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Roadmap and Lessons for Large Scale Synchrophasor System Deployment

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SUMMARY

Phasor Measurement Unit (PMU) and Phasor Data Concentrator (PDC) are the key elements for the realization of Synchrophasor based Wide Area Measurement System (WAMS) applications. The real-time precise, synchronized grid measurements captured by the Phasor Measurement Units (PMU) are time-aligned and concentrated by aggregate PDCs. If there are localized applications, such as distributed State measurement processing, the aggregate PDC may provide data to the local application. Same time, the time aligned data is transmitted to the control centers where the data is processed by superPDCs. Then, the synchrophasor data is distributed to the applications such as Wide Area Monitoring, Adaptive Protection, Fault Location and other synchrophasor end users such as ISO and neighboring utilities.

This paper presents functional and architecture considerations with the lessons learned from a project involving large scale deployment of PMUs and PDCs in North America. The functional considerations for PMU are highlighted to optimize the number of required devices and its placement by utilizing multiple CT/VT supported PMUs and practical PMU placement strategy. Another important device of WAMS, a PDC is presented with its desirable functions, such as multiple protocol support and seamless protocol conversion, remote diagnosis, multiple data rates, local archiving and visualization, etc. The architectural consideration such as PMU/PDC allocation, application specific data rate selection, network bandwidth reduction and appropriate protocol selection are explained in this work. Finally, an example of a large scale synchrophasor system deployment is presented with key lessons learned especially with advanced technology implementation, e.g. IEC 61850-90-5 based multicasting of Routable Sampled Values (R-SV), IEEE 1588 based time synchronization of PMUs, data redundancy using multiple Application Service Data Units (ASDUs), etc.

KEYWORDS

Phasor Data Concentrator (PDC), Phasor Measurement Unit (PMU), Wide Area Measurement System (WAMS).

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1. Introduction

Synchrophasor technology is key for wide area situational awareness . Figure 1 shows high-level hierarchy diagram of a Wide Area Measurement System. The diagram illustrates an example of distributed architecture with hierarchy and a central location for system wide analytics for a transmission system. Each of the substation monitoring and data concentration along the architecture may be designed for disaster recovery and for the grid resiliency needed.

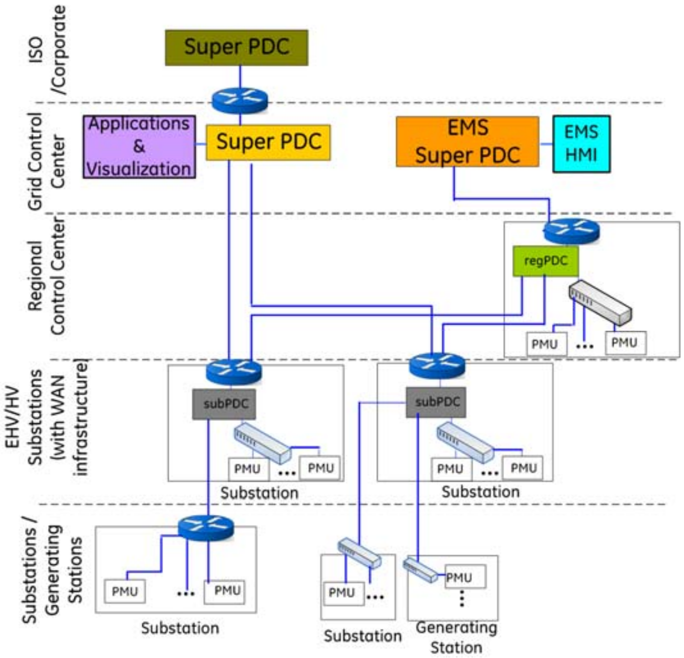

Figure 1 - Hierarchy of a typical Wide Area Measurement System (WAMS).

