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Event triggered state estimation techniques for power systems with integrated variable energy resources

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ABSTRACT

For many decades, state estimation (SE) has been a critical technology for energy management systems utilized by power system operators. Over time, it has become a mature technology that provides an accurate representation of system state under fairly stable and well understood system operation. The integration of variable energy resources (VERs) such as wind and solar generation, however, introduces new fast frequency dynamics and uncertainties into the system. Furthermore, such renewable energy is often integrated into the distribution system thus requiring real-time monitoring all the way to the periphery of the power grid topology and not just the (central) transmission system. The conventional solution is two fold: solve the SE problem (1) at a faster rate in accordance with the newly added VER dynamics and (2) for the entire power grid topology including the transmission and distribution systems. Such an approach results in exponentially growing problem sets which need to be solver at faster rates. This work seeks to address these two simultaneous requirements and builds upon two recent SE methods which incorporate event-triggering such that the state estimator is only called in the case of considerable novelty in the evolution of the system state. The first method incorporates only event-triggering while the second adds the concept of tracking. Both SE methods are demonstrated on the standard IEEE 14-bus system and the results are observed for a specific bus for two difference scenarios: (1) a spike in the wind power injection and (2) ramp events with higher variability. Relative to traditional state estimation, the numerical case studies showed that the proposed methods can result in computational time reductions of 90%. These results were supported by a theoretical discussion of the computational complexity of three SE techniques. The work concludes that the proposed SE techniques demonstrate practical improvements to the computational complexity of classical state estimation. In such a way, state estimation can continue to support the necessary control actions to mitigate the imbalances resulting from the uncertainties in renewables.

1. Introduction

State estimation is an essential method in control system engineering where the state of the system needs to be ascertained from potentially uncertain measurements of a partially understood dynamic system. It has been applied to many industrial applications including motors [1], robots [2], as well as bio- and chemical processing [3,4]. For many decades, it has also been a critical technology for energy management systems utilized by power system operators [5]. Over time, it has become a mature technology that provides an accurate representation of a system under fairly stable and well understood system operation. Because of the geographical distribution of the power system, it's state can not be observed directly. Instead, it must be inferred from measurements that include active power injections, reactive power injections, active power flow, reactive power flow, voltage magnitude and phase angle [6]. Although, these measurements (z) may contain errors or noise, the value of the state estimator is in its ability to give the least square error estimate of voltage magnitudes (V) and phase angles (θ) at every bus in a given power grid. This "best" estimate of system state is essential for power system operators to formulate appropriate downstream control actions.

In recent years, the growing demand for energy has resulted in the expansion of the power generation portfolio to include renewables such as solar and wind power. These Variable Energy Resource (VERs) inject uncertain amounts of power at time scales faster and generally dissimilar to that previously found in typical load profiles due to the unpredictable weather conditions [7]. Fig. 1 shows the square root of the power spectra of real power

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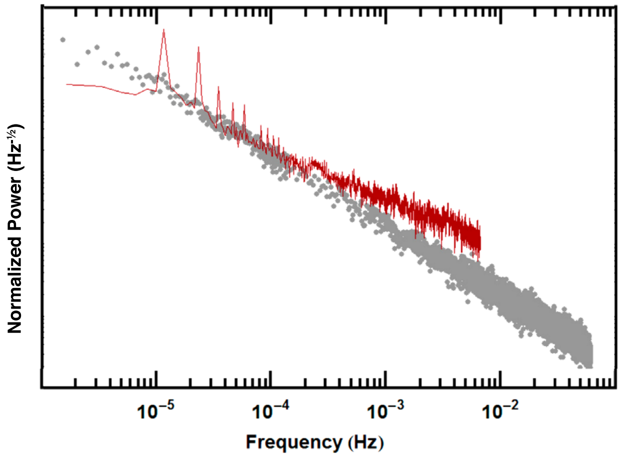

Fig. 1. Power spectra of real power output from 2 wind farms (in light grey) and a 4.6 MW Solar PV array (in Red) [8]. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

