Energy Storage Monitoring and Control For a Microgrid

Chuck Wells[1] (OSIsoft,LLC), Ph:650-504-6278; e-mail:cwells@osisoft.com
Kevin Meagher[2], William Torre[3] and Byron Washom[3]
[1] OSIsoft, LLC
[2] Power Analytics
[3]University of California at San Diego

ABSTRACT

Integrated monitoring and control of energy storage and other generating sources and loads in microgrids are important to ensure full realization of the benefits of energy storage. This paper describes ongoing projects at the University of California – San Diego (UCSD), 42 MW microgrid that integrates energy storage and associated monitoring and control.

The UCSD microgrid power distribution system, the central power plant and building facilities are highly instrumented including over 85,000 data streams that have been archived for nearly three years. The system is designed for efficient integration of distributed energy resources (DER). The microgrid controller is integrated with OSIsoft's PI data server on campus. Real time power system analysis is performed to verify reliability constraints for planning and operation of the microgrid as well as determine energy storage optimization.

The UCSD microgrid also has one of the largest installations of synchrophasors (phasor measurement units, PMU) in academia. PMU data are at the San Diego Supercomputer Center's (SDSC) in high density flash drive machines. Six PMU synchrophasors have been installed at the East campus substation. Six additional PMUs are planned to be installed on a distribution circuit to provide detailed understanding of the performance of high PV penetraton, EV charging, and energy storage on a distribution circuit. The microgrid controller is expected to utilize these data providing the capability to operate the UCSD microgrid in island mode if necessary. The CAISO, DOE, CEC and SDG&E are also collaboratively engaged to utilize the UCSD microgrid to improve management and efficiencies of the utility's and statewide grid operations such as demand response, excess generation, renewable supply, load balancing and power outages.

INTRODUCTION

The UCSD microgrid serves approximately 45,000 students, faculty and staff with a peak load of 42 MW. The microgrid includes two 13.5 MW combustion turbines and a 3 MW steam generator that can be used to produce electricity or chilled water for HVAC cooling. Supplementary gas fired boilers are used to generate steam for producing chilled and/or hot water supply for the building air conditioning systems. Additional electric powered chillers supply other cooling loads. The campus has approximately 3.0 MW of rooftop solar PV with essentially all suitable rooftops fitted with conventional solar panels. Concentrated PV systems are also included on campus providing high efficiency distributed solar power one of the east campus distribution circuits. A few of the buildings have solar thermal systems providing local hot water to the buildings.

A 2.8 MW fuel cell provides 2.8 MW of base load power. The unit is supplied with contracted biogas from the City of San Diego sewage treatment plant. Thus on an ideal day the campus can generate 36 MW of power or 92 percent of the peak load. The system also includes a 3.8 million gallon chilled water storage tank that provides chilled water for the campus HVAC system.

The campus is connected to the SDG&E area power system by two 69kV primary feeders via four breakers providing a three section high voltage bus supplying power to three UCSD owned wye-delta 25 MVA transformers feeding the main 12 kV substation bus as shown in Figure 1. This induces a minus 30 degree phase shift from the primary to the secondary. This is important information when for reconnecting to the area power grid from the island mode. The 12 kV bus includes three main beakers and three breaker ties. This allows the substation to be configured to use only two transformers to meet the campus loads as well as allowing operation of the system as two parallel microgrids each connected to one combustion turbine.

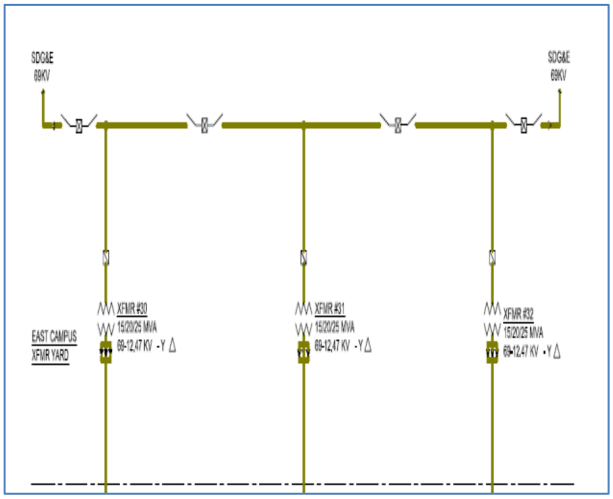


Figure 1: Incoming feeders from San Diego Gas and Electric

The main substation feeds the five campus distribution substations including East Campus Chiller plant, Central Utility Plant, North Campus, Revelle College, and Scripps Institute of Oceanography. A total of 14 main feeder circuits supply power to these substations as shown in Figure 3. Figure 2 shows the substation single line connection for the East Campus substation, which is typical of the other 12 kV substations on campus.

