectively. Similarly, $G_{|V|}, G_\theta, G_u$ *and* G_λ represent the partial derivatives of the injected reactive power with respect to the voltages, angles, control variables, and load parameter, respectively.

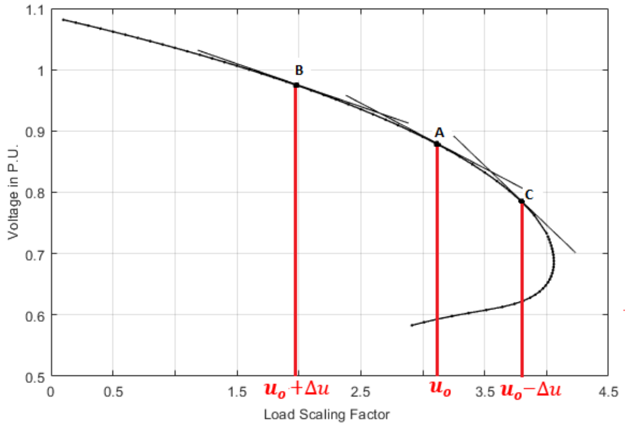

Fig.1. A PV curve with three operating points: current operating point (A) operating point with Δu >0 (B) operating point with Δu < 0 (C).

To find the sensitivities $d|V|/du_n$ and $d\theta/du_n$, the control variables are the only disturbance that should be considered here (i.e. λ remains fixed at the present operating condition). Thus, the equations given in (27) can be organized as:

$$\begin{bmatrix} F_\theta & F_{|V|} & F_u \\ G_\theta & G_{|V|} & G_u \end{bmatrix} \begin{bmatrix} d\theta \\ d|V| \\ du \end{bmatrix} = 0 \qquad (28)$$

The submatrices $F_{|V|}, F_\theta, G_{|V|}$ *and* G_θ can be directly found from Jacobian matrix of the base case. F_u and G_u are column vectors represent how the injected active and reactive power change with varying the control variable (i.e. Δu). These vectors are normally known by network operators [21]. For example, it is known how much reactive power could be injected by the action of each shunt capacitor. For tap changers, the vectors can be approximated by computing the power changes due to a tap change. This information can be obtained offline from the solution of two power flow runs with a tap position difference.

It is worth mentioning that the number of the unknowns in (28) equals to the number of power flow unknowns plus one additional unknown (i.e. du_n). The problem in this equation is that the number of equations remains unchanged. To solve this problem, a non-zero magnitude is assigned for du_n. For example, the additional equation could be $du_n = 1$.

3.3 Implementation of the Proposed Sensitivity Method for Preventive Control Selection

From the viewpoint of network operators, minimizing the control cost is an important issue for all electric utilities. Thus, most operators formulate the control cost as an optimization objective. Since this study aims to choose the most effective preventive controls, the various types of preventive controls are ranked based on their sensitivities. According to the obtained rank, only the most effective control variables (i.e. control variables with higher ranks) can be selected for the optimization or control space.

The proposed method can be implemented in the network control center for control selection and ranking. The nodal voltage and current phasors are measured using PMUs and sent through SCADA system onward to control center. The updated data of system admittance matrix are also transmitted to the controller via SCADA system. The control variables are also equipped with SCADA facilities to transmit the real-time information about the status of the control variables. According to the operating condition of power system, the proposed approach is then able to determine the most effective controls.

As mentioned in section 1, the value of TVSM varies from 0 to 1 and the instability condition occurs when TVSM = 0. A threshold value is normally determined by the network operator based on the operating experience. If TVSM value of the pilot bus is less than the threshold value, the proposed method will be performed to select the most effective controls variables. A flowchart for the proposed sensitivity method for control selection is shown in Fig. 2. It is assumed that n represents an index of the preventive controls, N is the number of available preventive controls, and *Sen* is the set of sensitivities of the preventive controls.

