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Hybrid state estimator considering SCADA and synchronized phasor measurements in VSC-HVDC transmission links

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ABSTRACT

This paper proposes a practical approach for implementing a hybrid state estimator by considering SCADA and PMU measurements in VSC-HVDC transmission links under a unified framework of reference. A proposed formulation for the PMU measurements associated with the VSC-HVDC state variables is derived from the first principles and is implemented into a weighted least square-based state estimation algorithm. In order to avoid numerical problems of convergence of the proposed state estimation approach, the set of current phasor measurements is represented in rectangular coordinates, such that their corresponding variances are also recalculated according to the uncertainty propagation theory. The state estimation process uses the measurement of one voltage phase angle as the global reference for the rest of voltage phase angles estimated at network buses and VSC-HVDC's voltage source converters. The proposed formulation improves the accuracy at which both network and VSC-HVDC state variables are simultaneously estimated based on the measurements provided by a SCADA system and PMUs. A Mexican interconnected 190-bus equivalent system is used as the test system in order to validate the effectiveness of the proposed hybrid state estimator.

1. Introduction

Because of the needs and requirements of today's lifestyle, modern electric power systems have to deal with the request for a constant increase in the bulk power transmission capacity. In addition, the constant increment of high penetration of intermittent energy sources, such as wind power generation [1], is causing higher power transfer through transmission corridors and calls to improve the control capabilities to properly match the required nodal balance between generation and demand of electric power, while maintaining the network's security and reliability. In response to the above-mentioned, the current networks' infrastructure is undergoing a transition process, which consists of integrating innovative and advanced technologies on measurement, telecommunications and control equipment, among others. In this sense, regarding the controllability of power systems, flexible AC transmission systems (FACTS) technology [2,3] as well as the high voltage direct current links (HVDC) technology [4] have demonstrated their capabilities and flexibility in fully controlling active and reactive power flows through transmission components and in providing reactive power support under several operating scenarios framed in a wide spectrum of time [2–4]. In addition, HVDC links are capable of improving the secure operation of power systems by avoiding disturbances' propagation between interconnected asynchronous systems and/or between interconnected control areas through tie-lines [5].

On the other hand, regarding the integration of advanced measurement schemes, the monitoring of modern power systems has been greatly improved by the emergence of the phasor measurement units (PMUs) [6,7]. These measurement devices can provide very accurate and synchronized positive sequence phasors of voltage and currents from the measured voltage and current waveforms. In addition to the accuracy, all phasor measurements available at different substations are synchronized with respect to a common synchronizing time signal provided by the global positioning system (GPS) of satellites [6,7]. At the same time, the advantages of integrating these technologies are giving way to the transformation of the control schemes and operation philosophies of transmission networks by improving the applications of the energy management systems (EMS) [8]. In this context, one of the most important functions performed in EMS is the state estimation process, which is the cornerstone of all on-line monitoring

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functions undertaken in EMS in order to guarantee the security of the transmission networks [9]. Based on a redundant set of available physical measurements traditionally collected through the supervisory control and data acquisition (SCADA) system, as well as the topological and physical characteristics of the transmission network, a state estimation process is used in real-time to compute all state variable values that determine the current operation state [9]. The state estimator's (SE) capability to process a redundant set of contaminated measurements, as well as its effectiveness in filtering the random measurement noise, both emphasize the high priority level of SE to the EMS performance in real-time monitoring [10].

