Automated test system to assess reporting latency in PMUs

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***Abstract*— This is a draft version of the paper available here: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7520346 The accuracy of the measurements provided by a Phasor Measurement Unit (PMU), such as phasor amplitude and phase angle, frequency and rate of change of frequency (ROCOF), can be very high. Nevertheless, other factors should be considered for a proper employment of the measurement devices. In particular, sufficiently low reporting latency should be guaranteed, to ensure that the PMU measurements are made available in a fair time. Many internal and external factors affect the overall latency of the output data of a PMU connected to a phasor data concentrator (PDC). Among them, it is possible to mention the type of the measurement algorithm, the processing time and the delay due to the transmission and the communication channel. The Standard IEEE C37.118.1-2011 defines the latency pertaining directly to the PMU. This paper proposes a simple and fast method to evaluate the PMU reporting latency, considering a high number of messages at high reporting rates. The method is based on the statistic evaluation of the difference of two timestamps provided by two independent time sources. The methodology is implemented in a prototyping architecture based on a general purpose modular data acquisition platform. The characterization phase of the obtained test system is illustrated in details. The obtained results prove that the system is compliant with the definition, the observation interval and the accuracy required by the Standard IEEE C37.118.1, along with its amendment IEEE C37.118.1a. Then, the test system is used to investigate the performance of commercial PMUs with different settings. The most significant results of this study are also presented and discussed.**

Keywords*— *Phasor Measurement Unit; PMU reporting latency automated test equipment; PMU dynamic behavior; IEEE C37.118.1;

I. Introduction

Phasor Measurement Units (PMUs) are assuming the role of crucial element for control and protection applications of the power systems. In the Wide Area Monitoring Systems (WAMSs) the number of PMUs is increasing exponentially. The modern communication technologies are becoming an important element to support the distributed measurement systems and the control applications for the power grids [1]. The measurements provided by remote PMUs can be compared, thanks to the proper time synchronization. In addition, the PMUs high reporting rate permits the dynamic behavior of the power system to be traced, therefore serving to keep it safe [2]. In [3] an idea of the PMUs spread in the USA power systems is provided.

In this scenario, it is essential to know when each measurement is available and how long does it take to perform the correct control actions. Therefore, it is important to evaluate the overall latency of the entire distributed measurement and control system, starting from the latency of each element [4].

A simple WAMS for synchrophasor measurement can be composed of one or more PMUs connected to a phasor data concentrator (PDC) that collects the measurements and can generally be far from the distributed measurement points [5]. The measurements provided by a PMU can be used for both off-line and real-time applications. In the first case, a typical use of the data is the so-called post-event analysis [6] to evaluate the cause of a failure. In this case, the overall latency is not a fundamental parameter, because the data are stored in the database of the PDC and recalled in case of need. Contrariwise, real-time applications for the protection and control of the power system grid require that the latency of the overall system does not overcome a given maximum value [7]. Internal and external causes introduce delay in the communication between PMU and PDC [5].

Focusing on the PMU reporting latency, all the delay contributions refer to the acquisition, estimation and transmission processes inside the PMU. The window length adopted by the measurement algorithm, the filtering stages and the processing time clearly sum up together to produce the time lag between the measurement reference time and the instant at which the measurement is available in the data packet at the network connection. In particular, the length of the observation window strictly depends on the required accuracy and, thus, on the algorithm chosen for the synchrophasor evaluation [8]. The typical range is from 17 ms to 100 ms [5]. Other factors that contribute to the latency are the measurement filtering and the time to process the data, which are in the typical range of 8-100 ms and 0.005-30 ms, respectively [5].

It is worth noting that the different delays contributing to the reporting latency can be variable even on the same PMU, depending on the available settings. In some commercial PMUs, it is possible to change the number of cycles (at the fundamental frequency) of the signals acquired for the evaluation of the synchrophasors. The synchrophasor Standard IEEE C37.118.1 [8] defines two performance classes, P and M, for applications oriented to protection and monitoring, respectively. The P class is intended for fast measurement response time, while the M class should be considered in case the measurement accuracy is of crucial importance. The number of cycles required for an algorithm compliant with the P class is usually lower than the number of cycles needed for an algorithm M class compliant.