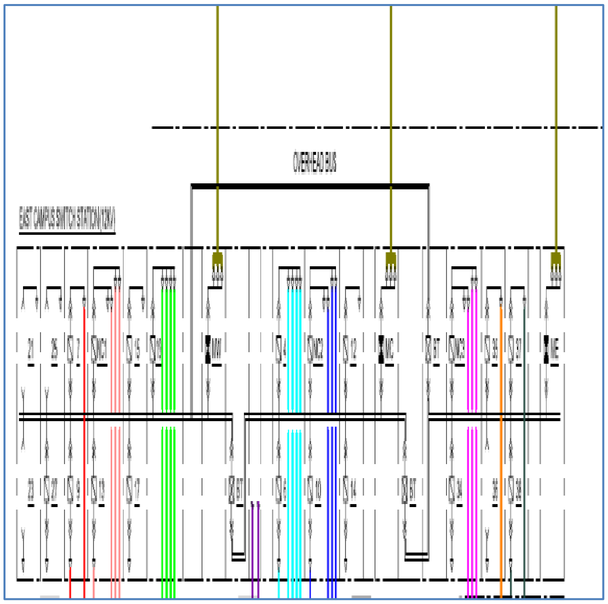


Figure 2 East campus substation main feeders to campus distribution substation.

The feeders supply power directly to four distribution substations on campus. From these, power is distributed to buildings and research facilities at 12kV levels as well as the Central Utility plant. At each building, 12kV/480 V transformers reduce voltage levels for consumption by the loads.

Figure 3 below shows a simplified one line schematic of the campus distribution system.

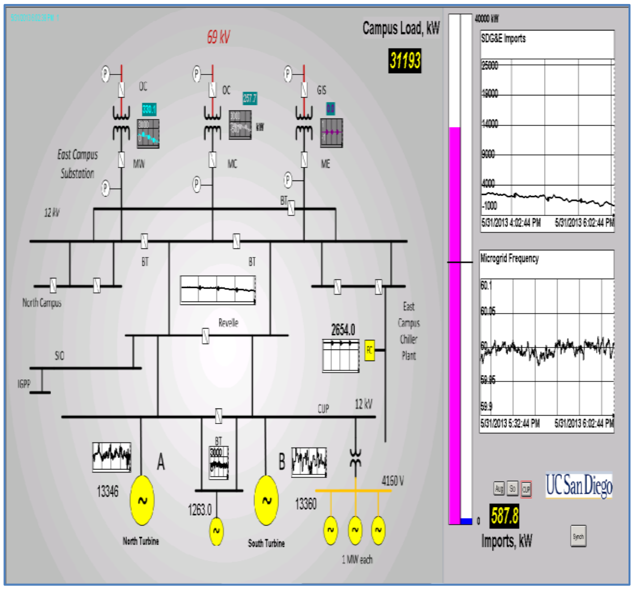


Figure 3 Simplified one line diagram of the campus electric power distribution system.

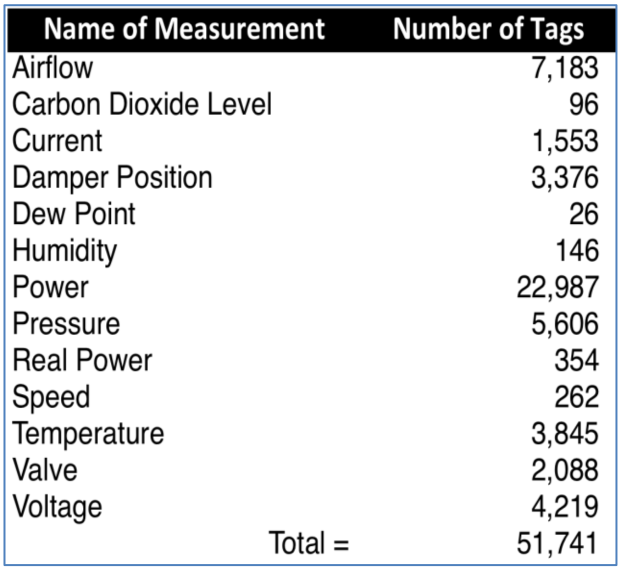
This OSI PI process book display incorporates the single line shown in Figure 3 as a live display. Mouse clicking on any object in this display screen brings the object to full screen resolution and supports panning and zooming. The power import to the University is shown at the bottom right in the black box with yellow numbers. The total load is shown near the upper right [31.193 MW]. Time is shown on the upper left is 6:02 PM on May 31, 2013. On the right hand side of the display are two 10 minute trend charts showing campus imports in kW and local microgrid frequency in Hz. The two vertical bars represent the total campus load and the imports. The operational goal is to minimize imports from SDG&E during normal load periods. At low loads and during quarter breaks and occasionally early in the morning hours, the imports are zero.

