

An End-to-End Cyber-Physical Infrastructure for Smart Grid Control and Monitoring

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Abstract—In this article, we propose a generic cyber-physical framework, developed in our laboratory, for smart grid control and monitoring in real-time. Our framework is composed of four key elements: (1) *system layer* which embeds a physical or emulated power system network, (2) *data analysis layer* to execute real-time data-driven grid analysis algorithms, (3) *backend layer* with a generic data storage framework which supports multiple databases with functionally different architectures, and (4) *visualization layer* where multiple customized or commercially available user interfaces can be deployed concurrently for grid control and monitoring. These four layers are interlinked via bi-directional communication channels. Such a flexible and scalable framework provides a cohesive environment to enhance smart grid situational awareness. We demonstrate the utility of our proposed architecture with several case studies where we estimate a modified IEEE-33 bus distribution network topology entirely from synchrophasor measurements, without any prior knowledge of the grid network, and render the same on visualization platform. Three demonstrations are included with single and multiple system operators having complete and partial measurements.

Index Terms—Cyber-physical system, full stack, phasor measurement unit, smart grid, testbed, topology estimation.

I. INTRODUCTION

The increased penetration of distributed energy resources to the traditional distribution grid and a complex nexus of Information and Communications Technology (ICT) infrastructure, built on top of it, represents a rapid paradigm shift in the way the grid is controlled and supervised. With the manifestation of ICT, two-way communication between the utilities and the customers is becoming more apparent. However, before deploying the entire ICT network to physical grids, it is required to define its communication framework and assess the performance in terms of flexibility, scalability, and security [1]. This necessitates the design of a cyber-physical (CP) infrastructure that replicates the real system through simulation and modeling. In addition to the communication, control and monitoring framework, it is required to integrate data-driven intelligent algorithms to support critical operations that require real-time status of the entire grid.

There are numerous examples of CP experimental environments, each developed with distinct utility and application, such as Phasor Measurement Units (PMUs) and Phasor Data Concentrator (PDC) framework testing [2], supervisory control

and data acquisition [3], wide-area monitoring and control [4], [5], cyber-security [6], [7] etc. Further, the frameworks differ in terms of core components. For example, real-time simulator [8], power hardware-in-loop [9] are used to emulate physical grids, and network simulator [10], generalized radio based wireless communication [11], publish-subscribe [12] protocol are used to emulate ICT. Moreover, some experimental environments are tailored to specific applications performed by distribution system operator (DSO), such as state-estimation [13], energy management [14], demand-response [15] etc. Although these diversities are beneficial to address specific challenges associated with smart grids, a unified framework is more suitable in experimental level to provide flexibility and scalability along with fidelity. Apart from unification, another important feature of CP framework is the capability to provide situational awareness of the grid. Modern distribution grids have meshy network structure compared to traditional radial networks. The complexity of such network is further exacerbated by geographical span of the system which may be divided into several sub-regions supervised by independent authorities. This poses a challenge in acquiring precise information about the grid network which is essential to ensure situational awareness. However, to the best of the authors knowledge, the state-of-the-art lacks an unified CP experiment platform which encapsulates the capability to provide real-time situational awareness. This article presents a flexible and scalable CP framework for smart grid control and monitoring manifesting the following major contributions:

- (i) design of a *generic* CP framework that is *flexible* to fit physical, emulated or custom smart grid components.
- (ii) implementation of a *scalable* framework capable of adapting to existing, customized and future ICT infrastructure.
- (iii) development of an architecture that is suitable for both (a) research environments where a support to customized grid analysis algorithms is the prime objective, and (b) enterprise-level where the fidelity to real-time complete situational awareness of the same is of utmost importance.

In this article, we utilize grid topology estimation technique [16] for situational awareness using our proposed framework. However, any generic smart grid control and monitoring functionalities can be tethered to our architecture.

