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NATIONAL RENEWABLE ENERGY LABORATORY

Development of a High Resolution, Real Time, Distribution-Level Metering System and Associated Visualization, Modeling, and Data Analysis Functions

J. Bank and J. Hambrick

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-56610
May 2013

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Prepared under Task No. SS12.1310

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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Acronyms

A/D	Analog to Digital
DEW	Distributed Engineering Workstation
DMD	Distribution Monitoring Database
DMU	Distribution Monitoring Unit
FPGA	Field-programmable Gate Array
GPS	Global positioning system
KML	Keyhole Markup Language
NTP	Network time protocol
NI	National Instruments
PDC	Phasor Data Concentrator
PMU	Phasor measurement units
PV	Photovoltaic
sbRIO	Single Board reconfigurable I/O board
SMUD	Sacramento Municipal Utility District
TVA	Tennessee Valley Authority

1 Introduction

Electrical distribution systems are changing rapidly. As smart grid technologies are being deployed, more and more control and communication is available. Photovoltaic (PV) generation, plug-in hybrid electric vehicles, and other battery energy storage technologies are adding additional power sources to distribution systems. These trends are challenging the traditional notions of distribution system operation, protection, and infrastructure development.

As these changes occur, research is needed to fully grasp the impacts they may have on distribution systems and the electric power system as a whole. A major driver of this research is the availability of appropriate case studies and data sets collected from systems featuring these new technologies. Additionally, as distribution systems become more complicated, improved situational awareness will be needed for proper operation. Thus, real-time data collection becomes paramount. As more generation and control systems are installed on the distribution level, the traditional view of the distribution network as a static system will be challenged. Data collection needs to be done at faster rates than what is currently available to meet these needs. Finally, increased system visibility is needed, necessitating the installation of additional metering solutions further down the distribution system and closer to the customer.

To support these research efforts, the National Renewable Energy Laboratory (NREL) is developing measurement devices and a supporting data collection network specifically targeted at electrical distribution systems. This measurement network is designed to apply real-time and high speed (sub-second) measurement principles to distribution systems that are already common for the transmission level in the form of phasor measurement units (PMUs) and related technologies.

The solution described here is designed to work around the constraints of existing metering solutions. Metering devices were designed and constructed from off-the-shelf components with in-house developed software and firmware. These meters draw on principles from both the phasor and power quality measurement sectors. They provide sub-second measurement of phasor and power quality values with real-time outputs. The output data streams are transmitted over the Internet to a central server for processing and storage. They are also designed for installation flexibility, being rated for extended temperature ranges and outdoor use. This allows for real-time metering of voltages, currents, and power at locations on the feeders and laterals, downstream of the distribution substation.

As streaming data comes in from this data collection network, it is passed on to several visualization applications and data analysis tools. This report contains an overview of the developed data collection system as well as a detailed look at some of the data collected to date and the applications using this information.

2 Metering Development

2.1 Design Requirements

This project focuses on metering requirements for pad-mounted distribution transformers. The meter needs to be placed within the transformer enclosure so that it can have direct access to the voltages and currents of interest. This places several constraints on the devices, all of which must be satisfied to ensure correct and reliable operation.

Environmental constraints are enforced on the metering device due to its placement within the transformer. The transformer enclosure is not water tight, so the selected meter must be rated for all-weather use. The other major environmental constraint is high temperatures. As the distribution

transformer will be generating heat while under operation, the meter needs to run under these higher ambient temperatures. This problem is exacerbated during the summer months. Additionally, being located inside a transformer enclosure places a significant size constraint on the devices, as they need to be capable of fitting within this confined space.

One of the major goals of this data collection system is to allow for integration of the results into a set of visualization packages and real-time simulations which evolve with the circuit state. To facilitate this, the metering devices must transmit their measurements to a data collection point immediately after they are taken. Thus, the device should be capable of connecting to a central server and transmitting data to it in real time. This also necessitates a persistent network or Internet connection; if this is not directly available at the metering locations, other provisions need to be made.

The real-time nature of the communications structure also requires a common timing source and time stamping across the system to maintain data integrity. Several options are possible including network time protocol (NTP), global positioning system (GPS), and various local network timing protocols. NTP is relatively simple to implement as the meter would already have an Internet connection. GPS timing requires a receiver and antenna for each unit, but provides a more accurate timing signal; the desired phasor measurement capabilities would require this increased accuracy.

Several off-the-shelf electrical metering products were evaluated with these requirements in mind. The majority of those considered did not meet all of the necessary environmental requirements including temperature, all-weather rating, and size. Additionally, the vast majority of commercially-available products had limited or no capabilities for real-time, point-by-point data transmission. Proprietary data transmission and storage formats also posed a major problem for planned open architecture and visualization tools. In the end, it was determined that a custom solution would be needed to meet all of the necessary requirements for this effort.

2.2 Hardware Considerations

The device developed for this distribution metering application is a Distribution Monitoring Unit (DMU). The DMU is based on a National Instruments (NI) Single Board reconfigurable I/O board (sbRIO)[1]. The sbRIO is specifically designed for the acquisition, processing, and interpretation of data in real time. This piece of hardware provides a platform on which a customized metering device can be built through the development of software in the NI LabVIEW graphical programming language.

Each sbRIO board contains a microprocessor and a Field-programmable Gate Array (FPGA) along with all of the necessary supporting components. Each board also provides several options for onboard digital I/O channels. The I/O capabilities can also be extended with up to 3 different NI C-series modules that provide a variety of functions including the advanced analog-to-digital conversion used in this application. Additionally, the sbRIO includes Ethernet and RS-232 ports for communication with other devices.

Accurate timing and location information for this application is achieved with a Garmin GPS receiver. This card provides GPS data to the DMU, which is then used to report an accurate measurement location and time. This GPS unit also supplies a 1 pulse per second signal that is used to phase lock the device's internal clock to improve the accuracy of the measurement timestamps and results of the time-dependent computations, such as phasor calculations.

A DMU 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

[1] http://www.ni.com/singleboard

cellular provider. For most installations with limited connectivity options, the cellular modem is usually outfitted.

Voltage measurement is achieved directly through clip-on voltage probes and a C-Series A/D which is rated up to 300 V_{RMS}. Higher level voltage measurements are possible, but would require a voltage divider or potential transformer. The current transformer selected for this application is a Rogowski coil. This clip-on current probe is easy to install and adaptable to a variety of applications. The drawbacks with these types of probes are that that any DC component in the current waveforms cannot be observed and that they have reduced accuracy at low current magnitudes (< 10 amps).

The other major internal hardware component is a power supply which draws AC power off of the input channels and supplies 24 V DC power to the electronics components. All of the components detailed here are available with operating temperature ranges greater than 70°C. The unit is enclosed in a NEMA–rated, water-tight polycarbonate case. These ratings were selected to enable deployment into a variety of locations on a distribution feeder including harsh environments, specifically inside the access panel of a distribution transformer.

2.3 Software Implementation

The NI sbRIO and C-series modules were selected because they provided an off-the-shelf, readily available development environment for the metering application. The two C-series modules used provided the necessary Analog to Digital (A/D) conversion to implement direct measurement of 120 V and 240 V signals and the low voltage output of the current probes, reducing the need for external signal processing on the input side. The sbRIO provides an FPGA for processing the A/D samples and computing the output metrics. Additionally, the microprocessor—also located on the sbRIO—allows for Ethernet-based data transmission. The integration of these two devices onto one board facilitates one continuous data flow, from sampling through metric computation and transmission, reducing development time.

Programming of both the FPGA and the microprocessor is done in the LabVIEW graphical programming environment. In the final implementation, the FPGA controls the A/Ds and sampling, including resampling algorithms, to convert the native sampling rate of 50 kS/sec to 256 samples per input cycle. This reduction to a constant number of samples per cycle of the line frequency improves the accuracy of the subsequent phasor, RMS, and power calculations. The FPGA also computes the output quantities including phasor and RMS measurements for each input voltage and current channel. The appropriate real and reactive powers for the installation along with temperatures are also computed here. Each of these calculations is implemented in a rolling window fashion and updated on each new sample; the eventual meter output value is drawn from these values at a specified data output rate. A more complete list of computed metrics for each model is available in Section 2.4. Finally, the FPGA also controls the data output rate through an interrupt signal sent to the microprocessor.

The other major component on the sbRIO board is the microprocessor. It controls the configuration settings of the meter, interfaces with the GPS card for timing information, performs post-processed measurement computation, and handles network communication. Input configuration settings of the meter include name, access credentials, output measurements, calibration factors, and various communication parameters; the microprocessor reads all of these from a configuration file and sets the meter up appropriately. The GPS card provides accurate timing and location information necessary to the time stamping of output data and accuracy of the phasor calculations. Several types of output measurement are derived from other outputs and thus are not necessary on the FPGA; the microprocessor handles these on an as-needed basis. The primary function of the microprocessor is to handle the C37.118 communications for data output. It waits for an incoming server connection on the TCP port; once one has been established, it begins pulling measurement values from the FPGA and

formatting them into C37.118 frames to be pushed to the data collection servers. The data output rate here is governed by the interrupt signals sent by the FPGA and is customizable.

2.4 Models of Meter-Developed and Output Measurements

To date, two models of this metering solution have been developed. They implement the calculations discussed above for each of the targeted installation types. Additionally, these units are fully reprogrammable once fielded and the specifications can be adapted as the data collection objectives change.

2.4.1 Residential Split-Phase Service Locations – Model SPDT

The SPDT model of the DMU is designed specifically for installation on the secondary side of split-phase (120 V/240 V) distribution transformers. The internal software algorithms have been designed to measure both of the hot legs referenced against the neutral along with all three of these currents. The appropriate total power is also calculated. This hardware and software build of the DMU is also appropriate for metering at the utility panel of a residential customer (120 V and 240 V service).

Representative photos of this unit are given in Figure 2-1 and Figure 2-2. Figure 2-1 shows one of these units with all of its peripherals attached including voltage probes, Rogowski coils, temperature probe, and antenna. Figure 2-2 gives an example of a typical installation inside the case of a distribution transformer.

Figure 2-1: SPDT Model of the DMU with peripherals
Photo by Jason Bank, NREL

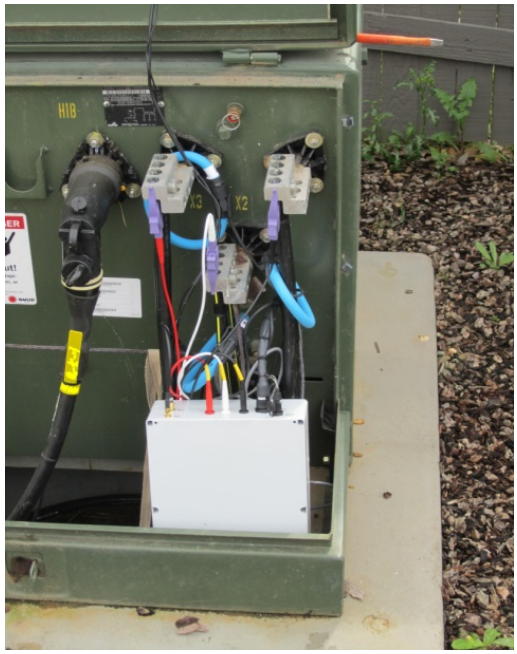


Figure 2-2: DMU installed on a transformer
Photo by Jason Bank, NREL

Output Measurements

This meter is configured to output 6 phasor measurements, a frequency measurement, 6 RMS measurements, 3 power measurements, 2 power factors and 2 temperatures. Detailed descriptions for each of these values are listed below.

Phasor Measurements, GPS clock time reference

- $\mathbf{V_1}$ – Magnitude and angle of the leg 1 voltage in volts-rms and degrees respectively. Referenced against the neutral conductor. Nominally 120 V_{RMS} for most installations.
- $\mathbf{V_2}$ – Magnitude and angle of the leg 2 voltage in volts-rms and degrees respectively. Referenced against the neutral conductor. Since both values are referenced to the neutral, $\mathbf{V_2}$ and $\mathbf{V_1}$ would normally be 180 degrees out of phase with each other. Nominally 120 V_{RMS} for most installations.
- $\mathbf{V_{12}}$ – Magnitude and angle of the total transformer secondary voltage in volts-rms and degrees respectively. Measured as the leg 1 voltage referenced against the leg 2 voltages, thus this value will normally be in phase with $\mathbf{V_1}$. Nominally 240 V_{RMS} for most installations.
- $\mathbf{I_1}$ – Magnitude and angle of the leg 1 current in amps-rms and degrees respectively. Polarity is such that for real power flow from utility to customer, $\mathbf{I_1}$ will be in phase with $\mathbf{V_1}$.
- $\mathbf{I_2}$ – Magnitude and angle of the leg 2 current in amps-rms and degrees respectively. Polarity is such that for real power flow from utility to customer, $\mathbf{I_2}$ will be in phase with $\mathbf{V_2}$.
- $\mathbf{I_N}$ – Magnitude and angle of the neutral current in amps-rms and degrees respectively. Polarity is such that for real power flow from utility to customer, $\mathbf{I_N}$ will be 180 degrees out of phase with $\mathbf{V_1}$.

