DEMYSTIFYING DISTRIBUTION PMUS: A COMPREHENSIVE GUIDE FOR DISTRIBUTION SYSTEM OPERATORS

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Abstract

Phasor Measurement Units (PMUs) have long been a cornerstone of monitoring and control in transmission systems, and their adoption in distribution networks is increasingly gaining traction. In this respect, this paper provides an in-depth analysis of Distribution-PMUs (D-PMUs) and their role in distribution grid digitalization. The discussion begins with an overview of D-PMU technology, highlighting the key differences with transmission PMUs, and their enabling technologies. Next, real-world use cases are reviewed, showcasing how D-PMUs enhance grid reliability, support renewable energy integration, and enable advanced distribution management systems. Finally the paper provides some reference architectures of a D-PMU system, with particular attention to its integration into control room solutions, bridging the gap between legacy infrastructure and this cutting-edge technology. By offering clarity on these aspects, this guide serves as a valuable resource for Distribution System Operators seeking to leverage D-PMUs for enhanced grid performance, reliability, and scalability in the evolving energy landscape.

1. Introduction

To meet the ambitious CO2 emission reduction and electrification goals set by national/international authorities, Distribution System Operators (DSOs) are asked to increase investments in grid digitalization. One of the main goals of such a process is to enhance the level of observability on their electrical infrastructure, which is seen today as the key to reliability, resilience, efficiency and operational excellence in modern distribution grids [1].

Distribution grid observability at scale is typically achieved via complex control room solutions such as Advanced Distribution Management System (ADMS), which combines control room solutions which before were split (e.g., SCADA, DMS, OMS, DERMS, etc.). ADMS offers to utility companies comprehensive tools to monitor, control, and optimize the operation of the distribution grid in real-time, but in order to properly function, they require the availability of high-quality data, something that today cannot be always guaranteed due to (1) the limited power grid instrumentation, (2) the heterogeneity and inconsistency of different data sources, as well as (3) the limited data availability and completeness. Indeed, ADMS still rely on legacy Intelligent Electronic Devices (IEDs) such as Fault Passage Indicators (FPIs), Remote Terminal Units (RTUs) and Protection relays, still deployed in a limited number of substations, or, where available, on low-voltage monitoring systems based on non-real-time measurement devices such as Smart meters.

To increase the amount and quality of the data managed and processed by ADMS and improve their performance, Distribution Phasor Measurement Unit (D-PMU) seem an extremely viable technology, on one hand for their inherently higher data quality, on the other hand for their capability to server multiple use cases simultaneously. Compared to traditional Phasor Measurement Units (PMUs), which were designed for transmission grid applications, D-PMUs are specifically designed to address distribution systems' unique needs and challenges both from an integration and application perspective.

In this respect, as the D-PMU technology becomes more mature and adopted, this paper aims at clarifying and demystifying several misleading concepts around it and to serve as a guide to DSOs that would like to implement such a technology in their distribution grids. The paper is structured as follows: Section 2 presents basic concepts about D-PMUs and compares them to traditional transmission PMUs. Section 3 discusses the requirements of D-PMU enabling technologies while Section 4 presents the most relevant PMU use-cases. Finally, Section 5 presents typical D-PMU system architectures.

2. Distribution-PMU basics

2.1. Phasors, synchrophasors and PMUs

The *phasor* transformation has been historically adopted in electrical engineering to simplify the analysis of electrical systems in sinusoidal steady state (i.e., *stationarity* *hypothesis*). Such a transformation allows to represent a sinusoidal function of time with a single complex value:

$$x(t) = A\cos(2\pi f t + \varphi_0) \Leftrightarrow X = A \cdot e^{j\varphi_0}$$

where A, f, φ_0 are the main tone (50/60 Hz) amplitude, frequency, and initial phase respectively.

