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VOLTAGE STABILITY MARGIN IDENTIFICATION USING LOCAL MEASUREMENTS AND LINEAR KALMAN FILTER

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ABSTRACT

Voltage stability investigation is of a great importance for long-term electric load expansion as well as power system operation. This paper presents a new algorithm for identification of voltage instability in a specified load bus in a power system. The proposed algorithm is based on the linear Kalman filtering algorithm and the maximum power transfer principle. The proposed technique is used to identify Thevenin's equivalent circuit at a bus for different loading conditions, either when the total system loads change at the same rate (long-term voltage stability problem) or when a load on a certain bus changes. The proposed algorithm uses the real measurements at the bus in question to calculate the load impedance. These measurements are the load voltage and current. Thus, it can be implemented on-line on the control centers to investigate the voltage stability. The proposed algorithm is implemented to the standard IEEE 30-bus system.

KEY WORDS: Voltage stability, Kalman filter Algorithm, Thevenin's circuit, maximum power transfer.

1. INTRODUCTION

Voltage stability and system security are of great concern to planning engineers in the electric power industry. Owing to several widespread system blackouts throughout the world, resulting from voltage collapse, the problem of voltage stability has attracted continuous interest of researchers in the last two decades. Reference [1] presents an approach using fuzzy set theory for voltage and reactive power control of power systems. This approach takes both voltage security enhancement and loss reduction into account, where the violation level of buses voltage and controlling ability of controlling devices are transferred into fuzzy set notation by using a linear model [14].

Reference [2] coordinates excitation and unified power flow control (UPFC) to improve power system transient and voltage stability. A robust approach is used to deal with uncertainties caused by parameter variations and the inclusion of UPFC controller. Simulation results show that the coordinated excitation and UPFC control is effective for transient enhancement. Modal analysis has been widely employed in voltage stability studies. Literature shows that monitoring the largest eignvalue/singular value as a function of load increase may drive one to incorrect conclusions, since these values present a sharp variation at the bifurcation point. Reference [3] applies the center manifold theorem to calculate some linear indices for voltage collapse analysis with the help of critical bus identification.

Reference [4] introduces the concept of interface flow margin in terms of steady-state voltage stability. The interface flow margin is available to determine the secure limit of the interface flow under a fixed load condition. Reference [5] develops a voltage security assessment tool based on fast time domain simulation engine. Its main features are the simulation of voltage stability phenomena and slow dynamics, the computation of different kinds of security margins, the suggestion and the validation of corrective actions.

Several analysis methods are available for long-term voltage stability. The V-Q curve power flow method is widely used by utilities and has some advantages. Long-term dynamic simulation with proper modeling, however, is clearly the most accurate simulation method. Results from the V-Q method can be misleading. The same is true of other power flow program based analysis employing conventional modeling. Results from these power flow methods may be pessimistic, causing an over-design or overly conservative operation [6]. A risk-based approach to security assessment for a voltage stability constrained power system is provided in Reference [7]. The risk calculation provided accounts for both future uncertainties on the system and the sequence associated with voltage collapse and violation of limits.

Effects of the generator excitation current limit, the on-load tap changer (OLTC) and load dynamics on voltage stability are analyzed in state space in Reference [8]. Reference [9] presents a data-processing method to estimate the proximity to voltage collapse. The method employs only local measurements-bus voltage and load current- and calculates the strength of the transmission system relative to the bus. The collapse occurs when the local load approaches this value.

The voltage stability of a system is determined by the dynamic characteristics of both the OLTC and the load. The reactive power allocation is used to control the voltage stability in Reference [10], where a method of determining the best location for shunt compensation is presented. The method is based on the sensitivities of the change in reactive power flow with respect to the change in reactive power injection. The linear programming optimization technique is used to find the amount of shunt compensation, where the objective is to minimize the risk of voltage collapse. A weighted least square minimization of the voltage deviation is applied in Reference [11] to put more weight on important load buses, i.e. it is acceptable to have relatively high or low voltages at connecting buses. This method does not solve exact load flow equations, and therefore it avoids inversion of full system size matrix.

