REVIEW OF MICRO PHASOR MEASUREMENT UNITS FROM THE PERSPECTIVE OF THE CONSUMER

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Abstract - *The infrastructure of the power grid has seen a significant change in the last few years, moving from a model of centralized power generation to one that is characterized by distributed generation from multiple small power plants that largely use renewable energy sources. As a result, new protection strategies are required for evolving distribution systems. These strategies must make use of cutting-edge protection devices and sensors, such as digital relays, phasor measurement units (PMUs), smart reclosers, and line sensors. In order to better understand prosumer applications, this article explores the use of PMUs in smart distribution grids.*

Key Words: *PMU; Prosumer; Islanding detection; Fault location.*

1. INTRODUCTION

Micro Phasor Measurement Units (μPMUs) are now essential parts of contemporary power grids due to developments in power system monitoring and control technology in recent years. By providing high-resolution, real-time measurements of voltage and current phasors at various grid sites, these small devices help utilities and operators improve the stability, dependability, and efficiency of the grid. Explaining PMUs from the consumer's point of view is crucial as scholars and professionals continue to explore the uses and advantages of these devices. The increasing penetration of distributed renewable generation has introduced significant uncertainties and randomness to the power distribution network operation [1]. The purpose of this study is to present a thorough overview of PMUs, emphasizing their function, role, and effects on consumers within the power grid ecosystem. Stakeholders can comprehend the impact of μPMUs on grid performance, resilience, and ultimately, the quality of service provided to end users, by gaining an understanding of them from the perspective of the consumer [2].

The paper begins by elucidating the fundamental principles behind PMUs and their pivotal role in enhancing the observability and stability of electric grids. It then delves into the architecture, functionality, and deployment considerations of PMUs, highlighting their ability to provide synchronized phasor measurements in real-time. Furthermore, the paper discusses the applications of PMUs in various domains, including wide-area monitoring, control, and protection, elucidating their transformative impact on grid operations. A mathematical tool for characterizing the waveform is the phasor. Synchrophasors are measurements made by a PMU of the waveform's amplitude and phase angle in relation to a GPS-synchronized signal [3]. To determine the transmission grid's operational condition, the synchrophasors, which were computed on the various grid buses, are correlated with one another (figure 1).

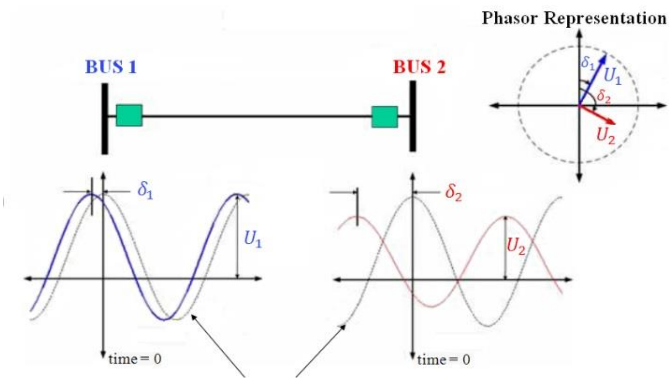

Figure 1 : Combination of phasors from two grid bus

Since 1985, PMU data with a set of voltage and current measurements have been utilized in state estimation (the process of predicting the condition of the grid on the basis of available measurements). Decentralized design and distributed computing at the substation level were used to develop this system, which was then divided into multiple sections (figure 2). Based on the state of the boundary node, the system coordinates the differences between neighboring systems to produce a uniform outcome. Each system completes its estimate separately. GPS-synchronized measurements enable the procedure to be distributed [4]. Monitoring the condition of a sizable chunk of the electrical grid is one of the primary uses for PMU data. Numerous utilities have created internal technologies to track the dynamics of the grid in real time and to trigger warnings that anticipate anomalous events in the system following a number of cascading failures in the eastern and western interconnectivity of the United States.

2. The Role of the PMU in the Actual Scenario

Phasor Measurement Units (PMUs), which offer real-time synchrophasor measurements of voltage and current throughout the grid, have grown to be essential components in contemporary power systems. Monitoring, control, and protection of the grid have been completely transformed by their ability to accurately measure the phase angle and magnitude of electrical quantities. In this study, we explore the theory underlying PMUs and clarify their use in real-world grid scenarios, emphasizing their importance in improving system efficiency, stability, and dependability.