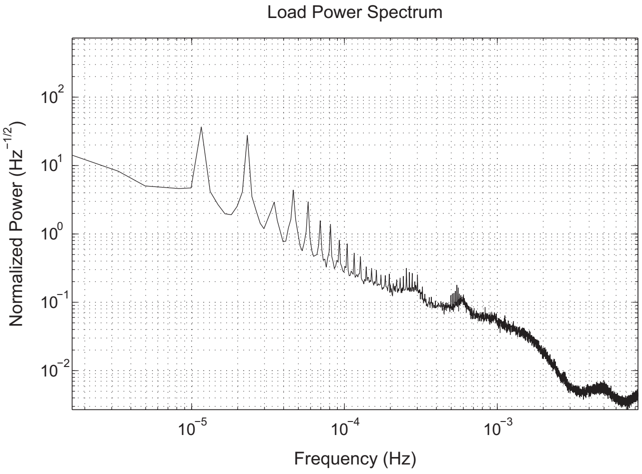

Fig. 2. Normalized power spectrum of real power load (data from Bonneville Power Administration [9]).

output from two wind farms and one solar PV array normalized by the peak load [8]. As shown in Fig. 2 [9], these power spectra have significantly different spectral content than that found in the similarly plotted load spectra [10,11]. Furthermore, our current abilities to forecast VER power output are also significantly less mature [12]. The resulting forecast errors are a reliability risk that power system operators must actively manage. Fundamentally, the dynamic nature of the power grid requires improvements in monitoring techniques to enhance the downstream situational awareness and decision making [13]. One high priority in that regard are the power grid buses at which VERs are sighted.

The emergence of variable energy resources also unhinges many of the conventional assumptions upon which the power grid was built. Traditionally, power networks consist of (1) a meshed transmission network connecting centralized generation units in a wide area, and (2) a radial distribution network delivering power to the final consumer. The former was viewed as more dynamic and requiring active monitoring and control. The latter was often treated fairly passively. This clear distinction between the transmission and distribution networks allows the study of the two types of networks separately and encouraged different standards and requirements for each type of network [14]. State estimation, as a classical technology of the transmission system, was designed to pick up bulk load variations in relation to their potential impacts on large scale centralized generation units. VERs, however, do not typically have the same technical and economic scale and are often sighted within the distribution system. As a result, the associated uncertain and non-dispatchable dynamics require the scope of monitoring to be extended to include the distribution system.

Extending the traditional deployment of state estimation in transmission systems' energy management systems towards the distribution system dramatically increases the computational load. Fig. 3 shows a network graph of the Western Electric Grid in the United States [15]. It shows a highly meshed transmission network connecting the highly radial distribution network. The number of nodes in the former is relatively small as compared to the latter. Although SE methods might be included in Distribution Management Systems (DMS) [16], such a strategy would result in a dramatic increase in the number of buses (or nodes) per unit area. The resulting computational expense restricts the ability to sample at higher speeds to improve monitoring [17,18].

1.1. *Relevant literature*

Classical State Estimation (CSE) of power systems uses a Weighted Least Square (WLS) jacobian-based algorithm to estimate the state vector subject to a steady-state nonlinear model of the power system. The algorithm is performed at regular intervals to update the state vector $x = [V, \theta]$ [5]. It has become the de facto standard of industrial practice in the power sector. As such, it forms the basis of comparison for the subsequent discussion. A conventional CSE implementation that addresses renewable energy integration is to solve the CSE problem (1) at a faster rate in accordance with the newly added VER dynamics (2) for the entire power grid topology including the transmission and distribution systems. Such a strategy, however, is unsustainable because the computational expense restricts the ability to sample at higher speeds to improve monitoring accuracy [17,18]. Therefore, the integration of renewable energy into the power grid requires power system state estimation algorithms that are less computationally intense than CSE.

In contrast, much of the literature focuses on the accuracy of state estimation exclusively and with little attention paid to the required computational resources [19–23].

1.2. *Contribution*

The contribution of this paper is two event-triggered state estimation techniques that address the real-time monitoring needs of power systems with integrated variable energy resources. These specifically require a reduction of computational time despite an increase in power system network size and increasing power variability. In [17], the concept of Event Triggered State Estimation (ETSE) using the variability in the wind was introduced. It proposes to perform the state estimation only when triggered by considerable

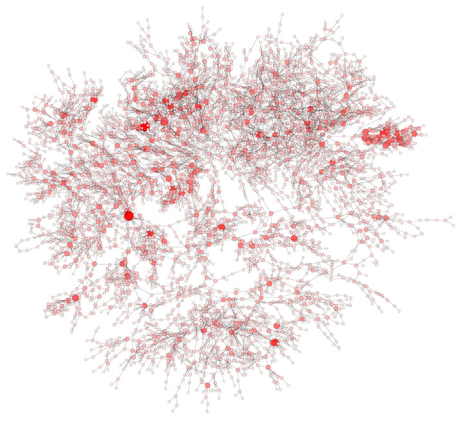

Fig. 3. Network graph of the western electric grid [15].