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Decentralized unscented Kalman filter based on a consensus algorithm for multi-area dynamic state estimation in power systems

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ABSTRACT

A decentralized unscented Kalman filter (UKF) method based on a consensus algorithm for multi-area power system dynamic state estimation is presented in this paper. The overall system is split into a certain number of non-overlapping areas. Firstly, each area executes its own dynamic state estimation based on local measurements by using the UKF. Next, the consensus algorithm is required to perform only local communications between neighboring areas to diffuse local state information. Finally, according to the global state information obtained by the consensus algorithm, the UKF is run again for each area. Its performance is compared with the distributed UKF without consensus algorithm on the IEEE 14-bus and 118-bus systems. The low communication requirements and high estimation accuracy of the decentralized UKF make it an alternative solution to the multi-area power system dynamic state estimation.

Introduction

Power system state estimator is an essential tool in energy management systems, whose objective is to reliably estimate the states of an interconnected electric power system by using redundant measurements. In the state estimation (SE), the redundant measurements, typically captured by the traditional supervisory control and data acquisition (SCADA) systems and more advanced synchronized phasor measurement units (PMUs), are imported into the estimator to determine the state vector including voltage magnitudes and angles at all buses in the power system [1]. The SE in electric power grids can be traced back to the pioneering work of Schweppe in 1970s [2]. Since then, numerous methods have been proposed to calculate the state vector of the power system. A comprehensive review and related references can be found in [3].

If the state vector is obtained at time k, from the measurement set of the same time, then the estimator is called static state estimator (SSE) [4]. So far much of the research on the SE has been focused on the SSE [5–7]. For example, the weighted least square (WLS) method, as one of the most classical SSE, is widely used to estimate the state of the system due to its simplicity and fast convergence properties. However, owing to a lack of the evolution information of the state over consecutive measurement instants, the SSE must be recalculated at the next time $k+1$ for a continuous monitoring of the power system. Hence, the SSE incurs heavy computational burdens due to the tremendously increasing scale and complexity of modern power systems. For overcoming the drawback, another SE method, called dynamic state estimator (DSE), was developed, wherein the state at the next time $k+1$ is recursively updated from the state once estimated at time k by using a new set of measurements, avoiding to run fully the SSE again. Furthermore, the forecasting ability of DSE provides vital advantages such as automatically ensuring system observability and identifying sudden changes of states. Based on the assumption that the system was in a quasi-steady state, Debs and Larson, who are pioneers in the development of DSE, proposed a simple state transition model to track the system operating conditions in the early 1970s [8]. The next breakthrough in DSE, proposed by Leite da Silva et al. in 1983, was to introduce a more appropriate state transition model whose parameters was online identified using the Holt's linear exponential smoothing technique [9]. Although numerous artificial intelligent based techniques have been proposed and implemented [10,11], Kalman filter techniques seem to dominate the literature. Since the measurement equations are nonlinear, the most commonly filtering technique used in DSE is the extended Kalman filter (EKF). However, the underlying approximations of the EKF to the posterior probabilistic density functions may lead to large errors and even divergence. Recently, a novel technique based on unscented Kalman filter (UKF) was proposed to cope with non-linearities in dynamic state estimation [12]. The overall impression of using UKF for DSE is its simplicity and low computational demand.

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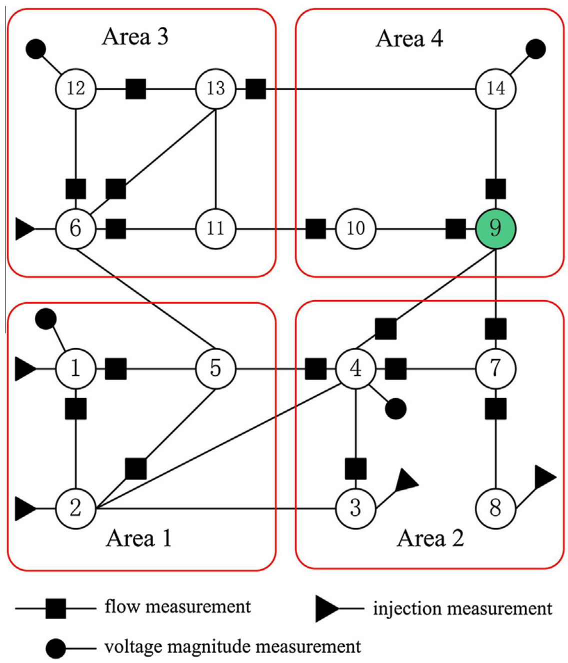

