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Voltage collapse detection based on local measurements

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A B S T R A C T

This paper is concerned with voltage collapse detection in power systems. The concepts of voltage support surface and local balancing equation are used. Likewise, the use of the impedance matching concept, requiring only measurements taken at the corresponding bus without needing a reference signal, is proposed. The impedance matching equation is solved by direct and a recursive least squares algorithm. The estimated equivalent impedance becomes a multiple of the load impedance. Thus, proximity indices to the point of collapse (PoC) that requires just voltage magnitudes are presented. Voltage instability is evaluated through direct detection of PoC in loads and transit (no-load) buses. Voltage stability margin calculation without requiring the load flow solution at the bifurcation point is proposed. Taking constant *P*–*Q* load characteristics into account, the method is tested on the IEEE 14-bus test system by the continuation power flow (CPF) to estimate the path that the impedance and the proposed indices follow through stable and unstable operation regions. A dynamic evaluation of the method is performed when exponential recovery and motor loads are embedded.

1. Introduction

The voltage stability is a dynamic phenomenon by nature, but the use of steady-state analysis methods is permitted in many cases. The voltage stability assessment of static and dynamic methods should be close to each other when appropriate device models are used and voltage instability does not occur during the transit period of disturbance. The adequate use of a load-flow program for voltage stability analysis must consider a variety of effects such as generator voltage control, reactive power compensation, the distribution of the real power among the generation units with active governors, the voltage characteristics of the loads, etc. Unfortunately the method is computationally time consuming and appropriated use is difficult for on-line applications, such as steady-state security assessment, which requires a fast assessment of the voltage stability conditions and an estimation of how far a given operating point is from critical state.

Nowadays, it is important developing novel applications and tools that allow monitoring the power system's operation in a safe way, and that help to prevent severe conditions that may lead to voltage collapse [1–5], which consequences have led to researchers to develop analytical methods in order to determine the causes and to propose strategies for attaining safe operation. The phasor measurement unit (PMU) technology, together with advances in computational tools, networking infrastructure and communications, have opened new perspectives for designing voltage instability detection (VID) [6]. Thus, synchrophasors are quite useful devices that help to acquire reliable information.

The stability of the power system cannot be fully guaranteed with steady-state studies. On the other hand, devices which may have a key role in the voltage instability include those which may operate in a relatively long time frame (for instance, over-excitation limiters of synchronous generators and the on-load tap changer). Static analysis is ideal for the bulk of power system studies in which the examination of a wide range of power system conditions and a large number of contingencies is required.

In [7] a method based on synchrophasor measurements is proposed for early detection of instabilities. By sensitivities, it estimates the proximity to the generator's limits; eigenvalues' calculation of a Jacobian matrix is required. Likewise, a full modeling of dynamic elements is needed.

A method for real time monitoring and stability analysis is proposed in [8]. Hyper-planes are built in order to identify weak regions and bottle neck transmission corridors; continuation power flows are used for these purposes. To define the off-line stability limits, simulations are carried out. On the other hand, in [9] an extended set of equilibrium equations is fitted to the available system state. Then, an efficient sensitivity analysis is performed. The sensitivities of the total reactive power generation respect to individual loads is taken into account. These sensitivities are used to

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identify when a combination of load powers goes through a maximum.

Looking for making real time decisions related to voltage collapse, the impedance matching condition has received great attention in the last two decades [9–18]. The impedance matching condition reflects the inability of the generation–transmission system to provide the power requested by loads. The Thévenin Impedance Matching (TIM) is a useful tool for voltage instability detection (VID); this equivalent [12], and the subsequent related contributions [11,13–18], has been proposed for real time power systems control and protection, and several proximity indicators based on this concept have been developed [10,19–21]. The well-known Thévenin equation at the ith bus may be written as,

$$E_{Thev} = V_i + Z_{Thev} \times I_i \quad (1)$$

where E_{Thev} is the Thévenin's voltage at the ith bus; V_i is the ith bus voltage; Z_{Thev} is the equivalent impedance at the ith bus, and I_i is the corresponding injected bus current.

On the point of collapse (PoC), the equivalent impedance at the ith bus ($Z_{Thev,i}$) is equal to the load impedance ($Z_{Load,i}$). The impedance ratio is defined as [10],

$$k_i = \frac{||Z_{Thev,i}||}{||Z_{Load,i}||} \quad (2)$$

and may be used as a voltage instability index. For stable operation $k_i < 1$; at the PoC $k_i = 1$; and, for unstable operation, $k_i > 1$.

