Application-Aware Adaptive Reporting of Synchrophasor Measurements

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***Abstract*—Phasor Measurement Units (PMUs) are capable of providing high speed and high-resolution wide area measurements typically used for situational awareness and advanced applications. A PMU for distribution systems also known as micro-PMU can provide data even at higher reporting rates. Despite its apparent advantages, reporting at a much higher rate introduces additional communication burden. This constraint will be even more critical with 'point to wave' reporting possible in future. Several applications do not require the measurements at that high reporting rate, e.g. state estimation or condition monitoring. Possible congestion in the network with several thousands of these devices may result in either significant delays or packet drops. This work is an efforts towards providing solutions for above challenges with an adaptive PMU, which is capable of adjusting reporting rate based on the communications network bandwidth and/or the application needs.**

***Index Terms*—PMU, Sampled Values, Communication System, Reporting Rate, Omicron**

I. Introduction

PMUs have increased the possibilities for different applications by their unique capability of time-stamped and high-resolution measurements. Large-scale PMUs deployment, however, shows multiple issues, e.g. the data quality issues [1] and the inability of some applications to use these high reporting rates. The high reporting rate of PMUs requires substantial bandwidth for its communication. Deployment of PMUs is growing and they have the potential to support or even replace the SCADA system in the future.

This paper addresses one of the fundamental problems that PMU faces regarding the data losses due to congestion in the communication networks. This mainly happens when the traffic in the communication network is high and causes congestion. Congestion monitoring and its causes are discussed in [2]. The loss of data is a loss of information and can lead to applications stalling. Power line communication (PLC) [3] or fiber optic communication [4] are commonly used for transmission systems. However, distribution systems and microgrids may be based on wireless communication technologies, which may have lower bandwidth and higher latencies. Most of the applications in the transmission system are centralized and used for wide-area monitoring at the control center as is depicted in Fig 1.

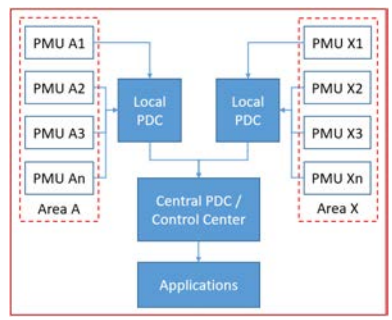

Fig. 1. Example of Synchrophasor Data Flow to applications.

Ongoing research is focused on developing a distributed [5] or decentralized [6] applications to address complex issues of the power system. This may require PMUs to be in different configuration settings for different applications. It may also be feasible to utilize a lower reporting rate for steady-state monitoring and then switch to a higher sampling rate as soon as a disturbance is detected. This strategy helps to conserve the bandwidth and reduces local data storage requirements during regular operation while enabling advanced algorithms (e.g. fast islanding detection) during disturbances. As more PMUs are deployed in the distribution system and microgrids, the issue of data loss will become more prominent and has to be addressed. It is worth mentioning that the applications may be designed to handle variable reporting rates. Since all the PMUs data points are time stamped, it will not be hard to adapt variable data reporting rates in applications. This will also enable utilities to explore variety in their communication system. PMUs data can then be transmitted using slower and readily available communication channels, like satellite or wireless communication systems.

We propose and have developed a prototype which demonstrates the variable reporting rate of PMU data. The operation of PMUs, according to the current standard and practices, requires the data to be transmitted at a fixed reporting rate

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and the data is aggregated at a regional or central Phasor Data Concentrator. This paper extends the fixed PMU reporting rate concept as defined in the current standard for Synchrophasor data transfer [7]. We propose to monitor the communication channel, and based on the available bandwidth, adjust the PMU data reporting rate to ensure continuous data availability. The variable reporting rate can also be used by the existing applications which require the PMUs to send data at lower reporting rates and other applications which require the data at a higher reporting rate for example like oscillation monitoring may need a higher rate to confirm mode estimation whereas state estimation can work at a lower reporting rate.

