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Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA,
IRVINE

DYNAMICS OF AN INTEGRATED PV/BATTERY SYSTEM FOR EV CHARGING IN A MICROGRID

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Laura Martinez de Novoa

Thesis Committee:
Professor Jacob Brouwer, Chair
Professor G. Scott Samuelsen
Professor Michael Green

2016

DEDICATION

To my parents.

“They did not know it was impossible, so they did it.”

Mark Twain

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NOMENCLATURE

AC	Alternating Current
AIRB	Anteater Instruction and Research Building
AM	Ante Meridiem
APEP	Advanced Power and Energy Program
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
CAISO	California Independent System Operator
CCM	Continuous Conduction Mode
CPV	Concentrated Photovoltaic
DC	Direct Current
DCM	Discontinuous Conduction Mode
DER	Distributed Energy Resource
DOE	U.S. Department of Energy
DRI	Demand Response Inverter
EISA	Energy Independence and Security Act
EMC	Electromagnetic Compatibility
ETAP	Electrical Transient and Analysis Program
EV	Electric Vehicle
EVCS	“Electric Vehicle Car Shade” Measuring Point
EVSE	Electric Vehicle Supply Equipment
GHG	Greenhouse Gases
G2V	Grid to Vehicle
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IHO	Individual Harmonic Order
IHD	Individual Harmonic Distortion
IL	Load Current
I_{sc}	Short Circuit Current
ISGD	Irvine Smart Grid Demonstration Project
kW	Kilowatt
kWh	Kilowatt hour
LV	Low Voltage
LP	Linear Program
MATLAB	Matrix Laboratory (<i>MathWorks, Inc.</i>)
MG	Microgrid
MMBtu	Million British Thermal Units
MPPI	Minimize Peak Period Impact

MV	Medium Voltage
MW	Megawatt
NEC	National Electrical Code
NIST	National Institute of Standards and Technology
PHEV	Plug-in Hybrid Electric Vehicle
PF	Power Factor
PLS	Peak Load shifting
PM	Post Meridien
PPS	Princeton Power Systems
PQ	Power Quality
PV	Photo Voltaic
p.u.	Per unit
PWM	Pulse Width Modulated
RES	Renewable Energy Sources
RMS	Root Mean Square
RPF	Reverse Power Flow
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SG	Smart Grid
SLE	State Load Estimator
SQL	Structured Query Language
THD	Total Harmonic Distortion
THD_i	Current Total Harmonic Distortion
THD_v	Voltage Total Harmonic Distortion
UCI	University of California, Irvine
VA	Volt-Amperes
Var	Volt-Amperes Reactive
V2G	Vehicle to Grid
ZEV	Zero Emission Vehicle

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ABSTRACT OF THE THESIS

Dynamics of an Integrated PV/Battery system for EV charging in a microgrid

By

Laura Martinez de Novoa

Master of Science in Mechanical and Aerospace Engineering

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Professor Jack Brouwer, Chair

Electric Vehicles (EVs) are emerging to play a key role in mitigating fossil fuel reliance and the environmental impacts brought on by the transportation sector. In parallel, it is essential that this growing electricity demand be met mostly with renewable sources. This study, as part of the Irvine Smart Grid Demonstration (ISGD) project, analyzes the effects of a renewable solar photovoltaic (PV) nanogrid — a small-scale, autonomous power system, that ultimately ties into the central electrical distribution grid — for EV charging associated with a controllable battery energy storage system, deployed in a primary circuit on the UCI (University of California, Irvine) Microgrid. The system's dynamic behavior is characterized for different control algorithms that govern battery dispatch, creating four different energy management strategies.

Power quality aspects of EV charging are also investigated, with a focus on harmonic distortion. A robust system design using delta-wye grounded transformers was shown to prevent any excessive harmonic currents from flowing upstream into the microgrid. Additionally, a diversity of EV charging loads promotes favorable harmonic cancellation.

A power flow model of the nanogrid was developed in a commercial power flow software (ETAP) and verified against smart meter data, which were used as inputs for the ETAP Real-Time module.

Lastly, a linear program was developed for optimally sizing nanogrid assets in the context of minimizing operation costs for the microgrid operator. The combination of an 80 kW PV array and a 95 kWh/45 kW battery energy storage system was shown to be the best option to power 20 Level-2 (7.2 kVA) EV chargers deployed at one of the university campus parking structures.

1. Introduction

Environmental concerns and fossil fuel depletion have spurred the latest research interests in shifting traditional power generation and transportation paradigms. Microgrids and nanogrids — self-contained, small-scale electric utility networks (grids) — with renewables as Distributed Energy Resources (DER) and Zero Emission Vehicles (ZEV) are emerging to play a key role in this endeavor. Both technologies have a great potential for offsetting fossil fuel reliance and greenhouse gas (GHG) emissions, and are predicted to see a significant growth in market share in the near future.

Microgrids are emerging to meet the growing demand for reliability and resiliency in the electricity market. Topologies containing DER can supply active power to local loads, potentially reducing power losses in the distribution system and enhancing some network characteristics such as power quality, voltage stability and spatial and temporal voltage profiles.

In parallel, transportation electrification offers numerous additional benefits. Electric vehicles (EV) comprise different design aspects that contribute to better performance when compared with gasoline and diesel engines, including a higher combined drivetrain efficiency and reduced criteria pollutant emissions. Moreover, by concentrating “well-to-wheel” emissions on the upstream “well-to-tank” processes, i.e., in the stage of electricity generation, EVs can potentially reduce greenhouse gas (GHG) emission rates [1], and depending upon renewable energy penetration combined with smart-charging scheduling, the dispatch of EV loads allows the grid to absorb otherwise curtailed renewable solar generation [2].

Yet, there are still major challenges associated with the integration of both aforementioned technologies into the power grid. Similar to the utility grid, microgrids face challenges associated with the intermittency of renewable energy sources (RES) at high market penetration, including solar PV, and randomly occurring loads associated with electric vehicle charging. One of the most common issues is to instantaneously balance energy supply and demand — both RES and unpredictable EV loads can create demand peaks and valleys in the power system load curve and thus create undesirable increases in capacity and grid management resources (e.g., monitoring, controls, energy storage) [3], [4].

Voltage unbalance is also a consequence of single or dual-phase EV charging, as reported in [5]. Moreover, if charging happens in an uncontrolled fashion, voltage profile variations become a typical problem when charging a large number of EVs [5]. Voltage stability (i.e., the system's ability to maintain steady acceptable voltages and waveform after a disturbance caused by sudden load changes) is also affected by high EV and RES penetrations [6], [7].

Many recent publications [8]–[18] show that EV charging can affect the Power Quality (PQ) aspects of the network, namely, a group of parameters that characterize the quality of the alternating current waveform, which are specified in ranges that guarantee acceptable system and equipment operation. Harmonics (i.e., frequency variations of the waveform that are not 60 Hz) are one of the main concerns in this regard. The total harmonic distortion for the voltage and current waveforms (THD_v and THD_i respectively) are the metrics typically used to quantify this issue. High THD levels are undesirable in a power

grid because they cause increased power losses, malfunction of electronic devices, and stress on network components such as transformers [8].

Other EV charging concerns include Power Factor (the ratio of real power to the reactive power flows in the grid) deterioration, as shown in [9], [10]. Excessive neutral wire currents caused by voltage unbalance and exacerbated by the presence of harmonics can damage the conductor are also a challenge that pose a risk to the utility grid network operation [11].

The U.S. EV market size is almost one-half of the world's EV market in 2015. When taking into account Plug-in-Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV), a total of about 400,000 units were sold as of December 2015 [19]. The state of California alone had a total of 129,470 units sold as of 2014 [20], with a target set for 1.5 million Zero-Emission Vehicles (ZEV) sold by 2025 [21]. The state's EV fleet represents nearly 40% of the national total units sold and more than any country total to-date, making the state the undeniable current global leader in transportation electrification. Yet, EVs' widespread acceptance relies heavily on battery range and recharging effectiveness from the driver's point of view [22], while also depending on the power quality for local electric utilities and end-users.

Given these trends, it is expected that the integration of these new components will affect the power quality, stability, integrity, and reliability of the power distribution system. In this context, this thesis analyzes the effects of intermittent renewable power generation and unpredictable EV charging loads on PQ in the presence of a controllable battery.