The diagram also shows the key breaker ties that can be used to control topology of the microgrid. As indicated above the microgrid can be run as essentially two microgrids in parallel with the East Campus substation by opening the tie breakers at Revelle and CUP.

UCSD MONITORING SYSTEM SUMMARY

The OSI PI System is used to monitor over 85, 000 data streams on campus. These include extensive information from key HVAC systems, the Central Utility Plant, the campus network model, and a number of meters monitoring power flow in key feeder circuits. PMU data is also archived in the PI system at data rates of 60 Hz.

Figure 4 below lists the types of measurements handled by the PI system: this does not include the PMU data.



Name of Measurement	Number of Tags
Airflow	7,183
Carbon Dioxide Level	96
Current	1,553
Damper Position	3,376
Dew Point	26
Humidity	146
Power	22,987
Pressure	5,606
Real Power	354
Speed	262
Temperature	3,845
Valve	2,088
Voltage	4,219
Total =	51,741

Figure 4 Types and number of power measurements on campus

These data are routinely used in big data analytics classes (e.g. CSE 291) as well as research projects at the SDSC in Predictive Analytics. A typical data set used in the Hadoop cluster is over 550 Gbytes in size.

The PMU measure voltage and current phasors as well as positive, negative and zero symmetrical components including real, reactive and apparent power. Several of the

PMU monitor the first fifty harmonics in current and voltage of each phase. Harmonic distortion is typically of concern in microgrids due to the low inertia of the system when operating in island mode. This is further exacerbated in microgrids with large percentage of directly connected solar PV power due to the injection of harmonics from the inverters.

RENEWABLE POWER INTERMITTENCY

As indicated above, UCSD has about 3 MW of rooftop solar PV on campus contributing up to ten percent of the distributed energy resources. The campus is located near the coastal fog line meaning that the fog burn off has a major impact in production. The rate of change of power output from the panels during the fog burn off is surprising as show in Figure 5 and Figure 6.

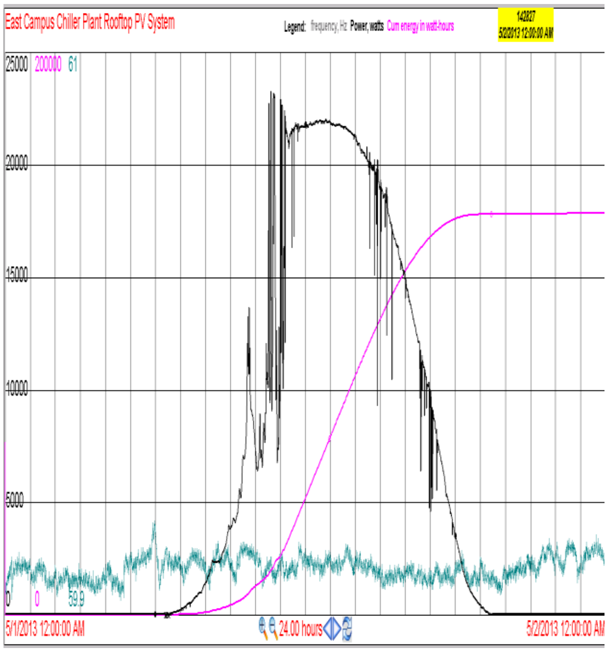


Figure 5 Full day view of panel output

The fog burn off in the morning hours causes large changes in local generation. The rate of change is much larger than expected as well as the magnitude of change as shown in Figure 6.

