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Simultaneous estimation of state variables and network topology for power system real-time modeling

N.S. da Silva [a], A. Simões Costa [a,*], K.A. Clements [b], E. Andreoli [a]

[a] Federal University of Santa Catarina, Brazil
[b] Worcester Polytechnic Institute, MA, USA

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ABSTRACT

A combined Weighted Least Squares (WLS) and Weighted Least Absolute Value (WLAV) strategy is proposed to devise a joint state and network topology (S&T) estimator for power system real-time modeling. This is accomplished by formulating S&T coestimation as a multi-objective optimization problem combining both analog measurement residuals and operational conditions dictated by circuit-breaker statuses. The former are treated as arguments of a conventional WLS function, whereas the latter exploits the selective properties of the LAV criterion. The paper presents the theoretical framework for S&T coestimation, and proposes a specialized primal/dual interior point method to solve the corresponding optimization problem. Results obtained by applying the joint estimator to the IEEE 24-bus test system and to a real metropolitan system in Southern Brazil are reported in the paper. They indicate that S&T coestimation is a very promising approach to provide simultaneous solutions to both real-time modeling problems.

1. Introduction

The performance of the Energy Management System (EMS) functions related to power system security assessment depends on the availability of a reliable real-time network model. Power system state estimation (PSSE) is the function responsible for building such a model by processing redundant, noise-corrupted, real-time analog measurements, gathered by the power network SCADA system. Traditionally, PSSE relies on a network model in which bus sections and switching devices are not explicitly represented. Instead, the topology is determined solely on the basis of online breaker status data by a network topology processor [1] and is assumed to be correct. The results produced by the network processor are subsequently used by the state estimator in order to produce the full real-time bus-branch model.

Although less often than with analog measurements, bad data may also occur among the digital measurements fed into the network configurator. Unlike PSSE, however, the network processor has few resources to effectively deal with gross errors among its input data. If not properly detected, such bad data materialize as topology errors, which tend to be strongly detrimental to the performance of conventional state estimators [1].

More recently, technology developments such as the deployment of intelligent electronic devices (IEDs) in substations have enhanced the amount and quality of the local information available to the functions in charge of the real-time modeling process. To take advantage of that, efforts have been made in order to explicitly represent real-time electrical network at bus-section level [2,3]. Those contributions led to the concept of generalized state estimation [1,2,4,5], as well as the introduction of operational and structural constraints into the PSSE problem formulation [5,6], leading to new approaches for topology error processing [6–9]. Despite those indisputable advances, the treatment of uncertain network topology remains a challenging problem demanding further research efforts. The need of accurate topology monitoring is further stressed by the recently renewed interest in applying optimal topology control as an operation strategy, either to cope with uncertainties due to large penetration of renewable resources in power systems [10], or to face increasingly stringent reliability requirements [11].

The work reported in this paper is motivated by the observation that the conventional methodology for power system real-time modeling completely decouples the problem into network configuration and state estimation. By doing so, the process does not benefit from the significant information on the network topology implicit in the analog measurements. As a matter of fact, recent research efforts rely on the same principles to devise real-time modeling improvements by extracting the information about network topology "hidden" in the measurements [12].

* Corresponding author. Tel.: +55 48 3721 4987; fax: +55 48 3721 9280.
E-mail addresses: nastasha@labspot.ufsc.br (N.S. da Silva), simoes@ieee.org (A. Simões Costa).

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Recently, a novel strategy to exploit the same idea has been suggested by Clements in [13]. It takes advantage of network modeling techniques at bus-section level and exploits the selective properties of the LAV criterion. The objective is to devise an estimator capable of jointly determining system states and network topology by processing analog measurements. Such an approach has been object of the exploratory work reported in [14], where a simplified "DC" network model is employed aiming basically at identifying different topology errors in previously determined bad data pockets.

This paper builds on those research efforts with the objective of conceiving a full state and topology coestimator. For that purpose, the problem formulation relies on a complete nonlinear model of the network, able to represent the effects of both active and reactive power flows. The proposed estimation algorithm is capable of extracting from the available analog measurements not only information on system states, but also the network topology. By that means, it is possible to either validate or rectify the results produced by the Network Processor without the need of tentatively experimenting with distinct alternative topologies.

To conciliate the simultaneous goals of estimating both state variables and network topology, a bi-objective optimization framework is employed. Accordingly, the objective function comprises two criteria, namely, a WLS term, which takes care of the analog measurements, and a WLAV term to process conditions that reflect the statuses of switching devices. In this paper, we often refer to our approach as *State and Topology (S&T) Coestimation*.

The solution of such a combined problem is obtained through a specialized algorithm based on interior point methods. Under adequate measurement redundancy levels, that is, assuming that the metering scheme does not contain critical measurements or critical sets [1,6], the results presented in the paper indicate that the proposed coestimator is able to converge starting from virtually any initial topology condition.

