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Synchrophasor Implementation Experience and Integration Challenges in Indian Grid

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SUMMARY

Wide Area Measurement System (WAMS) based on Synchrophasor units has evolved as a very essential tool for system operator in the recent years. It has given an insight into the dynamic characteristics of system, which helps in understanding the very fabric of power system operation and its analysis. Indian Grid has adopted this technology in 2010 and now more than 60 Phasor Measurement Units (PMU) in the form of Pilot projects are installed for the benefit of Grid Operators. To have a complete overview of National Grid, the data from regional pilot projects have been integrated at national level. The amalgamation of regional to national project with wide diversity has given a technical overview of the synchrophasor technology and understanding of the various challenges in its implementation. Since its inception, the synchrophasor information has been utilised in Indian grid in Real Time as well as Offline for operation, protection, root cause analysis and feedback to planner's purpose. This paper focusses on the various challenges faced during the implementation of pilot projects on WAMS in Indian grid and its utilization for Application development. Out of the many challenges, only few important, and which has serious impacts are discussed in this paper. This includes the integration of PMUs from different make, communication issues, synchronization and big data handling issues. These experiences gained under the pilot project will help in implementation of Unified Real Time Dynamic State Measurement system (URTDSM) project, which will cover all High Voltage nodes of Indian grid with more than 1700 PMUs in India.

KEYWORDS

IEEE C37.118, Indian Grid, Phasor Data concentrator, Phasor Measurement unit, Synchrophasor, Wide area monitoring System.

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1. Introduction

Phasor Measurements Units (PMUs) and its applications have evolved in the recent past based on the implementation experiences from the different grids across the world. In view of its increased importance in grid operation, the standards have also evolved over the time for better measurements and performance. The IEEE C 37.118-2005 [1] version has now been upgraded with the IEEE C 37.118-2011[2-3]. Along with that, IEEE C37.244-2013 Guide defines desired PDC functions to be applied on Synchrophasor streams [4]. Various ISO/TSO/operator in the world have opted for the Synchrophasor technology to look deep into the system dynamics in real time and operate the grid with enhanced reliability and security. In India, this technology was adopted in 2010 and now the Indian grid has more than 100 substations are installed across the grid [5]. During the implementation of pilot projects in India, various challenges have been faced and few of them are discussed in this paper. This experience will be helpful in implementation of Synchrophasor Technology at large scale.

2. Implementation Experiences and Challenges

The experience with Synchrophasor projects execution has been a roller coaster ride full of exhilaration and excitement in Indian Grid. Each regional grid has implemented its pilot project in their region through various vendors. Though the Synchrophasors data is presently available only from a few locations in the Indian grid, yet it has brought a paradigm shift in system operation and raised visualization and the level of understanding of the power system within the control centre after few months of its commissioning. It has now become an indispensable part of the data resource available at the Regional and National Load Dispatch Centre for operational and reliability purpose. The five years of experience has revealed several challenges that need to be addressed with the full-scale implementation of Synchrophasors Units across India. During Implementation, Utilization and Development phase several challenges were faced out of which few important one are given below:

1. Implementation Experience in Multi-Vendor environment
2. PMU Synchronization Error.
3. Communication Challenges in Integrating PMU.
4. Reliability of Synchrophasor data.
5. Synchrophasor Measurement Angle unwrapping.
6. Computation Challenges at Historian within 20ms.
7. Calculation of Sequence Components at PDC level.
8. Integration with SCADA State Estimator/EMS challenges.

These challenges along with few remedial solution based on the experience gained during execution of Pilot project are discussed in details in the coming sections.

3. Implementation Experience in Multi-Vendor Environment

The Synchrophasor technology around the globe has moved from its nascent stage to the next level where it is experimenting with different protocols for a better Phasor estimation and communication. Thus it can be said that synchrophasor technology is still evolving. Also, advanced applications based on Phasors at a central level vis-à-vis a distributed architecture is also being discussed aggressively.

The C37.118 standard has upgraded from 2005 version to 2011 and the guide for PDC has been published i.e. IEEEC37.244-2013 during the last couple of years. Equivalent IEC standard i.e., IEC 61850-90-5, is also picking up the market and most of the Substation Automation Systems are moving in this direction, this standard is expected to gain more momentum. It is under these situations the integration with Multi-Vendor system supporting different protocols becomes a challenge.