As shown in Figure 1, PDC functionality is classified based on its location in the hierarchal level as below:

- Substation/Nodal PDC: The substation PDC is installed at high voltage substations or aggregation site, and can also be connected to other, surrounding substation PMUs. The aggregate PDC is substation hardened hardware, processes subset of PMUs (e.g. 20-40 PMUs in the local area) at 60 to 120 frames per second (fps) to carryout local fast applications, such as RAS, adaptive protection, substation state estimation, etc. Depending on the applications and requirements, the aggregation site may also be a Cyber security facility.
- Regional Center PDC: The regional PDC is installed at regional control and operating centers if a utility has this level in their power delivery hierarchy. Normally, it supports a larger number of PMUs (e.g. 50 to 500 PMUs) at 20 to 60 fps for regional applications, event monitoring, post event analysis, etc.
- Super PDC: Super PDCs are normally installed at the main grid control center, where the grid EMS is deployed. It should be able to receive large number of PMUs 500 to thousands, may be at lower data rate 1 to 30 fps for control center applications and interface with EMS/SCADA.

2. Functional Considerations for PMU and PDC

2.1 Functional Considerations for PMU

In addition to producing the synchronized phasor data, the PMU may contain other basic functions such as magnitude or phase error corrections settings, user-defined event triggers, C37.118 protocol for transferring the phasor data as well as some advanced functions such as multiple CTs/VTs inputs, PMU aggregators and the latest IEC61850-90-5 protocol which transmits the synchrophasor data into the wide area networks.

A synchrophasor measurement device may allow single PMU function (with measurement of single bank of voltage and current CT/VT) OR it may offer enhanced capability to accommodate multiple CT/VT inputs. An example is illustrated in Figure 2 demonstrating that it is advantageous to support multiple CT/VT banks for standalone synchrophasor measurement devices. This reduces device count required in a substation for WAMS.

With multiple CT/VT inputs and different classes of data measurement (as per IEEE C37.118.1, P- and M-class), the synchrophasor measurement device should be able to stream individual data classes to redundant locations. These redundant locations may be SuperPDC-A and SuperPDC-B or SuperPDC and historian/auxiliary PDC. In either case, both P- and M-class data have redundant streams, i.e. total 4 streams while aggregating corresponding PMUs.

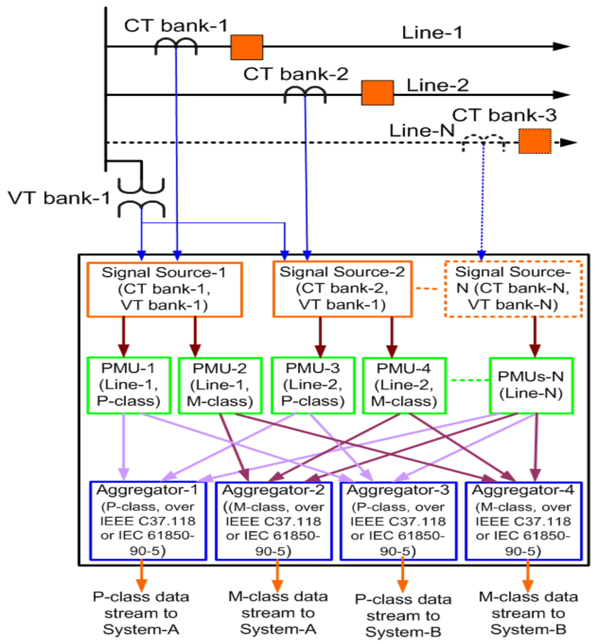

Figure 2 - PMU with multiple synchrophasor measurements & aggregators.

2.2 Functional Considerations for PDCs

A typical synchrophasor data concentrator system is shown in Figure 3. A PDC should be able to perform multiple functions, such as communicating with multiple PMUs, aligning all received data by time stamp, identifying missing data, archiving the data for post event analysis, aggregating and transmitting, and decimating and filtering the output streams as required by the receiving application.