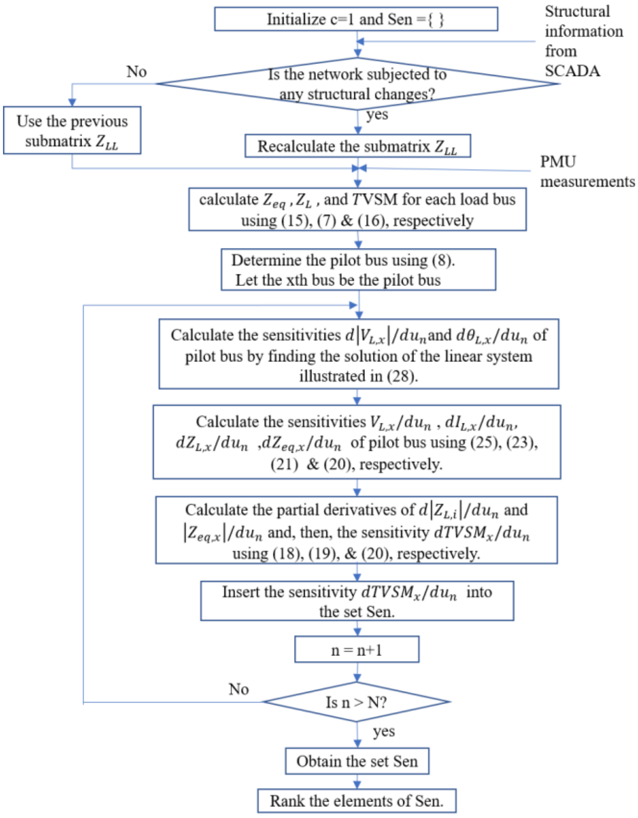

Fig. 2. A flowchart for the proposed sensitivity method for preventive control selection

4. Simulation Results

In this work, the accuracy of the proposed sensitivity approach for preventive control selection is examined on the IEEE 39 bus system and the IEEE 118 bus system. The system data and parameters are available in [46], [47]. The two systems and the proposed sensitivity approach were simulated in MATLAB environment. Several case studies (normal and contingency cases) are considered to check the validity of the proposed algorithm in choosing the most effective preventive controls. Sensitivity analysis results are done using the proposed method (TVSM-sensitivity method), linear sensitivity method [13], and CPF method [19]. The first two methods are employed to find the sensitivities (sensitivity of voltage stability margin to preventive controls). CPF method is employed to find the MLPs (MLPs obtained due to the action of preventive controls). To find the MLPs, CPF was performed after insertion of each preventive control, at a time. These methods are then employed to rank the preventive controls according to their effectiveness. In this study, the numerical values, control ranking, and computation time are considered for the comparison. In all cases, the smallest loading margin is used for sensitivity analysis.

For simplicity and without loss of generality, the generators' active power, capacitors, and tap changer transformers are selected to examine the proposed method in the ranking. However, the same validation can be done for other preventive controls, such as generators' reactive power.

4.1 New England 39-Bus System

The IEEE 39-bus system consists of 10 generators and 19 load buses. In this case study, the system relies only on generator`s output power for voltage control. The bus 39 is considered as the slack bus and therefore does not have to be involved in the preventive control selection. The active power generated by other generators are used as preventive controls. Loads of the network are multiplied by 1.42 to make the system more stressed. Different operating conditions are proposed for this system: normal operation and two contingencies (line 3-18 outage and line 16-17 outage). The proposed method is performed to compute sensitivities of TVSM with respect to generator`s output power.

The numerical results and control ranking obtained using the three methods at no contingency are presented in Fig.3. The ranking is illustrated with numbers in parentheses. The results obtained for the two contingencies are also illustrated in Fig.4 and Fig.5, respectively. The three figures (3,4 &5) show that the results of TVSM-sensitivity coincide with the results of the linear sensitivity method and CPF method for normal and contingency cases. The numerical values show that the errors in the sensitivities (obtained using TVSM-sensitivity and linear sensitivity) are small. The sensitivity ranking is also the same among the three methods. This demonstrates the accuracy of the proposed sensitivity approach in choosing the most effective preventive controls.

