Current Trends on Applications of PMUs in Distribution Systems

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***Abstract*—Distribution systems are evolving at a high pace largely due to the proliferation of DER, the growing utilization of DA, AMI, DMS, and the expected propagation of PEVs. This evolution is also leading to new challenges, for instance large penetration of intermittent DG can lead to noticeable impacts on distribution feeders. The coordinated implementation of Smart Grid technologies is called upon to handle these challenges. This paper explores the contribution that PMUs can provide to handling these challenges by examining recent research results on applications of synchrophasors in distribution systems. This review includes descriptions of representative works in a wide range of applications designed for smart distribution feeders, and some developments originally proposed for transmission level, but with equivalent applicability to distribution systems.**

***Index Terms*— Fault location, instrument transformers, load modeling, parameter estimation, phasor measurement units, power quality, power system harmonics, power system stability, protection, state estimation.**

I. Nomenclature

DER:	Distributed Energy Resources
DG:	Distributed Generation
DES:	Distributed Energy Storage
PEV:	Plug-in Electric Vehicle
DMS:	Distribution Management System
AMI:	Advanced Metering Infrastructures
IED:	Intelligent Electronic Device
NASPI:	North American Synchrophasor Initiative
PMU:	Phasor Measurement Unit
RTU:	Remote Terminal Unit
SCADA:	Supervisory Control and Data Acquisition
WAMPAC:	Wide Area Monitoring, Protection, Automation and Control

II. Introduction

THE ongoing evolution of power distribution systems driven by the implementation of the Smart Grid framework is introducing new challenges to operations and planning activities. Addressing these issues requires of new approaches and technologies to continue ensuring a reliable and secure supply to end users. Some of the most noticeable changes to the power distribution landscape are being driven by the proliferation of intermittent DG, PEVs, microgrids, and power electronic components. High penetration levels of intermittent DG can lead to significant impacts on planning and operations. For instance, fluctuating output from solar photovoltaic and wind plants can cause voltage and power variations in the feeders. Moreover, as penetration levels increase, concerns regarding stability and interactions among DG units are becoming more important. Uncontrolled PEV charging can lead to distribution equipment overloading and violations of low voltage limits. Furthermore, harmonic injection from power electronics components such as motor drives, fluorescent lighting, computers, and DER and PEV inverters can increase Total Harmonic Distortion (THD) levels on distribution feeders and modify the conventional patterns of voltage and current signals.

PMUs within the framework of WAMPAC are recognized to be an invaluable aid in ensuring the secure operation and stability of transmission systems. Therefore, as traditional radial distribution feeders evolve into highly complex, meshed, dynamic and active systems it becomes apparent that PMUs can provide similar functionalities and benefits to ensure reliable and secure supply. For instance, the deployment of PMUs at strategic feeder locations can increase the real-time monitoring, analysis and synthesis capabilities of utilities. PMUs can provide the required functionality and precision to obtain time synchronized phasors that can be used to improve distribution circuit characterization and develop monitoring tools to evaluate and mitigate the impact of intermittent DG. Despite the evident benefits, the application of PMUs in distribution systems is still largely under-explored (particularly at the implementation stage), this is mostly due to economic factors. However, since the drivers and needs for implementation are rapidly increasing there is a growing interest in applying PMUs to distribution systems.

The purpose of this paper is to review the prospective applications of PMUs in distribution systems, and to provide an insight into the concepts behind their potential implementation. Section III discusses this subject in more detail and presents a review of recent developments, including applications to state estimation, dynamic monitoring and protection, fault location, harmonics estimation, load modeling, parameter estimation, closed-loop operation of distribution feeders, and alternative PMU technologies suitable for distribution systems. Finally, section IV presents a concluding remarks and identifies areas that require further investigation.