To apply the phasor concept in the real world, where the stationarity hypothesis does not hold, the *synchrophasor* concept has been formulated as a phasor value calculated from voltage or current data samples using a standard, common time reference:

$$x(t) = A(t)\cos(\varphi(t)) + \varepsilon(t) \Leftrightarrow X(t) = A(t)e^{j\varphi(t)}$$

where $\varphi(t) = 2\pi f(t)t + \varphi_0$ and $\varepsilon(t)$ represents any "disturbance" superposed to the main tone (e.g. harmonics).

In order to measure synchrophasors, the PMU concept has been defined in [2] as a "device or function in a multifunction device that produces synchronized phasor, frequency, and rate of change of frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal". In this respect PMUs shall integrate the following minimum set of components (see Figure 1):

- A set of *Analog inputs*, acquiring voltage/current signal samples from voltage/current transformers.
- A *Processing unit* to extract the synchrophasor measurement from a set of previously acquired samples.
- A set of *Network interfaces* (wired/wireless) to stream the measured data using a synchrophasor data transmission protocol (e.g., [3]).
- A Time sync module (e.g., GPS receiver) for measurement time stamping.

While PMUs were originally offered as standalone devices, to optimize the total costs of ownership of such a technology, today an increasing number of vendors offer PMU functionalities integrated inside multifunction IEDs (e.g., protection relays, RTUs and Merging Units), thus offering such a technology for a more competitive price.

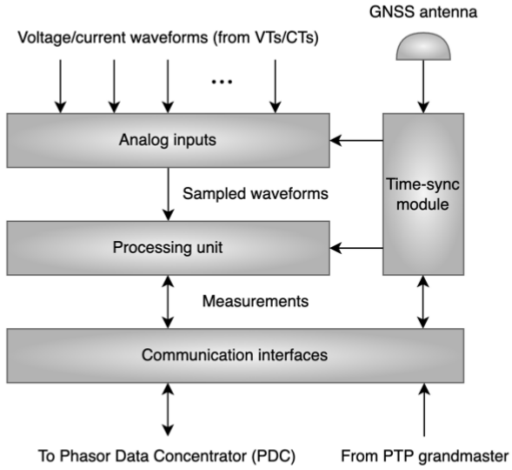

Figure 1 – Typical PMU architecture

Compared to conventional SCADA measurements, PMUs offer the following competitive advantages:

- **Accurate phasor measurements**: enabling the precise reconstruction of the fundamental (50/60 Hz) tone and the application of more sophisticated/performing grid calculations.
- **High speed/resolution measurements**: up to 100/120 measurement per seconds, enabling real-time monitoring of dynamic grid behaviours and grid transient (e.g., fault) detection/characterization.
- **Accurate time-synchronized measurements:** by leveraging sub-microsecond accurate time references, PMU measurements can be precisely correlated.

2.2. *Transmission and Distribution PMUs*

Although the PMU technology can be applied to any voltage level, its adoption cycle has started, more than 20 years ago, in transmission grids. Today, as the market becomes more mature and the costs of electronic components gets cheaper, PMU technology has become more accessible for DSOs.

Compared to transmission PMUs, D-PMUs are grid monitoring devices specifically optimized for operating in distribution grids. From an integration perspective, D-PMUs must guarantee an easy retrofit in distribution grids, where instrumentation is typically not present, space is limited, and communication capabilities can sometimes be offered via wireless technologies only. From a measurement perspective, D-PMUs must be extremely resilient to harmonic and inter-harmonic distortion and characterized by short response times and extended voltage/current measurement ranges to cope with fault conditions.

In this respect, D-PMU devices come with intrinsic differences compared to transmission PMUs, which are listed in Table 1.