The methodology can be tested over various other communication channels ,e.g. wireless [8], microwave [9], satellite [10] etc. One other enhancement that can be made with the available prototype and method is to request for a higher sampling data based on some trigger. A trigger based reporting rate change can be implemented for applications, for example, if oscillations are detected in an area the reporting rates can be increased to analyze the signal. This higher sampling data can also be the IEC 61850-9-2LE sampled values or a high reporting rate of PMUs [11]. One of the major applications of the adjustable reporting rate will be in edge computing and cloud computing, where need will be tighter constraints on the amount of data that can be transmitted.

II. PMUs, Communication Bandwidth and Applications

In this paper we analyze, propose and develop a prototype that can vary the Phasor Measurement Unit's (PMU's) reporting rate, i.e. the PMUs can have a variable reporting rate based on bandwidth availability and or application requirements. The variable reporting rate research is motivated mainly by two facts:

1) Congestion in Communication Network: It is a widely known fact that the PMUs have several issues, for example, data anomalies, estimation issues, GPS loss, and data packet losses to name a few. When the communication network is congested there can be data packet loss. Finally, the available bandwidth might not be enough for a smooth data transfer at the desired reporting rate.

2) Different PMU Rate required by applications: As already mentioned, not all the applications require a high reporting rate of 60 frames per second for their algorithm to work. Few algorithms are tuned and developed for lower reporting rates, e.g. 5 frames or 10 frames per second. The reporting rate requirements for several applications as defined in IEC/TR 61850-90-5 [12] are shown in Fig. 2.

It is typical for a receiving device, in most cases, the Phasor Data Concentrator (PDC) to request the configuration and the header of the PMUs during the startup which includes a fixed reporting rate and remains the same throughout the operation. When congestion occurs the data packets get dropped and missing data is reported. We propose that instead of getting no data at all, the reporting rate should always be reduced to ensure the wide-area measurements availability. Likewise, the applications using the PMU measurements can be designed to handle this variable reporting rate.

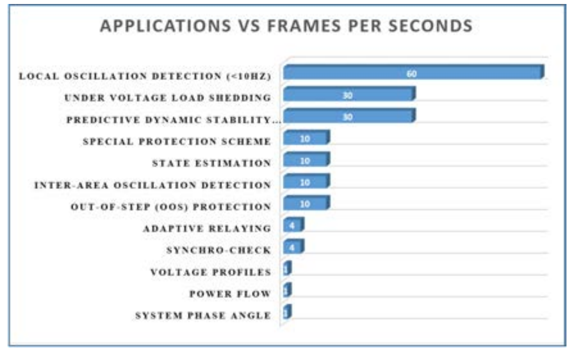

Fig. 2. Reporting Rate Requirements for Applications.

IEEE C.37.118.2 [7], Synchrophasor Data transfer standard analyzes the bits per second requirements for different types of reporting rate and message type. This is reproduced in Table I. It can be seen from the table with the increase of message content the bits per second (bps) requirement increases. It also increases when the reporting rate is increased and this increase is considerable in amount. For distribution level PMU the reporting rate can be as high as 120 frames per seconds and the measurements to be reported will be all three phases. While, the utilization of this high a reporting rate for distribution system applications is still being studied it is safe to assume that the bandwidth requirements will be more as compared to traditional PMUs.

III. Proposed Concept of Adaptive PMU

The driving factor for bandwidth as stated in the [7] is 'The required bandwidth will be dictated by the reporting rate and message size'. Whereas in this paper we implemented adjusting the reporting rate for PMU measurements based on available communication system bandwidth.

Fig. 3 outlines the typical PMU measurement process (in black), where the reporting rates and data packet configuration are fixed and bandwidth is allocated accordingly. The PMU measurement data frame at a set reporting rate is delivered to PDC or directly to the applications. This is the current state of art of PMU operations. We propose to introduce an additional block which will detect the congestion in the communication network and the available bandwidth. This will then feedback the desired reporting rate in real-time to the PMU Estimator which will adjust its reporting rate to avoid any data losses and lower the congestion in the network.