In modern electrical grids, distribution systems are managed through specially designed Distribution Management Systems (DMS) that apply control strategiesusing knowledge of grid states. The Distribution SystemState Estimation (DSSE) in a microgrid environment mustbe very sensitive to ensure correct communication between the different components; therefore it is necessary to collect data quickly, reliably and safely to perform correct actions downstream through the use of PMUs.

One such instance is the RT Dynamic Phasor Monitoring System (RTDMS) from Electric Power Group, which is a synchrophasor software program designed to give operators wide-area situational awareness in real time. In addition to monitoring phase angle differences, voltage and frequency stability, and tiny signal stability, it may also set off warnings for anomalous system situations.

PMUs are also used in electrical systems to solve vexing issues related to the protection of transmission lines that have multi-terminal line compensation, Flexible Alternating Current Transmission System (FACTS), or series installed [1, 5]. The availability of data synchronized with the Global Positioning System (GPS) and increasingly efficient communication networks enable the creation of precise differential relays for the protection of transmission lines, thereby improving the protection performance of the line by phasor measurements from the ends of the line [6]. Traditional systems simulate differential systems with phase comparisons.

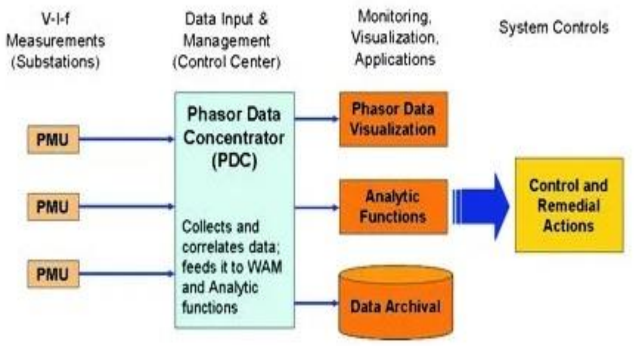

Figure 2: Block diagram of phasor measurement unit in the distribution grid.

The ability of the electrical power system to sustain steady voltages across all system buses in the wake of a disruption in the power supplied or absorbed after the initial operational condition is known as voltage stability. Voltage stability indices are determined using the PMU data to determine the maximum amount of power that can be delivered to the loads. Using Jacobian matrix-based or system variable-based methods, this data aids in the real-time prediction of power system instability and improved control actions to prevent cascading outages.

Inadequately damped rotor angle oscillations within a power system can result in instability and potential blackouts. These oscillations within the electrical grid are typically categorized into two types: forced oscillations and electromechanical oscillations. Forced oscillations commonly stem from external events rather than inherent system properties, whereas electromechanical oscillations encompass internal plant modes, local plant mode oscillations, inter area mode oscillations, and control mode actions. If left unchecked, these oscillations can precipitate generator failures. Phasor Measurement Unit (PMU) data proves invaluable in identifying undammed electromechanical oscillations, thanks to its high sampling rate, and in discerning local control modes within Flexible AC Transmission System (FACTS) stabilizer systems.

Lastly, the examination of angular oscillations and its evolution is made possible by the application of PMUs [7]. In reality, real-time data from PMUs can make it more accurate to identify whether an electrical system is approaching instability and, if so, to anticipate when to disconnect the grid in the best possible way to minimize the isolated grid portion and prevent a blackout.

With the use of PMUs, it is possible to examine the electrical system's frequency in addition to voltage and current. In fact, a generation loss can be connected to the magnitude of the frequency deviation [8]. Frequency is a crucial indicator of the equilibrium of the load resources. Even in the aftermath of a disruption, it is possible to assess the area of the electrical system and uncover lost generation thanks to the data tracked by PMUs.

A great example of frequency monitoring over large grids is the Frequency monitoring NETwork (FNET), created by Virginia Tech using frequency disturbance recorder (FDR) data from the three interconnects in North America. It can be more accurate to identify the ends of the island, assess whether grid separation is necessary to prevent a blackout, and assess whether a power system is approaching an unstable condition with the use of real-time data from PMUs.

PMUs have recently been employed in applications based on Rate of Change of Frequency (ROCOF) for three reasons:

- as a result of their ability to undertake quick and highly reactive measurements (signaling at tens of frames per second with uncertainty of a hundredth of Hz/s in stationary settings and a few units of Hz/s in disturbed conditions) [9].

