Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 10 (18): 2147-2153, 2010
ISSN 1812-5654

Power System Voltage Stability Assessment Using Network Equivalents-A Review

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Abstract: The voltage instability is a growing problem in the modern power systems and is associated with rapid voltage drop due to heavy load demand. Fast computing techniques have been tried to properly analyze the voltage stability for predicting the onset of voltage collapse so as to avoid any unwanted events of the system. Several approaches are available in the open literature for assessing the voltage stability of a power system. A fast and easier way to assess the voltage stability of power system is through its equivalent network and widely explored in current literature. This study presents a review on the voltage stability assessment methodologies particularly based on the network equivalent techniques.

Key words: Equivalent network, global voltage stability, local voltage stability, phasor measurement unit, load flow, optimal power flow, Thevenin's equivalent, voltage collapse, voltage stability margin

INTRODUCTION

The voltage drop along a transmission line mostly depends upon the type of load at receiving end. The consumer demanding more reactive power is responsible for higher voltage drops as voltage in power transmission system is strongly coupled with reactive power status of the system (Kundur, 1994; Taylor, 1994; Van Custem, 2000). If the reactive power demand goes on increasing then system suffer from a gradual voltage drop and at a certain load point it reaches the critical point beyond which no stable operating point is possible even with any type of corrective measures e.g. installation of SVC, use of FACTS controllers (Hingorani and Gyugyi, 1999; Thurkaram and Lomi, 2000; Song *et al*., 2004; Abido, 2009) or strategic load shedding. Efforts have been made by the researchers to analyze the power systems and to assess voltage stable state along with corrective measures to restrict voltage collapse (Chiang *et al*., 1990; Schlueter *et al*., 1991; Chakrabarti *et al*., 2002; Kundur *et al*., 2004; Attia *et al*., 2006) phenomena at any operating condition so as to help system planner and operator for better system operation with better voltage profile at load buses.

Identification of weak/weakest bus (Zambroni de Souza and Quintana, 1994; Rahman and Jasmon, 1995; Haque, 2003a; Wang *et al*., 2005) some time termed as critical bus is a major concern of voltage stability study along with development of different voltage stability indices (Lof *et al*., 1993; Dey and Chakrabarti, 2003; Augugliaro *et al*., 2007; Suganyadevia and Babulal, 2009) using load flow technique (Rahman and Jasmon, 1995; Nizam *et al*., 2006; Chakrabarti *et al*., 2010), transmission loss (Verbic *et al*., 2006), local measurements (Lee and Ong, 1998; Smon *et al*., 2006; Su and Wang, 2009), system loadability (Chebbo *et al*., 1992; Zambroni de Souza and Quintana, 1994; Turan *et al*., 2006; Hamada *et al*., 2010), singularity of load flow Jacobian (Lof *et al*., 1992; Chen and Wang, 1997; Verbic *et al*., 2006) to assess voltage stability margin (Soliman *et al*., 2003; Haque, 2003b; Haque, 2006; Bedoya *et al*., 2008; Fujisawa and Castro, 2008) and system critical load. A bibliography, based on the voltage stability of power systems is reported by Ajjarapu and Lee (1998). Off-line application being the inherent disadvantage of load flow solution compelled the researchers to develop on line tools for voltage stability study (Ajjarapu and Christy, 1992; Ajjarapu and Lee, 1992; Vu *et al*., 1999; Vaahedi *et al*., 1999; Wang *et al*., 2005; Smon *et al*., 2006; Wang *et al*., 2009; Su and Wang, 2009).

Gradually the concept of deriving two bus equivalent network of any multi-bus power network comes up to obtain a quick view of voltage stable states of the power system. In this regard several voltage stability indicators have been developed using Thevenin equivalent circuit (Rahman and Jasmon, 1995; Haque, 1995; Chen and Wang, 1997; Haque, 2003b) with on line phasor measurement (Smon *et al*., 2006; Wang *et al*., 2009; Su and Wang, 2009; EI-Amary and EI-Safty, 2010) or construction of special phasor diagram (Turan *et al*., 2006). Other type of single line two bus equivalents (Jasmon *et al*., 1991; Jasmon and Lee, 1991b; Chakrabarti *et al*., 2005; Nagendra *et al*., 2009) have also been developed including non linearity of load (Chebbo, *et al*., 1992; Hamada *et al*., 2010), based on phasor measurement (Gubina and Strmcnik, 1995;

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Liu *et al*., 2008). Some of the two bus equivalent methodologies developed are also capable to predict better scheme for strategic load shedding based on voltage stability criterion instead on the ground of the simple voltage magnitude criterion (Wiszbuewski, 2007). Later on development enable the equivalent system for on line study of voltage stability using the boundary of the voltage stability region in the P-Q plane (Haque, 2002, 2003a; Paosateanpun *et al*., 2006; Hamada *et al*., 2010) to get quick overview on the system voltage instability.