A next-generation suite of DER has been implemented into a primary 12 kV circuit at the University of California, Irvine (UCI) Microgrid, as part of the U.S. Department of Energy “Irvine Smart Grid Demonstration”. On the roof of a parking structure, 48 kW of PV panels have been deployed and 20 monitored EV chargers have been installed on its first floor. Outside, but immediately adjacent to the parking structure, a 100 kW/100 kWh battery energy storage system (BESS) has been integrated into a combined system. The system has an internal inverter that converts the photovoltaic, as well as the battery power outputs, from direct current (DC) to alternating current (AC). A Princeton Power Systems (PPS) site controller contains the algorithms for overall system behavior and four different control modes are implemented: Peak Load Shifting, Minimize Peak Period Impact, Cap Demand, and PV Capture.

A load flow model was developed in ETAP to characterize the effects associated with the integration of these elements into the UCI Microgrid and to analyze and assess any voltage deviations or concerns associated with the different battery operation modes.

To characterize the Power Quality aspects of EV charging, a two-week survey was performed on the system, with a focus on harmonic distortion. Lastly, an optimization study was performed to economically size the PV array and the storage assets for EV charging in a grid-tied microgrid topology.

Characterizing and understanding the dynamics of these systems is a pre-requisite to establishing the smart controls and other DER that will be required for microgrids to remain stable. This should allow utilities to become efficiently equipped to solve potential operational issues that DER and EV in combination can cause to other system components.

2. Goals and Objectives

2.1. Goals

The goals of this research are to establish the dynamic behavior of an advanced PV/battery system for electric vehicle charging in a microgrid, to define preferred battery dispatch strategies, and ultimately, to determine the optimal PV and battery storage combination in the context of minimum cost.

2.2. Objectives

In order to meet the goals of the research, five objectives are established:

Objective 1: Analyze BESS dynamics for different operation modes. Using an advanced nanogrid field platform (Car Shade system), obtain and validate Smart Meter data (EV charging load, PV generation, BESS dispatches, and grid power) to serve as inputs into the model, and characterize the system's dynamic behavior.

Objective 2: Develop and verify the Car Shade real-time power flow model
Develop a steady-state model to study load flows and power quality of the Car Shade nanogrid, and verify the model using "Real-Time" simulations compared against the model state load estimator results.

Objective 3: Analyze model outputs. Analyze model outputs, looking at power quality aspects and preferred battery dispatch strategies for EV charging.

Objective 4: Characterize power quality aspects of EV charging. Monitor the nanogrid site with a suitable power quality metering equipment to obtain high-resolution

data on current and voltage waveforms, and characterize the site power quality with a focus upon harmonic distortion and harmonic cancellation as a result of EV charging.

Objective 5: Optimal economical BESS and PV sizing for Car Shade + AIRB nanogrid. Optimally size a battery energy storage and PV array system to power the nanogrid with the addition of a classroom/laboratory building in the context of minimizing the cost for the nanogrid — or microgrid — operator.

3. Background

3.1. Microgrids: the shift towards decentralized power

One simple definition of a microgrid comes from one of its main compelling features: a grid-tied smaller scale power system that has the ability to island, i.e., completely disconnect from the main grid in a non-planned (e.g., in case of a blackout) or planned fashion. Another key feature of a microgrid is the ability to integrate clusters of DER into the local generation mix. A typical microgrid and its components are illustrated in Figure 1.

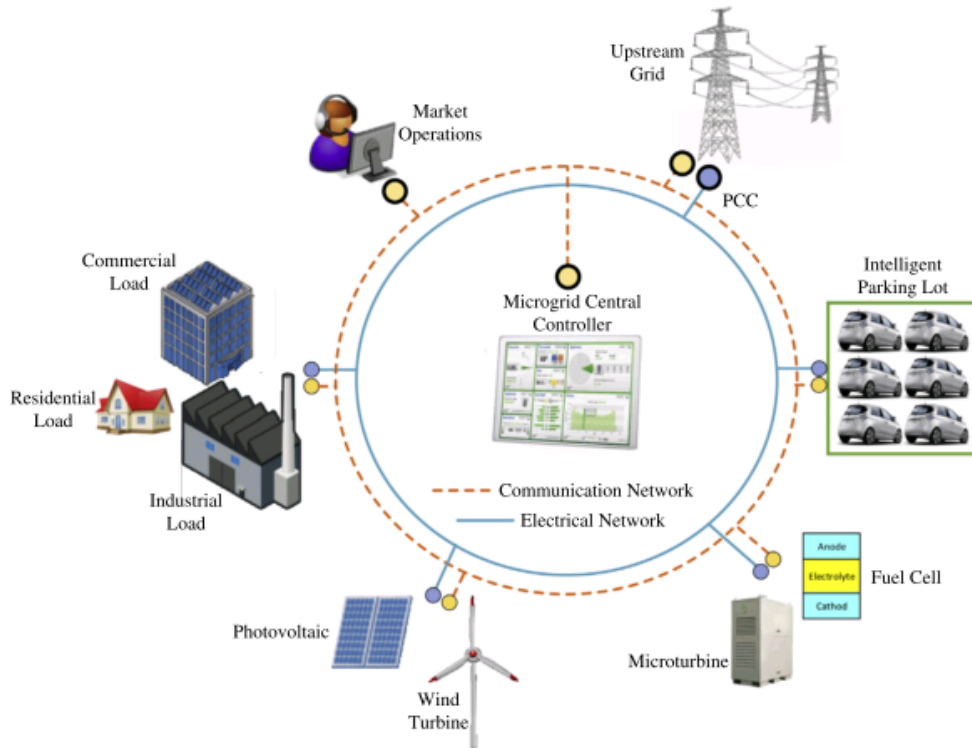


Figure 1: Typical microgrid topology [23]

Not all microgrids use renewable sources for their power supply, but an increasing number do — namely, renewable microgrids. These systems reduce local emissions from electricity generation, addressing climate concerns, and present a series of other advantages.

An increased reliability and resiliency, inherent to a smaller scale system, most times integrated with a storage/backup power components, add up a layer of consistency and more guaranteed uninterruptible power supply in microgrid systems. Moreover, a shift towards decentralized power, in a bottom-up configuration, balances local power supply/demand much more efficiently, may eventually reduce utilities' costs on grid infrastructure, and consequently, lower consumer prices.

Microgrid research and development has been drawing a lot of attention since 2012, when the hurricane Sandy hit New York and left much of the population powerless for over a week. These systems, however, are not a new concept. Currently in the U.S., there are 124 microgrids, often to power hospitals, universities, and military bases, adding up to 1.9 GW installed (Figure 2) [24]. A projected growth to a total of 2.8 GW is expected for the next five years, mostly in states such as California and New York [25].

Yet, what is still needed in microgrid research is to study how to include other renewable power sources, such as fuel cells and optimized control methods (general microgrid controllers). Moreover, new public policies on how utilities will operate and interact with such systems are essential for microgrid development.

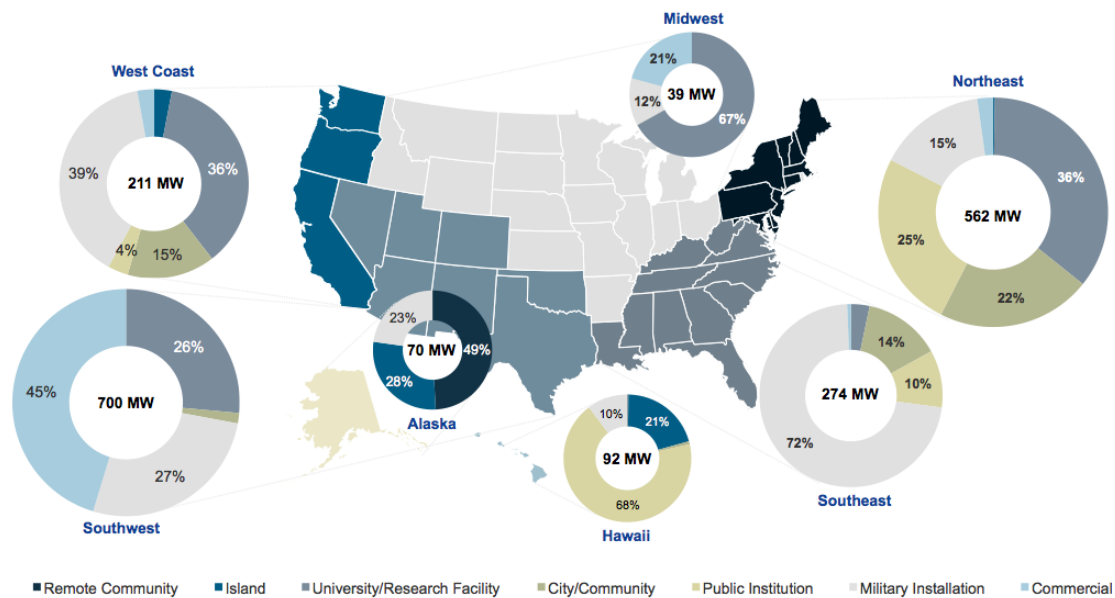


Figure 2: Total microgrid generation capacity by end-user type and region [24]

As grid modernization evolves incrementally over time, there is a need to accommodate a yet to be determined number of new products and services while it continues to operate. The interoperability capabilities between existing utility systems and

new technologies are evolving through the development of standards and best practices. These standards and best practices will help to build an open control architecture, apply existing internet protocol approaches, and define plug-and-play requirements.

