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Voltage stability monitoring of power systems using reduced network and artificial neural network

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ABSTRACT

This paper presents network reduction based methodologies to monitor voltage stability of power systems using limited number of measurements. In a multi-area power system, artificial neural networks (ANNs) are used to estimate the loading margin of the overall system, based on measurements from the internal area only. Information regarding the important measurements from the external areas is considered in measurement transformation through the network reduction process, to enhance the estimation accuracy of the ANNs. A *Z*-score based bad or missing data processing algorithm is implemented to make the methodologies robust. To account for changing operating conditions, adaptive training of the ANNs is also suggested. The proposed methods are successfully implemented on IEEE 14-bus and 118-bus test systems.

1. Introduction

The electrical power demand is increasing day-by-day, and the generation is limited. Deregulated and open electricity markets are norms of the day, and it is essential to maintain reliable and good quality of the electricity supply. All this has resulted in large interconnected power networks that are operated under heavily loaded conditions, and are often close to their stability limits. Power system voltage instability is now one of the challenging problems faced by the utilities. Modern day energy management systems (EMSs) have strong focus on online voltage stability monitoring [1–3].

The maximum power loadability limit of the transmission network is one of the widely used indices to represent the voltage security of a power system [4]. It is critical for the utilities to track how close the transmission network is, to its maximum loading limit, so that in case of emergency, proper control actions can be taken. A large amount of literature exists on the use of analytical methods for voltage stability monitoring [5–8]. The conventional P-V curves are extensively used by the utilities for determination of the maximum permissible loading [9]. Continuation power flow (CPF) method is frequently used for obtaining the P-V curves [4–6]. The loadability limit is determined by increasing the system load in a particular direction, representing the most probable stressing scenario. In order to monitor the voltage security in real-time, it is necessary that the process of measurement and estimation of the state variables and the analysis be performed within a desired time frame. Conventionally, remote terminal units (RTUs) have been used to collect measurements from various locations in a power system. The refresh rate of RTU measurements is typically a few seconds. With the advent of phasor measurement units (PMUs), it is now possible to obtain the measurement data at a sub-second rate [10–12]. In the presence of conventional measurements (from RTUs), the voltage phasors at the buses are obtained from the traditional supervisory control and data acquisition (SCADA) based state estimator (SE), typically every few minutes. Real-time monitoring of the power system, therefore, is not possible with the help of conventional SCADA based measurements. Because of high refresh rate and better accuracy, PMUs are increasingly being deployed in modern power systems. This paper presents an algorithm for fast monitoring of the voltage stability of the system, utilizing PMU measurements. A reduced network containing the buses observed by the PMUs is used to develop the proposed methodologies.

Many works have been reported in the literature, exploring the capability of artificial neural network (ANN) for voltage stability monitoring [13–17]. ANN is used in these works, typically to establish a relationship between a voltage stability indicator and the measurable power system parameters affecting the indicator. These methodologies require a large number of ANN inputs which significantly increases the ANN size and diminishes its accuracy. Refs. [18–20] discuss the assessment of voltage stability using

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artificial neural network with reduced set of inputs. The focus in these methodologies is on eliminating the redundant measurements and thus reducing the number of variables needed to assess the system voltage stability. It is assumed in these methodologies that a large number of measurement variables are available. The present work considers a more realistic scenario, in which only a few nodes in the system are assumed to have PMUs installed because of economic constraints. Only the data measured by these PMUs is utilized for stability analysis.

The computational burden, as well as, the communication requirement for the stability analysis of large interconnected power systems can be reduced by using a reduced power system model. The reduced model also renders the advantage of: (i) monitoring the system by using only a limited number of measuring instruments; (ii) eliminating the need for detailed model in electrically remote areas; and (iii) monitoring the interconnected system, in which participating utilities are reluctant to share vital data. Usually, a utility's own system is called the internal area. The rest of the system is called the external area for the internal subsystem under consideration. For running power system analysis functions in the internal area, the internal subsystem is typically modeled in detail. The external areas are usually represented by simple models, referred to as the external equivalent system. Numerous techniques for determining the reduced equivalent have been proposed in the literature [21–23]. In this paper, Ward equivalent technique is used and it is assumed that measurements of all the nodes in the internal area are available via PMUs.

