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Micro-Synchrophasor Data for Diagnosis of Transmission and Distribution Level Events

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Micro-Synchrophasor Data for Diagnosis of Transmission and Distribution Level Events

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***Abstract*—This paper describes the benefits of time synchronized advanced sensor data for event detection. We present measurement data collected from a network of micro-synchrophasors (μPMU) installed at Lawrence Berkeley National Laboratory (LBNL)–the first pilot network of distribution-level phasor measurement units (PMUs). The time-synchronized, high fidelity voltage magnitude and phase angle data described provides indicators for events originating at transmission or local distribution level events sensed through the LBNL network.**

***Keywords*—Distribution networks, transmission system, sensor measurements, synchrophasors**

I. Introduction

Today's power distribution systems were designed for one-way power flow and have minimal diagnostic capabilities for continually monitoring the operating state. The growth of distributed energy resources, including renewable generation, electric vehicles and demand response increases variability and uncertainty on the grid. When there are short-term and unpredicted fluctuations and disturbances on the grid, high resolution synchronized time series data could be beneficial for managing distribution networks and circumventing damage to valuable instrumentation and high impact loads. Micro-synchrophasors, or micro-phasor measurement units (μPMUs) are designed for direct measurement of voltage phase angle at the power distribution level to support a range of diagnostic and control applications [1].

Power Standards Lab (PSL) is developing high-precision μPMUs that are being deployed and studied by Lawrence Berkeley National Laboratory (LBNL). Specifically, LBNL is studying the benefit of synchrophasor data for diagnostic and control purposes in distribution systems [2, 3]. A network of these μPMU devices provide high-resolution GPS-enabled time synchronized power measurements that can be used to compare voltage and phase changes at multiple locations on the grid [4]. This capability would greatly benefit event detection, diagnosis and post-event analysis.

Through an Advanced Research Projects Agency-Energy (ARPA-E) award, these μPMUs are being deployed at multiple utility and campus locations, with the initial network of seven units installed on LBNLs 12 kV distribution grid. Three key objectives of this deployment are: (i) supporting distribution system planning and operation functions related to utility-owned infrastructure; (ii) diagnosing wide geographical system conditions with increased density of measurement nodes; and (iii) facilitating control of distributed energy resources (DER), including generation, storage and DR.

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II. Background

Historically, distribution operators have relied on limited measurement data including on or off status of smart meters and field crews to monitor and report on system status. Despite increasing prevalence of supervisory control and data acquisition (SCADA) and smart metering infrastructure, verification of system operation faults are mostly conducted manually, at the very basic level with field crew driving to check if a switch is open or closed, or to find the location of a downed line [5]. The source of disturbances, in particular power quality type voltage events, are often difficult to find, and harder to visualize. With the prior state of one-way power flow to distribution, it was not cost-effective to instrument distribution circuits with advanced monitoring equipment. However, with the growth of distributed energy resources and associated fluctuations and disturbances, there is an increasing need for extensive investment in sensing and communication equipment on the distribution circuit.

Our μPMU network records high resolution time-synchronized data at multiple locations on distribution circuits. The monitoring applications that can be supported by data obtained from our μPMU network include island detection, oscillation detection, fault location, identification of fault-induced delayed voltage recovery (FIDVR), distribution system state estimation, characterization of inertia contributed by individual generators, and supporting transmission system diagnostics [2].

Transmission level synchrophasor units and their use for fault diagnosis and detection have been extensively studied in the literature. Phasor technologies are first demonstrated in a joint effort by the Electric Power Research Institue (EPRI), Western Area Power Administration (WAPA), Department of Energy (DOE), and the Bonneville Power Administration (BPA) [6]. In an effort by the Consortium for Electric Reliability Technology Solutions (CERTS) [7], realtime monitoring and control applications using phasor measurements are developed and prototype applications are demonstrated. In [8], the authors present an arcing fault detection technique for extremely high voltage/ultra-high voltage transmission lines. In [9] the authors identify fauilt induced delayed voltage recovery (FIDVR) indicators observed before and after such events. The authors also present PMU measurements of a FIDVR event triggered by a sub-transmission fault.