This paper presents a new algorithm for identification of voltage instability in a specified load bus in a power system. The proposed algorithm is based on a linear Kalman filtering (KF) algorithm and the maximum power transfer principle. The proposed technique is used to identify Thevenin's equivalent circuit at a bus for different loading conditions, either when the total system loads change with the same rate (long-term voltage stability problem) or when a load on a certain bus changes. The proposed algorithm uses the real measurements at the bus in question to calculate the load impedance. These measurements are the load voltage and load current. Thus, it can be implemented on-line on the control centers to investigate the voltage stability. The proposed algorithm is implemented to the standard IEEE 30 bus system.

2. PROBLEM FORMULATION

The Thevenin's equivalent circuit at any load bus is given in Figure 1. The measured value at the load bus is the voltage amplitude, the load active and reactive power, and accordingly the load power factor and the load bus angle with respect to the slack bus. In this figure the following symbols are used

Z_{th} is the Thevenin's equivalent impedance at a certain loading condition seen by the load bus in question., $Z_{th} = R_{th} + jX_{th}$,

V_{th} is the Thevenin's voltage at a certain loading condition seen by the load bus under consideration

$V_{th} = a + jb$

I_L is the load current $= I_a + jI_r$

V_L is the load voltage $V_L = c + jd$

Z_L is the load impedance magnitude $= \dfrac{|V_L|}{|I_L|}$

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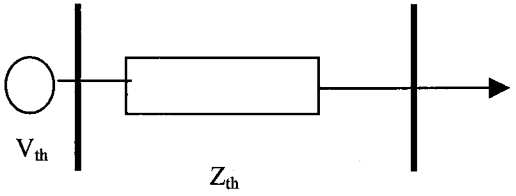

Load, $\mathbf{Z_L \angle \theta} = \dfrac{V_L}{I_L}$

Fig. 1 Thevenin's equivalent circuit at bus

At maximum power transfer, the point beyond which a voltage collapse occurs, the load impedance magnitude is equal to the Thevenin's impedance magnitude [1].
$|Z_L| = |Z_{th}|$

Applying KVL to the equivalent circuit at bus I gives

$$V_{th} = V_i + I_L Z_{th} \tag{1}$$

Where V$_{th}$ is the Thevenin's equivalent voltage seen by bus i, V_i is the voltage of bus i, it can be measured on line for on line identification or from the load flow analysis for long-term identification. I_L is the load current connected to bus i. It is also measurable quantity for on-line application. Or can be calculated from the load power and load voltage. Finally, Z_{th} is the Thevenin's equivalent impedance seen by bus i. Equation (1) can be written in rectangular form as:

$$a + jb = (c + jd) + (I_a + jI_r)(R_{th} + JX_{th}) \tag{2}$$

The real parts of the above equation give

$$a = c + I_a R_{th} - I_r X_{th} \tag{3}$$

While the imaginary part gives:

$$b = d + I_r R_{th} + I_a X_{th} \tag{4}$$

Equation (3) and (4) can be combined together to give equation (5)

$$\begin{bmatrix} c \\ d \end{bmatrix} = \begin{bmatrix} 1 & 0 & -I_a & I_r \\ 0 & 1 & -I_r & -I_a \end{bmatrix} \begin{bmatrix} a \\ b \\ R_{th} \\ X_{th} \end{bmatrix} \tag{5}$$

The above equation is valid at any load bus on the system. In vector form, equation (5) can be written at any load j as:

$$Z_j = H_j X + \zeta_j \tag{6}$$

For on-line voltage stability identification, j may by the loading condition at the bus in question for every hour, since the voltage and current and hence the load impedance are measurable quantities. However, for long-term voltage stability identification, j may be the percent load power more than the base load at each bus. If m measures are available, then equation (6) can be written in vector form as:

$$\underline{Z} = H \underline{X} + \underline{\zeta} \tag{7}$$

Where $\underline{Z}$ is a $2m \times 1$ voltage components vector, H is a 2m x 4 observation matrix, $\underline{X}$ is a 4 x 1 state vector to be identified and $\underline{\zeta}$ is a 2m x1 associated error vector to be minimized.