Besides, the latency can depend on the reporting rate chosen for the PMU. For these reasons, it is important to evaluate the actual reporting latency for every configuration chosen for the device.

Few devices can provide different types of measurements of the latency. Some PDCs, with time synchronization capability, could be used to evaluate the overall latency of the communication system [9], but these values do not comply with the synchrophasor Standard, that defines limits to the “PMU reporting latency”, provided only by the PMU device. In addition, to the best of authors' knowledge, there is only one commercial device [10] allowing the complete characterization of a PMU with the test suite suggested by the Standard. Nevertheless, it is expensive and not easily portable, due to its dimensions.

In the scientific literature, some papers concern the evaluation of the performance of commercial PMUs and prototypes for transmission and distribution networks [11]-[14], but the characterization is focused on the accuracy of the measurement of the electrical quantities. In [15] an evaluation of the measurement reporting latency for a specific PMU prototype is also presented. However, none of the aforementioned papers reports a latency measurement procedure.

In this context, this paper presents a methodology implemented in a reconfigurable device, referred to as PMU latency meter, PLM, in the following, for the automated measurement of the PMU reporting latency. The aim is to provide a simple method, compliant with the synchrophasor Standard, to evaluate the PMU reporting latency using a low cost hardware. The proposed PLM is based on a modular measurement architecture CompactRIO from National Instruments (in the following NI-cRIO), with time synchronization provided by a GPS receiver. Therefore, it is also easily portable for in field measurements. It was characterized and validated with respect to the standard procedures. In particular, the device proved to be able to receive and evaluate a high number of messages with high reporting rate, as required in the Standard IEEE C37.242-2013 [16].

The paper is organized as follows: an introduction to the evolution of the latency requirements and the definition provided by the standards is reported in Section II; a brief description of the architecture of the instrument and its characterization can be found in Section III; Section IV gives the test result for the reporting latency of commercial PMUs in different configurations setups.

II. PMU Reporting Latency and communication methods.

The Standard IEEE C37.118.1 [8], in subsection 5.3.4 concerning the measurement reporting latency, defines the PMU reporting latency as "*the maximum time interval between the data report time as indicated by the data time stamp and the time when the data becomes available at the PMU output*". It is then specified that: “*PMU real-time output reporting latency shall be determined for each reporting rate using at least 1000 consecutive messages. The reporting latency is the maximum of these values. The latency shall be determined to an accuracy of at least 0.0001 s.*”

The Standard IEEE C37.118.1a [17] specifies new limits for the PMU reporting latency. The maximum latency has to be computed on 1000 consecutive messages for each test case. The required time accuracy for PMU reporting latency evaluation has been updated from 100 µs to 2 ms.

The Standard provides two different limits for the maximum reporting latency of the two performance classes, depending on the reporting rate (RR). The RR that can be, for a system rated frequency of 50 Hz, 10, 25 and 50 frames/s (lower reporting rates and, in particular, a reporting rate of 1 frame/s are always available among the PMU settings).

The P class, specific for protection applications, has the limit (in seconds) equal to 2/RR. The M class, specific for measurement applications, has the limits relaxed to 7/RR, thus allowing the algorithms to work with a higher number of cycles in order to obtain a more accurate measurement result.

To exemplify the limits, a PMU for a 50 Hz system and with a reporting rate set to 50 frames/s must keep the latency below 40 ms for the P class and 140 ms for the M class.

The Standard IEEE C37.118.2 [5] proposes different techniques to send the measurements to a PDC. First commercial PMUs implemented the RS-232 serial communication, but today the IP (Internet Protocol) communication is largely used and both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are widespread. In this paper, the communications relying on both the IP/UDP and IP/TCP over Ethernet will be considered.

In [4], some information about the future updates of the Standard is reported. Concerning the latency, the novelties will include the reduction of the number of reporting rates, performance classes different with respect to the actual two ones, and a higher number of messages for PMU reporting latency evaluation. Following such suggestions, in this paper, the number of messages to evaluate the PMU reporting latency in the test setup is significantly increased.