This study presents the efforts in a nutshell to provide complete information regarding voltage stability in equivalent mode. The proposed methodologies for development of network equivalent available so far may be divided into three sections in broad sense i.e., based on Thevenin theory, by other innovative approach and based on on-line measurement.

REVIEW OF NETWORK EQUIVALENTS

A power system consists of several buses which are connected by means of transmission lines (Chakrabarti and Halder, 2008) and is becoming more and more complex to meet the continuous grow of electrical load demand. In general, the voltage stability assessment (Chakrabarti and Halder, 2008) of such a stressed system is very difficult. A fast and easier way to assess the voltage stability of the complex system is through its network equivalent with only one line. By using this equivalent system, the occurrence of voltage collapse of actual system can be studied easily in global mode (Jasmon *et al*., 1991; Gubina and Strmcnik, 1997; Dey *et al*., 2004; Wang *et al*., 2009; Nagendra *et al*., 2009) and it is not necessary to consider every line of the network separately. Also, the power system equivalents (Housos *et al*., 1980; Le *et al*., 1997; Fu *et al*., 1997) are of importance for the study of static characteristics (Sauer and Pai, 1990) of a large system when either the computer facilities for direct solution or the available solution time is restricted. The use of equivalent representation of the complex system is required frequently to simplify the lengthy calculations and analysis system stability easily. Due to simplicity of the single line equivalent technique (Jasmon and Lee, 1991a, b), stability analysis based on this equivalence is much simplified making it most suitable for use in real time power system monitoring. In addition, local methods (Verbic and Gubina, 2004) also give a very good insight into the nature of the voltage-collapse process and can easily be used for protection schemes.

This section provides the review of the network equivalent methodologies on the basis of Thevenin theory, other innovative approach and on line measurement, available for assessment of voltage stability in power system.

Development of network equivalent using Thevenin theory: Chebbo *et al*. (1992) used the concept of the two-bus theory to estimate the maximum loading capability of a particular load bus in a power system where the power system is first replaced by the Thevenin theory to get the two-bus equivalent model which include the effects of nonlinearity of loads and generators in the equivalent circuit though some repetitive computation in the original system is required to get the solution of the ultimate results.

Rahman and Jasmon (1995) also proposed a new voltage stability index which helps to identify the critical buses using Thevenin equivalent circuit of the power system referred to a load bus using a new load flow technique.

Haque (1995) uses the base case system information to find special two-bus equivalents of the system for analyzing the voltage stability problem thus determines the maximum loading capability, especially the reactive power demand of a particular load bus in a power system through the Thevenin equivalent circuit where generators are modeled to reflect actual operation, even for a change in operating conditions.

Vu *et al*. (1999) proposed a simple method of determining the voltage stability margin of a power system using some local measurements. The measured data are used to obtain the Thevenin equivalent of the system. The equivalent system is then used to determine the relative strength or weakness of the transmission network connected to a particular load bus.

Turan *et al*. (2006) gave the concept of a maximum power transfer phasor diagram using local measurements and estimated parameters of Thevenin equivalent for N-bus power system for easy evaluation the relations between major parameters affecting voltage stability margins. Critical values for major parameters and a voltage stability margin are evaluated from the constructed phasor diagram.

Load shedding often becomes the last line of defense to prevent the voltage collapse in the course of a developing disturbance. Wiszbuewski (2007) presented a criterion by measuring the variation of apparent load power against the change of load admittance (dS/dY) and the ratio of (Z_L/ Z_S) to initiate the load shedding instead of the voltage criterion but on the ground of the simple Thevenin circuit.

Other innovative approach to develop network equivalent of multi-bus power system: Jasmon *et al*. (1991) developed a technique for reducing a radial network into a single line equivalent whose parameters can be obtained from the results summary of any load flow study which could be used for the practical on-line monitoring of power system voltage stability. Jasmon and Lee (1991b) presented an innovative technique for load flow calculations and voltage instability analysis of distribution networks by reducing a radial network into a single line equivalent which simplifies lengthy calculations of an unreduced network and thus enables the fast computations of load flow solutions of distribution networks. The conditions for voltage collapse being derived from the single line equivalent; no voltage computation is required as all the voltages are eliminated from the governing equations which indicate the superiority of the technique compared to other known methods.

Strmcnik and Gubina (1996) made an analytical approach to find voltage collapse proximity determination based on a two-bus equivalent of a radial network where the voltage phasors at the both ends of the radial network are transformed in order to form the voltage phasors of its two-bus equivalent. Exact voltage stability limit relations for the equivalent derived from Jacobian matrix are established via geometrical relationship between both voltage phasors.

Chen and Wang (1997) described the DistFlow method to find the load flow solutions for radial power networks from which an equivalent 2-bus network can be obtained during the solving process where only one feasible voltage solution exists for a radial power network which can be judged directly from the sign of the Jacobian determinant of the equivalent 2-bus network obtained.

