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Abstract— **This paper describes a research project to develop a network of high-precision phasor measurement units, termed micro-synchrophasors or µPMUs, and explore the applications of µPMU data for electric power distribution systems.**

Index Terms—**Phasor measurement units, voltage measurement, power distribution, smart grids.**

I. Introduction

Historically, with mostly radial power distribution and one-way power flow, it was only necessary to evaluate the envelope of design conditions, e.g., peak loads or fault currents, rather than continually observe the operating state. But the growth of distributed energy resources introduces variability, uncertainty, and opportunities to recruit diverse resources for grid services. Multiple resources on each feeder cause more complex impacts on the circuit behavior that can be observed with voltage and current phase angle variations [1]. To address the resulting need for tools to better observe, understand and manage the grid at the distribution scale, the University of California, in conjunction with Power Standards Lab (PSL) and Lawrence Berkeley National Lab (LBNL), has begun a three-year project to develop a high-precision phasor measurement unit called a micro-synchrophasor or µPMU, and to study its applications for diagnostic and control purposes in distribution systems.

II. Project Overview

The µPMU builds on an existing commercial platform by PSL called the PQube, a high-resolution power disturbance recorder capable both of storing and analyzing data locally and of communicating live.[2] The key innovation is extremely precise time-stamping of measurements via GPS to allow the comparison of voltage phase angle down to small fractions of a degree. After developing and testing the µPMU, the project team will develop a live network of µPMUs, termed µPnet, to allow for real-time monitoring and two-way communication with the distribution grid. The initial installation will be at the pilot test site on the UC Berkeley campus, and subsequent installations of µPMUs on other distribution circuits are planned in collaboration with partnering electric utilities.

The central research questions is how voltage phase angle measurement might address both known and as yet poorly understood problems, such as dynamic instabilities on the distribution grid, to enable new applications in the context of growing distributed intelligence and renewable resource utilization. Through empirical measurements in conjunction with modeling and analysis of distribution circuits, it will examine the usefulness of phase angle as a state variable and identify challenges associated with key applications described below. The goal is a reference design for plug-and-play µPMUs and µPnet that could enable adoption of a new management approach for distribution systems.

III. Synchrophasor Technology

Today, synchrophasors are used almost exclusively to observe transmission systems. Although "distribution" PMUs may be deployed at distribution substations, their voltage angle measurements are usually referenced against angles elsewhere on the transmission grid, not the distribution feeder. "True" distribution applications are more challenging in several respects: 1) Voltage angle differences between locations on a distribution circuit will be up to two orders of magnitude smaller than those on the transmission network (tenths of a degree, not tens of degrees). 2) Distribution system measurements will be fraught with much more noise from which the angle signal must be extracted. 3) The costs must be far lower to make a business case for the installation of multiple PMUs on a distribution circuit, as compared to the transmission setting. 4) Yet the number of available empirical data points as compared to the number of network nodes is much smaller in distribution than in transmission, given that AMI meter data are not communicated in real-time.

The µPMU technology in this project is expected to discern angle differences down to ±0.01°, contextualize these phase angle data with a detailed power quality recording, and do so at a low installed cost. Its components include a PQube instrument that contains the measurement, recording, and communication functionality, a remotely-mounted micro GPS receiver, and a power supply with battery backup. PQubes continuously sample a.c. voltage and current waveforms at 256 or 512 samples per cycle, and trigger their internal digital oscilloscope recordings on Class A disturbances such as voltage sags, swells, interruptions, waveform changes, microsecond impulses, frequency changes, current inrush, overcurrent, etc. Simultaneously, PQubes record watts, watt-hours, volt-amps, VARs, voltage harmonics, current harmonics, voltage flicker, voltage unbalance, current

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unbalance, temperature, humidity, etc. Like PQube recordings, all µPMU data will be stored in files on a SD card which allows for months of data storage and assures data recovery if communications are lost during power system events. Internal Ethernet support includes a PQube web server FTP, and a universal email client. One specific challenge for the µPMU design is to electrically isolate the GPS receiver to resist lightning strikes, while accounting for signal latencies. In addition, the computation of phase angle at very high resolution is complicated by the presence of harmonics.