This idea can also be extended in case an application that usually requires the data at a lower reporting rate would require a high-resolution data, i.e. a higher reporting rate data in case a trigger is detected. An example of this scenario can be an event detection algorithm which simply detects a step change (5 frames per second) in amplitude, phase or frequency and for further analysis requests the PMU to send data at a higher reporting rate for further analysis, i.e. 30 frames per second.

TABLE I
BANDWIDTH REQUIREMENTS FOR PMU CONFIGURATIONS

S No.	Message Content	PMU Reporting Rate			
		10 fps	*15 fps*	*30 fps*	*60 fps*
1	2 phasors, all integers	6,720 bps	10,080 bps	20,160 bps	40,320 bps
2	2 phasors, all floating points	7,680 bps	11,520 bps	23,040 bps	46,080 bps
3	12 phasors, all integers	9,920 bps	14,880 bps	29,760 bps	59, 520 bps
4	12 phasors, 2 analog, 2 digital, all integers	10, 560 bps	15, 840 bps	31,680 bps	63,360 bps

[a]Transmission rate in bits per second (UDP/IP over Ethernet)

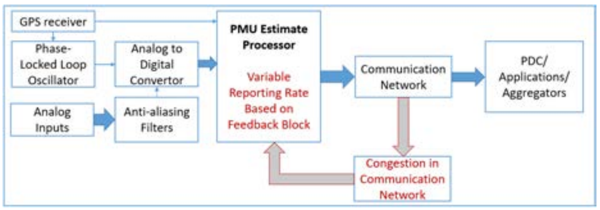

Fig. 3. Proposed Method to Trigger Variable Reporting Rate in PMUs.

Fig 4 shows a schematic diagram of a microgrid with PMUs and a view of a communication system. The PMUs can be strategically placed at buses of interest. This will help the control operators/ utility to receive data at a lower reporting rate than the sampled values. If there is further congestion, the reporting rate of PMUs can be adjusted again. In the microgrid model depicted in the figure, PMUs are installed on buses, which has loads or Distributed Energy Resources (DERs), and at the Point of Common Coupling (PCC). The PMUs send their measurements to a local data aggregator in that particular area. These aggregators further send the data to the Central Data Concentrator, or applications where monitoring and control actions can be taken. This central aggregator can also transfer the data to a utility Distribution Management System (DMS) based on the application requirements at the utility. The Local aggregator uses a common communication channel, which can be used by other IEDs as well. A congestion detector can detect the congestion in the communication network and will provide feedback to the PMU to reduce its reporting rate in case there is a congestion. This will ensure a continuous stream of data without loss of information. The reporting rate can again be lowered if the reporting rate requirement for applications is lower. This will avoid unnecessary data and make the applications faster. This PMUs will also help better monitor the DERs and will broadcast the data upstream to a central concentrator. The adjustable reporting rate will also be very useful if a wireless communication channel is used.

IV. PMU ESTIMATION ALGORITHM

The PMU measurement standards IEC/IEEE 60255-118-1 [13] requires the estimation to be made in terms of signal amplitude, phase, frequency, and rate of change of frequency. The signal is as defined in [13].

$$x(t) = A * cos(\omega.t + \phi) \tag{1}$$

where A is the amplitude of the signal, ω is the frequency in radian and ϕ is the phase. The Rate of Change of Frequency (ROCOF) as defined in the standard is given as in 2.

$$ROCOF(t) = \frac{df(t)}{dt} \tag{2}$$

Here it has to be noted that the ROCOF is obtained from the frequency estimates and its accuracy depends on the accuracy of frequencies. ROCOF will have to be the finite difference of two measured frequency. These measurements are really sensitive to the noise content in the signal especially frequency and ROCOF. We have used an algorithm, called SEMPR (Signal Estimation by Minimizing Parameter Residuals), which determines all the four estimates i.e. Amplitude, phase, frequency, and ROCOF simultaneously [14]. It addresses the fact that the frequency can change within an estimation window. This is required as these measurements are noise sensitive. Here we estimate all the 4 required quantities simultaneously in one window as given by Eq 3.

$$x(t) = A * cos[(\omega + \frac{C_\omega t}{2})t + \frac{C_\phi t}{2}] \tag{3}$$