Moghavvemi (1997) proposed a method for determining the voltage stability factor based on the concept of power flow thorough a single line equivalent. Adopting the technique of reducing the power system network into its equivalent single line system, a voltage stability factor is derived and used to examine the overall system stability.

Haque (2003b) proposed a simple equivalent model of the power system to generate the voltage stability boundary involving very little computations which does not require any repetitive load flow simulations and thus various voltage stability margins of the critical bus or area in a large power system can be directly determined from the generated stability boundary for different initial operating conditions with a high potential for on-line application.

With the concept of network equivalencing technique, Dey *et al*. (2004) developed a global voltage security indicator for assessing the voltage stability of actual system. Improvement of global voltage security is highlighted with the application of the static Var Compensator (SVC) in a typical weak load bus in the considered system.

Wang *et al*. (2005) developed a two-bus equivalent methodology based on tracking the weakest power transmission path by defining the weak power draining buses incorporating the electrical distance information and reactive generation reserves so that the on line voltage stability of the power system can be assessed correctly instead of using Thevenin equivalent parameters.

Chakrabarti *et al*. (2005) developed a unique methodology of off-line diagnosis of the weakest bus in a longitudinal multi-bus power network from conventional load flow technique using the concept of equivalencing the multi-bus network to two-bus radial system and by studying the necessary parameters of the equivalent system. A generalized voltage stability criterion being developed, it is applied to multi-bus power system adopting the developed equivalencing technique in order to obtain global voltage stable states.

A new equivalent model using Newton method or the least square estimation method with multiple continuous samples of PMU (Phasor Measurement Unit) measurements is proposed by Liu *et al*. (2008) to analyze and predict the voltage stability of a transmission corridor in terms of Available Transfer Capacity (ATC). This equivalent model retains all transmission lines in a transmission corridor, which is more detailed and accurate than traditional Thevenin equivalent model with acceptable computation burden.

An Equivalent System Model (ESM) including the effects of both local network and system outside the local network is developed by Wang *et al*. (2009) to derive the equivalent node voltage collapse index (ENVCI) using only local voltage phasors with accuracy in modeling and calculations and ease in real time or on-line applications.

Optimal power flow technique has been used by Nagendra *et al*. (2009) to develop a two bus series equivalent to diagnose the weakest part of the multi-bus power system and assess the voltage stability in a multi-bus power network in a global mode.

Hamada *et al*. (2010) described the boundary of the voltage stability region in the P-Q plane to get a quick overview on the system voltage at a certain loading condition using equivalent two-bus system for each loading condition as fixed two-bus system for all loading conditions would not give accurate results.

On-line measurement based network equivalencing techniques: Kashem *et al*. (1998) used only local measurements to find a proximity index based on the voltage to power sensitivities for predicting voltage collapse a load bus which is a measure of closeness of the current operating point to the stability limit point. The index can also identify the marginally stable operating point which may extend beyond the maximum power transfer point by estimating the network equivalent as viewed from a load bus.

Smon *et al*. (2006) simplified the determination of the Thevenin's parameters and enables derivation of the new local voltage stability index using Tellegen's theorem and adjoint networks which requires the voltage and current phasors measurements only, to evaluate the system's voltage stability at a bus and therefore it is very appealing for PMU-based online monitoring and protection schemes as it involves one-step calculation procedure.

Su and Wang (2009) used Wide Area Measurement System (WAMS) to convert the whole system into an equivalent two bus system by multiple measured synchronized phasors of the target bus and the buses connected to it with simple computation. An on line voltage stability index is developed based on the relationship of the load impedance magnitude and the Thevenin's equivalent impedance magnitude. Early prediction of voltage collapse has great advantages in reducing lot of reliability and economical problems.

EI-Amary and EI-Safty (2010) simulated an early voltage instability detector based on PMUs readings which are connected in the distribution system. The simulated detector depends on two parallel concepts for voltage collapse prediction, to give faster and precious response. In the first part, the Lookup table offline calculated values for I_{Lm} and V_{Lm} phasors using PSO technique are compared with the online PMUs readings. The objective function of the PSO depends on the system Thevenin equivalent as seen from the load terminal, which is connected to the PMU. The second main part of the algorithm is the online calculation of the ratio of the Thevenin impedance to the terminal load impedance (Zth/ZL) of the network, utilizing the readings of the connected PMU. The variation in Thevenin voltage is also used in voltage instability prediction. The Thevenin equivalent of the system contributes in voltage instability detection of the system.

CONCLUSION

Present literature review in the context of voltage stability assessment using network equivalent reveals that Thevenin's theory is mostly used to develop the equivalent of any multi-bus power network. Other innovative approaches have also been developed and found to be capable to provide a quick overview on voltage stability status of any power system. On line methodologies along with simple on line measurements helps system operator to get a authentic insight regarding system voltage stability. Some literature suggests proper corrective measure to arrest voltage collapse using voltage stability criteria using equivalent networks. The area of voltage stability study using network equivalent is quite new as compared to conventional techniques and may be more useful if FACTS devices be incorporated in future research.

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