II. OVERVIEW OF THE ARCHITECTURE

Our smart grid control and monitoring infrastructure is composed of four distinct layers that can communicate to each

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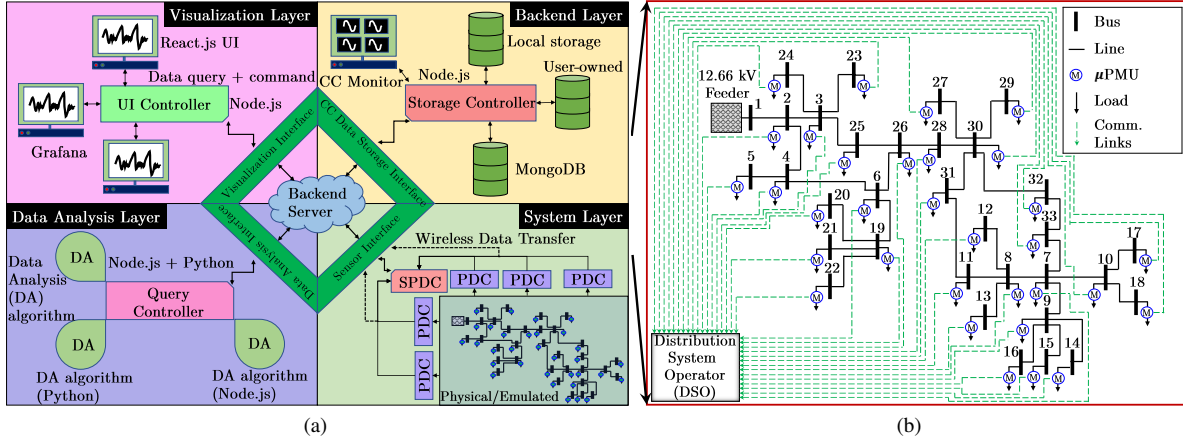


Fig. 1. Overview of the Proposed End-to-End Cyber-Physical Framework for Smart Grid Control and Monitoring, (a) generic architecture showing interconnected System, Backend, Data Analysis and Visualization layers, (b) deployment of the proposed framework on IEEE-33 bus distribution network

other, to provide complete configurability in terms of system control, monitoring and data analytics. Fig. 1(a) illustrates the architectural overview of the communication network between these layers. At the core of our proposed framework, there is a backend server that interconnects (1) *System layer*, constituting a physical (or emulated) grid and associated measurement devices, (2) *Backend layer*, involving data storage, local monitoring, (3) *Visualization layer*, where customized user-interfaces (UIs) can be deployed, and (4) *Data analysis layer*, where analytics algorithms can be executed by querying the stored data from the backend layer. Subsequent sections describe each layer with its specific functionalities.

A. System Layer

The system layer embeds a physical or emulated grid with several measurement devices deployed at different places in the network. Usually smart grids are equipped with PMUs, power flow meters, and various other sensors with specific functionalities such as breaker status measurement etc. While the traditional power flow measurement can be directly relayed to the control center (CC), PMUs require data aggregation at different points to efficiently manage the volume of data. PMUs utilize user datagram protocol (UDP) datagrams that are transmitted to PDCs. We develop multiple virtual PDCs, each aggregating distinct set of PMU measurements from the grid via Ethernet. Each PDC decodes the UDP datagrams from the PMUs under its supervision, and takes care of time alignment and missing or lagging measurements. Our data collection algorithm employs circular-buffers to store aggregated PMU data according to their timestamps. Transmission delays and missing measurements are taken care of using buffer and timer combinations. All the PDCs send their respective measurements, via wireless communication, to a virtual super PDC (SPDC) which aggregates them and sends to the CC via backend server. We assign unique identification numbers (UIDs) to all the PDCs and SPDC for authentication purpose. If backend server receives any data packet with unknown UIDs, the packet is dropped. A *sensor interface*, for bi-directional

communication between SPDC and backend server, enables CC to remotely control the system, as shown in Fig. 1. Note that our framework is agnostic to the type of measurement devices as long as the data is received with valid UIDs. Hence, along with PMU measurements from SPDC, distributed power measurements and breaker status, from respective sensors, can also be relayed to the backend server.

