Multi Function Instruments with PMU Capability and Post Disturbance Loss of Synchrophasor Data

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Abstract – Phasor Measurement Unit (PMU) data (or synchrophasors) has found increasing usefulness for transmission system visibility and performance monitoring. As such, synchrophasor data completeness is of significant importance. This paper discusses issues found with gaps in synchrophasor data coming from PMUs that are part of a multi-functional device.

I. INTRODUCTION

The Tennessee Valley Authority (TVA) is a generator and transmission owner/operator primarily serving local power companies and transmission-connected industries in the watershed of the Tennessee River Valley. This service area encompasses more than 10 million people, providing power through a network of 16,000 miles of high voltage transmission lines across a seven-state footprint.

TVA began the deployment of phasor measurement unit (PMU) based wide area measurement system (WAMS) in 2006, a network that has grown quickly as new, multi-function devices like relays, power quality monitors and digital fault recorders (DFR) with built in PMU functionality have been installed or added to substation control buildings. Originally seen as novel technology that would support the grid of the future, uses for PMU data (aka synchrophasors) were initially limited. In fact, PMUs were sometimes described as a solution looking for a problem. However, additional use cases for synchrophasors have been identified during the maturation of this technology. Currently, TVA is using synchrophasors to detect power oscillation events on the transmission system, evaluate generator responses to transmission system faults, calculate bus/node voltage unbalance using sequence components, and assess performance of solar generation plants during commissioning tests. Future plans include using synchrophasors to feed a new, real-time linear state estimator that is faster than traditional state estimators and always resolves to a solution.

Due to the increasing use of synchrophasors for visibility, system health, asset performance assessment, and linear state estimation, data completeness is an important consideration.

II. PROBLEM IDENTIFICATION

During routine post fault analysis of a generator response to a 500kV transmission line fault, missing data, or synchrophasor gaps, was discovered in a particular synchrophasor stream in the control center historian. Initially, it appeared that synchrophasor gaps were isolated to one PMU at Substation A. However, further investigation to determine extent of condition identified more locations where synchrophasor gaps existed. An example of synchrophasor gaps is shown in Figure 1.

Fig. 1. Substation A - Voltage Synchrophasor Plot with Missing Data Outlined in Red

Figure 2 shows missing synchrophasors from the viewpoint of tabular data retrieved from the historian. Notice that missing data shows up as “NaN”, or not a number.

	Timestamp	[953604] T	[953608] T\	[953634] T	[953639]	[953640] T	[953641] T	[953642] T	[953643] T	[953644] T	[953699] T	[953707] T	[953708] T	[953712] T
6	19:21:21.833	285.167	274.7973	4.38058	95436.8	-164.628	284.4705	71.91413	-48.95	51.45663	94990.16	-41.2955	668.8199	136.5879
7	19:21:21.867	282.8425	270.6399	3.416626	95340.4	-163.845	284.5793	72.98833	-48.7245	74.90512	94930.16	-41.8193	615.6281	137.6595
8	19:21:21.900	280.2798	267.1064	3.839778	95386.3	-163.974	282.6193	72.6384	-48.5468	74.9427	94999.7	-41.8097	623.9142	134.024
9	19:21:21.933	285.2067	274.0511	2.599536	95440.4	-163.87	283.6916	72.85287	-48.2002	69.59087	95012.77	-41.2835	670.1005	136.4725
0	19:21:21.967	285.8857	276.6122	2.489626	95475	-164.112	282.7854	73.08723	-47.9567	65.52541	95000.51	-41.1202	729.9105	138.5245
1	19:21:22.000	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
2	19:21:22.033	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
3	19:21:22.067	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
4	19:21:22.100	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
5	19:21:22.133	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
6	19:21:22.167	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
7	19:21:22.200	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
8	19:21:22.233	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Fig. 2. Substation A - Voltage Synchrophasor Tabular Historian Data with Missing Data Shown as “NaN”

III. SYNCHROPHASOR NETWORK DIAGRAM

TVA’s synchrophasor network layout, Figure 3, is a standard architecture where remote instruments, or PMUs, installed in substation control houses collect and produce synchrophasor packet streams that are sent to the phasor data concentrator (PDC) in the system control center via various communication backhaul mediums (i.e. fiber, T1, microwave, or 4G LTE). The PDC manages all connections with the PMUs across the grid and aggregates and time aligns the synchrophasor data and then pushes it to various applications for both storage (historian) and real-time monitoring. TVA utilizes the TCP/IP protocol for synchrophasor packet stream to the PDC and from the PDC to the end use applications.

