DISTRIBUTION-PMU DEPLOYMENT AND APPLICATIONS IN MICROGRIDS: THE EPFL UNIVERSITY CAMPUS CASE

Riccardo Vasapollo[1], Paolo Romano[1], Frédéric Gygax[2], Mario Paolone[2]*

[1]*Zaphiro Technologies, Lausanne, Switzerland*
[2]*École polytechnique fédérale de Lausanne, Lausanne, Switzerland*
**riccardo.vasapollo@zaphiro.ch*

Keywords: D-PMUS, PRIVATE GRIDS, MICROGRIDS, SITUATIONAL AWARENESS

Abstract

This paper presents the real-time situational awareness system based on Distribution-Phasor Measurement Units (D-PMUs) deployed in the medium-voltage grid of the EPFL campus in Lausanne, Switzerland. The system is composed of: (i) an advanced monitoring and sensing infrastructure featuring 57 D-PMUs and Rogowski current sensors, (ii) a dedicated IT infrastructure for data communication and time synchronization, and (iii) a software platform for real-time synchrophasor data collection, storage, and processing. The main contribution of the paper is twofold. First, it highlights the technical solutions adopted to deploy D-PMUs in this private grid, which can be replicated in similar environments. Second, it provides examples of real-world applications of the system including asset monitoring, fault detection and location, and dispatching of local feeders to address the challenges of such grids.

1. Introduction

The increasing operational challenges in modern power grids, driven by the intermittency and unpredictability of distributed energy resources (DERs), has amplified the importance of real-time monitoring and situational awareness provided by the Phasor Measurement Unit (PMU) technology [1]. While in transmission networks, PMUs are today a well-established technology, in distribution grids the adoption of such technology has started growing in the recent years, with unique opportunities emerging as Distribution-PMUs (D-PMUs) become cheaper and more accessible [2].

In distribution grids, two major types of grid operators exist: Distribution System Operators (DSOs), typically operating at a regional or national scale and owned by public entities, thus subject to governmental regulations, and Private grid/Microgrid operators, typically operating local area grids supplying energy to private entities such as industrial facilities, university campuses, airports, harbors and military bases. Such entities are typically driven by different objectives: DSOs often focus on power supply reliability, cost optimization and regulatory compliance. Private grid operators prioritize profit maximization, operational efficiency, and seamless integration of local generation and storage assets to maximize local self-consumption.

While the majority of PMU rollouts at the distribution level happens among DSOs (e.g., [3]), this paper presents the field implementation of a D-PMU based real-time situational awareness system in the private grid of the École Polytechnique Fédérale de Lausanne (EPFL) campus in Lausanne, Switzerland. This site offers a representative case study for such private grids, hosting a combination of photovoltaic (PV) distributed generation, a battery energy storage system (BESS), three data centers, Electric Vehicle (EV) charging stations, and various other unpredictable loads.

Whereas a previous publication [4] presented a preliminary PMU rollout in a limited portion of the EPFL microgrid, this work presents a full-scale rollout of the D-PMU technology in the entire medium-voltage grid supplying energy to the EPFL campus. The D-PMU system has been operational for over three years, offering a unique dataset and practical insights into the benefits and challenges of PMU deployment in such environments.

The paper is structured as follows: Section 2 illustrates the EPFL campus grid, Section 3 focuses on the System architecture, Section 4 showcases D-PMU use cases in EPFL private grid, and Section 5 presents the Conclusions.

2. The EPFL campus grid

The medium voltage (MV) grid of the EPFL campus is a typical example of a modern private grid, characterized by short line lengths (mostly under 100 m), significant load variability influenced by time of day, weather, and extensive use of power electronics and inverter-based resources. It includes two primary substations, 42 secondary substations, 1 switching substation, 102 MV-LV (20/0.4 kV) transformers and over 16 km of underground MV cables. The EPFL campus grid is operated at a rated voltage of 20 kV with an isolated neutral configuration, using an open-ring topology, which can be freely reconfigured by leveraging a major switching substation (bus 3 in Fig. 1).

