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Voltage Stability Evaluation by Using Maximum Power Transfer Phasor Diagram

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Abstract: From voltage stability point of view, maximum permissible loading limits must not be exceeded in operation of power systems. In this study, a maximum power transfer phasor diagram is proposed for easy evaluation the relations between major parameters affecting voltage stability margins. In construction of that diagram, local bus measurements and estimated parameters of Thevenin equivalent for N-bus power system are used. Critical values for major parameters and a voltage stability margin are evaluated from the constructed phasor diagram.

Key words: Voltage stability, voltage stability margins, maximum power transfer

INTRODUCTION

In recent years, economical and environmental reasons have forced the transmission systems to be operated closer to their security limits. Traditionally, their limits are associated with thermal and transient stability limitations. As a result of this new operating trend, power systems worldwide have become increasingly concerned with voltage stability and collapse problems (Van Cutsem and Vournas, 1998).

The voltage stability problem can be analyzed using the conventional P_V or Q_V curve. A series of Load Flow (LF) simulations with successively increased load at a constant power factor (pf) is usually required to generate the P_V curve of a particular bus. However, there is a critical load point beyond which there is no LF solution and thus the LF method would not converge. Such a load point represents the ‘knee’ point of the P_V curve. The Q_V curve is also plotted from the results of a series of LF simulations with slightly modified initial conditions. In generating the Q_V curve, the power of the candidate bus is kept constant and a fictitious synchronous condenser, without any reactive power limit, is added to the bus. The reactive power of the synchronous condenser is then plotted against the specified bus voltage. However, there is a minimum voltage beyond which the LF algorithm will again fail to converge and it represents the ‘knee’ point of the Q_V curve (Koessler, 1997).

The voltage stability problem can also be analyzed using the singularity criterion of the Jacobian matrix, multiple LF solutions, bifurcation theory, energy method and P_Q plane method which gives more compact evaluation for loading margins. All the methods described above require a considerable amount of calculations and thus cannot be candidates for on-line application (Alzahawi *et al.*, 2005).

Haque (2003) proposed a simple method of estimating the maximum permissible loading and voltage stability margin of a power system using some locally measurable quantities, such as bus voltage magnitude and the active and reactive components of load power. Any change in network topology or operating point usually modifies the system voltage profile and the method fully exploited this behavior of the system to update the estimated value of maximum permissible loading.

This study establishes a maximum power transfer phasor diagram which enables one to evaluate relations between the parameters affecting voltage collapse phenomena. By using given diagram, critical values for voltage stability and margin assessments will be written and the effects of local bus and system side parameters will be concluded easily. The maximum power transfer phasor diagram also gives a better understanding in voltage stability related courses.

MODELING OF THE POWER SYSTEM

It is a well known approach that a power system having any number of generators, transmission lines and loads can be modeled in a Thevenin Equivalent form. In Fig. 1 (Yalcin, 1995) Thevenin Equivalent of power system for load bus k having a load of $S_k = P_k + i.Q_k$ is shown.

At local bus k, load parameters such as voltage (V), current (I), power (P) and reactive power (Q) can be measured easily. So the problem is finding of Thevenin Equivalent Circuit parameters. To find Thevenin parameters an estimation method by using measured local bus parameters is necessary. An easy method of estimation is suggested by Haque (2003).

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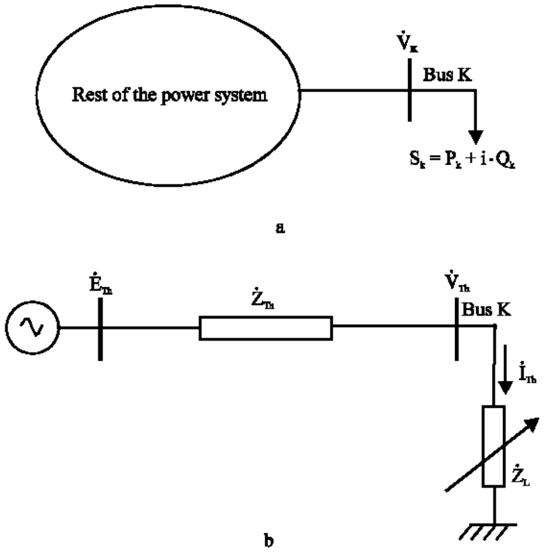

Fig. 1: Representation of load bus k in a general power system

DRAWING MAXIMUM POWER TRANSFER PHASOR DIAGRAM

From measurements at local bus k, the below parameters are obtained:

$$\dot{V}_k = V_k\angle 0\ \dot{I}_k = I_k\angle\varphi$$
$$P_k; Q_k$$

Estimated Thevenin parameters of power system are

$$\dot{E}_{Th} = E_{Th}\angle\delta; \dot{Z}_{Th} = Z_{Th}\angle\alpha$$

Short circuit current for bus K is

$$I_{k,sc} = \frac{E_{Th}\angle\delta}{Z_{Th}\angle\alpha} = I_{k,sc}\angle\delta-\alpha$$