Frequency Measurements

- **Frequency** – Frequency of the $\mathbf{V_{12}}$ waveform. Calculated by measuring the time span between consecutive rising zero crossings and inverting.

RMS Measurements, calculated over an 8-cycle moving window

- $\mathbf{V_{1\ RMS}}$ – Leg 1 voltage in volts-rms. Referenced against the neutral conductor. Nominally 120 V_{RMS} for most installations.
- $\mathbf{V_{2\ RMS}}$ – Leg 2 voltage in volts-rms. Referenced against the neutral conductor. Nominally 120 V_{RMS} for most installations.
- $\mathbf{V_{12\ RMS}}$ – Total transformer secondary voltage in volts-rms. Measured as the leg 1 voltage referenced against the leg 2 voltage. Nominally 240 V_{RMS} for most installations.
- $\mathbf{I_{1\ RMS}}$ – Leg 1 current in amps-rms.
- $\mathbf{I_{2\ RMS}}$ – Leg 2 current in amps-rms.
- $\mathbf{I_{N\ RMS}}$ – Neutral current in amps-rms.

Power Measurements, averaged over an 8-cycle moving window

- **|S|** – Total apparent power flow through the transformer in volt-amps. Implemented as $|\mathbf{S}| = \mathbf{V}_{1\,RMS} * \mathbf{I}_{1\,RMS} + \mathbf{V}_{2\,RMS} * \mathbf{I}_{2\,RMS}$, positive when real power is flowing from utility to customer, and negative if real power is flowing from customer to utility.
- **P** – Total real power flow through the transformer in watts. Implemented using a point-by-point multiplication of the voltage and current waveforms, $P_{INS} = V_1 * I_1 + V_2 * I_2$, and averaging over an 8-cycle moving window. This value is positive when real power is flowing from utility to customer, and negative if real power is flowing from customer to utility.
- **Q** – Total reactive power flow through the transformer in volt-amps reactive. Implemented using a point-by-point multiplication of the 90 degree phase shifted voltage and current waveforms, $Q_{INS} = V_1^{+90°} * I_1 + V_2^{+90°} * I_2$, and averaging over an 8-cycle moving window. This value is positive when the customer is consuming reactive power (inductive) and negative when the customer is supplying reactive power (capacitive).

Power Factor Measurements

- **pf** – Total power factor of the transformer, calculated as **P** divided by **|S|**.
- $\mathbf{pf_{DISP}}$ – Displacement power factor of the transformer, calculated as the cosine of the angle difference between the $\mathbf{V_{12}}$ and $\mathbf{I_1}$ phasors.

Temperature Measurements

- **Meter Internal Temperature** – Temperature measured on the printed circuit board inside the DMU in degrees Celsius.
- **Transformer Housing Temperature** – Temperature measured by DMU external temperature probe, in degrees Celsius. Normally this probe is located inside the transformer housing.

2.4.2 Three-Phase Service Locations – Model TPYT

The TPYT model of the DMU is designed specifically for installation on the secondary side of three-phase distribution transformers at the 277 V_{LN} or 120 V_{LN} levels. The internal software algorithms have

been designed to measure all three phases referenced against the neutral along with all three of the phase currents. The appropriate phase and total power values are also calculated. This hardware and software build of the DMU is also appropriate for metering at any three-phase point up to 300 V_{RMS}.

Figure 2-3 shows one of these units with all of its peripherals attached including voltage probes, Rogowski coils, a temperature probe, and an antenna.

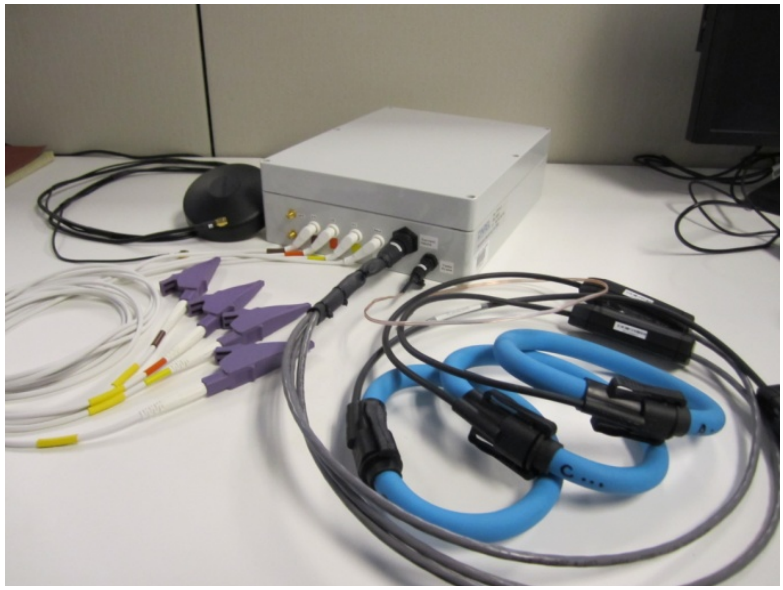


Figure 2-3: TPYT Model of the DMU with voltage, current and temperature probes attached
Photo by Jason Bank, NREL

Output Measurements

This meter is configured to output 6 phasor measurements, a frequency measurement, 6 RMS measurements, 12 power measurements, 1 power factor, and 2 temperatures. Detailed descriptions for each of these values are given below.

Phasor Measurements, GPS clock time reference.

- $\mathbf{V_A}$ – Magnitude and angle of the phase A voltage in volts-rms and degrees respectively. Referenced against the neutral conductor.
- $\mathbf{V_B}$ – Magnitude and angle of the phase B voltage in volts-rms and degrees respectively. Referenced against the neutral conductor.
- $\mathbf{V_C}$ – Magnitude and angle of the phase C voltage in volts-rms and degrees respectively. Referenced against the neutral conductor.
- $\mathbf{I_A}$ – Magnitude and angle of the phase A current in amps-rms and degrees respectively. Polarity is such that for real power flow from utility to customer, $\mathbf{I_A}$ will be in phase with $\mathbf{V_A}$.
- $\mathbf{I_B}$ – Magnitude and angle of the phase B current in amps-rms and degrees respectively. Polarity is such that for real power flow from utility to customer, $\mathbf{I_B}$ will be in phase with $\mathbf{V_B}$.
- $\mathbf{I_C}$ – Magnitude and angle of the phase C current in amps-rms and degrees respectively. Polarity is such that for real power flow from utility to customer, $\mathbf{I_C}$ will be in phase with $\mathbf{V_C}$.

Frequency Measurements

- **Frequency** – Frequency of the $\mathbf{V_A}$ waveform. Calculated by measuring the time span between consecutive rising zero crossings and inverting.

RMS Measurements, calculated over an 8-cycle moving window

- $\mathbf{V_{A\ RMS}}$ – Phase A voltage in volts-rms. Referenced against the neutral conductor.
- $\mathbf{V_{B\ RMS}}$ – Phase B voltage in volts-rms. Referenced against the neutral conductor.
- $\mathbf{V_{C\ RMS}}$ – Phase C voltage in volts-rms. Referenced against the neutral conductor.
- $\mathbf{I_{A\ RMS}}$ – Phase A current in amps-rms.
- $\mathbf{I_{B\ RMS}}$ – Phase B current in amps-rms.
- $\mathbf{I_{C\ RMS}}$ – Phase C current in amps-rms.

Power Measurements, averaged over an 8 cycle moving window

- **|S|** – Total apparent power flow through the transformer in volt-amps. Implemented as $|\mathbf{S}| = |\mathbf{S}|_A + |\mathbf{S}|_B + |\mathbf{S}|_C$, positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- $\mathbf{|S|_A}$ – Phase A apparent power flow through the transformer in volt-amps. Implemented as $|\mathbf{S}|_A = \mathbf{V}_{A\ RMS} * \mathbf{I}_{A\ RMS}$, positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- $\mathbf{|S|_B}$ – Phase B apparent power flow through the transformer in volt-amps. Implemented as $|\mathbf{S}|_B = \mathbf{V}_{B\ RMS} * \mathbf{I}_{B\ RMS}$, positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- $\mathbf{|S|_C}$ – Phase C apparent power flow through the transformer in volt-amps. Implemented as $|\mathbf{S}|_C = \mathbf{V}_{C\ RMS} * \mathbf{I}_{C\ RMS}$, positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- **P** – Total real power flow through the transformer in watts. Implemented as $P = P_A + P_B + P_C$, and averaging over an 8-cycle moving window. This value is positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- $\mathbf{P_A}$ – Phase A real power flow through the transformer in watts. Implemented using a point-by-point multiplication of the voltage and current waveforms, $P_{A\ INS} = V_A * I_A$, and averaging over an 8 cycle moving window. This value is positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- $\mathbf{P_B}$ – Phase B real power flow through the transformer in watts. Implemented using a point-by-point multiplication of the voltage and current waveforms, $P_{B\ INS} = V_B * I_B$, and averaging over an 8-cycle moving window. This value is positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.
- $\mathbf{P_C}$ – Phase C real power flow through the transformer in watts. Implemented using a point-by-point multiplication of the voltage and current waveforms, $P_{C\ INS} = V_C * I_C$, and averaging over an

8-cycle moving window. This value is positive when real power is flowing from the utility to customer and negative if real power is flowing from customer to utility.

- **Q** – Total reactive power flow through the transformer in volt-amps reactive. Implemented as $Q = Q_A + Q_B + Q_C$, and averaging over an 8-cycle moving window. This value is positive when the customer is consuming reactive power (inductive) and negative when the customer is supplying reactive power (capacitive).
- **Q_A** – Phase A reactive power flow through the transformer in volt-amps reactive. Implemented using a point-by-point multiplication of the 90 degree phase shifted voltage and current waveforms, $Q_{A\,INS} = V_A^{+90°} * I_A$, and averaging over an 8-cycle moving window. This value is positive when the customer is consuming reactive power (inductive) and negative when the customer is supplying reactive power (capacitive).
- **Q_B** – Phase B reactive power flow through the transformer in volt-amps reactive. Implemented using a point-by-point multiplication of the 90 degree phase shifted voltage and current waveforms, $Q_{B\,INS} = V_B^{+90°} * I_B$, and averaging over an 8-cycle moving window. This value is positive when the customer is consuming reactive power (inductive) and negative when the customer is supplying reactive power (capacitive).
- **Q_C** – Phase C reactive power flow through the transformer in volt-amps reactive. Implemented using a point-by-point multiplication of the 90 degree phase shifted voltage and current waveforms, $Q_{C\,INS} = V_C^{+90°} * I_C$, and averaging over an 8-cycle moving window. This value is positive when the customer is consuming reactive power (inductive) and negative when the customer is supplying reactive power (capacitive).

Power Factor Measurements

- **pf** – Total power factor of the transformer, calculated as **P** divided by |**S**|.

Temperature Measurements

- **Meter Internal Temperature** – Temperature measured on the printed circuit board inside the DMU in degrees Celsius.
- **Transformer Housing Temperature** – Temperature measured by DMU external temperature probe, in degrees Celsius. Normally this probe is located inside the transformer housing.

3 Data Collection and Archival

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 measurement device will stream data back to a central location in 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 will also be stored locally at the receiving end. Since no data is stored at the point of measurement, the only hard disk requirements are on the server end. With appropriate disk sizing and routine backups, all of the metered data can be catalogued, building a database that covers a continuous span starting from the installation time of the DMUs. The software supporting this network is fully open-source, allowing for customization if needed and complete visibility of the inner workings. Similarly, the data storage is done in an open format to promote data retrieval and analysis by a variety of applications.

