Electric Vehicle Transportation Center

Electric Vehicle Grid Experiments and Analysis

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EVTC Project 11 – Electric Vehicle Grid Experiments and Analysis

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The objective of the Electric Vehicle Grid Experiments and Analysis project was to conduct vehicle-to-grid (V2G) experiments, provide experimental data from V2G laboratory demonstrations and develop a communications module to enable external control of the CHAdeMO port on a Nissan Leaf electric vehicle. The V2G efforts also included the installation and operation of a bi-directional power system. A low-cost energy management system was also developed to manage operation of workplace electric vehicle chargers. The work was conducted by Richard Raustad, William Wilson and Tom Cummings of the Florida Solar Energy Center.

Final Research Project Report

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1.0 Abstract

This project developed a low cost building energy management system (EMS) and conducted vehicle-to-grid (V2G) experiments on a commercial office building. The V2G effort included the installation and operation of a Princeton Power System CA-30 bi-directional power system. These experiments targeted the reduction of utility peak electrical demand for a commercial office building. In each case, total building peak demand was managed through a computer algorithm to limit the charging rate of electric vehicles or used the vehicle's on-board traction battery as a storage device to minimize peak electrical loads.

2.0 Research Results

The Electric Vehicle Grid Experiments and Analysis project conducted two efforts – develop a low-cost building energy management system, and laboratory experimentation to collect V2G data from grid connected electric vehicles. These two efforts are described as follows:

2.1. Development of a Building Energy Management System

The first effort concentrated on developing a building energy management system (EMS) directed toward processes to reduce utility peak electrical demand for an office type of building. The FSEC facility, FSEC's workplace chargers (2 each, 1 phase, 208 VAC, 30 amp) and FSEC's DC fast charger (1 each, 3 phase, 480V, 60 amp) were selected as the end use devices for this analysis. These devices were measured and monitored using laboratory grade monitoring equipment as follows:

- An electric utility meter enhancement package was installed at the facility electric meter (see Figure 1).
- Dedicated power meters were installed at the workplace and DC fast charger locations.
- Dedicated data recorders were installed to monitor energy use every three minutes.
- Miniature microprocessors were installed in parallel to the dedicated data recorders to act as the EMS with data collected every minute.

The FSEC facility was instrumented to collect laboratory grade energy measurements using Campbell Scientific data loggers. The electric utility company installed a switch closure mechanism on the facility electric meter to provide a pulse output equivalent to 72 watt-hour/pulse. This measurement provided the baseline facility energy use data stream which could be used to compare other low-cost measurement techniques.

Figure 1. FSEC Facility Electric Meter and Junction Box Access to Switch Mechanism

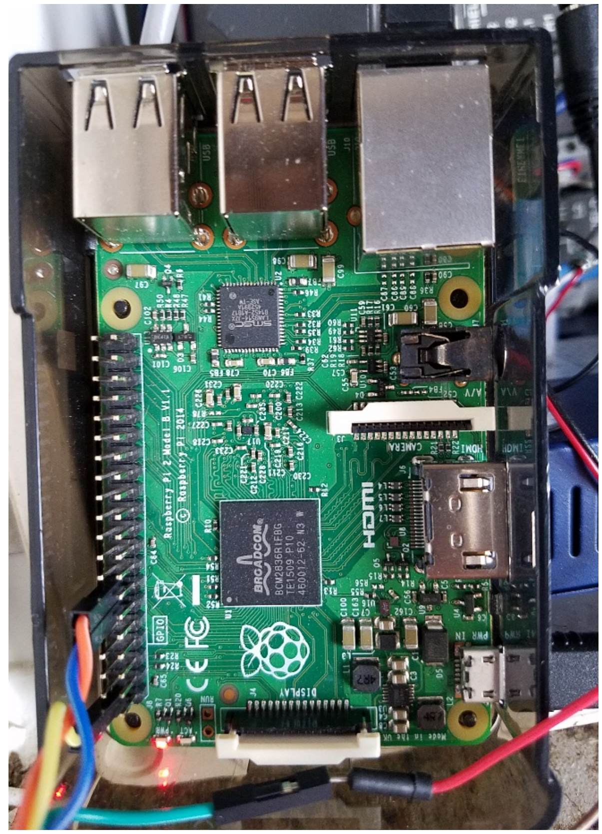

Figure 2. Raspberry Pi 2 Miniature-Computer for Parallel Measurement and Control

Figure 3 represents a comparison between the measured 3-minute facility energy with annotation of the corresponding electric utility billing information. For the data collected during the June 2014 electric utility billing period, measured energy is within 0.5% and calculation of the 30-minute running average facility demand agrees within 0.3%. The electric utility company billing statement only includes the meter read date, not the time-of-day. Even with this measurement uncertainty, the measured data agrees within 0.5% of that measured by the utility company. This is well within the accuracy requirements of 2% in accordance with Test Procedures and Accuracies of Consumer Metering Devices specified in Florida's administrative code 25-6.052, F.A.C[1].