The state space equation for system states can be written as:

$$\underline{X}(k+1) = \phi \underline{X}(k) + \underline{\upsilon}(k) \tag{8}$$

Equations (7) and (8) are now suitable for Kalman filtering applications. Steps behind the filtering process are explained in Appendix A.

3. TESTING THE ALGORITHM

The IEEE 30 bus system is used to test the proposed algorithm. Two tests are performed, while in the first test, the load power in a certain load bus is changed, while keeping the load power factor constant, gradually and Thevenin's impedance is predicted at different load buses. Figures 2, 3 and 4 show the variation of the load impedance as well as Thevenin's impedance with the load power at bus number 21, 26 and 30 respectively.

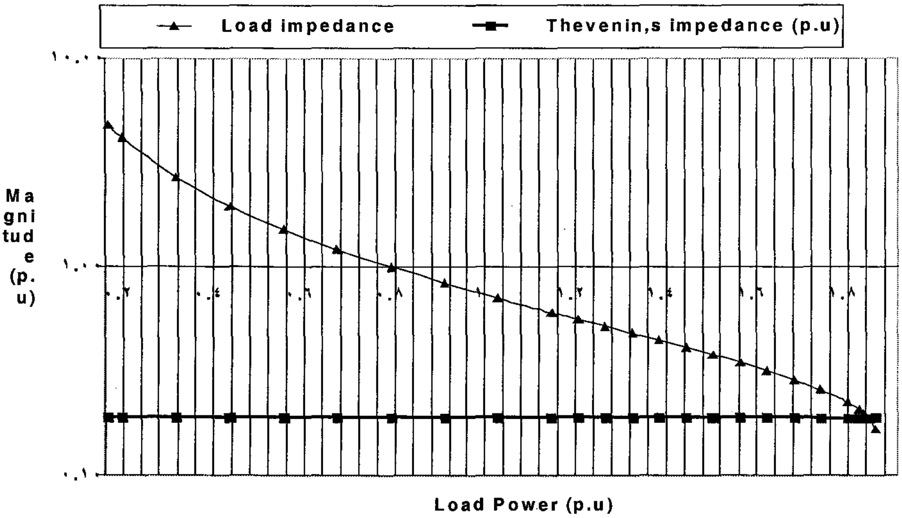

Figure٢ . Variation of load and Thevenin's impedances with load power at Node١#

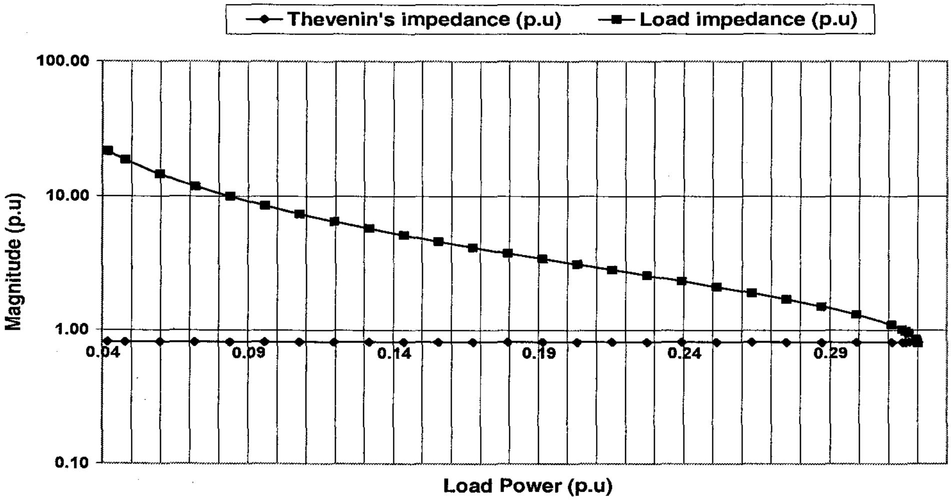

Figure 3. Variation of Load and Thevenin's impedances with load power at Node # 26