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III. Proposals for PMUs in Distribution Systems

The potential for PMU applications in distribution systems has been acknowledged by several authors [1] - [8]. In [1] Wache and Murray refer to the NASPI roadmap for possible applications of WAM, and suggest that some of them are useful for distribution systems. Besides the applications listed in the previous section, they also include post-mortem analysis, power system restoration and energy accounting as possible applications. In [2]authors indicate that in the next five years, new low cost PMU designs should be available for monitoring and islanding DG and microgrids. In [3] the institutional efforts being carried out by Indian utilities to incorporate PMUs to the transmission and distribution grids are highlighted. In [4] the authors discuss the development and deployment of a wide area monitoring and control platform involving PMUs installed at distribution level in several Nordic universities. PMU applications in distribution systems are contemplated in the IEEE Standard 2030 [5]. This document addresses the communications technology and interoperability between field devices, which need to be controlled and monitored via the backhaul network in a distribution substation, including but not limited to SCADA systems, IEDs, RTUs and PMUs. Protocols IEC 61850 [6] and IEEE Standard 1815 [7] are recognized as pertinent governing choices. Specific applications of PMUs in distribution systems are discussed in more detail as follows.

A. State Estimation with PMU measurements

Distribution state estimation, although still incipient, is becoming an intrinsic component of modern DMS. Unlike transmission state estimation, distribution state estimation has to deal with unbalanced systems that imply the use of appropriate power flow models. Beyond this, the weighted least squares method is typically applied to both system levels. As explained in [9], given the set of measurements, $\boldsymbol{z}$:

$$\boldsymbol{z} = h(\boldsymbol{x}) + \boldsymbol{e} \tag{1}$$

where $h(\cdot)$ is a nonlinear vector-valued function that relates measurements with the state vector $\boldsymbol{x}$, and $\boldsymbol{e}$ is the vector of error measurements, the estimator minimizes the objective function:

$$[\boldsymbol{z} - h(\boldsymbol{x})]^T \boldsymbol{R}^{-1} [\boldsymbol{z} - h(\boldsymbol{x})] \tag{2}$$

where $\boldsymbol{R}$ is the covariance matrix of the measurement errors.

In general there are two mathematically equivalent approaches to include synchrophasor measurements in state estimators [10]: 1) to design the estimator based on combined measurements from PMUs and from other conventional measurement devices, and 2) to add phasor measurements through a post-processing step. Although the first case is the most direct approach, the second case results in a linear estimation that could facilitate implementation in DMS.

The first approach is followed in [11] where the use of rectangular components of the voltage and current synchrophasors, leads to a linear form of (1) allowing a non-recursive estimation. In the same work the authors propose an alternative low-cost system to acquire not universally synchronized phasors, and describe the multiphase power flow model to be used for state estimation in distribution.

The direct incorporation of synchrophasors is also used in [12], where (1) is linearized around the presumed operating point. Then the estimated state vector is decomposed in its real and imaginary components, and the corresponding complex residual components are minimized independently in the least square sense. The resulting algorithm is proved by simulations to be well-conditioned and suitable for distribution state estimation.

The post-processing approach is used in [13] to incorporate different measurement technologies involving PMUs, smart meters and other conventional measurement devices, into distribution state estimators. Genetic algorithms are applied to determine the optimal measurement infrastructure and its location in a generic distribution system, by minimizing the financial costs and respecting boundaries on the overall uncertainty of the state estimator.

A method that differs from the conventional state estimation techniques is presented in [14], where a microgrid is topologically modeled by a factor graph. Here, bus voltages and branch currents are defined as random state variables which are topologically correlated. This state variable definition facilitates the adoption of a linear state estimator, and the application of a Belief Propagation algorithm to provide a robust estimation of the states by calculating the first and second order statistics. The method is apt to receive smart meter and PMU measurement data. In [15] and [16] the authors study the impact of model uncertainties on the parameter and state estimations, and propose the reduction of these effects using PMU measurements.

B. Dynamic monitoring and protection

Although the concept of phasor is defined for steady state operation, and transient conditions cannot be accurately described by phasors computed by PMUs, the capabilities of synchrophasors can be extended to dynamic monitoring applications, to provide tools to safeguard system operation and stability. In this section, applications on islanding detection, rotor angle estimation, and on the monitoring of disturbances in low voltage systems are reported.

In most cases, distribution system operation practices recommend to promptly detect islanding conditions when DG is installed, in order to avoid issues such as Temporary Overvoltage (TOV), reclosing out of synchronism, and damages to DG equipment [17], [18]. This fact has encouraged research towards applications of PMUs in this area. In [19] a passive islanding detection case is analyzed by installing one PMU in the substation and another one in the DG plant. These PMUs communicate to each other via intranet and TCP/IP, and provide measurements to a voltage angle difference algorithm. The system is implemented in an analog simulator and demonstrates its capability to detect islanding conditions with power imbalances of 1%.