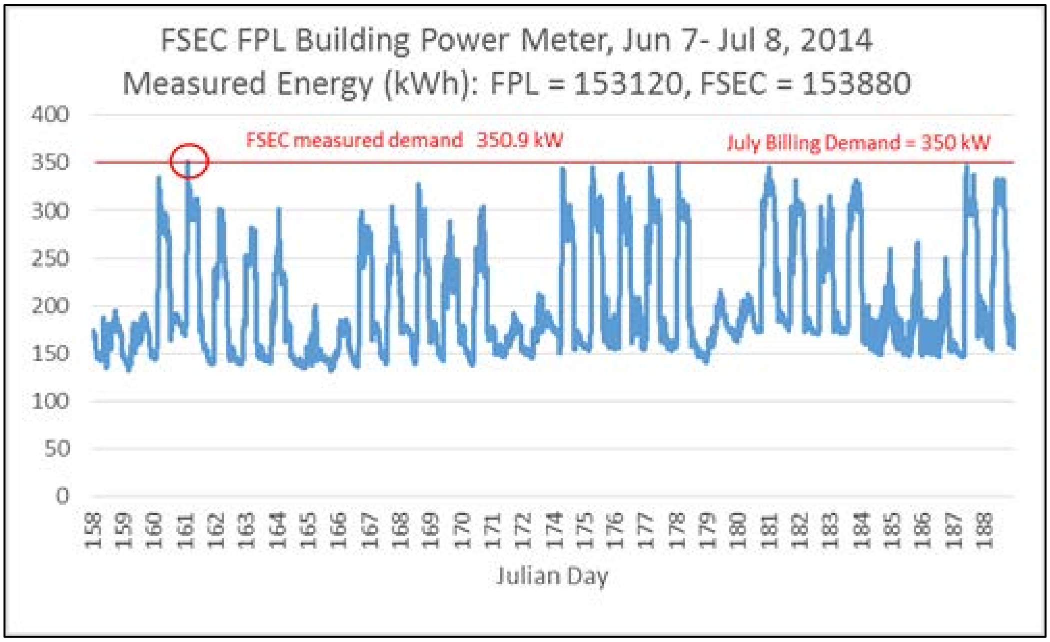

Figure 3. Comparison of FPL Billing Information to FSEC Measured Energy Use and Facility Demand

A second, much less expensive, Linux based data collection device (Raspberry Pi 2 Model B V1.1) was installed in parallel with the primary FSEC data recorder and each data recorder measures end use energy consumption. The microprocessors (see Figure 2) were programmed to collect the same energy data from the power meters using the digital input channels and provide control signals to workplace chargers via digital output channels. This miniature computer is connected to the FSEC central server via an Ethernet connection. The FSEC central server computer control system stores information collected from this low-cost distributed computer on a central SQL database and the system as a whole acts as a centralized energy management system (EMS). The information collected with the EMS system has been compared to historical records of building energy use and agrees within acceptable limits (see Figure 3). Figure 4 shows a representative day comparing the measured facility energy from the primary data recorder and that measured using the miniature computer.

The EMS data that was collected is used to monitor the FSEC building energy profiles and the EV charging station demands. The EMS system can then monitor building loads and make informed decisions on methods to reduce building peak demand for times when EVs are using the workplace chargers, the DC fast charger, or other peak loads are occurring. An EMS control algorithm was developed to deactivate distributed equipment when the building energy use is approaching the monthly peak demand. This algorithm's purpose was to limit or reduce utility monthly peak demand cost by modulating or disabling facility equipment while the building peak demand event occurs.