Supplying an average load of 7 MW with a peak of about 16 MW, this peculiar power distribution system serves the needs of over 15'000 students visiting the EPFL campus daily and about 370 research laboratories, while incorporating local generation capacities of 3.8 MW from distributed PV systems connected to the low voltage sides of the secondary substations. Additionally, the network hosts a Lithium-Titanate Oxide (LTO) BESS characterized by a rated power of 0.75 MW and an energy capacity of 0.56 MWh. The largest loads in the system consist of a centralized heat pumps (responsible for campus heating and cooling) with a rated power of 24 MW, 3 data centers with a cumulative rated power of 2.85 MW, and 288 kW EV charging stations across campus.

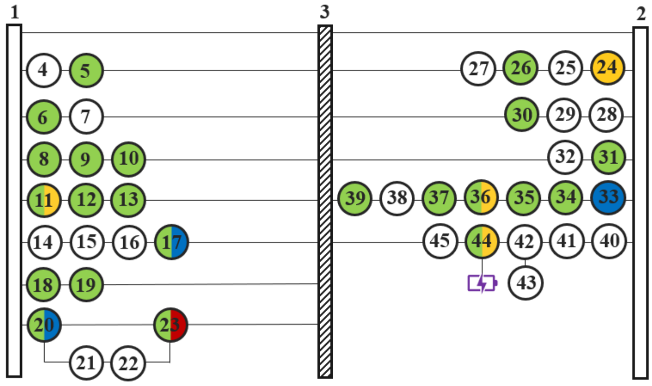

Fig. 1 – Single line diagram of the network

The mean, minimum, and maximum value of active power (P in MW) and reactive power (Q in MVAr) at the two primary substations (bus 1 and 2 in Fig. 1) between June 2023 and June 2024 are reported in Table 1 (the power is positive when exiting the bus, namely flowing into the network).

Table 1 – Active (P) and reactive (Q) power measurements at the two primary substations from June 2023 to June 2024

	P [MW]			Q [MVAr]		
	mean	**min**	**max**	**mean**	**min**	**max**
bus 1	4.19	2.02	8.19	-0.23	-0.56	0.40
bus 2	3.76	2.11	8.01	-3.42	-4.50	0.99
total	6.95	4.13	16.20	-3.65	-5.06	1.39

Before the D-PMU rollout, the grid was operated without a comprehensive real-time situational awareness system (SCADA or equivalent) and with the only real-time monitoring equipment (protection relays and PQ meters) being deployed at buses 1, 2 and 3. These conditions were making difficult the supervision and prediction of the grid's behavior which was increasingly impacted by the presence of intermittent loads and distributed generation. To address these challenges, a solution was developed in collaboration with the EPFL grid operator, to improve observability, enable continuous monitoring of the grid assets, and enhance fault management, ensuring the network could meet the demands of its dynamic environment, while limiting as much as possible the installation costs.

3. System architecture

The overall system architecture is presented in Fig. 2 and is composed by the following major components:

- A set of 57 D-PMUs, installed in the two primary substations, 42 secondary substations and in the switching substation (see Fig. 1).
- A Precision Time Protocol (PTP) [5] compliant high-speed fiber communication network for both data communication and time synchronization (see Section 3.2)
- A dedicated server in the main EPFL data center collecting, processing and storing D-PMU data using model-based analytics (see Section 3.3)