3.1 The OpenPDC Software Package

The Tennessee Valley Authority (TVA) has released its Phasor Data Concentrator (PDC) as an open-source suite of applications. This package, OpenPDC, is freely available for download complete with documentation[2]. OpenPDC is now maintained and developed by the Grid Protection Alliance. This code was developed to collect Phasor Measurement Unit (PMU) data from the Eastern Interconnect. TVA's PDC has been in operation since 2004, collecting, collating, storing, and outputting phasor data streams from various measurement locations around the Eastern Interconnect. As an open-source package, it is easily extensible and customizable, and can handle real-time data collection from a variety of sources.

This application parallels many of the desired requirements of the Data Concentrator system needed for this project. The individual measurement devices are being designed to communicate using the IEEE C37.118 Standard for Synchrophasors, which is one of the built-in protocols of OpenPDC. Thus, OpenPDC is capable of communicating with the NI-based metering devices without any modification. Although it was primarily designed for collection of phasor measurement data on the bulk transmission level, the design of the OpenPDC package is flexible enough that it can process any real-time data streams communicating over a variety of protocols.

OpenPDC also provides support for configuring output streams to other data processing and storage applications. For the basic functions needed by the Data Concentrator server(s) in this project, OpenPDC should be adequate directly out of the box. The data visualization modeling integration and quality monitoring features tied to this project are implemented as plug-ins for the base OpenPDC package.

3.2 Real-Time Data Collection Network

The basic system architecture is given in Figure 3-1. Each DMU collects data from its location and transmits the data over the Internet back to the data concentrator located at NREL. The data concentrator collates the multiple incoming data streams, producing one large data stream containing all of the information from the various DMUs. The concentrator data stream is then passed to the data historian. The data historian is responsible for maintaining and updating the database that stores all of the received measurements. The historian also acts as the data hub for other applications, including various visualization applications, data processing, modeling inputs, and data retrieval tools. The data visualization applications present live and historic data in a variety of informative displays. Depending on the number of fielded meters and their data rates, hardware requirements, and reliability concerns, the concentrator, historian, and visualization applications may be hosted on one or multiple servers.

[2] http://openpdc.codeplex.com/

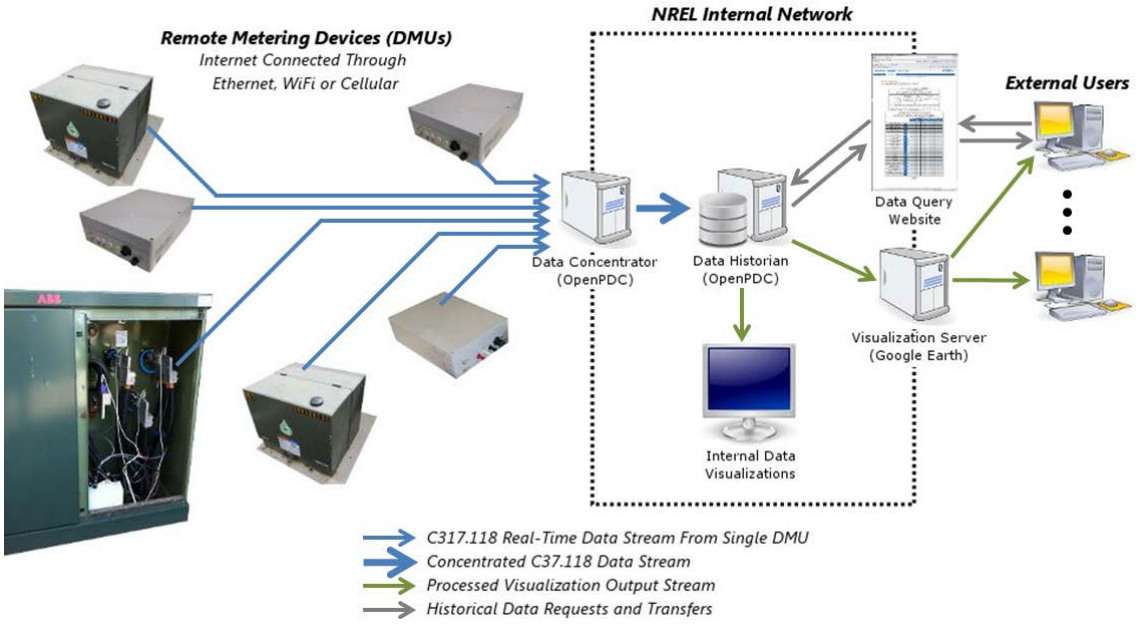


Figure 3-4: Data Collection Network Architecture

The individual meters and data collection servers communicate over the Internet using the IEEE C37.118 protocol[3]. This protocol details requirements for the accuracy and communications of PMU devices. In this communication structure, each individual meter acts as a TCP server and waits for an incoming connection from the data concentrator. When a connection is established, configuration information is exchanged and then data transmission begins. Each measurement set is packaged into a data frame, time-stamped, and transmitted to the data concentrator on a point-by-point basis. The configured data rate of the metering device sets the rate at which data frames are sent across the TCP connection.

The data concentrator maintains active connections to all of the fielded measurement devices. It also collates the incoming data frames by putting the measurements from the same time point into one augmented frame containing all of the measured values from that timestamp. In the system architecture of Figure 3-1, this combined data stream is then forwarded to the historian using the same C37.118 protocol for archival. OpenPDC handles the communications outlined in C37.118 and thus is used to implement these data collection and handling procedures.

When configured and deployed, each DMU is assigned a static IP address, which is then added to the OpenPDC configuration settings on the data concentrator. In operation, OpenPDC uses this address to establish the TCP connection to the DMU across the Internet.

[3] IEEE C37.118.1-2011 and C37.118.2-2011, IEEE Standard for Synchrophasor Measurements for Power Systems

4 Data Retrieval

To facilitate retrieval of data from the historian, a website has been developed. The website is the NREL Distribution Monitoring Database (DMD) query tool. It incorporates the data with other outside sources of distribution measurement data into one easy-to-use, HTML form-based tool for retrieving data sets. Internal and external (non-NREL) researchers can log onto this website, create and execute a database query, and download the results.

Security to the DMD site is controlled with username and password authentication. Each user is associated with one or more projects, which controls what data sets they can access. This structure is designed to allow the website to support multiple unrelated projects in one interface and keep the individual data sets separate from each other.

After creating an account and logging in, the user can specify a query with the HTML form given in Figure 4-1. The first field here specifies the active project; the user can select any project of which they are a member, and the remainder of the form will be set up based on the data sets that are associated with the active project. The next block of inputs set up the timing parameters for the data set that the user is requesting. User inputs here include the data set start time, end time, resolution, and output time formatting. The last block of inputs is presented as a table of checkboxes through which the user can specify which measurement vectors to include in the output data set. In this case, each column corresponds to a DMU and each row corresponds to a measurement available for that DMU.

Upon submitting the form shown in Figure 4-1, the DMD website connects to the historian and retrieves the requested data. This data is then formatted into *.txt files containing semi-colon separated values. The *.txt files are combined into one ZIP archive, which the user can download through the *Download Results* subpage of the DMD site. Depending on the size of the requested data set, it can take from several seconds to hours for the query to be processed and the results made available for download.

This website is set up so that data sources outside of this data collection effort can be incorporated into the tool including weather and irradiance data, utility SCADA data, and smart meter data among others. This allows for one interface for retrieving and preprocessing all of the data sets associated with any particular project. The major advantage of this capability is that data sets from several different sources are automatically time-aligned, collated, error-checked, and formatted into one output file to facilitate data analysis. As the name implies, it is currently focused on distribution-level monitoring projects.

Distribution Monitoring Database NREL

ABOUT THE DATABASE | QUERY DATABASE | DOWNLOAD RESULTS | MANAGE PROJECTS | LOG OUT

You are logged in as *john.doe@company.com*

Query the Database

To retrieve a dataset from the database, fill out this form describing the dataset you desire and click the *Submit* button at the bottom.

Active Project SMUD - RES/CES Update

Data Set Timing Parameters

Complete the fields below to define a timeframe for your dataset.
Note: The "with DST" time zone options take Daylight Saving Time into account, and the "without DST" options do not.

	Time & Date	Format	Time Zone
Start Time	hh:mm:ss dd/mm/yyyy	AM	GMT (without DST)
End Time	hh:mm:ss dd/mm/yyyy	AM	
Time Resolution*	1 second		
Output Time Format	Unix-Style Timestamp (Elapsed Seconds Since 00:00:00 Jan 1 1970 GMT)		

** Minimum of 1 second. Values greater than 1 will decimate from existing 1 second datasets by selecting the nearest point. Only accepts integers.*

Distribution Transformer Measurements (from DMUs)

Check the boxes for measurements you want to include in the dataset
To select or deselect entire rows or columns use the SET and CLR buttons

		Anatolia Transformers											
		2K9	9K2	3K7	8K2	9K1	1K8	2K1	8K5	10K5	4K7	5K7	2K7
		SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR	SET CLR
V1 Phasor Magnitude	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V1 Phase Angle	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V2 Phasor Magnitude	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V2 Phase Angle	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V12 Phasor Magnitude	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V12 Phase Angle	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
I1 Phasor Magnitude	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
I1 Phase Angle	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
I2 Phasor Magnitude	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
I2 Phase Angle	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
In Phasor Magnitude	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
In Phase Angle	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Frequency	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V1 RMS	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V2 RMS	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
V12 RMS	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
I1 RMS	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
I2 RMS	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
In RMS	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Apparent Power Magnitude (|S|)	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Real Power (P)	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Reactive Power (Q)	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Power Factor	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Displacement Power Factor	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Meter Internal Temperature	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Transformer Housing Temperature	SET CLR	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Submit

Figure 4-5: Example DMD Query Request Form

5 Meter Installation, Operation, and Lessons Learned

Once the meters were developed and tested, they were deployed into distribution circuits. The targeted circuits are associated with high-penetration PV and smart grid study projects currently underway at NREL.

5.1 Anatolia Solar Smart Community

The first set of DMUs was deployed into the Anatolia neighborhood southeast of Sacramento, California in the Sacramento Municipal Utility District (SMUD) service territory. The Anatolia Solar Smart Community is a neighborhood in which every house is built with integrated rooftop PV and several energy-efficient features. The neighborhood represents a high-penetration PV scenario with light load and several hundred rooftop PV systems averaging about 2.5 kW each. The DMUs were installed to provide data collection in support of this ongoing residential and community energy storage project. The provided data, in conjunction with a variety of other data sources, will be used to assess the impact of distribution battery systems in concert with residential rooftop PV generation.

A total of 12 DMUs were deployed into this circuit in 3 stages of 4 units. All of the units were mounted in residential split-phase distribution transformers. The individual transformers are pad-mounted and rated at either 50 kVA or 75 kVA, serving between 6 and 11 single-family houses. One of these installations is pictured in Figure 2-2. These units are equipped with a cellular modem for communication to the data concentrator.

As these were the first real-world installations of the meters, several problems were encountered and have been corrected or mitigated. During the early stages of the data collection at Anatolia, there were severe communications issues with units losing connection and never coming back, requiring a utility lineman to perform a hard reboot. This was primarily due to weak cellular coverage in the area and faulty communications between the sbRIO and the cellular modem. These issues have been corrected in software and firmware with improved communications, modified modem settings, and forced reboots on a periodic schedule.

5.2 Maui Smart Grid Demonstration Project

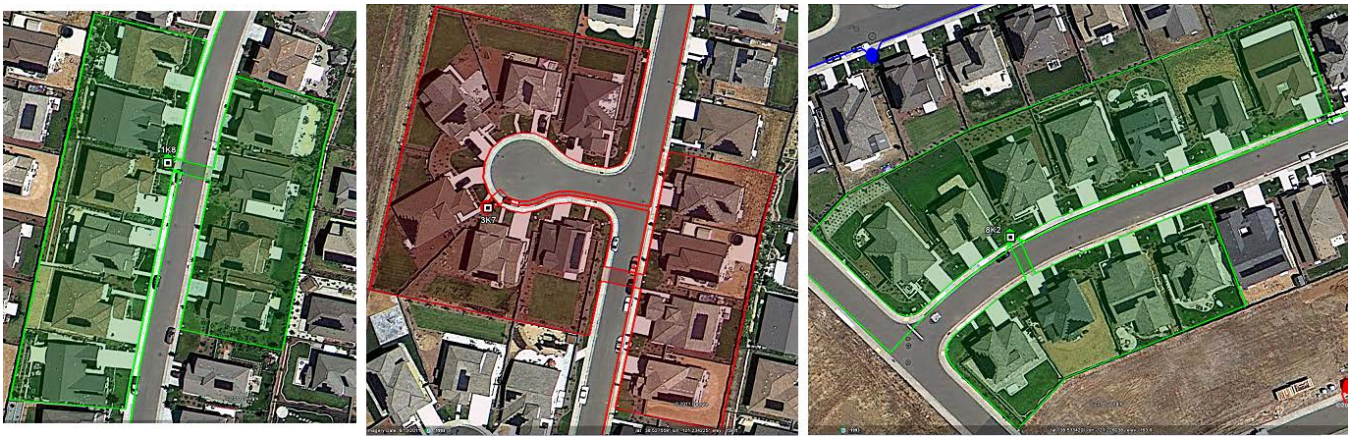
The Maui Smart Grid Demonstration Project aims to assess the operation and grid impacts of a variety of technologies including distributed PV, battery storage, electric vehicles, charging stations, distribution systems, and the associated communications structure. A selection of these devices will be installed on the island of Maui and specifically in the Kihei area. Over the operational period of the project, these devices will be evaluated and tested in a real-world environment.

