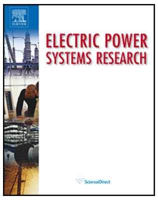
Electric Power Systems Research 160 (2018) 308–317

Contents lists available at ScienceDirect

Electric Power Systems Research

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



Synchronized measurement technology supported AC and HVDC online disturbance detection

M. Naglic[a,*], L. Liu[a], I. Tyuryukanov[a], M. Popov[a], M.A.M.M. van der Meijden[a,b], V. Terzija[c]

[a] Faculty of Electrical Engineering, Mathematics, and Computer Science, Delft University of Technology, 2628 CD Delft, The Netherlands
[b] TenneT TSO, 6812 AR, Arnhem, The Netherlands
[c] School of Electrical and Electronic Engineering, University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 13 December 2017
Received in revised form 6 March 2018
Accepted 8 March 2018

Keywords:
Online disturbance detection
PMU
HVDC
RTDS
Co-simulation

ABSTRACT

In electric power system, disturbance detection has become an important part of grid operation and refers to the detection of a voltage and current excursion caused by the wide variety of electromagnetic phenomena. This paper proposes a computationally efficient and robust algorithm for synchronized measurement technology (SMT) supported online disturbance detection, suitable for AC and HVDC grids. The proposed algorithm is based on the robust median absolute deviation sample dispersion measure to locate dataset outliers. The algorithm is capable of identifying the disturbance occurrence and clearance measurement sample based on the dynamic criteria, driven by present power system conditions. The effectiveness of the proposed algorithm is verified by real-time simulations using a cyber-physical simulation platform, as a co-simulation between the SMT supported electric power system model and underlying ICT infrastructure. The presented results demonstrate effectiveness of the proposed algorithm, making it suitable for an AC and HVDC online disturbance detection application or as a pre-step of backup protection schemes.

1. Introduction

In the recent years, the Smart Grid technological advances in terms of sophisticated intelligent electronic devices (IED), fast and reliable telecommunication links, and increased computational capacities have created new opportunities for design of advanced protection schemes [1].

Typically supported by a global navigation satellite system, the synchronized measurement technology (SMT) makes use of IEDs with specialized firmware or phasor measurement units (PMU) to deliver time-synchronized system-wide measurements in real-time [2,3]. SMT is the key element of wide area monitoring protection and control (WAMPAC) system [4,5], which is favourable to ensure a higher system stability and reliability.

1.1. *Paper motivation*

Nowadays, the power systems undergoes major changes towards a heterogeneous, widely dispersed, yet globally interconnected system with large-scale integration of distributed energy resources [6,7]. Due to the decreased system inertia and higher uncertainty associated with renewable energy sources, the power system have become more vulnerable, especially in terms of power quality and security of supply [8]. Without in-time remedial action, a severe disturbance can lead to a malfunction or break-down of hardware components and considerable economical loss, or, in the worst case scenario, to a complete power system blackout.

Therefore, adequate disturbance detection has become an important part of power system operation and protection and refers to the detection of a voltage and current excursion caused by a wide variety of electromagnetic phenomena [9]. An important requirement for disturbance detection techniques is to provide online, fast, and reliable detection of disturbances that potentially endanger the safe operation of electric power system.

A significant amount of work has been done to locally detect and monitor the grid operating conditions by leveraging the information extracted from signal samples [10,11]. The available disturbance detection methods can be generally classified into two groups. The first group consists of digital signal processing techniques, where the wavelet transform (WT) [12–15], Fourier transform [16,17] and S-transform [18,19] based methods are dominating. However, these methods require either a high

---

* Corresponding author.
E-mail address: m.naglic@tudelft.nl (M. Naglic).

https://doi.org/10.1016/j.epsr.2018.03.007
0378-7796/

measurement sampling rate or a long observation time interval associated with complex mathematical operations, thus making them less appropriate for real-time operation. In fact, WT based techniques are proven to perform well in identifying singularities in the decomposed signal components [20–22]; although the precise time localization of a transient can be ensured, the WT techniques are in general computationally costly, noise sensitive, and their performance depends on the utilized mother wavelet. On the other hand, the statistical techniques [23–25] are often less complex and computationally more efficient. However, many presented methods are prone to false-trigger events due to the fixed threshold used to identify a disturbance. The remaining challenge is to dynamically tune the disturbance identification threshold based on the present system conditions.

With the development of PMU, there was a parallel development of backup protection schemes utilizing the advantages of SMT. Authors in Ref. [26] make use of the characteristic ellipsoid method and a decision tree technique to monitor dynamic system behaviour, identify system events and their location. Although the results are promising, the heavy computational burden makes the algorithm not suitable for real-time operation. In Ref. [27] authors perform principal component analysis to predict the measurement trend and detect abnormalities resulting from unexpected sudden changes. Similarly, a centralised disturbance detection scheme was recently presented, based on the grid parameter estimation technique [28]. The impact of data drop and ICT delay on disturbance detection was also discussed. However, both papers fail to detail the disturbance identification threshold value.