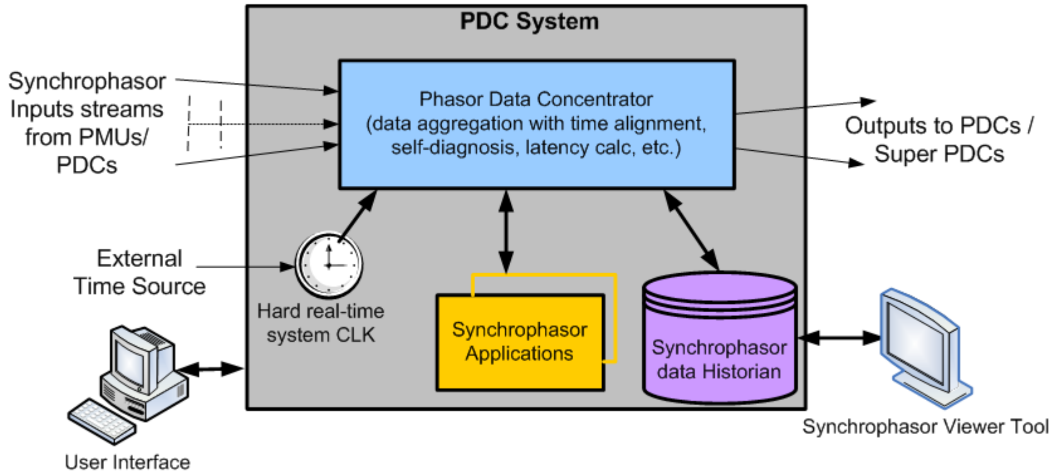

Figure 3 - A typical synchrophasor data concentrator system

The PDC function may be implemented in software or firmware embedded in dedicated hardware. Unlike software, embedded hardware PDC ensures functionality validated with substation hardened real-time platform with deterministic behavior.

In addition to the functions above, some of the functional considerations for PDC are described below:

- **Multiple Protocol Support & Protocol Conversion**

  With latest developments at international standard committees, the synchrophasor protocols include IEEE C37.118-2005, IEEE C37.118-2011, and IEC 61850-90-5 ed.1-2012.

- **Multiple Data Rates, Latency, and Wait Time**

  The data obtained by the PDC from PMUs, installed at different geographical locations, may have multiple reporting rates and may experience different latencies over the network. To address the variable data-arrival latency, a user-defined wait-time is also implemented to ensure that delayed PMU data can be included in the aggregated data frames. Proper use of wait time feature, in PDC, is a balance between application, data availability, size and data rates of data streams, and the memory available for buffering.

3. Architectural Considerations While Deploying WAMS

When deploying a large scale WAMS, some considerations need to be addressed during the planning stages.

3.1 PMU placement over the grid

The reference [9] provides a roadmap for optimal PMU placement. This paper describes architecture for "Analytic Hierarchy Process (AHP)" and the "Weighted Average Criterion" for prioritizing PMU placements.

3.2 PDC allocation

Another key challenge in Engineering the WAMS architecture is the allocation of PDCs over the wide area network, as well as design of the communication network. PDC allocation selection criteria should cover several parameters including, bandwidth availability, cyber security requirements, number of PMUs, number of Application Service Data Units (ASDUs) per data frame, envisioned wide area applications at PDC level, overall latency requirements, etc. Some of the reasons for substation PDCs selected in this large scale synchrophasor deployment include NERC CIP requirements, network isolation for external communication interfaces, aggregation of PMUs (with their respective ASDUs per date frame) at the aggregate level, and archiving & visualization at substation level.

Multiple ASDUs in a frame allows recovery from lost packets. User selects number of ASDUs to be included in a data frame. For example, if 3 ASDUs are configured per data frame, the ASDU 3 is the newest, and ASDU 1 is two samples old. However, this may add processing requirements on PDC.

3.3 Hybrid architecture

Hybrid architecture is a combination of both distributed (hierarchical) and centralized architecture with the goal of enabling the intended applications at each level efficiently. This can be achieved, for example, by deploying IEC 61850-90-5 based IP multicasting over the wide area network. The IEC 61850-90-5 standard allows UDP multicasting, so that synchrophasor data can be transmitted to multiple locations simultaneously. Figure 4 shows the substation PDC is directly streaming synchrophasor data to central location, similar to centralized architecture; and same stream is received by other intermediate PDCs (i.e. ancillary or regional PDCs) to enable regional WAMS applications.