NREL is providing data collection in support of this project with five DMUs and five irradiance sensors, located near distributed PV systems. The DMUs were installed on the secondary side of distribution transformers. Three of these units were installed on residential split phase transformers; one on a 120 Y commercial transformer and the final one on a 240 Y commercial transformer.

6 Collected Data Examples

To demonstrate some of the data collection results, some DMU data and solar measurements will be presented. This data set spans three days, September 24-26, 2011 for the SMUD Anatolia Neighborhood. These three days were chosen because they demonstrate three solar irradiance regimes. The 26th was an exceptionally clear day with a well-defined and smooth irradiance curve. The 25th was a cloudy day and the irradiance measurements reflect this with low solar resource available throughout the day. On the 24th there was intermittent and passing cloud cover resulting in periods of clear sky as well as more intermittent periods.

The three transformers include 1K8, 3K7, and 8K2. 1K8 and 3K7 serve 10 houses, and 8K2 serves 11 houses. 1K8 and 8K2 are located on Phase B laterals and 3K7 is on a Phase A lateral. These transformers and their service areas are given in Figure 6-1. The PV panels can be seen as black patches on the individual rooftops; most are facing south, with a few angled to the west or east depending on the available roof space.



1K8 3K7 8K2

Figure 6-6: Transformer service areas for example data set
©Google Earth

6.1 Transformer Power Flows and Solar Resource

Figure 6-2 gives the irradiance measurements as well as the real power metered at transformer 1K8 on September 26, 2011. The observed irradiance on this day (red plot) indicates a clear day by the very smooth curve and peak at midday. The solar measurement point is located 0.84 miles northeast of the transformer. This particular transformer serves 10 houses, each with about 2.5 kW of rooftop PV facing south/southwest. Since the distance from the irradiance measurement to the PV panels is relatively short, the irradiance seen by the panels should be similar to that of the measurement. The bottom plot of Figure 6-2 gives the real power measurements at this transformer over the course of the day. From midnight to 7:00 a.m., the load was stable at about 6 kW–7 kW. After this time, the PV began to output power. The transformer began back-feeding at about 9:00 a.m. when the PV offset the load and the power flow went negative. Throughout the morning daylight hours, production ramped up, reaching a peak at noon with the houses supplying about 9 kW to the utility. The PV output from 8:00 a.m. to 1:00 p.m. appears to be very smooth, as expected from the irradiance measurements. Starting at 2:00 p.m. the power measurements start to become very irregular and highly variable. This is most likely due to load behavior as opposed to PV variability, because the irradiance measurements are still smooth. This behavior continued throughout the evening after PV production stopped. Peak load on this transformer is observed at about 8:00 p.m.–9:00 p.m., which is typical of this residential feeder.

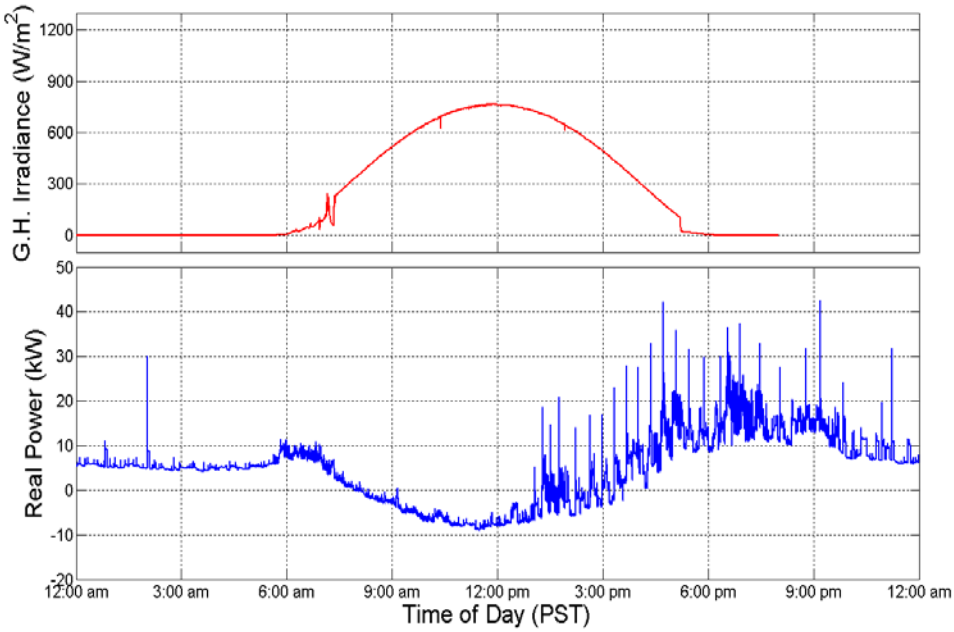


Figure 6-7: Irradiance and Real Power on September 26, 2011

While September 26 was a very clear day, the previous day was cloudy and overcast. The measured irradiance and power on September 25 are given in Figure 6-3. The irradiance was below 400 W/m^2 for the majority of the day, only exceeding that value for transient periods; this is in contrast to the preceding clear day plot, which demonstrated a smooth ramp up to about 780 W/m^2. The reduced solar resource on September 25 resulted in a significantly different power flow at the transformer.

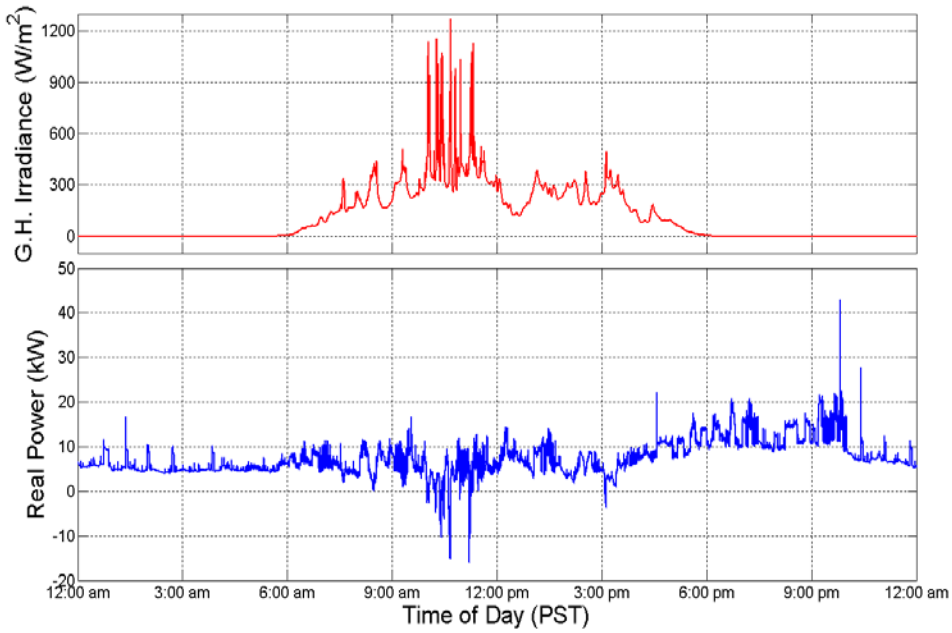


Figure 6-8: Irradiance and Real Power on September 25, 2011

Once again, the early morning load was stable and in the range of 6 kW. Since there is little PV generation on this day, the transformer does not show sustained back feeds during the daylight hours. There were, however, a few transient periods of PV production around noon that resulted in short periods of power flow towards the utility. Other than that, the stable 6 kW-7 kW of load is seen throughout the day with a peak load once again occurring in the 8:00 p.m.–9:00 p.m. time frame.

The third day in the example data is September 24, 2011. This was a day which demonstrated intermittent cloud cover. The irradiance and power plot for this day is given in Figure 6-4. The top plot demonstrates the typical irradiance curve with a peak at midday and shoulders on either side. The difference from the irradiance of Figure 6-2 is that several highly variable transient periods are seen throughout the day, which corresponds to passing clouds. The variable nature of the solar resource on this day appears in power data as a highly variable signal. During the nighttime an increased variability is also observed, indicating that the load also fluctuated significantly. Thus, it is hard to differentiate between the PV and load contributions to the increased variance in the measured power. On this day, back feed from the customer to the utility is also observed during the daytime, peaking at 10 kW around noon. As expected, the peak load on the transformer is observed in the evening around 9:00 p.m. at a value of about 12 kW.

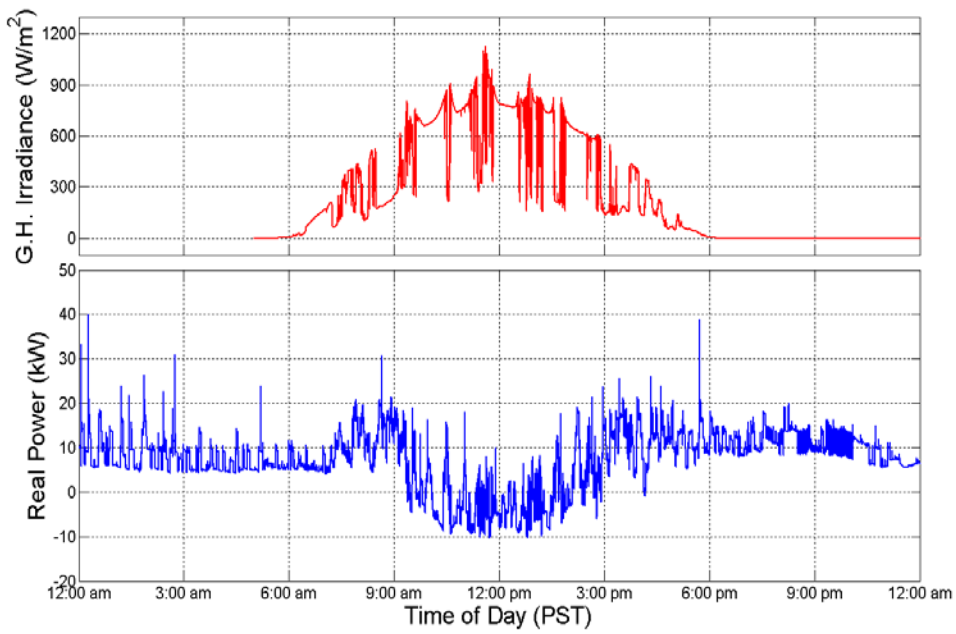


Figure 6-9: Irradiance and Real Power on September 24, 2011

The traces given here are typical of all of the metering locations throughout the Anatolia neighborhood. On days with adequate solar resource, all of the transformers demonstrate power flows from the residential PV back toward the utility, especially at peak times around noon. When there is little or no resource available, these conditions are generally not observed. Similar characteristics have also been observed in the metered locations on Maui.

6.2 Observable Load Characteristics

One of the most prominent features of the load profiles on the metered residential transformers is step changes in real and reactive power. An example of this is given in Figure 6-5. In this plot, the real power is plotted in blue while the reactive power is in red for one of the Anatolia transformers. In both traces, four step increases in power are seen with corresponding drops a few minutes later. This would indicate a large load switching on then off. Based on these traces, the load draws about 5 kW and 2 kVAR, indicating a power factor of 0.92. In general, all metered points in the neighborhood demonstrate this type of behavior, but not always, occurring most frequently in the afternoon and evening. Each time the load comes on, a transient spike in power is observed. The size of this load, the way it switches on and off, and the time of year would indicate an air conditioning system; the spikes at the start of each event could be explained by the associated motor starting.