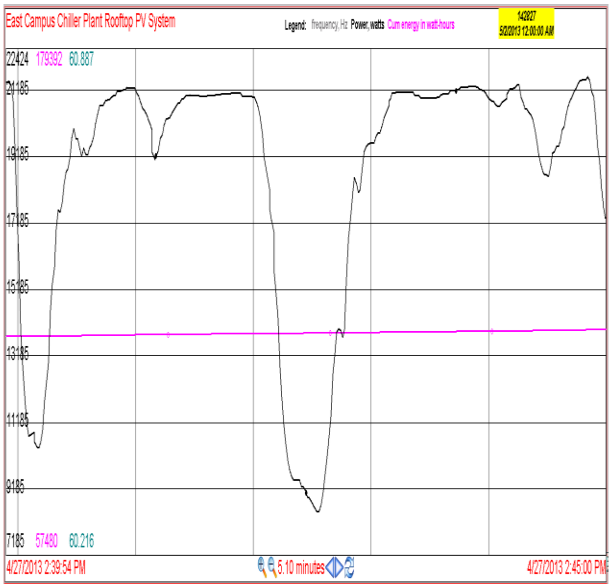


Figure 6. Rate of change of solar output, from full scale output to 30 percent in 30 seconds

This is a zoomed in view of a typical five minute period during the day. Note that this is in the early afternoon when the fog is rolling back in from the coast.

One potential use of the UCSD battery systems is to mitigate the behavior of the renewable PV sources on campus.

LOCAL MICROGRID DISTURBANCES

Microgrids have much less inertia than the area power systems to which they are connected. Consequently they must be "stiff" when connected in order to handle lower inertia and local disturbances inside the grid.

An example of microgrid disturbances is shown in Figure 7.

This shows a set of three typical oscillations inside the microgrid.

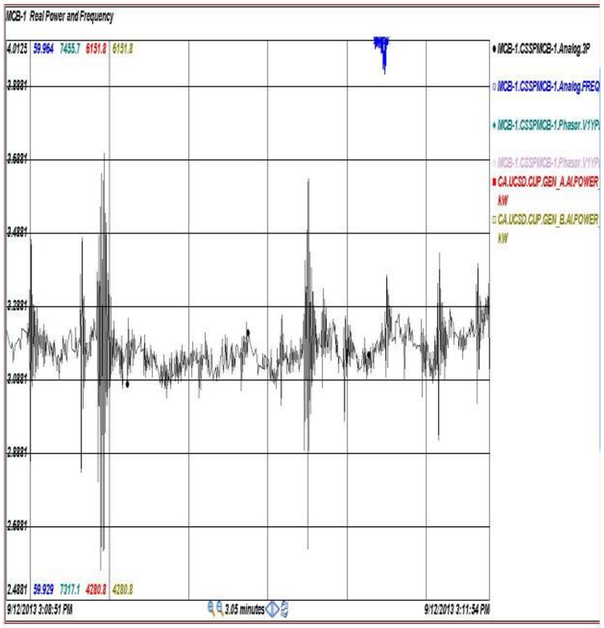


Figure 7 Local power oscillations inside the microgrid.

This is a series of three oscillations within a three minute period, they have magnitudes from 0.5 to 0.9 MW and periods of about 500 mS. A zoomed in view is shown in Figure 8.

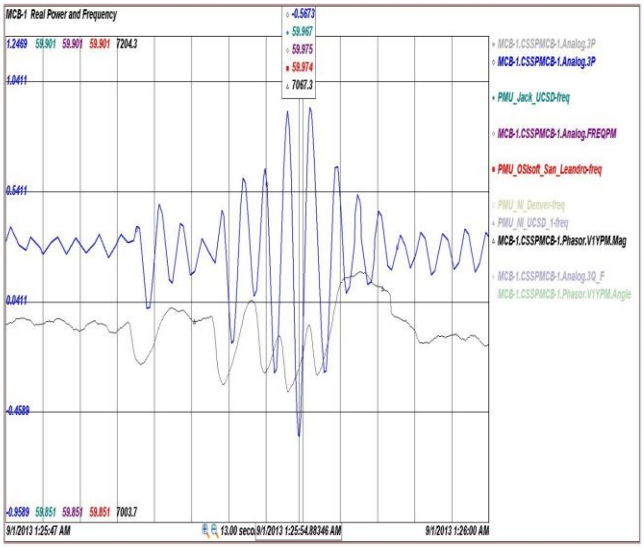


Figure 8 Zoomed in view of a typical disturbance.