- Because these PMUs make it possible to build a distributed measurement infrastructure that enables synchronous monitoring of the different nodes to estimate the state of the network.
- At last, we are able to duplicate the outcomes because of its system [10].

Based on the results, the PMUs are a good substitute for the load shedding relays in use today since they provide real-time, precise monitoring of both the fundamental frequency and its derivative. The ROC of index's predictive capability enables a more prompt and efficient response to transient occurrences, preventing system blackouts and promoting load recovery [11].

3. Features of the PMU available on the market

The features of Phasor Measurement Units (PMUs) available on the market can vary depending on the specific manufacturer and model. However, there are several common features that are typically found in PMUs:

High Sampling Rate: PMUs are known for their ability to capture synchronized measurements of voltage and current phasors at very high sampling rates, typically ranging from 1 kHz to several kHz. This high sampling rate enables the accurate capture of fast-changing grid dynamics.

GPS Synchronization: PMUs are equipped with GPS receivers for precise time synchronization. This ensures that measurements from multiple PMUs across the grid are accurately timestamped and synchronized, enabling coherent system-wide analysis.

Wide-Area Coverage: PMUs are designed to provide wide-area coverage of the power grid, allowing for the monitoring of electrical quantities at various locations, from transmission substations to distribution networks. This wide-area coverage enhances grid visibility and enables comprehensive system monitoring.

Real-Time Data Transmission: PMUs are capable of transmitting measurement data in real time to control centers or data repositories for analysis and visualization. Real-time data transmission enables grid operators to make timely decisions and respond swiftly to grid disturbances.

Accuracy and Precision: PMUs are engineered to provide highly accurate and precise measurements of voltage and current phasors. This ensures reliable data for grid analysis, control, and protection applications.

Compatibility and Interoperability: PMUs are designed to be compatible with existing grid infrastructure and communication protocols. Interoperability with other monitoring and control devices allows for seamless integration into grid management systems.

Data Processing and Analysis: Many PMUs are equipped with onboard data processing capabilities, including algorithms for phasor estimation, frequency tracking, and disturbance detection. Some PMUs also support advanced analytics and visualization tools for in-depth grid analysis.

Cyber security Measures: Given the critical nature of grid monitoring and control, PMUs often incorporate cyber security measures to protect against unauthorized access and data tampering. These measures may include encryption, authentication, and secure communication protocols.

Scalability: PMUs are designed to be scalable, allowing for the deployment of multiple units across the grid to meet specific monitoring and control requirements. Scalability ensures flexibility in adapting to evolving grid needs and expansion plans.

The PMU was initially developed by Power Sensors Limited (PSL) with the University of California and Lawrence Berkeley National Lab (LBNL) in 2015. The purpose was to address the need for tools to better observe, understand and manage the grid at the distribution scale .This �PMU was initially used for diagnostic applications and control applications of the distribution grid. A commercial �PMU was developed in which the main function of the device was to calculate voltage, frequency, and phase at the household voltage level. This unit operates at a consumer level voltage and has the capability to capture only one phase

In China, the installation of PMUs on the electricity grid has already started since 1995 and nowadays they have installed PMUs on all substations of 500kV and above, some important substations of 220kV and power plants of100MW and above for a total of over 3000 PMUs.

In America since 2007 PMUs have been introduced by transmission operators, thanks to the North American Syncrophasor Initiative 420 PMUs have been installed in North-East, 400 PMUs in Midwest, 150 PMUs in South, 120 PMUs in Texas, 500 PMUs in Western Electricity Coordinating Council (WECC) and at least 300 PMUs in Mexico [2].The results of this initiative have already demonstrated that these components are essential for controlling the power grid.

In Brazil, a project began in 2000 for the creation of a system for measuring the power grid through synchro phasors called SPMS.

In Russia, the presence of a very extensive network has allowed the installation of PMUs since 2005, and currently 45 PMUs are installed in the main plants and substations of the three models: Smart WAMS (RTSoft, Russia), Regina (ANIGER, Ukraine) and Power log (AENEA, Germany) .