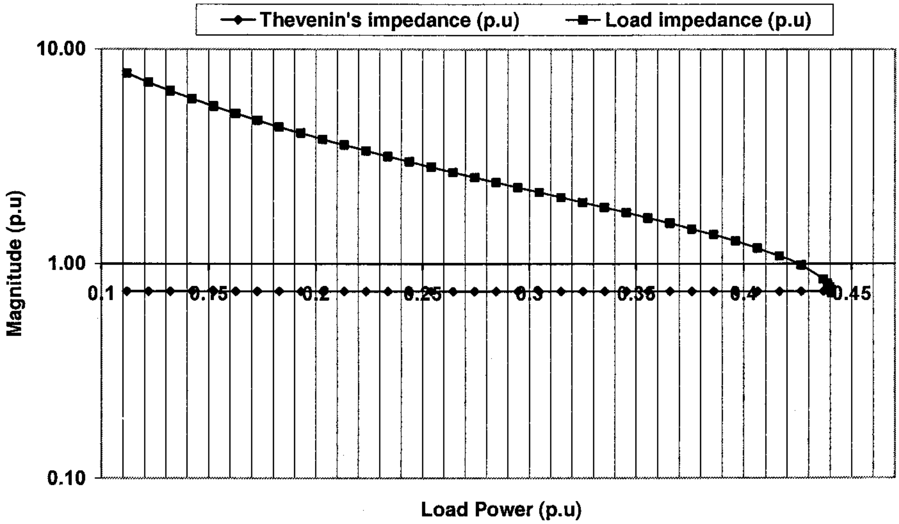

Figure 4. Variation of Load and Thevenin's impedances with load power at node # 30

Examining these Figures reveals the following remarks:

- The magnitude of Thevenin's impedance seen by each load bus under investigation is almost constant and does depend on the load power at that bus.

- The load powers at which the load impedance equals Thevenin's impedance, point of maximum power transfer, beyond which voltage instability occurs, are totally different for the three buses. For bus # 21 this power is 1.882 p.u more than the base power, while for bus # 26, this power is 0.32 p.u more than the base power. Finally, for bus # 30 this power is 0.44 p.u more than the base power.

- According to these figures, one can notice how much power the bus can feed its load before voltage instability occurs.

- It be noted from this study that bus # 21 is the strongest bus among these three buses. Sine a great amount of power be fed to its load before voltage instability occurs.

In the second test, the system loads on each load bus are changed with the same ratio. Figure5 gives variation of load and Thevenin's impedances with the load power at bus # 30. Examining this curve reveals the following:

- As system loads change with the same rate, the load impedance equals Thevenin's impedance at a load of 0.28 p.u, which is smaller than that if the load at bus # 30 changes alone.
- The load impedance and Thevenin's impedance at the critical point equal to 1.6 p.u, which is larger than that of the case when the load at bus # 30 changes alone.

