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New Approach for Measurement Data Handling in Cloud-Based Synchrophasor Systems for Smart Grids

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***Abstract* – The classical Wide-Area Monitoring System (WAMS) ischaracterized by a hierarchical architecture composed of Phasor Measurement Units (PMUs) and different levels of Phasor Data Concentrators (PDCs). The WAMS based on synchrophasor technology was originally designed for transmission systems; nevertheless, with the development of the smart grid paradigm, the benefits of this technology are being extended to the distribution network. Normally, PMUs send measurement data ata high and constant reporting rate to guarantee the monitoring of dynamic events in the electric transmission network.However, the typical communication systems expected to be used by distribution system operators will be generally shared and/or public and,in this case, the bandwidth available among PMUs and PDCs, or among the PDCs and the control center, is strictly dependent on the type of communication channel used and on thelevel of network traffic. In this context, a new transmission logic for thetransfer of data between PMUs and PDCs can be implemented. The strategy proposed in this paper is to increase the measurementreporting rate only when the electric system changes from a steady-state condition to a dynamic and potentially unsafe condition. The risk of losing important information related to the dynamic event is mitigated by sending the PDC measurements relating to pre-trigger events aggregated in the first data packet following the event detection.**

Keywords – PMU, PDC, Cloud, WAMS, Variable Reporting Rate.

I. INTRODUCTION

The Wide-Area Monitoring Systems (WAMSs) based on synchronized measurements are characterized by a hierarchical architecture composed of Phasor Measurement Units (PMUs) and different levels of Phasor Data Concentrators (PDCs)[1]. The PMU is the “sensor” device that measures electrical quantities, such as voltage and current phasors, frequency and rate of change of frequency (ROCOF) with an accurate time-tag based on the Universal Coordinated Time generally obtained from a GPS receiver or through IEEE 1588 (Precision Time Protocol) synchronization.

The role of the PDC is to collect and align measurements provided by the PMUs and to forward these data to the next higher PDC level and, finally, to the control center [2], which is in charge of the evaluation of the overall state of the electric grid. The WAMS based on synchronized measurements was originally designed for transmission systems, but, with the introduction of the smart grid framework, the benefits of synchrophasor technology are moving also to the distribution network[3]-[6].

The use of PMUs in the distribution network context represents a new challenge: the stand-alone PMUs and PDCs could be replaced by dedicated functionalities implemented in Intelligent Electronic Devices (IEDs) [7] or by existing measurement devices upgraded in order to build an Internet of Things (IoT) network with synchrophasor functionality[8]. In a synchrophasor system suitable for distribution grids, several measurement devices will be necessary and, in this new scenario, the classical hierarchical architecture can be inadequate, since it can be unable to manage many PMUs and/or PMU-enabled instruments. A solution can be represented by replacing the hierarchical structure of PDCs with a less expensive and rapidly scalable structure based on cloud computing.

Normally, in transmission system WAMS, PMUs send data at a constant rate of 50–60frames per second (fps) to guarantee the monitoring of dynamic events [9].However, the communication systems used by distribution system operators (DSOs) are expected to be shared and/or public[10] (alternative solutions based on a private cloud with a private communication channel may be too expensive for DSOs.). In this case, the bandwidth available for the devices involved is strictly dependent on the type of communication channel adopted.

In this context, the paper proposes a new logic aimed at modifying dynamically the reporting rate (RR) of a

PMU in order to increase it only when the electric system changes from a steady-state to a dynamic, and potentially unsafe, condition.

Furthermore, the risk, due to low steady-state reporting rate, of losing important information around the beginning of a dynamic event is mitigated by storing all the measurement data at the maximum rate inside the PMU and sending to the PDC aggregated information relating to the pre-trigger period in the first data packets after the detection of an event. The PDC specifically designed for the proposed architecture works as an IoT Gateway and can evaluate the content of the data packets received from all the connected PMUs (in this paper, IoT Devices).

In this way, the PDC shall act as the first element of the monitoring system with an overview of a section of the electrical grid.

II. THE PROPOSED ARCHITECTURE

Fig. 1 shows the typical hierarchical architecture o fa WAMS based on the synchrophasor technology described in the standard IEEE C37.118.2-2011 [2], with the PMUs as the basis and two levels of PDCs. In this case, the PMUs send their measurements over the communication network in data packets in compliance with the standard protocol by reporting up to 50 fps (for a system frequency of 50 Hz). It is also possible to find commercial PMUs with RRs higher than those required by the standard.