Fig. 1 illustrates the proposed µPMU capabilities and measurements, situated on a logarithmic time scale. Some of these placements are approximate and still to be refined, as we better understand the rates at which it is practical and useful to report certain measurements.

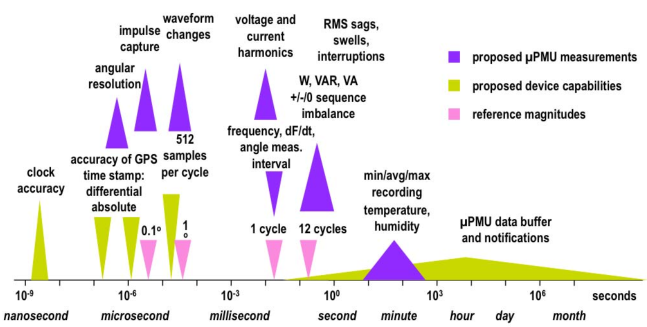


Figure 1. Time Scale for µPMU Performance

The µPMU device can be connected to single- or three phase secondary distribution circuits up to 690V (line-to-line) or 400V (line-to-neutral), either into standard outlets or through potential transformers (PTs) as found at distribution substations or could be added on primary distribution circuits. The low-voltage installation option affords simplicity and limits overall cost, although it also necessitates accounting for the effects of transformers on voltage angle through appropriate analytics.

IV. µPNET SYSTEM OVERVIEW

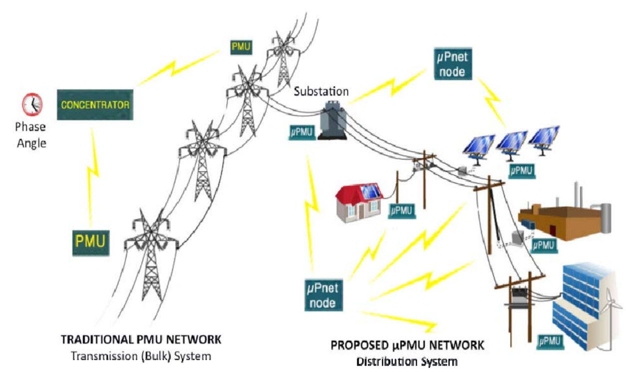
The true potential for the use of phase angle data in real-time applications lies in effective networking and data management. Our µPnet will build on the simple Measurement and Actuation Profile (sMAP) developed by UC Berkeley as a foundation for managing both real-time and archival data from a wide variety of physical sources.[3] The effectiveness of sMAP has been demonstrated in many energy-related applications, including active control of electric loads. Recognizing that information, while ever cheaper and more abundant, is often fragmentary, disorganized, available only in batch, or siloed into proprietary systems, sMAP is aimed to make information available and usable by providing a specification for transmitting physical data and describing its contents; a large set of free and open drivers with communicating devices using native protocols and transforming information to the sMAP profile; and tools for building, organizing, and querying large repositories of physical data.

Fig. 2 illustrates the deployment concept for µPnet. With µPMUs installed at multiple locations throughout a distribution feeder (e.g. the substation, end of feeder, and any key distributed generation facilities), µPnet is intended to support the analysis and operation of an individual feeder, multiple feeders from the same substation, or even contribute to the observation of transmission-level phenomena (e.g., via NASPInet). We anticipate about 10 µPMUs installed on a circuit and expect to learn more about useful deployment densities in particular situations. A key challenge will be accounting for the effects of distirbution transformers when measurements are made on the secondary side, but inferences made about the state of the primary circuit.

For real-time or quasi-real-time applications, a µPMU uploads its precisely time-stamped measurements through a suitable physical communication layer to a µPnet node, where it is compared against measurements from other µPMUs. µPnet is agnostic to the physical communication layer used, although the target speed and bandwidth constrains the selection of the most economical medium, probably 4G wireless service.

