Micro-Synchrophasors for Distribution Systems

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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. 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), is beginning 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 proposed 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 [1] 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, PMU data are used almost exclusively to observe transmission systems. Distribution system applications are more challenging in three respects: First, 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, rather than tens of degrees). Second, distribution system measurements will be fraught with much more noise from which the angle signal must be extracted. Third, 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. Our proposed µPMU technology is expected to discern angle differences to significantly better than $\pm 0.05^\circ$ (aiming for $\pm 0.01^\circ$), contextualize these phase angle data with a detailed power quality recording, and do so at a low installed cost.

The µPMU 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, 1-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 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

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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.

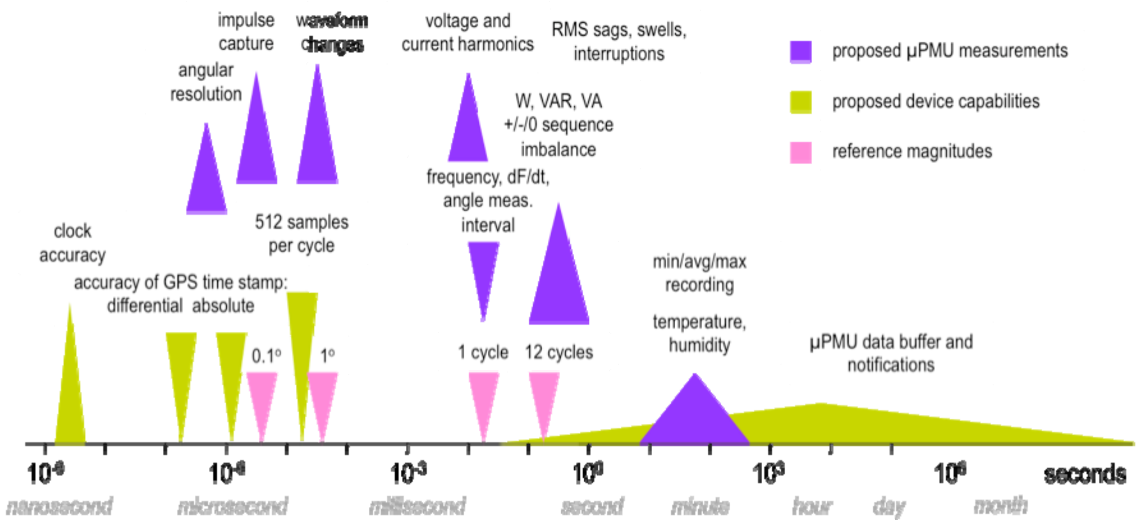

Figure 1. Time Scale for μPMU Performance

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.[2]

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.

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.

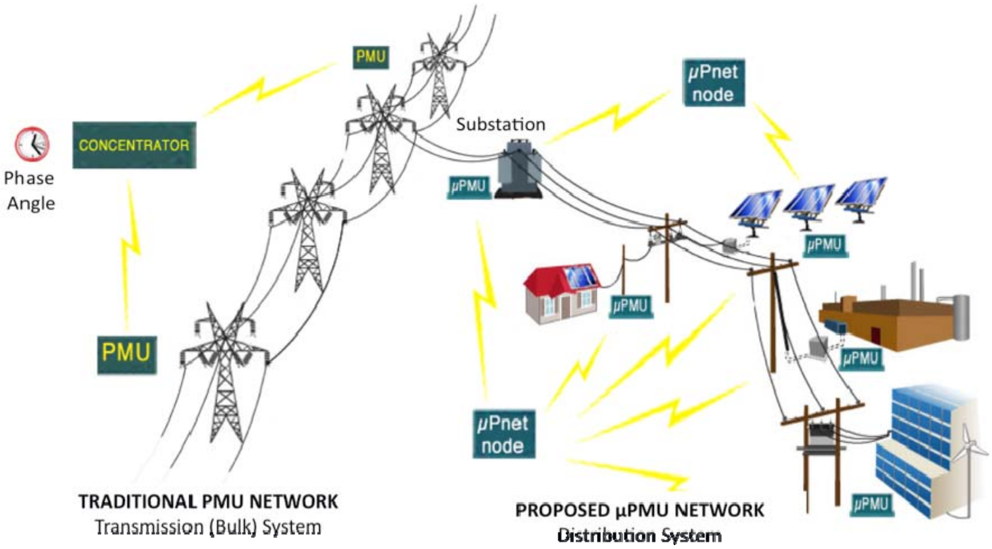

Figure 2. µPnet Concept

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.[3-5] Our research task 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. 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.

It is useful 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."

A. Diagnostic Applications

Diagnostic applications for consideration in this project include island detection, fault location and high-impedance fault detection, identification of fault-induced delayed voltage recovery (FIDVR), distribution system state estimation including reverse power flow detection and phase balancing, renewable generation monitoring, oscillation detection, characterization of generator inertia, and supporting transmission system diagnostics. After an initial screening for specific data requirements and practicality of field implementation, we will select a subset of these diagnostic applications for further algorithm development and testing.