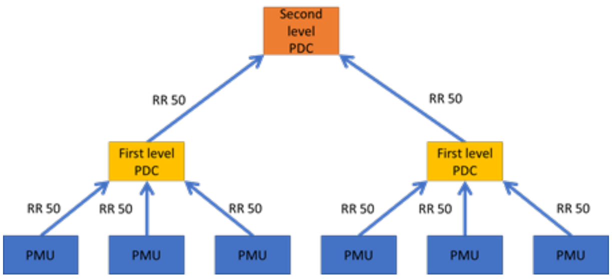

Fig. 1. Representation of the hierarchy WAMS based onPMUs and different levels of PDCs.

Generally, among the PMUs and the control center there are different levels of PDCs. The PDC builds a single output data stream with the data aligned input streams. The time to process incoming data and the output latency of the PDC are larger after each step of the PDC hierarchy.

The number of PMUs required for the electric distribution network is expected to be higher with respect to the transmission grid, due to the large number of nodes to be monitored. Consequently, the number and size of data streams could become difficult to manage.

Fig. 2 illustrates the architecture proposed for asynchrophasor system designed for a distribution network where the communication channel is shared and/or public.

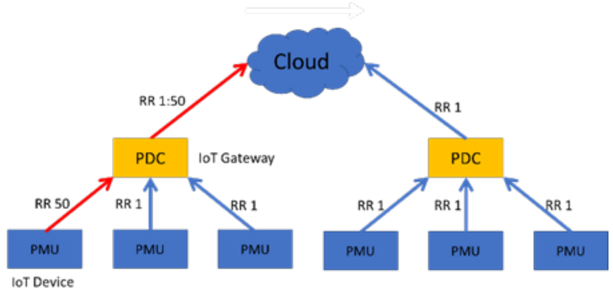

Fig. 2. Representation of proposed architecture based on flexible PMUs and a single level of PDCs.

In the figure, there is a single level of PDC that acts as a gateway between the devices in the field and the cloud, where the measurements are processed depending on the application (state estimation for real-time control but also off-line applications as post-mortem analysis are possible).

The PMU continuously produces and stores the data internally with the maximum reporting rate of the standard (RR = 50 fps) but, in the presence of a steady-state condition, sends the data to the PDC with a lower reporting rate (e.g. RR = 1 fps).

It is important to recall that, in the design of a PMU compliant with [1], the value of RR determines not only the number of measurements per second sent to the PDC, but also, for each compliance class and each nominal system frequency, the measurement performance of the device under specific test conditions. Thus, in the proposed architecture, where the actual PMU RR is constant (and the high-rate measurements are continuously stored in a circular buffer of suitable capacity), the metrological characteristics of the device do not change with the output RR, which, on the contrary, can be modified depending on the operating condition of the electric grid.

In the presence of a dynamic event detected in the electric network (e.g., a given threshold is exceeded), the PMU can activate the highest output RR and send also the pre-trigger data to the PDC, flushing the buffer.

III. TEST SETUP

In the following simulation tests, obtained in the LabVIEW environment, are presented to prove the performance of the proposed system under a dynamic event.

As a representative example of possible data management policies, in this paper the detection of a significant frequency deviation from the nominal value of 50 Hz has been addressed. In order to save a significant portion of the monitored phasors, the PMU is equipped with a circular buffer (managed with a First In First Out, FIFO, logic), which can host 1s of data stored at 50 fps. It is worth noting that, in practical cases, the dimension of the FIFO buffer should be chosen according to the maximum dimension of the data packet forwarded to the PDC in case an event is triggered.

a) Phase modulation test case

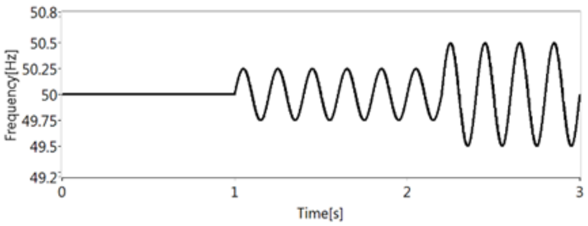

Fig. 3. Frequency test signal used for validating the proposed method based on the detection of the off-nominal frequency.

The synchrophasor standard [1] suggest a sinusoidal phase modulation signal to test the bandwidth of a PMU, using different modulation frequencies and a modulation level $k_a = 0.1$ rad.In such case, the maximum absolute variation from the nominal system frequency is:

$$\Delta_{fmax} = k_a \cdot f_m \quad (1)$$

where f_m is the modulation frequency.The highest $f_m$suggested by the standard is 5 Hz, which corresponds to $\Delta_{fmax} = 0.5$ Hz. On the contrary, considering a constantf_m,the deviation from the nominal system frequency is proportional to the modulation level k_a and Δ_{fmax} varies with the modulation level. It is thus possible to impose a threshold for dynamic condition detection on the maximum frequency deviation.