One major challenge was the precision in the measurement and reporting of the quantity from the different PMUs. Vendors are using different algorithms for calculation and reporting with in the IEEE C 37.118 standards provision [1-3]. In turn, precision in number of digits after decimal points reported by different PMU vendors for different parameters varies. This results in challenge in visualization, analysis and application development. For example, the df/dt measured from various PMUs is being reported differently. Figure 1 shows the Rate of Change of Frequency (ROCOF) from various PMUs for a quasi-steady state and transient condition as observed from different PMUs. It can be observed from Figure 1 that all four PMUs have different level of quantization and making alarms based on such different characteristic is difficult, unless these values are normalized to a common scale. During changing operating point from steady state to transient state, the event detection based on such a signal may lead to falsified information.

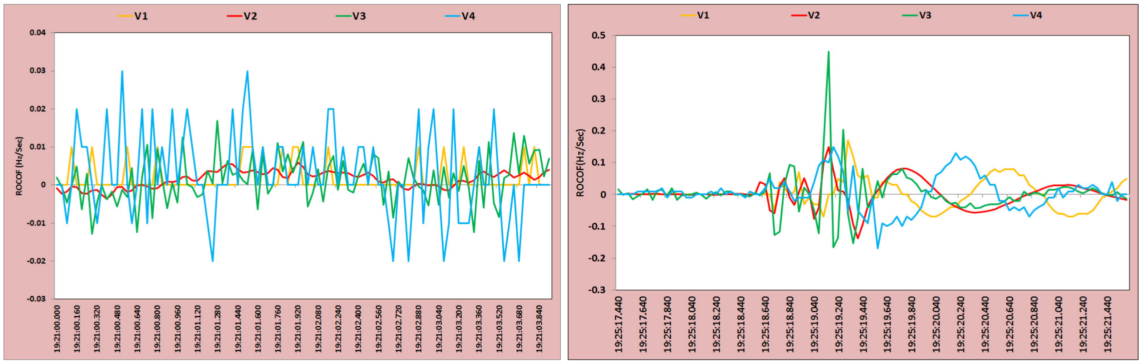

Figure 1: ROCOF observed from four different PMUs (a) during quasi steady state operation and (b) transient condition.

Further, it was observed that lower precision of frequency data has caused difficulty in the measurement aspect and data analysis and generation of oscillation alarms in Real Time. For Oscillation monitoring system (OMS), data quality should have higher precision, which should save a lot of time during its processing and analysis for detecting oscillation [5].

In addition, it has been observed that voltage and current phasor along with frequency and ROCOF are being received from all the PMU vendors. While the sequence component is dependent on vendors as few of them are providing partially limited to positive sequence and some others are not providing this information at all. It is known that sequence component is also more of use while developing linear state estimation functions, fault detection and its analysis based on Synchrophasor data. Such issues need to be taken into consideration while implementing a large-scale integration of PMUs.

Further, estimated power angles from different PMU units at same substation shall be within allowed error tolerance as per the standard

4. PMU synchronization Error

It has been observed in the pilot projects that several PMUs are out of synchronization for distinct reasons. Some the major reasons are GPS Antenna position misalignment, non-visibility of satellite and problems with the GPS receivers. If a PMU has lost synchronization lock with GPS time source, then it is required to detect a loss of time synchronization. This will cause the Total Vector Error (TVE) to exceed the allowable limit as per the C37.118-2011 standard from the time of synchronization loss or within 1 min of an actual loss of synchronization, whichever is less [2]. During such a case, a flag in the PMU data output i.e. STAT word bit 1 should be asserted until the data acquisition is resynchronized to the required accuracy level. When the PDC detects a synchronization error in the incoming PMU input, then the PDC reads Bit 13 of status word of incoming PMU Data frame, if it is set to 1, PDC displays incoming PMU as ‘Sync Error’. This helps in development of analytic and in selection criteria to alert the user as to whether they want to use this data for specific application.

