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Decentralized three-phase distribution system static state estimation based on phasor measurement units

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ABSTRACT

This paper presents a novel approach for static state estimation in electrical distribution systems, in which the state variables to be estimated are branch currents in rectangular coordinates. Branch current and voltage phasors are measured from a reduced number of PMUs located along a non fully observable electrical distribution system with radial topology. For the non-monitored buses, load pseudo-measurements are considered as a set of inequality constraints varying between upper and lower limits, which are adjusted during the safety barrier interior point optimization solution process (SBIPM). In order to track daily load variations, the initial load limits for the next time interval are obtained from the actual estimated loads at the non-monitored buses, considering the percentage of power variation at the exit of each lateral feeder. At each iteration of the SBIPM solution process, if any load is set to its corresponding limit, then a new limit margin is set accordingly, meaning that at the end of the solution process all the non-monitored loads are within specified bounds. The distribution network is also subdivided into subsystems considering a PMU allocation procedure in which each lateral feeder is estimated individually, yielding a naturally decentralized state estimator. In this decentralization context, priority loads, such as hospitals, police stations, telecom centers and places with high load density concentration can be considered as monitored subareas, exploring the radial topology of the distribution system. Tests are conducted on IEEE 33 bus test feeder and compared with an existing method in the literature to show the effectiveness of the proposed algorithm. Another simulation was conducted on a long lateral feeder of 57 bus in order to show the possibility of using the proposed technique for large scale distribution systems.

1. Introduction

Since it was firstly introduced by F.C. Schweppe [1], static state estimation (SSE) techniques based on the traditional weighted least squares method (WLS) represent one of the most important and useful tool for power systems real-time monitoring. The main objective is to estimate electrical quantities for a wide area using a minimum number of meters allocated into the power grid. For that purpose, the weighted difference between the measured values and their corresponding ones calculated as function of the states (nodal voltage magnitudes and angles for all the buses of the system) must be minimized according to iterative methods such as Newton-Raphson [1].

The developed methodology in [1–3] is very reliable provided the system is fully observable with redundancy, capable of detecting and identifying gross errors.

Based on this information, the observability analysis for measurement units allocation in order to provide reliable estimation results for a whole power system is very relevant [4,5].

Nowadays, power transmission systems are supervised by a combination of the traditional SCADA (Supervisory Control and Data Acquisition system) and PMUs, in which measured data is sent to the control center and processed to obtain the system states which are used for online security analysis, enabling the system operator to take decisions in time. A comprehensive literature survey is presented in [6], covering alternative methodologies for the SSE algorithms.

Differently from the transmission systems, the distribution networks present distinct characteristics such as their radial or weakly-meshed topology and unbalanced phases. Recently, the increasing use of power electronic based devices and distributed

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generation based on renewable sources such as wind power stations and photovoltaic panels have modified the system operation and controllability. This context has attracted the researchers to develop new technologies for distribution system operation and control.

The most critical problem within this context is that the distribution feeders are generally non-monitored. Actually, the only telemetered quantities in the majority of distribution systems are voltage and currents measured at substations. There are fewer actual measurements than states to be estimated. It means that the system is not fully observable.

Reference [7] presents a literature review on distribution system state estimation, including the main recent contributions to the state of the art. According to [7], with the gradual installation of smart meters in the context of the emerging distribution systems, the observability of the networks can be improved. The use of smart meters was also discussed on reference [8]. Reference [9] highlights the importance of using PMUs for providing satisfactory results. The main challenges found in the literature are related to the number of measurement units to be installed into the power grid to be monitored, their synchronization aspects and uncertainties related to load pseudomeasurements values.

In [10,11], load pseudomeasurements are considered for the non-monitored buses in order to restore the observability of the network. The states to be estimated may be nodal voltages or branch currents as presented in [12–14]. The second option has been widely used due to its low computational effort and numerical stability.

Various alternative algorithms considers the use of load pseudomeasurements and the developed methodologies includes artificial neural networks [15] or particle warm optimization [16]. However, the computational time associated to these algorithms are not adequate for real-time monitoring processes.

PMUs (Phasor Measurement Units) represent one of the most important technological evolution within the context of instrumentation and metering systems. They are capable of providing accurate measurements obtained from the network in high sampling rates (2880 samples per second according to the literature [17]). No matter how far from each other the measurement units are, the measures are all synchronized by GPS (Global Positioning System) and they are all sent to a PDC (Phasor Data Concentrator) where they can be analyzed in a control center and processed by a SSE technique in order to obtain an optimal estimate for the system state [18]. PMUs are considered important devices for the SSE, representing a sophisticated way to enormously increase the accuracy of the estimation results due to high precision of the equipment [17,9,19].