In the following,Δ_f=0.4 Hz is used to discriminate the dynamic condition and upper and lower frequency thresholds are defined as follows:

$$f_{threshold} = f_o \pm \Delta_f \quad (2)$$

Fig. 3 shows the frequency of the adopted test signal as a function of time where k_a changes with time. At the beginning, the test signal is in a steady-state condition with the nominal frequency ($k_a = 0$, no modulation).

After one second has elapsed, the test signal is phase-modulated with a modulation frequency of 5 Hz and two different levels of modulation factor. Between 1 s and 2.2 s the modulation factor is $k_a = 0.05$ rad, which leads to a maximum frequency deviation equal to Δ_{fmax} = 0.25 Hz.

After 2.2 s, a dynamic condition occurs when k_a becomes 0.1 rad. In this case, the maximum deviation from the nominal system frequency is Δ_{fmax} = 0.5 Hz that is above the fixed threshold.

For an efficient management of the proposed system, besides to the detection of a given frequency deviation ,an additional mechanism has been also implemented. To avoid continuous changes between the high and the low value of the reporting rate, the highest value is maintained for T seconds after the trigger, even if the dynamic condition returns below the threshold value.

b) Frequency ramp test case

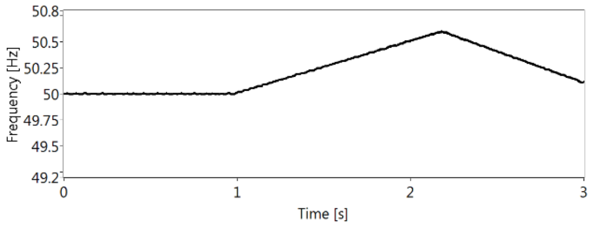

Fig. 4. Frequency variation with a positive and negative linear ramp test with different values of ROCOF.

A second simulation scenario is represented by a variation of the frequency with different values of ROCOF (Rate of Change of Frequency). The event shown in Fig. 4 comprises:

- a steady-state condition at the nominal system frequency between 0 s and 1 s.
- a positive frequency ramp at a rate of 0.5 Hz/s from 1 s to 2.2 s.
- a frequency ramp with negative ROCOF (–0.6 Hz/s) from 2.2 s to the end of the simulation.

During the ramp events, the values of the frequency are given by:

$$f(t) = f_{start} + R_f \cdot (t - t_{start}) \quad (3)$$

where f_{start} and $R_f$are the signal frequency at the ramp starting time $t_{start}$and the frequency ramp ROCOF, respectively. To simulate a real signal acquired from the power system, a uniform white noise of 50 dB was added to the test signal.

Using the same value of threshold applied in the dynamic conditions of the case a), the test signal reaches the threshold level after $t = 1.75\ s$.The implemented policy allows following the slow variation of the frequency after reaching the threshold value, that is after the critical or significant variation is detected, and saving the communication data in the steady-state case.

IV. TEST RESULTS

a) Phase modulation test case

Fig. 5-7 plots the frequency measurements received by the PDC relating to the test signal described in the previous section. Three different cases, corresponding to three different reporting rate policies, are shown:

- Case 0: the frequency measurements sent by the PMU with a constant low reporting rate (1 fps, thus giving 4 measurements).
- Case 1: the frequency measurements sent with a dynamic RR without pre-trigger data transmission (similarly to [8]).

- Case 2: frequencies measurements received by the PDC when the 1 s pre-trigger data are sent along with the variable RR.

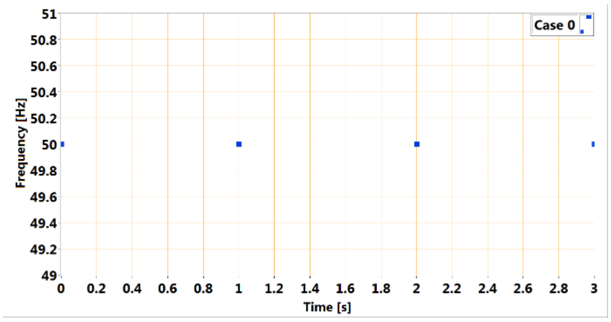

Fig. 5. Case 0: trend of data received from the PDC relative to a constant reporting rate policy equal to 1 fps.