Further in addition to the STAT word Bit 13, IEEE Std C 37.118.1-2011 specifies other signals which are intended to describe the time quality of the synchronization source. Each of the PMU output messages defined (Configurations 1, 2, and 3, Header, and Data) have a time quality field of 4 bits. This field allows the PMU to state the quality of the time source from clock locked, 1 ns to 10 seconds uncertainty (estimated worst-case error), or clock failure. Figure 2.a shows the time quality flags from a PMU. It can be observed that STAT also indicate the length of time the GPS clock has been unlocked.

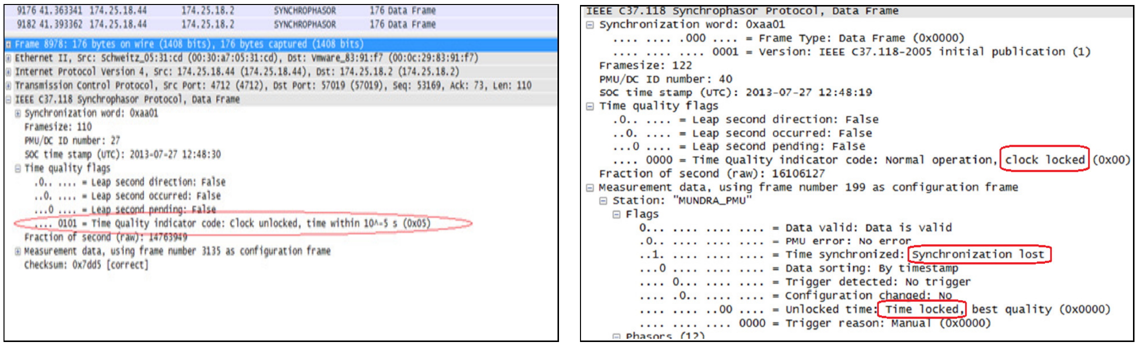

Figure 2: (a) Unlocked clock status in time quality flags in C 37.118 Data frame (b) Time Quality Flags in C 37.118 Data frame showing normal, locked clock

Even though a PMU clock may be unlocked for more than 1000 seconds, a good quality oscillator will be able to maintain better than 1 µs accuracy over this period of time. This field indicates the uncertainty in the measurement time at the time of measurement and indicates time quality at all times, when both locked and unlocked, and shows clock error indication while the clock is starting up.

In Figure 2.b, it can be observed that time synchronization status word bit is set 1, indicating the synchronisation is lost, however the unlocked time is having best quality flag, and the time quality flags also showing clock is locked. This may be due to improper time stamping in the PMU or GPS problem.

In another case, it is observed that there is Sync Error due to Fraction of Second (FOS) drift. On investigation, it is found that in that specific PMU, there is a constant drift in the FOS, due to which the quality of data has been getting invalid when sorted in the PDC. It was found that the time base in that PMU was 1000000 (as per relevant standards, there are PMUs that have this value as it can be 2^7). If a PMU is configured to report at 25 samples per second, then the FOS in C 37.118 data frame is expected to arrive as 0, 40000, 80000,….., 920000, 960000 (25 values for 1 second). However, the time that was being reported from the PMU were 30, 40030, 80030, 920030, 960030 etc. which was having a constant drift of 30 microseconds. The PDC works in data sorting manner, which is based on absolute time and expects an accuracy of 1 microsecond or better in the PMU time stamps. If the accuracy in time stamp is less than 1 microsecond, the corresponding PMU data will be flagged as "Data sort on arrival" instead of "Data sort on time stamp", as per IEEE C 37.118 standard. This has led to tagging the quality of the data arrived to be flagged as unreliable and the same is shown in Figure 3. The selection of time base for a PMU is thus very important.

