Electric Power Systems Research 160 (2018) 251–260

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A new unified approach for the state estimation and bad data analysis of electric power transmission systems with multi-terminal VSC-based HVDC networks

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ARTICLE INFO

Article history:
Received 4 November 2017
Received in revised form 6 March 2018
Accepted 7 March 2018

Keywords:
State estimation
VSC-HVDC grids
Multiple bad data
Phasor measurement units
SCADA

ABSTRACT

The aim of this paper is the proposal of a static state estimation approach suitable for electric power transmission systems containing fully controlled multi-terminal high voltage direct current networks. An integrated electric circuit model of the voltage source converter station, including its on-load tap-changer (OLTC) transformer, is used to determine the state variables associated with the AC–DC interface. These controllable variables are added to the state vector, together with the nodal voltages associated with the AC and DC networks, as well as the duty cycle of the DC–DC converters, for a unified SE solution in a single frame of reference. The SE problem is formulated based on Hachtel's augmented matrix method in order to directly consider the operational constraints associated with the AC–DC network. In addition, a new technique for performing multiple bad data analysis is proposed in which the original level of measurement redundancy is maintained unaltered during the estimation process. The applicability of the proposed SE approach and bad data analysis is demonstrated by estimating the operating state of two integrated AC–DC multi-terminal transmission networks. The numerical results show that the proposal retains good convergence properties in terms of the number of iterations required to achieve a reliable state estimation as well as robustness to deal with bad data.

1. Introduction

The evolution of electrical power transmission systems into larger interconnected networks includes the challenge of the integration of renewable power plants located offshore, where the random nature of the generation as well as the large distances to load centers make use of the voltage source converter-based (VSC) high voltage direct current (HVDC) technology one of the most feasible solutions for the efficient grid integration of these types of power plants. In this context, point-to-point HVDC systems have advanced in the direction of multi-terminal VSC-HVDC (VSC-MTDC) systems, with the North Sea Super DC Grid being the clearest example of this kind of system development [1]. In this specific case, the VSC-MTDC system will be used for interconnecting several offshore wind farms, offshore loads and the onshore power grids. On the other hand, since the VSC enables fast and independent control of active and reactive powers, as well as reversal of the power flow direction without changing the DC line's polarity, VSC-MTDC systems can be used to interconnect independent AC transmission systems and to provide balancing services between these AC networks.

Because of the advantages of using VSC-MTDC systems in some specific cases, power systems' application tools must be upgraded to estimate the operating state of AC–DC transmission systems, as well as to conduct system-wide studies. The state estimation (SE) is one of the most fundamental applications for efficiently operating and controlling electric power systems at both transmission and distribution levels. In contrast to the number of publications addressing the SE of power systems with VSC-HVDC links, however, very few papers have actually focused on mathematical formulations for estimating operating states of grids containing VSC-MTDC links.

The weighted least squares (WLS) method is employed in Ref. [2] to estimate the operating state of power systems containing both the back-to-back and the point-to-point VSC-HVDC links, where their operational constraints are treated as zero power injections (virtual measurements). In this case, only the voltage and current on the DC side of one of the converters comprising the HVDC link are included in the set of AC state variables to be estimated. A WLS-based state estimator that considers phasor measurement units

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https://doi.org/10.1016/j.epsr.2018.03.005

(PMUs) and point-to-point VSC-HVDC links is detailed in Ref. [3]. In this proposal, the AC–DC interface is represented by an ideal controllable AC voltage source. Furthermore, the DC link operation is modeled by an active power balance constraint expressed as a function of powers on the converters' AC sides and losses through the DC link. This constraint is included as a virtual measurement in the formulation. Furthermore, because of the way in which the VSC-HVDC link is modeled, only AC nodal voltage magnitudes and phase angles are considered in the set of estimated state variables. On the other hand, a proposal for integrating a VSC-MTDC model into a WLS-based estimator is reported in Ref. [4]. In this case, the VSC-based AC–DC interface considers the converter's AC side as a controlled AC voltage source, while the DC side is modeled as a controllable current source [4]. Hence, the power flow equations at both converter terminals are completely decoupled because they are only expressed in terms of their corresponding AC or DC variables. Moreover, the DC network is only composed of transmission lines linking converters' terminals such that the number of DC buses is also the number of converters. Finally, the state vector is augmented by including the voltages at both terminals of the AC–DC interface.

A PMU-only state estimation algorithm that considers classic HVDC links is proposed [5]. The formulation avoids using active and reactive power equations and depends on the knowledge of the control operation mode and control targets of the HVDC link. The state variables of HVDC links and the AC grid are estimated simultaneously by using the WLS algorithm, with the AC–DC interface represented by means of the voltage and current phasors at the points of common coupling (PCC) of DC links. In Ref. [6], a sequential WLS-based SE approach is presented where the AC grid and classic MTDC links are decoupled and solved independently by using SCADA measurements. In Ref. [7], a decentralized SE is proposed where the AC and VSC-MTDC grids are solved independently by using the concept of overlapped buses and SCADA measurements. In this case, the PCC buses are duplicated and appear in both networks such that the information in these buses is iteratively exchanged during the sequential SE solution process. The VSC-MTDC grid consists of HVDC links between converters and converter-less DC buses. The estimated variables correspond to the DC voltages, converter transformer tap positions and complex voltages at the PCC buses.