It is also clear from the results that the generator G38 owns the first rank among all control variables in the case with no contingency. For the contingency cases, the generator G37 occupies the first rank among all other control variables. This proves that the proposed sensitivity has the ability to change ranking based on the operating states of power systems.

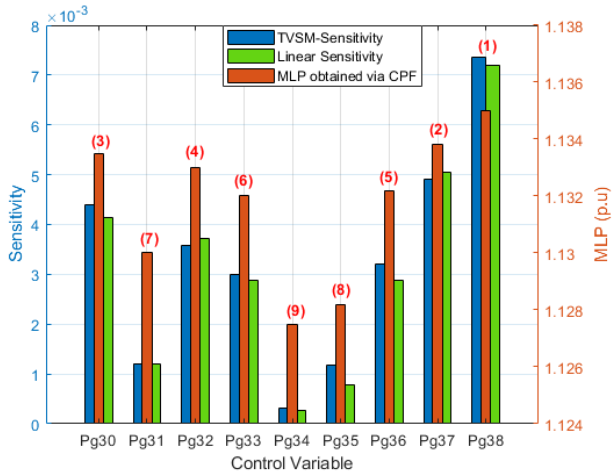

Fig.3. Sensitivity analysis results of the generator's output power at no contingency.

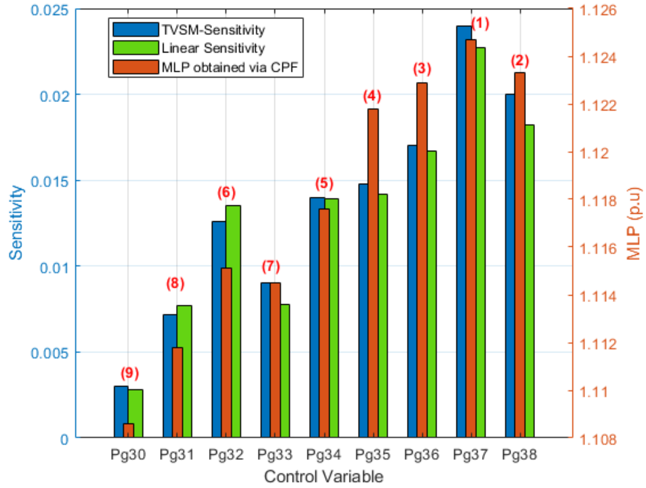

Fig.4. Sensitivity analysis results of the generator's output power for the line outage (3-18).

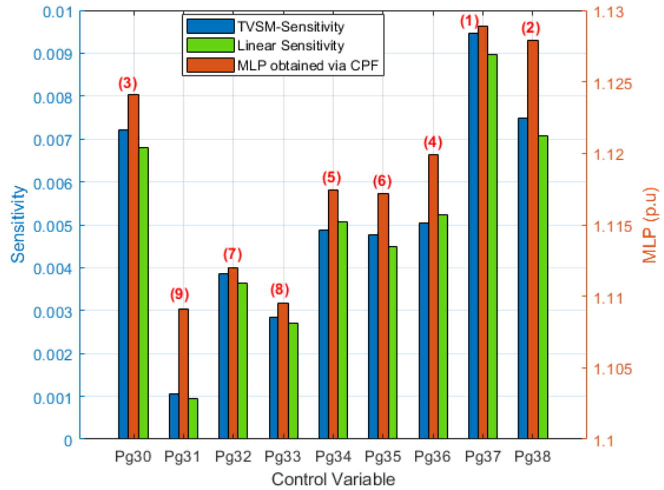

Fig.5. Sensitivity analysis results of the generator's output power for the line outage (16-17).

4.2 IEEE 118 -Bus System

In this section, a larger power network is considered to demonstrate the correctness of the TVSM-sensitivity approach in ranking the preventive controls. IEEE 118-bus system consists of 19 generators and 91 loads. Two types of voltage control are available in this study system: 11 shunt capacitors and 9 tap changer transformers as shown in Table 1 and Table 2, respectively. The bus 69 is selected as the slack bus. Network Loads are multiplied by 2 to make the system more stressed. Two contingencies (line 42-49 outage and line 38-65 outage) are proposed in this case study.

