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A three-phase algorithm for state estimation in power distribution feeders based on the powers summation load flow method

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ABSTRACT

State estimation approaches for use in transmission systems are common in the literature, however, there are few algorithms intended for distribution systems. This occurs, mainly, due to the small amount of measurement data available in real time and topological complexity of these systems. In this context, this paper proposes a new three-phase state estimation algorithm for radial distribution feeders, which is based on adjustment of loads from a dynamic utilization and imbalance factors, in order to model pseudo-measurements of powers, and take into account the imbalance of loads, frequently presents in feeders. The method performs the estimation by section, starting from the substation toward the loads, where estimated quantities in a section are used as pseudo-measurements to estimate the subsequent section. This procedure provides a computational optimization for real-time methodology presented here. Tests were performed in distribution feeders from a Brazilian power company and the results show satisfactory performance of developed state estimator in respect to adjustment of estimated values compared with corresponding real-time measured quantities.

1. Introduction

The state estimation is a mathematical tool developed for recognizing the power system states (magnitudes and angles of nodal voltages), by processing acquired measurements in real time for the observable part of the system. In this area, many researches with several types of approaches have been developed. However, the Weighted Least Squares (WLS) method is universally established in providing good performance to state estimation [1–3].

Most of the algorithms already developed based on WLS methodology are intended for use in power generation and transmission systems. Thus, there are a few algorithms developed specifically for distribution systems. This is due in part to the small amount of available real-time measurements, which requires the construction of pseudo-measurements based on data obtained off-line. In this sense, incompatibility between measurements and pseudo-measurements can cause convergence problems.

Besides the small amount of proposals related to distribution systems, many of them have serious limitations in respect to practical applications. A method for state estimation in balanced radial distribution feeders was developed by Ref. [4], which uses a set of measuring PQV (active power, reactive power and voltage) in a WLS formulation. The method has some limitations related to processing and communication channels for larger feeders. In Ref. [5], the authors use PQI measurements (active power, reactive power and current), which are converted into equivalent currents. Most of the currents taken as measurements are actually pseudo-measurements or estimates of current performed from a load curve and an average load factor updated every hour. These hourly pseudo-measurements are not enough for what is required in terms of accuracy of a state estimator, which should produce responses in smaller windows of time. Refs. [6,7] present a three-phase state estimation based on WLS methodology, however, the loads are represented with connection to neutral, in a four-wire system. These hypotheses actually do not occur in many real cases. A formulation of an estimator based on current injections and branch currents is presented in Ref. [8]. In the validation examples of the method, the authors consider many measurements in real time (12–50 measurements), simulated by solving a three-phase load flow. Without presenting any reasons, the authors adopt randomly

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errors equal to ±10% and ±30% for the measurements (actual) and pseudo-measurements, respectively. There is also no justification for adopting the weights of 1/3 for actual measurements and 1/50 for the pseudo-measurements. Another formulation based on a model of the three-phase network is presented in Ref. [9]. A stochastic model of load to reproduce the variations in weather is formulated and errors of the loads are assumed to range from 20% to 50%, depending on the type of consumer. To analyze performance of the proposed estimator, the author adopted two simplified test systems: one very small, consisting of five nodes, and the other regarded as a long feeder has only twenty nodes. The formulation also considers measurement of power flows in the input of the circuit, when in reality it is more common to measure the RMS current. In short, the presented cases correspond to test conditions of the algorithm quite different from practical reality. In [10], an algorithm for calculating three-phase load flow and state estimation is proposed. The algorithm requires many steps and is based on use of large number of measurements, which are not available in actual systems. Ref. [11] proposes adapting the WLS approach directly to distribution systems. The methodology adopts an extension of probabilistic load flow for radial systems. In the work, there is not an application in more complex real feeders to allow a better performance assessment of the estimator. In [12] a three-phase approach to state estimation for radial unbalanced and asymmetrical feeders is presented, using per phase measurements of voltage, active and reactive powers. The loads are modeled using an *Advanced Load Scheduling System* – in order to avoid pseudo-measurements – which does not correspond the reality of feeders in most countries. Another requirement is the definition of restricted measurement areas to achieve pre-estimation, in order to reduce problem size. In Ref. [13], the authors developed an algorithm for three-phase state estimation in radial feeders, which uses the procedures "forward propagation" and "backward propagation" to scroll through the feeder. The authors did not use the WLS method and associated random weights to measurements, which made the task somewhat rudimentary.

The three-phase state estimation methodology for radial distribution systems proposed in this work is based on WLS technique and uses the powers summation load flow methodology [14] to scroll through the feeder from the substation toward the loads, implementing the state estimation by section. This procedure coupled with the state estimation theory provides computational gain to perform the estimation even in small time windows, and this is the main contribution of this work. Moreover, a dynamically adjusted utilization and imbalance factors calculated in real time are determined to adjust the loads for each time window, avoiding incompatibility issues between pseudo-measurements of loads and actual measurements [15].

In Section 2 of this work, a theory of state estimation is reviewed in a quick summary. In Section 3 the powers summation load flow method is detailed. In Section 4, the methodology used for online adjustment of loads is presented. Section 5 illustrates the equations used to build the state estimation process. In Section 6, the procedure for detecting and identifying possible bad measurements in the estimation process is described and in Section 7, the results obtained with the application of the developed methodology are analyzed.