In order to compute $Z_{Thev,i}$, (1) may be rewritten in matrix form as

$$\begin{bmatrix} 1 & 0 & -g_i & -h_i \\ 0 & 1 & -h_i & -g_i \end{bmatrix} \begin{bmatrix} E_{Thev,r} \\ E_{Thev,i} \\ R_{Thev,r} \\ X_{Thev,i} \end{bmatrix} = \begin{bmatrix} u_i \\ w_i \end{bmatrix} \quad (3)$$

where $E_{Thev} = E_{Thev,r} + jE_{Thev,i}$; $V_i = u_i + jw_i$; $I_i = g_i + jh_i$; $Z_{Thev} = R_{Thev,r} + jX_{Thev,i}$. Note that elements g_i, h_i, u_i and w_i are directly available from measurements at the local bus. The unknowns become $E_{thev,r}$, $E_{thev,i}$, $R_{thev,r}$, $X_{thev,i}$. Measurements taken at two or more different times are required to calculate the unknowns. These measurements must be referenced to avoid invalid estimation caused by the discrepancy between the system frequency and the PMU sampling frequency, which will cause a drift in the measured phase angles [16,17]. The reference signal usually comes from another bus in the system, which implies the need of robust communication schemes to ensure a proper operation of the protection and control systems based on this estimation. To suppress oscillations, a larger data window needs to be used. Therefore, the estimation attempts to minimize the error in the least squares sense [12]. By recursive least squares the expression is solved in [14]. In [15] the model parameters are estimated by an adaptive algorithm, assuming zero resistance. The method is extended to *transit* buses (no-load buses) in [18]. A method based on three successive PMU measurements is developed in [16]. Likewise, a nonlinear least squares strategy is used in [17]. Based on the Tellegen's theorem, in [13] it is shown that solution to (3) becomes $Z_{thev} = \Delta V_i^* / \Delta I_i$, where the increments are calculated between two consecutive measurements.

In this paper, an impedance matching algorithm that uses only measurements taken at the corresponding bus, without needing a reference signal, is proposed. For this application, PMU is not absolutely necessary to estimate equivalent parameter. The use of no-referenced measures and the need of load variation at several samplings imply that remote terminal units (RTU) data can be used. The concepts of voltage support surface, local balancing equation, and local impedance matching are presented. Based on the concept of a voltage support surface, different proximity indices to PoC are derived. The distance from the critical state is usually quantified by one of the so-called voltage stability indices. The extended use of indices as those studied in this paper, lies in the fact that they are useful tools for estimating the proximity to voltage collapse in power systems. It is intended to analyze indices able to be used under on-line environment. In this context, it is relevant that such indices are reliable, using enough information, available from conventional measurements received at the control centers, and with competitive time consuming. In the first part of the paper, an exploration of indices satisfying the above-mentioned requirements is made. The second part presents simulations with the purpose of showing that the analyzed indices satisfy conditions which make them useful for detecting the point of collapse (PoC). Results indicate that the studied indices give a right picture of what could be expected, and are compared respect to the widely used continuation power flow (CPF). The path that proposed indices follow through stable and unstable operation regions is analyzed. Additionally, a dynamic evaluation of the method is performed for different load configurations.

2. Voltage collapse indices

For the purpose of this paper, the power flow model is used, where the variations of constant active and reactive powers are assumed to be the main parameter driving the system to a singularity. Although this simple system model is certainly not adequate to thoroughly study the voltage collapse phenomenon, for certain particular dynamic models, the power flow equations yield adequate results, as singularities in the related power flow Jacobians can be associated with actual singular bifurcations of the corresponding dynamical system [22]. Moreover, regardless of the direct relations between singularities of the power flow Jacobians and the actual bifurcations of the full dynamical system, it is always of interest to determine the system conditions where the power flow problem is not solvable, as most operating decisions nowadays are made on-line based on power flow solutions. Thus, various utilities throughout the world currently use indices as those here discussed, and base some of their operating decisions related to voltage collapse problems mostly on a power flow system model [22].

Multiplying (1) by V_i^*, the next expression is obtained,

$$||V_i||^2 + ||V_i||e^{-j\theta_i}V_{0i} - \frac{S_i^*}{Y_{equ,i}} = 0 \quad (4)$$

where

$$V_{0i} = -E_{Thev} \quad (5)$$

$$Y_{equ,i} = -\frac{1}{Z_{Thev,i}} \quad (6)$$

A similar expression may be written from the power balance equation at the ith bus,

$$V_{0i} = \sum_{j=1 j \neq i}^{n} \frac{Y_{ij}V_j}{Y_{ii}} = ||V_i||e^{j\theta_i} \quad (7)$$

$$Y_{equ,i} = Y_{i,i} \quad (8)$$

In (4)–(8), V_{0i} is the *voltage support* complex term, $Y_{equ,i}$ is the equivalent admittance, and S_i is the complex power; * means conjugate. Eq. (4) is not restricted to load buses. Note that, for a set of measurements V_i, P_i and Q_i, there are infinite number of combinations for the equivalent impedance and the voltage support term. Likewise, it is worth noting that voltage V_{0i} implicitly takes grid's