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Wide-area measurement-based voltage stability sensitivity and its application in voltage control

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ABSTRACT

This work proposes a measurement-based voltage stability index, namely wide-area measurement-based voltage stability sensitivity based on *L* index. The sensitivities of *L* index with respect to nodal reactive power (Q) and real power (P) injections are first derived. The derived *L-Q* and *L-P* sensitivities analyze the impact of nodal injection to nodal voltage stability and can help determine the reactive power compensation and emergency load shedding amount for voltage stability control. To improve the computational efficiency, a simplified *L* index, L', along with its sensitivities with respect to nodal reactive and real power injection (L'-*Q* and L'-*P* sensitivities) are derived which makes the proposed approach suitable for the practical large-scale systems. Moreover, a control strategy for voltage stability is proposed based on the *L-Q*, *L-P*, L'-*Q*, and L'-*P* sensitivities. The proposed sensitivities and control strategy are tested on the New England 39 bus system and the IEEE 118 system. Test results on both systems verify the proposed sensitivities and the control strategy by demonstrating their accuracy and robustness in voltage stability assessment and control. In conclusion, the proposed measurement-based sensitivities can be applied to voltage stability assessment and control by using the wide-area measurements.

1. Introduction

In large scale interconnected power systems, increasing penetration of renewable energy and ever growing demand have challenged the systems to operate closer to their voltage stability limits [1–7]. Consequently, voltage stability assessment (VSA) and control have received increasing attention [8–12].

Indeed, voltage stability has always been a major concern in modern power systems and has been extensively explored in the literature. In VSA, various voltage stability indices (VSIs) have been proposed for analyzing and monitoring the system stability [12]. Theses VSIs include the voltage stability factor (VSF) [13], loading margin [14], smallest eigenvalue of Jacobian matrix [15], voltage instability proximity index (VIPI) based on saddle-node bifurcation (SNB) [16], voltage controllability index (VCI) [17], local loading margin index (PLmgn) [18], closest loadability limit (CLL) based on multiple load flow solutions [19], etc. These indices have been widely used in VSA applications for assessing voltage stability and their sensitivities have been studied to evaluate impacts of parameter change on VSA. However, the aforementioned indices are all based on the power flow model of the system, which makes their accuracy highly dependable on the accuracy of the system model. In fact, models and parameters of a practical power system are updated by an energy management system (EMS) whose accuracy is affected by measurement noise, errors, and other uncertain factors. Moreover, the computational costs of these power-flow-based indices and their sensitivities increase drastically as the system scales up. Consequently, these model-based indices and sensitivities are mostly applied in system planning and other offline studies rather than in online applications.

Recently, the development of wide-area measurement systems (WAMS) has provided alternative VSA approaches to traditional model-based ones. Aided by WAMS, such measurement-based VSAs have become an important research area [20–34]. In [22], an online voltage security assessment based on a decision tree that is trained with offline simulation but makes decisions on phasor measurement unit (PMU) measurements has been proposed. In [23], an online VSA approach for system status monitoring and voltage collapse prediction is proposed through calculating the line stability index. In [24], a local voltage stability index based on Tellegen's theorem is proposed. In [25], by analyzing the voltage deviation of two consecutive measurements, a new online voltage stability index is proposed. In [26], based on the Thevenin

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equivalent circuit, an online VSA approach assessing three types of transfer margins (real, reactive, and apparent power) is proposed. In [27], a local voltage stability index, L index, with the range between 0 (no load) and 1 (voltage collapse) is proposed. Based on the L index of [27], an improved L index incorporating ZIP load model (ZIP load is a combination of constant-impedance, constant-current, and constant-power load component) is proposed in [28]. In [29], a hybrid approach which is capable of assessing voltage stability for N − 1 contingency is proposed. VSA approaches introduced by [23–29] are all based on Thevenin equivalent circuit of the power system. Theoretically, within a short time period, the outside system supplying one particular load bus can be represented by the two-bus Thevenin circuit. In [30], three consecutive measurements of voltage and current from PMU are used to correct the phase drifts caused by the measurement slip frequency. Although, in theory, the outside system can be equivalent into a Thevenin circuit, such strong simplification will lose important information or characteristics of the highly nonlinear power system.