The sensitivity analysis results obtained by TVSM sensitivity, linear sensitivity, and CPF method for the two contingencies are illustrated in Fig.6 and Fig.7, respectively. From the results, it is clear that the errors in the sensitivities are also small. The ranking obtained via TVSM-sensitivity method coincides with the ones obtained using the other methods for the two contingencies, which verifies again the accuracy of the proposed approach in choosing the most effective preventive controls. However in case of line 42-49 outage, we can notice that there is an exchange in control ranking between the T59-63 and C48. The ranks in case of TVSM-sensitivity method are 6^{th} and 7^{th} for T33-38 and C48, respectively. In case of linear sensitivity analysis, the two ranks are exchanged. This occurs because both controls have very similar sensitivities.

It can also be seen from the results that the shunt capacitors C79 & C82 occupy the most preventive control during line 42-49 outage. However, for the line outage 38-65, the shunt capacitors (C48 & C45) have the higher ranking among all other control variables. This demonstrates again the ability of TVSM-sensitivity method in preventive control selection upon different operating conditions.

Table 1 Shunt capacitors of IEEE118- bus system

Capacitor #	Capacitor Name	Var (p.u)
1	C34	0.14
2	C44	0.10
3	C45	0.10
4	C48	0.15
5	C74	0.12
6	C79	0.20
7	C82	0.20
8	C83	0.10
9	C105	0.20
10	C107	0.06
11	C110	0.06

Table 2 Tap changer transformers of IEEE 118-bus system

Tap #	Branch	Min (p.u)	Max (p.u)
1	5-8	0.9	1.1
2	25-26	0.9	1.1
3	30-17	0.9	1.1
4	37-38	0.9	1.1
5	59-63	0.9	1.1
6	61-64	0.9	1.1
7	65-66	0.9	1.1
8	68-69	0.9	1.1
9	80-81	0.9	1.1

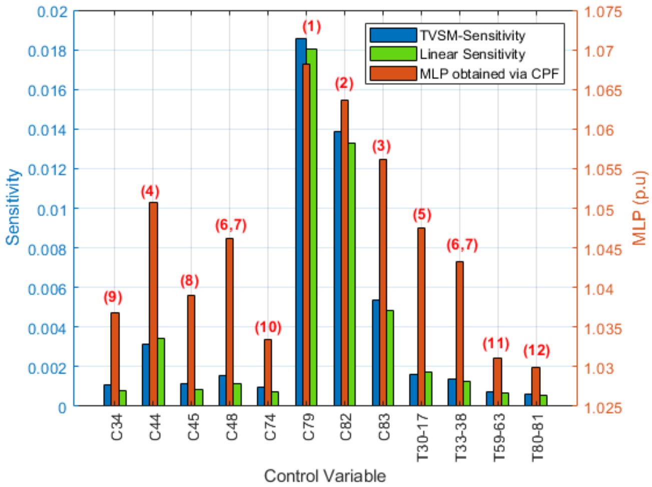

Fig.6. Sensitivity analysis results of the preventive control variables for the line outage (42-49).

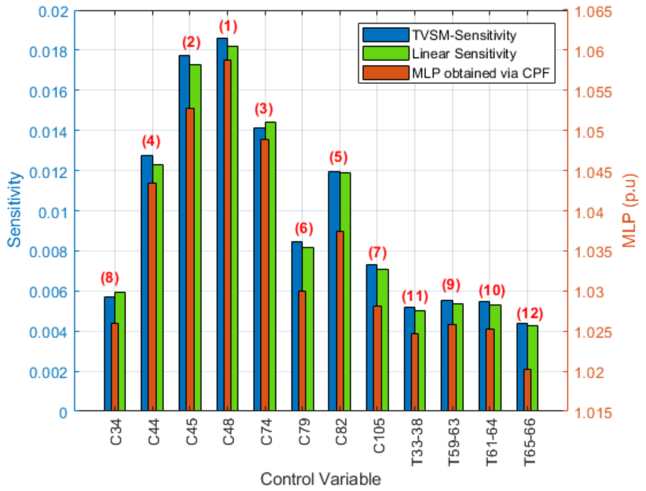

Fig.7. Sensitivity analysis results of the preventive control variables for the line outage (38-65).

