Electric Power Systems Research 152 (2017) 122–129

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

State estimator for electrical distribution systems based on an optimization model

Felipe G. Duque, Leonardo W. de Oliveira, Edimar J. de Oliveira*, André A. Augusto

Department of Electrical Engineering, Federal University of Juiz de Fora-UFJF, Juiz de Fora, MG, Brazil

ARTICLE INFO

Article history:
Received 1 March 2017
Received in revised form 7 July 2017
Accepted 9 July 2017

Keywords:
State estimation
Optimal power flow
Electrical distribution systems
Phasor measurement units
Measurement system design

ABSTRACT

State estimation (SE) has become an important aspect of real-time management of electrical distribution systems (EDS). However, it is a challenging problem, mainly due to the network model complexity and the lack of a reliable measurement infrastructure capable to cope with a variety of network configurations. This work presents an Extended Optimal Power Flow (E-OPF) for SE in EDS that considers different network configurations. The active and reactive power loads are handled as extended variables in the optimization model that are constrained by upper and lower bounds obtained from historical data. The objective function combines the state estimation error (SEE) from the known Weighted Least Squares (WLS) approach with additional indexes related to the state variables, which improve the SE process. The combination of different indexes and the handling of power loads as optimization variables without needing precise historical data are novelty for SE and consist of the main contributions for an EDS that, in general, has few available data. The computational efficiency when different topologies are considered and in situations where the WLS estimator might fail is also a suitable feature of the proposed approach. The known 16-bus and 33-bus test systems are used to assess the proposed methodology. An illustrative application of the proposed approach in a Phasor Measurement Unit (PMU) allocation problem is also presented.

1. Introduction

The smart grid concept has introduced new challenges for the design, operation and control of electrical distribution systems. A distribution control center needs real-time information about the grid to deal with such challenges. State estimation has been widely used in transmission systems to attain similar goals, being also the natural approach for distribution systems [1].

However, due to the complexity and peculiar characteristics such as radial topology, unbalanced loads, poor metering and low X/R ratio, classical state estimation algorithms cannot be directly employed in distribution systems [2]. Convergence problems as well as unsuitable state estimation can arise from the use of transmission approaches in EDS, which requires more robust algorithms [3,4]. The success of control actions with the support of a state estimator is strongly influenced by the estimation precision at every moment [5]. Therefore, new technologies and approaches have been investigated to make the state estimation effective for EDS [6].

There are several studies that seek to improve the accuracy of a SE process [7,8]. They have pointed out the need for acquiring information with appropriate precision and update rate. In this context, synchrophasors stand as a promising technology to improve traditional control and data acquisition systems, as the Supervisory Control and Data Acquisition (SCADA) [9]. A system that includes SCADA and PMU is presented in Ref. [10] for state estimation through the traditional Gauss–Newton method [10]. The approach uses a metric for the PMU allocation based on three important requirements, convergence, observability and performance. A research process is presented in Ref. [11] for developing high precision PMU known as micro-synchrophasors for EDS.

An overview of the historical PMU evolution that covers technological issues and applications can be found in Ref. [12]. The importance of PMU for an improved monitoring, protection and control of electrical power networks has been discussed by several authors [13,14]. Recent surveys show that it is not required to take measures throughout the network, since some voltage and current measurements together with the knowledge of the network topology can enable its observability even at unmonitored points. It motivates the investigation of approaches to ensure the system observability and the state estimator effectiveness [3–5], as well as to define strategic points to be monitored [14–16].

* Corresponding author.
E-mail address: edimarj.deoliveira@gmail.com (E.J. de Oliveira).

http://dx.doi.org/10.1016/j.epsr.2017.07.009
0378-7796/

Nomenclature

x^*	Measured values
$\hat{x}$	Estimated values
x	Actual values from load flow
N_b	Total number of buses
$h(\hat{x})$	A nonlinear function that relates the state variables with the measures
W	Covariance matrix of measurement errors
Ω_k	Set of the buses connected to bus k through distribution branches
Pg_k, Qg_k	Active and reactive power generated at bus k, respectively
p_{km}, q_{km}	Active and reactive power flow at branch km, respectively
I_{km}	Current at branch km
y_{km}, g_{km}, b_{km}	Admittance, conductance and susceptance of branch km, respectively
y^{sh}_{km}, b^{sh}_{km}	Shunt admittance and susceptance of branch km, respectively
V_k	Voltage magnitude of bus k
θ_k	Phase angle of bus k
$\hat{x}_{min}$, $\hat{x}_{max}$	Lower and upper limit of estimated variable $\hat{x}$, respectively
C	Set of network configurations
Pl_k, Ql_k	Active and reactive load demand at bus k, respectively; represent the extended optimization variables in the proposed algorithm

In Ref. [14], a metaheuristic algorithm is proposed aiming at providing the SE with the minimal number of required measurements from PMU that provides the full observability. In Ref. [15], it is proposed a method to determine the type and location of measurement devices for SE of three-phase distribution networks by means of automatic metering reading that uses current magnitude and phase angle as state variables. The location of PMU to perform the state estimation of three-phase EDS is proposed in Ref. [16] by applying a greedy search algorithm and integer programming.