III. The PMU Reporting Latency Measurement System and its Characterization

The PMU reporting latency is, as aforementioned, linked to the time when PMU output is ready and is thus denoted by the first transition of the first bit of the output message at the communication interface point. Measuring such instant can be a troublesome or, at least, a long procedure. Thus, the idea underlying the proposed PLM is to evaluate the latency by measuring the delay between the data timestamp indicated in each PMU message and the instant when the message is received by the PLM itself. To correctly evaluate the latency, the PLM must have an accurate time source and the additional delay introduced by the measurement chain must be kept small to guarantee that the uncertainty is under the limit fixed by [17].

For this reasons, the PLM is implemented using the real-time embedded controller NI-cRIO. The system is a reconfigurable device and, in the adopted configuration, is composed by a real-time controller NI-9014, a Field Programmable Gate Array (FPGA) module embedded in the chassis NI-9113 and a time synchronization module NI-9467. The NI-9467 includes a GPS receiver that offers an accurate time source (accuracy ± 100 ns) to synchronize the embedded clock of the FPGA module and to provide the Coordinated Universal Time (UTC) to the real time controller. For this reason, every message from a generic PMU under test is tagged with the UTC timestamp at the arrival in the real-time controller.

Following the definition of the Standard, it is possible to express the single reporting latency (RL) value as:

$$RL = t_1 - T_{stamp} \quad (1)$$

where T_{stamp} is the data report time as indicated by the timestamp in the synchrophasor measurements and t_1 is the time when the data is available at the PMUs output, defined as the time of the first bit transition of the measurement data packet at the PMU communication interface.

The distance between the PMU under test and the PLM is small and the delay due to the link is negligible (from 3.4 μs/km to 6 μs/km [5]). In this case, it is possible to consider the time instant when the data are available at the output of the PMU equal to the time when the packet is available at the input of the NI-cRIO.

Nevertheless, the time instant when the measurement becomes available at the output of the PMU under test could be different with respect to the time instant when the measurement is available for the real-time controller, due the delay introduced by the hardware between the communication module and the real-time controller. For this reason, it is necessary to characterize the processing time of the PLM and compare it with the accuracy requirements.

The characterization of the PLM was performed following the test architecture shown in Fig. 1.

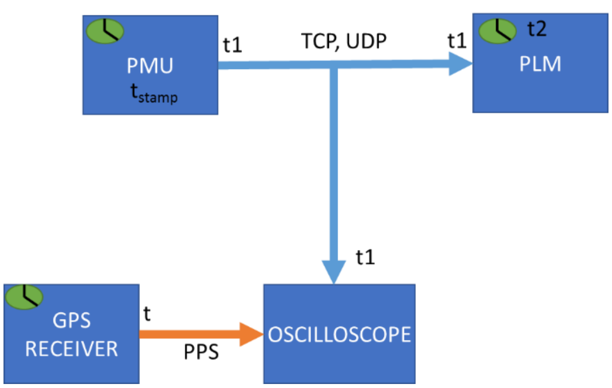

Fig. 1. Block diagram of the system used for the characterization of the PLM.

Using the oscilloscope, the latency RL is measured as the time delay between the analogue Pulse Per Second (PPS) signal, which represents the occurrence of the UTC second given by the GPS receiver, and the first bit of the packet signal collected from the Ethernet cable connection, following the definition of the standard.

The PLM evaluates the reporting latency for each message packet sent by the PMU as a time difference:

$$RL' = t_2 - T_{stamp} \quad (2)$$

where, as aforementioned, t_2 is the UTC time when the message is available in the real-time controller. To guarantee the compliance with Standard IEEE C37.118.1a, the uncertainty of RL' must be within the accuracy limit of 2 ms.

In order to properly evaluate RL, an oscilloscope Tektronix MSO 3014 (2.5 GS/s, time-base accuracy ± 100 ppm) was used as reference device.

One channel of the MSO 3014 acquires the digital message leaving the PMU and directed to PLM. A second channel acquires the PPS signal provided by a GPS receiver Symmetricom XL-750 (time accuracy ± 100 ns). The time difference between the two signals can be measured using cursors.

Setting the PMU at a reporting rate of 1 frame/s, each measurement occurs at the PPS transition and the measurement is tagged with the corresponding second timestamp, as it is described in the synchrophasor definition [8]. In this way, the correlation between T_{stamp} of the message, represented by the PPS signal, and the time lags RL and RL' is kept.