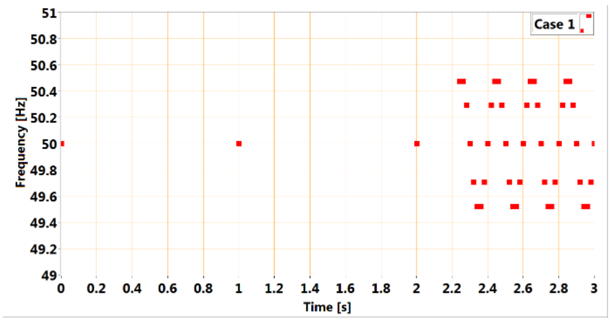

Fig. 6. Case 1: trend of data received from the PDC relative to a variable reporting rate policy.

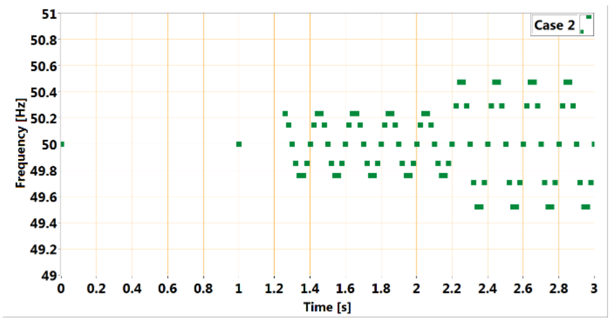

Fig. 7. Case 2: trend of data received from the PDC relative to the variable reporting rate and pre-trigger data.

In Case 0, the measurements are received every second and, as described by the synchrophasor standard, the RR is not sufficient to follow the sinusoidal variation of the frequency (it is far below the Nyquist frequency of the occurring dynamics).

Case 1 represents an adaptive reporting rate and the highest reporting rate (50 fps) starts when the value of the frequency exceeds the threshold imposed ($t = 2.22$ s). In this case, it is possible to follow the dynamic event as it occurs, but it is not possible to understand how the frequency evolved to reach the critical level that distinguish the steady-state from the dynamic condition.

Case 2 covers this gap as the measurements relating to the pre-trigger event are forwarded to the PDC in the first packet following the event. The PDC aligns the data to show the evolution of the frequency before the event occurred.

b) Frequency ramp test case

The second test scenario presents a steady-state signal at the system frequency combined with two linear frequency ramps with different levels of ROCOF, as described in Section III.b.

Figures 8–10 show the measurement data received by the PDC from the PMU under the aforementioned three different reporting rate policies.

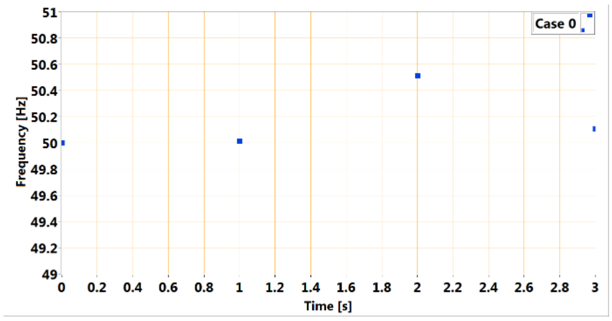

Fig. 8. Case b: trend of data received from the PDC relative to a constant reporting rate policy equal to 1 fps.

Figure 8 represents the frequency monitored for 4 s, with the lowest RR suggested by the synchrophasor standard (Case 0). It is important to highlight that for the RR lower than 10 fps, PMUs are not subject to the dynamic requirements and thus their configuration and measurement algorithm can be very different from those suitable to follow the signal changes as under linear frequency ramp conditions.

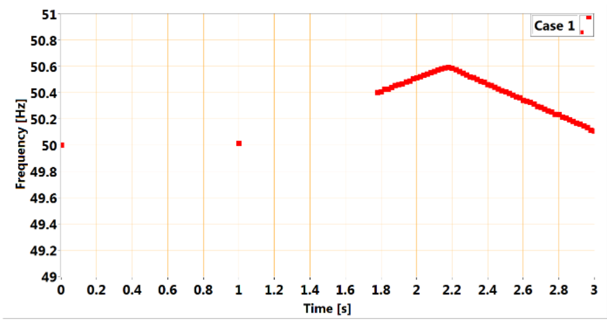

Fig. 9. Case b: trend of data received from the PDC relative to a variable reporting rate policy.

The trend of the frequency measurements received by the PDC from a PMU with a variable RR (Case 1) is shown in Fig. 9. To save the communication bandwidth, the PMU can adapt between two RRs: 1 fps when the frequency is under the threshold and 50 fps after the threshold has been exceeded ($t = 1.78\ s$).