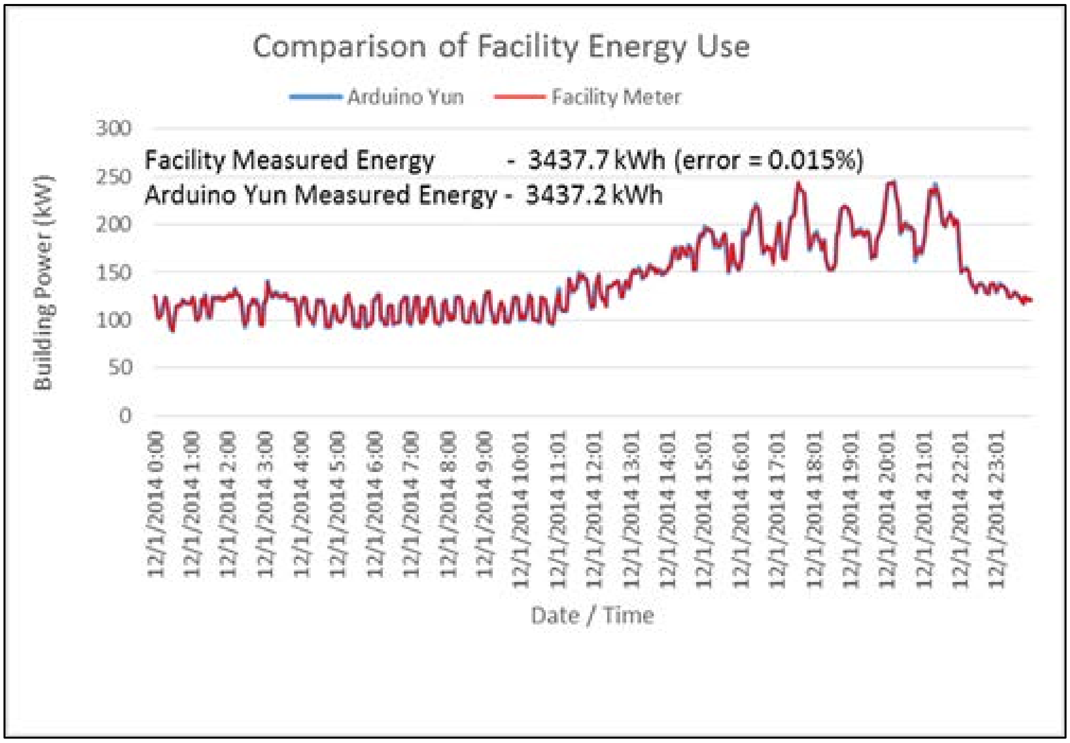

Figure 4. Comparison of Facility Measured Energy and Parallel Measurement

The EMS system followed the building loads (primarily monthly peak loads) and then disabled the workplace chargers when the building peak demand exceeded the previous recorded maximum demand. The previous month's demand is reset each month, using 70% of the previous month's peak demand, to: 1) allow the EMS system to adjust to monthly (seasonal) changes in peak demand, and 2) allow a target demand value that will not disable the workplace chargers for several days at the beginning of the new month.

An additional distributed load resource was then incorporated into the control algorithm. The central chilled water plant compressors were connected to the low-cost EMS by programming the chiller controller to limit chiller capacity to 60% of maximum when detecting a switch closure input to the chiller controller. This capability was added in June 2016. The switch is controlled by the EMS system and closes the switch when the DC fast charger is active *and* the facility is experiencing a peak event. This same control is used to limit morning chiller startup so that peak events do not occur early in the morning. Including this additional resource into the EMS system provides two functions: 1) it limits the morning startup chiller electrical demand, and 2) provides a means to control facility peak demand when the public DC fast charger is active (instead of turning off or modulating the public charging station when the facility is experiencing a peak event).

Over two years of data have been evaluated. This data shows that workplace chargers intermittently impose a monthly demand charge on the electric utility bill. This is dependent on the time the workplace chargers are utilized. Further analysis has determined that these costs can be minimized or eliminated with a predictive control algorithm. Using historical energy data, various control techniques were analyzed for their impact on building peak electric demand. The raw historical data was compared to algorithms which used a simple exceeding peak control (i.e., turn off chargers when peak is exceeded), one that controls the chargers when the peak is close to being exceeded (immanent), one using a predictive function to determine when energy use increases rapidly and will exceed the peak in the near future (rate-of-change), and finally a combination of the two latter control techniques. When the workplace chargers are not controlled, building peak demand increases during times of the year when the HVAC system is not setting early summer morning peaks prior to occupancy. When workplace chargers are actively controlled, using progressively more advanced control algorithms result in additional electric demand savings. From this analysis, it is apparent that active control of workplace chargers can help reduce facility peak demand as shown in Table 1.

Table 1. Charging Station Control Simulation and Optimization Results

Month	Facility Maximum Peak Demand (kW)	Control Algorithm Impact on Facility Electric Peak (kW)				
		No Control	Exceeding Peak	Immanent Peak	Aggressive Rate-of-Change	Immanent + AROC
May	330.9	0.0	0.0	0.0	0.0	0.0
June	337.8	4.0	2.1	0.0	0.0	0.0
July	366.0	0.0	0.0	0.0	0.0	0.0
Aug	355.8	0.0	0.0	0.0	0.0	0.0
Sep	353.8	0.0	0.0	0.0	0.0	0.0
Oct	337.5	12.0	7.9	6.3	0.7	0.7
Nov	319.7	12.0	6.2	0.0	4.4	0.0
Dec	328.6	12.0	11.2	8.8	2.0	2.0
Jan	287.6	12.0	9.1	7.5	0.7	0.0
Feb	280.6	12.0	7.2	4.8	0.4	0.4
Mar	325.1	12.0	4.8	0.0	1.5	0.0
Charger Availability:		100.0%	99.4%	96.4%	97.1%	95.6%

The use of a low-cost building EMS that includes workplace chargers and allows commercial building operators to minimize electric utility bills will provide benefits to employees through free or low-cost workplace chargers.

Note is made that the detailed description of the building and charger data and of the control algorithm is presented in the final report for EVTC Project #3[2].

2.2. Vehicle-to-Grid (V2G) Experiments

The second effort involved using FSEC's EV laboratory facility where electric vehicles were charged and discharged through a computer assisted communication network. The lab was configured in April 2014 and has conducted experiments on EV vehicles (Nissan Leafs) which are connected electronically through their CHAdeMO charging port. A controller was built to allow the vehicle battery to be accessed for discharging through external load supply equipment. Lab experiments have also successfully coupled an EV for storage interactions with the output of a PV system.

Preliminary testing of V2G technology was conducted to show proof-of-concept and identify issues when an EV traction battery is used as energy storage. Laboratory sensors were calibrated and the EV was connected to a grid-tied PV system, a stand-alone PV system and finally a high-powered grid-tied bi-directional power supply. The following sections describe the results.