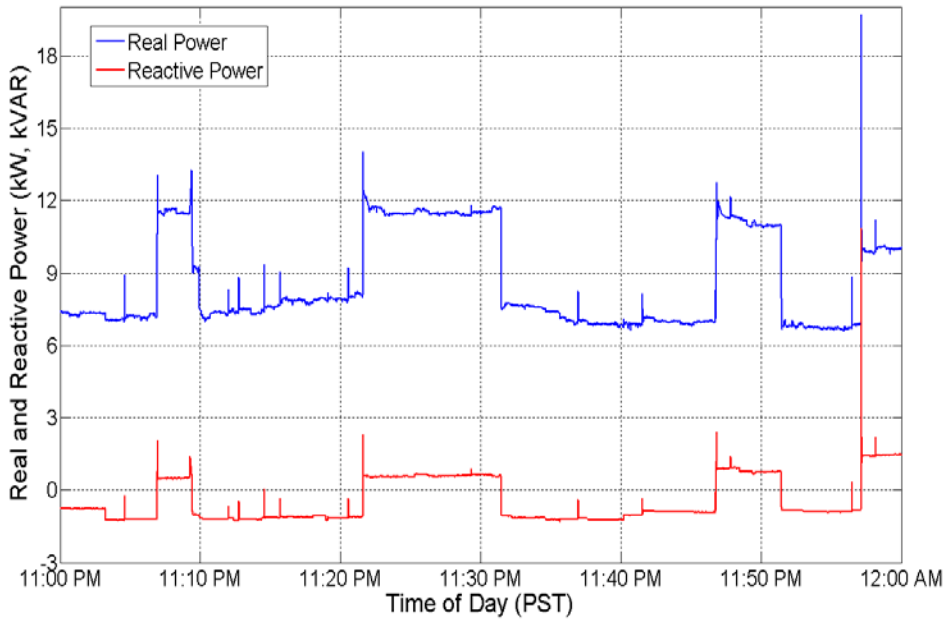


Figure 6-10: Transformer Load, 11:00 p.m. to 12:00 a.m. on September 26, 2011

Since the transformer feeds ten houses of similar construction, the observed switching action is not indicative of one load but ten systems of similar size and on similar control systems. Each of these events could be from a different house on the transformer. Further reinforcing this point, several events have been observed in which two of these loads are switching in the same time period and the effects are stacked together.

The transformer secondary voltage corresponding to the time frame of Figure 6-5 is given in Figure 6-6. For reference the estimated load status has been included here as the red square wave at the top of the figure. A high value on this waveform indicates that the load is on while a low value is off. The square wave was derived from the preceding reactive power plot. The transformer voltage is given by the blue trace. When the load is on a depressed voltage is observed as would be expected from the increased power demand. For example at 11:22 p.m. the load switches on and the voltage immediately drops by about 0.3 volts. When the load switches back off at 11:31 p.m. a voltage rise is observed, also of about 0.3 volts. This behavior is seen for each of the load switching events.

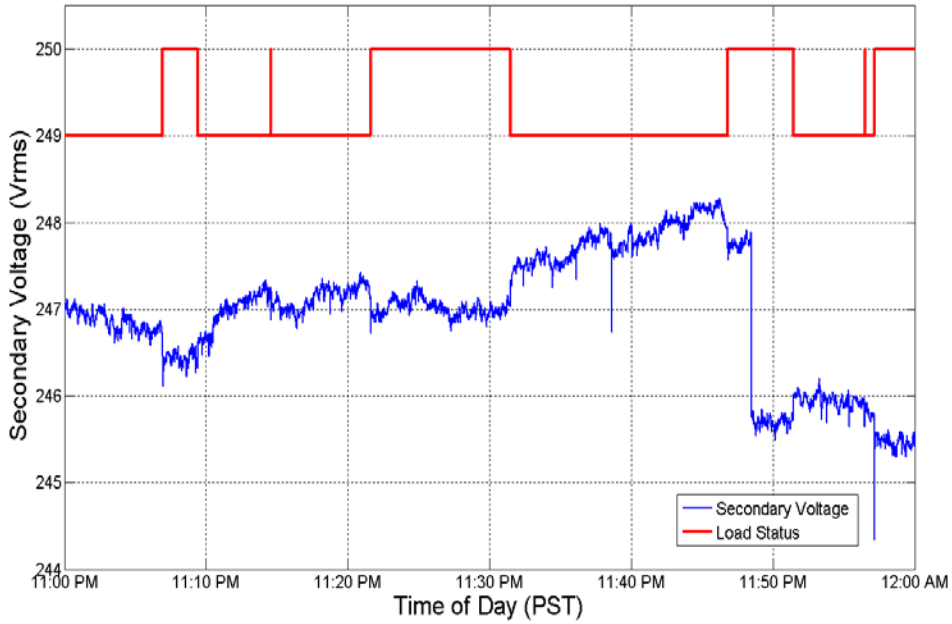


Figure 6-11: Voltage profile corresponding to load switching events

Also on Figure 6-6 a steep voltage drop of 2 volts is seen at about 11:48 p.m. this seems to be uncorrelated to the load events and is probably due to voltage control actions on the feeder. Possible reasons would include actions by switched capacitor banks or tap changers at the substation. Reinforcing this observation is the voltage profile of the other two transformers during the same timeframe. These waveforms are given in Figure 6-7. The blue trace is the transformer voltage from before while the black trace gives the voltage measurement for 8K2 and the red trace is the voltage of 3K7. The sharp voltage drop is also observed at the same time on the other two meters. Since these transformers are on different phases and relatively isolated from each other the inciting event would have occurred further upstream, at some three phase device, possibly in the substation. As expected the voltage on the other transformer shows no correlation to the previous load switching events with no sharp voltage changes at those times.

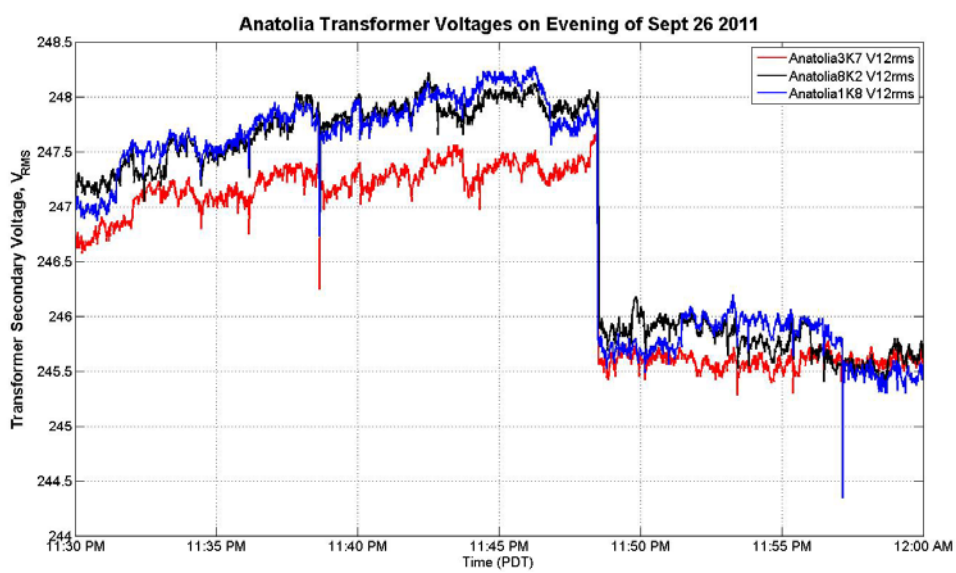


Figure 6-12: Three transformer voltages on September 26, 2011

The data from the installed DMUs has been cataloged starting with the individual install dates up to the present. These data sets are available to researchers at NREL and other project team members. The graphs and discussions in this section are intended to demonstrate the types of data being collected and some basic observations, and are not intended to be exhaustive studies of the metered circuit.

7 Development of Visualization Applications

Two separate data visualization applications have been developed to date. The first is based on Google Earth® and is intended to be a more generic geospatial view of a distribution circuit. It displays circuit infrastructure and real-time measurement data across a distribution circuit. This visualization is intended for a wider audience and thus exploits the user friendly nature of the Google Earth interface. The second visualization application is based on the LabVIEW software; it connects directly to any C37.118 data feed and displays data in real time through a series of rolling strip charts. As it requires higher installation overhead and a more robust communication connection, this display is more suited for internal use.

7.1 Real-Time Visualizations in Google Earth

The primary data visualization package described here is based on Google Earth software, which was chosen for a variety of reasons. Firstly, it is freely available for download from the Internet, allowing end users easy access to the necessary software. Secondly, it provides an intuitive interface for navigation of the globe allowing for a geographic layout of measurement data. The Google Earth package also provides some support for dynamic display features. Finally, it is supported by a large set of documentation detailing all of the necessary source files and data structures.

7.1.1 OpenPDC Historian Outputs

The starting point for any real-time data visualization application is the OpenPDC historian, which ultimately receives all of the incoming measurement data. OpenPDC is open-source and extensible through the use of custom adapters. An adapter is an event-driven data processing layer within OpenPDC. Adapters take measurement data and perform predefined operations on them to produce formatted outputs, check for data quality issues, or perform data analysis tasks. Each adapter can have one or more triggers based on the arrival of new data, threshold detection, and missing data alarms among others. The extensible nature of OpenPDC allows for the development of user-defined adapters written and compiled as dynamically linked libraries.

For the Google Earth visualization package, a custom output adapter was developed with triggers on the receipt of each new measurement point. When a new set of measurements arrives, this adapter creates a Keyhole Markup Language (KML) file as required for Google Earth and saves it to an externally-visible FTP site, which users can then access.

7.1.2 Google Earth Objects and Dynamic Capabilities

Google Earth is capable of rendering several types of objects and overlaying them on the globe. Available objects include points, lines, polygons, image overlays, simple three-dimensional shapes, and models created in external programs (i.e. Google Sketch-Up). It is these objects which are used to visualize the incoming data streams. The objects are specified as part of a KML file. The KML files contain lists of the object vertices specified as coordinates of latitude, longitude, and altitude. Formatting and colors are also specified as part of the KML. The structures of KML files are similar to common XML and are fully documented in Google's help pages.

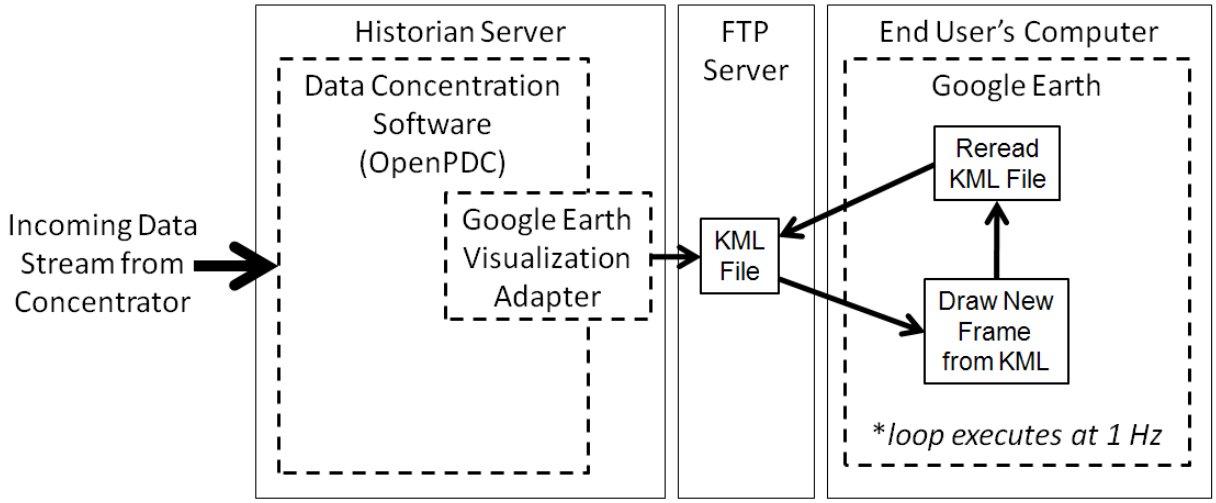
Dynamic displays are not included in the current version of Google Earth. What is provided is an automated KML file reload feature. The display reloads the same file over and over; if another program continually modifies the KML file, resizing and moving the objects, a moving display is built up frame by frame. It is this functionality which is exploited to feed live data into a Google Earth-based display.