4.3 Validation of the proposed sensitivity method upon different levels of control actions

This section demonstrates the correctness of the proposed sensitivity approach in choosing the most effective preventive controls by applying the control actions in four steps. The value of MLP was calculated for each control level via CPF method. The control variables are then classified according to values of MLP. The IEEE 39- bus system is selected as the study system in this subsection. Considering the two contingency scenarios (line outage 3-8 and line outage 16-17) of the test system, the proposed sensitivity approach is performed under four levels of the generator's output power. Levels 1, 2, 3 and 4 represent 0.95, 1.0, 1.05 and 1.1 of the rated generator's output power, respectively.

The results of TVSM-sensitivity analysis upon different control levels for two contingencies are presented in Fig.8 and Fig.9, respectively. The control variables are ranked according to their sensitivities. The ranking is illustrated with a number between parentheses.

From the results, it is clear that the ranking obtained via CPF during the four control steps coincides with the one obtained via TVSM sensitivity method. The ranks of control variables remain the same among the four control steps. For example, considering the line outage (3-8), the output power by the generator G37 is the most effective control variable for all the control steps. In contrast, the output power by the generator G30 is the lowest effective control variable for all the control steps. Besides, we can see from the results that as the level of control action is increased, the value of MLP is increased among all the control variables. These results validate the applicability of the proposed sensitivity method for control selection.

For the second contingency (line outage 16-17), the Pg34 and Pg35 (owing the 5th and 6th rank, respectively) have almost the same value of MLP. This can be explained by referring to Fig.5 which shows that both control variables have very similar sensitivities.

It is worth mentioning that the same validation can be done for other preventive controls, such as tap changer transformers and shunt capacitors.

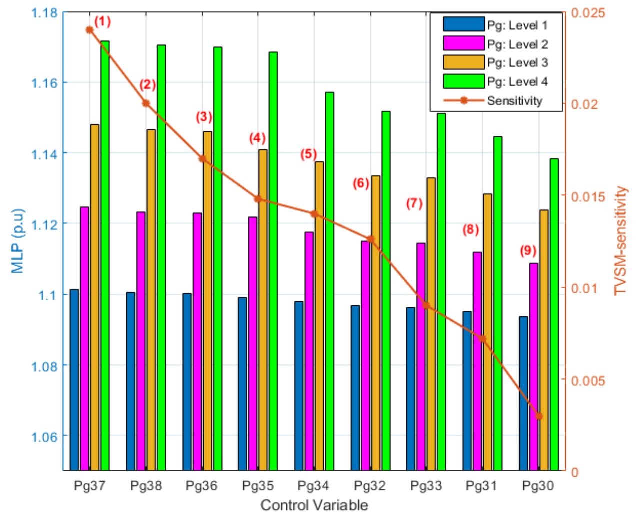

Fig.8. Ranking TVSM-sensitivity analysis of the preventive control variables (at four levels) with CPF results for the outage of line (3-18)

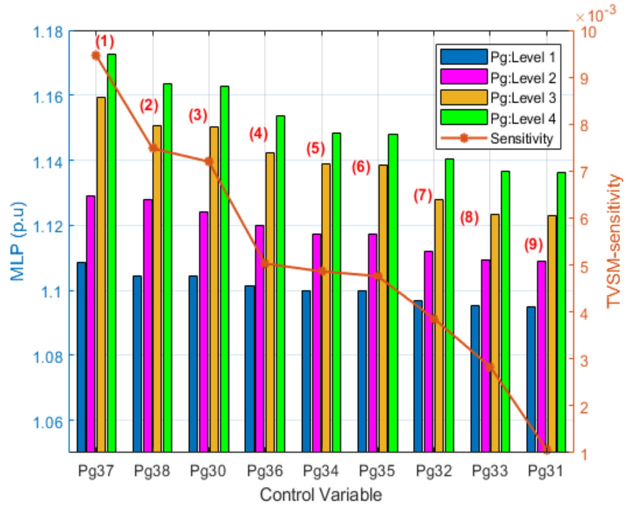

Fig.9. Ranking TVSM-sensitivity analysis of the preventive control variables (at four levels) with CPF results for the outage of line (16-17)