Based on the mentioned above, this paper proposes the direct integration of VSC-MTDC grids in a Hachtel-based SE algorithm that considers both SCADA and PMU measurements. The VSC-MTDC network is not restricted to transmission lines connecting VSCs such that different voltage levels of transmission lines can be considered in the DC network. A set of equality constraints is also proposed for representing the operational restrictions associated with the VSC model adopted in this paper. Note that these constraints are directly taken into account in the problem formulation instead of by using virtual measurements with high weighting factors. Lastly, the estimation is carried out in a unified manner where the state variables associated with the DC grid and the converter stations are simultaneously estimated together with the AC nodal voltages. Those state variables correspond to the nodal voltages at the DC grid, the duty cycles of the DC–DC converters, the modulation index and phase angle of each VSC, as well as the tap ratio of the transformer connecting the converter station to the AC grid.

Bad data filtering is an essential component of the state estimation process and is used to remove all measurements with gross errors in order to obtain an accurate estimate of the system's operating state. In all the proposals mentioned above, the largest normalized residual test is used for bad data rejection. Note, however, that if there is one bad datum present at least two state estimates must be performed to eliminate it. This drawback can be overcome by eliminating more than one of the erroneous measurements [8,9], but in both cases, the elimination of measurements could lead to a problem of observability. On the other hand, instead of eliminating measurements, all measurements with large residuals can be reweighted at each iteration of the solution process to reduce their influence on the final estimates [10–12]. Note, however, that some reweighted measurements are not necessarily erroneous, i.e. their large residual value is caused by the smearing effect. Unlike these proposals, a new practical bad data analysis is proposed, in which multiple bad data are detected, identified and corrected within the iterative solution of the estimation process. The detection and identification of bad data are based on two filtering processes associated with the largest normalized residual and the smearing effect, while the correction of bad data is performed in order to accomplish values of estimated residuals lower than the specified *Th*-sigma rule.

Summarizing the information mentioned above, the most important features of the new proposed approach are as follows.

In this proposed approach, the nodal voltages at the DC grid, the duty cycles of the DC–DC converters, the VSCs' control variables, as well as the on-load tap-changer of the transformer connecting the converter station to the AC grid, are simultaneously estimated together with the AC nodal voltages. In this case, the VSCs' control variables are associated with the pulse-width modulation (PWM) index and the phase control signal. This set of estimated variables differs substantially from other proposals that only estimate the voltage magnitude on the converter's DC side [2,4–7] and the on-load tap-changer [6,7]. Note that the estimation of DC and AC variables is sequentially performed in Refs. [6] and [7].

Unlike all other proposals [2–7], the multi-terminal DC network considers DC–DC converters for representing how the DC power can be transmitted at different voltage levels. In this context, the proposal straightforwardly estimates the different DC voltage magnitudes at which the DC network is operating. Furthermore, the formulation permits considering two or more VSC-MTDCs embedded within a large AC system or connecting two or more independent AC transmission systems.

The VSC-MTDC systems are incorporated into a Hachtel-based state estimation, with the operational constraints of the VSC-based AC–DC station model directly considered in the formulation. On the other hand, these operational constraints are considered virtual measurements with high weighting values in Refs. [2–6] because they adopted a WLS-based state estimator.

Based on the fact that residuals are considered variables to be estimated in the Hachtel method, a new bad data analysis is proposed where the original number of measurements used for the estimation is not altered because the bad data are corrected during the iterative estimation process. This contrasts with the bad data analysis used in all the proposals reported above, where bad data are eliminated from the set of measurements.

The unified state estimation of AC and DC variables is performed by simultaneously processing measurements provided by a SCADA system and PMUs, which is not the case in all other proposals.

2. AC–DC state estimation problem

In this proposal, the estimated state variables $\hat{\boldsymbol{x}} \in \Re^{n}$ in the AC–DC power system correspond to the nodal voltage magnitudes and relative phase angles in AC networks, nodal voltage magnitudes in DC networks, as well as state variables associated with the VSC and DC–DC converters:

$$\hat{\boldsymbol{x}} = \left[\hat{\boldsymbol{\theta}}_{ac}\ \hat{\boldsymbol{V}}_{ac}\ \hat{\boldsymbol{V}}_{dc}\ \hat{\boldsymbol{x}}_{VSC}\ \hat{\boldsymbol{x}}_{DCDC}\right]^{\mathrm{T}}. \tag{1}$$

The superindex T denotes transposition; vectors and matrices are denoted in bold italic letters, and the estimated values of state variables are given in per-unit. In this case, a nodal voltage reference