The communication interval between a µPMU and a µPnet node may vary, as appropriate for the application, e.g., once per cycle, every few seconds, or through reports triggered by anomalous measurements. µPMU data may feed into more than one µPnet node, where each node may be equipped with different analytic capabilities. A µPnet node may reside on a portable computing station with appropriate communication link. Depending on the application for which µPMU data is to be used, analyzed data may be displayed at the node in visual format, or forwarded in distilled form to other users. For example, a digest could be sent to the distribution system operator, or a control signal could be sent from the µPnet node to selected devices.

Figure 2. µPnet Concept



The µPnet infrastructure will also be agnostic to the specific PMU device communicating with it, since standard protocols and file formats are used. The intent of µPnet, based on the simple and open-source approach of sMAP, is to enable a maximal variety of devices and strategies to play together. One goal of this project will be a set of simple specifications or reference designs that any hardware and software vendor could meet, in pursuit of affordable and mutually compatible components of information and control strategies for distribution system operations.

V. Applications for µPMU Data

A broad spectrum of potential distribution system applications could hypothetically be supported by µPMU data (or, in some cases, by conventional PMU data), as has been noted in the literature.[4-6] One of our research tasks is to specify, or at least narrow down, the requirements that various power distribution-related applications will impose on data resolution, accuracy, communication speed, signal latencies, volume and continuity of data transfer, as well as placement of the µPMU on the distribution circuit. We then intend to evaluate applications in terms of the data requirements to support them, and the advantage afforded by voltage angle as a state variable as compared to conventional techniques.

Essentially, there are two types of observations of circuit conditions to be made by µPMUs: steady-state and dynamic circuit behavior. We expect these to have distinct requirements in terms of both data reporting and device placement, as shown in Table I. It is worth noting that high sampling rates are not important for obtaining angular resolution, which depends rather on the accuracy of the time stamp, but for understanding events (such as transients and harmonics) that occur on sub-cycle time scales.

TABLE I. Expected Data requirements for different classes of µPMU applications

	Sampling rate (per cycle)	**Angle resolution (milli-deg)**	**Spatial resolution (placement)**	**Data volume (Bandwidth)**	**Communication speed**
Steady-state circuit behavior	1-2	10-300	Sparse	Medium but continuous	usually low
Dynamic circuit behavior	2-512	10-50	Dense	High but could be intermittent	usually high

It is also important to distinguish diagnostic from control applications: that is, using µPMU data to help operators better understand the present or past condition of the distribution system, or to inform specific control actions to be taken (likely by automated systems) in more or less "real-time." We initially focus on diagnostic applications.

A. Diagnostic Applications

Diagnostic applications for consideration in this project include the following:

1) Unintentional island detection

The objective is to quickly and reliably recognize a potentially unsafe situation where a set of distributed generation (DG) generators and loads have separated from the grid but continue to energize their local portion of the network. Today's inverters have very reliable anti-islanding protection. However, with greater penetration of diverse distributed resources and more complex dynamics on distribution circuits, it may become increasingly difficult to distinguish fault events from other abnormal conditions where it is desirable to keep DG online (for example, low-voltage ride-through).

2) Topology status verification

The objective is to detect or confirm the actual status (open or closed) of field switches whose indicators may be unavailable remotely or considered unreliable. Knowledge of the network topology is essential to inform safe operations and accurate estimation of the system state.

3) Phase identification and balancing

The simple yet important function here is to identify the connection of single-phase loads and laterals to phases A, B or C, to facilitate proper balancing. Direct phase angle measurement with a portable device on the secondary distribution system could be a uniquely quick and easy way to ascertain this.

4) Reverse power flow detection

The goal is to identify, or rather anticipate, when power flows in reverse direction on a radial distribution feeder. While reverse flow may be unproblematic in some situations, its significance depends on the type of protection system design used, and whether the coordination of protective devices could be compromised under reverse flow conditions [7]. Voltage regulation may also be impacted by reverse flow, if control systems are designed based on the assumption of a declining voltage profile toward the end of the feeder.