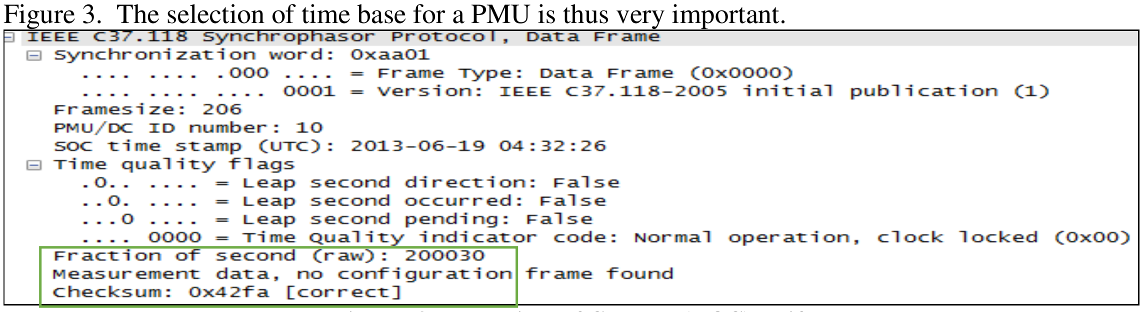

Figure 3: Fraction of Second (FOS) drift

Such issues about the synchronization aspect of PMUs are very serious in view of the losing important data from the PMUs when they are required. As observed, these can be addressed with the proper configuration of PMU, PDC and utilization of Time flag.

5. Communication Challenges in Integrating PMU

The success of any Wide Area Measurement system depends on the availability of the data from the various PMUs installed in the field. During the execution of pilot PMU projects in India, establishing communication links / channels between geographically remote substations having PMUs and regional control centres had been one of the major challenge. This was one of the prime factors for relocating few PMUs to different substation where communication medium was available. The communication channels used were either dedicated fibre optic channel or Enterprise Wide Area network or leased communication lines. Communication path in case of Enterprise WAN is shared with other applications, which thus compromised the data reliability/latency. In terms of Bandwidth either 64 kbps or 512 kbps or 2 mbps channel were used for PMUs communication to PDC at Control centre. Table 1 shows the latency observed between the various make PMUs having different signal composition with the bandwidth of communication channel used.

Table 1: Average Latency observed with different communication channels and PMUs

PMU Make	IEEE Standard	Composition of Signals				Communication Bandwidth average latency (in ms)		
		Phasor	Analog	Frequency	Total	64 kbps	512 kbps	2 Mbps
Make 1	C.37.118-2011	12	8	2	22	625	350	300
Make 2	C.37.118-2005	6	32	2	40	-	-	50
Make 3	C.37.118-2005	12	-	2	14	-	-	60
Make 4	C.37.118-2005	18	4	2	24	-	-	160
Make 5	C.37.118-2005	13	3	2	18	-	-	150

From the above table it can be observed that, each make of PMU has different number of signals, which have to be transmitted to the PDC. The latency in the range of 600-700 ms is observed over 64 kbps channel which is not desirable for some sensitive applications. A minimum of 512 kbps channels is recommended for PMU data transmission as the latency is reduced to more than half of what was observed in case of 64 kbps. The IEEE C 37.118-2011 standard PMU has more latency compared to the PMUs following C37.118-2005 standard for almost same number of signals. In addition, it can be observed that the latency increases as the number of phasors and number of total signals are added to the data stream sent to PDC. This suggests that with increase in number of signals from a single PMU, higher bandwidth will be necessary. The optimum use of communication channel bandwidth needs to be further investigated for lower latency rates during execution of large number of PMUs installation.

6. Reliability of Synchrophasor Data

The reliability of the Synchrophasor data is of utmost importance as the unreliable data. Unreliable data will result in false alarms and potentially incorrect decision making by the system operator or user of the data and applications. This is important for utilisation of Synchrophasor data for advanced application development. Even with a healthy PMU in place, there had been instances of data loss which are either due to:

- Issues with the Communication link between PMU and PDC.
- Loss of time synchronization of individual PMU

Due to any communication loss, there could be complete loss of data from one or more locations or sometimes intermittent data loss is for small durations. Such data loss has to be detected by the application to discard the unreliable data during analysis and results should be based only on the available dataset. For example, applications like Oscillation Monitoring System (OMS) and Angle Monitoring Applications need to detect such conditions, and should have the capability to discard the unreliable data to avoid wrong results and information. Therefore, the designing of various applications has to consider of all the possible scenarios of data loss and unreliable data.