In [20] the authors design a synchrophasor estimation technique based on Discrete Fourier Transform (DFT) tone-reconstruction, aimed to reduce the Total Vector Error (TVE) and to make the PMUs suitable for the monitoring of electromechanical transients. The method was implemented in a microcontroller, and experimental tests were conducted on a distribution system with an 80 MW combined cycle plant connected to the substation. Islanding and reconnection tests demonstrate the ability of the proposed algorithm to monitor transient conditions in short cable links, allowing the development of protection and control procedures in transmission or distribution lines. PMU measurements are also used to provide accurate rotor angle estimates of synchronous generators, which are used in conventional centralized and distributed generation. Examples of this can be found in [21] and [22], where synchrophasor data supports the design of digital filters and estimators that make available rotor angle information for control applications.

A proposal considering the use of PMUs as part of an adaptive protection scheme is presented in [23]. This method aims to deal with protection coordination issues in distribution circuits with a high penetration of distributed generation. This is accomplished by installing PMUs in all DG plants and using protective relays to partition distribution zones with an approximate DG – load balance.

The optimal placement of PMUs in a distribution system, based on a criterion of "nodes with the softest characteristics" is explained in [24], where the method was used to place six PMUs in an industrial park at medium and low voltage levels. The cited experiment produced high precision monitoring data to analyze the system in normal and disturbance conditions. This reference also shows that with accurate monitoring, the localization of disturbances in the system is facilitated through voltage signal delay analysis.

C. Fault location and detection

Accurate fault location and detection are critical activities to ensure reliable and safe power delivery to customers. There are numerous proposals for fault location and detection and they have become standard function of most modern protective devices. However, many of these proposals and products were developed for radial distribution feeders. Hence as distribution systems evolve into active and dynamic networks, new algorithms for fault location and detection are required. For instance, in [25], fault location in distribution circuits is performed by computing actual pre and post fault voltage variations, and comparing with hypothetical voltage variations assuming the fault occurred at predetermined buses. This reference introduces a method which does not rely on protection devices to locate faults, but instead uses PMU measurements of voltage and current to compute the Thevenin equivalents for positive, negative and zero sequence impedances. These measurements are located at the DG sites and are used in conjunction with the three phase impedance matrix at the substation bus, to compute the fault location based on the comparison of voltage differences throughout the circuit. Fault location in aged transmission or distribution lines is complicated by model imprecisions resulting from changed parameters. Similarly, underground lines pose difficulties to the prompt location of faults. An alternative to address this problem is presented in [26], by locating PMUs in both ends of the line and using distributed line model and modal transformation theory to locate any type of faults. The method is evaluated using ATP/EMTP showing high accuracy in fault location calculations under various system and fault conditions. To overcome limitations of overcurrent protection relays in detecting high impedance faults, [27] proposes a technique that takes advantage of the sampling windows used to compute current phasors, to identify when a PMU is using mixed pre and post fault data in transient conditions. This detects the moment when the transient is taking place, and produces a quality measure that allows the detection of any transient condition, including high impedance faults. Another PMU placement scheme optimized for fault detection can be found in [28].

D. Harmonic estimation

Precise estimation of harmonic levels plays an important role in power quality applications, which are important for customers with sensitive loads. Although individual DG and PEV inverters must comply with harmonic emission limits set by utility or industry standards, the cumulative effects and interactions of harmonics injected by large number of inverters may cause impacts in the distribution system that need to be accurately identified [29]. A concept of harmonic synchrophasors and a measurement technique to evaluate the amplitude and phase of the harmonic components is reviewed in [30]. In this reference, modular hardware is used to measure harmonic synchrophasors, introducing a cost reduction strategy for implementation in distribution circuits, which consists in exploiting communication links that are usually present between nodes, to avoid the necessity of GPS receivers in all nodes. The experimental characterization tests are performed on a three-phase low-voltage distribution system.