5) State estimation

State estimation means identifying as closely as possible, from available network models and empirical measurements, the operating state of the a.c. system in near real-time. This state is completely described if the two state variables that drive real and reactive power flow – namely, voltage magnitude and phase angle – are known or computed for every node in the network, given connectivity and impedances of network branches. State estimation is generally more difficult for distribution than for transmission systems. This is because distribution systems are harder to model (owing to untransposed lines with phase imbalances, small X/R ratios, large numbers of connecting load points, and less redundancy from Kirchhoff's laws) and present a high-dimensional mathematical problem, while at the same time offering few physical measurements to inform the state estimation. Data from µPMUs could explicitly provide these state variables to directly feed into a Distributed State Estimator (DSE), which in turn may provide information to a Distribution Management System (DMS).

6) Fault location

The goal is to infer the actual geographical location of a fault on a distribution feeder to within a small circuit section (compared to the distance between protective devices) by using recorded measurements of voltage angle before and during the fault, and interpreting these in the context of a circuit model. Algorithms exist for locating faults through proper analysis of monitored data, but the quality of available measurements on distribution circuits is often insufficient to support them. We expect that voltage angle might enable fault location with greater precision than before.

TABLE II. SUMMARY OF ATTRIBUTES OF μPMU APPLICATIONS

Diagnostic Application	Competing conventional strategies	Likely advantage of voltage angle	Likely technical challenges
Unintentional island detection	various	possibly faster, greater sensitivity and selectivity, possibly less expensive	speed
Oscillation detection	none	unique	unknown
Reverse power flow detection	detect with PQ sensor (V mag, I mag & angle)	may extrapolate to locations not directly monitored	algorithm using minimal placement
FIDVR detection	detected with V mag	possibly less expensive, faster	easy
FIDVR prediction	none	may be unique	unknown
Fault location	various	possibly better accuracy, i.e. locate fault more closely with δ than V	need high resolution, fast data
High-impedance fault detection	various, difficult	possibly better sensitivity and selectivity with δ	unknown
Topology detection	direct SCADA on switches	possibly fewer measurement points, independent validation	algorithm using minimal placement
State estimation	computation based on V mag measurements	possibly fewer measurement points, better accuracy, faster convergence	algorithm using minimal placement
Dynamic circuit monitoring	high-resolution PQ instruments, none for δ	uniquely capture oscillations, damping	data mining for relevant phenomena
Load and DG characterization	limited observation with PQ instruments	uniquely capture dynamic behaviors	data mining, proximity to subject
Unmasking load/DG	none	may be unique	unknown

7) High-impedance fault detection

The objective is to recognize the dangerous condition where an object such as a downed power line makes an unintentional connection with the ground, but does not draw sufficient current to trip a protective device (since it mimicks a legitimate load).

8) Oscillation detection

Subsynchronous oscillations are known to exist on transmission systems, and higher-frequency oscillations could conceivably occur on distribution systems, unobserved by conventional instrumentation. These could be the result of power exchange between and among distributed energy resources, or any resonance phenomena on the circuit. Low-frequency modes of oscillation, though normally well damped, constrain a.c. transmission paths and can grow destructive if underdamped. It took synchrophasors to recognize their existence, and effective control methods are still in development. Observation of oscillation modes on the island of Maui, measured at transmission voltage but across a small geographic scale (tens of miles), suggests that future distribution systems with high penetrations of solar and wind generation could also experience oscillation issues [8]. Transmission system models did not predict oscillations, nor do distribution system models; the only way to find out if any oscillations exist – and if so, to characterize them – is to look.

9) Characterization of distributed generation

The goal is to qualify and quantify the behavior of inverters in relation to stabilizing system a.c. frequency and damping disturbances in power angle or frequency. Specifically, this means observation of inverter real and reactive power output at very small time scale relative to line voltage, frequency and angle, with particular emphasis on the response to abnormal and transient conditions.

10) FIDVR identification and risk detection

Fault-induced delayed voltage recovery (FIDVR) is an unstable operating condition that results from the interaction of stalled air conditioners with capacitor bank controls. Anticipating FIDVR before it occurs would hinge on identifying in near real-time the varying contribution to total customer load from devices such as single-phase induction motors in residential and small commercial air conditioners that pose an increased risk.