TABLE I. PMU REPORTING LATENCIES MEASURED BY OSCILLOSCOPE AND PLM WHEN THE PMU IS SET AT RR = 1 FRAME/S

Test	Latency *RL* (Oscilloscope) [ms]	Latency *RL'* (PLM) [ms]	Difference [ms]
1	145.89	146.67	0.78
2	146.08	146.81	0.73
3	145.87	146.64	0.77
4	146.20	146.82	0.62
5	146.15	146.76	0.61
6	145.85	146.48	0.63
7	145.66	146.28	0.62
8	145.94	146.60	0.66
9	146.91	147.58	0.67
10	146.16	146.95	0.79

In Table I, the sample results of 10 measurements of the latency RL provided by the oscilloscope, and of the latency RL' provided by the PLM for RR=1 frame/s are shown.

The differences of the latencies (always positive) can be seen as the time necessary to evaluate the message in the real-time controller when the data is ready in the input of the communication module and the following holds:

$$RL' - RL = t_2 - t_1 \quad (3)$$

Such differences are always below 1 ms, thus confirming the suitability of the PLM measurements for PMU reporting latency evaluation and its compliance with the standard accuracy specification.

The lowest standardized reporting rate is 10 frames/s. Therefore, to enrich the characterization of the device and to verify compliance with [17], the test was performed also at RR=10 frames/s. Ten sample evaluations, corresponding to measurements performed at different fractions of second, can be found in Table II, showing similar results with respect to the case of RR=1 frame/s. The latency measurements can be very different but the additional time delay is close to be constant. Consequently, even if it is not strictly required, it could be partially compensated to enhance the accuracy of the PLM.

For RR>10 frames/s, the measurement of *RL* with the oscilloscope becomes more difficult, because the number of packets in the same observation window increases and the packet correlation is more cumbersome. However, some tests have been made and conclusions similar to those reported in Table II can be drawn.

TABLE II. PMU REPORTING LATENCIES MEASURED BY OSCILLOSCOPE AND PLM WHEN THE PMU IS SET AT RR = 10 FRAMES/S

Message	Latency *RL* (Oscilloscope) [ms]	Latency *RL'* (PLM) [ms]	Difference [ms]
0	134.55	135.37	0.82
1	92.62	93.35	0.73
2	84.35	85.12	0.77
3	84.36	85.13	0.77
4	84.37	85.15	0.78
5	84.38	85.15	0.77
6	84.28	85.04	0.76
7	84.28	85.05	0.77
8	84.38	85.15	0.77
9	84.28	85.05	0.77

IV. TEST AND RESULTS

In order to show the practical usefulness of the proposed PLM, two commercial PMUs have been tested.

The first one, referred to as PMU 2005 in the following, is a device compliant with the old version of the standard IEEE C37.118-2005, where the latency was not a necessary requirement. In the PMU 2005, it is possible to change the number of cycles of the acquisition window from 1 up to 8 cycles. In the following tests, the configurations with 2 and 8 cycles have been chosen, as an example of the typical acquisition windows of the algorithms for protection and measurement applications, respectively. Moreover, it is possible to change the reporting rate of the device up to 50 frames/s, with either TCP or UDP communications.

The second PMU, called PMU 2011 in the following, is a more recent device built in compliance with the last version of the standard (i.e. [8]), but before the last amendment of 2014 [17]. In the PMU 2011, it is possible to select the P class or the M class, without knowing the number of cycles used for each algorithm. The reporting rate can be up to 100 frames/s, but, for the scope of this work, the PMU is tested at 10 frames/s.

TABLE III. PMU 2005 REPORTING LATENCY MEASURED OVER 6000 UDP MESSAGES (REPORTING RATE RR=10 FRAMES/S)

# of cycles	PMU Reporting latency [ms]	
2	**Max**	**146.7**
	Mean	92.6
	St. Dev.	17.0
8	**Max**	**148.4**
	Mean	138.3
	St. Dev.	2.6

In the Tables III and IV the results of the PMU 2005 reporting latency in terms of maximum value, mean, and standard deviation are shown for 6000 messages, with UDP and TCP communication, respectively. In the UDP case, the maximum value of the reporting latency is similar for the configurations with 2 and 8 cycles but the mean values show the higher impact on latency of a larger acquisition window for both UDP and TCP cases.