In Ref. [17], a method that considers the availability of communication is proposed to limit the measures required to monitor voltage, stability and oscillations in a power system and to support the PMU deployment. A state estimation method is presented in Ref. [18] that seeks to improve the consistency of measures through the angle bias and treatment of errors due to problems in communication channels or in the data acquisition. In Ref. [19], a nonlinear programming model is presented to maximize the redundancy in measurements and the observability from a limited number of PMU and communication channels. An optimization algorithm based on dynamic programming is proposed in Ref. [20] to include the representation of random active power load changes in the state estimation process, where the number of meters should be reduced. However, the aforementioned approaches do not take into account the variability of the network changes and its impact on the measurement redundancy and the SE observability and accuracy [21].

Under the previous background, the present work proposes a new methodology based on an Extended Optimal Power Flow (E-OPF) model for state estimation in EDS. A novelty from previous works in the literature consists of applying an optimization procedure for SE without the need of precise historical load data, which fits the context of lack of measures in typical EDS. It is achieved by defining the power loads as optimization variables within relaxed ranges. Therefore, the E-OPF gives the optimized load values that minimize the deviation between the measures of state variables, phase angle and voltage magnitude, and their corresponding actual data, which fits in the convergence the actual network loads with suitable precision. Another novelty is to consider in the objective function of the proposed E-OPF the state estimation performance from the WLS approach with additional indexes related to the state variables, which improves the SE process as shown in the results. The computational efficiency is due to the relaxed load range, which makes the convergence of the optimization procedure easy, as well as due to the application of the interior point method to solve the E-OPF. Therefore, the main contribution is to develop a novel approach for state estimation of EDS in an efficient manner that allows taking into account variations in the network configuration with suitable processing time, without requiring precise load data from the network. From the previous aspects, the proposed methodology can estimate the system state even in critical measurement redundancy conditions with easy convergence features and minimal error in the estimation process, which make the new methodology suitable for EDS. The computational efficiency is shown by applying an exhaustive search technique to determine the locations of PMU that maximize the SE performance. The 14-bus and 33-bus test systems are used to evaluate the effectiveness and robustness of the proposed E-OPF algorithm.

2. Proposed methodology

2.1. The E-OPF model

The network equations are defined in polar coordinates and the estimated state vector '$\hat{x}$' is formed by the voltage magnitude and phase angle of all buses, as given in Eq. (1).

$$\hat{x}_k = \left[\hat{\theta}_k, \hat{\theta}_{k+1}, \ldots, \hat{\theta}_{Nb}, \hat{V}_k, \hat{V}_{k+1}, \ldots, \hat{V}_{Nb}\right] \quad (1)$$

The vector of measured values x^* is obtained from the voltage phasors acquired by PMU. Notice that conventional measures from SCADA systems can also be used in x^*, which extends the applicability of the methodology. From the available measures, the state estimation performance can be calculated by using Eq. (2).

$$SEE = \min\left[x^* - h(\hat{x})\right]^T W^{-1}\left[x^* - h(\hat{x})\right] \quad (2)$$

The SEE of Eq. (2) is from the known WLS approach. Although this metric has been widely used in the literature, its performance can be affected when the measurement redundancy is low, as occurs in EDS [22]. In order to improve the state estimation precision in such conditions, the proposed approach adds two terms to Eq. (2) to obtain the objective function (*OBF*) of the E-OPF, which should be minimized. The added terms are indexes related to the magnitude and phase angle of voltages, *IVM* and *IPA* respectively, as proposed in Ref. [23] and formulated hereafter with small modification.

$$IVM = \max_k \left|\frac{|\hat{V}_k| - |V_k^*|}{|V_k^*|}\right| \quad (3a)$$

$$IPA = \max_k \left||\hat{\theta}_k| - |\theta_k^*|\right| \quad (3b)$$

The indexes of Eqs. (3a) and (3b) correspond to the Least Absolute Values (LAV) of the state estimation errors. Therefore, the proposed state estimation procedure combines the SEE and LAV-based indexes to improve its efficiency for EDS. Therefore, the proposed E-OPF for distribution system state estimation is formulated in Eqs. (4a)–(4i), where the estimated variables $\hat{\theta}_k$ and $\hat{V}_k$ are handled as independent optimization variables:

$$OBF = \min\left(SEE^c + IVM^c + IPA^c\right) \quad c \in C \quad (4a)$$