Such efforts have been managed by several entities such as the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce, and the Institute of Electrical and Electronics Engineers (IEEE). Lack of agreement on the details of the standards between stakeholders and those who issue the standards have slowed the implementation of microgrids with smart grid technologies.

3.1.1. Nanogrid, the Microgrid Jr.

Similar to the microgrid, the nanogrid (Figure 3) is an even smaller scale system that is able to island from the main grid — in this case, the microgrid. Nanogrids, elsewhere called fractal grids, typically serve a single customer or facility, and can be either AC or DC. The solar plus energy storage nanogrid is the most common of its kind.

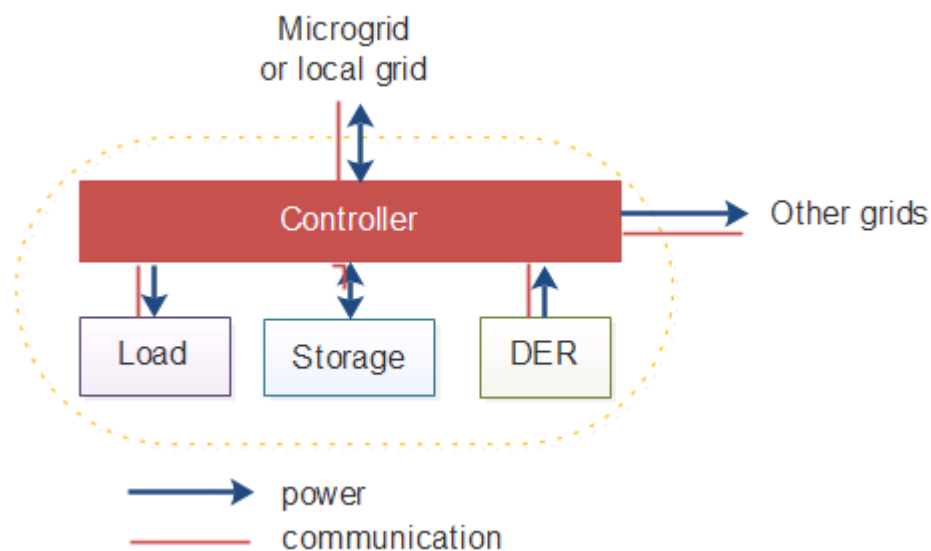


Figure 3: Typical nanogrid schematics (adapted from Nordman & Christensen 2013)

The authors in [26] compile a list of key needs and goals for nanogrids, such as:

1. Enable “plug-and-play” integration of local renewables and local storage, as well as optimal storage management.
2. Support a layered architecture for communication among energy-using devices, to obtain the value that layering provides in term of reliability inherent in distributed control.
3. Create a universal technology, to drive down prices and drive up availability.

A near-term need to build nanogrid platforms, which fully implement hardware and control algorithms, in order to prove increased efficiency and value of such systems is also emphasized in [26].

3.2. University of California, Irvine Microgrid

The UCI Microgrid (Figure 4) serves over 30,000 students and staff. It annually supports \$330 million of sponsored research, and comprises power generation, storage and control technologies with a major goal of producing zero net Carbon emissions by 2025. It powers a 24 MW peak electric load, which consists of a variety of building types such as classrooms, research laboratories, offices, and housing communities. Other loads consist of heating (14-94 MMBtu/hour) and cooling (600-15,000 tons).

A variety of energy sources power the main microgrid circuits: (1) On-campus central plant facility, consisting of a 13.5 MW gas turbine generator and a 5.6 MW steam power plant, associated with thermal energy storage, and (2) 1 MW of peak roof-mounted solar distributed throughout the campus, (3) 3 MW of peak parking structure mounted solar PV

generation, and (4) 153 kW of solar concentrated power provided by two dual-axis concentrated PV panels, made by Amonix [27].

The microgrid is comprised of ten 12 kV feeders (UC-1 through UC-10) that originate from the interconnection with the utility grid, a Southern California Edison (SCE) 66 kV source (from McArthur Substation), at the UCI Substation. Each of these 12 kV feeders supplies a number of other 12/0.48 kV substations that feed the diverse set of campus loads.

A 2.0 MW, 500 kWh battery energy storage system is to be located at the UCI Substation to assist the balance between the dynamic PV generation and the UCI central plant generation mix. This balance is important so that UCI honors the interconnection agreement in place with SCE, which prohibits any inadvertent energy export.

On an average day, about 1 MW is imported from Southern California Edison to meet the campus loads [27].

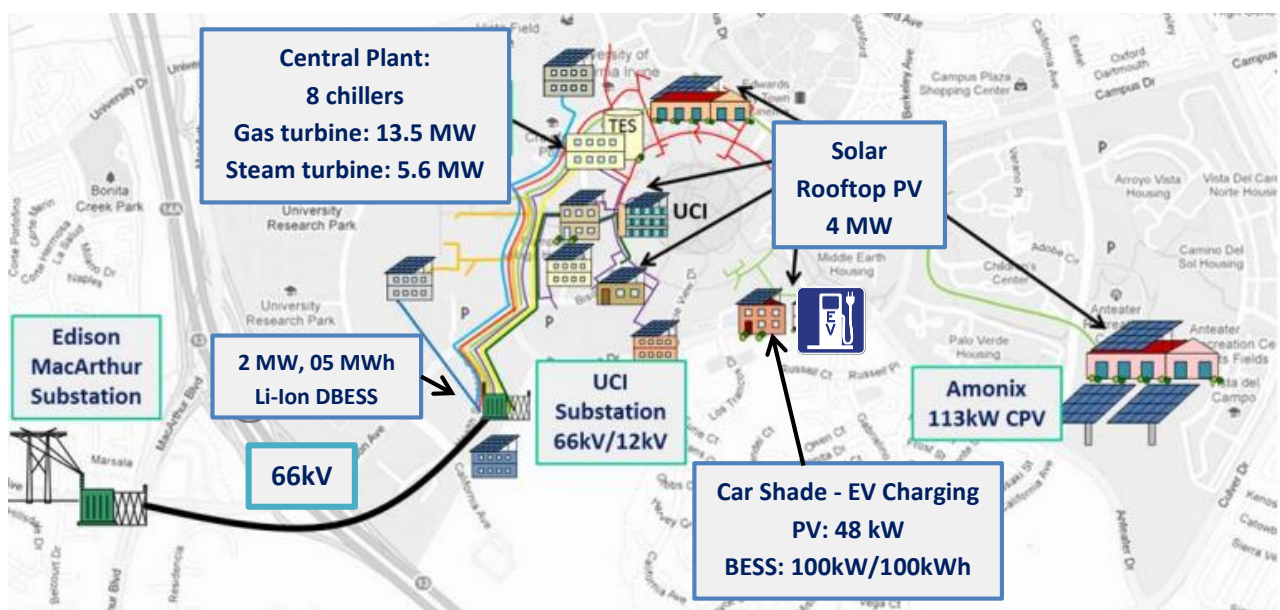


Figure 4: UCI Microgrid [27]

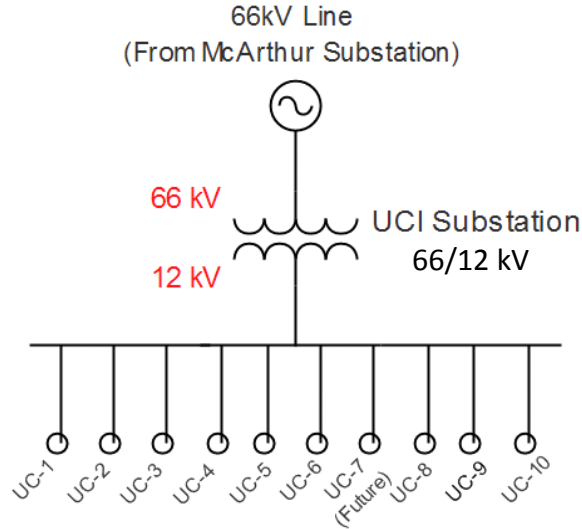


Figure 5: Primary Circuits of the UCI Microgrid

3.2.1. MelRoK System

The UCI Microgrid has over 140 building loads, 96 of which have meters currently connected to a central metering cloud database, the *MelRok*© System. Through an analytics software tool (*EnergiStream*©), near-real-time data can be plotted and historical data can be retrieved in different resolutions: 15, 5 or 1 minute.