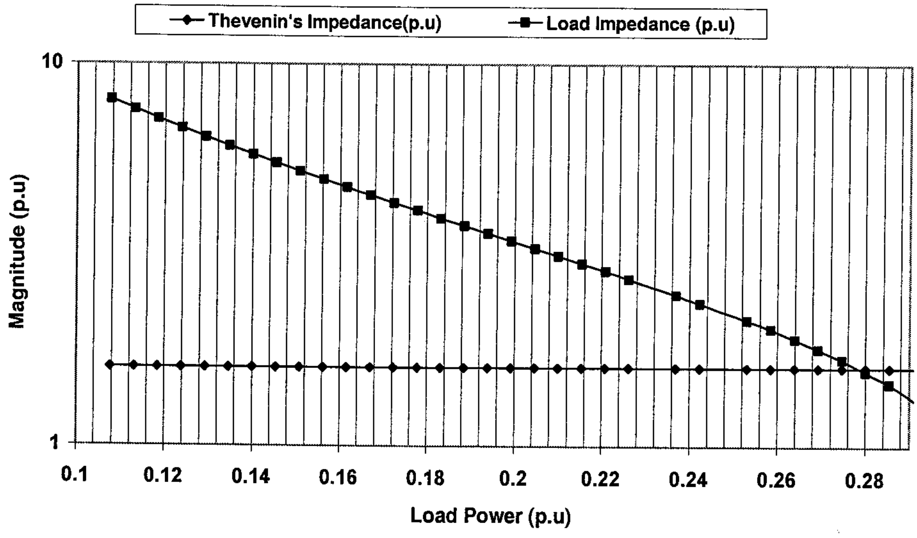

Figure 5. Variation of load and Thevenin's impedances with the load power at Node # 30, System loads change with the same rate

- The critical point in this test occurs at load power smaller than that occurs in the first test for the same load bus.

4. CONCLUSIONS

In this paper Kalman, filtering algorithm is implemented to identify the critical point beyond which voltage instability may occur. Two tests have performed. In the first test, the load power at a certain load bus is changed while the load power factor is kept constant and Thevenin's impedance is measured, during the range of variation, for other load buses. The range of variation should include the critical point. This test can be applied for short-term voltage stability studies. In the second test, the loads of the system in all load buses are changed with the same ratio, long-term voltage stability and Thevenin's impedance is measured for a specific bus in question. The only measurements needed, in the two tests, are the load voltage and load current at the bus in question. The results obtained in this paper show that Kalman filter algorithm is an effective algorithm for measuring Thevenin's impedance for short-term and long-term voltage stability studies, unlike the other techniques available in the literature that use the bus impedance matrix or single value decomposition technique.

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APPENDIX A

Kalman Filter Algorithm

In the implementation of Kalman filter, the mathematical model for the system under consideration should be in the state form as:

$$x(k+1) = \phi(k)x(k) + \omega(k) \tag{A1}$$

and the observation (measurement) of the process is assumed to occur at discrete points of time in accordance with the relation:

$$z(k) = H(k)x(k) + v(k) \tag{A2}$$

Assume that we have a prior estimate $\bar{x}(k)$, and its error covariance matrix $\bar{P}(k)$; then the general recursive filter equations are as follows:

(i) Compute the Kalman gain filter, K (k), as

$$\mathrm{K(k)} = \bar{\mathrm{P}}(\mathrm{k})\,\mathrm{H}^{\mathrm{T}}(\mathrm{k})[\mathrm{H(k)}\,\bar{\mathrm{P}}(\mathrm{k})\,\mathrm{H}^{\mathrm{T}}(\mathrm{k}) + \mathrm{R(k)}]^{-1} \tag{A3}$$

(b) Compute the error covariance for the update

$$P(k) = [I - K(k)H(k)]\bar{P}(k) \tag{A4}$$

(c) Update the estimate with the measurement z (k) as:

$$x(k) = \bar{x}(k) + K(k)\left[z(k) - H(k)\,\bar{x}(k)\right] \tag{A5}$$

(d) Project ahead, the error covariance and the estimate

$$P(k+1) = \phi(k)\,\bar{P}(k)\phi^{T}(k) + Q(k) \tag{A6}$$

$$x(k+1) = \phi(k)\,\bar{x}(k) \tag{A7}$$

Initialization of the Kalman Filter

For off-line application, it is necessary to initialize the recursive process of the Kalman filter, with an initial vector x_o^- and its initial covariance matrix P_O. In addition, the system and measurement noise variances are needed.

A simple deterministic procedure is implemented to calculate the initial process vector, as well as its covariance matrix, using the static least error squares estimate of the previous measurements. Thus, in general the initial process vector may be computed as:

$$\bar{x}_O = \left[H^T H \right]^{-1} H^T z \tag{A8}$$

and the corresponding covariance error matrix is

$$P_O = \left[H^T H \right]^{-1} H^T \tag{A9}$$