This trend shows the power in blue and the voltage in gray. Note that this disturbance affects both frequency and voltage. This implies that the system is closely coupled, that is the real and reactive power injection into the system affects both frequency and voltage. This is shown in more detail in Figure 9.

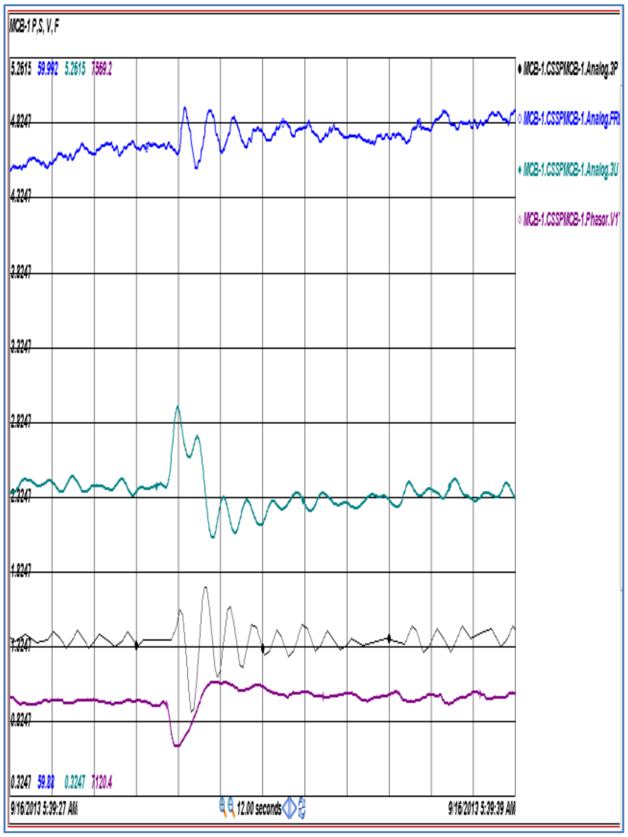


Figure 9 Real and apparent power, frequency voltage at MCB-1

This shows the coupling between real and apparent power and voltage and frequency. Specifically, the frequency, real and apparent power increase but voltage decreases. Power system engineers often assume that frequency and voltage are independent phenomena, but in fact they are closely coupled as discuss later in this paper.

The oscillations in the microgrid have been routinely analyzed for more than one year. The technique used for analysis was developed by

Prof. Raymond de Callafon in the Mechanical and Aerospace Engineering department. The method is called “realization.” It automatically detects microgrid disturbances and then computes the optimal linear model for the disturbance. This includes the number of state variables, order of the system, the eigenvalues of the system, the damping and modes of the system. A typical example is shown below in Figure 10.

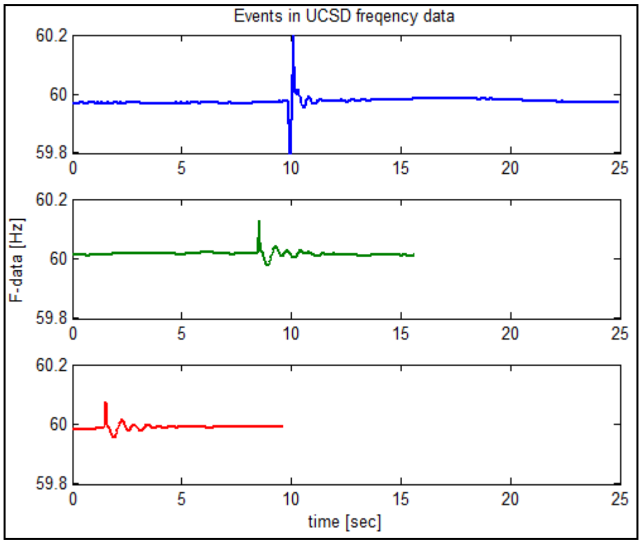
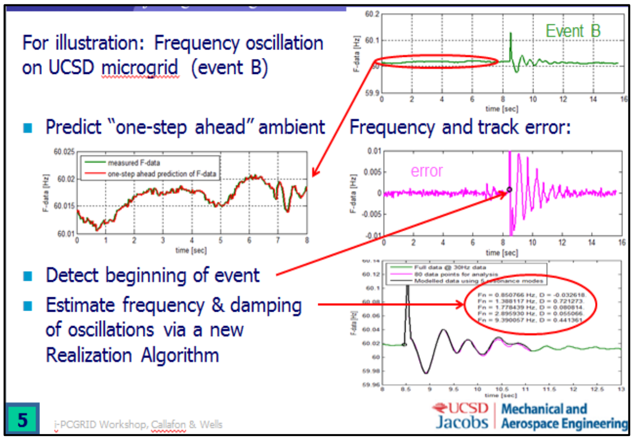


Figure 10 Example of typical oscillations inside the microgrid

The analysis of one of these events is shown below in Figure 11.