Fig. 1. The IEEE 14-bus system divided into four areas. PMU bus 9 shown as a green circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In today's large scale interconnected electric power systems and future smart grid operations, a fast and accurate state estimator is needed for wide-area monitoring, protection, and control (WAMPAC) [13]. However, the measurements and the state vector become extremely large. For requiring the state of the entire system to be available to all the regional transmission organizations, transferring huge amounts of data from the measurement units to the centralized state estimator is obligatory, which leads to increase the cost requirement for the communication link. Hence the centralized SE proposes tremendous computation challenges for the large power grid. An alternative is to use a decentralized architecture by dividing the large power system into smaller areas and running local state estimators in each area to obtain the global state estimate. In the fully decentralized architecture without central computer, each local state estimator communicates only with its neighbors [3]. The decentralized multi-area SE approaches have many advantages over the traditional centralized SE solutions such as reducing the tremendous computational complexity and improving the robustness of the system. Several approaches to both static and dynamic decentralized SE have been proposed in the literature. In [14], a distributed state estimator to solve the multi-area state estimation problem was provided, where the overall system was decomposed into a certain number of non-overlapping areas on a geographical basis. In [15], a fully distributed state estimation algorithm for wide-area monitoring in power systems was proposed. An unbiased estimate of the entire power systems states can be achieved by iterative information exchange with designated neighboring control areas. In [16,17], the alternating direction method of multipliers was utilized to the distributed and robust state estimation procedure. A lot of benefits of the distributed state estimation by introducing the PMUs were presented in [18,19]. In [20], a dynamic and hierarchical state estimation approach has been proposed, wherein the extended Kalman filter has been used for the filtering procedure. To avoid a so-called 'data tsunami' phenomenon when the smart grid is fully deployed, the authors of [3,21] proposed an event-triggered approach to the distributed state estimation, where the local areas updates their state estimates only when needed and cooperate only when such an action is informative. In [22], a new distributed agent-based SE considering controlled coordination layer was presented. A detailed survey of multi-area state estimation is given in [23]. In the very recent paper [24], a decentralized algorithm for real-time estimation of the dynamic states of a power system was proposed. However, our work is obviously different from the paper [24] in terms of the objects of study and the methods though the titles of two papers are similar. First, our work is to dynamically estimate the magnitudes and phase angles of voltages for a multi-area power system, while the paper [24] is to estimate the dynamic states of the generators; second, we used a consensus algorithm to decentralized UKF, while the paper [24] was based on treating some of the measured signals as pseudo inputs to obtain decentralization of UKF. Therefore, to the best of our knowledge, there were no reports of application of the decentralized UKF based on the consensus algorithm to the multi-area dynamic state estimation, which motivates the present work.

The main objective of this paper is to propose a decentralized UKF approach to dynamic state estimation in multi-area power systems. An interconnected multi-area power system is partitioned into a certain number of non-overlapping areas. At time k, each area is first executed independently for the UKF based on local measurements. Given the obtained mean and covariance for each area, a bounding ellipsoid in the state space is formed to represent local posterior. Then individual smallest axes-aligned boxes containing the ellipsoids are constructed in a distributed manner. To reduce additional communication overhead, a consensus algorithm is performed to reach a global feasibility set by communicating the boxes with pre-specified neighboring areas. Next, new outer bounding ellipsoids are defined based on the global feasibility set. Eventually the UKF correction step with the latest ellipsoids is run again. During the DSE, a central coordinator, which is always deployed in the traditional two-level multi-area SE is not required. Only limited data exchanges between neighboring areas are employed in our proposed approach. The approach is inspired by a number of recent advances in distributed adaptation for sensor networks [25,26]. Specifically, in [25], a set-membership constrained particle filter approach was developed for distributed implementation of sensor network state estimation. Compared with this work, our approach is differed in terms of these two aspects: different final estimate step of the approach and different application background.

The paper is organized such that 'Local area dynamic state estimators based on the unscented Kalman filtering' describes the local area dynamic state estimators based on the unscented Kalman filtering, 'Consensus algorithm' describes the consensus algorithm for multi-area power system SE, 'Final estimate of states' describes final SE step after performing the consensus algorithm,

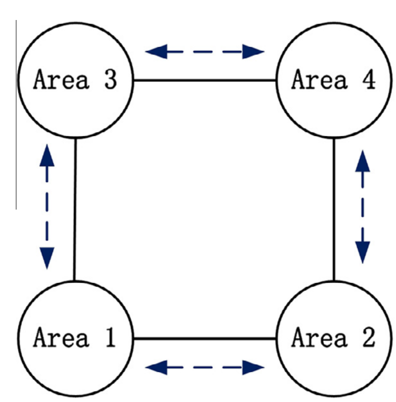

Fig. 2. The communication graph of IEEE 14-bus system.