Table 1 – Transmission vs. Distribution PMU

Transmission PMU	Distribution PMU
Analog inputs	
High voltage/current inputs for conventional VTs/CTs already installed in transmission substations are typically sufficient.	Low-power inputs for non-conventional VTs/CTs are typically required for retrofit purposes. Interoperability with conventional VTs/CT is also recommended.
Synchrophasor measurement	
P/M-class compliancy as defined in IEC/IEEE 60255-118-1 Std. is sufficient for most applications.	Higher harmonic resiliency and wider measurement ranges than those specified in IEC/IEEE 60255-118-1 Std is typically required.
Time synchronization	
Typically, via external PTP/IRIG-B master clocks.	Typically, via integrated GNSS receiver.
Data communication	
Typically, via private TSO “wired” network.	Mostly via 4G/5G-LTE wireless network.
Size	
No strict requirements.	Small to fit in compact distribution substations.
Installation	
Panel/rack mount.	Mostly wall-mount (indoor), or pole mount (outdoor).
Costs	
EUR 2000-3000 per bay.	EUR 1000 per bay.

3. D-PMU enabling technologies

The deployment of D-PMUs requires the availability of other complementary technologies that are presented in this Section with respect to their requirements.

3.1. Instrument transformers

To measure voltage/current synchrophasors, D-PMUs must be able to interface to voltage/current transformers (VTs/CTs) to scale-down high voltage/current signals to suitable levels. Depending on the target PMU application, such function could be either offered by conventional VTs/CTs based on electromagnetic principles or by non-conventional VTs/CTs using more advanced technologies like resistive/capacitive dividers for voltage and Rogowski coils for current measurement. The former are a more established technology but suffers of limited performance (linearity, saturation, accuracy, etc.) and are difficult to retrofit in compact substations. On the other hand, the latter offer higher performance in a more compact (i.e., easy to retrofit) format, with more competitive prices.

In this respect, except for the case of primary substations, where conventional VTs/CTs are already installed, non-conventional VTs/CTs represent a more convenient solution for D-PMUs, particularly in the case of substation retrofit applications which require compact/non-invasive solutions.

3.2. Communication networks

When designing a PMU system, a crucial step is the selection of the communication network to be used between PMU devices and the central collection point, which, depending on the application, can be up to hundreds of kilometres apart. Such a selection shall be based on different factors, including but not limited to costs, coverage and supported data rates of the selected technology, but also data availability, end-to-end latency and reporting rate requirements of the target application. In this respect, Table 2 reports, typical PMU data rates/ volumes requirements, which, thanks to the “data compression” capabilities offered by the phasor transformation, can be provided by different communication technologies.

Table 2 –PMU data rate/volume requirements for different combinations of reporting rates and reported phasor

Reported Phasors	PMU reporting rate	
	1 Hz	*50 Hz*
6	0.9 kbps (0.3 GB/month)	41 kbps (13.5 GB/month)
16	1.6 kbps (0.5 Gb/month)	73 kbps (23.9 Gb/month)

For PMU applications, the preferred solution has been historically the use of fiber networks, both for their performance (allowing to support mission-critical/hard-real time applications like wide are protections), their accurate time dissemination capabilities (see Section 3.3), and for their inherent security. Still, such a communication technology is only marginally available in distribution networks, being only deployed in primary substations and few strategic secondary substations (depending on the DSO, between 0-20% of the secondary substations).

In this respect, in the past decade, cellular networks (4G/5G LTE) have emerged as the favourite solution to deploy D-PMUs, for their good trade-off between deployment time/costs and performance. The only drawback of such a solution is that public cellular networks are shared with other users, and dedicated Service Level Agreement cannot be necessarily guaranteed. In this respect, in the recent years, the concept of private LTE networks has emerged as a viable solution for utility companies, for their capability to offer higher security, reliability standards than public LTE, particularly for high demanding applications like distribution automation (e.g., wide are protections).

3.3. Time synchronization technologies

A PMU requires time synchronization to a UTC time reference that is typically provided by Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Galileo and BeiDou, which offer the required synchronization accuracy and global coverage for a relatively low cost. In practice, in transmission substations, this is typically implemented via a local (substation) master clock able to disseminate the time reference to multiple PMU devices via the PTP [4] or IRIG-B [5] protocol.