4.4 Robustness of the proposed sensitivity method during different loading levels

This section aims to emphasize that the proposed sensitivity approach has the ability to accurately classify the control variables under different loading levels. In other words, the proposed approach has the capability to correctly rank the controls based on their effectiveness even when the network is operated at conditions far away from the critical point (i.e. the nose point of PV curve). IEEE 118-bus system is chosen as a test system. Considering the non-contingency case, the proposed sensitivity method is performed under three loading levels: loading level 1(near the nose point of the PV curve) and loading level 2&3 (far away from the nose point). The results are compared with the results of CPF method. The control variables are also ranked according to their effectiveness in improving the voltage stability margin.

The sensitivity analysis results of the shunt capacitors and tap changer transformers under three loading levels are presented in Fig.10 and Fig.11, respectively. From TVSM-sensitivity results, we can notice that control variables keep their sensitivity ranks during the three loading level. These results coincide also with results of CPF method. This demonstrates that the proposed method is not limited to points near MLP, but it is effective even when the operating state is far away from the critical point (i.e. stable operating points).

The TVSM-sensitivity method can identify the most effective control variables even when subjected to inaccuracy in estimating the voltage stability margin.

4.5 Application of the proposed sensitivity method in voltage stability control

The previous sections show that the proposed sensitivity can guide system operators to find the most effective actions for voltage stability control. This section demonstrates the applicability of the proposed sensitivity in improving the loading margin. Since the proposed approach is able to rank the preventive controls according to their efficiencies, the control variable that owns the first rank is used for voltage control at the first step. The change amount in 1st rank control variable (Δu_1) can be obtained as:

$$\Delta u_1 = \frac{\Delta\Upsilon}{\Upsilon_{u1}} = \frac{\Upsilon - \Upsilon_o}{\Upsilon_{u1}} \quad (29)$$

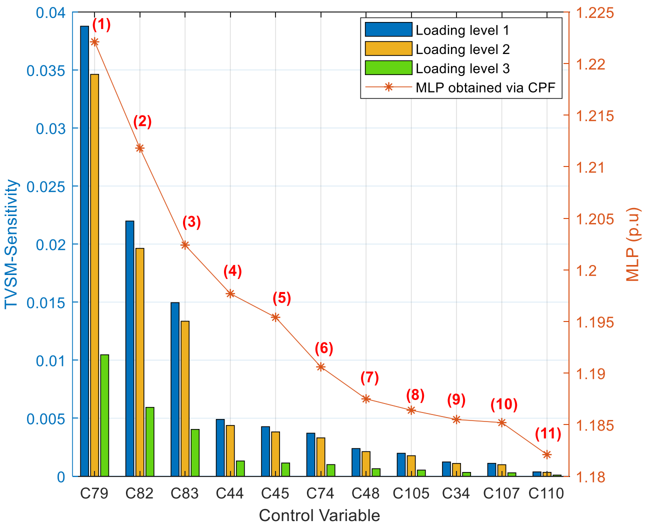

Fig.10. Ranking TVSM-sensitivity analysis of the shunt capacitors under three loading levels with CPF results with no contingency