TABLE IV. PMU 2005 REPORTING LATENCY MEASURED OVER 6000 TCP MESSAGES (REPORTING RATE RR=10 FRAMES/S)

# of cycles	PMU Reporting latency [ms]	
2	**Max**	**145.2**
	Mean	107.1
	St. Dev.	12
8	**Max**	**207.7**
	Mean	201.4
	St. Dev.	2.9

It is important to notice the high standard deviations for the 2 cycles configuration in both UDP and TCP cases. This is due to the peculiar implementation system. In particular, the time distance between the sent messages is not costant for PMU 2005 but depends on the fraction of the second when the measurement is performed. Fig. 2 shows an example of the mean latency (the standard deviations are also reported to give an idea of the low variability), evaluated by PLM for the PMU 2005, in the 2 cycles UDP case over 6000 messages, as a function of the message position inside the second (time resolution of 100 ms, for RR=10 frames/s). The maximum value of the mean latency corresponds to the message referred to the PPS (0 message), which is thus responsible for the maximum latency value in Table III, while the other messages latencies are closer to the global mean value shown in Table III.

It is worth noting that the Tables do not report the limit of the current Standard because the PMU 2005 was not developed to pass this test.

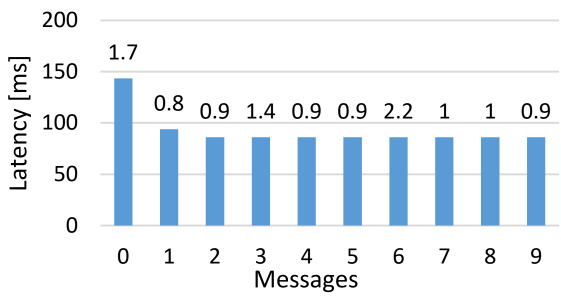

Fig. 2. PMU 2005. Mean value (blue bars) of the latency of UDP messages for each tenth of second. The corresponding standard deviation are reported (in milliseconds) on top.

The maximum PMU reporting latencies obtained from the PMU 2011, over 6000 messages using both the UDP and TCP communication protocol, are reported in Tables V and VI, respectively. Different latencies are obtained using either the P class or the M class configurations, but in both cases the valued measured by the PLM are widely below the maximum value suggested by the Standard.

TABLE V. PMU 2011 REPORTING LATENCY MEASURED OVER 6000 UDP MESSAGES (REPORTING RATE RR=10 FRAMES/S)

Algorithm	**PMU Reporting latency [ms]**	
P	**Max**	**26.6**
	Mean	26
	St. Dev.	0.1
	(Limit)	(200)
M	**Max**	**406.4**
	Mean	405.3
	St. Dev.	0.2
	(Limit)	(700)

TABLE VI. PMU 2011 REPORTING LATENCY MEASURED OVER 6000 TCP MESSAGES (REPORTING RATE RR=10 FRAMES/S)

Algorithm	**PMU Reporting latency [ms]**	
P	**Max**	**28.3**
	Mean	27.1
	St. Dev.	0.2
	(Limit)	(200)
M	**Max**	**406.6**
	Mean	405.9
	St. Dev.	0.2
	(Limit)	(700)

The results for both protocols and for both algorithms are quite similar. However, in terms of mean values of reporting latency, as expected, the UDP communication has better performance with respect to TCP.

CONCLUSIONS

The high measurement reporting rate is one of the key elements that are favoring the success of the PMUs in the Wide Area Monitoring Systems. However, in order for this feature to be really effective in real-time applications for protection and control, the compliance with the Standard on synchrophasors should be ensured not only in terms of measurement accuracy, but also in terms of latency.

To evaluate the reporting latency of a PMU, an automated test unit is proposed, using a portable and reconfigurable hardware with time synchronization. The characterization tests demonstrates the practical applicability of the proposed system, which can thus be used to evaluate the performance for either commercial PMUs or laboratory prototypes.