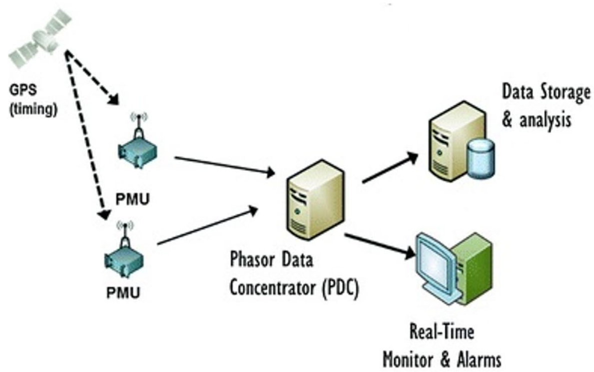

Fig. 3. Synchrophasor Network Diagram

The root cause analysis of missing PMU data in the end use historian and real-time monitoring applications, discussed later, focused on the components of this network diagram. That is, the PMU, the communication path between the PMU and the PDC, and the PDC itself.

IV. PMUs – INSTRUMENTS USED FOR SYNCHROPHASOR MEASURMENTS

The term PMU is the identifier for any instrument that measures and transmits synchrophasor data according to a standard communication protocol such as IEEE C37.118 or IEC TR 61850 90 5. The PMU can be a stand-alone physical unit or one of many functional modules within one physical multi-function device. In addition to stand-alone PMUs, TVA uses the following types of multi-function devices with PMU functionality as a source of synchrophasor data:

1) Power Quality Monitor/Revenue Meter – a multi-function device with the primary purpose of recording power quality parameters, revenue metering data, and transient oscillography records triggered by voltage sags, excessive residual current, or other setting parameters.

2) Digital Fault Recorder (DFR) – a multi-function device with the primary purpose of recording extended oscillography records (several seconds in length) at a sampling rate of 128 samples/cycle or more that are triggered by transient system events such as voltage sags or excessive residual currents.

3) Relays – a multi-function device with the primary purpose of providing protection and control functions for transmission lines, breakers and transformers with primary functions transient system events such as excessive residual, neutral or phase currents.

Prior work by the North American SynchroPhasor Initiative (NASPI) considered some of the performance concerns in multi-function devices related to the interaction between primary functionality and the PMU functionality [1]. Of particular interest is how device computer processing resources are allocated to the different functional units in a multi-functional device.

V. INVESTIGATION OF ROOT CAUSES FOR MISSING SYNCHROPHASOR DATA

A. Network Latency

It is well documented that synchrophasor data timeliness and completeness is heavily influenced by the latency introduced by information communication technology (ICT). That is, the communication backhaul paths between the remote PMU and the centralized PDC and the network routers that regulate and direct the packet flow [2]. Much research has focused on quantifying the latency introduced by each component that makes up the ICT and quantifying the maximum number of PMUs in a WAMS before network congestion becomes an issue [3]. Other research has focused on the best tools to characterize delays and packet losses in synchrophasor data [4].

What is notable in the literature reviewed in preparation for this paper is the time scale for latency and synchrophasor packet delays is in terms of milliseconds. TVA's experience, noted in the problem identification of Section II above, demonstrates data gaps issues in terms of seconds. It seemed apparent that something more than typical network latency was at play here.