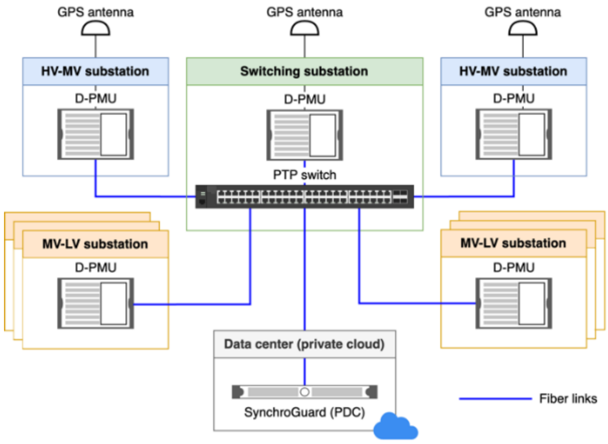

Fig. 2 – Simplified *system* architecture

3.1. Measurement infrastructure

D-PMU measurement infrastructure is composed of 57 SynchroSense devices from Zaphiro Technologies which were provided in dedicated wall-mount cabinets including: (i) a D-PMU device (ii) a power supply unit, (iii) a fiber media converter to directly interface with fiber links, and (iv) a supercap-based Uninterrupted Power Supply (UPS) to guarantee a stable power supply also during disturbances such as blackouts (see Fig. 3).

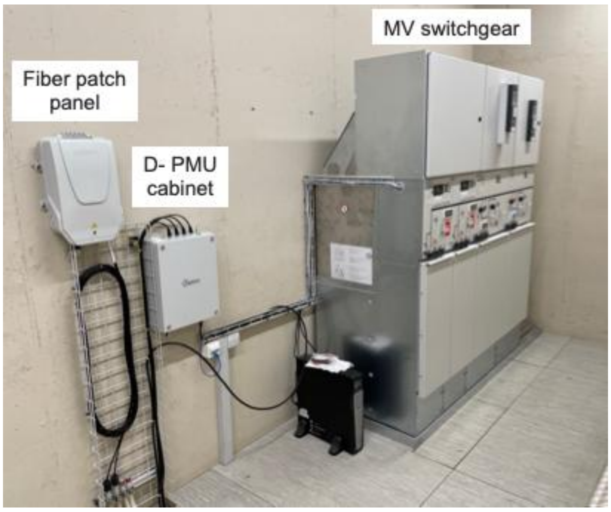

Fig. 3 – D-PMU installation in an *EPFL* substation

Every D-PMU measure current synchrophasors via clamp-on current sensors based on Rogowski coil technology from LEM, which have been installed in every line departure and, where possible, on every MV-LV transformer. In total, in the entire EPFL campus 266 three-phase current sensors have been deployed. Voltage is measured only by seven D-PMU devices, by leveraging existing Voltage Transformers (VTs) already installed in the two primary substations and in the switching substation.

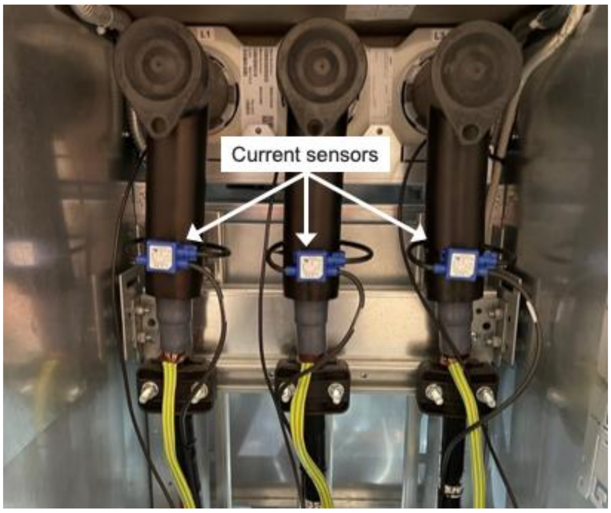

Fig. 4 – Clamp-on current sensors inside an MV switchgear

Synchrophasor data are transmitted by SynchroSense via one of the available ethernet ports, using the IEEE C37.118 protocol [6] at a reporting rate of 50 frames per second. Absolute time synchronization is achieved either via an embedded GNSS receiver if the D-PMU is connected to a dedicated GNSS antenna, or via PTP if not (see Section 3.2). In total, only four D-PMUs are connected to a GNSS antenna.

