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A unified framework for wide area measurement system planning

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ABSTRACT

Wide area measurement system (WAMS) is one of the essential components in the future power system. To make WAMS construction plans, practical models of the power network observability, reliability, and underlying communication infrastructures need to be considered. To address this challenging problem, in this paper we propose a unified framework for WAMS planning to cover most realistic concerns in the construction process. The framework jointly optimizes the system construction cost, measurement reliability, and volume of synchrophasor data traffic resulting in a multi-objective optimization problem, which provides multiple Pareto optimal solutions to suit different requirements by the utilities. The framework is verified on two IEEE test systems. The simulation results demonstrate the trade-off relationships among the proposed objectives. Moreover, the proposed framework can develop optimal WAMS plans for full observability with minimal cost. This work develops a comprehensive framework for most practical WAMS construction designs.

1. Introduction

Wide Area Measurement System (WAMS), as a reliable monitor of the power network, is considered one of the most important components in the smart grid [1]. In contrast to the current supervisory control and data acquisition (SCADA) system, measurements of the system states are conducted at a much higher rate (5–60 samples per second versus one per 2–6 s). In addition, all system phasors are developed simultaneously and continuously, rendering real-time knowledge of power system parameters possible [2]. As a result, WAMS can significantly improve the performance of power grids by supporting more accurate state estimation, fault detection, stability assessment, remedial control actions, etc. [3,4].

A typical WAMS comprises synchrophasor measurement devices and Phasor Data Concentrators (PDCs) for aggregating and relaying synchrophasor data. These two major components form a hierarchical structure, connecting through a communication infrastructure (CI). While Phasor Measurement Units (PMUs) are widely employed in WAMS, the recently available Dual-Use Line Relays (DULRs) introduce variability to the modern WAMS construction [5]. DULRs are the protection digital relays for transmission lines and transformers which can report synchrophasor data while providing system protection [6]. Due to its characteristics of being installed along transmission lines and at transformers, DULR is also called “branch PMU” in some previous research [7,8]. Although DULR can only monitor the voltage phasor of its adjacent bus and the current phasor of the branch, it is still promising due to its low construction cost [5].

Despite much work on WAMS planning, there seems no unified WAMS planning framework that jointly optimizes multiple important objectives simultaneously for placing both measurement devices and PDCs in the system. Moreover, despite the decreasing device costs for constructing WAMS, utilities are still a long way from achieving full-installation of PMUs and PDCs across the grid. Meanwhile, better WAMS construction strategies are still welcomed due to their better system reliability and cost-efficient properties.

In addition, much previous work suffers from unrealistic assumptions, which have been thoroughly discussed in [5]. For instance, while some work considers installing PMUs at buses, they should actually be placed at substations which is a collection of multiple buses. When a PMU or DULR is being installed, the respective substation needs to be interrupted leading to a substantial cost in WAMS construction [9]. Consequently a comprehensive model is required to account for all kinds of WAMS installation costs.

Moreover, as PMUs are generally assumed to be installed on buses in the literature, two buses connected with transformers are both considered observable if either one is equipped with a PMU. However, this hypothesis relies on a model of transformer tap positions as fixed network parameters. The estimated bus voltages, power flows and injections with a transformer with incorrectly modeled or inaccurately measured tap ratio can deviate significantly from their actual values, resulting in inaccurate system state estimation [5,10]. Last but not least, a majority of previous work assumes that PMUs are equipped with unlimited measurement channels to observe the current phasors of all connecting branches. Other work focuses on minimizing the number of

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channels required in WAMS [11]. However, none of the existing work determines which branches are observed by each PMU. When given optimal branch allocations for PMUs, we can further improve the measurement performance of a WAMS.

In this paper we propose a unified framework, aiming to fulfill different construction requirements for WAMS. The main contributions of this work are listed as follows:

- We propose a unified framework for WAMS planning, in which PMU, DULR, and PDC placements are jointly optimized simultaneously.
- We consider a realistic cost model for WAMS construction including the power system substation interruption cost during installation.
- We consider a practical substation model with unknown transformer tap ratio, which can better facilitate the utilization of measured system synchrophasors.
- We consider the channel limits of PMUs, and jointly determine which branches should be observed, aiming to provide full observability with the least devices.
- Pareto solutions can be determined for decision making considering various requirements of WAMS.

The rest of this paper is organized as follows. Section 2 gives a brief literature review on WAMS construction research. Section 3 introduces the system model which allows us to design a unified WAMS planning framework. Section 4 formulates a multi-objective WAMS planning problem for developing WAMS construction plans. Section 5 demonstrates the implementations of the proposed framework on IEEE test systems, and compares them with the state-of-the-art solutions. Finally, we conclude this paper in Section 6 with discussions on the proposed framework.