Lets define

$$-\beta = (\delta - \alpha) + \varphi$$

In Thevenin impedance triangle $\alpha + \gamma = 90°$.
From Fig. 1 voltage equation is

$$\dot{V}_k = \dot{E}_{Th} - \dot{Z}_{Th}\cdot\dot{I}_k \tag{1}$$

and load equation

$$\dot{V}_k = \dot{Z}_L\cdot\dot{I}_k \tag{2}$$

From the equality of Eq. 1 and 2

$$\dot{E}_{Th} - \dot{Z}_{Th}\cdot\dot{I}_k = \dot{Z}_L\cdot\dot{I}_k$$

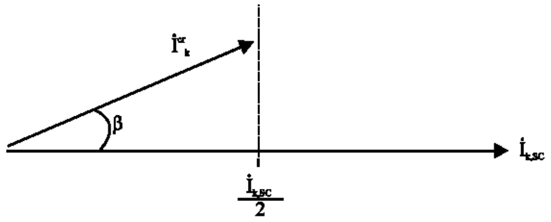

Fig. 2: Current phasors

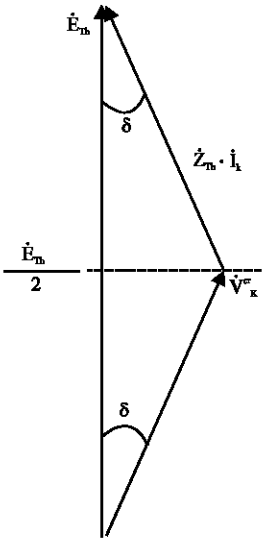

Fig. 3: Voltage phasors

For maximum loading $Z_L = Z_{Th}$ and the other parameters will then be critical:

$$\dot{E}_{Th} - 2\cdot\dot{Z}_{Th}\cdot\dot{I}^{cr}_k = 0$$

$$\dot{I}^{cr}_k = \frac{\dot{E}_{Th}}{2\cdot\dot{Z}_{Th}} = \frac{\dot{I}_{k,sc}}{2}$$

For maximum loading $\dot{I}^{cr}_k$ is always on the dashed line perpendicular to $\dot{I}_{k,sc}/2$

From Fig. 2, critical current magnitude of bus k can be written as:

$$I^{cr}_k = \frac{I_{k,sc}}{2\cdot\mathrm{Cos}\beta} \tag{3}$$

For maximum power transfer; $Z_L = Z_{TH}$

$$Z_{Th}\cdot I_k = Z_L\cdot I_k = V^{cr}_k$$

Phasor diagram of Eq. 1 is given in Fig. 3. From the diagram, it can be easily shown that $\dot{V}^{cr}_k$ is always on the dashed line perpendicular to $\dot{E}_{Th}/2$ with the magnitude of

