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A flexible platform for synchronized measurements, data aggregation and information retrieval

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ABSTRACT

Synchronized measurements enable a number of applications, which shape most of the features of the smart grid paradigm. Phasor measurements units (PMUs) have an increasing role in power system state estimation, detection of inter-area and other low frequency oscillations, parameter identification, power system control and protection. Although standardization is in place for both information retrieval and data communication, there is a need to further optimize the way measurements obtained from sources with different reporting rates are exploited, by designing a platform flexible enough to simultaneously run in real time most of these PMU-based applications. In this paper such a platform is presented. It encompasses multiple PMUs from different vendors, manages detailed information about the measurement chain and its associated uncertainties and exploits a unique communication infrastructure with OpenPDC as the underlying layer for data fusion. It is based on a powerful Java EE7 application that extends OpenPDC and represents the environment for extracting, managing and processing the information. The Java EE7 application has been developed aiming for security, scalability, portability, concurrent access and big data processing. Such goals could have not been achieved without making some of the latest enterprise technologies work together. The end result can be exploited as a highly capable and interactive processing node within the grid and it also hints at important features that can be included in the upcoming IEEE C37.247 Standard for Phasor Data Concentrators for Power Systems.

1. Introduction

Synchronized measurements have been developed originally for protection purposes and then evolved to adaptive control, state estimation and recently to applications and deployed beyond the substation level [1], [2]. A recent subset of such sensing elements is represented by PMUs, which greatly extend the area of potential applications, beyond the realm of protection and control [3]. One of the most exploited field is the use of PMU data for linear or hybrid state estimation [4–7]; furthermore, there are direct applications in power system control, like detection of inter-area [8] and other low frequency oscillations [9], parameter identification [10], protection [11] etc. A recent topic covered by PMUs is the one of power quality monitoring [12] and, although steady state conditions are a pre-requisite for such analysis, the emerging active distribution grids reveal phenomena for which geographical data correlations are needed and now possible [13]. In many of the emerging control applications, both time- and space data aggregation is needed. The applications based on measurement information retrieved from several nodes of the system need a synchronization protocol. The required clock precision is dependent on

Abbreviations: 3G, mobile communication standard with a minimum data rate of 2 Mbit/s; 4G, mobile communication standard succeeding 3G; AES-256-CBC, Advanced Encryption Standard with 256 bit Cipher-Block Chaining; API, Application Programming Interface; CA, Certificate Authority; CSV, comma-separated values; DN, designated node (ICN architecture); DNAT, Destination Network Address Translation; GPS, Global Positioning System; ICN, Information Centric Network; IED, Intelligent Electronic Device; Java EE, Java Enterprise Edition; JAXB, Java Architecture for XML binding, mapping XML into Java classes; JAX-RS, Java API for RESTful Services, mapping HTTP requests into Java classes; JMS, Java messaging API; JPA, Java persistence API; JSF, Java server faces, enterprise standard for rendering the web page content; JSON, JavaScript Object Notation, alternative standard to XML; JTA, Java transaction API; OpenPDC, 3rd party Phasor Data Concentrator; PDC, Phasor Data Concentrator; PMU, phasor measurement unit, estimates the phasor associated with an electrical waveform. The measurements are time stamped according to a UTC time reference; PPP, point to point protocol; REST, representational state transfer, abstract architecture for designing web services; RP, Rendezvous Point (ICN Architecture); SHM, Shared Hardware Memory; SNAT, Source Network Address Translation; SSL, Secure Sockets Layer; TCP/IP, the Internet protocol suite, TCP and IP are its most important protocols; TLS, Transport Layer Security; UDP, User Datagram Protocol; VPN, Virtual Private Network; WvDial, pronounced weave-dial, a utility that helps with modem based connections; XML, Extensible Markup Language.

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the application, the standards maturity and available technology. Presently, SCADA is the reference for the space-aggregated measurements provided by electronic equipment (IEDs) while PMUs enable a higher level of synchronization quality. Synchronization of various sources of information is the PDC's responsibility, in addition to the task of collecting the measurement data from the PMU devices in order to further correlate and consolidate the information based on the time stamps.

Summarizing the requirements of data fusion from the perspective of already in-use applications, the goal of this work has been the development of a full platform, flexible enough to simultaneously run in real time most critical control algorithms based on PMU-like synchronized measurements. Hence, the platform has to fulfil several requirements: it is able to accommodate several PMUs from different manufacturers, providing space-scalability (the number of PMUs to be integrated); it should ensure appropriate information retrieval along the measurement chain with full knowledge of its associated measurement quality.

The solution presented in this paper is using a unique communication infrastructure, with OpenPDC [14] the underlying layer for concentrating the information from data received with heterogeneous reporting rates; the core of the architecture is a Java EE7 application that extends OpenPDC and represents the environment for extracting, managing and processing the data.