For illustration: Frequency oscillation on UCSD microgrid (event B)

- Predict “one-step ahead” ambient Frequency and track error:
- Detect beginning of event
- Estimate frequency & damping of oscillations via a new Realization Algorithm

Figure 11 Example of realization method

One of the possible roles of energy storage devices could be help regulate voltage and frequency inside the microgrid even when connected to the area power system. The control algorithm for frequency and voltage control could be based on the model developed using the “de Callafon” realization algorithm.

BATTERY SYSTEMS SUMMARY

UCSD currently has the following battery systems operating or planned to be installed on campus:

- Sony/ Panasonic energy storage, 60 kW/ 60 kWh, Lithium- Ion
- Second life battery testing, 120kW/300 kwH, Lithium Ion
- ZBB/ Sunpower 100 kW, 300 kWh Zn-Br flow battery – expected to be operational October, 2013
- BMW 108 kW/ 180 kWh, Li-ion Mini E – expected to be operational October, 2013
- SGIP 2.5 MW, 5 MWh – Currently in design (stage)
- Maxwell Ultra-capacitors (two system being installed on campus) – currently in design

These systems are distributed across the campus and connected to 12 kV circuits fed by the microgrid substation feeders. A brief description of these systems follows:

Sony/Panasonic

This system is a 60kW/60 kWh system installed in 2011. The system consists of approximately 1500 Li-ion cells manufactured by Sanyo and wired in series/parallel to supply power to an inverter feeding a local 480 volt circuit. Panasonic rooftop PV panels provide power to the system that normally will discharge the battery system during the peak load hours and then charge them during the during the early morning hours. This causes a leveling of the peak loads during the day.

Second Life Battery Project

The California Center for Sustainable Energy (CCSE) and the University of California, San Diego (UCSD), in partnership with the National Renewable Energy Laboratory (NREL), are currently operating a one-of-a-kind advanced PEV lithium-ion battery test facility within the UCSD microgrid environment in order to determine the viability and potential value of used PEV batteries in post-vehicle, stationary energy storage applications. This project is funded by NREL through the U.S. Department of Energy's (DOE's) Vehicle Technologies Program.

The battery testing process involves a variety of tests via the Battery Control Software (BCS). Modbus is the protocol being used to communicate with the Battery Control Software.

The Battery Test Facility includes two inverters. Each inverter has a capacity of 60 kW providing up to 120 kW of power. There are two batteries per converter operating in parallel.

Three A123 batteries and one EnerDel battery are in operation. The A123 Systems Packs have a nameplate capacity 21 kWh. The A123 Systems Module has a nameplate capacity 4.2 kWh. The EnerDel battery has a nameplate capacity 22 kWh. The used PEV batteries have lower capacity than their nameplate capacity. The A123 Systems Module has a continuous charge power limit of 4.6 kW, a continuous discharge power limit of 13.2 kW, a 10-second pulse charge power limit of 25.0 kW, and a 10-second pulse discharge power limit of 40.4 kW. The A123 Systems Packs have a continuous charge power limit of 23 kW, a continuous discharge power limit of 66 kW, a 10-second pulse charge power limit of 120 kW, and a 10-second pulse discharge power limit of 202 kW. The EnerDel Pack's power limits vary. When cycling the batteries, the capability of the inverters is usually the limiting factor in potential power output.

UCSD has done extensive testing of the batteries over the past two years and is now using them in innovative ways such as shifting peak demand and for closed loop control of local frequency

ZBB/ Sunpower CSI 100 kW/300 kWhr Zinc – Bromine Flow Battery

A 100 kW/300 kWhr zinc – bromine flow battery system is being installed and should be operational by the time of this conference. This energy storage system will be coupled with local load at the East Campus Chiller plant and roof top flat panel PV solar. This project is funded by the California Public Utilities Commission (CPUC) / California Solar Initiative (CSI). The control and operation of this energy storage system is focused on determining the potential economic benefits of demand reduction using energy storage. Sunpower is responsible for developing the control system that will optimize the operation of the energy storage system to maximize demand reduction. Remote control capability will be provided through interface with UCSD's control system. In addition all data points in the Power Conditioning System as well as the energy storage Battery Management System will be collected using the UCSD OSI Soft PI system.