7.1.3 Interfacing Google Earth to the Live Data

To support the Google Earth display, a KML file needs to be generated and then updated at the desired frame rate of the display. The KML file generation has been implemented using a custom output adapter

on the historian server. This adapter runs continuously as a background process, processing the incoming data sets as they arrive into the KML output. On each new data set (generally once per second), the adapter extracts the necessary data points and then uses them to create the Google Earth objects and display features. The adapter then writes the objects into the KML file, overwriting the previous contents. The adapter will then wait for the next new set of data to arrive, restarting the process. In this manner the KML file is linked to the incoming measurement data.

The generated KML file is located on an FTP site hosted at NREL and is available to remote users with proper username and password authentication. To view the graphical displays, users must have Google Earth installed on their local machines. Within Google Earth, a network link can be set up by specifying the KML file location and the desired update rate. Through this network link, the Google Earth installation on the user's machine will continuously poll the KML file on the visualization server and thus build the dynamic display frame by frame. The flow chart for this entire system is given in Figure 7-1.



- *On the arrival of each new measurement set the adapter on the historian generates the KML output and overwrites the existing file*
- *The loop on the user's computer continually reloads the KML file from the FTP site, updating the displays*

Figure 7-13: Google Earth-based visualization flow chart

7.1.4 Results and Screenshots

Several examples of the Google Earth-based display features are presented and discussed. These examples are normally dynamic displays, but are presented here as a series of screen captures in an attempt to highlight the temporal nature of these displays.

As a demonstration of what Google Earth is capable of doing with dynamic displays, several examples have been prepared using the SMUD Anatolia distribution feeder. Anatolia is of particular interest because it is a community in which every house is built with 2 kW_{AC} on average of rooftop PV. This results in a high penetration of distributed generation on the feeder and within the neighborhood in particular. This distribution circuit was the first target of metering installations and has 12 DMUs installed into residential split-phase distribution transformers throughout the neighborhood.

As part of this and previous research projects, SMUD has provided circuit models for the Anatolia Distribution System. This data included the geographic information system coordinates in a state plane format. These coordinates were translated into latitude and longitude pairs using the freely available

CORSPCON version 6.0[4]. This software is produced and maintained by the U.S. Army Corps of Engineers specifically for the purpose of translating geographic data among various types of coordinate systems. Once the coordinates were translated, a Visual Basic script was used to convert them into a KML file as objects. This allows Google Earth to render the circuit. Once placed on the globe, the circuit elements were cleaned up and the positions were adjusted to match up with the satellite imagery.

The end result of this translation is the graphical representation of the Anatolia circuit in Figure 7-2. Here, the 3 Phase Feeder conductors are drawn in gray while the Phase A, B, and C Laterals are rendered in brown, yellow, and orange respectively. The distribution transformers are rendered as short cylinders but are not visible in this view. All of the standard Google Earth controls are available so that the user can zoom in and move around to better see the circuit components.

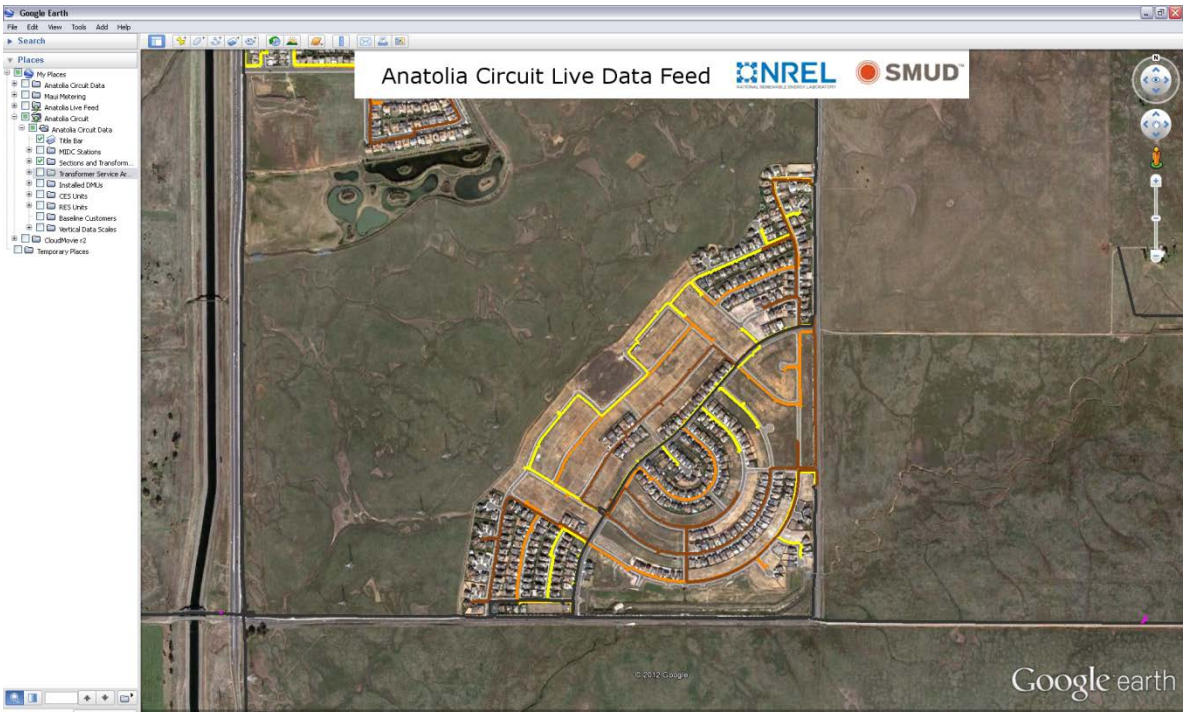


Figure 7-14: Anatolia feeder and laterals
©Google Earth

Several other features were incorporated into this circuit backdrop. Some of these other features are shown in Figure 7-3. The most obvious of these is the transformer service areas. A polygon was drawn for each of the distribution transformers which covers all of the houses served. These polygons are shaded according to the phasing and are shown with the large color patches in Figure 7-3. The metered transformers are also labeled with white and blue squares. Other features available in this display include the locations of residential- and community-level battery installations, and the NREL solar data metering locations from the Measurement and Instrumentation Data Center[5] system.

[4] United States Army Corp of Engineers, "*CORPSCON Version 6.0,*" http://crunch.tec.army.mil/software/corpscon/corpscon.html

[5] *NREL Measurement and Instrumentation Data Center*, www.nrel.gov/midc

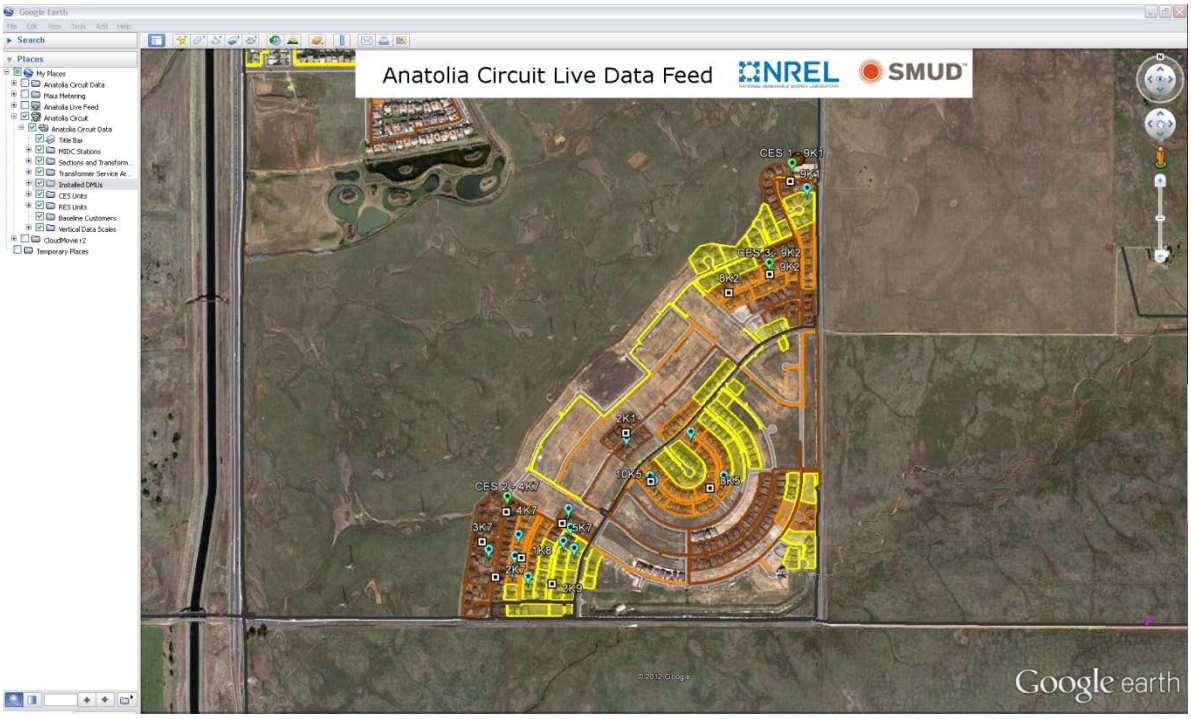


Figure 7-15: Anatolia circuit with transformer service overlay, battery systems, and metering locations ©Google Earth

A closer view of a metered transformer is given in Figure 7-4; in this case, transformer 1K8. This transformer is located on one of the Phase B laterals as indicated by the orange shading. This transformer is serving the ten houses shaded. Three of these houses include Residential Energy Storage systems which are indicated by the teal markers.

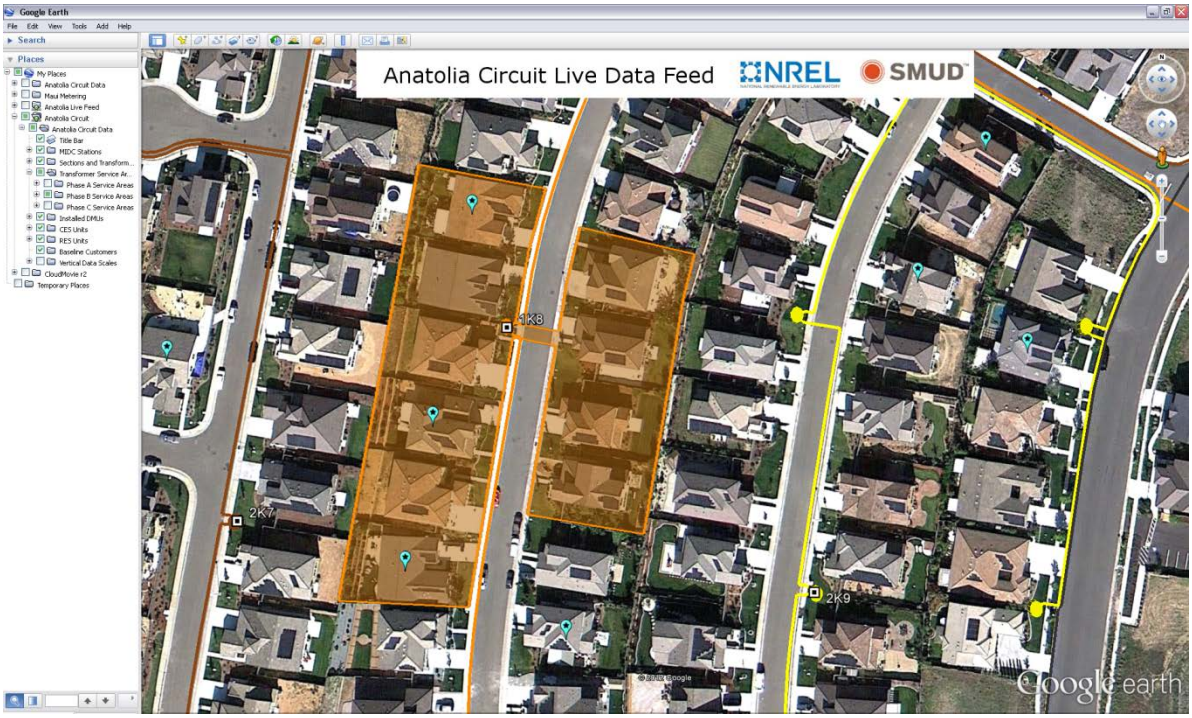


Figure 7-16: Example of a metered transformer ©Google Earth

With the circuit infrastructure laid out on the globe, the next step was to incorporate incoming data streams with the display by scaling geometric objects based on the data values and placing them in the

correct places. A dynamic display is achieved through the continual reloading of newer KML files. Once the adapter is running these files become available and can be linked from Google Earth.