Events on distribution can be either caused or exacerbated by local conditions in switching and load, but also can originate at transmission and impact various types of load differently at the local level. Distinguishing and characterizing these differences are dependent on the event characteristics but also the properties of the load. Several researchers have proposed energy disaggreation or non-intrusive load monitoring (NILM) frameworks to tackle the problem of building/neighborhood-level appliance/load identification. The main motivation behind these frameworks is to identify the operation of individual loads based on single point measurements at a building's main panel and/or electrical meter to infer characteristics of the individual loads [10, 11] and/or estimate neighborhood-level metrics for certain types of loads (e.g., air-conditioners) [12, 13]. A discussion of event detection algorithms and a comparison of the existing NILM algorithms can be found in [14] and [11] respectively. Recently, using advanced metering infrastructure to do load identification/energy disaggregation has been granering interest in the research community [12, 13]. Although, the advanced metering infrastructure provides important insights into customer level consumption patterns, they provide limited insight into load characteristics. High-frequency datasets provide necessary information that can facilitate extraction of features pertaining to the electronic make-up of the load. For instance, features like start-up transients are an artifact of in-rush current required to start the device, and are more pronounced in inductor-based loads. A significant portion of the research uses engineered features formed by high-fidelity measurements at the building-level to do load detection and classification [15, 16, 17].

We believe that μPMUs provide not only invaluable insight into distribution network conditions, they compliment the fault detection and diagnosis at the transmission system level. Furthermore, they can provide valuable insight in to the load identification/energy disaggregation problem.

One type of event that can be observed—and that is of concern in this paper—is a voltage sag, which is a short duration reduction in rms voltage [18], which can be caused by a short circuit, overload or starting of electric motors. A voltage sag could be a local experience, for example by a large motor start on the distribution system, or caused by external forces, such as a transmission line fault at the source to the distribution grid. Distinguishing between these types of events is a useful feature of time synchronization of data. One example where such a feature is useful is in the identification of the source of an outage for DER. Outages of large DER sites can have significant negative economic impact on their bankability and operational characteristics, steps can be taken to mitigate such an impact for example tuning specific inverter ride through requirements for the area which they are electrically located. This tuning and proactive mitigation strategy cannot be completed without the assistance of time synchronized voltage and current data.

A voltage sag occurs when the rms voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle to one minute. μPMUs measure voltage phase angle, the precise difference in timing on the AC grid. Relevant phase angle differences on distribution systems are small (fractions of a degree) and not readily measurable with existing transmission system synchrophasors.

III. μPMU Technical Description

Power Standards Laboratory has developed and manufactured a new μPMU device [3], based on their commercially available power quality recorder, the PQube funded initially via ARPA-E project micro-synchrophasors for distribution. PQubes continuously sample ac voltage and current waveforms at 256 and 512 samples per cycle, simultaneously with a wide range of power quality measurements and environmental conditions. 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 in standard outlets or through potential transformers (PTs) as are already found at distribution substations. It could also be added on primary distribution circuits if necessary.

Enabled with a remotely-mounted micro GPS receiver, the key advantage of the phasor measurement units is voltage measurements with precise time stamps to compare the phase angle between different locations, down to the very small variations (fractions of a degree) that exists on distribution circuits. μPMUs measure voltage phase angle to a 0.01 degree accuracy, giving measurements of the precise difference in timing on the AC grid. All measurement values are aligned in time to better than 1 microsecond between any pair of μPMU devices.

The Quasar software infrastructure developed at UC Berkeley builds on the simple Measurement and Actuation Profile (sMAP), a foundation for managing both real-time and archival data from a wide variety of physical sources [19]. The μPMU devices communicate live via ethernet to the Quasar server, which handles storing and displaying the data for comparison and analysis. This capability allows for real-time monitoring of distribution events, as well as capturing measurement data for post-fault analysis.

LBNL has installed μPMU devices in seven locations at LBNL on separate busses downstream from the distribution substation feeder head, as shown in figure 1. This is the first μPMU network to be installed on a real electrical grid. There is also one μPMU installed at PSL. The μPMU devices relevant to this paper are: Grizzly, A6, and Bank514 at LBNL in Berkeley, CA, which are electrically connected to approximately 20 miles of transmission line to PSL located in Alameda, CA. Note that Grizzly and A6 are on the same distribution feeder, while Bank514 is on a separate feeder.