The policy of variable RR highlights the dynamic event and saves the communication bandwidth in the synchrophasor system during the steady-state period, but it does not allow following the whole trend of the event before the threshold level is reached.

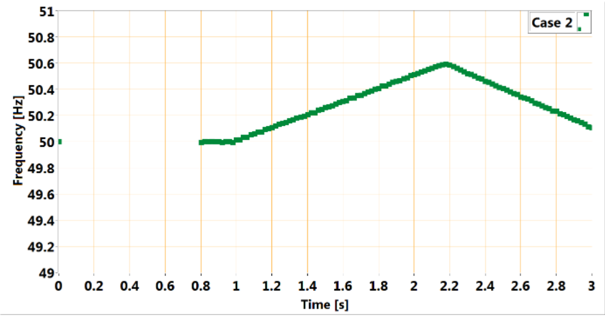

Fig. 10. Case b: trend of data received from the PDC in case of variable reporting rate and pre-trigger data.

To overcome this gap a pre-trigger policy should be applied. Fig. 10 shows the data received by the PDC from the PMU with variable reporting rate and pre-trigger data. In this case, it is possible to follow the trend of the signal whose frequency has exceeded the threshold. The data stored in the circular buffer cover 1 s at RR = 50 fps before the trigger event that causes the highest RR to be activated $(t = 0.8\, s)$. Such buffer size allows a relevant look-back interval, while avoiding a too large backup packet transmission.

Moreover, it is interesting to note that both in Case 1 and Case 2, during the negative ramp period, the dynamics is followed below the threshold limit thanks to the holding period introduced to avoid a jerky evolution of the RR.

V. CONCLUSIONS

To bring the benefits of synchronized measurements from the transmission to the distribution level, the classical architecture of the wide area monitoring system needs to be adapted to the new context. In this proposal, a new architecture of synchrophasor system based variable reporting rate on cloud solutions is proposed. To manage efficiently data transmission and to save bandwidth in the case of shared and/or public communication channels, the reporting rate of the PMU is changed using a selectable threshold, driven by the dynamic events possible in the electric distribution systems. The possibility of losing relevant information around the beginning of a dynamic event is mitigated by sending to the PDC the measurements relating to the pre-trigger event in the first data packet following the event detection. Examples of the application of the proposed solution have been discussed, thus proving how the use of such adaptive policies can help bandwidth saving while preserving important information and details when dynamics occur. It is possible to define policies able to follow both very fast events and slower evolutions. The pre-trigger data are always useful to complete the available information, so that it is possible to analyze the event origin or early behavior without the risk to be too sensitive and thus affected by negligible fluctuations.

REFERENCES

[1] *IEEE Standard for Synchrophasor Measurements for Power Systems*, IEEE Std C37.118.1-2011 Revis. IEEE Std C37118-2005, pp. 1–61, Dec. 2011.

[2] *IEEE Standard for Synchrophasor Data Transfer for Power Systems*, IEEE Std C37.118.2-2011 Revis. IEEE Std C37118-2005, pp. 1–53, Dec. 2011.

[3] D. Bulic, R. Jancic, V. Kirincic, and S. Skok, *Monitoring of low voltage facilities using synchronized phasor measurements*, in 2013 36th International Convention on Information Communication Technology Electronics Microelectronics (MIPRO), 2013, pp. 1231–1234.

[4] M. Pignati et al., *Real-time state estimation of the EPFL-campus medium-voltage grid by using PMUs*, in Innovative Smart Grid Technologies Conference (ISGT), 2015 IEEE Power Energy Society, 2015, pp. 1–5.

[5] 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.

[6] A. von Meier, D. Culler, A. McEachern, and R. Arghandeh, *Micro-synchrophasors for distribution systems*, in ISGT 2014, 2014, pp. 1–5.

[7] P. Castello, P. Ferrari, A. Flammini, C. Muscas, P.A. Pegoraro, S. Rinaldi: *A distributed PMU for electrical substations with wireless redundant process bus*, IEEE Trans. Instrum. Meas., vol. 64, no 5, pp. 1149-1157, May 2015.

[8] P. A. Pegoraro, A. Meloni, L. Atzori, P. Castello, and S. Sulis, *PMU-Based Distribution System State Estimation with Adaptive Accuracy Exploiting Local Decision Metrics and IoT Paradigm*, IEEE Trans. Instrum. Meas., vol. 66, no. 4, pp. 704–714, Apr. 2017.

[9] *Reliability Guideline, PMU Placement and Installation, DRAFT*, May 2016, Available online, www.nerc.com."

[10] C-DAX Deliverable D5.2, *Test Results of Field Trial with C-DAX Compatible Grid Devices*.