B. Backend and Data Analysis Layer

The backend server, maintained by the CC, is responsible for integrating the system with other components of our framework. The received measurements from SPDC are stored in a database. The *CC data storage interface* is an application programming interface (API), with abstraction layer, to support different database (DB) architectures. Multiple different DBs can be accessed using common function call from CC data storage interface, while DB specific functionalities and queries are implemented in *Storage Controller* block. Such a generic framework provides scalability in terms of supported DB architectures. Stored data can be asynchronously fetched for real-time monitoring and further data-driven analysis of the grid. However, resource intensive data analytics and learning algorithms can throttle the backend server if run directly on the server workstation. Therefore, we implement a separate *Data Analysis (DA) Layer* with a query based *DA interface* which routes the queries to the respective DB via CC data storage interface. Note that, several independent DA algorithm can be run in parallel with our architecture. If the queries from multiple DA algorithms are different in terms of structure and the data they request, proper routing of the same is handled in *Query Controller* block. The results of these analyzes are published on user web applications utilizing a visualization interface as shown in Fig. 1. Upon receiving the data transfer request from the DA layer, for result publication, backend server routes it to a UI controller in the visualization layer. For continuous monitoring of the system, backend can be instructed to automatically send data from the storage to the UIs at certain intervals configured by the user. We encapsulate

Algorithm 1: Learning Grid Topology [16]

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Function getTopology ( $[\mathbf{V} \ \boldsymbol{\theta}]^T \in \mathbb{R}^{2N \times S}, \tau \in \mathbb{R}^+, \mathcal{V}$ ):
   $\mathcal{E} \leftarrow \phi$ ;  $\boldsymbol{\Sigma}_{(\mathbf{V}, \boldsymbol{\theta})} \in \mathbb{R}^{2N \times 2N} \leftarrow \text{covariance}([\mathbf{V} \ \boldsymbol{\theta}]^T)$ ;
   $\begin{bmatrix} \mathbf{J}_{\mathbf{V}\mathbf{V}} & \mathbf{J}_{\mathbf{V}\boldsymbol{\theta}} \\ \mathbf{J}_{\boldsymbol{\theta}\mathbf{V}} & \mathbf{J}_{\boldsymbol{\theta}\boldsymbol{\theta}} \end{bmatrix} \leftarrow \text{inverse}(\boldsymbol{\Sigma}_{(\mathbf{V}, \boldsymbol{\theta})})$ ;
  foreach  $i, j \in \mathcal{V}$  do
    if  $\mathbf{J}_{\mathbf{V}\mathbf{V}}(i, j) + \mathbf{J}_{\boldsymbol{\theta}\boldsymbol{\theta}}(i, j) < -\tau$  then
       $\mathcal{E} \leftarrow \mathcal{E} \cup \{\{i, j\}, \{j, i\}\}$ ;
    end
  end
  return  $\mathcal{E}$ ;

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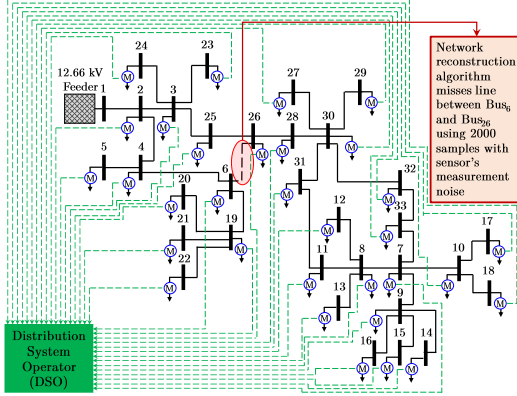


Fig. 3. Demonstration-1: DSO reconstructs grid topology, in real time, using comprehensive set of PMU data utilizing proposed cyber-physical framework

is used to estimate $\mathcal{G}$ with a empirically tuned non-negative constant τ . [16] is referred for specific details and the proofs of the algorithm which we omit here to conserve space.