2.2.1. Sensor Calibration

An Electronic Measurements, Inc. reference DC power supply Model EMS 300-16-2-D S/N 98B-4109 was used to calibrate laboratory measurement equipment. This reference DC power supply has 0.1% regulation and 0.05% stability with a maximum output ripple of 150 mV. The output range of voltage and current is 0-300 volts and 0-16 amps.

Measurement equipment used for V2G tests included an Ohio Semitronics CTA101 DC current transducer using a CT100LT open loop Hall Effect 100:1 current transformer and VTU-008B 0-400 volt isolated DC voltage transducer. The current transducer output a 0-100 mV voltage signal while the voltage transducer output a 0-1 mA signal converted to voltage using a precision 2000 ohm resistor. This system provided a calibrated power signal transducer as shown in Figure 5. These signals were monitored using a 10-bit analog to digital (A/D) converter. The system as a whole was calibrated to within 0.26% of the measurement.

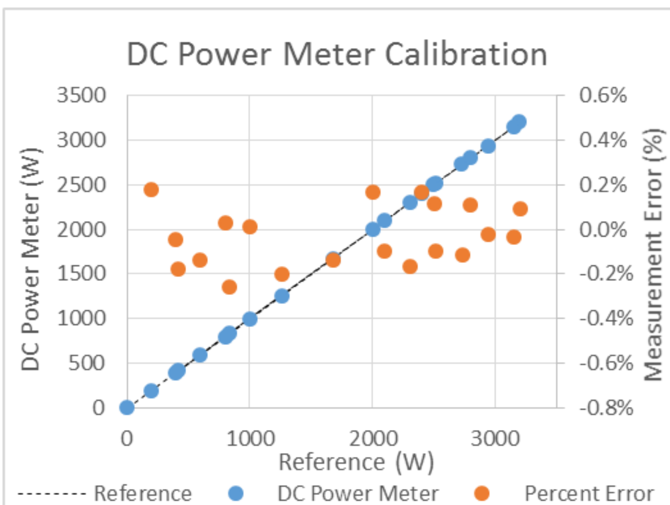

Figure 5. Laboratory Meter Calibration Results

2.2.2. Vehicle-to-Grid using Photovoltaic System Inverters

Photovoltaic (PV) installations are increasingly common and at times include integral backup battery storage. Although some PV installations do not include battery storage, the proliferation of EV's into today's society present an opportunity to eliminate or minimize the capital costs associated with stationary battery modules. The EV traction battery could be used to replace or supplement the battery storage system commonly used in PV systems.

To investigate these applications, an existing PV system installation panel was used for demonstration as shown in Figure 6. The panel includes a Schneider Xantrex XW4548 Hybrid Inverter/Charger and power distribution panel which interconnects PV panels, the utility electric transmission system and the battery bank. The XW battery bank is 48VDC nominal consisting of 4 series connected 12V 96AH gel batteries (50% max discharge = 2.3 kWh's). The inverter/charger controls the flow of energy from the utility electric transmission grid and supplies energy to both an alternating current (AC) and direct current (DC) bus in the distribution panel. The inverter/charger also acts as the battery bank charge controller. The load center acts as a variable load bank to test various configurations and performance of PV controllers. Additional loads can be added to the system via the critical load panel electrical receptacles at the right of the figure.

A Schneider Electric Xantrex XW MPPT 80 600 Solar Charge Controller was added to the existing system to demonstrate the concept of connecting an EV traction battery to a PV system. This new controller interfaces with a DC source up to 600 VDC and couples that source with the existing power distribution panel. A Nissan Leaf was connected to the Xantrex solar charge controller using the vehicle's CHAdeMO DC fast charging port.

To connect the EV traction battery to the PV panel's solar charge controller, the high voltage pins of the CHAdeMO DC fast charging port were connected to the DC inputs of the solar charge controller. This connection is mono-directional where the vehicle battery can only be discharged and is similar to the connection of PV panels that can only supply energy to the charge controller. A microcontroller was used to command the EV, via the communication pins on the CHAdeMO port, to discharge the traction battery. When the command is sent to the EV, energy flows from the vehicle toward the electric utility grid and battery storage system. Communication with the vehicle included commands to tell the vehicle what current draw was expected at any given time. A feedback loop monitored the current on the CHAdeMO port DC input pins and fed that information back to the vehicle as a command for a specific amount of current (amps). The feedback loop is necessary to sustain energy transfer otherwise the vehicle will interrupt the process and terminate the energy transfer.

This configuration simulated an electric vehicle connected to a typical PV system where the vehicle traction battery acted as a supplemental battery to the existing battery bank. Although this configuration does not allow the vehicle traction battery to be charged, re-configuring the system to use a DC-DC converter instead of the solar charge controller would have enabled charging and discharging to occur.

The system was operated in grid-connected mode, micro-grid mode and vehicle-to-vehicle (V2V) mode. For the grid-connected configuration, the electric utility meter turned backwards since the EV was exporting energy. During the micro-grid tests, the electric utility service was disconnected and the system operated as a stand-alone electricity generator. For vehicle-to-vehicle testing, one Nissan Leaf was connected to the Xantrex solar charge controller while a second Nissan Leaf was connected to the critical load panel receptacle.