3.2. *Communication infrastructure*

D-PMU data communication to the central data processing platform and absolute time synchronization of the D-PMU devices leverage a high-speed fiber network that connects all D-PMU devices installed in the EPFL campus. The fiber network is based on a star topology, where the center of the star is represented by a network switch (from Cisco Catalyst 9400 series) installed in the switching substation and the "leaves" are the D-PMU devices, which are directly connected to dedicated fiber links (see Fig. 2). Thanks to such a solution, overall end-to-end latencies and packet losses are extremely limited, with average values <31 ms and <0.01% across all devices during the period from June 2023 to June 2024.

Absolute time synchronization of the D-PMU devices leverages mostly PTP [5]. Four D-PMU devices, directly connected to a dedicated GNSS antenna, act as potential PTP grandmaster clock. Based on the reported clock class, clock accuracy and priority, the PTP Best Master Clock Algorithm (BMCA) determines the most suited D-PMU in the EPFL campus grid to function as a grandmaster clock and drive the time of the other devices. Such a solution has demonstrated to achieve accuracies lower than 200 ns as demonstrated in Fig. 5, where the time synchronization error of four D-PMU devices which are also connected to a GNSS antenna (used as time reference) is shown.

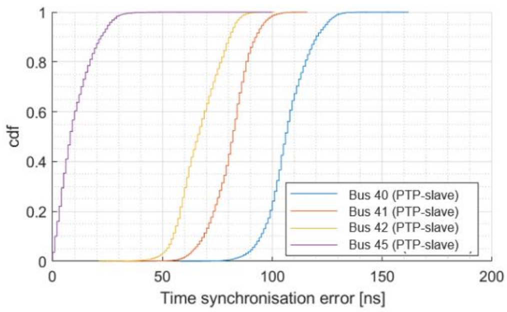

Fig. 5 – PTP time synchronization error of four D-PMUs connected to a GNSS antenna

3.3. *D-PMU data processing platform*

The D-PMU data processing platform is hosted on a dedicated server in EPFL main data center and is based on Zaphiro Technologies SynchroGuard solution, a software platform leveraging a micro-service, event-driven architecture running on a Kubernetes cluster. The software platform main modules (services) are highlighted in Fig. 6. A Phasor Data Concentrator module collects and time-aligns D-PMU data from the field. A Topology processor module updates the grid model based on the field measurements or other information (e.g., switches status). A State Estimation module estimates nodal voltages as well as current/power flows in every substation. A Fault location module detects, classify and locates faults in the monitored grid. A PQ monitoring module calculates PQ indicators, detects and classifies PQ events with the possibility to identify the root cause. Data is shared between the various modules using a high-speed data bus. A time-series database guarantees long-term storage of D-PMU measurement and derived quantities. Integration with 3rd party SCADA systems is enabled by a virtual SCADA gateway (integration with EPFL SCADA is under development).

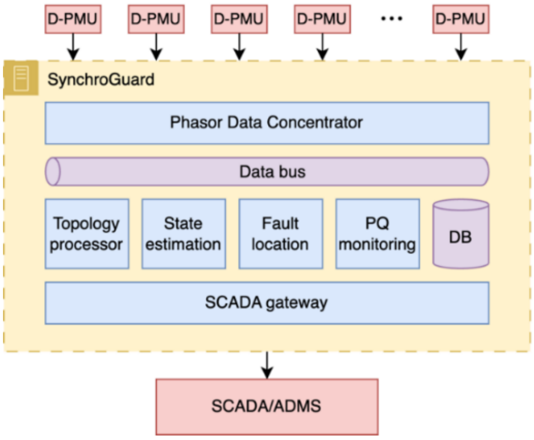

Fig. 6 – D-PMU data platform architecture

4. D-PMU use cases in EPFL campus grid

This section provides real examples of how the systems has been utilized by EPFL grid operator to improve grid operations and optimize grid investments.