C. Demonstration-1

In this demonstration, a DSO (shown in Fig. 3) has the access of all 32 PMUs in the IEEE-33 bus network. The proposed CP architecture is utilized to find the efficacy of the topology estimation algorithm. It uses various numbers of time-series samples of measured voltage phasor magnitude and angle from the complete sets of PMU (i.e. 32 PMUs). Measurement noise (within $\pm 1\%$ of full scale measurement) of sensors are also included to showcase the accuracy of the estimation. As a metric for efficiency, error in estimation is defined as the ratio of the sum of number of false lines identified and true lines missed, to the total number of lines in the network. Fig. 4 shows the error plot of the topology estimation algorithm used in the architecture w.r.t various number of samples with and without sensor noises. It is observed that measurement noise degrades the performance of the algorithm. As a part of demonstration, two experimental results are showcased here. As shown in Fig. 3, with comprehensive sets of 2000 samples of phasor measurements without noise from 32 PMUs, the DSO estimates the topology with absolute accuracy using the estimation algorithm. However, when measurements are corrupted with sensor noises, the DSO misses line connecting bus 6 and 26 as shown in Fig. 3. The efficacy of the algorithm in this case-study with 2000 samples are also shown in Fig. 4.

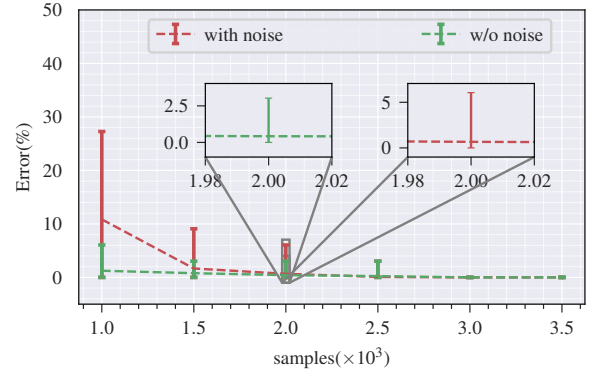


Fig. 4. Topology estimation error plot for 1000 runs with various number of samples of phasor measurements from 32 PMUs in IEEE 33 bus network used for Demonstration-1. Dashed line indicates the mean error rate.

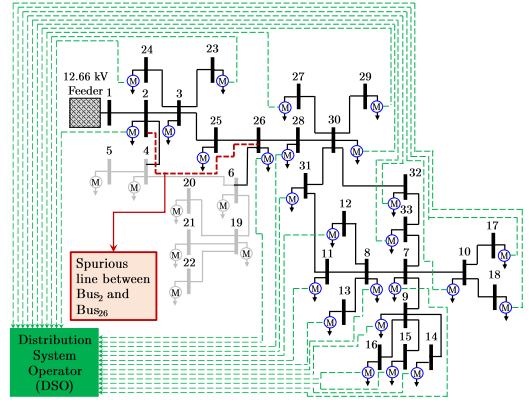


Fig. 5. Demonstration-2: PMUs at buses 4–6 and 19–22 are malfunctioning. DSO reconstructs the grid topology using rest of the available PMU data.

D. Demonstration-2

In this demonstration, a DSO (shown in Fig. 5) has partial access to PMUs in the IEEE-33 bus network. Due to malfunction, PMUs at bus $\{4, 5, 6\}$ and $\{19, \dots, 22\}$ are not sending measurements to the DSO. The proposed CP architecture is utilized by the DSO to estimate the topology using the topology estimation algorithm with 2000 time-series samples of measured voltage phasor magnitude and angle from the partial sets of PMU. The estimated topology is shown in Fig. 5. It can be observed that the algorithm finds the network with all visible PMUs. However, as PMUs at buses $\{4, 5, 6\}$ and $\{19, \dots, 22\}$ are not visible, the algorithm finds a spurious link between bus 2 and 26. This spurious link suggests the DSO that there is possibly a loopy network between bus 2 and 26. In fact, network connecting buses $\{4, 5, 6\}$ and $\{19, \dots, 22\}$ is the actual hidden loopy network in the original system.