Two schemes for estimating the voltage instability in an interconnected power system are presented in this paper, using the reduced equivalent of the entire network. The fundamental motive of this research is fast and accurate assessment of the voltage stability of an entire network based on the data measured by PMUs at certain critical nodes. A feed-forward back-propagation network (FFBPN) is used to estimate the maximum loadability of the network. In the first scheme, complex bus voltages measured by the PMUs are used as the input to the FFBPN, and the available loadability margin is used as an indicator of the system voltage stability. In the second scheme, before estimating the system voltage stability margin, an FFBPN is first used to estimate the external network bus voltages by using the internal network bus voltages. The proposed networks have the ability to get adaptive training, when subjected to any new training pattern, following a change in the system operating condition. The proposed strategy is applied to IEEE 14-bus and 118-bus systems. The complex bus voltages measured by using PMUs may be subject to data packet loss or bad data. The bad data are recognized using *Z*-score algorithm [24]. The dropped data packets are compensated by using polynomial curve fitting. A method to update the ANN weights to incorporate a new training pattern is also presented.

The key contributions of this paper are the following.

- Utilizing the voltage phasors measured by PMUs located at internal buses of the system to determine the system voltage stability.
- Although changes in the internal area parameters are reflected by PMU measurements, changes in loading condition for external area are unaccounted. For more accurate estimation of voltage stability, an ANN and ward reduction based method is presented to account for changes in the loading in the external area.
- To further strengthen the reliability in determination of system voltage stability, a bad data detection and correction method based on Z-score algorithm is presented.
- The power system may undergo changes after installation of ANN. To accommodate for these changes in the system, an adaptive training technique for ANN is also presented.

The paper is organized as follows. Section 2 illustrates the ward reduction technique, Section 3 defines ANN scheme for the proposed methods of voltage stability monitoring with load variations, Section 4 proposes a scheme to address bad or missing data, and the problem of updation of ANN weights is discussed in Section 5. The analysis of the results is given in Section 6, and Section 7 concludes the paper. A description of voltage stability indicator is presented in Appendix A.

2. Ward reduction

One of the important aspects of the proposed methodology is the use of reduced network representation of the power system. This enables the monitoring of the voltage stability of the system by observing fewer number of nodes and in reduced amount of computational time. Ward reduction technique [21,25] is adopted in this paper for carrying out the network reduction function. The construction of Ward's equivalent starts from the solved model of the entire interconnected power system. The injected current $\mathbf{i}(i)$ at each bus i is determined from the bus's known complex power injection $\mathbf{s}(i)$ and voltage $\mathbf{v}(i)$.

$$\mathbf{i}(i) = \mathbf{s}^*(i)/\mathbf{v}^*(i) \tag{1}$$

Gaussian elimination technique is used in this method to get the reduced network and current vectors. The nodal equations describing the power system are given by,

$$\mathbf{Y}_{bus}\mathbf{v} = \mathbf{i} \tag{2}$$

where $\mathbf{Y}_{bus}$ is the $n \times n$ bus admittance matrix, $\mathbf{v}$ is the $n \times 1$ vector of complex voltages at all nodes, and $\mathbf{i}$ is the $n \times 1$ vector of complex currents injected at all nodes.

After elimination of the kth node, $\mathbf{Y}_{bus}$ is modified as,

$$\overline{Y}'_{ij} = \overline{Y}_{ij} - \frac{\overline{Y}_{ik}\overline{Y}_{kj}}{\overline{Y}_{kk}}; \;\forall i,j = 1,\ldots,n;\; i,j \neq k \tag{3}$$

where $\overline{Y}'_{ij}$ are the elements of the new $(n-1)\times(n-1)Y_{\text{bus}}$ matrix.

The modified current vector, $\mathbf{i}'$, is given by,

$$\mathbf{i}'(i) = \mathbf{i}(i) - \frac{\overline{Y}_{ik}}{\overline{Y}_{kk}}\mathbf{i}(k); \;\forall i = 1,\ldots,n;\; i \neq k \tag{4}$$

If the network is reduced to r nodes, a new bus admittance matrix of dimension $r \times r$, and a new current injection vector of dimension $r \times 1$ is obtained. The modified current vector is converted back into power injections for analysis purpose [21,25–27]. This reduced network carries full information of the original power system at the base case.

3. Proposed ANN architecture

The feed-forward ANNs employing back-propagation learning algorithm are used in this work as a mapping tool to estimate the available loadability margin of the system. The feed-forward networks are capable of approximating any measurable function to the desired accuracy level [28]. The back-propagation steps repeatedly adjust the weights of the connections in the network to minimize the mean squared error between the desired output and the output of the ANN. In this work, the ANNs are trained by using Levenberg-Marquardt algorithm [29].

The maximum loadability limit is considered in this paper as a measure of the voltage stability of the power system. If the total system load exceeds this limit, it will result in voltage collapse and possibly blackout. The objective here is to determine the point of maximum loadability so that corrective and/or preventive actions can be taken to avoid any voltage instability problem. In