Deployment of High Resolution Real-Time Distribution Level Metering on Maui

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Deployment of High-Resolution Real-Time Distribution Level Metering on Maui

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Abstract

In order to support the ongoing Maui Smart Grid demonstration project advanced metering has been deployed at the distribution transformer level in Maui Electric Company's Kihei Circuit on the Island of Maui. This equipment has been custom designed to provide accurately time-stamped Phasor and Power Quality data in real time. Additionally, irradiance sensors have been deployed at a few selected locations in proximity to photovoltaic (PV) installations. The received data is being used for validation of existing system models and for impact studies of future system hardware. Descriptions of the hardware and its installation, and some preliminary metering results are presented. Real-time circuit visualization applications for the data are also under development.

1. Introduction

The ongoing Okinawa-Hawaii Smart Grid Demonstration project is preparing to install several different types of smart grid equipment into the distribution system in the Kihei area of Maui. This equipment includes advanced Distribution Management Systems, electric vehicles and chargers, and battery storage technology along with upcoming distributed PV installations. The goal of this project is to demonstrate all of these systems in concert on a real distribution network, and how they can improve efficiency and operation through advanced renewable integration and energy management and control systems.

To support these efforts the National Renewable Energy Laboratory (NREL) has been deploying advanced metering into the area in preparation of the upcoming base lining and experimental data collection needs. This includes advance real-time distribution level metering which has been developed at NREL. The distribution metering is focused at the low voltage points on the system and provides high-resolution power quality and Phasor data in real time through an active Internet connection. Additionally NREL is collecting solar irradiance data to assess the available resource and the impact on PV generation in the Kihei area.

The measurement data is archived on servers housed at NREL and will be used in several different aspects of the project. Initially, they will provide model validation input as the circuit is simulated which will also tie in with system impact studies of the upcoming smart grid equipment. In the later phases of the project, the collected data will be used in an experimental fashion to assess the system impacts and benefits of the equipment after it has been installed and operational.

This paper presents a brief technical overview of the installed metering equipment and some preliminary data collection results.

2. Distribution Transformer Monitoring

The transformer monitoring for this project is provided by NREL's real-time distribution monitoring network. This network is made up of remote metering devices which communicate to a set of data collection servers. The metering devices are built from off-the-shelf hardware with custom-developed software to handle data collection, processing, and communications. They implement phasor calculations similar to phasor measurement units [1] and additionally include power quality calculations. Hereafter the distribution transformer meters are referred to as Distribution Monitoring Units (DMU).

2.1. DMU Overview

Design of the DMUs has been specifically targeted for installation at remote and disparate points within a distribution feeder. Ease of installation was a major requirement so that the DMU could be installed at any location—ranging from the service panel of a single home up to the distribution transformers and medium voltage locations (assuming proper potential transformers were added).

Voltage sensing of this application is done directly using clip on voltage probes. The current sensing is provided by Rogowski Coils. These probes allowed for quick installation in a wide range of locations.

Two different models of DMU have been deployed on Maui. The first unit is designed for installation at 120/240 volt (V) split-phase locations and outputs the Phasor and root mean square measurements for the three voltages and currents along with all of the associated power measurements and temperature measurements.

The other installed model is designed for installation at three-phase locations, both 120 Y and 277 Y locations, and outputs the individual phase voltages, currents, apparent, and real and reactive powers along with temperature measurements.

Installation locations for these metering units were selected based on importance to model validation and proximity to PV generation. This range of potential installations also dictated the design be self-contained and able to withstand all weather conditions and temperature extremes.

Each unit transmits its data points in real time through an Internet connection. This connection can be in the form of a Wi-Fi or wired Ethernet connection if available. Additionally, each meter can be outfitted with a cellular modem. This modem provides an Internet connection through the 3G network of a cellular provider. The DMUs deployed into the Kihei circuit are equipped with this cellular modem and transmit data at one point per second.

2.2. Data Collection Network

One of the major reasons for designing this metering device from the ground up is to allow for the design of a data collection network. In this architecture, each DMU streams data back to a central location in real time or near real time. As data is received by the collection server, it is made available to a variety of visualization and analysis applications. The received data is also stored locally at the receiving end.

The basic system architecture is given in Fig. 1. Each DMU collects data from its location and transmits the data back to the data concentrator located at NREL. From there, it is distributed to various visualization applications and data services both internal and external to NREL.