The total campus building load (kW) plot over a week using the *EnergiStream*© user-interface is illustrate in Figure 6. Besides active power, it is also possible to retrieve voltage (V), current (A), reactive power (kVAR), total power (kVA), and power factor signals for each individual metered location.

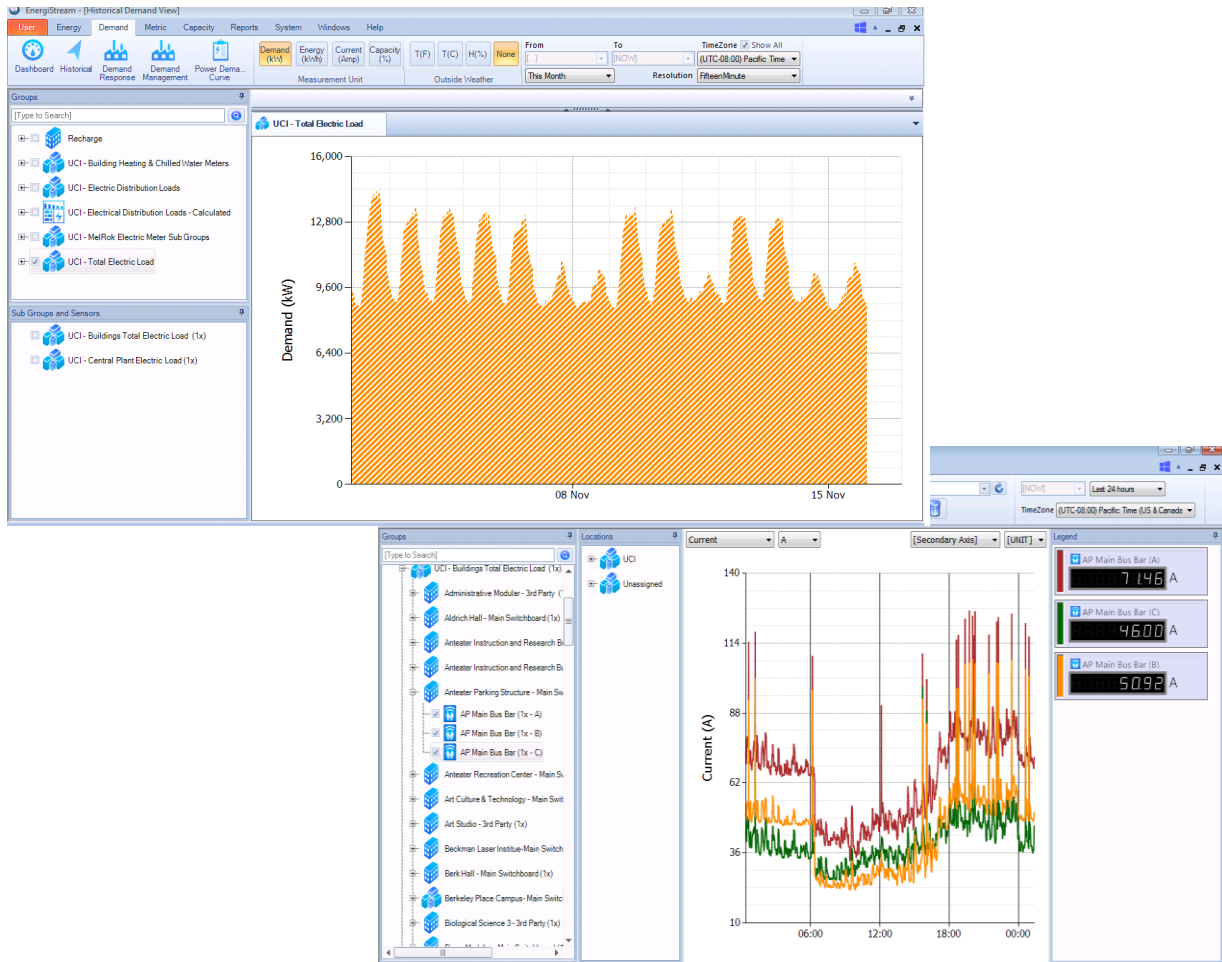


Figure 6: Melrook System – *EnergiStream* environment

3.2.2. Experimental Platform: The Car Shade system

The experimental platform selected for this study, named the “Car Shade” system, is a unique public EV charging station installed into the UCI Microgrid as part of the Irvine Smart Grid Demonstration (ISGD) project of Southern California Edison in collaboration with the Advanced Power and Energy Program (APEP) of UCI.

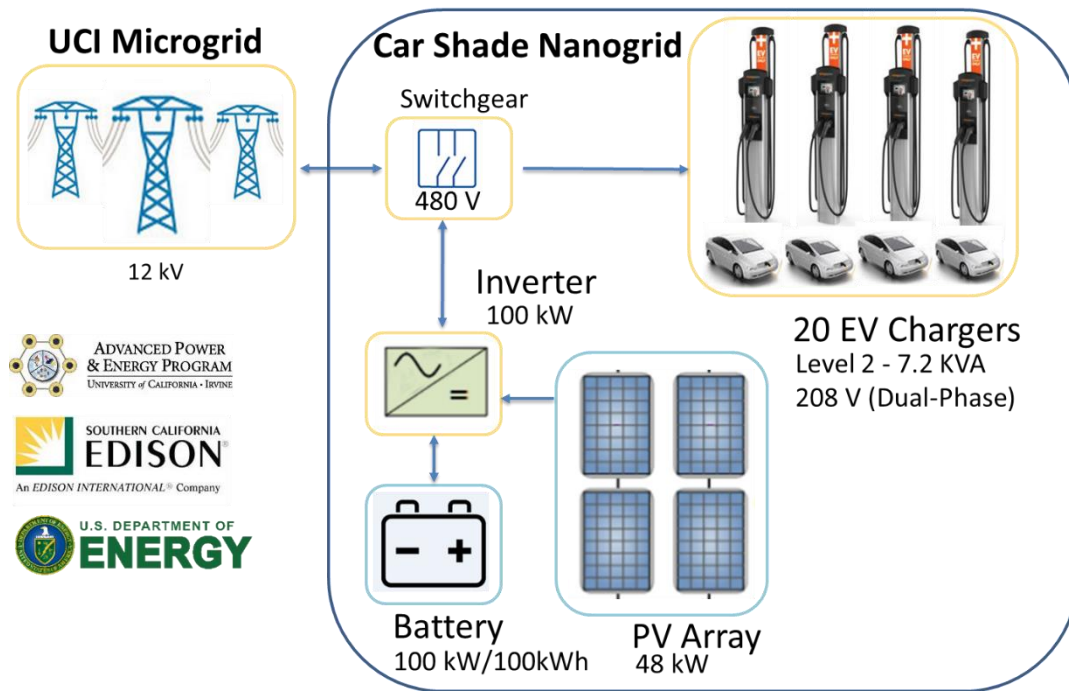


Figure 7: Car Shade system schematic

The Car Shade nanogrid is connected to a primary circuit at the UCI Microgrid through a 1 MVA (12KV/480V) transformer (T-131). This transformer also feeds the Anteater Parking Structure and the Anteater Instruction and Research Building (AIRB) loads. The circuit that feeds T-131 originates from the UC-9 12 kV circuit. A DC bus connects the rooftop solar PV and the battery energy storage system (BESS). An inverter feeds the power from the DC bus to the AC part of the system.

