Control Engineering Practice 53 (2016) 160–172

Contents lists available at ScienceDirect

Control Engineering Practice

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

Power system observability and dynamic state estimation for stability monitoring using synchrophasor measurements ☆

Kai Sun [a,*], Junjian Qi [b], Wei Kang [c]

[a] Department of EECS, University of Tennessee, Knoxville, TN 37996, USA
[b] Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] Department of Applied Mathematics, Naval Postgraduate School, Monterey, CA 93943, USA

ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form
2 December 2015
Accepted 31 January 2016
Available online 15 February 2016

Keywords:
Observability
Dynamic state estimation
Synchrophasor
PMUs
Rotor angle stability
Unscented Kalman filter

ABSTRACT

Growing penetration of intermittent resources such as renewable generations increases the risk of instability in a power grid. This paper introduces the concept of observability and its computational algorithms for a power grid monitored by the wide-area measurement system (WAMS) based on synchrophasors, e.g. phasor measurement units (PMUs). The goal is to estimate real-time states of generators, especially for potentially unstable trajectories, the information that is critical for the detection of rotor angle instability of the grid. The paper studies the number and siting of synchrophasors in a power grid so that the state of the system can be accurately estimated in the presence of instability. An unscented Kalman filter (UKF) is adopted as a tool to estimate the dynamic states that are not directly measured by synchrophasors. The theory and its computational algorithms are illustrated in detail by using a 9-bus 3-generator power system model and then tested on a 140-bus 48-generator Northeast Power Coordinating Council power grid model. Case studies on those two systems demonstrate the performance of the proposed approach using a limited number of synchrophasors for dynamic state estimation for stability assessment and its robustness against moderate inaccuracies in model parameters.

Published by Elsevier Ltd.

1. Introduction

The penetration of a large number of intermittent power generations using renewable energy brings increasing uncertainties to daily operations of interconnected power grids. Early indication of wide-area stability problems is crucially important for control centres to prevent cascading power outages and blackouts (Dobson, Carreras, Lynch, & Newman, 2001; Qi, Dobson, & Mei, 2013; Qi, Sun, & Mei, 2015). In the US and many other countries, synchrophasors, e.g. Phasor Measurement Units (PMUs), are being installed and networked onto transmission systems to provide high-resolution wide-area measurements synchronized using real-time GPS signals. Electricity utilities are building PMU networks to collect data from dispersed PMUs and then send the data to online stability applications at control centres. As of today there are still large technical gaps in applying PMU data effectively for real-time stability analysis and for the control of power grids. Most existing PMU applications are based on direct visualization of PMU data for operators to monitor the grid, which, however, cannot provide in-depth information about the dynamic behavior of the whole grid under disturbances, e.g. contingencies, load changes and unpredictable variations with renewable generations.

In fact, the data in time series collected from networked PMUs makes it possible to reliably predict the dynamic behavior of the entire grid. Thus, the observability based on data from networked PMUs and methods of real-time state estimation of the dynamic grid need to be studied (Kang & Sun, 2013). The goal of this paper is to develop and validate the fundamental theory and the methodology for designing efficient PMU networks by maximizing the observability of potential instabilities and unmeasured states. In addition, an unscented Kalman filter (UKF) based data fusion algorithm is also developed. Some fundamental questions on designing a PMU network are such as how to evaluate networked PMUs in terms of the observability to the presence of instability, and how to develop computationally efficient algorithms for estimating state variables not directly measured by PMUs.

While the theory and algorithms for the filtering and optimal sensor design have been developed for many years, some recent

☆This work was supported in part by the University of Tennessee, Knoxville, the CURENT Engineering Research Center, and AFOSR.

* Corresponding author.
E-mail addresses: kaisun@utk.edu (K. Sun), jqi@anl.gov (J. Qi), wkang@nps.edu (W. Kang).

http://dx.doi.org/10.1016/j.conengprac.2016.01.013
0967-0661/Published by Elsevier Ltd.

results in Kang and Xu (2009a,b) can be used to quantitatively measure observability for large-scale nonlinear systems. Methodologies of optimal sensor placement based on observability Gramian have been developed for weather prediction (Kang & Xu, 2012) and chemical engineering (Singh & Hahn, 2005, 2006). In power systems, most of research on PMU placement is for static state estimation and, hence, is mainly based on the topological observability criterion and focuses on the binary connectivity graph (Baldwin, Mili, Boisen, Boisen, & Adapa, 1993). Under this framework, many optimization approaches have been proposed, e.g. mixed integer programming (Xu & Abur, 2004; Gou, 2008), binary search (Chakrabarti & Kyriakides, 2008) and genetic algorithms (Aminifar, Lucas, Khodaei, & Fotuhi-Firuzabad, 2009; Milosevic & Begovic, 2003).

In this paper, we extend existing results on observability and dynamic state estimation for nonlinear dynamic systems to explore and analyze the observability of power grids and to address some of the aforementioned issues on PMU network design. In Section 2, we first introduce the concept of observability and its computational algorithm. This concept is fundamental to the evaluation of PMU networks. It is utilized to determine the number and siting of PMUs so that the state of the system can be accurately estimated in the presence of instability. Then, an UKF is introduced as a tool to estimate the states that are not directly measured by PMUs. In Sections 3 and 4, we illustrate the methodology developed in detail using a 9-bus 3-generator power system model. In Section 5, we test its performance on a 140-bus 48-generator power system, i.e. a reduced model of the Northeast Power Coordinating Council (NPCC) power grid in North America.