BMW

UCSD along with the California Center for Sustainable Energy (CCSE) has been investigating the potential feasibility of utilizing used batteries from electric vehicles (EV) as a low cost source of batteries for stationary energy storage applications. UCSD has developed and installed a test stand that includes bi-directional inverters that allow testing of these used (2nd life) EV batteries. Based on promising results of testing of these batteries, UCSD and BMW proceeding forward with design and installation of a full scale energy storage system utilizing 6 battery packs from BMW Mini-E electric vehicles. This (108 kW/ 160 kWh) energy storage system utilizing 2nd life batteries. This energy storage system will also be linked to UCSD's master microgrid controller and the OSI PI data acquisition system. This energy storage system is expected to be operational by the time of this EESAT conference.

SGIP

UCSD has purchased a 2.5 MW/ 5 MWhr energy storage system and has begun design of this new system. The system will be coupled with UCSD's 3 MW of PV solar generation and microgrid to minimize campus energy production costs. The design of the system is underway, and will include close coupling of controls with UCSD's microgrid master controller and data acquisition system. The comprehensive data monitoring planned to be included will provide one of the most detailed performance evaluations of a large scale energy storage systems ever undertaken. The fact that this will be the largest energy storage system operated on a university owned utility grid with one of the most sophisticated monitoring and control systems will provide a unique opportunity to obtain valuable performance data and research for the advancement of energy storage.

Maxwell Ultracapacitors

UCSD and Maxwell Technologies Inc. will be installing a 28 kW energy storage system utilizing super-capacitors. This system will be coupled with an existing 28 kW Concentrated Photovoltaic System (CPV) provided by Soitec Inc. A small 7kW Soitec CPV was first installed and demonstrated at UCSD and which led to the commercial development of the 28 kW CPV system. The energy storage system has only 5 minutes of energy storage capacity, and control will be focused on utilizing super-capacitors to smooth out intermittency and to improve ramp rates in the CPV energy production caused by cloud reduction of solar radiance. The control system for the energy storage system will be linked to UCSD's advanced solar forecasting system to allow advance intelligence for controlling the energy storage to minimize the impacts of intermittency cause by varying solar radiance.

BATTERY MONITORING

Monitoring systems for storage systems could include string voltage and current, individual cell voltage and current (computed internal resistance), temperature, voltage drop and outside ambient conditions.

One monitoring system being studied by UCSD for Li-ion batteries could be designed as shown below in Figure 11.

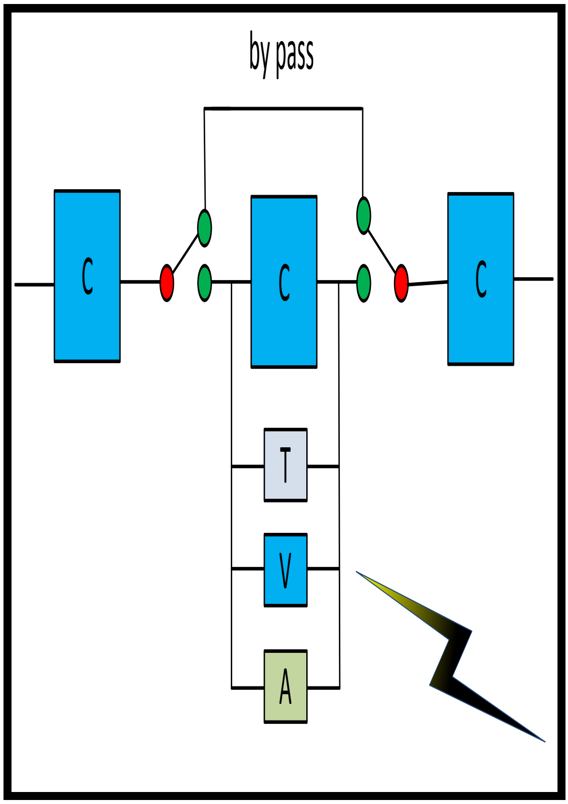


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Figure 11 Example of automatic by-pass of faulted cell.