If deployed online, measurement-based VSA approaches introduced in [20–34] are capable of increasing the situational awareness of the system operators by providing fast real-time assessment of the voltage stability. However, the approaches based on the Thevenin circuit, which is essentially a black box model, provide little analytical information of the system besides the one dimensional stable or instable information. Moreover, the existing works did not provide sensitivity analyses on the parameters of the Thevenin circuits, which are crucial for voltage stability prediction and control. From the view point of system operators, the information regarding which controls to take when facing the situation of voltage instability is equally important as the awareness of the instability. Clearly, in the existing works, there is significant effort regarding the latter issue, which focuses on improving the efficiency and accuracy of the measurement-based VSA [31–33], but little attention paid to the former issue of voltage stability prediction or control.

With such motivation, based on [27,28], this work provides the sensitivity analyses of the L index through its differential equation. The sensitivities of L index to nodal reactive and real power injection, i.e. L-Q and L-P sensitivities, are derived in order to investigate the impact of nodal injection on the voltage stability margin. Then, a simplified L index, L' and its sensitivities to nodal reactive and real power injection, L'-Q and L'-P sensitivities, have been proposed based on the same assumption made when deriving the DC power flow for transmission level. The L' index as well as the L'-Q and L'-P sensitivities are highly computational efficiencies and are suitable for large-scale interconnected power systems. Moreover, enabled by the proposed sensitivities, a voltage stability control strategy is proposed, which provides the system operator with effective control decisions on reactive power compensation and load shedding. Finally, the proposed sensitivities and control strategy are verified and analyzed on the New England 39-bus system and IEEE 118 bus system.

2. Voltage stability index and its simplification

2.1. Voltage stability index and sensitivities

Several approaches of PMU-based voltage stability assessment have been proposed in the literature and are compared in [34]. This work is based on the coupled single-port circuit (CSPC) concept proposed in [10]. The power system can be modelled as a multi-port network. All the generators and load buses are brought outside of the network. And the branches and the tie buses, the buses with no current injection to, are modelled inside the network. According to Kirchhoff's current law (KCL) in bulk power systems, the nodal current injections vector can be expressed as:

$$\begin{bmatrix} \boldsymbol{I_G} \\ \boldsymbol{I_L} \\ 0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{Y'_{GG}} & \boldsymbol{Y'_{GL}} & \boldsymbol{Y'_{GK}} \\ \boldsymbol{Y'_{LG}} & \boldsymbol{Y'_{LL}} & \boldsymbol{Y'_{LK}} \\ \boldsymbol{Y'_{KG}} & \boldsymbol{Y'_{KL}} & \boldsymbol{Y'_{KK}} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_G} \\ \boldsymbol{V_L} \\ \boldsymbol{V_K} \end{bmatrix} \tag{1}$$

where $\boldsymbol{V_G}$ and $\boldsymbol{I_G}$ are voltage and current vectors of generator buses; $\boldsymbol{V_L}$ and $\boldsymbol{I_L}$ are voltage and current vectors of load buses; $\boldsymbol{V_K}$ is voltage vector of interconnecting buses where no load or generator is attached to; Y'_{GG}, Y'_{GL}, Y'_{GK}, Y'_{LG}, Y'_{LL}, Y'_{LK}, Y'_{KG}, Y'_{KL}, and Y'_{KK} are corresponding submatrices of the system admittance matrix.

Eliminating the interconnecting buses, two types of buses are remained: the set of generator buses, $\boldsymbol{\alpha_G}$, and the set of load buses, $\boldsymbol{\alpha_L}$. The system in (1) can be further expressed by

$$\begin{bmatrix} \boldsymbol{I_G} \\ \boldsymbol{I_L} \end{bmatrix} = \begin{bmatrix} \boldsymbol{Y_{GG}} & \boldsymbol{Y_{GL}} \\ \boldsymbol{Y_{LG}} & \boldsymbol{Y_{LL}} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_G} \\ \boldsymbol{V_L} \end{bmatrix} \tag{2}$$