The C terms are the coefficients of the rates of change of frequency and phase. The terms ω and $C_\phi/2$ are together known as frequency, and the term C_ω is the rate of change of frequency or ROCOF. Frequency includes a component due to a change in the phase relative to the reference; that is the speed of the system being measured compared to the reference. Each of these parameters is an output required from the PMU. A common way to define "frequency" is "the derivative of phase," but phase must then be defined as the complete argument of the cosine. One way to measure frequency is to split the sampled value stream for the window into two parts and perform a finite difference calculation on the phase between the first part and the second. ROCOF might then be measured by a finite difference calculation based on two successive frequency measurements. SEMPR was developed to avoid these finite difference calculations; they are noise sensitive, and the measurement results do not apply at the same moments. The effectiveness and results of the algorithm are presented in [15]. It has to be noted that the accuracy requirements for measurement class i.e. PMU with lower reporting rate, and a higher data cycle for estimation window has a tighter accuracy requirement when compared to the performance class PMUs. This method is used to demonstrate

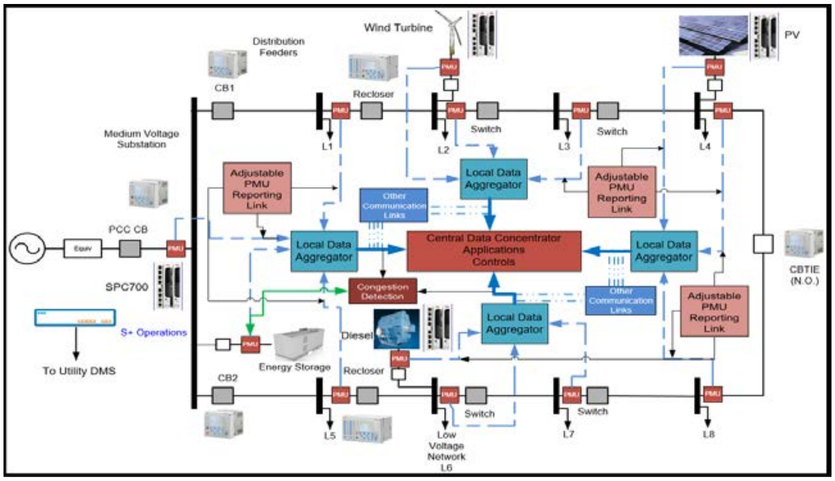

Fig. 4. Integration of Adaptive PMU Within the Cyber-Power System

that the estimation is less error-prone when the estimation window is large.

V. Prototyping the Adaptive PMU

To test the proposed method we have developed a prototype that works based on the flowchart given in Fig 5. The sampled values are generated using a Merging Unit. The Merging Unit can take input from a simulation done in Simulink or can just generate samples based on some simple input of amplitude and frequency.

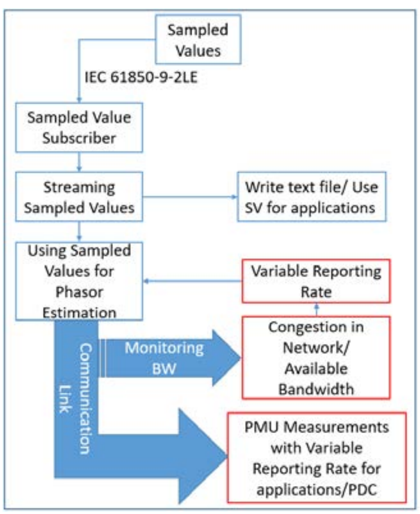

Fig. 5. Adaptive PMU and Data Flow

The generated sampled values are then published on the IEC 61850 Process Bus using the IEC 61850-9-2 protocol [16]. The published sampled values are then subscribed on a Linux based commodity off-the-shelf single-board computer with multi-threading capability. The sampled values can then be stored in a text file or used directly for applications on the same Linux board, it can be downsampled and transmitted to other devices or applications. The PMU based trigger can be activated to send the sampled values if an event is detected in the system for further diagnosis.

