21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

Micro Phasor Measurement Units: a Review from the Prosumer Point of View

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Abstract. In recent years, power grid infrastructure has moved from a centralized power generation model to a paradigm in which generation capacity is distributed across an increasing number of small power plants that rely on renewable energy sources. Systems for emerging distribution systems need a very new protection paradigm, architecture and philosophy making use of new protection devices and sensors such as digital relays, phasor measurement units (PMUs), smart reclosers and line sensors. This article examines the application of PMUs in smart distribution grids and from the point of view of prosumers.

Key words. PMU; Prosumer; Islanding detection; Fault location; Power quality monitoring.

1. Introduction

An electrical power system is generally very complex and it is necessary to continuously monitor/protect its elements in order to avoid serious contingencies. The traditional system for Supervisory Control based monitoring And Data Acquisition (SCADA) is unable to acquire system dynamics due to its low resolution, unsynchronized measurements of system parameters and incomplete information on system behavior [1], therefore one of the first uses of PMUs was to expand the measurements of conventional SCADA systems obtaining estimates of values every 4-5 sec. for parameters such as frequency, phase angle and amplitude ensuring that system parameters were always within limits [2, 3].

Phasor measurement units (PMUs) are devices used to detect electrical waveforms in order to analyze an electrical grid and identify potential problems. The phasor is a mathematical method of describing the waveform. A PMU measures the amplitude and phase angle of the waveform with respect to a signal synchronized by GPS: these measurements are called synchrophasors The synchrophasors, calculated on the different grid bus, are then correlated with each other to identify the operating status of the trasmission grid (figure 1).

PMU data have been used in state estimation (process of estimating the state of the grid on the basis of available measurements) since 1985 with a set of voltage and current measurements. This system was created through decentralized architecture with distributed computing at the substation level, dividing the system into several parts (figure 2). Each system performs its estimate independently and the system coordinates the differences between adjacent systems based on the state of the boundary node to obtain a uniform result. Measurements synchronized with GPS allow you to distribute the process [4]. One of the main applications of PMU data is the monitoring of the state of a large portion of the electricity grid. After several cascading outages in the eastern and western interconnection of the United States, many utilities have developed internal tools to monitor the dynamics of the grid in real time and also activate alarms that predict abnormal conditions of the system.

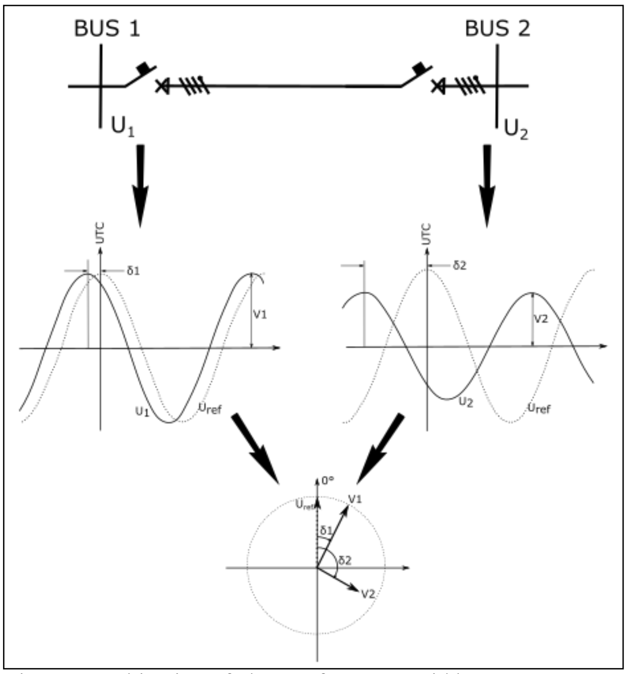

Fig. 1. Combination of phasors from two grid bus.

2. The role of the PMU in the actual scenario

In modern electrical grids, distribution systems are managed through specially designed Distribution Management Systems (DMS) that apply control strategies using knowledge of grid states. The Distribution System State Estimation (DSSE) in a microgrid environment must be 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 example is Electric Power Group's RT Dynamic phasor Monitoring System (RTDMS), a synchrophasor software application to provide operators with real-time wide area situational awareness. It can provide small signal stability monitoring, voltage and frequency stability monitoring, phase angle differences, and can also trigger alarms on abnormal system conditions [3].

Another use of PMUs in electrical systems is in the solution of annoying problems on the protection of transmission lines equipped with series, Flexible Alternating Current Transmission System (FACTS) or multi-terminal line compensation [1, 5]. Traditional systems simulate differential systems with phase comparisons, through the use of PMUs the availability of data synchronized with the Global Positioning System (GPS) and increasingly performing communication networks allow the creation of precise differential relays for the protection of transmission lines, improving thus the protection performance of the line by phasor measurements from the ends of the line [6].

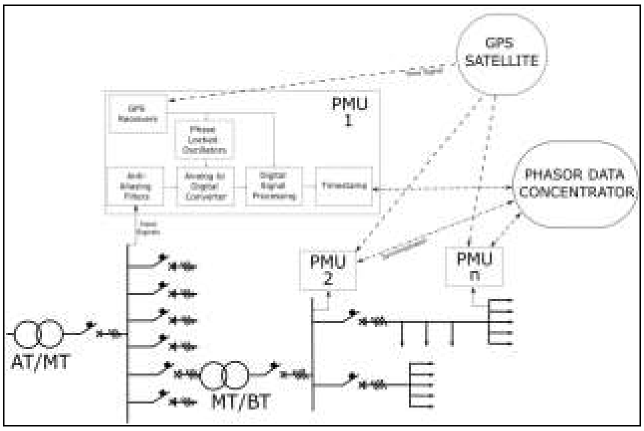

Fig. 2. Block diagram of phasor measurement unit in the distribution grid.

Furthermore, the use of PMUs in the protections makes it possible to improve the adaptation of the changing conditions of the system dictated by the load curve through real-time measurements. These adaptive relays allow to modify their characteristics to adapt to the conditions of the system by estimating the current state of the grid unlike traditional relays in highly interconnected grids [2].

Voltage stability is the ability of the electrical power system to maintain constant voltages on all the system buses after being subjected to a disturbance of the supplied and/or absorbed power subsequent to the initial operating condition. To know how much power can be supplied to the loads, voltage stability indices are estimated using the PMU data. Such data helps to predict power system instability in real time to perform better control actions in order to avoid cascading outages through Jacobian matrix based or system variable based algorithms.

Poorly damped rotor angle oscillations of generators in a power system can lead to unstable conditions and blackouts. The oscillations in the electrical grid can be divided into two categories, namely forced oscillations and electromechanical oscillations. Forced oscillations are usually caused by an external event rather than a property of the system itself, while electromechanical oscillations are internal plant mode, local plant mode oscillations, interarea mode oscillations, actions of the control mode which if not damped can lead to generator failure. PMU data is very useful for detecting undamped electromechanical oscillations due to its high sampling rate and realizing local control modes of FACTS stabilizer systems.

Finally, the use of PMUs also allows for the analysis of angular oscillations, allowing for the analysis of its evolution [7]. In fact, with real-time data from the PMUs, it can be more precise to determine if an electrical system is heading towards an unstable system and therefore to predict, if necessary, an optimal disconnection of the grid to avoid a blackout by minimizing the isolated grid portion.

In addition to the voltage and current through the use of the PMUs it is also possible to analyze the frequency of the electrical system. The frequency is a key indicator of the balance of the load resources, in fact a generation loss can be correlated to the size of the frequency deviation [8]. The data monitored with the PMUs make it possible to reveal the lost generation and analyze the area of the electricity system even in the post-disturbance period. A great example of frequency monitoring over extended grids is the Frequency monitoring NETwork (FNET) built by Virginia tech using Frequency Disturbance Recorder (FDR) data from the three interconnects in North America.

With the help of real-time data provided by PMUs, it can be more accurate to determine whether a power system is heading towards an unstable state, whether or not grid separation is required to avoid a blackout, and to define the ends of the island.

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

- thanks to their characteristic of performing fast and highly reactive measurements (signaling speed of tens of frames per second and uncertainty in stationary conditions of the order of a hundredth of Hz/s and some units of Hz/s in disturbed conditions [9]);
- thanks to the fact that these PMUs allow the creation of a distributed measurement infrastructure that allows the estimation of the state of the network through the synchronous monitoring of the various nodes;
- finally thanks to its system it allows us to replicate the results [10].

Based on the results obtained, the PMUs prove to be valid alternatives to the current loadshedding relays as they allow an accurate and timely monitoring of the fundamental frequency and its derivative for the first time. The predictive ability of the ROCOF index allows for a more effective and timely response to transient events, thus avoiding the occurrence of system blackouts and leading to load recovery [11].

3. Features of the PMU available on the market

In the mid-1970s the American Electric Power begins research on digital relays thanks to Professor James Thorp of Cornell University. The first prototype of modern PMU technologies in the world was born at Virginia Tech in the early 1980s [2]. Ever since then, Professor Thorp has been a stalwart in computer relaying research and in PMU research. Even to this day he contributes to the research at Virginia Tech, where he became a Department Head of Electrical and Computer Engineering Department in about 2003.

Around 1990 work was seriously begun to create a stand-alone PMU capable of measuring positive-sequence voltages and currents using global positioning system (GPS) satellite transmission to synchronize the measurements across the power system.

The μPMU 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 μPMU was initially used for diagnostic applications and control applications of the distribution grid. A commercial μPMU 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 of 100MW 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 synchrophasors 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 Powerlog (AENEA, Germany) [2].

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 India and 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), Doble Engineering Company, Electric Power Group, ERLPhase Power Technologies, Green Mountain Power, Intel, Macrodyne, Power Sensors, PowerWorld, Quanta Technology , Schneider Electric, and Siemens [12].

PMUs can be distinguished into two main models, as defined in the IEEE standard, namely M-class and P-class. P-class PMUs are optimized for accuracy in a dynamic environment, while M-class PMUs remain accurate over a wider 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 sinewave 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 P PMUs 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 case 50 frames per second); Class M PMUs are rated at the lower of 5 Hz and Fs/5 (10 Hz).
- The linear ramp in the system frequency is applied as balanced three-phase input signals. For synchrophasor estimation, to be compliant, a class P 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 the range ±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 interconnected 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 [11, 15]. Grid-connected mode is the main operating mode, it can be divided into two subcategories:

- 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 the critical 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 allowing real-time management and offline engineering analysis to improve the reliability and efficiency of the grid and reduce operating costs [17].

MicroPMUs 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 phasors 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 [3].

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 with the presence of RES [20]. PMUs can be very useful for locating 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 regardless 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 a 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 to maintain 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 [11]. 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 hardware for measurement purposes.

5. 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) [19], however, they do not find a great application in distribution systems. Furthermore, the use of synchrophasors in distribution grids involves 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 microPMUs which have better performance in terms of resolution and measurement precision and a lower construction cost than the PMUs used in transmission systems [26, 27]. 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 μPMUs [26].

The use of microPMUs in distribution systems can be divided into two macro categories: diagnostic applications and control applications. The former are used by grid operators in order to know the current operating conditions and study of anomalous events in the grids, while the latter allow the creation of automated systems for specific actions in almost real-time [7].

The positioning of the PMUs in the distribution grids can be achieved by following optimization processes [28]. The optimizer can evaluate various options: the presence of passive nodes, the redundancy of the measures, a limited number of channels for each PMU, the change of grid structure and the monitoring of some nodes of the grid to evaluate the island operation or the line impedance [29, 30].

6. Conclusion

PMU applications still face many challenges in distribution systems, such as inadequate 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 cyberthreats 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 a review 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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