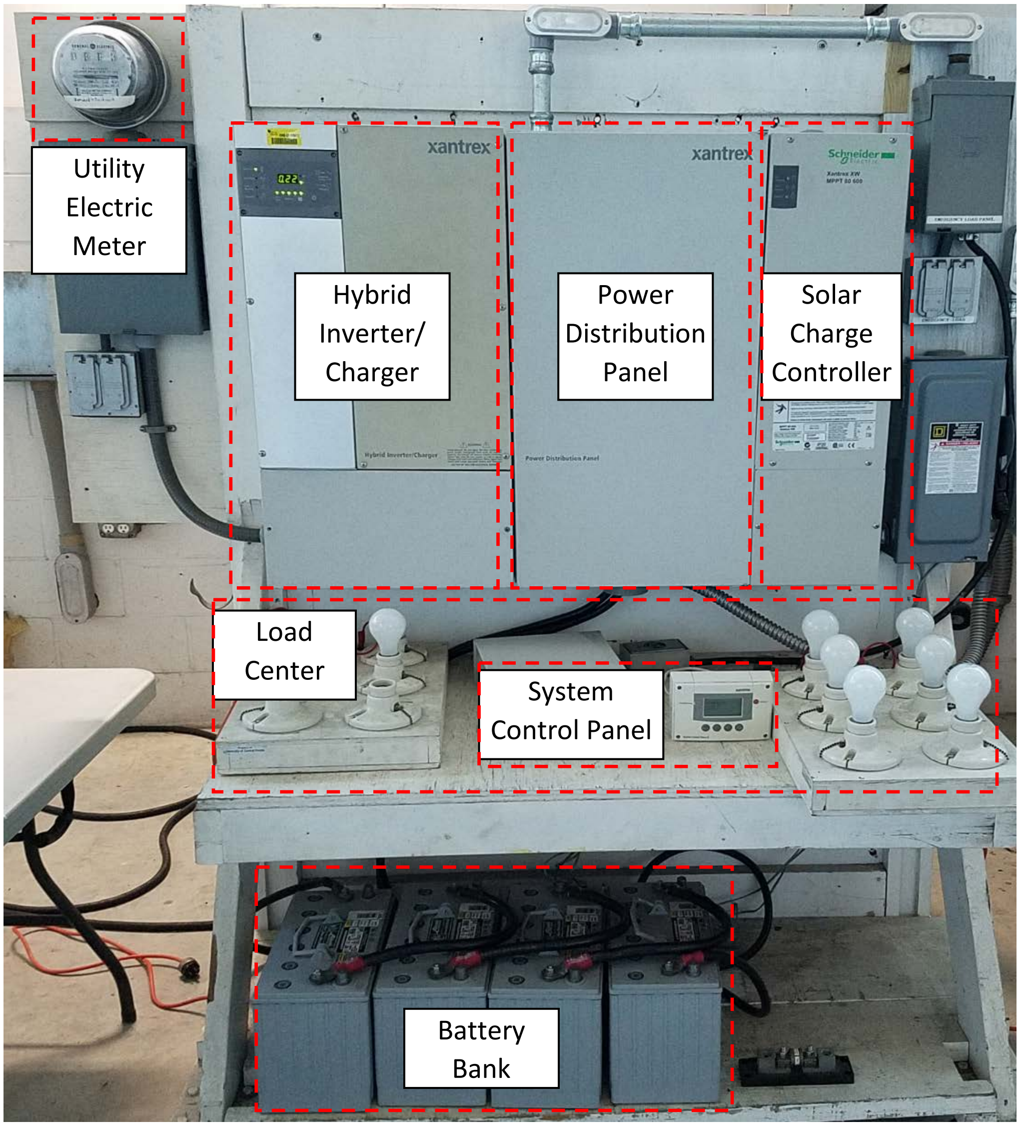

Figure 6. Photovoltaic Training Panel and Hardware

The initial test represented a PV system connected to the utility electric grid. In this configuration, the solar charge controller maximum power point tracking (MPPT) algorithm was disabled in software and values for MPPT set point voltage were manually entered at the control panel. A second software parameter, the maximum charge rate, was used to adjust the discharge rate of the EV traction battery. These parameters allowed the operator to control the EV traction battery discharge rate using both battery voltage and controller charge rate. Additionally, these software parameters could have been changed dynamically using an external software program connected to the system via a network connection although this functionality was never tested. For this test, the operator adjusted these settings while monitoring the voltage of the EV traction battery. The results are shown in Figure 7. All measured data reflect information gathered while exporting energy from the EV traction battery directly to the PV system distribution panel. The hybrid inverter/charge controller determined if that energy would be used to charge the battery bank, serve critical electrical loads or feed the electric utility grid.