The Car Shade nanogrid is comprised of:

- A 48 kW rooftop PV array;
- 20 monitored Level 2 (7.2 kVA) EV chargers;
- A 100 kW/100 kWh battery energy storage system;

- A 100 kW Princeton Power Systems (PPS) Demand Response Inverter (DRI) with a site controller;
- Two 75 kVA 480/208 V step-down transformers.

A simplified one-line diagram representation of the nanogrid is shown in Figure 8.

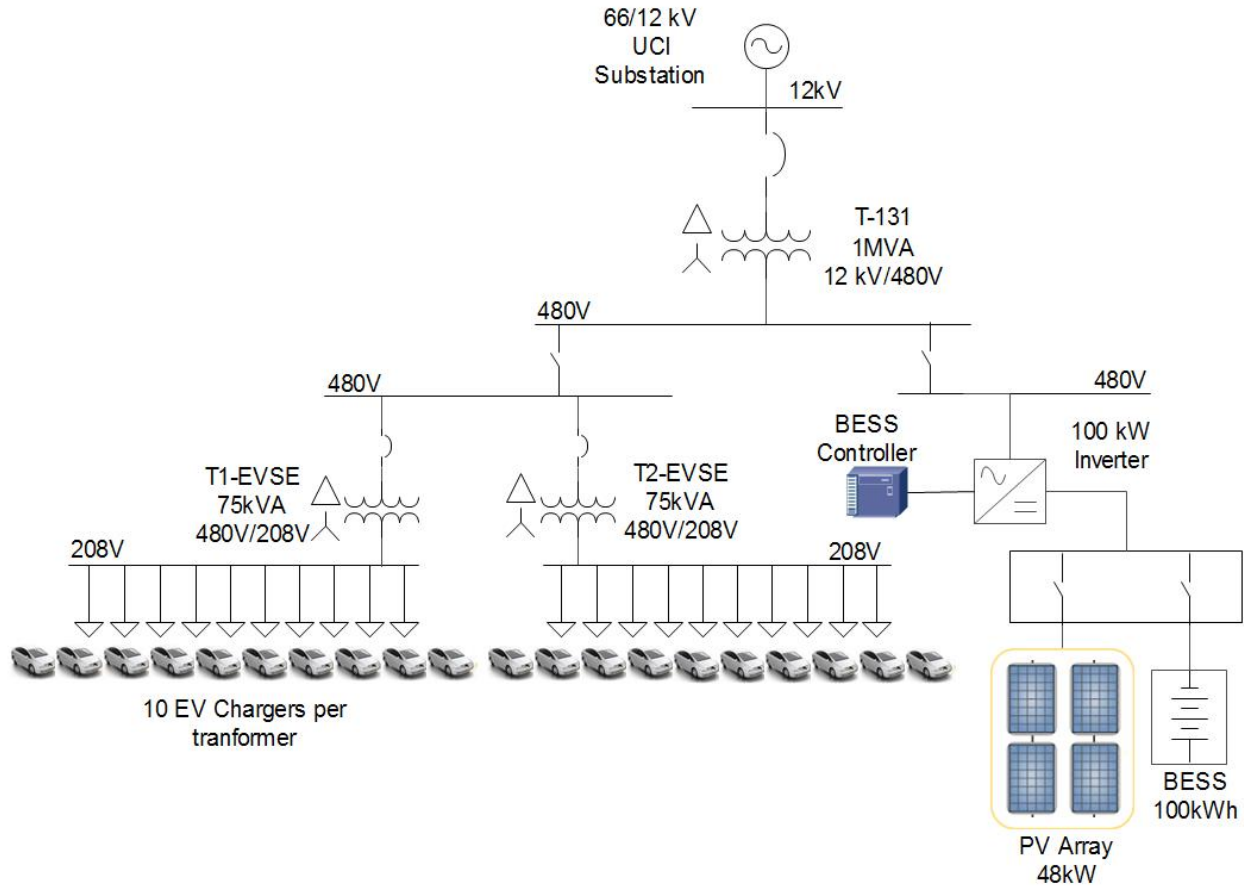


Figure 8: Car Shade Project One-line diagram representation

3.2.2.1. Battery Energy Storage System

The purpose of the BESS is to reduce the EV charging demand imposed upon the UCI Microgrid by managing both storage and discharge of the solar PV energy generated on

site. It also has the ability to shift energy between on and off-peak periods by the use of specific control algorithms.

The system is comprised of a 100 kWh Samsung Lithium-ion battery and a PPS DRI inverter and site control system. All BESS components, PPS inverter and the site controller are enclosed by a standard ISO shipping container, shown in Figure 9.



Figure 9: Battery Energy Storage System Enclosure (left) and Samsung cells (right)

The BESS site controller has different operating modes that contain the algorithms for overall system behavior:

1. **Peak Load Shifting:** Charges the BESS overnight and discharges it in the afternoon EVSE peak, shifting the afternoon load peak to the nighttime.
2. **Demand response event:** Controls the system to charge/discharge at a given power level until the battery limits are reached. The power output/input levels are determined by signals (demands) controlled by SCE.
3. **UCI Peak Shaver:** Controls BESS charging/discharging in order to bring the power consumption in the point of connection of the Car Shade to the grid to

a specified threshold, ultimately aiming to reduce the 15-minute customer demand charges.

4. **SCE Peak Shaver** Operates similarly to the UCI peak shaver mode, actively setting in a certain threshold based on historical data.
5. **Minimize Peak Period Impact (MPPI):** Like the UCI Peak Shaver mode, but ultimately aiming to cap the EVSE demand completely during the UCI Microgrid peak demand period.
6. **PV smoother:** Uses the battery system to lower the fluctuation in the PV power output by limiting the ramping rate at any given point in time by either charging or discharging the battery.

3.2.2.2. Inverter

The inverter used in the Car Shade allows for the integration of the PV Array and BESS, the DC portion of the system, to the EVSE loads and the UCI Microgrid, the AC portion. The inverter used is the Princeton Power Systems DRI-100 PPS is a controllable 4-Terminal power converter (E-QUAD™ power flow control technology shown in Figure 10) which enables dynamic control of four bi-directional loads/sources — (1) PV (DC), (2) Battery (DC), (3) AC Load or DC Fast Charge, and (4) Grid — through a central high-frequency link. Besides the equipment grid-connecting capabilities, port 4 is currently not used. Instead, port 3 is connected to a switchgear that feeds the AC EVSE loads and ties the system to the UCI Microgrid.



Figure 10: PPS DRI-100 E-QUAD™ Power Flow Control Technology

The BESS system also has capabilities of trimming back loads during the grid's peak usage time, as well as voltage and frequency regulation in the bus that it is connected to. It has two operating modes that determine to which signals the inverter responds:

1. Demand Response Mode

In order for the inverter to respond to the BESS Site Controller control modes, described in the previous section, it must be set in the demand response mode. The site controller can then set output/input power levels. If the battery is at or below that set point, then no further discharge can occur. The inverter manager is used to enable or disable export of PV or battery power by preventing reverse power flow at the AC interface.

2. Distributed Generation Mode

In order to use the PV power without curtailment, the inverter must be in this mode.

In this mode the BESS immediately charges the battery using either PV or grid power.

Some of the inverter specifications are listed in Table 1:

Table 1: PPS DRI-100 Inverter Specifications

General Specifications	
Power Ports	(1) DC PV or Battery
	(2) DC Battery
	(3) AC Grid
	(4) AC Load or DC Fast Charger
DC Specifications	
Power Rating	100 kW
Voltage Range	280 - 600 VDC
PV MPPT Range	280 - 580 VDC
Max Current	330 A
AC Specifications	
Power Rating	100 kW
Voltage Range	480 VAC +- 10%
Maximum Current	133 A
Power Factor	0.95 (lag) – 1 –0.95 (lead)
Harmonics	< 5% THD
Efficiency	96%

3.2.2.3. Rooftop Photovoltaic Panels

The *SunPower* E20 series solar array installation on top of the Anteater Parking Structure is presented in Figure 11. These specific panels have one of the highest efficiencies currently on the market (20.4%). The cell technology includes a thick copper foundation that adds strength, no grid lines on the front of the cell, which helps to absorb

more sunlight, and thick connectors to help with strain relief. Each of the 128 panels has a peak power of 327 W and a rated voltage of 54.7 V.



Figure 11: Anteater Parking Structure rooftop solar PV

3.2.2.4. Electric Vehicles Supply Equipment (EVSE)

An EVSE is the equipment used to connect the vehicle and the electricity source, also known as the charging station. The currently installed chargers are Level 2 *ChargePoint* CT-4000 (Figure 12) chargers, which are provided power from a 208 V supply at 16 A, 24 A, or 30 A, resulting in a 3.8 W – 5.8 kW – 7.2 kW rated power range for each charger.