In distribution grids, such time-dissemination solutions can only be replicated in primary substations but are not economically viable for secondary substations or pole mounted solutions. In this respect, to achieve PMU synchronization in distribution grids, the most common solution is to adopt D-PMU devices that already embed a GNSS receiver and connect them to a dedicate antenna, typically mounted outdoor to offer the best sky visibility.

In congested urban environment, such an approach might suffer from limited performance (particularly in so-called “urban canyons” where the sky visibility is reduced), risk of vandalism to the antenna or the unfeasibility of pulling out the cables in case of underground substations. In such conditions, another viable solution is to leverage PTP to synchronize the PMU to a master clock placed in another substation (typically the primary substation). Such solution requires the availability of a fiber network (usually more common in urban distribution grids) which integrates active components (e.g., switches) that support PTP and can act as “transparent clocks”.

4. D-PMU use-cases

Thanks to synchrophasor inherent higher data quality, which allows to use them for a wide range of applications, and their unique capability to scale easily to the entire grid of a DSO, D-PMUs can serve simultaneously multiple use-cases, with a clear focus on medium-voltage distribution. At this voltage level, PMU technology has been used for the following major control room use cases (see also [6]):

- **Real-time grid supervision**: by leveraging advanced model-based grid analysis techniques, D-PMUs offer real-time monitoring capabilities, which can be easily integrated in control room solutions (see Section 5.1).
- **Fault location**: thanks to the capability to monitor fault transient from different grid locations, D-PMU data can be used to estimate the fault location more accurately and reliably than conventional solutions based on non-synchronized measurements.
- **Congestion analysis**: by leveraging state estimation techniques which combine a limited number of PMU measurements with the grid model, line/transformer congestions can be accurately estimated.
- **Power quality (PQ) monitoring**: by using time-synchronized measurements, not only PQ event can be detected and classified, but also their root cause can be precisely identified. Additionally, PQ paramterts can be estimated based on PMU measurements.
- **Predictive maintenance**: thanks to the higher sensitivity of PMU measurements, incipient faults can be detected. By training Machine Learning models with these data, disruptive outages can be forecasted.
- **Distribution automation**: distribution automation applications can leverage the availability of distributed, time synchronized measurement along a MV feeder, to implement advanced automation solutions (e.g., FLISR, wide area protection).
- **DER management**: real-time PMU measurements can be used to build sophisticated control schemes for Distributed Energy Resources (DERs) management which rely on the knowledge of the grid state.

On top of these applications, the time-resolution, quality and coverage of D-PMU data can also be leveraged for other use cases outside of the control room, such as post-mortem analysis, grid planning and TSO-DSO coordination.

5. D-PMU system architecture

At the medium-voltage distribution level D-PMUs are typically deployed at the primary substation and in few strategic secondary substations (or pole-mounted locations) and coupled with a data platform that processes the D-PMU measurements and integrates with 3rd party systems like SCADA/ADMS (see Section 5.1). The placement and number of D-PMU devices, as well as the optimal mix of voltage and current measurements, mainly depends on the target application requirements, data processing techniques, as well as by other technical limitations such as accessibility and communication network coverage.

From an IT perspective, different architectures can be adopted depending on the target use cases, the available DSO communication and processing infrastructure and the optimal mix between capital and operational expenses. A typical architecture usually adopted when integration with 3rd party utility systems (e.g., SCADA) is required and which limits the cybersecurity exposure is represented by a fully on-premises architecture (see Figure 2-a). According to such an architecture the D-PMUs communicate using dedicated (private) fiber links where available or a secured (e.g., via encrypted VPN tunnels) cellular network, directly with a D-PMU data platform hosted within the DSO network perimeter (e.g., in the data centre) which collects, stores and process D-PMU data and shares the relevant information with the control room operator.