Some of the dynamic features are presented in Figure 7-5. In this case, the secondary voltages are being displayed for three of the metered transformers; 3K7, 4K7, and 1K8. Transformers 3K7 and 4K7 are on a Phase A lateral and are serving the houses in the brown shaded area. Transformer 1K8 is the same one pictured in Figure 7-4 and serves ten houses on Phase C. The most recent voltage measurement is indicated by the height of the white cylinder at the transformer location. Previous voltage values are drawn as a white tail extending to the right hand side. For these displays, the scale is given by the image behind and to the left of the cylinder.

The arrows on the ground level of Figure 7-5 indicate the measured power flows through the transformer. The red arrow is scaled by the real power and the blue arrow is scaled by the reactive power measurement. The scaling factor on the reactive power is four times larger than that of the real power. This is done so that the reactive power arrow appears on the display. If the two arrows are the same relative size, the observed power factor is 0.97. In both cases, the direction of the arrow gives the power flow direction, with north indicating flow toward the utility and south toward the homes.

Google Earth has been configured to reload the KML file every second, synching it to the live feeds, updating the voltage traces, and rescaling the power arrows with every new data point.

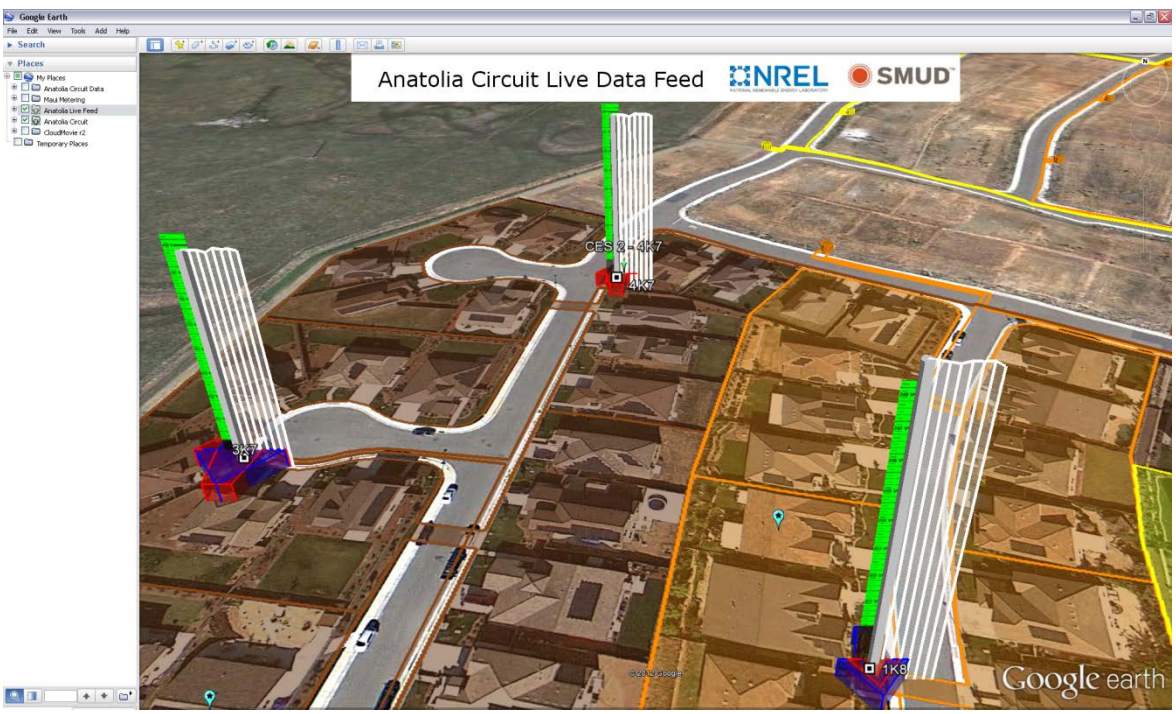


Figure 7-17: Transformer secondary voltages and power flows on 3K7, 4K7, and 1K8 ©Google Earth

Figure 7-6 is a closer view of Figure 7-5 with the voltage scale on a transformer visible in greater detail. Here we can see that the voltage is just over 247 V. Historic values extend off to the right, and we can see that the voltage value has been stable over the past eight seconds.

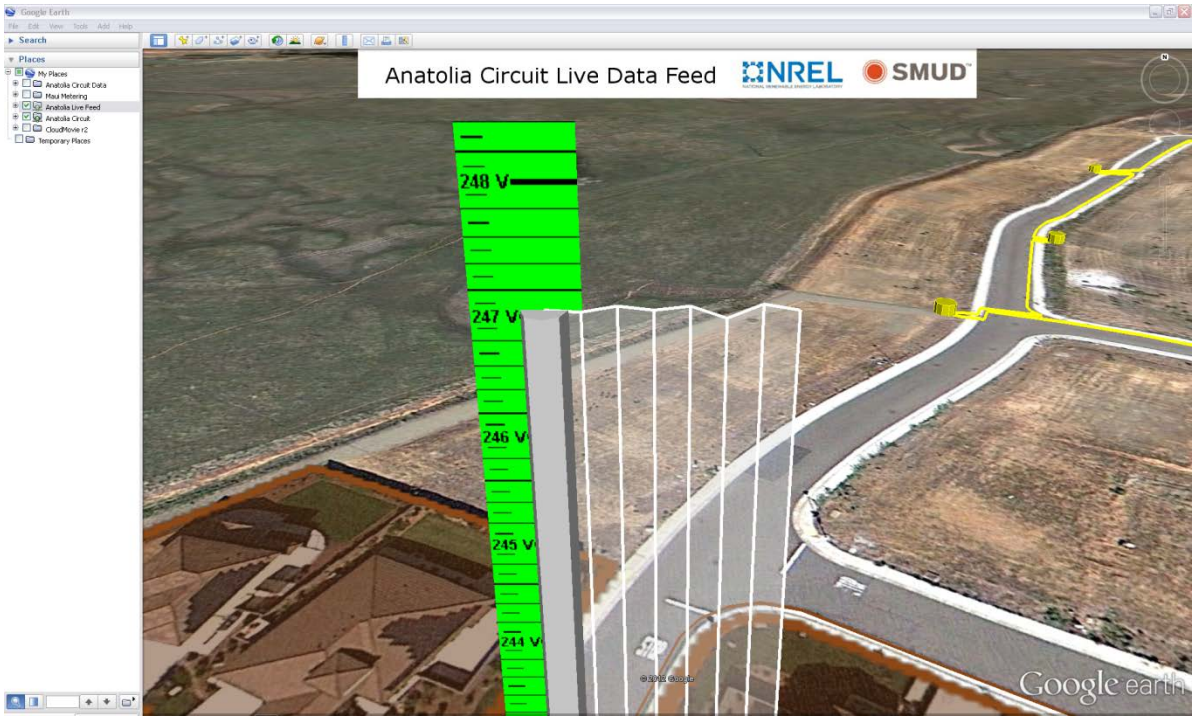


Figure 7-18: Closer view of voltage scale indicator
©Google Earth

In addition to the three transformers shown here, 12 others throughout the neighborhood have been instrumented. Live data feeds like the ones above are available at all of these points, building a picture of this system spatially and temporally. The user is capable of panning across the Anatolia circuit using the Google Earth controls to observe how a particular system parameter is varying throughout the service area.

Although the Google Earth captures shown here are specific to the SMUD-Anatolia circuit, the interface is general enough that it can be provided for any instrumented circuit. Given the proper location and circuit infrastructure information, similar displays can be built up for other distribution circuits with installed real-time metering.

7.2 LabVIEW-Based Visualization Tool

In addition to the Google Earth display, another visualization package has been developed which is focused on live rolling strip charts. This package is based on NI LabVIEW software and communicates directly with the data historian server using the IEEE C37.118 protocol. To facilitate this connection, an output stream has been configured on the historian to stream the concentrated C37.118 data sets. Users can then connect to this output from the LabVIEW-based tool to view live data.

Using this package, users can select a variety of displays which present the incoming data in a series of strip charts for each of the C37.118 data types including phasors, frequency, and analog and digital signals. The information displayed on each chart is selected with a series of pull-down menus. Up to ten channels can be viewed simultaneously on each strip chart.

For this application, the C37.118 communication drivers were developed within the LabVIEW environment to handle a direct connection with the data stream available in OpenPDC. Since the communication supporting this display package is based on the IEEE standard, the data streams flow in as a live feed and all of the charts are updated accordingly. Additionally, the LabVIEW-based visualization software is capable of connecting to any measurement device or data concentrator which can output data formatted according to the IEEE standard.

Examples of phasor-based displays are given in Figure 7-7 and Figure 7-8. Figure 7-7 presents the phasor measurements as a set of strip charts with the magnitude plotted on the top chart and the angles on the bottom chart. With these displays the phasors can be tracked in real time. On the left side of the screen, the user can select any of the available measurements with the pull-down menu and the display will be updated accordingly. The charts shown in this image are based on live data streams collected from the DMUs.

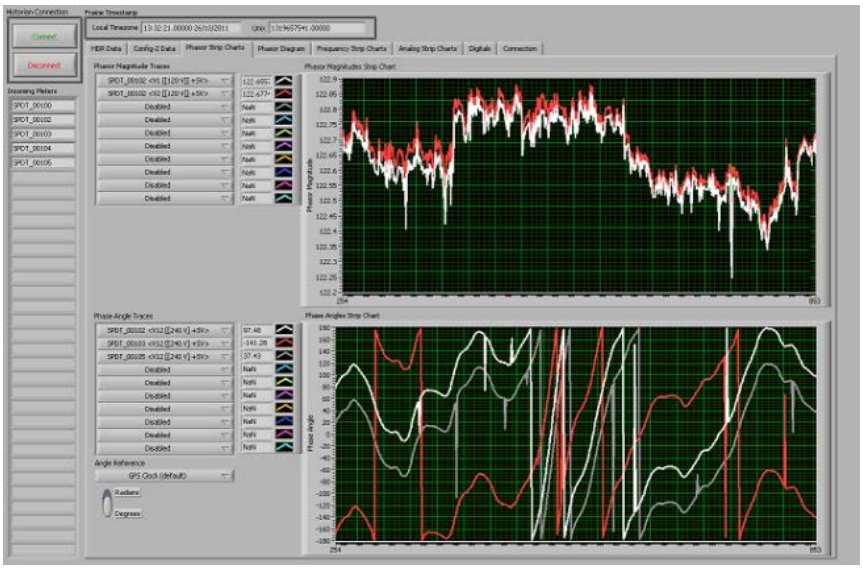


Figure 7-19: Phasor strip chart display

The other phasor-based display is presented in Figure 7-8; this is a phasor plot. Once again, any of the available measurements can be selected for display and viewed live. This display does not include the time history of the previous one, but it does give a clearer picture of the phase delays and magnitudes with respect to each other. In Figure 7-8, all 6 phasors from one transformer have been plotted; the inner green circle is a scale reference at a magnitude of 120 and the outer red scale is 240.

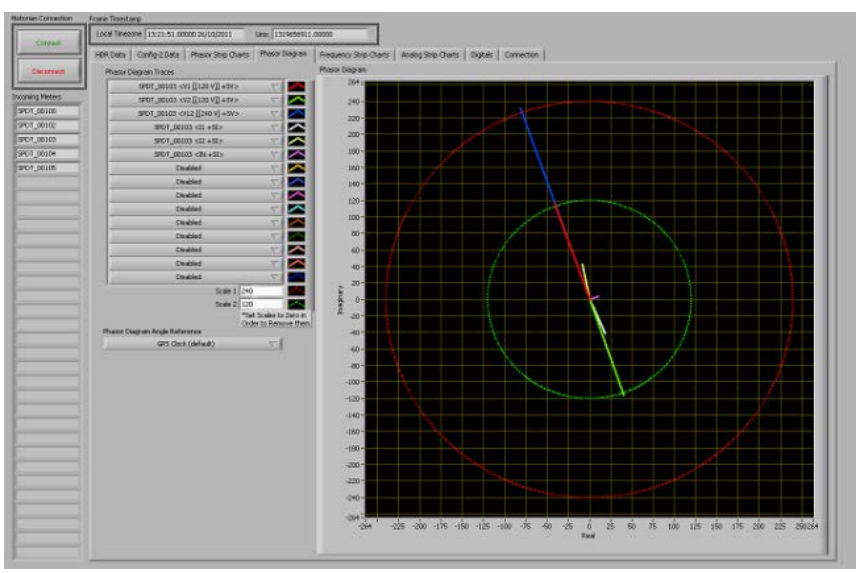


Figure 7-20: Phasor diagram display

One last example of the LabVIEW-based visualization software is shown in Figure 7-9: the analog measurement strip charts. In the case of the DMUs, all of the RMS, power, power factor, and temperature measurements fall into this category. Once again, the chart traces are selected through a series of pull-down menus on the left side of the screen. The top chart displays real-time real and

reactive power measurements from two of the metered transformers. The bottom chart plots the power factor from the same two transformers.