In [31], a distribution harmonic state estimator is developed using a modified Particle Swarm Optimization (PSO) algorithm. This method uses PMU data, line and DG parameters, pseudo measurements, and known uncertainties, to estimate the harmonic phasors through minimization of the error between PMU measurements and estimated values. A similar goal based on PMU measurements is pursued in [32], where a weighted least squares algorithm is applied along with singular value decomposition to estimate the harmonics. Here, a genetic algorithm optimization method is designed to optimize the location and quantity of phasor measurement units, by minimizing a cost-based objective function and securing complete observability.

E. Load modeling

Accurate load modeling is becoming increasingly important in system analysis and operations; specific applications include estimating precise system stability limits and evaluating benefits of Volt-VAR Optimization (VVO) and Conservation Voltage Reduction (CVR) programs. The goal in [33] is to estimate frequency dependent load models that are accurate for normal and transient conditions. This is done using a harmony search algorithm and by representing the conventional distribution load models in symmetrical parameters that can be paired with symmetrical components of voltage and current coming from PMUs. A different approach is followed in [34] to demonstrate that WAM – based composite load modeling produces better validation results as compared to the traditional static load modeling. This is accomplished via model order reduction using the trajectory sensitivity method. Reference [35] reports the use of PMU signals in system identification in Australia. Transfer functions are built taking advantage of the low noise characteristic of synchrophasors measurements, allowing the determination of correlations between frequency and different types of loads.

F. Parameter estimation

Synchrophasor applications have been studied to estimate model parameters in distribution feeders to palliate the effects of model imprecision [36], [37]. Reference [36] uses Monte Carlo simulation to calculate and validate line parameters. In [37], a multi-run optimization method is designed to solve for the resistive and reactive parameters of a three phase feeder, from the measurements of real and reactive power flows at both ends of the feeder. A procedure based on post-disturbance measurements of active and reactive power from PMUs is proposed in [38] to estimate the parameter values of an equivalent wind farm model. The model is validated using a typical frequency response of the system when experiencing a large power disturbance. In distribution systems analysis it is common to use Thevenin equivalents representative of upstream or high voltage networks to improve model and simulation accuracy of specific feeders. The on-line computation of Thevenin equivalents using PMU data is addressed in [39], this reference also introduces a method to filter out noise that could be present in the measurements due to transient conditions.

G. Further developments on synchronized measurements

Other exigencies that distribution systems may impose on PMUs are pointed out in [40], including a diminished frequency stillness, nonlinearity and asymmetry in steady state conditions. A Synchronous Measurement Unit (SMU) is proposed as a generalized instrument capable of characterizing point-to-point energy transfers, with a variable resolution according to the dominant phenomena taking place. A custom platform is presented to study the performance of different PMU algorithms in a variety of conditions, including those expected in distribution circuits.

In [41] the authors use GPS receivers, general purpose data acquisition hardware and a programmable digital signal processing algorithm, to design a flexible measurement system for measuring synchronized phasors, as an alternative to commercial PMU devices that can be appropriate for massive use in distribution systems. In a similar fashion, [42] incorporates a Network Time Protocol, and [43] applies an Internet Protocol for the same purpose of making synchrophasor technology more accessible to distribution grids.

H. Closed-loop operation of distribution feeders

Distribution systems are under an unprecedented evolution driven by the proliferation of DER, particularly by the need to accommodate growing penetration levels of photovoltaic DG and PEV. The intermittent nature of this type of DERs and the uncontrollability of PEV charging are impacting distribution planning and operations, resulting in the need for robust real-time control algorithms that allow operating this highly dynamic system within quality, reliability, efficiency and security requirements. However, control-based solutions are bounded by physical limitations imposed by radial[1] distribution grids, e.g., feeder capacity and stiffness. Therefore, integrating growing amounts of DER also requires using alternative operation modes of distribution feeders. Specifically, closed-loop operation combined with real-time active control, integrated DERs dispatch and intelligent PEV charging management present a promissory solution for maximizing grid's ability to integrate larger amounts of renewable generation [44], [45].

Historically, suburban and rural distribution systems have been designed and operated in a radial fashion. Despite its evident efficiency and reliability shortcomings, the radial structure has been predominant since it requires relatively simple and economical operation practices and protection schemes. Other solutions require more advanced equipment, protection and control technologies, which are difficult to justify from an economic standpoint. Proliferation of DERs and in particular of residential-size photovoltaic DG affecting suburban feeders is starting to cause noticeable impacts, particularly in "weak" feeders. These impacts are expected to grow should distribution systems continue to be operated in a radial manner. These impacts include voltage fluctuations due to output intermittency, power quality issues (e.g. long-term flicker), interactions with voltage control and regulation equipment (load tap changers, line voltage regulators, capacitor banks), increase in losses, protection system issues (e.g. TOV due to accidental islanding), and stability problems.