7. Synchrophasor Angle Measurement Unwrapping

One of the core concepts that Synchrophasor data has been envisioned to assess the angular separation between two nodes in Real Time providing information about the stress on the grid under various operating conditions. Earlier it was only possible through the state estimator output which has a time lag, bias and mainly depends on the topology and bad data processing.

Synchrophasors supporting IEEE C 37.118 standards report over a range of $\pm\pi$ radians or $\pm 180^{o}$; hence, they "wrap" at the end of the range limits, which is a discontinuous signal, and need to be addressed in a streamlined way. These discontinuities result in faulty analysis of grid instabilities, especially when considering the angle difference between two separate locations on the grid. Subtraction of two discontinuous angles results in a discontinuous signal as can be observed from figure 4. While having 4-5 PMUs, calculation of angular difference using commonly available unwrapping algorithms can solve the problem. However, the problem will become significant while dealing with missing data frames and handling a few thousands PMUs.

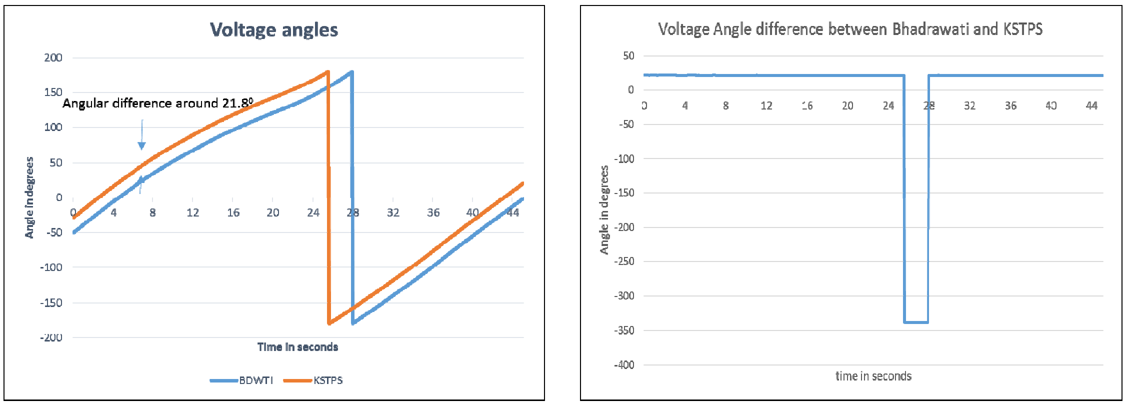

Figure 4: (a) Reported Angle as per C 37.118 Standard (b) Angle difference between Korba and Bhadrawati calculated.

To illustrate this, two distinct nodes are selected and their reported absolute angles are shown in Figure 4.a, their angular difference is shown in Figure 4.b. Here the angle is converted in between 0-360 degrees and it is observed that at the point of discontinuity there is a large change in the angular separation as calculated.

Quite often a PDC may not receive some frames for various reasons, during this period angle difference between two distinct nodes will have to be handled carefully so as not to have any false alarms. In figure 5.a, a few samples are missing in Bhadrawati PMU which can be further observed as an error when angular separation is calculated as shown in figure 5.b. The error in angle difference observed was around 7.6º during the missing samples. Even though there is no event, the angular difference plot shows an angle dip, which can give false alarms.