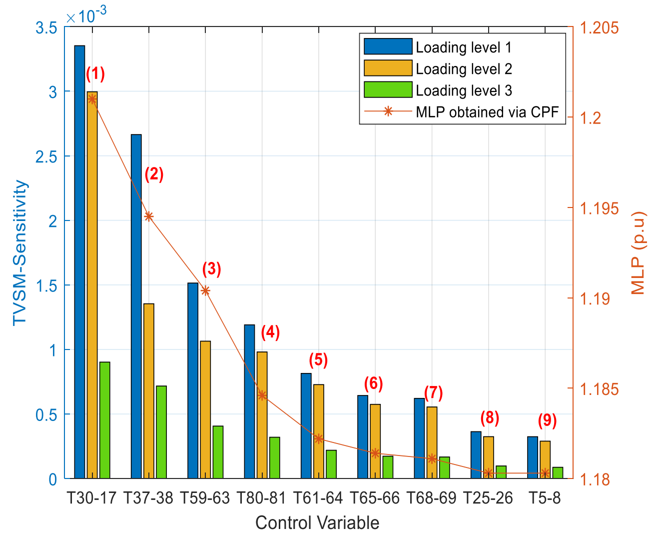

Fig.11. Ranking TVSM-sensitivity analysis of the tap changer transformers under three loading levels with CPF results with CPF results with no contingency.

Where $\Delta\Upsilon$ is the change amount of the index TVSM that should be compensated to improve the voltage stability. Υ_o is considered as the threshold of TVSM index of pilot bus while Υ is the index of TVSM of pilot bus before implementing control actions. Υ_u represents the sensitivity of TVSM to the control variable u. The number "1" denotes for the 1st rank control variable.

If the 1st rank control variable has no enough ability to restore the voltage stability beyond Υ_o, the 2nd rank control variable will also be used for voltage stability control and so on. The change amount in xth rank control variable can be determined as:

$$\Delta u_x = \frac{\Delta\Upsilon - \Upsilon_{com}}{\Upsilon_{ux}} \quad (30)$$

Where Υ_{com} represents the compensated amount in TVSM index due to the higher rank controls and can be calculated as:

$$\Upsilon_{com} = \sum_{k=0}^{N} \Delta u_k' \Upsilon_{uk} \quad (31)$$

Where N represents the number of higher rank controls which used for voltage stability control. $\Delta u_k'$ represents the available amount of kth control variable.

As a result, the selected preventive controls will be able to satisfy the condition (32). This condition ensures that the system is secure.

$$\Upsilon_{u1}\Delta u_1 + \cdots + \Upsilon_{ux}\Delta u_x + \cdots + \Upsilon_{un}\Delta u_n \geq \Delta\Upsilon \quad (32)$$

Where n is the number of the selected preventive controls.

Remark 2: Since this work does not aim to develop an approach for voltage stability control, the proposed method was validated through a simple control method (similar to the method presented in [41]). However, the proposed method can be validated through different voltage control techniques. For example, only the most effective controls can be used in an optimization method for preventive control.

The first two scenarios presented in section 4.1 for IEEE 39-bus system (at no contingency and for the line outage 3-18) are considered in this section to demonstrate the applicability of the proposed approach in voltage stability control. The sensitivities can be found from the results in that section while Υ_o is assumed to be 0.25 for both scenarios. It is also assumed that each control variable has a reserve of 2.0 p.u.

Remark 3: For examination purposes, Υ_o is assumed to be 0.25. However, a threshold value is normally determined by the network operator based on the operating experience.

For IEEE 39-bus system at no contingency and according to (29), it was found that the amount of the required change in 1st rank control variable (Pg38) is 0.94 p.u. Since Pg38 has enough ability to compensate this value, Pg38 is the only control variable that will be used for voltage stability control. For the scenario at the line outage (3-18), it was found that the amount of the required change in 1st rank control variable (Pg37) is 2.81 p.u. Since Pg37 has no enough ability to compensate this value, the full reserve amount of Pg37 will be used. According to (31), the compensated amount in TVSM index due to Pg37 action is 0.048. Thus, the amount of the required change in 2nd rank control variable (Pg38) is 0.972p.u, which will be successfully compensated with no need for other control variables. Fig. 12 and Fig. 13 show the compensated amounts in TVSM among all load buses at both scenarios.

