DATA DRIVEN APPROACH FOR MONITORING, PROTECTION AND CONTROL OF DISTRIBUTION SYSTEM ASSETS USING MICRO-PMU TECHNOLOGY

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ABSTRACT

This paper describes applications for micro-PMU technology that address emerging issues in the distribution system due to stresses from dependencies on high DER penetration and microgrids. Lessons from the deployment of micro-PMU technology at a major utility and microgrid are shared in the paper, offering opportunities for enhanced analytics to inform command and control methods to manage the impact of these dependencies on events in distribution networks.

INTRODUCTION

In recent years, the dynamic and unpredictable behavior of distribution networks has grown considerably due to the emergence of customer side technologies for which they were not designed. These resources - including demand response, intermittent and distributed energy resources, and electric vehicles are behind the meter. At high penetration levels these resources have the potential to place a strain on the distribution network. In tandem, the distribution grid is aging significantly, making equipment more susceptible to stress, which could result in increasing equipment failure. For example, transformer failures account for a larger share of equipment issues impacting grid resiliency and reliability. Transformer failures rates reached 2% of the installed base in 2010 [1] and the trend is expected to rise rapidly in the near future. Anomalies and outages can be related to factors such as weather and stochastic generation, equipment degradation, or physical and cyber security attacks. High penetration DER and microgrids increase system vulnerability to these factors. Predictive analytics offer tools for managing these resources to minimize and mitigate the impacts from adverse events.

The research described in this paper utilizes high fidelity distribution level phasor measurement units (µPMU's developed by Power Standards Laboratory) to detect anomalies on the distribution network that, without measurement and analytics, may have gone unnoticed. With these measurements, analytics can help assess the risk of outages and negative impact on the distribution system and can be utilized in proactive mitigation strategies. These strategies may positively engage DER. While categorizing events such as current and voltage transients is useful, the presence of anomalous behavior in itself is a key indicator of degrading grid performance.

Recently distribution grid analytics are coming to use data from smart meters; however, limitations in communications, data type, and data volume, and consumer privacy concerns, have limited the use of such data to basic applications such as narrowing the location of outages. These limitations can be overcome by using distribution level synchrophasor data, and synchronizing metadata and power flow models, which our research shows to offer a significant improvement in the speed and accuracy of anomaly prediction. This improvement is an important step toward realizing the vision of a smart grid with real-time distributed dynamic control and optimization of electric power grid, DER, and microgrids for resilience, economic coordination, reduced environmental impacts, and self-healing.

Microgrids benefit both the customers and the distribution system by creating controllable entities that potentially can integrate significant amounts of renewable generation, reducing congestion on distribution feeders and enhances the reliability and resiliency for the customers, and reduces operation costs. These benefits can be enhanced with integration of predictive protection methodologies, such as those offered by µPMUs with control systems and operations.

The analytics described in this paper are extended beyond the distribution system to consider precursors for DER and microgrid operations within the context of the larger bulk power system. If significant bulk power level events are occurring and impacting the distribution system, an islanded operation scenario enhances the security of supply. Likewise, events at the distribution level may impact transmission, such as cascading outages caused by the disconnection of large amounts of behind the meter solar generation. In this work, we identify the risk of impact to a microgrid or load at points in the Lawrence Berkeley National Laboratory substation [2], Southern California and in future will consider a microgrid at the Philadelphia Navy Yard. Understanding the signature characteristics of distribution system events will serve to advance feeder level power system models and improve reliability.

BACKGROUND

When considering the microgrid and aggregated DER as an integral part of the power delivery system, there are two individual perspectives for maintaining reliable operations, the bulk system or grid operator, and the microgrid operator/controller. Both of these perspectives can be considered as an automated machine function, or a human in the loop. These two operators should coordinate any decision to island a microgrid on the occurrence of an abnormal event, or outage, or economic benefit. These decisions are predicated on the quality and timeliness of data and analyses – useful information.

A system operator may decide on what load entities should be separated, or shed, in case of a cascading failure, planned through a series of scenario simulations and then programmed into automated protection operations and operator decision processes. When the feasible islanding points are given to the system operator, e.g., the locations of microgrids in the system, the system operator may decide when and where to disconnect. From the grid operator's point of view, islanding a microgrid could be considered equivalent to pre-contingency load shedding. However, with the microgrid capabilities, the load remains served, benefitting both customers and utility.