In a separate thread with the above discussed PMU estimation algorithm, the streaming sampled values are passed based on the expected PMU reporting rate. The PMU estimation algorithm starts producing PMU estimates based on the timestamped sampled values. The initial reporting rate can be set by the user at the time the program is instantiated or a default reporting rate of 30 frames per second can be used.

If the initial reporting rate is set at, 60 frames per second then the PMU estimation algorithm's data window of sampled values will be 1 electrical cycle. Once the buffer worth of one electrical cycle is filled it is then passed to the estimation algorithm to get the PMU estimates. Similarly, if the reporting rate is to be lowered as a result of congestion detection in the network, from 60 frames to 30 frames per second, the buffer size will be increased to 2 electrical cycles. Now 2 electrical cycles will be used to make the PMU estimates. This increases the accuracy of the estimation and also lowers the reporting rate of PMUs reducing the congestion in the network.

Once the congestion in the communication network is reduced, the reporting rate can be increased again. The sampled value buffer can be adjusted and estimates will be produced accordingly. The PMU estimation algorithm in this prototype has been tested on a sampled value of 80 samples per cycle. The algorithm in offline testing has been tested to work on 24 samples per electrical cycle.

A brief description of the exact setup is described in Fig 6 where the microgrid is modeled in Simulink which stores the simulation in Omicron CMC-356 readable format. Omicron device reads this simulation file and is capable of producing and publishing up to 3 sampled value streams based on IEC-61850-9-2LE specification at 80 or 256 samples/cycle. These published sampled values are then subscribed by the subscriber based on the IEC-61850-9-2LE on the COTS board. The values are then decoded to produce voltages and current sampled values. Once the sampled values start getting subscribed on the COTS Linux board, a separate thread is called which starts PMU measurement estimation. The variable reporting rate has also been implemented on the same prototype board. These PMU values can then be broadcasted for further use or can be directly used for applications.

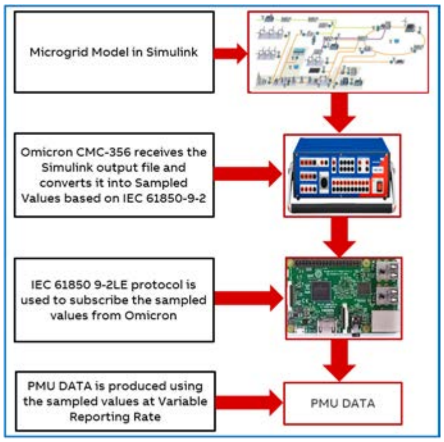

Fig. 6. Testbed for Validation of the Developed Prototype

VI. Results for Varying Reporting Rate with Prototype

Sampled values with varying and constant frequencies were generated such that the frequency is increased to 60.25 Hz from nominal 60 Hz. These sampled values were then fed to the adaptive PMU estimation algorithm. The reporting rate for this particular analysis was set to be 30 frames per second. It is a standard industry practice to operate the PMUs at this reporting rate. The results of the algorithm are as shown in Fig 7. It can be seen that the frequency increases to 60.25 and settles for some time before returning to nominal 60 Hz. This shows the effectiveness of the estimation algorithm.

Now we analyze the effect of congestion in the communication network which sends the PMU a command to lower its reporting rate from 30 frames per second to 15 frames per second. As can be seen from Fig 8.

Around 0.8 seconds the congestion in the communication network increases and the PMU adjusts its reporting rate to half, i.e. 15 frames per second. It changes back its reporting rate to 30 frames per second at 2.35 seconds when the congestion reduces. If the reporting rates were not changed, packet will be dropped for the congestion period. This will be a frequent occurring scenario in the field-deployed PMUs. This helps in avoiding the scenario where there would be data loss. The complete loss of data would not let the log, application or an operator capture the changes in frequency that happened during this period.

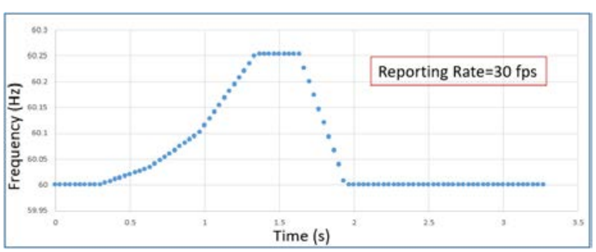

Fig. 7. Fixed PMU reporting at 30 frames per second.