In Europe in recent years, PMUs have been developed whose measurements are exchanged between Transmission System Operators (TSO) for the calibration of the dynamic models of the system: MIGRATE project (Massive InteGRATion of power Electronic devices)

The global market for syncrophasor is valued at 151.3 million US dollars in 2020 and is expected to reach 708.7 million US dollars by the end of 2026, growing at a CAGR of 24.4% during 2021-2026. In the next five years, the global consumption volume of Synchrophasor will show a further upward trend, the expected consumption volume in 2022 will be 4521 units. Particularly, in some emerging countries, such as Indiaand Brazil among others, the installation capacity of the synchrophasor will exhibit an upward growth rate in the future, due to the national policy and the advantage of PMUs over to SCADA [12].

The main manufacturers of PMUs are ABB, GE Grid Solutions, and Siemens Energy and the global average sales price will be around $74596/ Unit in 2022. The market is not only influenced by the price but also by product performance. Other Prominent Vendors in the market are BEIJING SIFANG AUTOMATION, Comverge (part of Itron), Double Engineering Company, Electric Power Group, ERL Phase Power Technologies, Green Mountain Power, Intel, Macro dyne, Power Sensors, Power World, Quanta Technology, and Siemens.

PMUs can be distinguished into two main models, as defined in the IEEE standard, and namely-class and P-class. P-class PMUs are optimized for accuracy in a dynamic environment, while M-class PMUs remain accurate over a wide range of frequencies [13].

The PMU measurement accuracy estimation system is the Total Vector Error (TVE) as a percentage. TVE is a function of both magnitude error and phase angle error. In steady-state conditions, the maximum allowed TVE is 1%. Based on the measurement and qualification standards, PMUs are subject to various tests, in particular:

- Measurement bandwidth is evaluated by applying sine wave amplitude and phase modulation to a set of balanced three-phase voltage and current waveforms. The maximum TVE in the measurement bandwidth test range should not exceed 3%. Class PPMUs shall be rated in the range 0.1 Hz to less than 2 Hz up to Fs/10 (5 Hz, where Fs is the PM signaling frequency, in this case50 frames per second); Class M PMUs are rated at the lower of 5 Hz and Fs/5 (10Hz).

- The linear ramp in the system frequency is applied as balanced three-phase input signals. For synchrophasor estimation, to be compliant, a class PMU must maintain 1% TVE over a range of ±2 Hz from the nominal frequency, and a class M PMU must maintain 1% TVE over therange±5Hz.

- Phase changes in phase angle and magnitude to determine the response time, delay time, and overshoot in the measurement.

4. The PMU in low voltage power systems: the Prosumers

Modern grids are increasingly becoming microgrids with inter connected loads and distributed energy resources acting as a single controllable entity with respect to the grid [14]. The operating modes of these microgrids can be essentially three: grid-connected, islanded, or mixed-mode operation [15]. Grid-connected mode is the main operating mode; it can be divided into two sub categories:

- Passive mode: energy is taken from the grid and distributed to local loads. For the grid, such behavior is seen as a consumer.

- Active mode: the energy produced by Renewable Energy Resources (RES) feeds all the local loads and part of the energy feeds the grid. For the grid, such behavior is seen as a producer.

The island mode is a special condition of such microgrids. In this situation, the internal energy generation of the microgrids feeds the local loads and there is no connection to the grid. This operation is useful for increasing the reliability and resilience of the system by powering thecritical loads when there are interruptions on the network due to faults [16].

The design, construction and, operation of such emerging distribution systems requires the introduction into electrical grids of new devices with digital relays combined with time-synchronized phasor measurement systems that represent both the amplitude and phase angle of sine waves and they are time-synced to be exact. PMU measurements allow you to record the electrical quantities in the various nodes of the grid allow in real time management and offline engineering analysis to improve the reliability and efficiency of the grid and reduce operating costs [17].

Micro PMUs with very accurate results can be created more economically, (an order of magnitude), than current commercial PMUs allowing the installation of many more PMUs and providing much higher resolution of the distribution grid. Compared to transmission systems, distribution systems have short line lengths and limited power flows, hence very small phase differences between the voltage phasor of different buses. PMUs can play an important role in the monitoring, control and protection of distribution systems due to the dynamic load changing due to Distributed Energy Resources (DER) [18], phase angle also plays an important role in the analysis of distribution systems.

A. *Fault location*

Fault finding in the Distribution Grid (DG) has been performed with analysis based solely on voltage [15], with fault current based methods, impedance-based methods [19], traveling wave-based methods and signal injection techniques, but they all have limitations in networks withthe presence of RES [20]. PMUs can be very useful forlocating and detecting faults in the distribution system due to their high speed and time-synchronized phasor measurements. The method proposed in [21], for example, correctly identifies the faulted line regard less of the connection of the neutral, the type of fault, the fault impedance, and the position of the fault along the line.