1) Unintentional Island Detection

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 (which mandate disconnection) from other abnormal conditions where it is desirable to keep DG online (for example, low-voltage ride-through). The comparison of phase angle between a potential island and the rest of the grid is the most definitive test that offers not only high sensitivity, but specificity – i.e., ruling out an island if the phase angle remains locked, and thus allowing generators to remain online when they are needed most. Preventing DG from unnecessary trips during stressed grid conditions has important implications not only for distribution power quality and reliability but for transmission operators as well, who are increasingly concerned about the vulnerability of the grid to cascading events behind the substation.

2) Fault Detection and Location

Protective devices on distribution circuits are generally based on overcurrent relays that respond to a combination of current magnitude and duration. This makes it very difficult to detect high-impedance faults, where the fault current is similar in magnitude to load current. Furthermore, once a fault is isolated, its exact location is difficult to determine remotely. The actuation of a particular circuit breaker or fuse only identifies a general section of a feeder where the fault has occurred. The standard approach then is for line crews to physically patrol the length of the faulted line section, looking for damaged equipment. This process is time-consuming and costly, even more so for underground cables.

Algorithms exist for recognizing high-impedance faults as well as 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 µPMUs will allow fault detection and location with much greater precision than before, even with relatively few devices deployed on a circuit. This is because voltage angle measurement makes it possible to compute changes in impedance between two measured points, and thus diagnose a fault even if the current magnitude is insufficient to trip a protective relay. The impedance between the faulted point and a PMU on either side then also indicates the relative location of the fault. If successful, methods based on µPMU measurements could drastically reduce service restoration times, and enhance safety by ensuring reliable fault detection.

3) FIDVR

Fault-induced delayed voltage recovery (FIDVR) is a condition marked by a prolonged period of voltage recovery after a low-voltage event due to a relatively brief fault, followed by voltage overshoot and a period of high voltage. FIDVR is caused primarily by single-phase residential air conditioners that stall under low voltage and draw large currents before triggering a thermal switch that trips them off. The resulting loss of load then causes a high voltage condition, which can in turn trigger corrective devices such as switched capacitor banks and create further instability. FIDVR is a problem identified at the transmission level, but will likely be resolved in distribution where the problem originates. The diagnostic challenge, for which µPMU data may be suitable, is to quickly distinguish the unique characteristics of FIDVR from other types of abnormal voltage conditions, or even anticipate a FIDVR event, so as to avoid overcorrection and perhaps develop effective active mitigation measures.

4) State Estimation

State estimation, or identifying the steady-state voltage magnitude and phase angle at each node in a network, significantly informs the situational awareness of human operators as well as many automated control actions in a power system. However, 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. Direct voltage angle measurements on a feeder could vastly speed up and improve the accuracy of state estimation techniques.

5) Reverse Power Flow

A simple yet important aspect of the distribution system operating state is reverse power flow on any line segment. The significance of reverse flow hinges on the type of protection system design used by the utility, and whether the coordination of protective devices could be compromised under reverse flow conditions. While some circuits may be able to safely backfeed all the way through the substation, others could introduce problems that would be expensive to remedy with bi-directional protection.

One way to take advantage of µPMU data would be to detect reverse power flow on any feeder segment with a minimal placement of physical devices throughout the circuit. Owing to the information conveyed by phase angle, fewer points may have to be instrumented than with conventional current measurement, potentially making the µPMU approach more economical.

6) Renewable Generation Monitoring

Besides line flows, a key aspect of situational awareness for distribution operators is knowledge of generation resources and loads on a circuit. With much DG connected behind the meter, however, only *net* loads are visible to the operator. This type of masking of generation and load compromises forecasting for both sides of the equation, and makes it difficult if not impossible to estimate N-1 contingencies (such as a common-mode generation trip following a disturbance). It is conceivable that analysis of µPMU data could help "unmask" net metered generation to assist in both distribution system operation and planning. Though we are not yet certain whether and how such an algorithm will work, the significant practical value of this application justifies exploration.

7) Oscillation detection and Generator Inertia

Voltage phase angle provides unique visibility of dynamic behaviors such as power oscillations. 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 [6]. 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.

Related to oscillations, generator inertia plays an important role in stabilizing a.c. systems. It may become increasingly important to understand the impact of switch-controlled generators (i.e., inverters and advanced wind machines) displacing rotating machines, and how the former might be programmed to to provide the best stabilizing effect. Direct measurement of phase angle may support the quantitative analysis of inertia properties.

8) Transmission System Diagnostic Support

Though our research will focus on distribution system applications, we also intend to examine how µPMU data can usefully supplement transmission PMU data. Our approach envisions µPMUs and µPnet nodes dedicated to distribution system or microgrid environments, with capability for communicating with other PMU systems as needed, through NASPInet-defined gateways and via the appropriate communications protocols. The design intent of our µPMU network is to use the same file formats and data exchange methods that are established (or in the process of being established) at the transmission level, such as IEEE C37.118 for synchrophasor measurements and data formatting, and IEC 61850 for data exchange, to provide a basis for seamless integration if desired. This will require consistency with data security criteria according to NERC and FERC.

B. Control Applications

Possible control applications include protective relaying under two-way flow, volt-VAR optimization, coordination of resources on a microgrid, intentional islanding and re-synchronization of microgrids, and the creative recruitment of distributed resources for ancillary services.

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 [7]. We plan to examine whether and how the same could be done in distribution systems.

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 [8].

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 [9].

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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