Voltage, amperage and temperature is monitored across each cell and communicated to a battery monitoring system using wireless technology. In the event of a fault within a cell, it would be automatically bypassed by opening the isolation switches between each cell.

Active research is underway at UCSD to implement this type of monitoring system[1].

It is also likely that advanced measurement technology could be applied to battery monitoring systems. For example GMR devices could be built into each cell of the battery to measure the magnetic and electrostatic fields around each cell. With a temperature sensor included in the monitoring device, the complete health of each cell could be monitored at a very low cost. The data from these devices could be sent wirelessly to a nearby battery monitoring system.

Similarly, the by-pass switches could also be built-in to the cell monitoring and control device.

BATTERIES AS CONTROL SYSTEMS FOR A MICROGRID

Peak Shifting

The most common use of batteries on campus is for reducing peak demand. This is implemented on the Sanyo/Panasonic battery system as well as the Hopkins second life battery system. These systems charge the battery during the peak solar production during the day and discharge to the power grid during the evening hours. Also included is a mechanism to charge the battery during the early morning hours when power is inexpensive.

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[1] Graduate student research under direction of Prof Raymond de Callafon, MAE Department, Jacobs School of Engineering.

Frequency regulation

A second approach to battery control systems is to charge and discharge the battery for local frequency control. For example if microgrid frequency is below 60 Hz, the grid is in an energy deficit and thus the battery should be discharged. Similarly, if the microgrid frequency is above 60 Hz, there is excess energy stored in the microgrid and the battery should be charged (the excess energy is stored in the central power plant power generators by causing them to accelerate.) We propose simple PID (proportional, integral, and derivative) control as the first simple control that could be implemented. This control would of course be subject to constraints of temperature, voltage, current and state of charge constraints.

A second method of frequency control would by use of Model Predictive Control (MPC) technology. This technology was developed in the early 1990s and has been extensively used in many industries, most frequently in gas turbine control systems. This technology determines the optimal control law in real time, subject real time constraints as mentioned above.

Decoupled control of frequency and voltage

A third method of control is decoupled control of voltage and frequency using a four quadrant inverter associated with the battery system. A four quadrant inverter is required for charging and discharging and could be used to supply or absorb inductive or capacitive VARs.

As demonstrated above, low inertia microgrids have faster dynamic response than large scale power grids; hence, microgrid control systems must be designed to provide fast and stable closed loop response to disturbances inside the microgrid when in island mode. Both frequency and voltage must be controlled by the controller; however injection of real or reactive power into the grid will affect both frequency and voltage as shown below.

$$\mathrm{P} = \frac{3\mathrm{VEsin}(\delta)}{2\mathrm{X}}$$

$$\mathrm{Q} = \frac{3\mathrm{V}}{2\mathrm{X}}(\mathrm{V} - \mathrm{Ecos}(\delta))$$

$$\delta = \delta_{\mathrm{V}} - \delta_{\mathrm{E}}$$

$\mathrm{V} = \text{generator output terminal voltage}$

$\mathrm{E} = \text{bus voltage}$

Thus any change in P or Q will cause a change in the voltage difference between the power source and the bus as well as the angle difference. The angle difference is simply the integral of frequency; hence, frequency will also change. This implies that decoupling controllers should be used for control of microgrids.

One such controller is described in US Patent 8,498,752 “Decoupling Controller for Power Systems.” Decoupling controllers have been used in the process industries for many years, most commonly in the paper industry. Basis Weight and Moisture decoupling in paper machine controls is routinely implemented in most of the over 12,000 paper machines worldwide. In this controller, the steam valve and the stock valve are modulated in response to changes in basis weight and moisture. These systems also have long time delays that have to be compensated by the controller. These controllers are often called model reference controllers and are also known as “robust” controllers.

FUTURE RESEARCH

Cell monitoring and performance assessment

Automatic control of battery string connections could substantially improve performance and safety of batteries and ultra-capacitors.

A program for optimum allocation of energy storage is required. This would depend on the forecast of available solar energy as well as constraints on the capacity of the energy storage devices and their current rate of charge. The state of the energy storage system would have to include the current capacity and the current state of charge.

Improved solar forecasting will be important in controlling the energy sources in the microgrid, and will be demonstrated in the Maxwell super-capacitor project discussed earlier in this paper. UCSD has extensive on -going research in in this area.