With sufficient information available a microgrid operator may decide to desynchronize when the risk of outages outweighs the presumed cost of islanding. Whether the microgrid operator has the authority to make this decision may depend on the size of the microgrid load, the rules of the main grid operation in the jurisdiction, and the judgment of the main grid operator in a particular situation. Additionally, the microgrid controller may have its own criteria as to whether it is safe to desynchronize at a given moment. The system operating limits and interconnection reliability operating limits of a grid operator can be established based on simulations with a discrete set of scenarios, but the decisions at a given situation are largely based on the operator's judgment and experience [3]. This is not dissimilar to decision making of microgrid operations. However, a microgrid controller may be able to adopt a decision-making procedure that is more informed and systematic than at the main grid level. This is because a microgrid has a smaller set of elements in the system, thus creating fewer scenarios of boundary conditions of operation [3].

Both these scenarios are inherently dependent on the real-time data that is made available to controllers/operatos. The availability of micro-synchrophasor measurements, translated into a risk of event, can provide more accurate footprints of past events (both in time and geographic locations), thus contributing to a systematic procedure for predicting and managing outages

The majority of literature on control theory for microgrids focuses on protection scheme when the utility supply is at risk, and strategies for response after islanding. [4-10] discuss protection strategies for a microgrid and the low-voltage distribution system that it is connected to. A control strategy of a series inverter between the microgrid and utility grids is studied in [4]. Control schemes for distributed generation, storage, and inverters after islanding are proposed in [5]. [8] proposes a principle of "partitioning" the microgrid into multiple regions to minimize interruption of service to loads. A general protection philosophy is laid out in [8], where the authors argue for the same protection strategies for both connected and islanded operation of a microgrid. Fault events that lead to islanding of a microgrid are discussed in [9], where it points out that an unplanned islanding process is dependent on factors such as pre-islanding operating conditions, the type and location of the fault, the islanding detection time interval, the feasible post-fault switching actions, and the type of distributed generation units within the microgrid. Standards and common practices of operating microgrids have been published, for example, in [11, 12]. The IEEE 1547 standard for Distributed Energy Resources Interconnection and Interoperability with the Electricity Grid address the interconnection of DER and the utility grid is one such standard [12]. However, it does not address DER self-protection or planning, designing, operating, or maintaining the customer/local facilities and the utility grid, which is relevant to islanding operation decisions for a microgrid.

The use of high fidelity grid data to enable intelligent proactive decisions on whether or when to island a microgrid has been less studied. As pointed out earlier, this is mostly because of the nature of outage management practice at the system level that depends on the operator's judgment and experience due to the complexity of the system and the variety of factors attributed to potential risky scenarios. This paper explores ways to reduce the ambiguity of this procedure by using analytics of synchrophasor data to quantify the risks of outages in terms of both probabilities of the events and their consequences.

SENSORS AND VISUALIZATION

Micro-phasor measurement units (μPMUs) are high-precision instruments designed for making synchronized, time stamped measurement of voltage magnitude and phase angle at the power distribution level. The work described in this paper is based on a project funded by ARPA-E to develop μPMU hardware, software, and early applications [4]. μPMUs are deployed in the field on the LBNL campus and with several partner utilities, of which we present data from in this work. The μPMU is a development of the PQubes which continuously samples A.C. voltage and current at 512 samples per cycle at the fundamental frequency, When equipped with a high-precision GPS receiver for time stamping, and with appropriate firmware, the PQube becomes a μPMU that continuously computes and streams rms magnitudes and phase angles twice per cycle (100 or 120 Hz).

In order to classify and attribute risk to a specific event causing an outage, we utilize a multi-resolution search algorithm, which leverages the Berkeley Tree Database (BTrDB). The construction of this database is not the subject of this paper and can be reviewed in [15]. We query BTrDB, and its statistical summaries of data for any time range, or continuously throughout the measured data period. If an event trigger is identified, the algorithms will dive into further data detail, and pull the individual detailed sample level data. Clusters of events can be obtained and compared utilizing this method and additional clustering techniques, for example, k-means clustering [16] and kernel Principal Component Analysis [17]. One example is detection of voltage events, which could be sags related to distribution or transmission operations, motor starts, voltage regulation actions from upper or lower network, or a large load step. While many data analytics strategies can evaluate the presence of voltage events, the key in these analyses is the synchronization, and evaluation of relational events to enable a risk based analytics methodology. While the presence of a singular voltage sag, for example, is not risky, a voltage sag plus recloser action, or a voltage sag in tandem with a tap changer action could be considered a higher risk, or indicative of a failure. Repeated voltage and current transients could also indicate a repeated tree strike or animal activity for which the microgrid operator may desire to take action, or enable the grid operator to desynchronize a portion of the load and distributed generation, un-loading the line, and allowing time for a crew to be dispatched.

EVENTS ANALYSIS

High risk type events that are discussed in this paper include those driven by the bulk system (transmission level), local behavior (load, DER and distribution networks), and external factors (tree strikes, animals, weather).