IV. Event Detection: Transmission vs. Distribution

Observing μPMU voltage magnitudes and current angles at multiple locations can provide indications and guidance as to whether the event occurred on the transmission or distribution circuit. Synchronized measurements can reveal phenomena that are common at separate geographical measurement locations. Distribution impacts can be visualized on the transmission system, and vice versa.

A. *Transmission-level Events*

A voltage sag was detected at the Grizzly μPMU at LBNL. Upon further investigation of data from the other μPMU devices in Berkeley and Alameda, the voltage magnitudes are

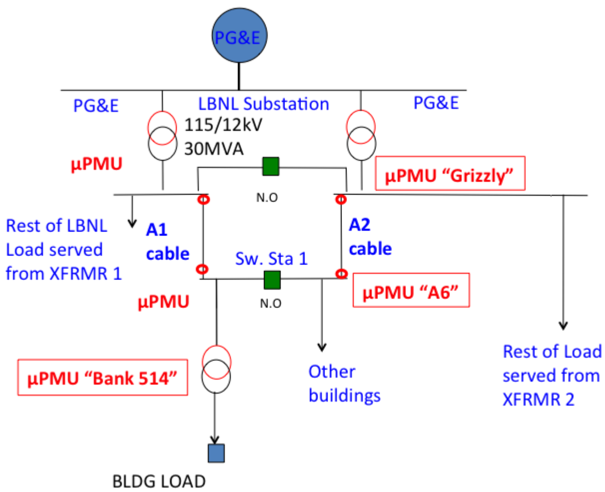
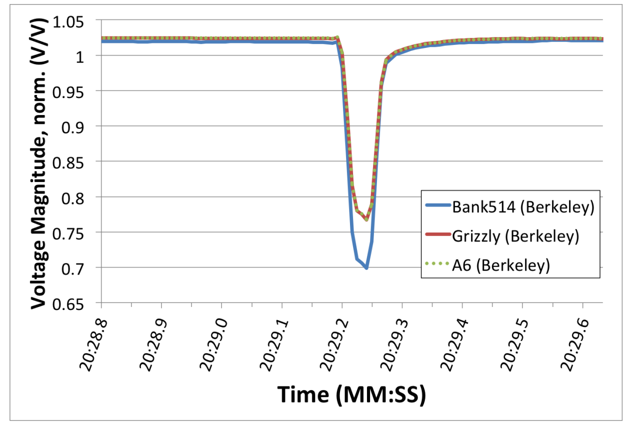
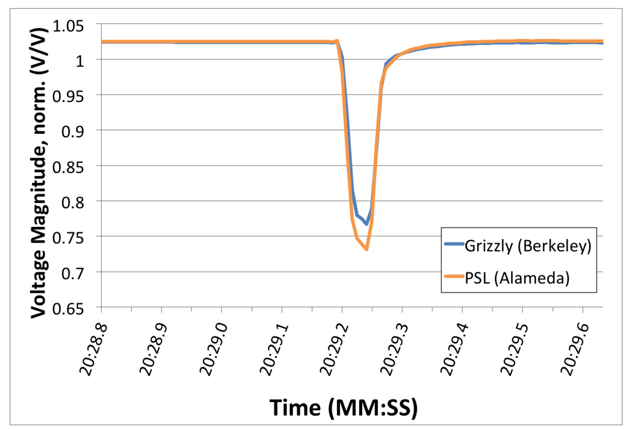


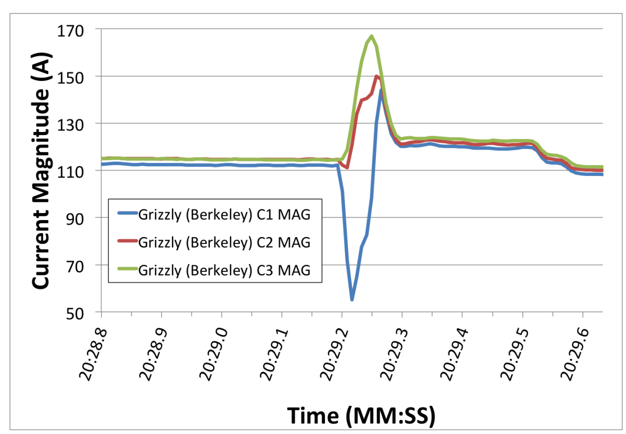
Fig. 1: LBNL μPMU deployment map (simplified)



(a) Voltage magnitudes (L2 phase) measured by μPMU devices at LBNL (Berkeley), normalized to bus nominal voltages.