Extensive research has been carried out in the last decade for the implementation of FACTS controllers in state estimation algorithms [11–18]. Furthermore, a comprehensive survey of different FACTS models and solution techniques used for the state estimation problem with FACTS is reported in [18]. Regarding state estimation of power systems with embedded HVDC links, an approach to incorporate classical HVDC links into power system state estimation is provided in [19]. The AC/DC and DC/AC interfaces of the HVDC model are represented by means of series-connected classical converters through a common DC link. This proposal considers AC-side and DC-side measurements of the HVDC link. In [12], a state estimation approach for power systems with multi-terminal DC (MTDC) systems is proposed, where the available set of MTDC measurements consists of AC-side and DC-side measurements as well as AC/DC interface system measurements at the classical converter stations. In [20], a new modeling of the voltage source converter (VSC) is proposed in order to incorporate the HVDC link based on VSC (VSC-HVDC) into power systems' state estimation through its AC-side and DC-side measurements. A practical implementation of a VSC-HVDC model into a weighted least square-based (WLS) state estimation algorithm is described in [21]. In this case, a back-to-back series connection of the VSC DC-side is considered, and thus, only AC-side measurements are available. In [22,23], AC-side and DC-side measurements of the VSC-HVDC links are considered in order to formulate two state estimation schemes. A distributed state estimator based on network decomposition for hybrid AC/HVDC grids is proposed in [22], whereas a state estimator for HVDC systems is proposed in [23] which is based on a multiagent genetic algorithm. Note that in all the above proposals the measurement schemes are supplied only by SCADA systems, i.e. no PMU measurements have been considered. On the other hand, there exists a linear state estimation proposal for hybrid AC/DC networks, which is based on the integration of a classic model of HVDC link into a WLS state estimation algorithm [24]; its measurement scheme, however, is uniquely based on PMU measurements, which requires a measurement infrastructure that is thus far economically infeasible to support [8].

It is well-documented how the integration of synchronized measurements provided by PMUs has improved the state estimation performance capability of SCADA-based SE [25,26]. PMUs improve the estimation's accuracy by providing both nodal voltage and branch current phasor measurements; furthermore, the system measurements' redundancy is increased, which directly improves the network observability [27] and the performance of bad data identification methods [28].

Based on the monitoring advantages of PMUs, the formulation and code of a SE must consider these kinds of measurements, together with those provided by the SCADA system to properly estimate the nodal voltage profile of the electric network along the operating status of FACTS and VSC-HVDC control devices. Regarding FACTS controllers, a SE considering FACTS controllers and PMU measurements is proposed in [29], which provides the mathematical representation of PMU measurements associated with FACTS controllers in terms of both FACTS and network state variables, as well as the practical implementation of these equations into a WLS-based state estimation algorithm. According to the best of the authors' knowledge, though, a state estimation approach of power systems considering PMU measurements and VSC-HVDC links has not been reported on yet. In this sense, this paper proposes a hybrid state estimator which considers SCADA and PMU measurements for power systems with embedded VSC-HVDC links. Such a proposal consists of developing from the first principles, a mathematical model of HVDC-PMU measurements, as well as an approach for its practical implementation into a WLS-based SE algorithm under a unified framework of reference that also considers SCADA measurements. The effectiveness of the proposed hybrid SE as well as the suitability of the developed PMU measurements formulation are proved throughout the estimation of the VSC-HVDC control variables along with the power system state variables of an equivalent of the Mexican power system consisting of a 190-bus network.

2. General formulation for hybrid state estimation

A state estimation mathematical model is the analytical formulation of an optimization problem to obtain the best estimate of the power system state variables. The formulation of a state estimation model is traditionally based on a measurement model, which allows representing the mathematical relation between the available set of physical measurement values and the system state variables throughout the following expression [9]:

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

where for the purpose of this paper proposal, $\boldsymbol{z} \in \Re^m$ is the set of SCADA and PMU measurements, $\boldsymbol{z} = [\boldsymbol{z}^{SCADA}\boldsymbol{z}^{PMU}]^t$, the superindex t indicates transposition; $\hat{\boldsymbol{x}} \in \Re^n$ is the set of network and VSC-HVDC estimated state variables, $\hat{\boldsymbol{x}} = [\hat{\boldsymbol{x}}_{AC}\hat{\boldsymbol{x}}_{HVDC}]^t$; $\boldsymbol{h}(\cdot) \in \Re^m$ is a vector of nonlinear functions relating state variables and physical measurements through the mathematical model of the system, $\boldsymbol{h}(\cdot) = [\boldsymbol{h}^{SCADA}(\hat{\boldsymbol{x}}_{AC}, \hat{\boldsymbol{x}}_{HVDC})\boldsymbol{h}^{PMU}(\hat{\boldsymbol{x}}_{AC}, \hat{\boldsymbol{x}}_{HVDC})]^t$, which is referred to as estimated measurements; and $\boldsymbol{\varepsilon} \in \Re^m$ is the vector of uncorrelated measurement errors representing imperfections of real measuring devices.