B. *Islanding detection*

Two types of islands can occur within a microgrid: intentional and unintentional. The first is required by the DSO and is necessary for grid maintenance. The second occurs due to fault conditions, in this case, due to management safety. In microgrids it, therefore, becomes important to be able to identify the island state of the grid [22]. The methods for detecting the island in a distributed system with RES can be classified into three categories: active methods which include the active frequency drift method and the phase shift method, passive methods which include over/under voltage, over/under frequency, and communication based methods such as power line signaling based scheme [23].

C. *Load shedding scheme*

A major concern related to DG is the impact on system stability due to the interaction between generators and load characteristics. Furthermore, load dynamics are also changing due to the increase in the number of electric vehicles and inverter-based loads. Therefore, accurate load modeling is required for system analysis and operations. In the management of micro-grids it is important to have a generation adaptive load, therefore one of the applications of PMU is for the implementation of a load shedding scheme. This methodology allows maintaining the stability of the feeding system. New load shedding techniques are based on frequency and rate of frequency change leading to a better understanding and estimation of load to be shed to improve accuracy. To this end, PMUs are used to measure real-time synchronized phasor data to improve system event and disturbance analysis.

D. *Power Quality monitoring*

Although the PMU provides positive sequence voltage phasor data at a rate of 50/60 samples per second, while the power quality (PQ) monitor provides instantaneous voltage data at a much higher rate on the order of about ten kHz, the errors relating to voltage dips are contained in the order of 5%. Thus, PMU provides relatively accurate results in the minimum positive- sequence voltage magnitude information.

The increasing penetration of solid-state power-transforming devices such as inverters and rectifiers into the distribution system leads to power quality problems such as harmonics [24]. These harmonics must be identified correctly to maintain power quality for residential and industrial customers. One technique for measuring harmonic synchrophasors in a distribution system involves the use of high-precision GPS receivers and general purpose acquisition hard ware for measurement purposes.

6. Advantages in adopting PMU in low voltage systems

In low voltage distribution systems, the relationships between voltage quantities, angles, and power flows are less approximate than in transmission lines; furthermore, in distribution systems the phase unbalance cannot be neglected, complicating the study of power flows [25]. As explained in the previous paragraphs, PMUs have been adopted for a long time in the supervision and protection of transmission systems; in particular on wide area monitoring systems (WAMS), however, they do not find a great application in distribution systems. Furthermore, the use of synchrophasors in distribution grids in valves further difficulties related to:

- Small angles of difference on the distribution lines of the order of tenths of a degree;
- The presence of noise in the measurements of the distribution circuits, linked both to the randomness of the loads and to the presence of a greater harmonic spectrum caused by the great diffusion of electronic converters;
- The costs of the PMUs if referred to transmission systems are reduced thanks to the size of the system, while in distribution systems due to the proximity of the nodes they increase;
- The adoption of a low-cost, very efficient and reliable monitored data communication system.

In distribution systems, therefore, different applications have been developed called D-PMUs or micro PMUs which have better performance in terms of resolution and measurement precision and a lower construction cost than the PMUs used in transmission systems [25]. Furthermore, the greater interest in the analysis of the distribution system with the increasing penetration of distributed production from RES and the opening of the liberalized energy markets contribute to the study and research of PMUs.

7. Conclusion

PMU applications still face many challenges in distribution systems, such as in adequate phasor measurement accuracy and the lack of a communication network infrastructure that can support a large number of sensors and actuators with different technologies, but also advanced and persistent cyber threats facing critical infrastructures such as the intelligent grid are also exponentially increasing and require a sophisticated defense strategy.

In addition to RES and electrical energy storage, active loads such as demand-responsive loads and electric vehicles will also increase. All these factors introduce new challenges in the operation, planning, protection and control of distribution grids.

The communication systems used and the PMU calculation algorithm will have to face the growing challenges of modern networks; therefore they will have to be increasingly robust and reliable.

This article presents are view of the phasor unit of measurement applied to distribution grids that will radically change in this decade. Above all attention was given to its working principle and the various applications in this context. For detailed analysis, the appropriate references have been cited.

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