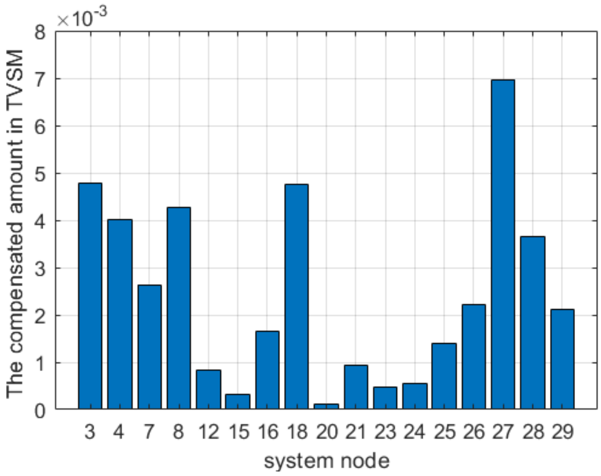

Fig.12. The compensated amounts in TVSM of IEEE 39-bus system at no contingency.

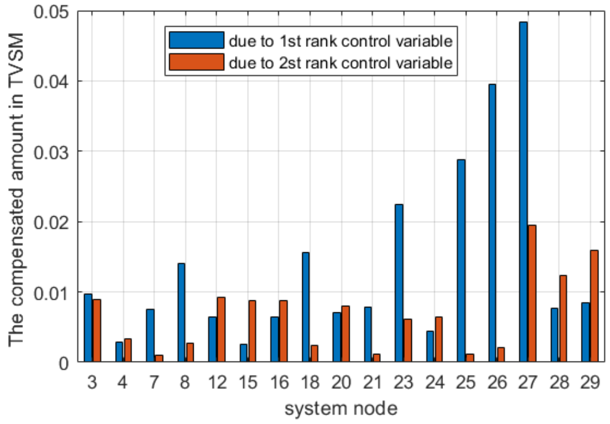

Fig.13. The compensated amounts in TVSM of IEEE 39-bus system for the line outage 3-18

4.6 Comparison of computation time

The computation time of the proposed approach and the linear sensitivity approach proposed in [13] is done in this section. The time includes the calculation of the voltage stability margin and the sensitivity analysis. IEEE 39-bus system at no contingency and IEEE 118-bus system with line 42-49 outage are used to investigate the results of this section.

For IEEE 39-bus system at no contingency, the results show that the calculation time of the proposed method is 0.23s. In contrast, 0.48s are required for the linear sensitivity method calculations. For IEEE 118-bus system with line 42-49 outage, 0.34s and 0.71s are required for the calculation of the proposed method and the linear sensitivity method, respectively. The difference in time calculation (0.25s or 0.37s) is due to the fact that the method proposed in [13] depends on solving the left eigenvectors of eigenvalues zero of the Jacobian matrix at the critical point while the proposed method depends on only solving differential equations. For M number of the preconceived contingencies, the difference in the calculation time will be multiplied by M (i.e. 0.25×M). This difference can also be much higher in case of practical system and optimization-based control. The time analysis is achieved using an i7–8850 H CPU @ 2.60 GHz laptop.

5. Conclusion

In this study, TVSM-sensitivity approach for preventive control selection in modern power systems is developed. The proposed method is successfully validated on two IEEE bus systems (39 & 118 bus systems) under different operation conditions. Simulation results show that the proposed sensitivity approach gives quantitative analyses of the impact of control variables on TVSM. The results also show that the sensitivity coefficients obtained using the proposed approach coincide with the results of the linear sensitivity method and CPF method. It is clear that the proposed approach has the ability to correctly rank the control variables.

The comparison of computation time is also investigated in this work. The results show that the proposed method is much faster than the classical method (linear sensitivity method). This demonstrates applicability of the proposed method for online applications.

In the future, our goals are to consider multiple critical contingencies in the analysis and develop a decentralized-based preventive control selection. The development of a new impedance loading margin with the aid of a state estimator is also part of our vision.

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