1.2. Paper contributions

This paper proposes a novel SMT-supported online disturbance detection algorithm, which can be utilized as a pre-step of AC and HVDC protection schemes or an online disturbance monitoring application. The proposed disturbance detection algorithm is based on the median absolute deviation (MAD) sample dispersion method, which is a robust statistical measure of univariate dataset variability. The emphasis of the proposed algorithm is on fast response and low computational burden, making it suitable for the online operation. The algorithm is shown to be capable of detecting disturbances in AC and HVDC grids, which are seen as sudden deviations (short-duration dips, swells, interruptions) in the SMT measurements. Disturbances include but are not limited to short circuit faults, line trips and reclosing actions, and large loss of generation or load. Each identified disturbance is characterized with the start and end measurement sample of disturbance occurrence and clearance respectively. To the best authors' knowledge, this paper for the first time makes use of PMUs to deliver time synchronized measurements of HVDC grid.

The effectiveness of the proposed algorithm is verified by real-time simulations using a cyber-physical simulation platform and a small test system model, which includes an HVDC multi terminal configuration based on the modular multilevel converter (MMC) technology. The simulations are performed on the RTDS® real-time power system simulator with integration of the actual SMT components and online disturbance detection center (DDC) as software-in-the-loop.

The aim of this paper is to present a novel SMT-supported online disturbance detection algorithm and its performance capabilities for AC and HVDC. The remainder of the paper is organized as follows: Section 2 presents the data acquisition for AC and HVDC systems. Section 3 presents the algorithm formulation applied to process the data and detect disturbance. Section 4 demonstrates the cyber-physical simulation platform and the used power system model. Section 5 presents the results and discussion. Finally, Section 6 concludes the paper.

2. Data acquisition

In a power system, a voltage or current oscillation signal can be expressed as a sum of complex sinusoidal signals and noise, as:

$$x(t) = \sum_{k=1}^{n} A_k e^{-\sigma_k t} \cos(\omega_k t + \phi_k) + \varepsilon_k(t) \tag{1}$$

where $n \in \mathbb{N}$ is total number of signal components, A is amplitude, σ is damping ratio, ω is angular frequency, ϕ is phase, and ε represent noise and DC decaying offset of each signal component.

Typically, bus waveform signals are fed through adequate current and voltage transformers to the waveform input channels of a PMU device [4]. Recently, several papers [29,30] were published about the digital signal processing methods for a PMU synchrophasor estimation. Through these methods, voltage and current synchrophasors of the fundamental frequency component and the instantaneous system frequency can be determined from waveform samples.

In order to extend the proposed approach to disturbance detection on an HVDC grid, the IEEE Standard C37.118 messages are exploited as a medium for transferring time-synchronized HVDC measurements. In this case, the HVDC voltage and current analog signals of appropriate levels are fed into PMU multi-functional analog input channels. The signal (voltage and current) magnitudes are sampled and transferred as “single point-on-wave” values in 16-bit integer or IEEE floating-point format [2]. Since the analog signal sampling (in case of a GTNET PMU) is done after the synchrophasor estimation (windowing), it is prudent to delay the HVDC input signals for the duration equal to the half of the synchrophasor estimation window length (group delay compensation [2]) as:

$$\tau_{analog} = \frac{N}{2Fsf_0} \tag{2}$$

where N denotes the windowing filter order, Fs is the ADC sampling rate (samples/cycle), and f_0 is the nominal system frequency. In this way, the HVDC measurement sampling is time-aligned with the AC synchrophasor estimation timestamp.

In general, any measured signal of interest can be exploited for disturbance detection. In this paper, the instantaneous positive sequence voltage magnitude and the HVDC voltage magnitude measurements are used for AC and HVDC respectively. In this way, only one source of measurements (positive sequence) can be used to detect single-phase and multi-phase AC disturbances.

3. Methodology

It is assumed that in an electric power system only the N_b buses of interest are monitored with a PMU device. With M being the total number of most recent past measurements (samples) within the observation time interval (window), the samples (measurements of interest) to be examined are defined as $x_{i,k}$ where $k = 1, 2 \ldots M, \in \mathbb{R}^M$ and$i = 1, 2, \ldots N_b, \in \mathbb{R}^{N_b}$ also called the sample vector $X_i = \left[x_{i,1}\, x_{i,2} \ldots x_{i,M}\right]$ of bus i. The dataset containing sample vectors from all N_b buses is presented by the following time series matrix W, as:

$$W = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{N_b} \end{bmatrix} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,M} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N_b,1} & x_{N_b,2} & \cdots & x_{N_b,M} \end{bmatrix} \in \mathbb{R}^{N_b \times M} \tag{3}$$