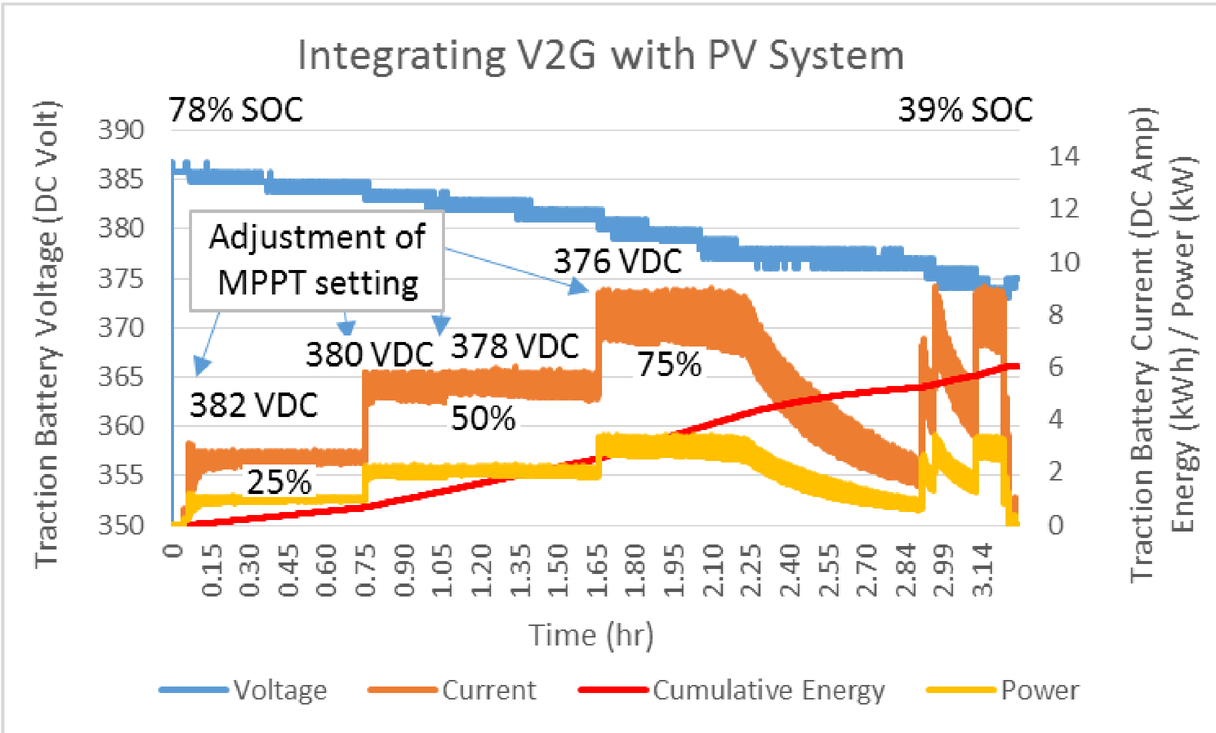

Figure 7. System Parameters during V2G w/PV Testing

During this test, the controller's MPPT voltage setting was manually adjusted during the first 2 hours of the test to maintain access to the energy stored in the EV battery (i.e., so the controller would not shut down the test). As the EV traction battery voltage approached the MPPT setting, the MPPT set point was slightly lowered to prevent the controller from limiting available current. At just over 2 hours into the test, the MPPT voltage was not adjusted to investigate the controller's current limiting capabilities when the EV traction battery voltage approached the MPPT voltage setting. At this point, the controller began to reduce the current draw from the vehicle battery to maintain the MPPT voltage set point of 376 VDC. At nearly 3 hours into the test, the current/power export was nearing zero. The MPPT setting was further reduced and exported energy responded accordingly. Simple manipulation of the controller's MPPT voltage setting allowed the operator to manage the power export capability of this V2G system.

Also during this test, the controller's maximum charge rate parameter was changed from 25%, to 50%, and finally to 75% to determine the impact this parameter had on overall system performance. As the maximum charge rate percentage increased, the current draw from the EV traction battery also increased. The power exported from the EV was fed directly to the utility grid and/or PV system battery bank as a proof-of-concept for V2G using a PV system.

The parameters described above were adjusted manually during this test to familiarize the operator with how these parameters change system performance. Note that the MPPT voltage setting could have been set at the minimum expected traction battery voltage, however, this test was a learning experiment in the various means of controlling energy flow from the EV traction battery to the PV system and how that energy flow was affected by PV controller settings. During this test, the EV traction battery exported 6 kWh's of stored energy, the EV battery state-of-charge (SOC) dropped from 78% to 39% and the operator easily adjusted power output with simple changes to the controller settings. This same test could have been automated by sending the adjusted settings directly to the controller via a network connection.

2.2.3. Micro-Grid using EV and Photovoltaic System Inverters

The concept of using EVs for micro-grid applications was also investigated for feasibility. The electric utility service was disconnected from the PV panel and the system allowed to operate as a stand-alone micro-grid electricity generator. The connected vehicle is shown in Figure 8 with the load center energized.

