Electrical Power and Energy Systems 28 (2006) 324–330

ELECTRICAL POWER & ENERGY SYSTEMS

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An improved method for assessing voltage stability based on network decomposition

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Received 12 October 2005; accepted 13 December 2005

Abstract

In this paper, we present an improved method for assessing the voltage stability based on network decomposition. It is an analytical approach to find the radial paths that are transformed into two-bus equivalents combined with an analytically proven test for the voltage-collapse proximity measure that has a physical meaning. The first modification allows for power-flow tracing that obtains the generator active- and reactive-power shares on each section of a radial path. The shares make it possible to allocate the transmission losses among the generators, which are required to assess the voltage-collapse proximity. Based on the reactive-power tracing, the improved approach also makes it possible to assess the availability of reactive-power sources and their ability to supply load buses. The proposed solution is faster than the existing search algorithm and gives more accurate results. The method was tested on the IEEE 39-bus test system.

Keywords: Network decomposition; Power-flow tracing; Radial paths; Voltage-collapse proximity; Voltage stability

1. Introduction

Changes in the energy market have introduced new requirements for the operation and control of power systems. The objectives in this new environment are a higher return on investment and a more efficient exploitation of the existing network infrastructure. A consequence of these changes is that transmission lines are reaching their voltage-stability margins.

Voltage instability can be caused either by the inability of reactive-power sources to produce enough reactive power to supply load buses, or by the inability of the power lines to transmit the required reactive power to the buses. Although the nature of the voltage instability is dynamic, many system-oriented approaches are based on static models [1–5] because of their simplicity. Dynamic methods [3–6] are a far better choice if a more comprehensive analysis is required. They are, however, more time consuming. Most of the available static methods are based on an analysis of the system's Jacobian matrix, either by exploiting its sensitivity [3,7] or by determining its closeness to the singularity [5,8,9]. Since these solutions sometimes have no clear path to a physical interpretation of the process, two new methods with a physical meaning were recently proposed. The first method is based on network decomposition [10–13], which means it is more complex and time consuming; the second method is based on local phasors [14,15], which means it is faster and more exact, and it provides results by considering two operating states with a slight difference in the total system loading. The main problem with this second method is the selection of these two states. However, another problem is that this method does not identify whether the voltage collapse is caused by a lack of reactive-power production or by an insufficient power-transfer capability.

In this study, we looked at modifying the method based on network decomposition in the hope that it would provide us with a new, faster, and a more exact approach. A novelty of the proposed solution is the incorporation of reactive-power tracing, which is required to define the voltage phasors of each bus of a two-bus equivalent of the radial transmission path. On this basis, two voltage-collapse proximity indices can be formulated. These indices are related to the inability of the sources to produce enough reactive power to supply a critical load bus and the inability of the power lines to transmit the required reactive power to the bus.

Since the proposed approach is based on power-flow-tracing methods, it is essential to point out that several solutions have already been proposed [16–20], of which the decoupled TGDF

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doi:10.1016/j.ijepes.2005.12.005

method [21] seems to be the most appropriate for coping with the voltage-stability assessment. Our proposed method allocates the transmission losses among the generators without any matrix expansion; it is also appropriate for reactive-power analyses. Our method is faster, especially when compared to the TGDF method [16,17], which can also be applied to the area of voltage instability discussed in this paper.

The proposed modified method, based on network decomposition, was exhaustively tested on the IEEE 39-bus test power system. According to the results, which show the advantage of the new solution, it can be concluded that the method is suitable for a more appropriate contingency analysis.