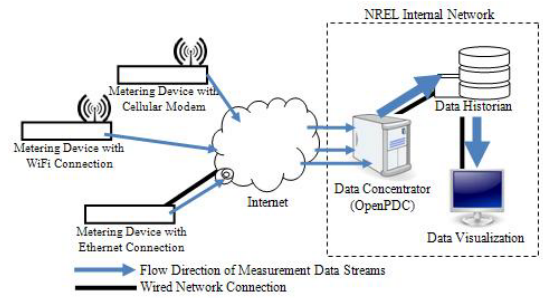

Fig. 1: Simplified data collection network architecture

The server side Data collection and storage architecture is handled by the OpenPDC software package [2]. This is an open-source software package designed for Phasor data collection and storage, initially developed by the Tennessee Valley Authority and is now maintained by Grid Protection Alliance.

This application parallels many of the desired requirements of the data concentrator system needed for this project. The individual DMUs are designed to communicate using the Institute of Electrical and Electronics Engineers (IEEE) Std C37.118 for synchrophasors [3], which is one of the built-in protocols of OpenPDC. Thus, OpenPDC is capable of communication with the metering devices without any modification. This software package is used on both the Data Concentrator and Historian servers located at NREL. The data flow architecture of this protocol and software package also supports the desired real-time data transmission for the visualization applications.

3. Irradiance Measurements

In addition to the above electrical metering, NREL has also deployed a set of five irradiance sensors, located near current and future PV installations, in order to assess the available solar resource in the area. These units are part of the Measurement and Instrumentation Data Center (MIDC) and collect one-second global horizontal irradiance measurements and relay them back to a separate set of servers in one-hour batches. More information on MIDC and publically available data from other projects are available at *www.nrel.gov/midc*.

4. Metering Installations

The metering equipment described above was installed during April 2012 with the help of MECO engineers and linemen. Three split-phase DMUs were installed on the secondary side of residential distribution transformers. Two of the three-phase DMUs were installed on the secondary side of commercial transformers, one of which was a 277V Y location and the other was a 120V Y secondary. The Irradiance sensors were also deployed at this time at sites near existing and planned PV installations in order to investigate the resource variability, generation impacts, and effects of the PV on the distribution system.

In Fig. 2 the installation on the 120V Y secondary transformer is shown. Here the white DMU box is in the lower left of the access panel. The voltage and current probes can be seen connected to the transformer z-bars. Additionally, a combined cellular and Global Positioning System, GPS, antenna has been mounted on the top of the transformer. The GPS provides both location and accurate timing information. Data is output through the onboard cellular modem and antenna.

Fig. 2: Metering installation on a three-phase transformer
Photo by Jason Bank, NREL

One of the installed LiPod irradiance sensors is shown in Fig. 3. This unit is located in the Kihei substation on Maui. This unit is mounted on a tripod and holds a Licor irradiance sensor at the very top of the assembly. Inside the data pack at the top of the tripod is a data logger with a cellular modem and GPS receiver. The data logger records one-second global horizontal irradiance measurements and then outputs them to the MIDC data servers at one hour intervals over the cellular connection. The solar panel shown here provides power to the electronics in the data pack.

Fig. 3: Irradiance sensor installed in Kihei substation
Photo by Jason Bank, NREL

5. Preliminary Measurement Results

Data has been collected and archived dating back to the equipment installation dates. This project is still in the data collection phases and in-depth analysis has not yet begun. What follows are some interesting examples of the type of data that has been collected.

Several of the metered transformers serve commercial and residential customers with installed rooftop PV systems. Measurements taken from one of these transformers are given in Fig. 4. The top trace in red is the global horizontal irradiance measurement take from a nearby sensor. It was a relatively clear day, especially in the morning with a clear ramp up to midday. In the afternoon, a few clouds passed through as evidenced by the variability in the irradiance. The power flow through the transformer is given in the blue trace on the bottom of the plot. Here, a positive value indicates power flow from the utility to the customers and negative flow is from the customers to the utility. During midday when the irradiance is highest the flow toward the utility through this transformer reaches about 15 kW.

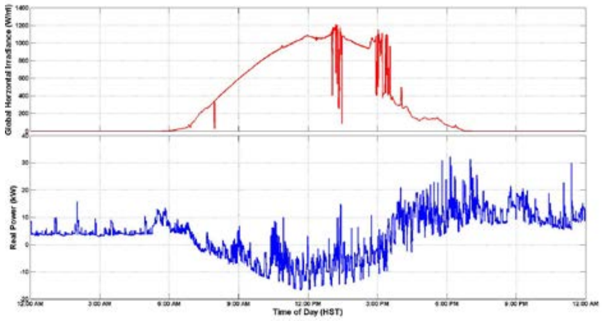

Fig. 4: Measured irradiance and transformer power flow, April 25th 2012

Review of Fig. 4 shows that the power flow is highly variable—this is probably not a result of the PV production as the available solar resource is smooth, especially in the morning. In this case, the variability in power is more likely a result of the demand. Regularly sized steps in power are also occurring which would indicate the switching of a load.