3.4 Optimize bandwidth using data multicasting

One of the major challenges with WAMS deployment is the network bandwidth requirement. If the amount of data over the WAN is not optimized based on application requirements, it can result in needlessly high bandwidth requirements and network latencies. One of the ways of reducing the network bandwidth requirement is through the use of IEC 61850-90-5 based R-SV multicasting (IGMPv3 support). Figure 4 compares the two different communication modes: IEEE C37.118 based unicasting over TCP/IP or UDP/IP (client/server mechanism); and IEC 61850-90-5 based UDP multicasting (publisher/subscriber mechanism). In case of UDP multicasting, the common routing links would only carry one message, and it would reach to all subscribed destinations using IGMPv3 routing mechanism. This way, the volume of data on common communication links would be reduced by the number of destination.

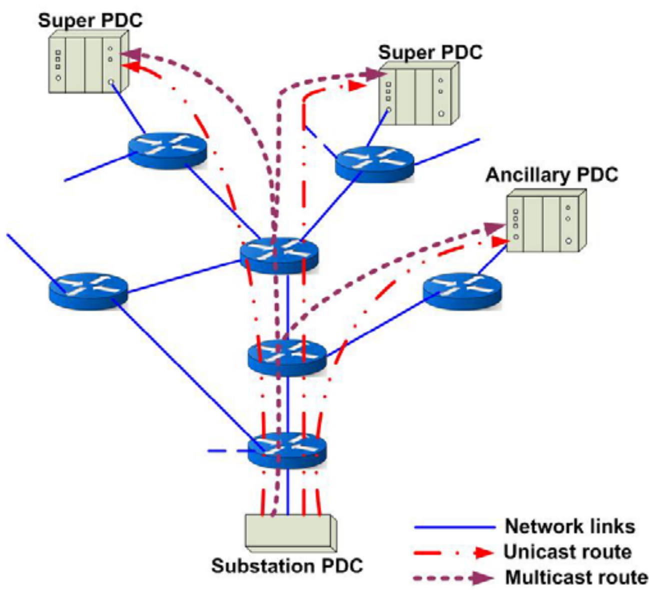

Figure 4 - Synchrophasor data communication modes: unicast vs. multicast.

In addition to multicasting, other parameters which can influence the bandwidth requirements are: 1) Use of substation PDCs (as explained in previous section); 2) Number of PMUs (optimum allocation to support a specific application); 3) Data rate; 4) Number of phasors, analogs and digitals; 5) Selectable signal/channel based mapping in a substation PDC.

4. Deployed Synchrophasor System Architecture – an Overview

Figure 5 illustrates an overview of a system primarily based on the synchronized phasor measurement technology. The system consists of various types of Phasor Measurement Units, Substation Phasor

Data Concentrators, control center / Super Phasor Data Concentrators, and a number of advanced applications at substation or control center level such as system data management and archiving, visualization, enhanced energy management system, and analytical applications.

Major system requirements for the overall architecture are listed below:

i. High reliability requirements: Redundancy → fail safe

ii. High security requirements (e.g., NERC CIP compliance)

iii. Flexible and Expandable system

iv. External interface requirements, e.g. interface with EMS

In addition, it is recommended to calculate the bandwidth requirements based on amount of data, protocol used, and other networking/system parameters.