VII. Conclusions

This paper presented the concept and functional prototype development and validation results of the adaptive PMU,

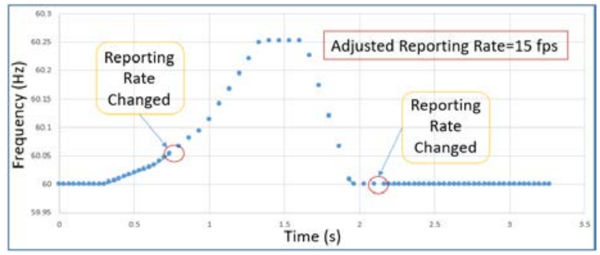

Fig. 8. Variable PMU reporting at 30 and 15 frames per second.

which adjusts its reporting rate based on two factors: communications system availability and application requirements. The congestion in the communication system is monitored online and the reporting rate is reduced in real-time as needed to ensure all the important communication take place without any loss of information. Additionally, the proposed adaptive PMU can also be used to report at varying rates adopting to a specific application needs changing with operating conditions.

References

[1] P. Banerjee, S. Pandey, A. Srivastava, and D. Lee, "Testing and validation of synchrophasor devices and applications," in *Power System Grid Operation Using Synchrophasor Technology*, pp. 41–75, Springer, 2019.

[2] Sandvine, "Network congestion management: Considerations and techniques." http://sandvine.com/hubfs/downloads/archive/whitepaper-network-congestion-management.pdf.

[3] B. Naduvathuparambil, M. C. Valenti, and A. Feliachi, "Communication delays in wide area measurement systems," in *Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory (Cat. No. 02EX540)*, pp. 118–122, IEEE, 2002.

[4] N. Grote and H. Venghaus, *Fibre optic communication devices*, vol. 4. Springer Science & Business Media, 2012.

[5] L. Yan, Z. Xiaoxin, and Z. Jingyang, "A new algorithm for distributed power system state estimation based on PMUs," in *2006 International Conference on Power System Technology*, pp. 1–6, IEEE, 2006.

[6] I. Kamwa, R. Grondin, and Y. Hébert, "Wide-area measurement based stabilizing control of large power systems-a decentralized/hierarchical approach," *IEEE Transactions on power systems*, vol. 16, no. 1, pp. 136–153, 2001.

[7] "IEEE standard for synchrophasor data transfer for power systems," *IEEE Std C37.118.2-2011 (Revision of IEEE Std C37.118-2005)*, pp. 1–53, Dec 2011.

[8] V. C. Gungor and F. C. Lambert, "A survey on communication networks for electric system automation," *Computer Networks*, vol. 50, no. 7, pp. 877–897, 2006.

[9] K. Feher, "Digital communications: microwave applications," *Englewood Cliffs, NJ, Prentice-Hall, Inc., 1981. 285 p.*, 1981.

[10] B. R. Elbert, *The satellite communication applications handbook*. Artech house, 2004.

[11] R. E. Mackiewicz, "Overview of IEC 61850 and benefits," in *2006 IEEE Power Engineering Society General Meeting*, pp. 8–pp, IEEE, 2006.

[12] IEC Technical Report 61850-90-5:, "Communication networks and systems for power utility automation – part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118," Edition 1.0, 2012.

[13] "IEEE/IEC international standard - measuring relays and protection equipment - part 118-1: Synchrophasor for power systems - measurements," *IEC/IEEE 60255-118-1:2018*, pp. 1–78, Dec 2018.

[14] H. Kirkham and S. Pandey, "Is ROCOF measureable?," in *2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pp. 1–5, IEEE, 2018.

[15] H. Kirkham, S. Pandey, and D. Laverty, "Test results from the SEMPR PMU," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, IEEE, 2018.

[16] C. Brunner, G. Lang, F. Leconte, and F. Steinhauser, "Implementation guideline for digital interface to instrument transformers using IEC 61850–9–2," *Tech. Rep.*, 2004.