11) Unmasking loads from net metered DG

The goal is to infer the amount of load being offset by distributed generation (DG) behind a net meter through measurements and correlated data obtained outside the customer's premises. Estimating the real-time levels of renewable generation versus loads would allow for better anticipation of changes in the net load, by separately forecasting the load and generation, and for assessing the system's risk exposure to sudden generation loss. At the aggregate level, this information is of interest to system operators for evaluating stability margins and damping levels in the system.

Table II summarizes our preliminary thinking about likely advantages of high-resolution voltage angle measurements as compared to conventional techniques to support the listed diagnostic applications.

B. Control Applications

Beyond enhanced diagnostic capabilities, synchrophasor data may enable more refined management and active control of distribution systems. Possible control applications include the following:

1) Protective Relaying

Reverse power flow was noted above as a condition that can be important to diagnose and avoid, but another approach is to employ protection schemes that safely accommodate reverse flow. Without requiring a costly replacement of protective devices, it may be feasible to develop supervisory differential relaying schemes based on μPMU data that recommend settings to individual devices based on overall system conditions, which might include reverse flow. This approach is being demonstrated and tested at the transmission level in a DOE-funded Adaptive Relaying project [9].

2) Volt-VAR Optimization

We do not expect that voltage angle measurement would afford an inherent advantage over magnitude for feeder voltage optimization, but the capability to support this important function alongside other applications could add significantly to the business case for µPnet deployment.

3) *Microgrid Coordination*

To advance the opportunities for active control based on µPMU measurements, we will study requirements for hierarchical, layered, distributed control of an islandable cluster of aggregated distributed resources and identify the merits, if any, of angle as a state variable. Microgrid balancing and synchronization is an application with a longer strategic time horizon, but one where the use of voltage angle as a control variable is expected to be crucial.

Generation and load within a power island can be balanced through conventional frequency regulation techniques, but explicit phase angle measurement may prove to be a more versatile indicator. In particular, angle data may provide for more robust and flexible islanding and re-synchronization of microgrids. A convenient property of PMU data for matching frequency and phase angle is that the measurements on either side need not be at the identical location as the physical switch between the island and the grid. A self-synchronizing island that matches its voltage phase angle to the core grid could be arbitrarily disconnected or paralleled, without even momentary interruption of load. Initial tests of such a strategy with angle-based control of a single generator were found to enable smooth transitions under continuous load with minimal discernible transient effects [10].

Comparison of angle difference between a microgrid or local resource cluster and a suitably chosen point on the core grid could enable the cluster to provide ancillary services as needed, and as determined by direct, physical measurement of system stress rather than a price signal – for example, by adjusting power imports or exports to keep the phase angle difference within a predetermined limit. A variation of this approach, known as angle-constrained active management (ACAM), has been demonstrated in a limited setting with two wind generators on a radial distribution circuit [11].

In combination, these capabilities imply the possibility of distributed resources able to smoothly transition between connected and islanded states, and capable of providing either or both local power quality & reliability services, and support services to the core grid, as desired at any given time. Though the business case for this type of flexibility (essentially a form of redundancy) is not obvious at present, considerations of security and infrastructure resiliency may support the development of such strategies in the future.

VI. Conclusion

In conclusion, affordable, high-resolution measurement of voltage phase angle may offer significant new options for actively managing distribution systems with diverse resources and growing complexity. Before any of the above applications can be practically evaluated, however, it will be necessary to simply observe what phenomena can in fact be detected at the resolution of the µPMU, and what can be reliably deduced from those empirical observations. Absent any specific knowledge of the actual resolution required to observe important phenomena, the general approach is to begin by deliberately oversampling, and then use empirical observations to determine how much was unnecessary. The null hypothesis, which we cannot reject out of hand, is that ultra-high-resolution voltage phase angle measurements on distribution circuits yield nothing interesting, nor actionable. Perhaps the most exciting aspect of this project is that we don't know just what to expect.

VII. Acknowledgments

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