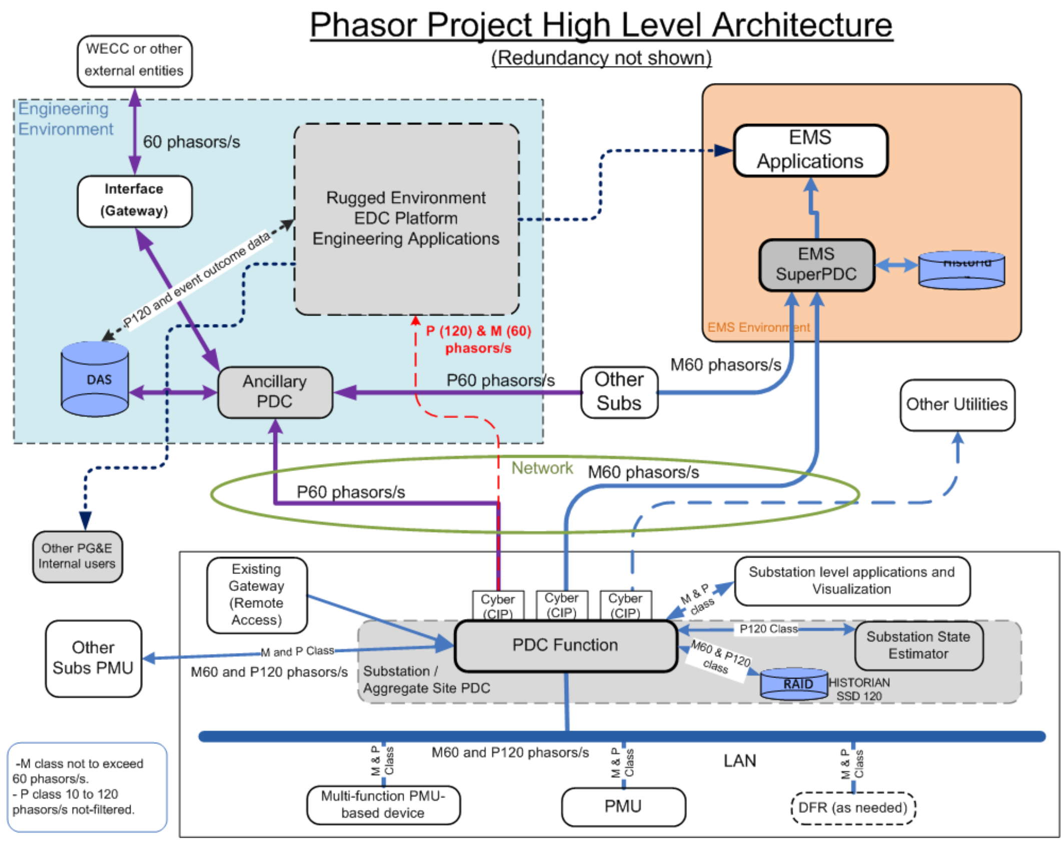

Figure 5 - Simplified Example of Advanced Synchrophasor Architecture

5. Key lessons

The following is a list of the main lessons learned during this project involving large scale deployment of PMUs and PDCs in North America:

1. Implementation agreements and interpretation of requirements/standards: it is important to make sure that all vendors agree to a common implementation for the project requirements.

2. Proof-of-Concept (PoC) setup of a scaled-down system model in a laboratory environment is important to conduct the PMU testing and identify various issues before large scale deployment.

3. Firewalls: It is important that the configured firewall allows the required protocol traffic, e.g. for IEC 61850-90-5, the firewall should allow IGMPv3 traffic.
4. Device remote diagnosis: WAMS devices (PMUs / PDCs / SuperPDCs) should be able to provide local statistics/diagnostics data to central locations for troubleshooting.
5. Time synchronization system: some GPS clocks do not include time quality information in IEEE 1588/C37.238 or IRIG-B outputs. Accurate time quality information is critical for WAMS implementations, and this should be verified in GPS clocks before deployment.
6. Sequence Of Event (SOE) or alarm tracking needs to be implemented using alarm managers in order to quickly identify and manage the system wide log.
7. Configuration and commands can use TCP/IP stack for reliable transfer; whereas, for the continuous data stream it is advantageous to use UDP/IP or UDP multicasting.
8. Effect of filtering, especially on M-class data, was investigated. Filters may or may not preserve M-class data accuracy. Hence, it is important to use data quality flags which can differentiate between real measured data and interpolated data (e.g. in case of missing frames). This quality flag can be used to select only the real measured data in case one of the end applications cannot handle interpolated data.
9. Up/Down-conversion for time-alignment: in case all received PMU data at the PDC are not at the same rate, the up/down conversion filters can be used to time align and aggregate all PMU data into one data stream. However, it is important to differentiate between real measured data and filtered/modified data.

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