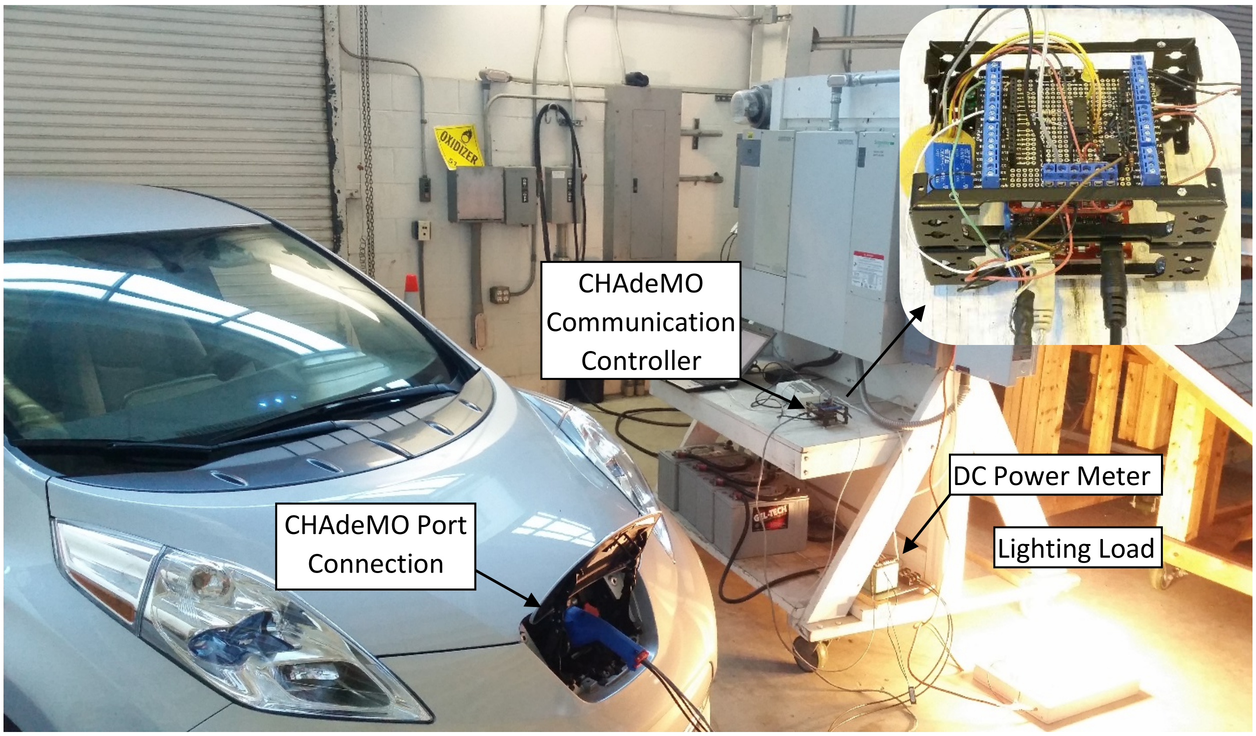

Figure 8. Operational Micro-grid Application using Electric Vehicle

Measured parameters collected during micro-grid operating mode are shown in Figure 9. To begin the test a request was sent to the vehicle to discharge the EV traction battery. At this time the charge controller's MPPT reference voltage was set at 393.8 VDC. As the EV traction battery discharged the stored energy, the battery voltage dropped to near the MPPT reference voltage. The charge controller gradually reduced current draw to maintain the MPPT reference voltage (at hour = 0.1 – 0.2). The MPPT reference voltage was then lowered and the controller responded by increasing the battery discharge rate to provide power to the load center. Later in the test, the lighting load was reduced and then turned off. A small electric oven was then connected to the load center. The oven's electric element cycled on and off to warm the oven to the operating temperature. The energy consumed by the oven gradually lowered as the oven temperature reached the temperature setting.

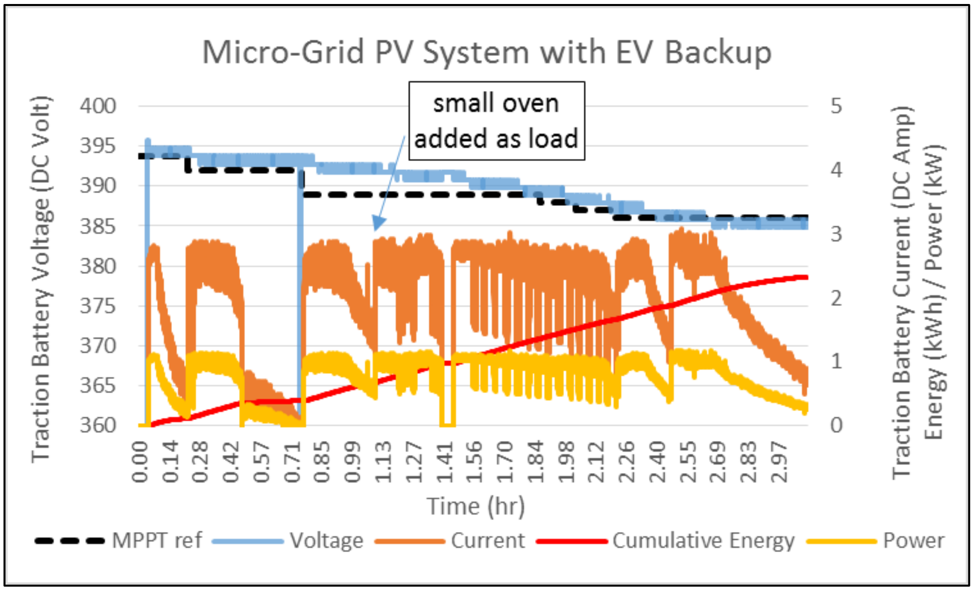

Figure 9. System Parameters during Micro-Grid Testing

A second Nissan Leaf was plugged into a receptacle served by the critical load center (see right of solar charge controller in Figure 6) to increase the load and provide energy transfer from one vehicle to another. After about 6 kWh of energy were transferred, the vehicles connections were switched and the test repeated.