(b) Voltage magnitudes (L2 phase) measured by μPMU devices at LBNL (Berkeley) and PSL (Alameda), normalized to bus nominal voltages.



(c) Current Magnitudes measured by the Grizzly μPMU at LBNL (Berkeley).

Fig. 2: Transmission-level event: Voltage sag in Berkeley and Alameda.

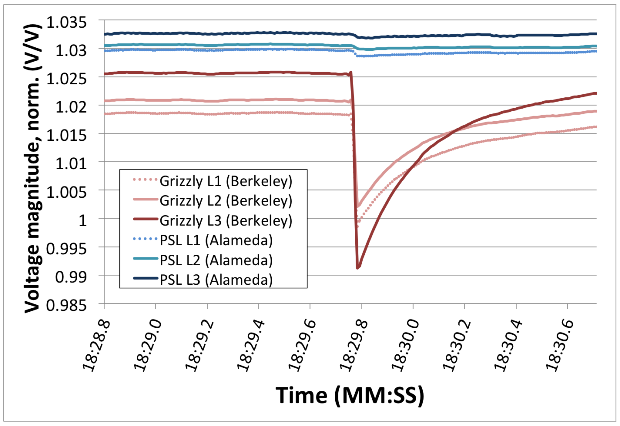
of comparable values. Figure 2 shows the voltage sag event, with voltage magnitudes on L2 phase at LBNL and PSL, and current magnitude recorded at the Grizzly μPMU at LBNL. At LBNL, the Grizzly and A6 μPMU devices are on the same distribution feeder, while the Bank514 μPMU is on a separate feeder. This voltage sag occurred simultaneously at the LBNL and PSL locations, which is a strong indication that this was a transmission-level event.

The voltage sag was approximately 0.3 to 0.35 per unit for more than 3 cycles, detected on Phase 2, at both Grizzly, A6, bank 514 and the Alameda location simultaneously. There was a moderate but not significant temporary increase in current in response to the voltage sag.

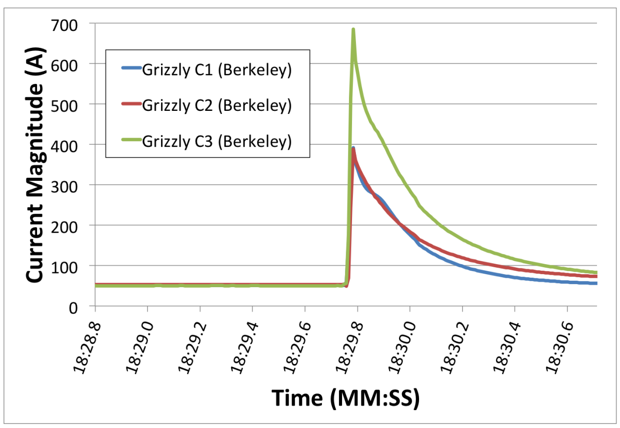
B. Distribution-level Events

Using the same network of data we can distinguish a distribution level event on the LBNL campus. In this particular event there is a transient current spike at approximately 10 x the normal current drawn at this location, followed by a local voltage decrease. The voltage decrease was not of sufficient magnitude or time to be considered a sag. As we move geographically further from the current event measurement, the magnitude of the voltage event decreases, which indicates this was a local event.