where $\boldsymbol{Y_{GG}} = \boldsymbol{Y'_{GG}} - \boldsymbol{Y'_{GK}}\boldsymbol{Y'^{-1}_{KK}}\boldsymbol{Y'_{KG}}$, $\boldsymbol{Y_{GL}} = \boldsymbol{Y'_{GL}} - \boldsymbol{Y'_{GK}}\boldsymbol{Y'^{-1}_{KK}}\boldsymbol{Y'_{KL}}$, $\boldsymbol{Y_{LG}} = \boldsymbol{Y'_{LG}} - \boldsymbol{Y'_{LK}}\boldsymbol{Y'^{-1}_{KK}}\boldsymbol{Y'_{KG}}$, $\boldsymbol{Y_{LL}} = \boldsymbol{Y'_{LL}} - \boldsymbol{Y'_{LK}}\boldsymbol{Y'^{-1}_{KK}}\boldsymbol{Y'_{KL}}$.

Let $\boldsymbol{Z_{LL}} = \boldsymbol{Y^{-1}_{LL}}$, (2) can be expressed by

$$\begin{bmatrix} \boldsymbol{I_G} \\ \boldsymbol{V_L} \end{bmatrix} = \begin{bmatrix} \boldsymbol{Y_{GG}} - \boldsymbol{Y_{GL}}\boldsymbol{Z_{LL}}\boldsymbol{Y_{LG}} & \boldsymbol{Y_{GL}}\boldsymbol{Z_{LL}} \\ -\boldsymbol{Z_{LL}}\boldsymbol{Y_{LG}} & \boldsymbol{Z_{LL}} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_G} \\ \boldsymbol{I_L} \end{bmatrix} \tag{3}$$

From (3), the terminal voltage of a load bus can be expressed by

$$\boldsymbol{V_L} = \boldsymbol{Z_{LL}}\boldsymbol{I_L} + \boldsymbol{Z_{LG}}\boldsymbol{V_G} \tag{4}$$

where $\boldsymbol{Z_{LG}} = -\boldsymbol{Z_{LL}}\boldsymbol{Y_{LG}}$.

According to (4), the detailed expression of voltage at load bus j, $\dot{V}_{Lj}$, is

$$\dot{V}_{Lj} = Z_{LLjj}\dot{I}_{Lj} + \sum_{\substack{i \in \alpha_L \\ i \neq j}} Z_{LLji}\dot{I}_{Li} + \sum_{k \in \alpha_G} Z_{LGjk}\dot{V}_{Gk} \tag{5}$$

where $\dot{I}_{Lj}$ and $\dot{I}_{Li}$ is the current injection at load bus j and i respectively; Z_{LLjj} is the self-impedance of load bus j; Z_{LLji} is the coupling impedance between bus j and i; Z_{LGjk} is coupling impedance between load bus j and generator bus k; and $\dot{V}_{Gk}$ is the terminal voltage at generator bus k.

Express $\dot{V}_{Lj}$ in (5) in terms of a combination of a voltage source $\dot{V}_{eqj}$ and current source $\dot{I}_{eqj}$:

$$\dot{V}_{Lj} = Z_{eqj}\dot{I}_{Leqj} + \dot{V}_{eqj} \tag{6}$$

where

$$\dot{I}_{eqj} = \dot{I}_{Lj} + \sum_{\substack{i \in \alpha_L \\ i \neq j}} \frac{Z_{LLji}}{Z_{eqj}}\dot{I}_{Li} \tag{7}$$

$$\dot{V}_{eqj} = -\sum_{k \in \alpha_G} Z_{LGjk}\dot{V}_{Gk} \tag{8}$$

$$Z_{eqj} = Z_{LLjj} \tag{9}$$

Multiplying $\dot{V}^*_{Lj}$ to both side of (6) yields

$$V^2_{Lj} + \dot{V}_{eqj}(\dot{V}_{Lj})^* = Z_{eqj}\dot{I}_{eqj}(\dot{V}_{Lj})^* \tag{10}$$

Define the equivalent apparent power at load bus j as $\dot{S}_{eqj} = \dot{V}_{Lj}(\dot{I}_{eqj})^*$. With $Y_{LLjj} = 1/Z_{LLjj}$, (10) can be further expressed as

$$V^2_{Lj} + \dot{V}_{eqj}(\dot{V}_{Lj})^* = (\dot{S}_{eqj})^*/Y_{LLjj} \tag{11}$$

Based on (11), the voltage stability index for load bus j, L_j, proposed in [27,28], L_j, can be represented as follows: