Phasor Measurement Units for the Distribution Grid: Necessity and Benefits

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Abstract—**High penetration levels of distributed energy resources (DER) and active loads in the distribution grid can change the traditional grid from a slower-changing radial network to a multi-source network with faster dynamics. Although overall system reliability and quality of supply can in principle be improved under this paradigm, new control and protection challenges could arise that may not be adequately addressed using the traditional approaches. The conventional control and management of the distribution grid where only voltage magnitudes are measured and utilized at the control center could undermine these new dynamics and may potentially lead to severe complications in grid operation. A system-wide dynamic analysis and control of the distribution grid therefore seems crucial for optimal system operation. This would require new phasor data, coming from Phasor Measurement Units (PMU), to be incorporated into the functions of Distribution Management System (DMS). This paper discusses the potential applications within the DMS that can benefit from PMU data.**

Index Terms—**Phasor Measurement Unit, Synchrophasor, Distributed Energy Resource, Distribution Management System, Microgrid, Smart Grid.**

I. INTRODUCTION

PHASOR Measurement Units (PMU) have been in use in the power transmission system (110kV and above) in order to provide accurate voltage phasor measurements, to be used in various control, protection, and monitoring applications. Traditionally at the distribution level (34.5kV and below), and in the absence of a widespread penetration of DER and active loads with dynamics (e.g., demand responsive loads, electric vehicles), the bus voltages are denoted by their magnitudes only, and the phase angle measurements, often due to their generally small values, have not been of great interest to the utility engineers.

However, with the projected penetration (in excess of 30% in some areas) of DER and active loads under the Smart Grid paradigm things are likely to change. New dynamics are introduced in the distribution grid, especially in the stand-alone applications of Microgrids, which did not exist before. Rotating machine based DERs, with their corresponding power angle and rotor speed, introduce additional dynamics into the grid. Non-dispatchable energy resources such as small scaled wind turbines and rooftop photovoltaic panels –if deployed in large numbers– are likely to introduce a higher level of fluctuations in the voltage, power, and perhaps even frequency in specific islanded operation modes. In addition to all this, a high penetration level of DER in the grid –dispatchable or non-dispatchable– will transform the distribution system from a traditionally radial network to one with multitude of doubly-fed lines and bidirectional flow of power. All this could introduce new challenges in planning, monitoring, control, management and protection of the distribution grid, which would require a dynamic analysis and control of the grid taking into account not just the voltage magnitudes, but the phase angles as well. This situation would therefore justify the need for measuring voltage and current phasors in the distribution grid.

Accurate phasor measurement can be achieved by deploying dedicated PMUs across the distribution grid, or utilizing the built-in phasor measurement functionality of many protective relays. The new dynamic snapshot of the system developed in this way can now be incorporated into the distribution management system (DMS) in order to provide monitoring, control, energy management and protection schemes more suitable for this new situation.

The focus of this paper is on potential applications of PMUs at the distribution level, and the benefits gained from their deployment in the grid. Some case studies are also provided on the IEEE 34-bus system to show how penetration of renewable energy resources can change the quasi-steady-state nature of the distribution grid.

II. PHASOR MEASUREMENT UNIT

Steady state sinusoidal quantities of the power system are best represented through phasors. A sinusoidal function $x(t)$ with magnitude X_m and phase angle δ can be expressed as a phasor X:

$$\begin{aligned} &x(t) = X_m \cos(\omega . t + \delta) \\ &X = X_r + j.X_i = (X_m / \sqrt{2}) \times e^{j.\delta} \end{aligned} \qquad (1)$$

The concept of synchronized phasor, also commonly referred to as synchrophasor, was then introduced as a phasor calculated from data samples using a standard time signal as the reference for the measurement [1]. A phasor measurement unit (PMU) is a device that measures the voltage and/or current waveforms at the point of connection to the grid, using synchronized sampling by means of a common time reference for all locations, commonly facilitated through the Global

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Positioning System (GPS) satellite time reference (Fig. 1). Phasor technology adopted by the PMU helps create a system-wide dynamic snapshot of the power grid. It enables wide area visibility, and allows for distributed sensing and coordinated control. This fact leads to it being considered one of the most important tools for system monitoring and situational awareness. In general, a PMU can be either a dedicated device, or an added functionality incorporated into an intelligent electronic device (IED). The data provided by the PMU are then collected at the Phasor Data Concentrator (PDC) that waits for all the measurements to arrive, sorts them and consequently aggregates them for more efficient transmission.

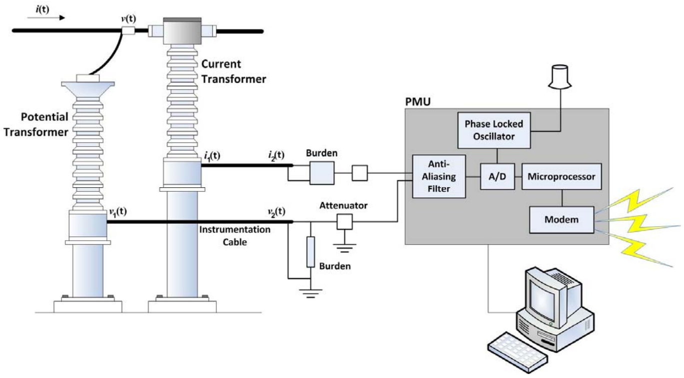

Fig. 1. Schematic diagram of a PMU connected to the power system.

For the 50Hz system, PMU is often required to have 10 or 25 samples per second, while for a 60Hz system, it is required to have 10, 12, 15, 20 or 30 samples per second [1]. A PMU can provide precision in phase angle measurement up to 1μs error (e.g., 0.021°). In general, the limiting factor for the accuracy of PMU implementations is the dynamic performance afforded by the voltage and current measurement transducers [2].

The accuracy of a PMU is often expressed in terms of Total Vector Error (TVE), which is defined as the difference between the measured values and theoretical values at the time of measurement, as shown in (2).

$$TVE = \sqrt{\frac{(X_r(t) - X_{r,meas})^2 + (X_i(t) - X_{i,meas})^2}{X_{r,meas}^2 + X_{i,meas}^2}} \tag{2}$$

III. PMU FOR DISTRIBUTION GRID

Traditionally, PMUs have been mainly utilized at the transmission level. However, with the large scale deployment of DER in the distribution system, and the forecasted penetration of active loads with faster dynamics, the picture is likely to change. Some of these aspects are briefly discussed in this section.

A. *Stability Analysis and Monitoring*

With high penetration of DER, especially if the distribution network is weak, e.g., due to deferral in capital investment, stability may become an important issue. In the presence of DER, transient stability, long-term dynamic stability, and voltage stability need to be studied [3], with frequency stability becoming a factor only at very high penetration levels [4]. Loads with fast changing dynamics, e.g., electric vehicle charging stations, may create the same complications as DER. As a result of these, the distribution system may experience fast excursions in voltage, active power, reactive power, or maybe even frequency, which would require accurate phasor measurements. These impacts are especially considerable for Microgrids that can at times be islanded from the distribution grid [5]. PMUs can improve the monitoring experience of the system operator by providing a dynamic snapshot of the system during normal as well as abnormal operation modes [6].

Furthermore, as distribution networks become more dynamic, there will be some stability events which can be monitored and analyzed using only distribution level PMUs observing into the transmission system [7].

B. *Protection*

While protection of the traditional radial distribution grid is provided by overcurrent protection devices that detect a fault and disconnect the circuit downstream, introduction of DER in the system introduces bidirectional flows of power, and possibly phase angle deviations. The latter may be addressed by using PMUs.

Another concern in protection is with regards to the standing phase angle that develops across a recloser during the reclose operation. This is an especially difficult problem with large DER penetrations that do not trip off-line gracefully as well as with loads with large quantities of spinning mass. PMUs can be used to check the phase angle and close the recloser at a time when the systems are most closely synchronized. This may also allow for quicker reclose operations, reducing the inconvenience of momentary power interruptions [8], [9].

Bidirectional flows of power would require replacing the overcurrent functionality with directional one. This is often achieved by simultaneously looking at the voltage and current waveforms. However, in an attempt to avoid installing voltage measurement devices at the LV network, some methodologies have been proposed that consider the change in the phase angle of the current waveform for detecting the fault direction [10]. At the distribution level, the shift in the phase angle is in the range of microseconds, and therefore accurate phase angle measurement would be necessary.

C. *State Estimation*

In general, PMUs have a great effect on state estimation as they allow the direct measurement of the state vector, which is made up of bus voltages' magnitudes and power angles, thereby significantly reducing the computational time of the estimator while increasing its accuracy [11]. While distribution state estimation is not widely implemented at this time, it can bring several benefits to the system, e.g., parameter estimation for verifying the status of capacitors and regulators and estimating conductor sizes.

On the other hand, PMU-enabled dynamic states estimation has been proposed that predict the state of the system using the differential equations governing the system behavior [12].

These can be applied to small scale system such as Microgrids, industrial parks or electric shipboard power systems.

D. Voltage/Var/Watt Control

As opposed to the traditional distribution grid, where the active and reactive power balance equations have always been described based on the quasi-steady-state values, the modern grid equipped with DER and active loads may require a more dynamic approach for VVWC. This would especially be crucial in small scale power systems such as Microgrids and electric shipboard power systems where phase angle cannot be ignored without loss of precision. A dynamic modeling of the problem requires use of instantaneous active and reactive power quantities, defined based on the instantaneous values of the currents and voltages.

E. Fault Location

Fault locating algorithms work based off of traveling wave phenomena theory; and as such they do not use the power angle information provided by a PMU, but instead the precise time-stamped data afforded by the PMU's clock [13]. The added-value offered by the PMU here is accuracy. Whereas the few *km* tolerance of other methods may be sufficient for protective relays it is not as useful to crew who must locate and repair the line [13]. This precise fault location capability is also good for automatic restoration programs to pinpoint the location that needs to be sectionalized [2]. PMUs also help with fault detection on parallel lines [7], which are likely to become more common in the distribution grid.

F. Loads with Fast Dynamics

Electric vehicles are forecasted to be deployed in large numbers in the transportation fleet of future. While currently these vehicles only use the power grid to charge their batteries, it is envisioned that they may also be used as mobile resources of energy storage to be injected into the grid at the time of need. This service, often referred to as vehicle-to-grid (V2G), can in principle provide peak load shaving, smoothing generation from non-dispatchable renewable energy resources and act as a reserve against unexpected outages [14]. The V2G application can be implemented for groups of vehicles parked at a charging station, or a large number of individual vehicles connected to their corresponding charging poles. However, some researchers argue using EV in day-ahead generation scheduling or peak shaving is not nearly as beneficial as using the technology to provide ancillary services, such as providing spinning reserves and voltage and frequency regulation [15]-[17]. Traditionally, due to relatively slow V2G communication and activation system, EVs are not expected to participate in primary reserve service; however, with a local fast responding frequency measuring device such as a PMU such capability would be attainable [15].

G. Summary

Capital investment may be the biggest impediment to large scale deployment of PMUs in the distribution grid, both for the PMU itself and the required communication infrastructure. The benefits gained in terms of reliability, security and operational efficiency of the grid has to justify the cost of installing PMUs. This requires a case by case analysis and to a large extent depends on the penetration level of DER and active loads in the system of interest. When a system can be comfortably modeled and analyzed in the quasi-steady-state condition, the use of PMUs may be hard to justify; however, as the penetration level increases, the grid undergoes a major change and becomes a dynamic system that needs dynamic data for optimal operation.

IV. REQUIRED SPECIFICATIONS FOR DISTRIBUTION PMU

The characteristics of the PMUs to be used at the distribution level deserve additional attention. Distribution systems have characteristics that are different from those of the transmission systems. Shorter line lengths, smaller power angles and higher harmonic levels are some of the differentiating factors that make phasor measurements at the distribution grid more vulnerable to errors, and create additional challenges. It is therefore necessary to revisit the typical measurement error of the PMU and verify it for the type of application it is being used for. Different applications have different vulnerability levels towards measurement errors, which need to be evaluated prior to the usage of PMU measurements.

PMUs at the distribution level must have lower TVE values and most importantly, phase uncertainties because of smaller line lengths and more limited power flows compared to the transmission network. To counteract this, advanced signal processing techniques can be employed. Carta *et al* [2] proposed the estimation of the phasor quantities through a Discrete Fourier Transformer (DFT) with both fixed and variable width sampling windows. Borghetti *et al* [5] proposed a method based on DFT tone identification fed through time-domain analysis. These methodologies are also designed to be robust to input distortions caused by harmonics, although voltage and current transducers are a more significant source of error for harmonic phasors due to their non-ideal frequency response [18].

To address issues with smaller phase shifts, simultaneous sampling of all the inputs must be used as the delay from non-simultaneous polling would create unacceptably high phase shifts [18]. In general, higher sampling rates and use of more precise current and voltage transducers may be necessary.

V. CASE STUDIES

A. Test System

Several case studies are performed in this section to analyze the impact of renewable energy resources on the performance of the distribution system. These tests are performed on the IEEE 34-bus test distribution system [19] (Fig. 2). The system is modeled and analyzed in PSCAD/EMTDC environment. It has a voltage level of 24.9kV, and supplies a combination of unbalanced spot and distributed loads, in the form of constant impedance, constant power and constant current loads. The system is equipped with two in-line regulators to maintain a good voltage profile, and an in-line transformer that reduces the voltage to 4.16kV for a short section of the feeder.

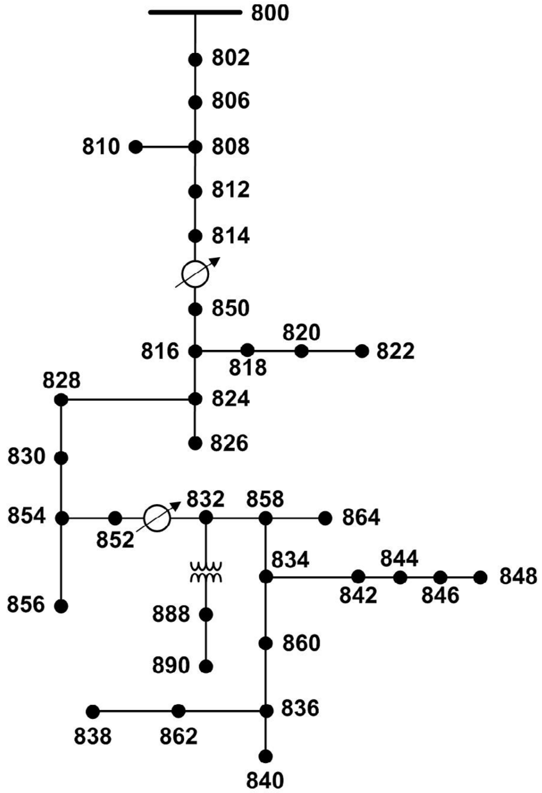

Fig. 2. Schematic diagram of the IEEE 34-bus test distribution system.

B. Test Scenarios

The performance of the system is evaluated in the presence of renewable energy resources. Photovoltaic (PV) and wind energy resources are added to the system in multiple steps of penetration levels. Table 1 lists the different penetration levels and resource combinations studied.

TABLE I – CASE STUDY SCENARIOS

Case	Renewable Energy Resource	Penetration Level
1	PV	5%
2	PV	10%
3	PV	20%
4	PV	30%
5	PV	40%
6	PV	50%
7	Wind	5%
8	Wind	10%
9	Wind	20%
10	Wind	30%
11	Wind	40%
12	Wind	50%
13	Mixed (PV, Wind)	2.5%, 2.5%
14	Mixed (PV, Wind)	5%, 5%
15	Mixed (PV, Wind)	10%, 10%
16	Mixed (PV, Wind)	15%, 15%
17	Mixed (PV, Wind)	20%, 20%
18	Mixed (PV, Wind)	25%, 25%

The PV/wind resources are meant to represent either bulk energy resources at the medium voltage level, or aggregated low-voltage network resources such as rooftop PV and/or small-scale wind turbines. The locations for the PV panels and wind turbines are randomly chosen. Some of these units are modeled as three-phase power sources, and some as single-phase ones, to represent realistic combinations in distribution systems. Penetration level is defined here based on the percentage of the total active power load on the feeders. Clearly, penetration levels based on energy, and not capacity, would have resulted differently.

C. Resource Modeling

When available, secondly data has been used to represent the renewable energy resources. For PV, solar irradiance data on the city of Oahu, HI have been chosen [20]. This dataset presents one of the most severe cases of consistent solar variability in the US. The solar irradiance data is available with 1-second time resolution which seems appropriate for the purposes of this study. Irradiance measurements are provided through an array of 17 sensors over a 1km by 800m site. The selected day for the simulations is 6/13/2010, whose daily irradiance is illustrated in Fig. 3. When analyzing the variations of solar irradiance, spatial distribution is almost as important as temporal distribution. In order to portray the spatial difference between the locations of the PV panels along the feeder mains, three datasets are selected from 3 different sensor data available in [20].

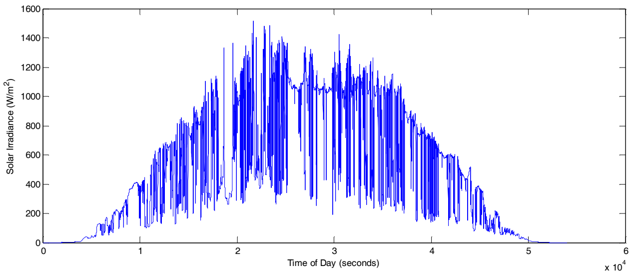

Fig. 3. Solar irradiance data, Oahu, HI, 6/13/2010.

Wind data is also modeled based on the model available in PSCAD. Different mean wind speeds are selected so as to represent the spatial distribution of the wind across a typical distribution system. Also, in order to represent the secondly variations of wind power, a random walk noise has been superimposed on the mean wind speed.

D. Simulation Results

Some sample waveforms are presented in this section as a representative of the results of the case studies. In the following graphs, line voltage and line active power at node 816 are illustrated (except mentioned otherwise); however, the severity of the oscillations are more or less the same for all nodes. It can be seen that as penetration levels increase, as expected, the magnitude of the oscillations increases (for instance, comparing Figs. 4 and 5). This indicates that the system moves away from a quasi-steady-state mode towards one with secondly dynamics, which requires dynamic analysis. Throughout the simulations here it has been assumed that the PV/wind resources are at Maximum Power Point Tracking (MPTT) mode, without reactive power control, which explains why the voltages experience a considerable amount of oscillations. Clearly, efficient operation of this system would require integration with solutions such as voltage/var/watt control. However, this would now require dynamic system analysis and control.

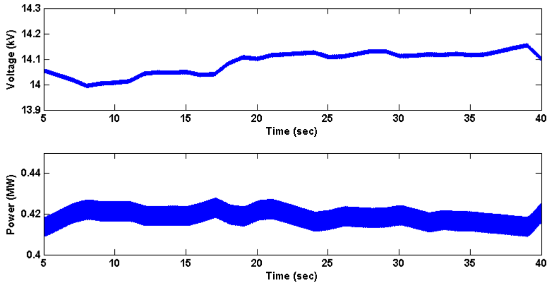

Fig. 4. Voltage and active power measured at node 816 with 10% PV penetration.

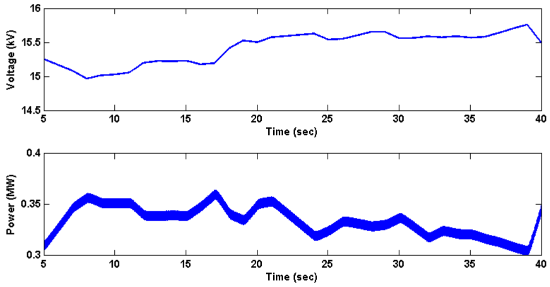

Fig. 5. Voltage and active power measured at node 816 with 50% PV penetration.

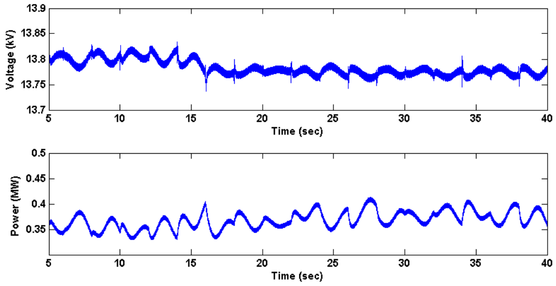

Fig. 6. Voltage and active power measured at node 816 with 50% wind penetration.

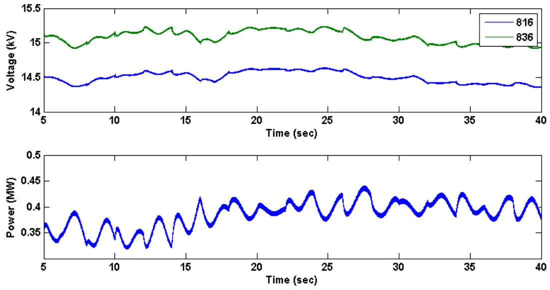

Fig. 7. Voltage at nodes 816 and 836, and active power measured at node 816 with combined 25% wind penetration and 25% PV penetration.

VI. NON-PMU ALTERNATIVES

During the transitional stage from quasi-steady-state network operation to a more dynamic one, when cost of PMU cannot be easily justified, there are some non-PMU alternatives that can be used. Some examples appear below.

A. Stability Analysis

Probably the most common way to mitigate the stability considerations of DG without PMUs has been to prevent them from providing ancillary services. However, ancillary services from DG are important for the simple reason that if DG only displaces the energy produced by central generation but not the associated flexibility and capacity, the overall cost of operating the entire system will rise.

B. Protection

To get around insufficient phase angle information when performing reclose operations, reclosers are sometimes equipped with long delays between the trip and close operations in order to try to ensure all DG units have tripped offline and to allow spinning loads to de-accelerate to the point that closing in on them is not harmful. The best solution to standing phase angles across a breaker are to measure the power angle directly on the terminals of the recloser, a solution that would be more precise and cheaper than PMUs (which are unlikely to be located exactly at the recloser).

C. State Estimation

Distribution state estimation can naturally be performed without PMUs. To get around insufficient measurements, distribution state estimators could employ "pseudo-measurements," which are calculated values from a load-flow model. Because of the low confidence given to pseudo-measurements compared to actual measurements, computation time would be slower and the results may be less accurate [21]. Some algorithms improve on this by using historic load data gathered offline to aid real-time calculations [22].

D. Load Modeling

Currently, load modeling is also performed without distribution PMUs and instead relies on educated guesses on the part of system engineers. While these guesses are usually accurate and/or the need for a precise load model is not always necessary, about 50% of utility engineers are unsatisfied with their load models [23], often due to the fact there have been several historic circumstances where inadequate load modeling has contributed to instabilities. An example is the Tokyo system collapse of 1987 which was partly caused by an underestimation of the reactive power consumption of air-conditioning loads [23].

To avoid this, in lieu of or in addition to PMUs, several system operators are working on gathering more detailed end-use data, installing transient recorders, and conducting field tests to develop new models or validate existing representations [23]. However, most of these efforts could be enhanced with greater PMU penetration.

E. Microgrid Management

Synchronization of Microgrids is already facilitated using a host of conventional relays at the point of common coupling. While this is a more economic advantage in the short term and with small numbers of Microgrids, in a distribution system where Microgrids can form in many locations and take many forms based on optimal system conditions, the use of PMUs with state estimation techniques is likely to be more beneficial and economical than installing relaying at every possible interconnection point (so long as enough PMUs are installed to provide observability into the islands).

F. Fault Location

Currently, impedance estimation is used in distance protection relays without PMUs. However, some feel that this leads to fault locating algorithms being too unpredictable to be used in practice; due to sensitivities to inaccuracies that arise from trying to detect the fundamental phasor in the presence of harmonics, frequency deviations, and noise [13], all of which are aided by PMUs but not eliminated. For most other fault locating applications, manpower intensive techniques, such as visual feeder inspection or the use of specialized underground fault detection equipment, can be used.

VII. CONCLUDING REMARKS

Phasor measurement units have proved to be useful assets on the transmission grid, increasing the quantity and quality of measurements within the power system. As distributed generation proliferates throughout the distribution system, causing it to no longer be quasi-stationary, PMUs will become a necessary part of the sensory of the distribution grid. In addition to the typical benefits PMUs bring to the transmission system, such as state estimation, stability analysis, and enhanced protection, distribution PMUs are likely to find usage in distribution applications such as generation/load estimation, Microgrid operation and management, as well as control schemes for EV vehicle-to-grid applications.

While cost might be a prohibitive factor in some cases, non-PMU solutions are likely to be adopted by the utilities in the short run; however, as the number of DER units and active loads in the distribution system increase, the advantage offered by PMUs (or the disadvantages by lack thereof) are expected to overshadow the associated costs. This paper discussed some applications in the distribution system for which PMUs may be very beneficial.

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