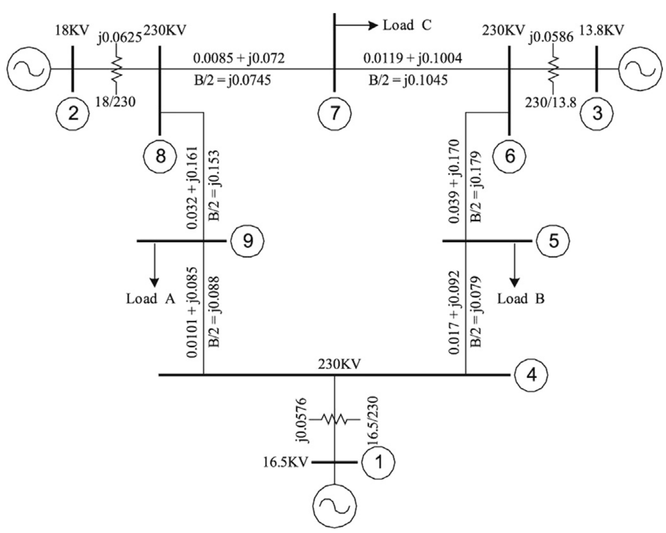

Fig. 1. A 9-bus 3-generator system and parameters.

2. Observability and UKF

This section introduces the concept of unobservability index and an UKF based state estimation method.

2.1. Observability

In Kang and Xu (2009a,b), a quantitative measure of partial observability is defined for general dynamical systems. For power systems, we adopt a simplified version of that definition. Consider any system defined by ordinary differential equations (1), where $x \in \mathbb{R}^n$ is the state variable and $y(t) \in \mathbb{R}^m$ is the output given by sensor measurement.

$$\frac{dx(t)}{dt} = f(t, x(t)),$$
$$y(t) = h(x(t)). \quad (1)$$

In this section, we define the observability with initial condition $x(0)$, which uniquely determines the trajectory of a system. The definition can be easily modified to define the observability for $x(t_0)$ with any given time $t = t_0$. Suppose x and y lie in normed spaces with norms denoted by $\|x\|$ and $\|y\|_Y$ respectively.

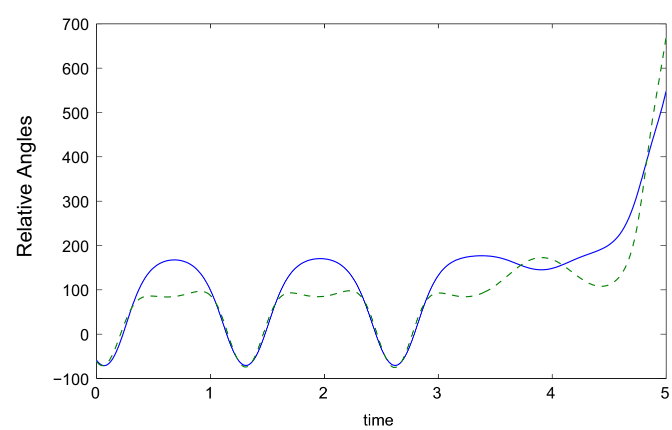

Fig. 3. Relative angles of an unstable trajectory. Solid line: $\delta_2 - \delta_2$; dashed line: $\delta_3 - \delta_1$.

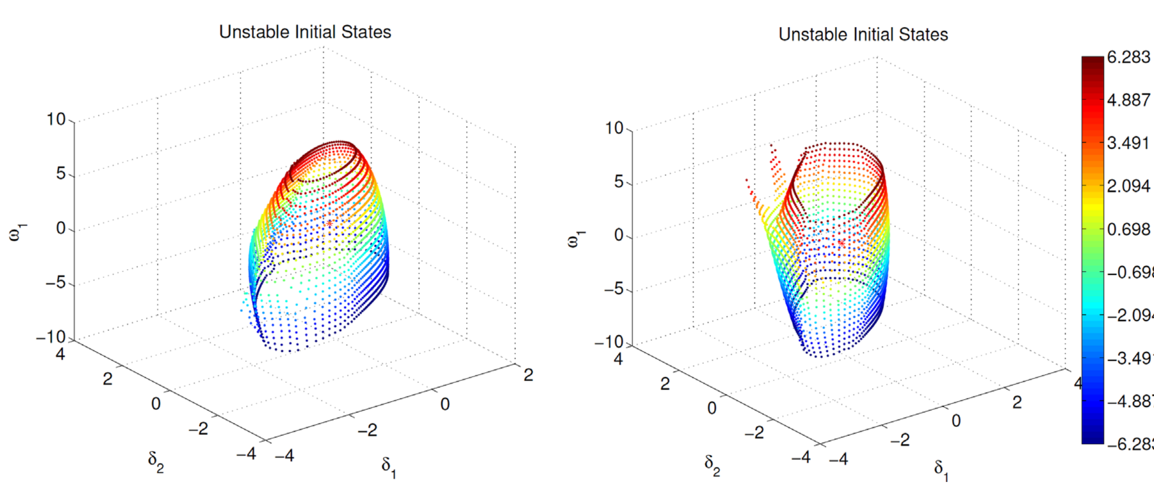

Fig. 2. Envelopes of the DOA in $\delta_1\delta_2\omega_1$-space with $\Delta\omega_2 = -1$ and 0 Hz.