Section 2 reviews the basics concepts of state estimation conducted at bus-section level, including the notions of operational and structural constraints. The S&T coestimation method is introduced in Section 3, where its mathematical formulation as well as the solution approach based on the specialized interior point method are presented. Section 4 describes the coestimation algorithm. Results of several case studies conducted on an IEEE benchmark system and a real Brazilian sub-network are presented and discussed in Section 5. Some remarks on the performance and applicability of the coestimation approach are listed in Section 6. Finally, Section 7 summarizes the main conclusions related to the proposed methodology.

2. Network modeling

2.1. Measurement model

Let us consider an N-bus power system represented by the bus-branch model, on which N_m measurements are taken. The state vector for this system comprises $n = 2N - 1$ state variables, namely, $N - 1$ bus voltage angles and N bus voltage magnitudes. The measurement vector, the state variables and the measurement errors are related by the following measurement model:

$$\mathbf{z}_m = \mathbf{h}_m(\mathbf{x}) + \boldsymbol{\varepsilon}_m \tag{1}$$

where $\mathbf{z}_m$ is the $N_m \times 1$ measurement vector, $\mathbf{x}$ is the $n \times 1$ state vector, $\mathbf{h}_m(x)$ is the $N_m \times 1$ vector of non-linear equations that relate the measurements to the state variables, and $\boldsymbol{\varepsilon}_m$ is the $N_m \times 1$ random vector of measurement errors. The conventional approach to PSSE relies on the Weighted Least Squares (WLS) method to obtain the state estimates. Accordingly, the following objective function, given by the weighted sum of squared residuals, is minimized:

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

where $\mathbf{r} = \mathbf{z} - \mathbf{h}(\hat{\mathbf{x}})$ is the vector of estimation residuals and $\mathbf{R}$ is the covariance matrix of the measurement errors, $\boldsymbol{\varepsilon}_m$. Although alternative formulations including constraints have been proposed in the literature, conventional PSSE is usually formulated as an unconstrained optimization problem.

When parts of the power system are represented at the bus section level, the corresponding switching branches are included in the network model and the active/reactive power flows through them are defined as new state variables [3]. As a consequence, the dimension of the state vector will be increased by $2n_d$, where n_d is the number of modeled switching branches. In other words, we redefine $n = 2N - 1 + 2n_d$. In addition, switching branch statuses describing the network topology, as well as zero injections at internal substation nodes, are included into the estimation problem as equality constraints. Hence, bus-section level PSSE is formulated as a constrained optimization problem. The above mentioned constraints are detailed next.

2.2. Operational and structural constraints

The explicit representation of a given substation at the bus section level relies on the addition of *operational constraints* to the PSSE problem [6]. Such constraints model the current statuses of the substation switching branches by defining proper relationships between the related state variables. Accordingly, if switching branch $k - l$ is assumed closed, the voltage drop across its terminal nodes is zero, so that the corresponding operational constraints take the form [3,6]:

$$\begin{cases} \theta_{kl} = \theta_k - \theta_l = 0 \\ v_{kl} = v_k - v_l = 0 \end{cases} \tag{3}$$

where θ_i (v_i) is the nodal voltage angle (magnitude) at bus i. Likewise, an open switching branch is characterized by the fact that the power flows through it are zero [3]. As a consequence, the corresponding operational constraints are [6]:

$$\begin{cases} p_{kl} = 0 \\ q_{kl} = 0 \end{cases} \tag{4}$$

where p_{kl} (q_{kl}) is the active (reactive) power flow through branch $k - l$.

The extended state vector $\mathbf{x}$ is then defined as

$$\mathbf{x} = [\boldsymbol{\theta}^T, \mathbf{v}^T, \mathbf{p}^T, \mathbf{q}^T]^T \tag{5}$$

where $\boldsymbol{\theta}$ and $\mathbf{v}$ are sub-vectors comprising the voltage angles and magnitudes at all modeled electrical nodes, and $\mathbf{p}$ ($\mathbf{q}$) are sub-vectors of active (reactive) power flows through all modeled switching branches. The set of relationships conveying the statuses of all explicitly represented switching branches are gathered together into the equation

$$\mathbf{h}_o(\hat{\mathbf{x}}) = \mathbf{H}_o \hat{\mathbf{x}} = 0, \tag{6}$$

where $\mathbf{h}_o(\hat{\mathbf{x}})$ is the *vector of operational constraints* and $\mathbf{H}_o$ is the $n_o \times n$ matrix of operational constrains compose by 0, 1 and -1 with $n_o = 2n_d$ is the number of operational constraints. Notice from Eqs. (3) and (4) that $\mathbf{h}_o(\mathbf{x})$ is in fact linear on $\mathbf{x}$, although we continue to employ the nonlinear vector notation in order to comply with the remaining constraints.

Another set of constraints are also needed to provide a detailed representation of network substations. The so-called *structural constraints* [6] are employed to model zero injection electrical nodes,