Equipment and Distribution Driven Events

Two types of issues are generally of interest in distribution system diagnostics: power quality events, and longer-term degradation. While these issues are often considered separately, predictive analytics lies at the junction of power quality monitoring and long-term equipment health. Specifically, a power quality event can be indicative of a degradation issue: for example, in the case in [17], voltage sags indicate an event related to the on-load tap changer (OLTC) transformer. Subtle triggers and behavior, which are only visible through high-resolution measurements, are key to this application, but translating the data to actionable information is a limitation [18], [19].

Other event types to be considered, and at present measured in the dataset, are equipment mis-operation, tree strikes and animal issues on distribution feeders, and lightning insulator failure. While some of these events are not easily preventable, extraction of the repetition of the event behavior allows for risk based analysis and preventative action. For example, if minor tree strikes are detected often on a particular section of a line, tree trimming could be prioritized there before a more major outage or fire occurs. Integration of such event signatures into the predictive analytics tool and identifying repeated events enables operators to determine the risk for particular locations, and take preventive action such as dispatching a tree trimming crew. **Figure 1** shows a series of events that resulted in a large PV site tripping, independently verified, by a bird contacting a distribution line and becoming attached to the line, with a subsequent fuse blow.

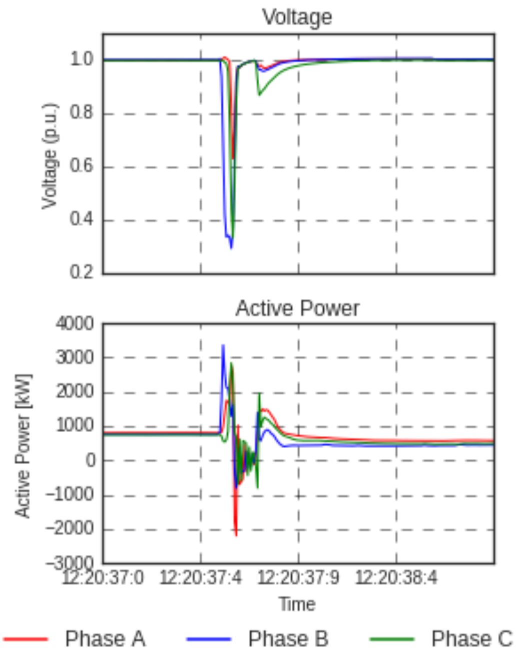

Figure 1. Signature of a bird versus a distribution feeder and subsequent fuse blow on a distribution line

A key feature of this µPMU-based event detection is that it may reveal high-impedance faults that draw insufficient current, or that draw a fault current for too short a time, to trip any protective device. While it would generally be undesirable to change protective relay settings to be exceedingly sensitive and cause nuisance trips, µPMUs can at least give operators visibility of fault events to help decide on appropriate preventive measures where possible. The following example, **Figure 2**, is also identified and verified from the utility dataset, where an animal made contact across two phases of a distribution line resulting in an outage of the DER site.

Weather and Cascades

Weather is a known cause of significant problems on both transmission and distribution, with storm preparation being a well-known contingency for operators across the world. Lightning strikes are often unpredictable and can be damaging if the system is not protected appropriately. While the damage can be limited, outages related to the protection of the system can also be significant. The example below illustrates the µPMU measuring the lightning strike and resultant DER outage at a location in Southern CA (Figure 3).

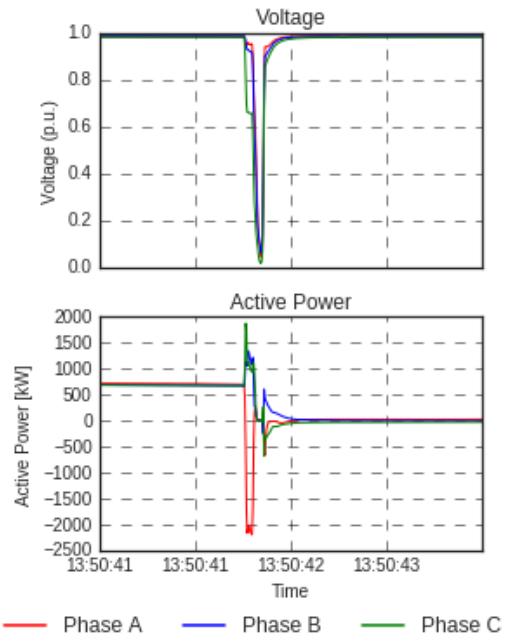

Figure 2. Measured high fidelity voltage and active power at the point of connection of the DER site captured a phase-to-phase contact of a rat with the distribution line, and subsequent trip of the DER