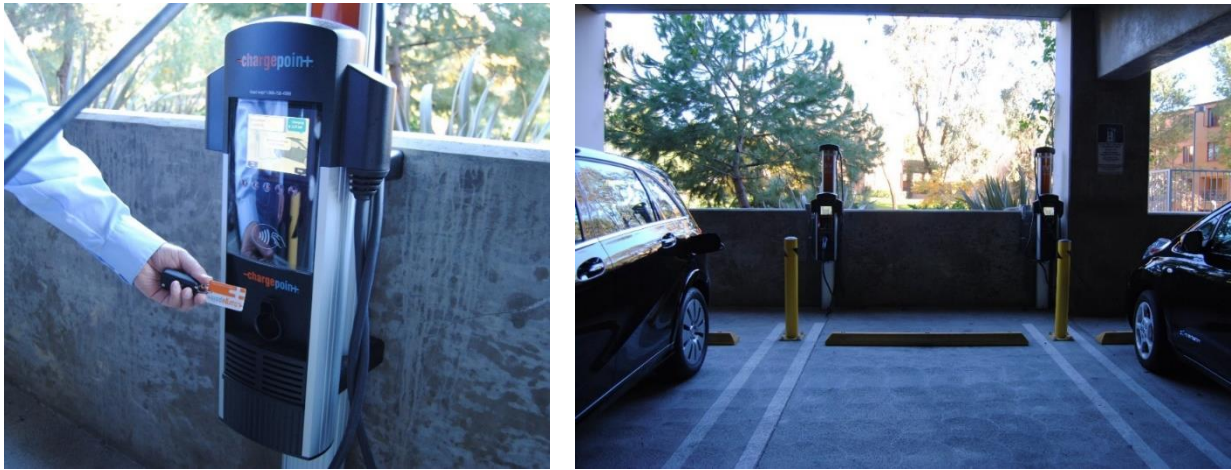


Figure 12: ChargePoint Network EVSEs

These EVSEs are dual-phase, or line-to-line loads, i.e., they are powered by a combination of 2 phases in the 3-phase system: AB, BC, or CA. Figure 13 shows the schematic of the EVSE wiring in a 3-phase panel. Here, the neutral wire is not used by the EVSEs.

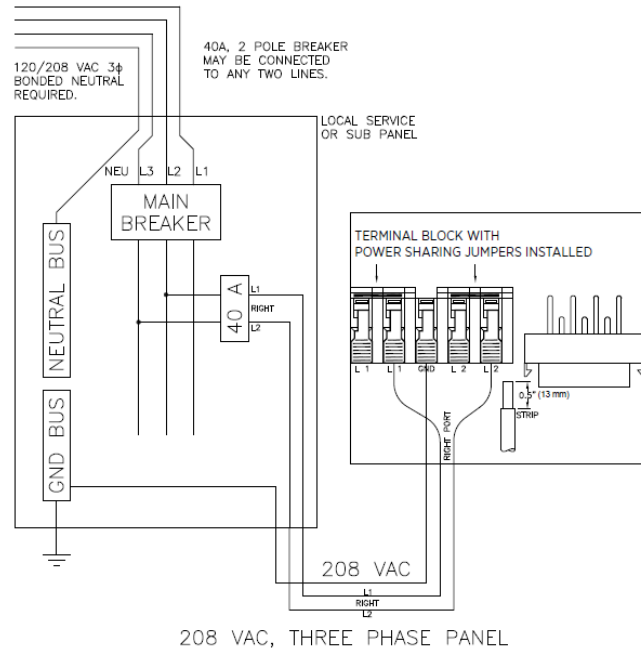


Figure 13: EVSE wiring scheme: Single port 3-EVSE and 3-phase panel [28]

3.2.2.5. Metering

The energy monitoring of the system is accomplished by three different sources.

Three *EIG Shark*© Meters, which pick up the total EVSE loads, the AC side of the inverter (BESS + PV), and also the Car Shade nanogrid/UCI Microgrid interconnection point (EVCS).

A secondary metering platform, the *Trendpoint*© system, which consist of 20 Current Transformers (CTs), pick up each EVSE individually (Figure 13). Finally, the PPS inverter is equipped with internal meters, which pick up signals from the total PV generation and BESS charge/discharge individually.

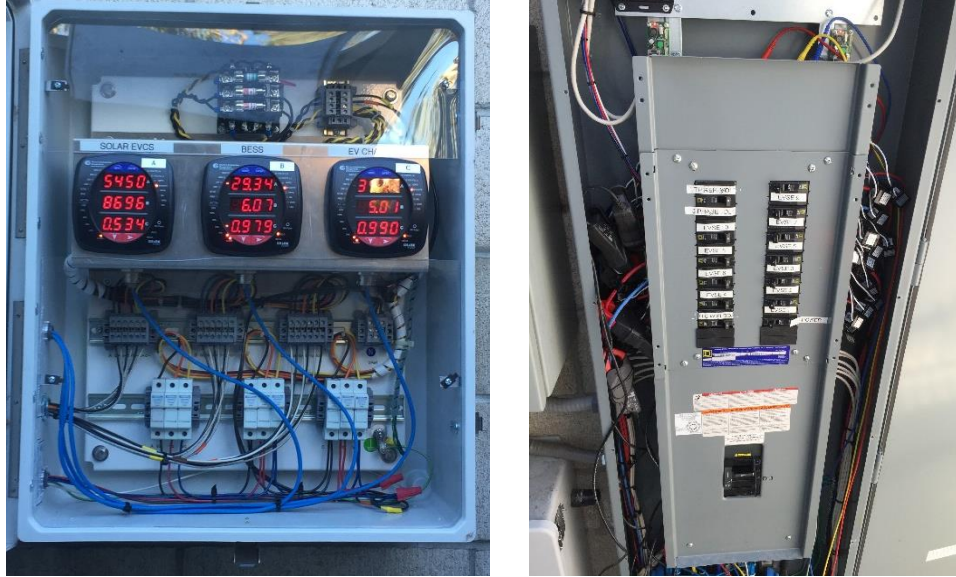


Figure 14: *EIG Shark*© meters (left) and *Trendpoint*© CTs (right)

The location of all metering installed, as well as the adopted sign convention (generation/load and charge/discharge) for power flows are shown in Figure 15. The Shark Meters are shown in points [1],[2], and [3], the *Trendpoint*© system is shown in point [4], and the inverter meters are shown in [5] and [6] of Figure 15.