2. Related work

With the increasing demand of synchrophasor measurement in modern power systems, utilities need a methodology to construct WAMS optimally. Canonically most optimal WAMS construction work focused on finding the minimal number of PMUs to ensure full system observability, subject to pre-defined constraints. This so-called optimal PMU placement problem and its variants have been investigated intensively in the past two decades. A wide range of solution methods have been developed to achieve the optimal solution of this NP-hard problem, including but not limited to integer programming [12], metaheuristics [13], exhaustive search [14], weighted least square algorithm [15], etc. Interested readers can refer to [16,17] for more details of PMU placement methodologies.

Besides construction cost, system measurement reliability is also critical for WAMS construction. System states of line outages and loss of measurements need to be considered in order to design a robust and reliable WAMS. An intuitive solution to address these system failures is to install duplicate measurement devices to observe the same bus and this is called measurement redundancy. Due to its simplicity, this technique has been widely adopted (see [12,18] for examples). However this scheme may potentially lead to over-installation of PMUs in the system [5]. As an alternative, a reliability-based PMU placement model is proposed where the possibility of maintaining full observability is investigated [8]. This model considers a trade-off between the total number of PMUs installed and the WAMS reliability, resulting in more versatile placement solutions [17].

Concurrently optimizing PMU and PDC placement is another research direction related to WAMS planning. [4] manipulates the placement of measurement devices and PDCs to construct multiple data paths for the generated synchrophasors to overcome CI failures in WAMS. [11,19] try to minimize the system scale of CI to reduce the WAMS construction cost.

There is also recent work analyzing WAMS construction from the perspective of graph theory and network equivalency [20]. While satisfying the conventional bus observability constraint, [21] also enables estimation of system dynamic models by network reduction approaches. The results can be further employed to update the offline system model.

Besides, there is also research investigating the integration of WAMS construction with other power system applications and services [20,22]. For instance, state estimation is among the most important power system applications which can greatly benefit from WAMS. In [23], the impact of PMU placement plans on the reliability of state estimation subject to data integrity issues is investigated. The proposed mechanism can also provide estimated system parameters given measurement redundancy. Other analyses take power stability analysis [24–26] and oscillation monitoring [27] into consideration. Another widely investigated integration considers power system cyber-security. For passive cyber-attack prevention, constructing WAMS and its protection facilities strategically is widely adopted [28]. Much research has been conducted in this direction, see [29,30] for instance. Refs. [31,32] provide thorough surveys on this topic. Another interesting direction considers communication infrastructure in designing WAMS construction and operation plans. For instance, through proper software layer design, data communication quality-of-service can be guaranteed [33]. Cloud computing may also greatly contribute to improving the communication and computing network efficiencies [34]. The above are examples of existing research on applications and extensions of the WAMS construction problem. They all indicate the significance of optimal WAMS construction strategies. However, due to the limitations of most previous WAMS construction work introduced in Section 1, a generalized and realistic formulation of the WAMS construction problem is required.

3. System model

Fig. 1 depicts a schematic WAMS architecture, where PMU, DULR, PDC, and the central controller form a hierarchical structure over CI, which serves as the media for data transmission. PMU and DULR interface WAMS with the power system and they comprise current transformers (CTs), voltage transformers (VTs), instrumentation cables, and synchronous GPS clocks. Synchrophasors measured by these devices are transmitted to one or multiple layers of PDCs located at selected locations in the system, where the data are aggregated, compressed, and sorted into a time-stamped measurement stream [35]. In general, the data stream is then fed into application software at the central controller for system state monitoring and control decision generation with various control objectives. For simplicity, in this work we assume one layer of PDCs is utilized in WAMS, while multiple layers can be easily adopted into the proposed framework.

3.1. Power system and network observability

We model the power network with an undirected graph $G(\mathscr{V},\mathscr{E})$, where $\mathscr{V}$ and $\mathscr{E}$ are the sets of buses and branches, respectively. There are K substations, each of which, denoted by $\mathscr{S}_k$, comprises a subset of

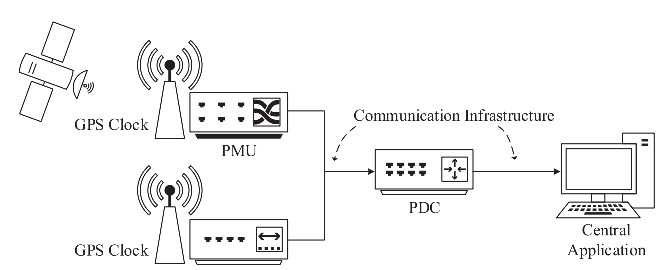

Fig. 1. Components of a wide area measurement system.