In comparing Figure 1 and 2 the different event signatures can be clearly identified, in the case of the rate there was a phase to phase fault and a drop in active power to zero, indicating the generation had tripped, whereas in the bird case there was a smaller voltage event but higher current draw resulting in the blown fuse. In both cases the protection operated as planned. The majority of these events have been measured in close proximity to the cause of the issue. An additional type of measurement is to evaluate non-specific, yet relational, variability in measured time series. The example in Figure 4 was measured at Lawrence Berkeley National Laboratory (data is available via powerdata.lbl.gov). The first plot, October 13th, illustrate a normal operations day, where load variability is normal. The second plot illustrates stormy conditions at the LBNL substation head, where there were significant customer outages in the bay area, and variability.

While the specific event classification and event analysis is dependent on power systems knowledge, this class of unspecified noise could be considered risky. Smaller microgrids, for example, at this point could have chosen to island. There were approximately 23,000 customer outages [20] during this event in the local area. Without a very detailed model, the exact cause of the variability is impossible to recreate, but for security of supply in microgrids, the variability increases risk and allows for advanced preparation without need to receive significant information from the utility.

FUTURE WORK AND CONCLUSIONS

The data and work presented in this paper are an initial step towards developing an advanced predictive analytics application which ingests and processes high fidelity measured power grid information to develop proactive control and mitigation strategies for events impacting distribution networks with a high penetration DER and microgrids. Numerous events have been identified from measurements and analysis at real locations, as opposed to simulations, where these strategies could be used effectively. Future work is proposed at test locations on distribution networks where a variety of scenarios and innovative strategies can be applied.

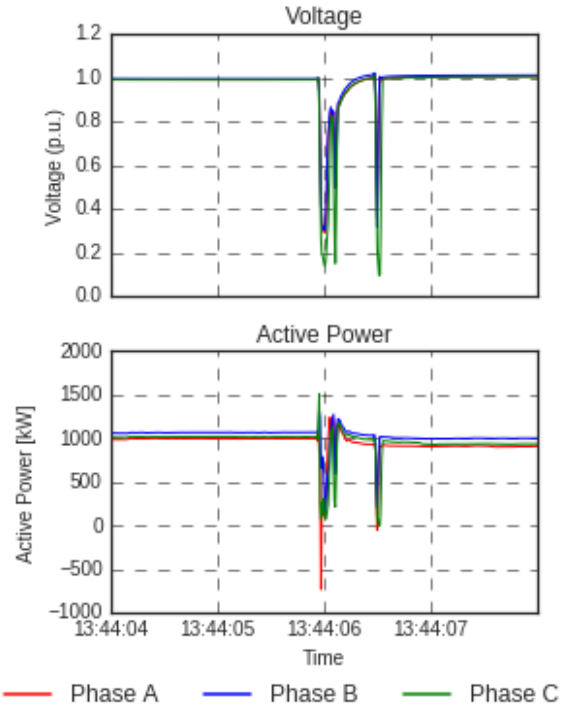

Figure 3. Lightning strike measured at substation of large DER site

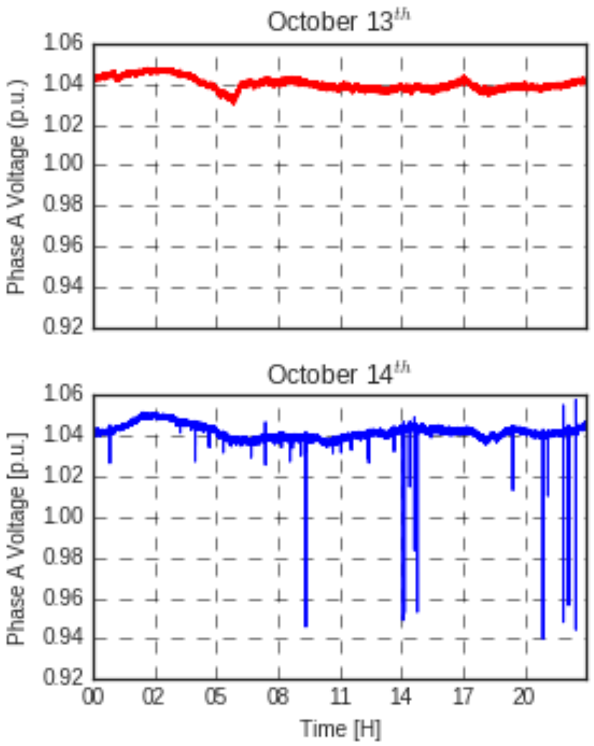

Figure 4. Variability in Voltage measured at LBNL during normal and storm conditions indicative of a risky scenario for operation

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