With these installations, several points across the distribution system are metered. This allows a more comprehensive view of the entire circuit. Fig. 5 demonstrates some of the voltage corrective actions on this circuit. The three different secondary voltages from the residential transformers are plotted over a time span of two hours. Voltage corrective action on the circuit can easily be observed here as step changes in the voltage. The red and black traces shown are on the same feeder as they see the same switching event. The transformer represented by the blue trace, however, is on a different feeder and being regulated by a different device as evidenced by the switching event at a different time. The high correlations of the red and black traces reinforce this. Observation also demonstrates the feeder voltage profile and that the transformer represented by the black trace is further from the substation than the red trace.

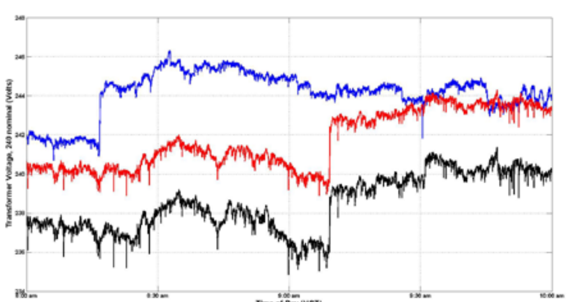

Fig. 5: Voltage measurements on three transformers, April 25th 2012

6. Load Characteristics

As qualitatively observed in the daily power output in Fig. 4, the load introduced more variability than the PV generation on the selected day. This was due to the switching of one or more loads. These events are more clearly demonstrated in the time frame of Fig. 6. Here, the black trace is the real power flow through the transformer and the red trace is the reactive power. This data set was recorded from 1:30 p.m. to 3:30 p.m. when the PV system was producing and the power flow was negative (toward the utility). Several times, the load switches on and then off about ten minutes later. The steps in real power also correspond to steps in reactive power. This would indicate a load or multiple similar loads of 4 kW and 2 kVAR, switching on and off at regular intervals.

Fig. 6: Load switching events

The load demonstrated by Fig. 6 has been observed on multiple transformers and occurs for several hours in a row, particularly in the afternoon and evening. Given the size, power factor, time of day, and switching nature it is mostly likely an air conditioning load. The frequency at which it switches can be explained by multiple similarly sized air conditioners on several buildings but connected to the same distribution transformer, all operating in the same time frame.

6.1. Assessment of Load Variability

Accurate load modeling is a major influence on validating the circuit models and for assessing the expected impacts of upcoming distribution management devices and control schemes. Mitigating the impacts of PV variability also plays into the objectives of this project. As shown in Fig. 4 and Fig. 6 the load is also a source of variability on short time scales (on the order of minutes), especially down at the transformer level monitored here.

To quantify the short-term load variability and nature of its distribution, the data must first be detrended and the median absolute deviation across a data set will be computed. The detrending algorithm is demonstrated in Fig. 7. A moving median filter is passed through the measured signal in order to filter out the short-term variability leaving the longer-term trend. Here three different median filters were implemented, one with a 1-minute window to capture the shorter term trend, another with a 15-minute window, and finally one with a 1-hour long window to track the slower load responses.

In Fig. 7 the raw data is plotted in blue, the 1-minute median filter is in red, the 15-minute filter is in black, and the 1-hour filter is in green. During this time span, a few of the load switching events discussed earlier are present along with several shorter spikes. Here it is observed that the 1-minute window tracks the switching event closely while removing the shorter term spikes. This occurs because the 1-minute window is significantly shorter than the period which the load is on. The longer 15-minute window follows the more general trend and tracks through the center of the load events, effectively considering the load switching as part of the variability. The 1-hour window is flatter, tracking even fewer load characteristics. These windows will be used as the basis for the variability assessments, with the short window capturing the shorter term response and the longer windows showing slower effects.

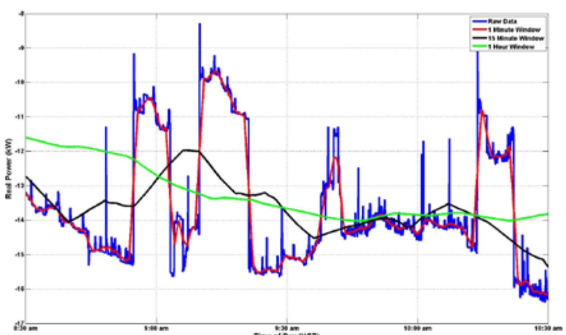

Fig. 7: Effects of median filtering on power measurements

The load variability of a data set will be assessed using the above trending methods in conjunction with the median absolute deviation (MAD). The MAD is a measure of the variance of a data set similar to the standard deviation but since it employs the median rather than the mean it is more robust in the face of outliers and noisy input data. The MAD is computed here as follows:

$$MAD = median\left(\left|\frac{X_i - median(X)}{median(X)}\right|\right)$$

It is the median value of the difference between a sample and the data set median normalized by the data set median. In this case the data set median will be given by the trend as computed by the moving median filters of Fig. 7. The inner term of the MAD is analogous to the residual error between the sample value and the trend. The subtraction operation in this equation is accomplishing the detrending operation.