2. State estimation theory – an overview

The state estimation problem is basically constituted by an over determined nonlinear equations system [1,2]. According to (1), the model of state estimation, based on measurements and pseudo-measurements (measurement model), relates the measured values of the monitored quantities and the state variables.

$$\boldsymbol{z} = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{e} \tag{1}$$

In (1), $\boldsymbol{z}$ is the measurement vector $(m \times 1)$; $\boldsymbol{x}$ is the vector of state variables $(n \times 1)$, $n < m$; $\boldsymbol{h}(\boldsymbol{x})$ is a vector of functions of $\boldsymbol{x}(m \times 1)$ that relates the measurements and pseudo-measurements with the state variables; $\boldsymbol{e}$ is the vector of errors $(m \times 1)$ inherent to measurements and pseudo-measurements.

Thus, the state estimation may be formulated as an optimization problem, applying the methodology of weighted least squares [1]. Therefore, it is necessary to minimize the objective function, described in (2).

$$\boldsymbol{J}(\boldsymbol{x}) = [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})^{\mathrm{T}}]\boldsymbol{R}_z^{-1}[\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})] \tag{2}$$

where $\boldsymbol{R}_z$ is the covariance matrix of the measurements and pseudo-measurements errors, which is responsible for weighting the errors. The estimated state variables, $\widehat{\boldsymbol{x}}$, are obtained by an iterative process described by (3).

$$\begin{aligned} \boldsymbol{G}(\boldsymbol{x}^t)\Delta\boldsymbol{x}^t &= -\boldsymbol{g}(\boldsymbol{x}^t) \\ \boldsymbol{x}^{t+1} &= \boldsymbol{x}^t + \Delta\boldsymbol{x}^t \end{aligned} \tag{3}$$

where $\boldsymbol{t}$ is the iteration counter; $\boldsymbol{g}(\boldsymbol{x})$ is the gradient of $\boldsymbol{J}(\boldsymbol{x})$; $\boldsymbol{G}(\boldsymbol{x})$ is the Gain matrix, which depends of the applied minimization method (Gauss Newton or Newton Raphson).

According to Gauss Newton method, a Taylor series expansion should be used to (1), resulting in (4).

$$\boldsymbol{h}(\boldsymbol{x} + \Delta\boldsymbol{x}) \cong \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{H}(\boldsymbol{x})\Delta\boldsymbol{x} \tag{4}$$

Combining (2) and (4), results in (5).

$$\boldsymbol{J}(\Delta\boldsymbol{x}) = [\Delta\boldsymbol{z} - \boldsymbol{H}(\boldsymbol{x})\Delta\boldsymbol{x}^{\mathrm{T}}]\boldsymbol{R}_z^{-1}[\Delta\boldsymbol{z} - \boldsymbol{H}(\boldsymbol{x})\Delta\boldsymbol{x}] \tag{5}$$

where $\Delta\boldsymbol{z} = \boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})$ and $\boldsymbol{H}(\boldsymbol{x}) = \partial\boldsymbol{h}/\partial\boldsymbol{x}$ is the Jacobian matrix.

Applying first-order optimal condition to (5), results in (6).

$$\frac{\partial\boldsymbol{J}(\Delta\boldsymbol{x})}{\partial\Delta\boldsymbol{x}} = -\boldsymbol{H}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{R}_z^{-1}[\Delta\boldsymbol{z} - \boldsymbol{H}(\boldsymbol{x})\Delta\boldsymbol{x}] = 0 \tag{6}$$

Eq. (6) may be rearranged to obtain (7), which is known as Gaussian normal equation.

$$[\boldsymbol{H}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{R}_z^{-1}\boldsymbol{H}(\boldsymbol{x})]\Delta\boldsymbol{x} = [\boldsymbol{H}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{R}_z^{-1}\Delta\boldsymbol{z}(\boldsymbol{x})] \tag{7}$$

The iterative process based on (7) determines the estimated states. Thus, comparing (7) and (3), the gain matrix, $\boldsymbol{G}$, can be expressed by (8).

$$\boldsymbol{G} = \boldsymbol{H}^{\mathrm{T}}(\boldsymbol{x})\boldsymbol{R}_z^{-1}\boldsymbol{H}(\boldsymbol{x}) \tag{8}$$

The determination of $\boldsymbol{G}$ and the solution of the system defined by (7), for each iteration, may be computationally expensive, especially for large distribution systems. The following sections show the development of a methodology, based on the powers summation load flow algorithm [14], which allows a significant reduction of computational effort required to the present problem of state estimation.

3. Powers summation load flow methodology

Before introducing the proposed state estimator model, a brief description of the power summation algorithm for load flow calculation is presented. The algorithm starts with reducing the feeder to only two nodes (source and load). Thus, the magnitudes of voltages at both nodes may me be related to each other by means of a biquadrate equation. After calculating the voltage at the load node, this turns into source node. A new branch is considered, connecting this last source node to another node with an equivalent powers summation load. This procedure is repeated until cover the entire