4.1. Grid observability for asset monitoring

Leveraging the state estimation module, the system provides a real-time picture of the grid operating conditions including voltages at all buses, and powers/current flows in every line/transformer with 1 second resolution and <100 ms time latency. These information can be used in various grid applications, including real-time voltage monitoring and congestion management of transformers and lines. As an illustrative example, Fig. 7 presents boxplots of voltage magnitudes and line loadings estimated by the system from June 2023 to June 2024. The results highlight that voltages do not change significantly because the lines are short, and the power flows are not high enough to cause a significant voltage drop (the maximum voltage variations are within ±0.1%). Also, in both feeders, most lines exhibit low loading percentages, generally below 20%. Notably, the lines 2-31 and 31-32 show higher loading percentages peaking near or above 40% due to the large reactive power generated by the capacitive loads of experiments conducted in bus 31 and 32.

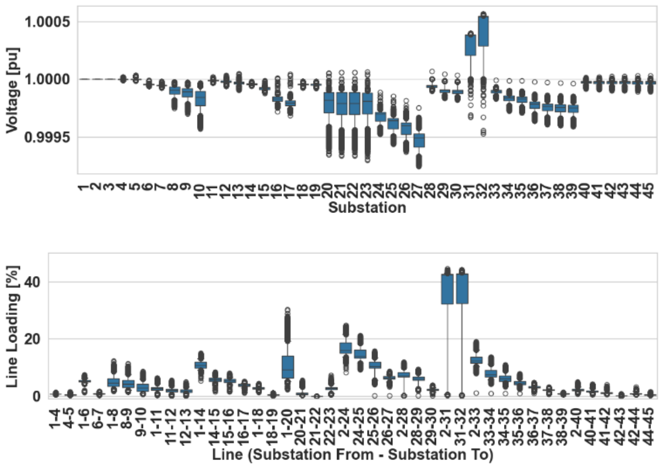

Fig. 7 – Boxplots of voltage magnitudes (top) and line loading (bottom)

4.2. Dispatching of local feeders of the grid

The deployed D-PMU monitoring infrastructure is not only used by the EPFL campus grid operator for grid operations and planning purposes, but also by EPFL researchers to develop innovative solutions for distribution grid monitoring and control. A major experiment being carried in the EPFL campus has been designed to validate the use of utility-scale BESS to increase the grid hosting capacity and security, reduce grid reinforcements, and enable the cost-effective deployment of PV and distributed storage. For this purpose, an advanced controlled framework was developed and tested, involving the deployed D-PMU based infrastructure and two algorithmic layers: (i) a day-ahead scheduling problem, and (ii) a real-time dispatch plan tracking problem. The day-ahead scheduling involves computing a dispatch plan based on forecasts of uncontrollable stochastic generation and demand, using decision variables such as active/reactive power setpoints for controllable resources (e.g., distributed batteries, demand-side management, and controllable distributed generation). The real-time dispatch tracking problem ensures adherence to the day-ahead computed plan by leveraging updated forecasts of uncontrollable stochastic generation/demand and the real-time state of controllable assets. Furthermore, by using optimal power flow (OPF)-based controls, this problem is responsible for satisfying grid operational constraints, including branch power/ampacity limits and nodal voltage constraints.

A critical component for effective real-time OPF control is represented by the availability of a situational awareness system that informs the controller of the grid's current state [7]. In fact, without such a grid situational aware system, the real-time dispatch tracking problem would be myopic regarding the grid state and unable to guarantee to operate the grid within its design bounds. In this regard, the D-PMU based situational awareness system at the EPFL campus has been successfully utilized to dispatch a portion of the EPFL medium-voltage power grid through the coordinated control of electric vehicles and batteries [8], [9].

4.3. *Fault location & Root cause analysis*

By leveraging D-PMU time-synchronized measurements, fault location and root cause analysis can be highly enhanced compared to conventional relaying approaches. An interesting case of how this can be applied to real case scenarios is represented by the cascading fault event that took place at EPFL on the 10th of January 2022. The D-PMU measurements collected during this disruptive event, not only allowed a prompt location of the various faults, but also to reconstruct the sequence of events and identify the root cause.