E. Demonstration-3

In this demonstration, two DSOs (as shown in Fig. 6) have partial access to PMUs in the IEEE-33 bus network. Due to locational advantage, DSO-1 has access to PMUs at buses $\{2, \dots, 6\}$ and $\{19, \dots, 26\}$. DSO-2 has access to PMUs at buses $\{7, \dots, 18\}$ and $\{27, \dots, 33\}$. The tie-line between bus

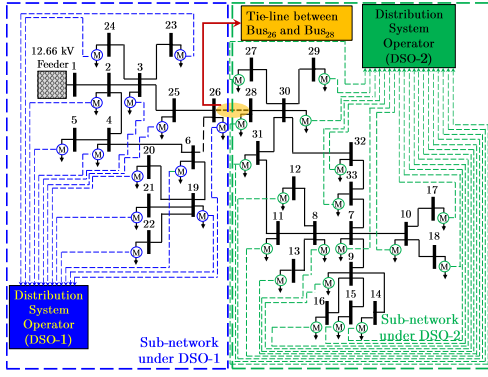


Fig. 6. Demonstration-3: DSO-1 and 2 utilize PMU data from Sub-network-1 and 2 respectively and reconstruct the corresponding topologies, in real time.

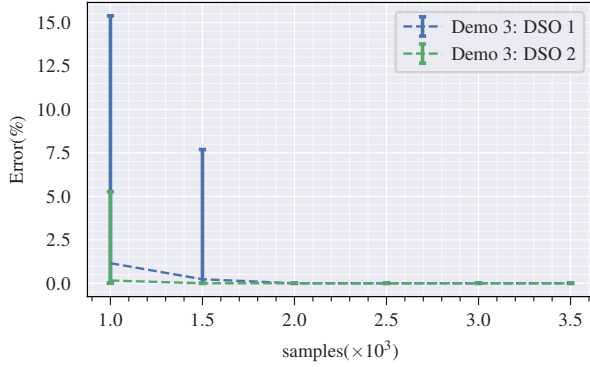


Fig. 7. Topology estimation error plot for 1000 runs with various number of phasor measurement samples from PMUs deployed in their respective sub-networks used for Demonstration-3. Dashed line indicates the mean error rate.

26 and 28 is an additional information that both DSOs know. The proposed architecture is utilized by both the DSOs to find the efficacy of the algorithm using various numbers of time-series samples of measured voltage phasor magnitude and angle, to estimate respective topologies (networks inside blue box for DSO-1 and green box for DSO-2). Sensor noises are also included to showcase the accuracy of the estimation. Fig. 7 shows the error plot of the same w.r.t various number of samples for this particular case. One experimental result is showcased in Fig. 6, with partial sets of 2000 samples from PMUs at buses $\{2, \dots, 6\}$ and $\{19, \dots, 26\}$ for DSO-1 and PMU measurements at buses $\{7, \dots, 18\}$ and $\{27, \dots, 33\}$ for DSO-2. Both estimate their respective topologies with absolute accuracy using the estimation algorithm.

IV. CONCLUSIONS

The proposed CP framework, for smart grid control and monitoring in real-time, is developed in laboratory setup. It consists of system, data analysis, backend and visualization layer. For demonstration, a real-time simulation of modified IEEE-33 bus distribution network is done with the control and monitoring layer, realized in server workstation. For validation, a topology estimation algorithm is executed in the workstation communicating with the test system and three

case-studies are showcased. These validations form the basis for the authors to further extend and include various other control and monitoring functionalities in the framework. For future work, such functionalities will be included in order to shape the framework to be more generic and useful for real operation under smart grid paradigm.

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