$$V^{cr}_k = \frac{E_{Th}}{2\cdot\mathrm{Cos}\delta} \tag{4}$$

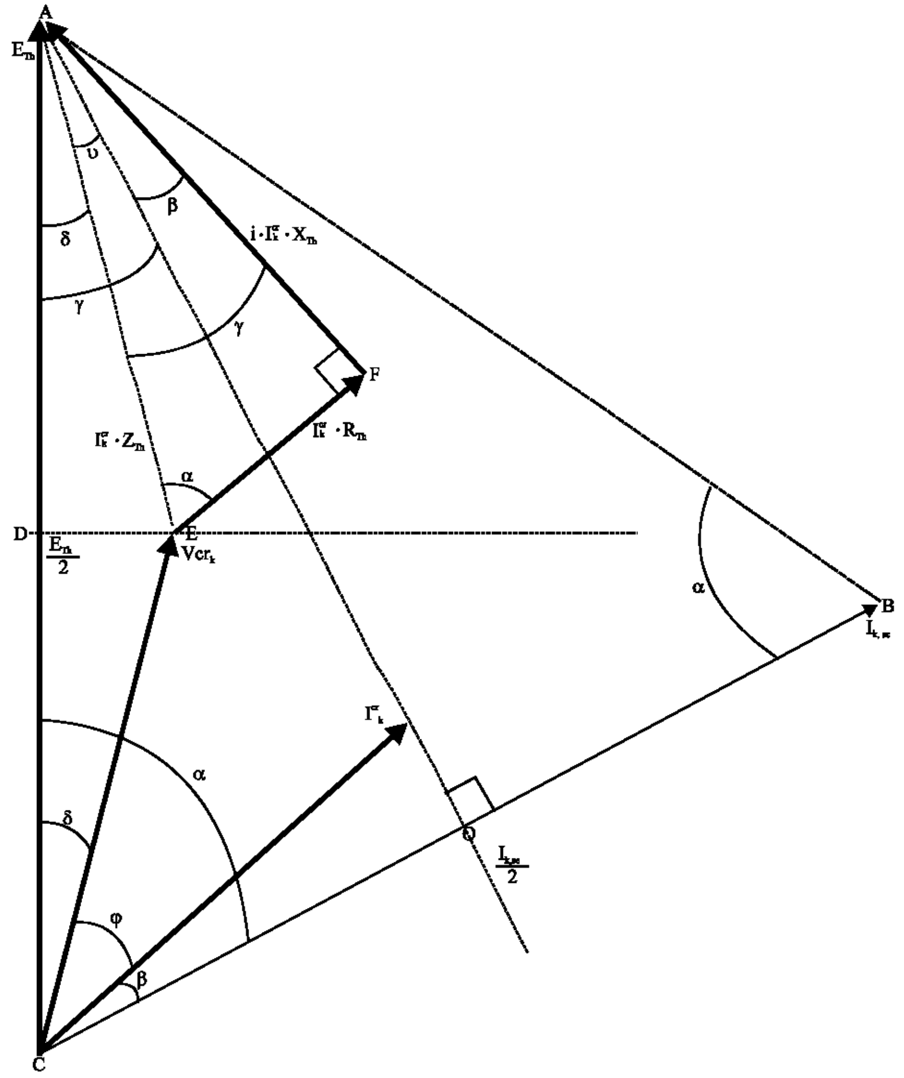

Fig. 4: Maximum power transfer phasor diagram

By the above parameters and Eq. 1, 3 and 4, we can construct the maximum power transfer phasor diagram given in Fig. 4.

In phasor diagram ABC is an isosceles triangle; triangles AEF and ACO are similar.

RESULTS

To get the critical values, first of all, lets fix some equalities in Fig. 4:

$v = \gamma - \beta$ and with the other relation
$v = \gamma - \delta$ yields

$$\beta = \delta \tag{5}$$

Equation 5 shows that at maximum power transfer point $\beta = \delta$. This result decreases the parameters for maximum loading expressions and it will be easier to express critical values in terms of δ.

From the voltage stability point of view, resultant critical values of major parameters will be given as follows:

$$V_k^{cr} = \frac{E_{Th}}{2 \cdot \mathrm{Cos}\delta} \tag{6}$$

$$I_k^{cr} = \frac{I_{k,sc}}{2 \cdot \mathrm{Cos}\delta} \tag{7}$$

By using Eq. 6 and 7:

$$S_k^{cr} = \frac{S_{k,sc}}{4 \cdot \mathrm{Cos}^2\delta} \tag{8}$$

where $S_{k,sc}$ is the short circuit apparent power for bus k.

From Fig. 4, we can define the angle φ in terms of α and δ:

$$\gamma + 2.\delta + \varphi = 90°$$
$$\alpha + \gamma = 90°$$

$$\varphi = \alpha - 2.\delta \tag{9}$$

Where α is the angle of system Thevenin impedance. Critical active power;

$$P^{cr}{}_k = S_{k,cr} \cdot \mathrm{Cos}\varphi$$

$$P^{cr}{}_k = S_{k,cr} \cdot \mathrm{Cos}(\alpha - 2\delta) \tag{10}$$

Critical reactive power;

$$Q^{cr}{}_k = S_{k,cr} \cdot \mathrm{Sin}\varphi$$

$$Q^{cr}{}_k = S_{k,cr} \cdot \mathrm{Sin}(\alpha - 2\delta) \tag{11}$$

Determination of the maximum loading of a power system is essential for operating the system with an adequate security margin. Different security margins were defined in the literature (Alzahawi *et al*., 2005). In this paper, a new security margin is proposed as follows:

$$\mathrm{VSM}_I = \frac{I_k^{cr} - I_k}{I_k^{cr}} \tag{12}$$

CONCLUSION

This study proposes a very simple method for estimating maximum permissible loading and Voltage Stability Margin (VSM_I) of a power system using maximum power transfer phasor diagram constructed by some measured local bus parameters and estimated system side parameters.

By use of proposed phasor diagram, for the maximum loading condition, the angle β is proofed to be equal to δ in Eq. 5. All critical values evaluated are given as a function of δ which is the major parameter in stability studies. Obtained critical values are not fixed and depend on the system Thevenin parameters and loading conditions. Therefore, critical values and VSM_I have to be updated with online measurements and estimation. With the maximum power transfer phasor diagram constructed in this study, it will be easier to understand and express the relations affecting voltage collapse phenomena. That phasor diagram will also be used in voltage stability related courses with the benefit of easiness.

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