Different solutions to these issues have been proposed and they usually imply modifying the operation settings of existing components such as line voltage regulators (e.g., to co-generation or bi-directional operation), regulating the output of DG units, and limiting islanded operation (e.g., using direct transfer trip schemes). These solutions are generally successful for low and moderate penetration levels; however, large penetration levels require more complex and expensive approaches such as using DES, and dynamic volt-VAr compensation via DG inverters or advanced components (e.g., distribution-class STATCOMs). In a general sense, these solutions can be seen as a temporary fix to a more fundamental problem caused by the radial operation of the system. At a conceptual level, most of the problems caused by high penetration levels of DG are prompted by the equivalent impedance at the point of interconnection (POI), i.e., by the system stiffness. Expectedly, in radial systems, stiffness is inversely proportional to the distance from the substation; therefore, the farther the POI from the substation, the more severe the impacts. "Looping" two or more radial feeders has the direct effect of decreasing the POI impedance, augmenting the maximum DG penetration level allowed without deteriorating system performance. It is worth noting that

[1] Although distribution feeders with DG are not strictly radial, for the purpose of this discussion radial feeders are those bounded by normally-open devices (regardless of the presence of DG)

closed-loop operation is not a new practice, utilities have operated closed-loop feeders for special applications since the dawn of power delivery, and today spot networks and secondary networks are widely utilized in downtowns of large metropolitan areas. However, they are not common in suburban areas, where radial operation is still predominant, and where residential photovoltaic DG is proliferating. It is important mentioning that utilities are starting to explore closed-loop operation as part of Smart Grid initiatives [46].

Provided that adequate monitoring, control, protection and automation systems are in place, closed-loop operation of distribution feeders leads to increased reliability and efficiency, e.g., reduced voltage drop and losses, reduced voltage sensitivity to DG output fluctuations, and more efficient use of available feeder capacity. All these benefits also apply to PEV integration and can boost allowable penetration levels of this technology. For instance, controlled charging of PEVs is likely to shift overloads upstream, from distribution transformers to primary lines, due to coincident PEV charging; the required additional feeder capacity can then be redistributed by closed-loop operation.

PMUs can play a key role in providing accurate and synchronized high-resolution measurements that can be used for protection, automation and control of closed-loop feeders with high penetration of intermittent DG. This type of application can prove beneficial not only for medium-voltage closed-loop operation but also for conventional secondary networks, such as those used in downtowns of large metropolitan areas, which are also starting to experience important proliferation of intermittent DG [47], [48]. Data provided by PMUs would be critical for ensuring the secure operation of this highly complex and dynamic network.

IV. Final Remarks

There is growing interest in the industry in utilizing PMUs in distribution system applications. This interest has been mainly prompted by the increasing penetration levels of new sources and loads, particularly of photovoltaic DG. Although economic factors still limit the widespread implementation of PMUs, more distribution equipment is starting to include this capability either as an optional or standard feature [49]. This is a clear indication that the industry is foreseeing utilizing PMUs to address some of the emergent needs and challenges discussed in this paper. Other challenges for implementation include selection of adequate communications and information technologies for handling massive volumes of data provided by PMUs, and the respective data storage, processing, and analysis limitations. Here a critical aspect is the need to process the data provided by PMUs to be able to accomplish the functions described in the previous sections. It is important to mention that in applications such as protection this needs to be done in real-time while in others such as load modeling the objective is to process historical data and provide distribution engineers with valuable information rather than with large volumes of raw data. Hence specific data processing algorithms must be developed to extract the pertaining information for each application. Another critical aspect is the optimal selection of sampling rates and identification of minimum number and location of PMUs in distribution feeders. This will avoid overloading communication means and data storage facilities while still accomplishing the functions of interest. All these are important areas that require further research in the near future in order to set the foundations for the implementation of PMUs in distribution systems.

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VI. BIOGRAPHIES

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