In [20] a distribution system static state estimator based on an extended optimal power flow is proposed. Although the estimation errors are reduced compared with other alternative methods, the formulation is single phase and uses base case central values based on historical load data.

Paper [21] was also previously published having similar ideas as in [20] to test the main advantages of using OPF and PMU measurements to solve the SSE problem. From this publication the following requirements to make this technique more robust was detected: (i) The formulation must be three-phase; (ii), The CPU timings must be improved; (iii) The SSE must follow the daily load curve with high precision.

Bad data analysis for distribution SSE is presented in references [22,23] using the traditional weighted least squares method, being the load pseudomeasurements treated on the objective function.

This paper presents a novel approach for the distribution state estimation, considering branch currents as state variables to be estimated in rectangular coordinates for unbalanced three-phase distribution systems. Branch currents and nodal voltages are provided by the PMUs installed at monitored buses. The non-monitored load buses are considered as inequality constraints, which are bounded considering the daily load variation from previous estimation time interval. Additionally, the distribution network is also subdivided into subsystems considering a PMU allocation procedure, in which each lateral feeder is estimated individually, yielding a decentralized state estimator in order to save CPU timings. The SBIPM has been modified in such a way that the non-monitored load quantities, for each phase, are as close as possible to their corresponding limits but never reach the barrier values. The advantage of the methodology over alternative methods is the use of a reduced number of installed PMUs along a non-fully observable distribution feeder and its capability of giving reliable state estimation results. Results are compared with existing methods in the literature to show the effectiveness of the proposed methodology.

2. Static state estimation formulation

As already mentioned the electrical distribution system is assumed to be radial and PMUs are allocated at the beginning and end of each lateral feeder. In this approach, a minimum number of PMUs is allocated into the system, being equal to twice the number of lateral feeders, subtracted to the number of laterals with the same sending end PMU. However, for long lateral feeders it might be necessary to make additional PMU allocations along the feeder. As the system is radial, provided that the voltage is measured at the beginning of each lateral feeder, synchronized by GPS, to give the voltage reference, the decentralization and use of parallel processing becomes a very efficient way to save CPU timings. Fig. 2 shows this decentralization strategy in which five subsystems are obtained.

Then the SSE formulation for a given lateral feeder considering measurements from two PMUs, being one at the beginning and the other at the end of the feeder, the state variables $\hat{x}$ can be obtained by using the optimization problem which is formulated as shown in Eq. (2):

$$Min \quad J_i = \frac{1}{2}\sum_{j=1}^{2m}\left(\frac{z_j^s - h_j^s(\hat{x})}{\sigma_j}\right)^2 \tag{1}$$

Subject to:

$$\begin{aligned} & l_{P_k}^s \le P_k^s \le u_{P_k}^s \\ & \qquad\qquad k = 1:L \\ & \qquad\qquad s = a, b, c \\ & l_{Q_k}^s \le Q_k^s \le u_{Q_k}^s \end{aligned} \tag{2}$$

where:

$$l_{P_k}^s = (1 - p_k^s)P_k^{s(t-1)} \tag{3}$$

$$u_{P_k}^s = (1 + p_k^s)P_k^{s(t-1)} \tag{4}$$

$$l_{Q_k}^s = (1 - q_k^s)Q_k^{s(t-1)} \tag{5}$$

$$u_{Q_k}^s = (1 + q_k^s)Q_k^{s(t-1)} \tag{6}$$

$$\hat{x} = \begin{bmatrix} I_{1,r}^s & I_{1,m}^s & I_{2,r}^s & I_{2,m}^s & \dots & I_{N_l,r}^s & I_{N_l,m}^s \end{bmatrix}^T \tag{7}$$

$$z = \begin{bmatrix} I_{km_b,r}^s & I_{km_b,m}^s & I_{km_e,r}^s & I_{km_e,m}^s \end{bmatrix}^T \tag{8}$$

$$p_k^s = \left(\frac{P_{km_b}^{s(t)} - P_{km_b}^{s(t-1)}}{P_{km_b}^{s(t-1)}}\right) \tag{9}$$