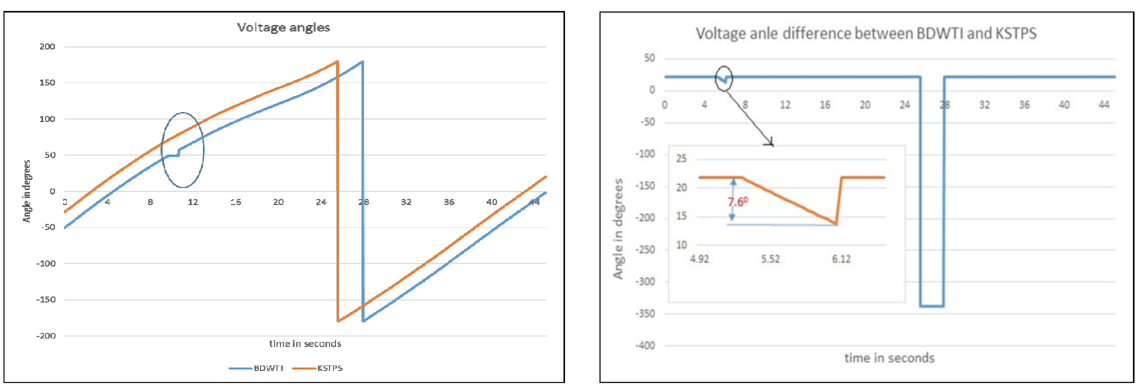

Figure 5: (a) Reported Angles plot for missing Bhadrawati PMU data (b) Angular difference between Bhadrawati and KSTPS in case of missing Bhadrawati PMU data

Such issues of unwrapping of an angular difference during normal scenario with missing data and synchronization issues needs to be addressed with intelligence in the analytics engine. Solving the wrapping issue results easier to real time PMU applications and also helpful in offline analysis. It is expected that, unwrapping algorithms should run in real time without taking significant calculation time. Further, selecting reference angle for calculation of relative angles is a complex issue; however, following approaches can be deployed based on the experiences:

- Calculate Center of Inertia (COI) and take the nearby PMU as reference angle.

- Check df/dt for typical event; take nearby PMU angle, which is having highest df/dt as reference.
- Take generation rich area PMU angle as reference and calculate other load rich area relative angles.

8. Computation Challenges at Historian Within 20 ms

After the streamlining of all the PMUs to a PDC, there shall be simple mathematical calculations on each sample, which need to be performed in real time. Currently PMU to PDC reporting rate is 25 frames/seconds in India, so every 40 millisecond, there is a new measurement available at PDC or historian, and hence before arrival of next measurement calculation output should be available for visualization. Therefore, it is recommended to have execution speed such that all calculations 20 milliseconds or better for 25 frames/second configuration.

9. Calculation of Sequence Components at PDC Level

The use of sequence component is very well known in the power system. As discussed in the paper, some PMU manufacturers do not provide a complete set of sequence components. So, one of the option is to calculate the sequence components of voltages and currents at the PDC. However, this is good as long as the number of PMUs being supported is not high. Nevertheless, with deployment of a large number of PMUs, calculating sequence components in PMU shall be a preferable option and vendors need to implement functionality as an optional feature to provide complete set of Phasors and their sequence components.

10. Integration with SCADA State Estimator/EMS Challenges

The last part of the challenges was to integrate the WAMS with the existing SCADA system. In order to get the advantages of WAMS data for good visualization and State Estimation in SCADA, it is necessary to integrate two. Until the complete SCADA is migrated to PMU measurements, these two technologies will likely have to mutually co-exist. There are various ways to integrate WAMS data to SCADA and some are as under:

1. ICCP
2. IEC 60870-5-104

Integration of WAMS with SCADA several options have been considered, the use of ICCP and IEC 60870-5-104 has been considered and in place within several installations. The following points were found to be important to consider during such integration efforts:

1. Down sampling of phasor data to a level compatible to SCADA
2. PDC shall be able to send Angular Difference measurements to SCADA system, instead of Absolute angles, which are discontinuous signal, and there may be possibility of negative effect on State estimator convergence. However Angular difference from PDC to SCADA with matching reference bus in PDC and Slack bus in State estimator can improve the solution accuracy and performance.

All such challenges have to be addressed for better visualization and situational awareness with the help of Wide Area Measurement system. There is a need of further development in these fields from the industry and academia side for better integration and utilisation of the technology at control Centres.

Conclusion

This paper has focussed on the various integration issues and challenges faced during the commissioning of pilot project of Synchrophasor in India. Out of these challenges, integration of various make PMUs, calculations and providing Sequence components at PDC etc. need to be solved by common specification and proper compliance of PMUs to relevant standards. The challenges associated with communications need to be addressed prior to commissioning of project for its successful implementation. Other issues like Time Synchronization, Angle Unwrapping, Reliability of data needs to be addressed during Application development. Overall, this paper provides a feedback for implementation of large-scale project on WAMS in any electrical grid in future. Further, it has given feedback to developers and designers in the WAMS area for making the technology more robust.

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