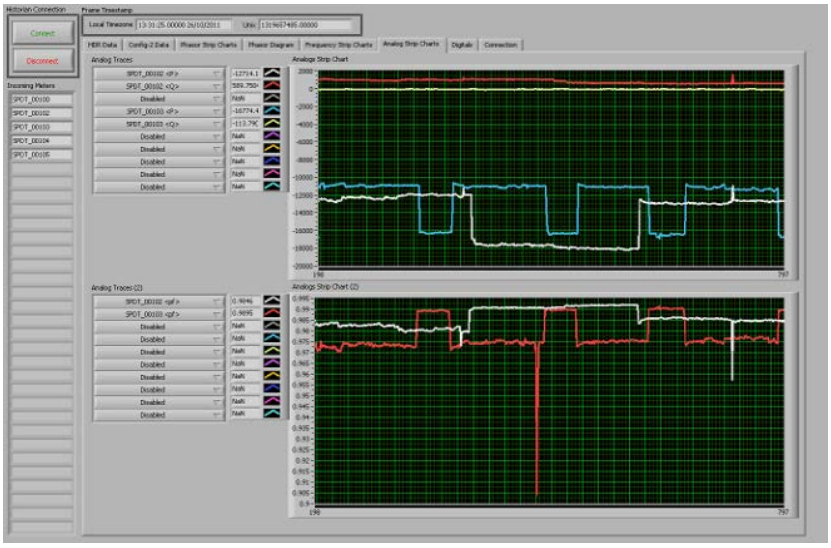


Figure 7-21: Analog strip chart display

8 Modeling Integration with Data Streams

One application of the real-time data feeds is improving the relevancy and accuracy of distribution system models. Integrating real-time measurements into distribution models allows the models to more closely reflect the physical system. Given sufficient computational resources, the incoming data can be used as inputs to a distribution system model, which can then be solved, building a more complete picture of the system. Doing this in a real-time, point-by-point fashion extends the real-time visualizations with data points estimated by the model solution. To demonstrate this integration, a distribution modeling software platform, Distributed Engineering Workstation (DEW), was tied into the data stream.

DEW is an extensible distribution modeling software platform that allows a user to extend the core functionality of a program through a well-defined application programming interface. In this case, an application was written that allows DEW to import data from the data historian server into the distribution models. Once imported, the data can be used to scale loads to better match what is currently happening in the physical system.

To accomplish this integration, a number of mappings were made between physical equipment locations, and historian data identification numbers. These mappings tie a measurement vector to the location of equipment in the models. Most of these mappings were completed manually using configuration files that are read during software initialization. Figure 8-1 shows an example of a configuration file. For example, measurement 233 in the historian server is the real power measurement coming from the DMU located in transformer 2K7 at Anatolia. The first point entry in the XML of Figure 8-1 ties this measurement identification number to the 2K7 load value within the DEW model of the system.

```xml
<?xml version="1.0" encoding="utf-8"?>
<configuration>
  <historianURL>http://10.20.9.26</historianURL>
  <point_map>
    <point>
      <historianID>233</historianID>
      <UID>2_K_7_Load</UID>
      <phases>A</phases>
      <type>power</type>
    </point>
    <point>
      <historianID>234</historianID>
      <UID>2_K_7_Load</UID>
      <phases>A</phases>
      <type>reactive_power</type>
    </point>
    <point>
      <historianID>39</historianID>
      <UID>3_K_7_Load</UID>
      <phases>A</phases>
      <type>power</type>
    </point>
    <point>
      <historianID>40</historianID>
      <UID>3_K_7_Load</UID>
      <phases>A</phases>
      <type>reactive_power</type>
    </point>
    <point>
      <historianID>264</historianID>
      <UID>4_K_7_Load</UID>
      <phases>A</phases>
      <type>power</type>
    </point>
    <point>
```


Figure 8-22: Example configuration file

Once it reads the configuration files, the application searches the circuit model for matching components. If an appropriate match is found, the application associates relevant values (type of electrical parameter, phase, etc.) with the modeled components. Through this association, the measurement values coming from the DMUs are linked to the circuit model.

After all associations have been made, the application runs load estimation and power flow on the circuit. With the links between the data collection and modeled system, the available real-time measurements replace the applicable pre-existing load values in the model. The resulting circuit solution now includes up to date measurement information, improving the model outputs. Together, these applications allocate load and generation on the circuit and perform a basic electrical analysis. Since the complete circuit model has been solved, estimated values of unmetered locations are also provided. The implementation of this circuit solution has also been incorporated with the real-time feeds, providing a solution to the model for each timestamp, upon arrival of each new data set. The values generated from this analysis can be fed into other, more advanced applications such as hardware-in-the-loop simulation or advanced visualization (described below). A flow chart of the developed architecture showing these relationships is given in Figure 8-2.

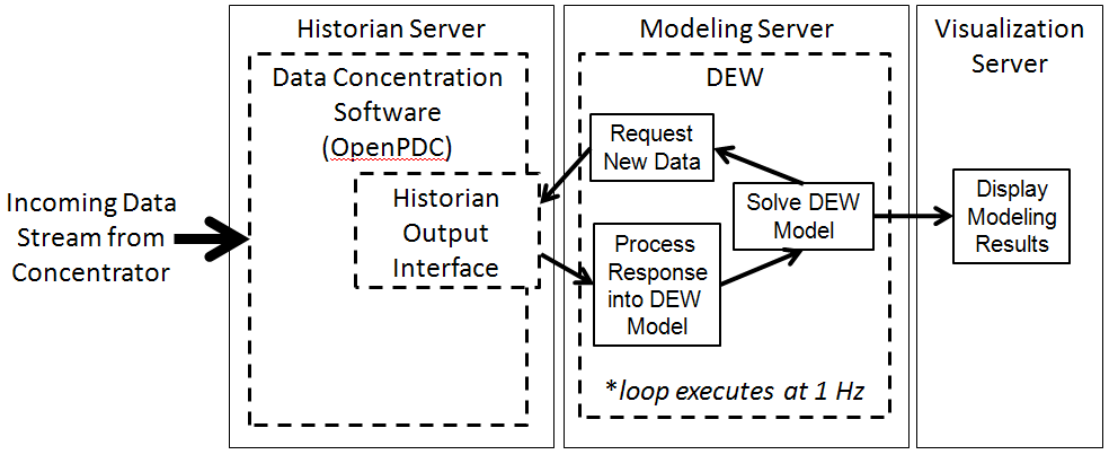


Figure 8-23: Data collection and modeling Integration flow chart

9 Incorporation of Modeling Results with Visualization

To add functionality to the visualization capabilities described above, an application was written in DEW that outputs circuit data to Google Earth in a format congruent with the visualization techniques described in Section 7.1. This capability will provide a more complete picture of a given circuit, as the output from the model solution is now incorporated into the geographic display. This feature also provides flexibility for visualizing different simulated scenarios independent of live data.

The first step in the implementation of a visualization application based on the DEW modeling results is a mapping between the modeled elements and their appropriate locations within Google Earth. While both Google Earth and DEW contain spatial information that describes the circuit, differences in the coordinate systems as well as minor inconsistencies between the two programs makes some translation necessary. A configuration file was generated which matches individual components with a latitude and longitude, defining their position on the globe. This file is read when the application is started and provides locations of the circuit elements to be plotted in Google Earth. The application then matches the modeled elements with the items in the configuration file, and builds the necessary KML file containing the computed real power, reactive power, and voltage level values for each matched location. The construction of this KML file is included in the *Solve DEW Model* block of Figure 8-2. Once built, the file is passed on to the visualization server as indicated. As with the previous Google Earth visualization, a user can then connect to the visualization server to retrieve and display this file.

Figure 9-1 shows the outputs of the modeling integration incorporated into the Google Earth displays described in Section 7.1. The voltage real and reactive power is plotted for each distribution transformer in the neighborhood. The outputs of the simulation tool are plotted within the context of the existing circuit map and metering locations, filling in unknown points of the map with the results from the data-driven model solution. The point-by-point resolving of the model based on new data allows this display to be updated in real time as with the previous one.

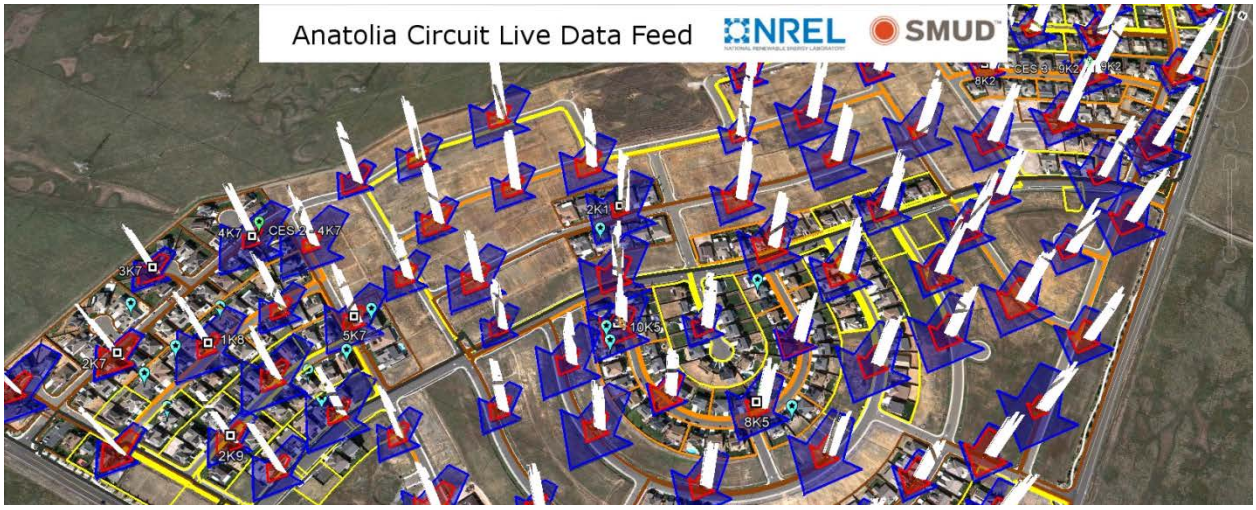


Figure 9-24: Visualization driven by model
©Google Earth

10 Conclusions and Continuing Work

Over the past two years, NREL has been developing a high-speed, real-time measurement and data collection network specifically targeted for distribution-level applications. This network has gone live, collecting high resolution data from a few different distribution feeders. One-second data sets have been collected and stored from a large number of measurement vectors, spanning more than a year. This data is cataloged on internal servers and is used to support research projects that assess the impacts of distributed generation and smart grid technologies.

Several visualization packages have been developed which are fed by these real-time data streams. The primary display is based on Google Earth. It can display real-time voltage and power measurements from a distribution circuit on the surface of the globe, providing a temporal and geospatial view of the circuit. This particular display is designed to be user-friendly and portable, requiring only an Internet connection, Google Earth software, and proper login credentials.

The secondary visualization program sacrifices portability to provide a more complete strip chart display based in LabVIEW. Any available measurement vector can be selected and added to the rolling graphs with new measurement values added to the plots as they come in.

Finally, the data streams have been integrated with a distribution system modeling package, allowing the measurements to inform the solution of the distribution circuit and estimate values for unmetered locations. These results can also be fed back into the visualization packages in real time, building a more complete picture of the system state.

There are several continuing developments for this data collection network. Deployment into other distribution circuits has already begun and will continue. Functionality is being added to the DMU to provide additional measurement outputs. A lower-cost metering solution is under development that will facilitate larger-scale deployments and cost-effective metering of individual households. Several network and server upgrades are currently in development which will facilitate increased data rates and provide increased system reliability.