When the 1-minute window filter is used as the reference in the MAD calculation the result gives the load variability over a 1-minute time scale. If the 15-minute or 1-hour window is used instead, the variability will be based on that timescale. These calculations result in three measures of load variability, one based on short term load changes and two others based on longer term effects. In the case of the observed load effects of Fig. 6 the 1-minute window will treat the load switches as part of the trend while the 15-minute and 1-hour windows will treat them as part of the load variability.

The preceding detrending procedure and variability measure was computed over a week of real power measurement data in late April for all five of the instrumented transformers. Variability metrics were computed for the 1-minute, 15-minute and 1-hour filters. The results are summarized in Table 1.

Table 1: Load variability metric at instrumented transformers

Transformer	1 Min.	15 Min.	1 Hour
Res 1	0.017	0.137	0.203
Res 2	0.031	0.194	0.242
Res 3	0.037	0.204	0.264
120 Y	0.025	0.146	0.159
277 Y	0.012	0.068	0.068

In Table 1 Res 1, Res 2, and Res 3 are the three instrumented residential transformers (split-phase 120/240 V secondary); the two three-phase transformers are named by their secondary voltage configuration. As expected, all of the 15-minute and 1-hour based metrics are higher because the median detrending is less sensitive to the load measurements and more of the changes in power are treated as excursions. Additionally, the 15-minute and 1-hour intervals produce metrics of similar size and both are generally 5 to 10 times larger than those of the 1-minute window. This indicates that most of the load switching and variability is on the order of a few minutes (longer than 1 minute but less than 15). When using this method to assess load variability it is important to consider the intended application and what rate of change in load is of concern, and then tune the variability metric to that value.

In general, the three-phase transformers are demonstrating less variability. On all time intervals their metrics are demonstrating lower values that the residential transformers. This is primarily due to a more constant load shape at those locations.

7. Impacts of PV Variability

The same metrics used to assess the load variability were also applied to the irradiance measurements over the same time span. All of the instrumented transformers include sites with PV production, thus the power measurement contains a dependence on the solar resource. This dependence may not be a direct correlation, however, due to several effects, most notably the distance between the irradiance measurement and the PV system.

Applying the discussed variability metric to the three active irradiance measurements over the same week's worth of data gives the results of Table 2.

Table 2: Variability metric at irradiance stations

Irrad. Sens.	1 Min.	15 Min.	1 Hour
1	0.002	0.074	0.240
2	0.001	0.049	0.161
3	0.001	0.035	0.149

The results in Table 2 indicate that the solar resource variability for this data set is encountered mostly on longer time scales. The 1-minute window produces very low metric values while the 1-hour window is orders of magnitude higher. These results imply that the resource variability is observed primarily on time scales in excess of 15 minutes.

Comparing Table 1 to Table 2, it is observed that the solar resource variability for this data set is significantly lower than that of the load on the 1-minute and 15-minute time scales. The variability metrics based on hourly windows fall into a similar range though. This would indicate that on 1- and 15-minute intervals, the observed variability in power flow is primarily due to load effects and had less dependence on the PV generation. On the hourly basis the variability of the solar resource is on par with that of the transformer power flow and may have significant impacts.

8. Conclusions

In order to support an ongoing smart grid demonstration project on the Island of Maui, NREL has deployed several pieces of metering equipment to collect data at the distribution transformer level and solar resource data. These are all one-second data sets and provide valuable information on the state of the distribution circuit. As this project develops, the data will be used to assess the advantages and drawbacks of smart grid equipment that will be installed in the future.

To date, five transformer meters and five Irradiance sensors have been installed, and data is being collected and archived. The data analysis stage has not yet begun in earnest with only a few preliminary assessments presented here. Some interesting features of the collected data sets have been presented including a case in which power was flowing toward the utility through a distribution transformer due the presence of PV and light loading conditions. Operation of voltage control devices within the distribution circuit can also be observed as step changes in voltage by this metering.

As the modeling and simulation portion of this project begins, more accurate load models are becoming important. To achieve this, some preliminary assessment of load variability has been done based on robust variance statistics. This metric can be tuned to look at different time scales, and assess the time dependence of certain load characteristics including how particular switched loads behave. One type of loads has been identified that switched on and off at a rate of about ten minutes. The developed variability metric demonstrates this time dependence through a series of progressively larger time windows used as a base.

The same metric was also applied to solar irradiance measurements to estimate the expected variability in PV generation sources and how PV generation relates to the observed load variability.

9. References

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