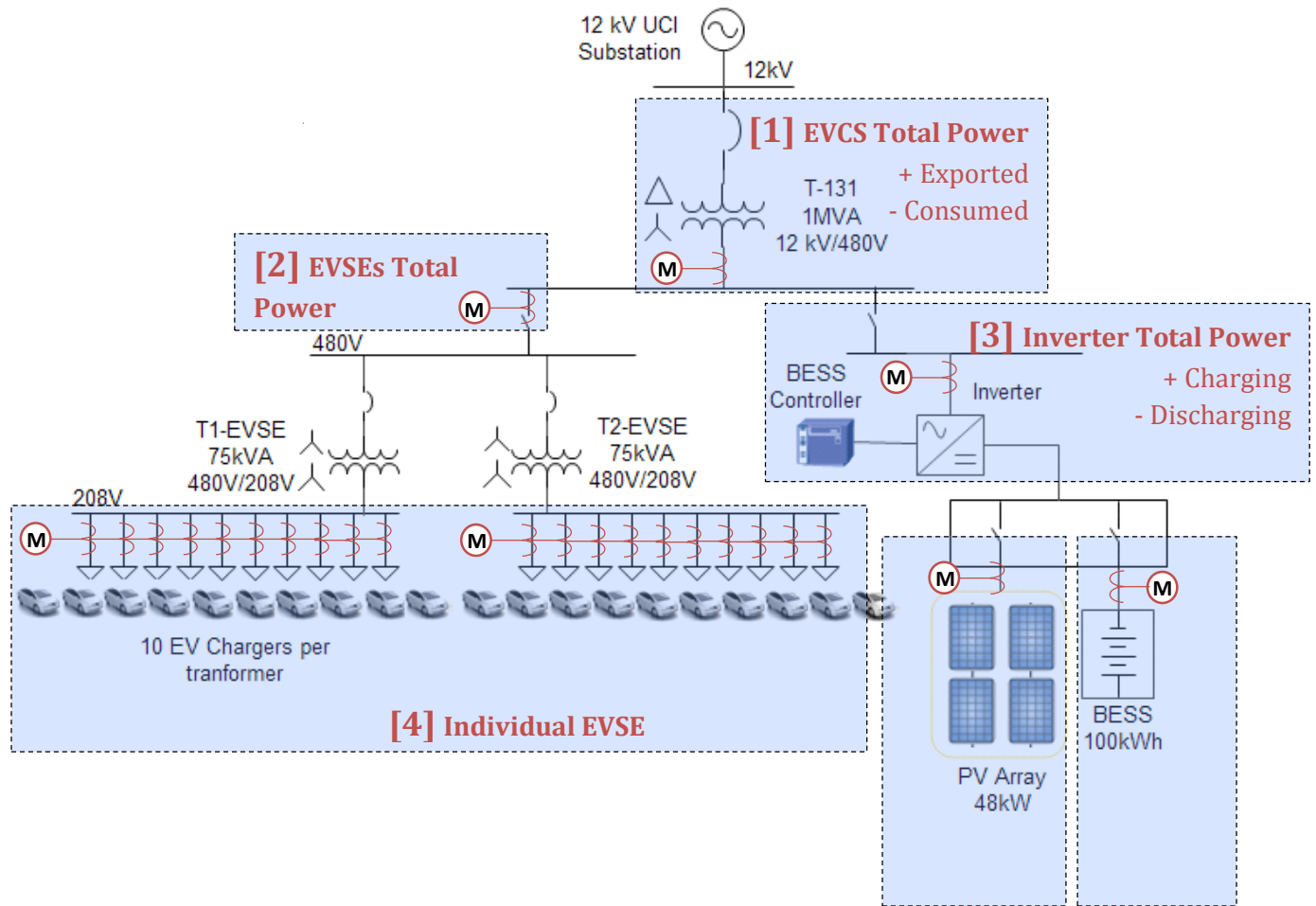


Figure 15: Car Shade Smart Meter locations

3.2.2.6. ChargePoint online portal

The *ChargePoint*® network of EV chargers features an online cloud portal that features a near-real-time graphic interface for data analytics and downloadable customized reports. Figure 16 shows the 20 Car Shade chargers mapped as *ChargePoint*® network charging locations.

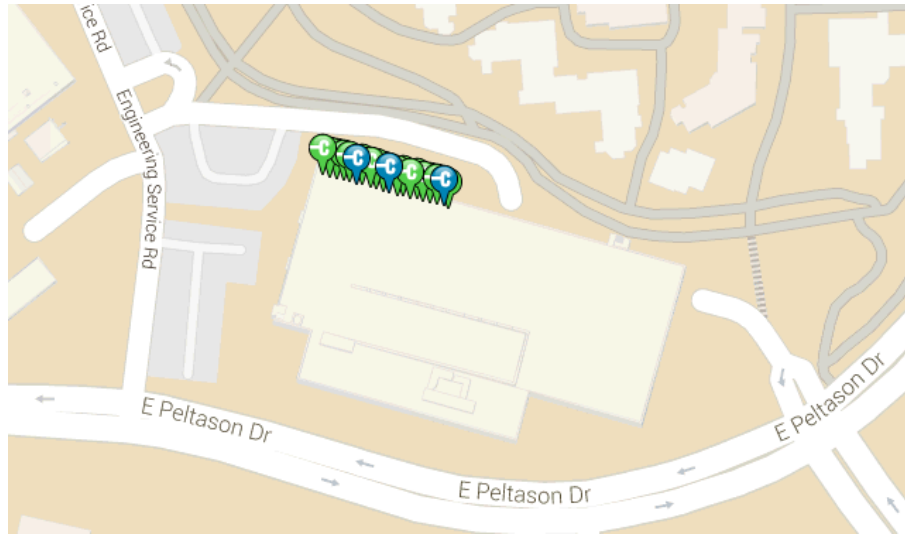


Figure 16: Car Shade chargers at the Anteater Parking Structure [29]

Types of energy analytics available include the following.

1. Historical EVSE energy totals

The bars in Figure 17 represent the daily energy usage and the green trend line represents the accumulated total energy over time. These types of graphs provide useful information such as the typical weekday energy consumption by the station, which in the case of the Car Shade, averages 300-400 kWh, and the weekend energy usage, which drops to less than 100 kWh.

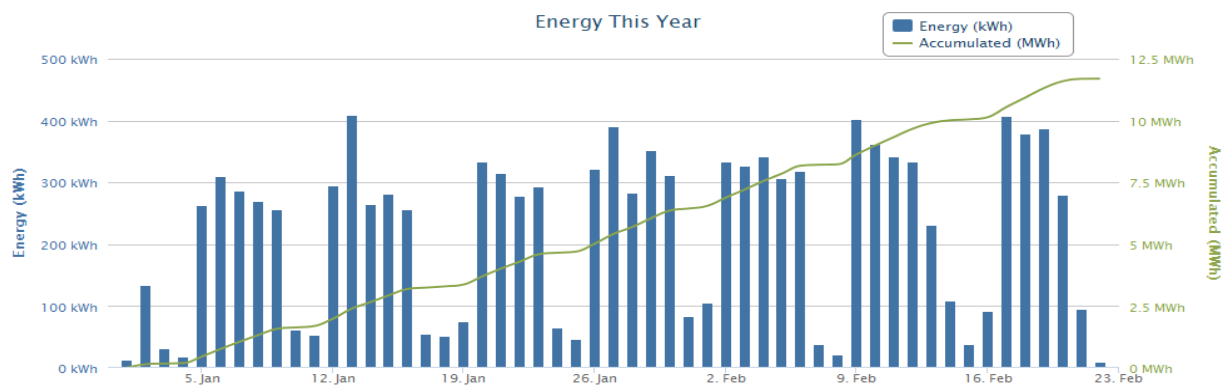


Figure 17: Daily and accumulated energy consumption at the Car Shade [29]

2. Unique drivers per day

An average of 30 drivers use the Car-Shade charging system in a given weekday.

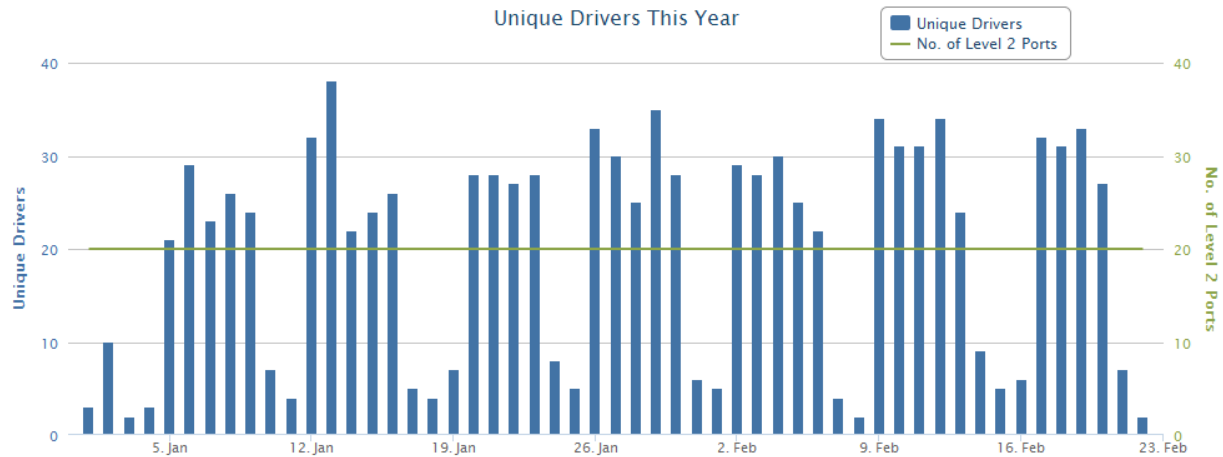


Figure 18: Daily unique drivers at the Car Shade [29]

3. Sessions length:

Available in a histogram form. From Figure 19, it can be that the charging durations vary from two to five hours. A few sections with a very long duration above 10 hours occurred. The average charging duration is about 4:30 hrs.