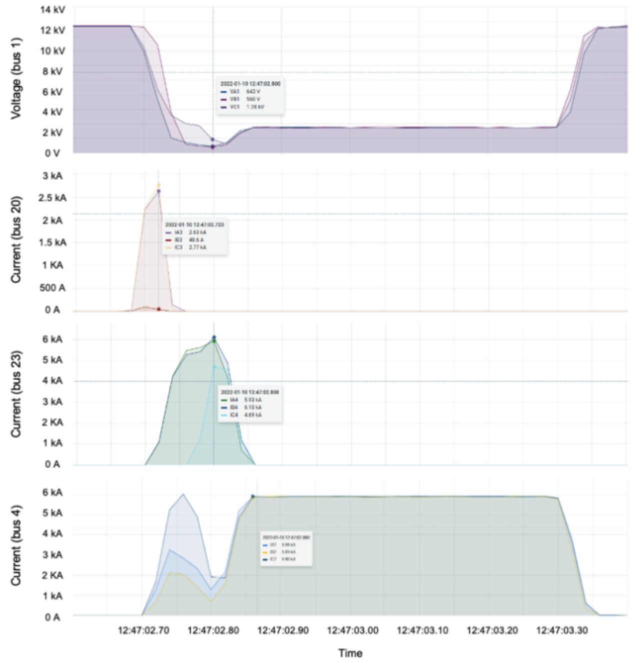

Fig. 8 – Measured voltages and currents during the cascading fault event at EPFL on the 10th of January 2022.

As shown in Fig. 8, first a fault is triggered by a heat-pump connected in bus 20 which was improperly commissioned. Then, an overvoltage caused by the tripping of the breaker, generates a cascading fault at bus 23, which is promptly cleared, and at bus 4, which lasts longer (around 600 ms) due to an old electromechanical relay that was replaced after this event.

Thanks to the precise reconstruction of this sequence of events, EPFL could assign the various responsibilities of the disaster and recover the entire value of the damaged grid assets.

5. Conclusions

According to the author best knowledge, this paper presented, for the first time, the full deployment of a real-time situational awareness system based on D-PMUs in a university campus medium voltage grid. The article first presented the technical solutions adopted to deploy such a system, then it highlighted some of the enabled use-cases, including asset monitoring, fault location, and dispatching of local feeders. This paper can serve as a solid base for other private grid operators interested in deploying D-PMUs in their electrical infrastructure, as many of the presented technical solutions can be replicated elsewhere. On the other hand, the list of presented use cases is definitely non exhaustive, as many other applications, specifically focusing on private grid operators' specific needs, could be developed, leveraging the availability of high quality D-PMU measurements.

6. References

[1] NASPI, "Synchronized Measurements and their Applications in Distribution Systems: An Update" (2020)

[2] A. von Meier et al., "Precision Micro-Synchrophasors for Distribution Systems: A Summary of Applications," IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 2926–2936, Nov. 2017

[3] D. Echternacht et al., "Smart Area Aachen - in field test of meter placement and state estimation algorithms for distribution grids," in 2015 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT LATAM), Oct. 2015, pp. 435–439.

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

[5] IEEE 1588: "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems", 2019

[6] IEEE C37.118.2: "IEEE Standard for Synchrophasor Data Transfer for Power Systems", 2011

[7] R. Gupta et al., "Reliable Dispatch of Active Distribution Networks via a Two-Layer Grid-Aware Model Predictive Control: Theory and Experimental Validation," IEEE Open Access Journal of Power and Energy, vol. 9, pp. 465–478, 2022.

[8] R. Gupta et al., "Grid-Aware Distributed Model Predictive Control of Heterogeneous Resources in a Distribution Network: Theory and Experimental Validation," IEEE Transactions on Energy Conversion, vol. 36, no. 2, pp. 1392–1402, Jun. 2021.

[9] R. K. Gupta et al., "Grid-aware Scheduling and Control of Electric Vehicle Charging Stations for Dispatching Active Distribution Networks. Part-I: Day-ahead and Numerical Validation," Apr. 19, 2024.