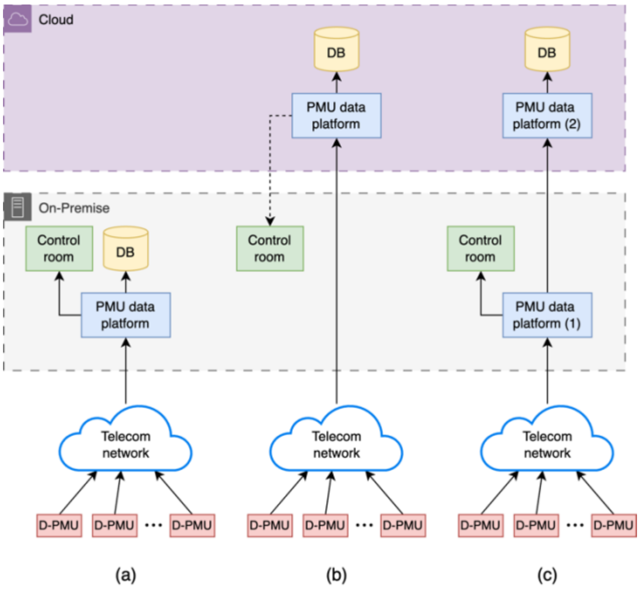

Figure 2 – Typical PMU system architecture: (a) fully on premises, (b) fully on cloud and (c) hybrid.

Another solution which is being adopted by smaller DSOs or private grid operators that do not necessarily own a data centre, is to deploy the D-PMU data platform on a public (e.g., AWS, Azure) or private cloud (see Figure 2-b). According to such an architecture, a direct communication link between the D-PMUs and the cloud solution is established, typically via a secured VPN tunnel over a 4G/5G LTE network. In this case integration with control room solutions is typically absent or limited, by leveraging a SCADA gateway deployed on premises.

A further solution which takes the best from the previously presented approaches is represented by a hybrid (or cloud-edge) architecture (see Figure 2-c). According to such an architecture, only a limited set of services of the PMU data platform are deployed on premise/on the edge (e.g., at the primary substation) based on their integration requirements either with the control room or any controllable grid resource. The rest of the services and the long-term data storage solutions are instead deployed on cloud, to facilitate the data accessibility, the system maintenance and the development and integration of new software modules.

5.1. Control room integration

Today, control room solution such as ADMS or SCADA offer either limited or no PMU data collection/processing capabilities. On the other hand, they offer different interfaces to collect measurements and alerts generated by conventional IEDs using standard SCADA protocols (e.g., IEC 60870-5-104, DNP3, OPC-UA, IEC 61850).

In this respect, a typical solution to integrate PMUs in control rooms is by interfacing to external PMU data platforms which can map PMU measurement or PMU-derived information to SCADA protocol data points and report alerts as well as measured/calculated information to the control centre. Due to the limited data processing/storage capabilities of today's control room solutions and to the fact that SCADA protocols have not been designed for high data rate communications, such an approach comes with the main limitation that not every measured/calculated value can be reported to the SCADA and will only be accessible in the PMU data platform. In this respect, a more advanced and efficient solution to integrate PMUs in control room solutions, is by leveraging APIs to access the PMU data platform database.

6. Conclusions

D-PMUs have achieved a level of technological maturity that positions them as viable alternatives to traditional grid monitoring technologies like FPIs and RTUs. With their unique capability to provide superior data quality and seamlessly scale across an entire DSO grid, D-PMUs stand out as an optimal choice for advancing ADMS and similar control room solutions.

This paper has aimed to clarify various aspects of D-PMU technology, from field deployment to integration within control room operations. By addressing these critical dimensions, the discussion highlights how D-PMUs can play a central role in enhancing the reliability and efficiency of distribution network management. Their adoption represents a significant step towards more advanced and scalable solutions for DSOs worldwide.

7. References

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