B. PDC Data Loss Interval Setting

Initial attempts to ascertain the cause of missing data focused on the PMU and whether it failed to process the synchrophasors or send them to the PDC. While reviewing the PMU communication logs, it was noticed that the PDC had reset the connection to the PMU during a fault event on the transmission system – Figure 4.

```
[1/1/2021 1:14:53 AM] [PMU]Cmd(Stop Sending TCP([redacted]) Data)
[1/1/2021 1:14:53 AM] [PMU]SvrT([redacted]) Disconnected.
[1/1/2021 1:14:56 AM] Fault F3838
[1/1/2021 1:15:00 AM] Fault E3837
[1/1/2021 1:15:03 AM] [PMU]SvrT Connected to ([redacted])
[1/1/2021 1:15:03 AM] [PMU]Server([redacted]) is calling in
[1/1/2021 1:15:03 AM] [PMU]Cmd(Stop Sending TCP([redacted]) Data)
[1/1/2021 1:15:04 AM] [PMU]Cmd(Get TCP([redacted]) CFG2)
[1/1/2021 1:15:04 AM] [PMU]Cmd(Start Sending TCP([redacted]) Data)
```

Fig. 4. PMU Communication Log Showing Reset of Synchrophasor Stream by PDC

Why would the PDC reset the connection to the PMU? After further review, it was discovered that the PDC utilized by TVA has a *Data Loss Interval* setting, which is a self-healing feature to monitor for data loss. If the PDC stops receiving synchrophasor measurements from a PMU, the PDC will wait an amount of time defined by the *Data Loss Interval* setting before closing and then attempting to re-establish the connection with the PMU, an action demonstrated by the PMU communication logs of Figure 4. The default setting for the PDC used by TVA is 5 seconds as shown in Figure 5.

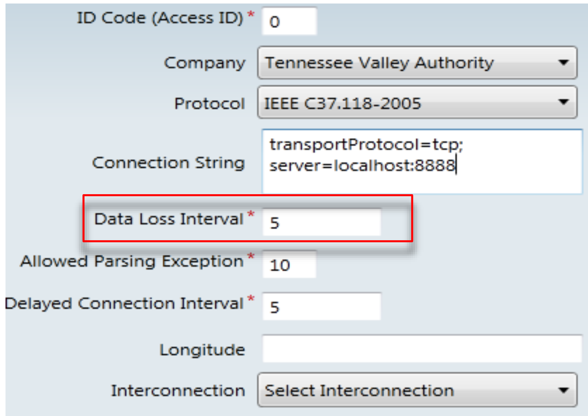

Fig. 5. Data Loss Interval Setting in PDC used by TVA

It was apparent that the data gaps resulted from a reset of the PMU-PDC connection, but what led to the operation of the *Data Loss Interval* timer? Also, why did the data gaps appear to always coincide with a transient, fault event on the TVA system? The answer to these question is discussed next.

C. Multi-Function Device Resource Constraints

For the discussion that follows, it is important to note that Substation A PMU is a multi-function DFR having the capability of continuous waveform capture, transient record capture, and sequence of events recording among several others. From here on, this device will be noted as PMU-A.

From the PMU-A communication logs (Figure 4), there was a suggested correlation between the transmission fault event and the activation of the central PDC *Data Loss Interval* timer. To determine if this correlation was definite or coincidental, one input channel of PMU-A was subjected to a voltage sag condition using a three-phase relay test set in order to initiate a transient record capture by the instrument. Using this process, a reset of the connection between PMU-A and the central PDC was repeatedly observed. This confirmed the correlation between the seconds long data gaps and periods when PMU-A was processing a transient event record. The next step was to determine what was happening to the synchrophasor stream during these time periods.

To understand the relationship between the missing synchrophasors and transient record capture operation of PMU-A, a local computer running a test PDC/historian application was connected directly to PMU-A with the connection to the central PDC remaining such that PMU-A had two PDC connections. A network packet analysis application was installed on the computer running the test PDC which allowed for monitoring of the network traffic between PMU-A and test PDC/historian. Using the method mentioned previously, a transient record capture was initiated on PMU-A. From this it was determined that the synchrophasor packet/frame transmission rate from PMU-A was reduced from its normal rate when the device was active performing its primary function (i.e. transient record capture). In fact, there were periods over 5 seconds where no synchrophasor frames were transmitted, which is the mechanism that led to the operation of the 5 second *Data Loss Interval* timer in the control center PDC. As before, there was a seconds long data gap in the central historian. However, it is important to note that no missing synchrophasors were observed in the test/PDC historian which indicates that PMU-A reliably produced, retained and sent all necessary synchrophasors.