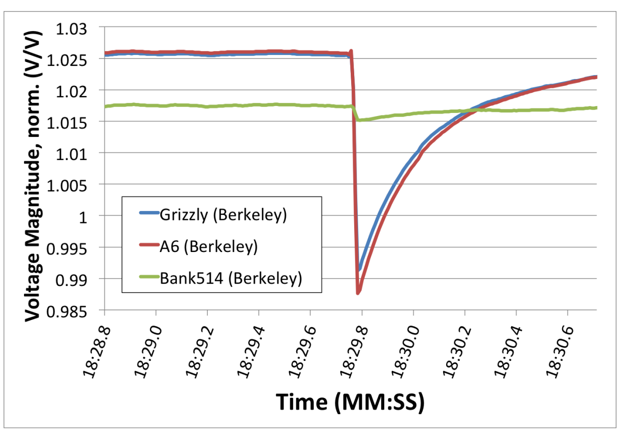
Figure 3a shows the voltage magnitudes detected in Berkeley and Alameda, and Figure 3b shows the current magnitude of the current spike at LBNL. Although the effects in Alameda were miniscule in magnitude, it was clearly identifiable with the μPMU network by simultaneity. Even when comparing the voltage magnitudes detected in Berkeley on separate distribution feeders (Grizzly and A6 on the same feeder, and Bank514 on a separate feeder), figure 3c shows that there is a significant difference between the two feeders. The synchronized μPMU devices detected a disturbance of about 0.0015 p.u. at Bank 514 (in Berkeley) and also picked up on a 0.0003 p.u. disturbance at PSL (in Alameda).



(a) Voltage magnitudes measured by μPMU devices in Berkeley and Alameda, normalized to bus nominal voltages.



(b) Current magnitudes measured by the Grizzly μPMU in Berkeley.



(c) Voltage magnitudes (L3 phase) measured by μPMU devices on different feeders in Berkeley: Grizzly and A6 on the same feeder, and Bank514 on a separate feeder. Normalized to bus nominal voltages.

Fig. 3: Distribution-level event: Arc flash in Berkeley.

V. Benefits of μPMU Data for Diagnostics

Distribution planners and operators require high-quality data delivered in a timely manner so that they can make valid choices in both the near and long term. Timeliness will depend on the application of the data; for example, operations require short-term decision making information, while planning may require longer-term calibration data.

Each of the above data sources, like power systems themselves, have inherently different time scales of importance. For example, economic price signaling to DR could be on an hourly basis, but could also inform customer behavior and therefore load in shorter time steps once DR is activated. Weather data for forecasting of short-term variability is on the seconds-to-minutes time scale. Grid and component models require scales from sub-cycle to seconds to hours. Future distribution grid planning and management decisions will require knowledge of evolving grid conditions that is collected at many different time scales; therefore, planning and operational software applications will need to be prepared to take in different formats and fidelity.

VI. Conclusions

A network of time synchronized μPMU devices would be instrumental for reducing downtime and failure for sensitive equipment with high usage at commercial, industrial, and laboratory facilities. The capability to detect and distinguish transmission-level and distribution-level events is a significant step towards solving critical issues stemming from costly and unpredictable interruptions. We are exploring applications of μPMU data in distribution systems to improve operations, increase reliability, and enable integration of renewables and other distributed resources. Synchronized distribution level phasor measurements can enhance planning for power flow and system control, security and resiliency in the modernized grid.

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VII. Biographies

Anna L. Liao (M'15) received the M.S. in Robotics from Carnegie Mellon University and B.S. in Electrical Engineering and Computer Sciences from UC Berkeley. She is currently a Scientific Engineering Associate at Lawrence Berkeley National Laboratory in Berkeley, CA. Her current research interests include: software algorithms and data analysis of networked micro-synchrophasors; and software and hardware integration for field studies of energy efficiency in residential and small commercial buildings.

Emma M. Stewart (M'08) completed her undergraduate degree in Electrical and Mechanical Engineering from the University of Strathclyde in 2004 and a PhD in Electrical Engineering in 2009. She joined BEW Engineering (now DNV KEMA) as a Power Systems Engineer in March 2009 and held the position of Senior Engineer in the Transmission and Distribution team where she led distribution modeling and analysis and high renewable penetration studies for California Solar Initiative Studies. Dr. Stewart joined Lawrence Berkeley National Laboratories in 2013, and is currently engaged in distribution measurement and analysis techniques for smart grid applications.

Emre C. Kara (S'12 M'14) received his M.Sc. degree in building engineering from Delft University of Technology, the Netherlands in 2010 and his Ph.D. degree in Civil and Environmental Engineering from Carnegie Mellon University, Pittsburgh, PA. He is currently a post-doctoral researcher at Lawrence Berkeley National Laboratory, Berkeley, CA. His research interests include understanding the energy use of buildings, modeling and control of building loads to provide demand response services to increase power system reliability.