The WLS algorithm consists of minimizing the objective function (2), defined as the sum of the weighted squares of the measurement noise vector, i.e. the difference between the measured values $\boldsymbol{z}$ and their estimated values $\boldsymbol{h}(\hat{\boldsymbol{x}})$. Therefore, the vector value that satisfies the first-order optimality condition (3) is the best estimate value $\hat{\boldsymbol{x}}$ of the system state [9]:

$$J(\hat{\boldsymbol{x}}) = (\boldsymbol{z} - \boldsymbol{h}(\hat{\boldsymbol{x}}))^t \boldsymbol{R}^{-1}(\boldsymbol{z} - \boldsymbol{h}(\hat{\boldsymbol{x}})) \tag{2}$$

$$\frac{\partial J(\hat{\boldsymbol{x}})}{\partial \hat{\boldsymbol{x}}} = \boldsymbol{H}(\hat{\boldsymbol{x}})^t \boldsymbol{R}^{-1}(\boldsymbol{z} - \boldsymbol{h}(\hat{\boldsymbol{x}})) = \boldsymbol{0} \tag{3}$$

where $\boldsymbol{R}$ is a diagonal covariance measurement matrix, and $\boldsymbol{H}(\hat{\boldsymbol{x}}) = \partial \boldsymbol{h}(\hat{\boldsymbol{x}})/\partial \hat{\boldsymbol{x}}$ is the Jacobian matrix of the estimated measurements.

The set of measurements of a SCADA system traditionally consists of power injections, power flows and voltage magnitudes as follows: $\boldsymbol{z}^{SCADA} = [\boldsymbol{P}_{inj}\boldsymbol{Q}_{inj}\boldsymbol{P}_{branch}\boldsymbol{Q}_{branch}\boldsymbol{V}]^t$, while PMUs provide a set of measurements composed of nodal voltage and current flow phasors: $\boldsymbol{z}^{PMU} = [\boldsymbol{\theta}^{PMU}\boldsymbol{V}^{PMU}\boldsymbol{I}_{branch,r}\boldsymbol{I}_{branch,i}]^t$. The set of estimated state variables are defined by $\hat{\boldsymbol{x}} = [\hat{\boldsymbol{x}}_{AC}\hat{\boldsymbol{x}}_{HVDC}]^t = [\hat{\boldsymbol{\theta}}\hat{\boldsymbol{V}}\hat{\boldsymbol{\theta}}_{vR}\hat{\boldsymbol{V}}_{vR}]^t$, where $\hat{\boldsymbol{x}}_{AC}$ represents the estimated state variables of network, while $\hat{\boldsymbol{x}}_{HVDC}$ corresponds to the set of estimated control variables of the VSC-HVDC links. On the other hand, the corresponding set of estimated measurements $\boldsymbol{h}(\hat{\boldsymbol{x}}) = [\boldsymbol{h}^{SCADA}\boldsymbol{h}^{PMU}]^t$ provided by the SCADA system and PMUs is defined by $\boldsymbol{h}^{SCADA} = [\hat{\boldsymbol{P}}_{inj}\hat{\boldsymbol{Q}}_{inj}\hat{\boldsymbol{P}}_{branch}\hat{\boldsymbol{Q}}_{branch}\hat{\boldsymbol{V}}]^t$ and $\boldsymbol{h}^{PMU} = [\hat{\boldsymbol{\theta}}^{PMU}\hat{\boldsymbol{V}}^{PMU}\hat{\boldsymbol{I}}_{branch,r}\hat{\boldsymbol{I}}_{branch,i}]^t$, respectively. Based on these