Besides the standardized compliance verification, the long tests that can be run by the automated system allow a statistical analysis to be performed on a large amount of data. On this basis, the behavior of the PMUs under different configurations can be better understood, even when, as often occurs, explicit detailed information about the implemented functionalities are not available. This can be particularly useful in a heterogeneous WAMS network, with PMUs from different vendors and different production dates, which means different constraints on latency.

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REFERENCES

[1] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, G. P. Hancke, “Smart Grid Technologies: Communication Technologies and Standards” in Industrial Informatics, IEEE Transactions on, vol.7, no.4, pp.529-539, Nov. 2011.

[2] J. De La Ree, V. Centeno, J. S. Thorp, A. G. Phadke, “Synchronized Phasor Measurement Applications in Power Systems” IEEE Trans. Smart Grid, vol.1, no.1, pp.20-27, June 2010.

[3] S. Mousavian, J. Valenzuela, and J. Wang, “A Probabilistic Risk Mitigation Model for Cyber-Attacks to PMU Networks,” IEEE Trans. Power Syst., vol. 30, no. 1, pp. 156–165, Jan. 2015.

[4] K. E. Martin, “Synchrophasor Measurements Under the IEEE Standard C37.118.1-2011 With Amendment C37.118.1a,” *IEEE Trans. Power Deliv.*, vol. 30, no. 3, pp. 1514–1522, June 2015.

[5] “IEEE Standard for Synchrophasor Data Transfer for Power Systems,” *IEEE Std C37.118-2-2011 Revis. IEEE Std C37.118-2005*, pp. 1–53, Dec. 2011.

[6] R. M. Moraes, H. A. R. Volskis, and Y. Hu, “Deploying a large-scale PMU system for the Brazilian interconnected power system,” in *Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008*, 2008, pp. 143–149.

[7] P. Kansal and A. Bose, “Bandwidth and Latency Requirements for Smart Transmission Grid Applications,” *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1344–1352, Sept. 2012.

[8] "IEEE Standard for Synchrophasor Measurements for Power Systems," *IEEE Std C37.118-1-2011 Revis. IEEE Std C37118-2005*, pp. 1–61, Dec. 2011.

[9] G. Renal, M. Kanabar, and V. Muthukrishnan, "Practical aspects of testing Phasor Data Concentrators for wide area monitoring systems," in *2014 IEEE 27th Canadian Conference on Electrical and Computer Engineering (CCECE)*, 2014, pp. 1–6.

[10] http://support.fluke.com/calibration-sales/Download/Asset/9010663_ENG_A_W.PDF

[11] D. M. Laverty, R. J. Best, P. Brogan, I. Al Khatib, L. Vanfretti, and D. J. Morrow, "The OpenPMU Platform for Open-Source Phasor Measurements," *IEEE Trans. Instrum. Meas.*, vol. 62, no. 4, pp. 701–709, Apr. 2013.

[12] P. Castello, P. Ferrari, A. Flammini, C. Muscas, and S. Rinaldi, "A New IED With PMU Functionalities for Electrical Substations," *IEEE Trans. Instrum. Meas.*, vol. 62, no. 12, pp. 3209–3217, Dec. 2013.

[13] P. Romano and M. Paolone, "Enhanced Interpolated-DFT for Synchrophasor Estimation in FPGAs: Theory, Implementation, and Validation of a PMU Prototype," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 12, pp. 2824–2836, Dec. 2014.

[14] P. Castello, J. Liu, C. Muscas, P. A. Pegoraro, F. Ponci, and A. Monti, "A Fast and Accurate PMU Algorithm for 'P+M' Class Measurement of Synchrophasor and Frequency," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 12, pp. 2837–2845, Dec. 2014.

[15] P. Romano, M. Paolone, "An enhanced interpolated-modulated sliding DFT for high reporting rate PMUs," in *IEEE International Workshop on Applied Measurements for Power Systems Proceedings (AMPS),* pp.1-6, 24-26 Sept. 2014

[16] "IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control," *IEEE Std C37.242-2013*, pp. 1–107, Mar. 2013.

[17] "IEEE Standard for Synchrophasor Measurements for Power Systems – Amendment 1: Modification of Selected Performance Requirements," *IEEE Std C37.1181a-2014 Amend. IEEE Std C371181-2011*, pp. 1–25, Apr. 2014.