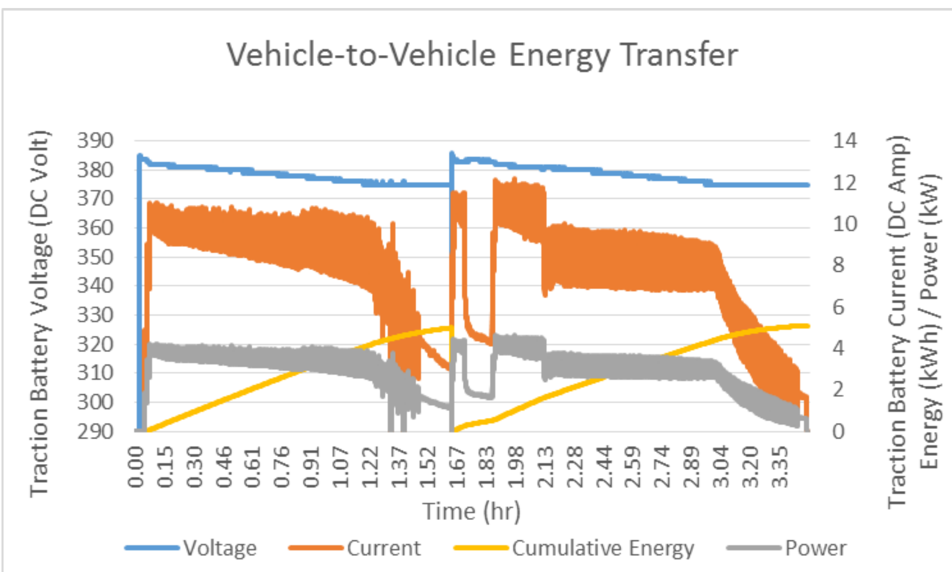

Figure 10. Two Nissan Leaf's Connected to PV System Installation Panel

Each of these tests confirm that EV traction battery stored energy can be harvested to provide electrical services for a variety of configurations. The EV can be used to feed energy directly to the electric utility grid (non-micro grid configuration), act as a supplement or replacement for a PV battery bank and transfer energy from one vehicle to another using existing components of today's standard PV systems.

2.2.4. Vehicle-to-Grid using External Bi-Directional Power Supply

As an integral part of the V2G effort, a Princeton Power System (PPS) CA-30 bi-directional power system was purchased, installed and set-up for initial experiments. This power system allows for power to flow in two ways -- from a building to an EV (charging the battery) or from an EV to a building (discharging the battery). V2G energy management may become more popular in the future to help manage electric utility transmission grid operations and grid quality. An article was published in the Electrochemical Society Interface magazine regarding the role of V2G in the future electric transmission system[3].

Figure 11. Princeton Power Unit

The Princeton Power unit directs power through a front panel control board or through electronic communications with the FSEC's existing building EMS system. The Princeton Power System is capable of charging a vehicle at up to 100 Amps at 28 kW and discharging the vehicle at up to 120 Amps at 32 kW. The DC rating is 280-500 VDC and connects through a vehicle's CHAdeMO high speed charging port. Experiments were planned for using EV batteries to shift building peak demand, offset DC fast charger operation, and develop third party (i.e., utility companies) access protocols.

Initial efforts to develop network communication with the Princeton unit involved monitoring the Open Charge Point Protocol (OCPP) network communications from this unit during power up and front panel operation. Communication with the PPS unit evolved to include networked communication to start a transaction, stop a transaction, check vehicle state-of-charge (SOC), select charge or discharge mode and select the rate of energy transfer. This communication capability will be incorporated into the existing EMS system to include the PPS as an additional resource for building energy management.

3.0 Impacts/Benefits

The experimental data from the V2G experiments is a critical part of developing potential interactions between EV owners and their respective utility company. The project's efforts to develop a low-cost building EMS that includes workplace chargers will allow commercial building operators to minimize electric utility bills while providing a benefit to employees through free or low-cost workplace chargers. Other building resources (e.g., HVAC, lighting or other equipment) could also be included to further minimize commercial electric costs. If building owners and operators are convinced that costs can be controlled, free workplace charging could be widely deployed without reservation.

The impact of V2G in the future transportation system is far reaching. The electric transmission system can benefit from V2G by allowing electric vehicles to act as distributed electricity generators or providing regulation services to improve the quality of transmitted electricity. Revenue from these services could improve the economics of EV ownership and create other business opportunities not currently available. V2G can also provide an emergency backup service for residential and commercial buildings, or provide a means of storing energy for wind and PV. These are but a few opportunities available to transportation vehicles of the future.

4.0 References

1. "Electric Service by Electric Public Utilities", Florida Administrative Code & Florida Administrative Register, Rule 25-6.052 – Test Procedures and Accuracies of Consumer Metering Devices.
2. Raustad, R. (2016) "EV Workplace Charging Energy Use and Cost Case Study", FSEC-CR-2037-16.
3. Raustad, R. (2015). "The Role of V2G in the Smart Grid of the Future." The Electrochemical Society Interface. Spring 2016. DOI: 10.1149/2.F04151IF.