2. Proposed improvement of the method

To understand the proposed modification, the original method needs to be briefly described. The most common static approach to voltage-stability assessment is an analysis of the Jacobian matrix. For a two-bus network with a constant voltage amplitude at the input bus 1, $U_1=$const, the Jacobian matrix **J** indicates the voltage instability when its determinant takes the value:

$$\det\mathbf{J} = \frac{\partial P_2}{\partial \delta_2}\frac{\partial Q_2}{\partial U_2} - \frac{\partial P_2}{\partial U_2}\frac{\partial Q_2}{\partial \delta_2} = 0, \tag{1}$$

where the voltage phasors are denoted as $U=U\cdot e^{j\delta}$ with indices 1 and 2 at the input bus and load bus, respectively. P_2 and Q_2 are the active and reactive powers at the load bus. The method based on network decoupling assumes that the voltage phasors contain enough information to detect the voltage instability [11]. For the simple two-bus power system with the generator bus 1, the load bus 2 and the corresponding phasor diagram in Fig. 1, a critical condition for stable operation is reached when the voltage drop ΔU_{12} is equal to the load voltage U_2

$$\Delta U_{12} = |U_1 - U_2| = U_2, \tag{2}$$

Combining (1) and (2) leads to the following expression:

$$U_1 = 2U_2\cos\delta_{12}, \tag{3}$$

which implies that the applied approach based on voltage phasors is suitable for the voltage-proximity assessment.

2.1. Two-bus equivalent of the radial network

The method is also able to apply this concept successfully to radial networks with several load buses, Fig. 2. The radial

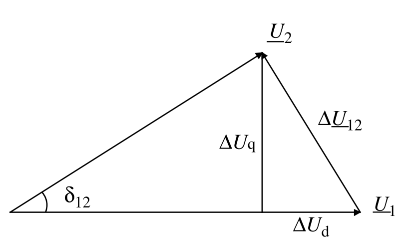

Fig. 1. Phasor diagram for a two-bus power system.

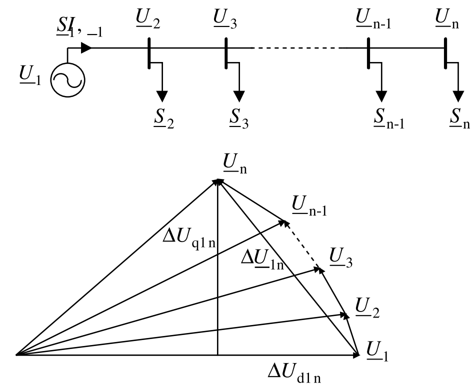

Fig. 2. Radial network and corresponding phasor diagram.

network fed by the generator contains a series of nodes feeding various loads $S_i=P_i+jQ_i$ that all match the generator's active P_1 and reactive Q_1 powers. The voltage phasors at the generator node and at the radial network end node are U_1 and U_n, respectively. Sections along the path are defined by the impedances and loads causing active and reactive transmission losses. They result in the voltage drops ΔU_{d1n} and ΔU_q 1n in the radial network as follows:

$$\Delta U_{d1n} = \frac{P_1\sum_{ij\in\Gamma}L_{ij}^P + Q_1\sum_{ij\in\Gamma}L_{ij}^Q}{P_1^2+Q_1^2}U_1, \tag{4}$$

$$\Delta U_{q1n} = \frac{P_1\sum_{ij\in\Gamma}L_{ij}^Q - Q_1\sum_{ij\in\Gamma}L_{ij}^P}{P_1^2+Q_1^2}U_1, \tag{5}$$

where L_{ij}^P and L_{ij}^Q denote the active- and reactive-power losses in the section i-j of the radial network, respectively. Γ is the set of sections (lines) of the observed radial network.

To apply the concept based on voltage phasors to radial networks the method constructs a two-bus equivalent of a radial network utilizing its operational parameters, as described in [11]. The equivalent should reflect the common properties of the original radial network and make possible a voltage-stability assessment. The input power, the load impedance at the end of the radial network as felt by the input bus, and the voltage drop along the path have to be retained. This set of conditions leads to the following expressions with the exact derivation in [11]:

$$U_1I_1 = U_1'I', \tag{6}$$

$$U_1U_n = U_1'U_2', \tag{7}$$

$$\frac{U_1'}{U_1} = \frac{I_1}{I'} = \frac{U_n}{U_2'}, \tag{8}$$

$$\Delta U_{d1n} = U_d', \tag{9}$$

$$\Delta U_{q1n} = U_q', \tag{10}$$

where U_1' and I' are the voltage and the injected current at the generator bus of the two-bus equivalent, respectively. U_2' is the voltage at the load bus, and U_d' and U_q' are the voltage drops of