Considering the power systems protocols for information retrieval, an autonomous communication infrastructure independent from that of the substations has been developed, concentrating the synchrophasor data into a central server. This communication layer used for illustration makes use of Romania's and UK's extensive 4G coverage area and is secured at three different levels: authentication through certificates, encryption and firewalling.

After the PMU measurements are transmitted to the PDC (subject to the IEEE C37.118 standard [15]), data are extracted from the PDC through a Java EE7 application. This enhances the PDC with additional functionality, like accounting for the instrument transformers measurement uncertainties, while keeping the data processing layer separate from the actual PDC, and therefore maintaining for the latter a high level of reliability.

The proposed data hub solution ensures: (i) keeping track of the PMUs deployment with all the technical details of their connection to the grid, (ii) defining customized data extraction queries for particular power system applications, time alignment and .CSV extraction for an easy post-processing experience, and (iii) automatically filtering out the unnecessary data for data storage optimization. Another important feature is the accessibility of all the key resources in machine readable format like XML or JSON through RESTful web services. These resources can be accessed automatically by other measurement equipment (like, for example, smart meters) or other digital devices connected to the active nodes within the distribution grid, if needed. This platform has been tested so far against five simultaneous connections extracting data from three different geographical locations, but the system is scalable for many more connections, as the code has been implemented according to the robust enterprise Java EE7 Standards [16], ensuring optimized interactions between the business logic and persistence layers, transactions management, resource pooling, support for distributed databases, etc. The security, scalability, portability, concurrent access and big data processing capabilities achieved through the development of the Java EE7 application bring an additional dimension of novelty for the proposed solution.

The paper is split into eight sections. Section 2 briefly describes the measurement setup and provides examples of connections within substations, as part of the illustrative deployment. Section 3 details the communication infrastructure. Section 4 represents the practical assessment of the communication latency and comparisons with similar work in the literature. Section 5 presents the development of the Java EE7 application. Section 6 encompasses practical results achieved through the developed platform. Section 6.1 presents an example of a real time power system visualization application running on the resulting platform. This particular example glues all the pieces together and demonstrates the functionality and flexibility of the whole system. Section 6.2 presents a simple but powerful data mining algorithm running on the current platform. The data received within the PDC is analysed and only data segments showing power system disturbances are extracted. The latter can serve as input for a series of more advanced algorithms. Section 6.3 details a more advanced application running on the flexible platform: estimating the dynamic characteristic of loads. Section 7 compares the resulting platform with the IEEE C37.244 Standard [17] and the Information Centric Networks (ICN) paradigm. Section 8 is reserved for conclusions.

2. Measurement setup and data environment

The setup we use as an illustration of the proposed solution and tested in the work reported in this paper comprised of five PMUs: four Arbiter 1133A Power Sentinel units [18], which we will call in the following A-type PMU and one SEL 487-E [19], named in this paper S-type PMU. Each A-type PMU has two three-phase measurement channels: one is dedicated to voltage measurements (either direct connection to LV networks or indirect, by using potential transformers) and one to current measurements (either direct connection up to 20 A/phase or indirect, by using current transformers). The S-type PMU can be configured with up to eight measurement channels: two independent three-phase voltage channels and six three-phase current channels. The A-type units, due to their easy-connection are well suited for mobile applications like, for example, monitoring one grid element (power transformer, cable, overhead line) at both ends for deriving its electrical parameters; the S-type is best used to monitor the energy transfer across the busbars within a substation. A list of PMU deployments within substations has been provided in Table 1.

A communication infrastructure capable of sending the synchrophasor data to a central location for processing purposes has been firstly designed. The lack of Internet access in most substations has been the first barrier to overcome. Furthermore, because the technical details of the measurement chain are specific to each measurement setup deployment, additional functionalities have to be embedded within the PDC. Also, in order to increase data availability for concurrent access required by various signal processing applications, the need of a universally available data repository with certain features, like .CSV files extraction, time alignment, filtering, etc. is highlighted. A conceptual view of the developed platform is depicted in Fig. 1.

3. Communication infrastructure

The extensive 3G and 4G coverage areas have been an incentive to develop an independent communication infrastructure, where the functionality is encapsulated into a VPN server and several powerful customized routers (Fig. 2).

In order to be able to implement the flexibility and security requirements for this solution, a Linux distribution for embedded devices was chosen, which allows building and deployment of the customized operating system onto the limited memory and processing capabilities of a simple router. After analysing and comparing three different Linux distributions: OpenWRT [20], DD-WRT [21] and TomatoUSB [22], the latter was the winning solution, provided its balance between the already available packages and the degree of freedom to add new ones. When configuring the routers