Once the mechanism of the synchrophasor packet frame transmission rate change was understood, the obvious fix was to modify the *Data Loss Interval* setting in the central PDC from 5 seconds to something larger. TVA arbitrarily chose to move the setting to 30 seconds since the primary goal was data completeness during times of transient system events. After changing this setting in the central PDC, a transient record capture was initiated on PMU-A, again using the method mentioned previously. This time, there were no missing synchrophasors in the central historian. While PMU-A still had a delay in sending synchrophasors, the extended *Data Loss Interval* timer prevented the central PDC from resetting the connection to PMU-A during these synchrophasor packet transmission delays (<30 secs).

D. Further Testing

To further investigate the PMU-A synchrophasor packet sending delay, PMU-A was triggered with multiple back to back voltage sags, an action that would simulate a three shot breaker reclose cycle. During this kind of scenario, PMU-A captured multiple transient records back to back to back. During this type of PMU-A operation, there was no reset of the PMU-A to central PDC connection (i.e. *Data Loss Interval* time not exceeded). However, there remained the occasional missing synchrophasor in the central historian – compare Figure 2 to Figure 6. This suggests a more complex mechanism at work that involves the latency of the ICT connecting PMU-A to the central PDC, a topic which involves TCP send/receive buffer size, Nagle algorithm, round trip time, bandwidth delay product and other TCP/IP protocol specifics which are beyond the scope of this paper [5].

23:54:55.133	0	0	1424.225	149.686	0	-89.4864	0.002747	0	150.7626	
23:54:55.167	0	0	1425.682	149.6695	0	-89.5194	0.002747	0	150.7572	
23:54:55.200	0	0	1425.24	149.6585	0	-89.6182	0.002747	0	150.6693	
23:54:55.233	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	N
23:54:55.267	0	0	1421.669	149.5047	0	-89.6677	0.002747	0	150.6033	
23:54:55.300	0	0	1422.47	149.5157	0	-89.6732	0.002747	0	150.5978	
23:54:55.333	0	0	1421.471	149.5047	0	-89.7556	0.002747	0	150.5045	

Fig. 6. Missing Synchrophasors in Central PDC With Multiple Back to Back PMU-A Transient Record Capture

E. Local Station PDC/Historian

The results showed no missing synchrophasors in the local PDC/historian under any testing scenario conducted. Thus, a reasonable solution to guarantee data completeness is the use of a station PDC/historian that can capture synchrophasors from all devices connected on the same local network. This assumes that the station local network latency is negligible no matter the number of connected PMUs or other devices. By using a local PDC/historian, the central PDC can connect to the local station PDC/historian to retrieve synchrophasors making ICT latency a non-issue. If the data is complete in the local historian, then it can be complete in the central historian. That is, the central PDC can continue to request synchrophasors from the local station historian as many times as necessary to fill in any missing data making considerations for complex aspects of TCP/IP protocol like send/receive buffer size, round trip time and packet loss no longer necessary.

VI. CONCLUSIONS

It was shown that in the multi-function PMU-A device, the primary device function seems to take priority for computing processor resources. This does not indicate that the device is unable to perform all its functions well. Instead, it indicates that operators of a synchrophasor network must account for frame packet latency originating from the PMU device itself in the synchrophasor network design. If a large, continuous synchrophasor gap (seconds) is experienced for all channels from a particular PMU, the cause is almost certainly a data loss delay timer setting in the PDC that is resetting the connection to the PMU. The solution could be as simple as adjusting a *Data Loss Interval* timer setting in the PDC. If only a few synchrophasors are missing, the cause is most likely due to ICT latency issues. The simplest solution in this case could be installing a local station PDC/historian. If a local station PDC/historian is not possible, then the potentially very difficult task of understanding and optimizing the performance of all the components in the ICT design would be necessary (i.e. communication backhaul path mode, core router design, QoS, etc.)

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