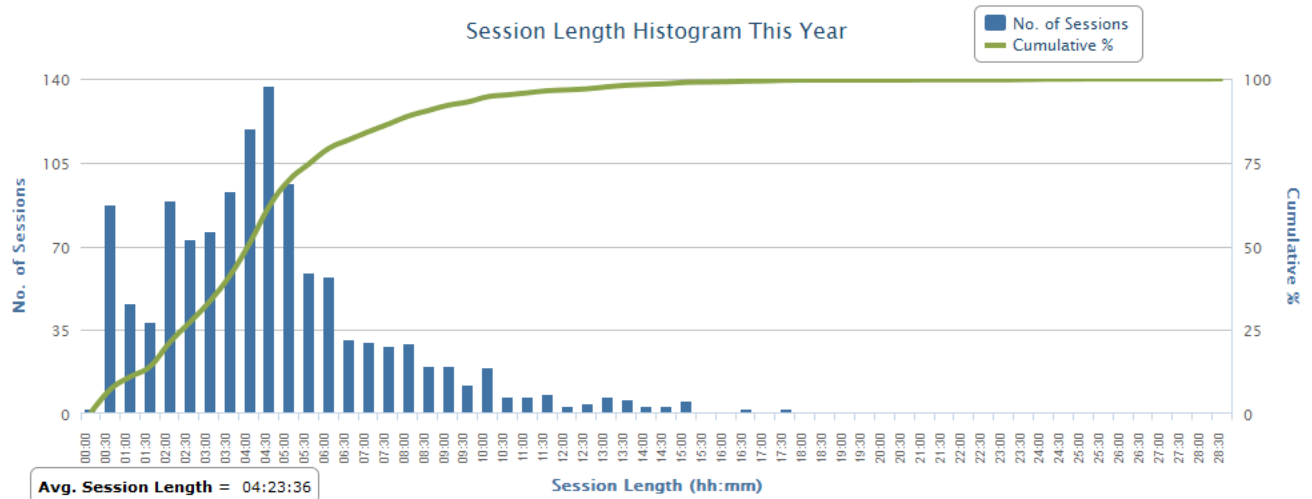


Figure 19: Charging session length at the Car Shade [29]

4. Green House Gas (GHG) emissions savings (daily and accumulated)

GHG emission savings are calculated by the portal based upon the tailpipe emissions avoided with the use of electricity that is generated with rather cleaner sources. The main GHG are carbon dioxide, CO₂, methane, CH₄, nitrogen oxides, NO_x, and tropospheric ozone, O₃. Figure 20 shows that daily, 100 to 150 kg of GHG emissions are avoided. Since January 1, 2015, all savings added up to about 5 tons.

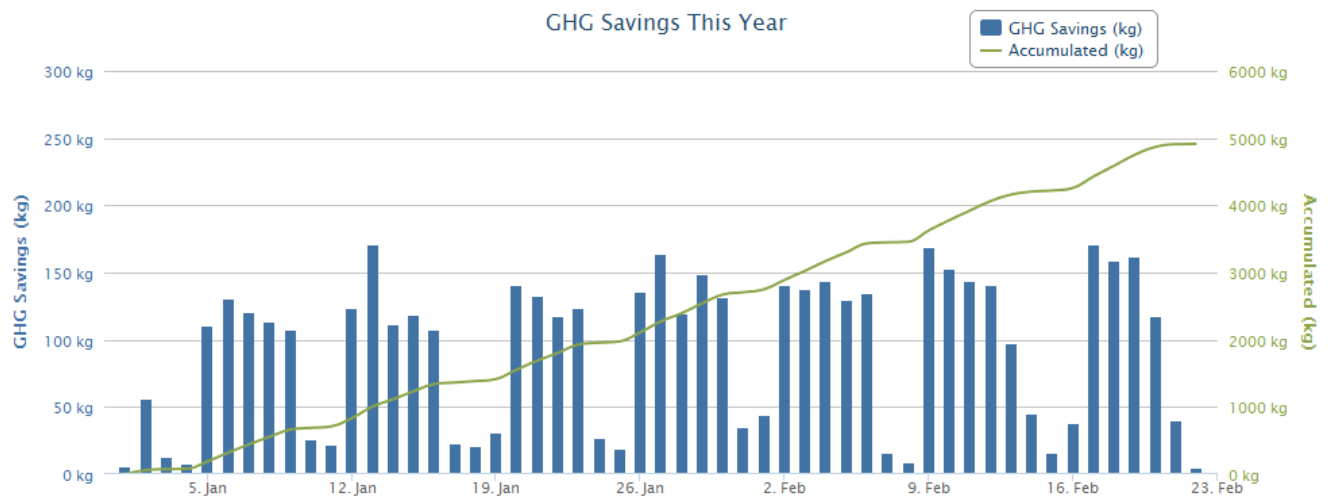


Figure 20: GHG emissions savings of the Car Shade project [29]

3.3. Power Quality and Reliability

Utilities are expected to supply high quality and reliable electric power to their users. A power quality problem can be manifested in either a voltage, current or frequency deviation from normal operations, which can ultimately result in equipment failure or malfunction on the customer side. Typical power quality problems faced by national major utilities range from occasional short-duration voltage reductions or an increase in magnitude — sags or swells — to ongoing, yet intermittent, voltage variations and

harmonic distortion [30]. In the last few decades, power quality did not have an impact on most loads connected to the grid, and was not a major concern amongst utility companies. The newfound concern is not because power quality on the supply side has worsened with time; in reality, it has improved. The increase in concern is due to the introduction of more sensitive power-electronics-based equipment, which has turned the same environment much more sensitive to these variations.

Indices of reliability in a power system measure frequency and duration of supply interruptions for an individual customer. One of these indices is the Average Service Availability Index (ASAI), which is the ratio of hours of available service in a year to the hours in a year. Since most customers experience an average of one hour of interrupted supply per year, utilities usually claim their service is 99.99% reliable. However, electric power reliability is a term whose meaning has been expanded; a reliable power not only has the traditional goal of reducing sustained interruption, but the added goal of an increased level of the quality of the power delivered.

In a similar way, the power quality and reliability (PQ&R) requirements within a microgrid, which directly interfaces with the mains utility network, are an important area of study. Hence, the installation of DER, including renewable resources, needs to be designed only to enhance the local and the central grid's characteristics and operation.

Typically, microgrids have the ability to island whenever the central grid experiences voltage challenges or blackouts. When completely isolated, the system inverter will normally operate to ensure local voltage support. In addition, islanding these resources

requires that the islanded system be safe for line workers and that the process of islanding does not negatively affect the local PQ&R.

3.3.1. Power Quality Definitions

One of the main definitions of Power Quality (PQ) was presented by the Institute of Electrical and Electronics Engineers (IEEE) Standard 1100-1999 [31] as “The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and also compatible with the premise wiring system and other connected equipment”. The International Electrotechnical Commission (IEC) has also defined PQ as a “Set of parameters defining the properties of power quality as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, waveform)”. Thus, PQ can be generally defined as a set of adequate operational limits for electrical equipment that guarantee both acceptable performance and lifespan.

For a more practical understanding, three categories can be defined for different types of PQ events, as shown in Table 2. Each of these PQ events can be grouped into three categories: (1) voltage stability issues, (2) continuity of supplying power issues, and (3) voltage and current waveform issues. Most of these electromagnetic phenomena occurring on a power system are categorized by duration and magnitude. By knowing both of these parameters, a given PQ event can be represented in the magnitude-duration plane, as presented in Figure 21. In terms of magnitude, the events are split into three regions:

- Interruption, when the voltage magnitude is zero.
- Undervoltage, when the voltage magnitude is below its nominal.

- Overvoltage, when the voltage magnitude is above its nominal value.

In terms of duration, the events can be classified as:

- Instantaneous: transient and self-restoring events with a very short duration of less than 30 cycles.
- Momentary: events that allow automatic restoration of a pre-event issue with a short duration of less than 3 seconds.
- Temporary: events that allow manual restoration of a pre-event issue with a duration of less than 1 minute.
- Sustained interruption: events that require repair or replacement of defective equipment with a duration of anything more than 1 minute.

Table 2: Power Quality Events – Grouped [32], [33]

Voltage Stability	Continuity of Supplying Power	Voltage/Current Waveform
• Undervoltage & Overvoltage • Voltage Sag • Voltage Swell • Phase Shift • Flicker • Frequency	• Momentary interruption • Temporary interruption • Sustained Interruption	• Transients • Three-phase Voltage Unbalance • Harmonic and Interharmonic Voltage and Current • Notch

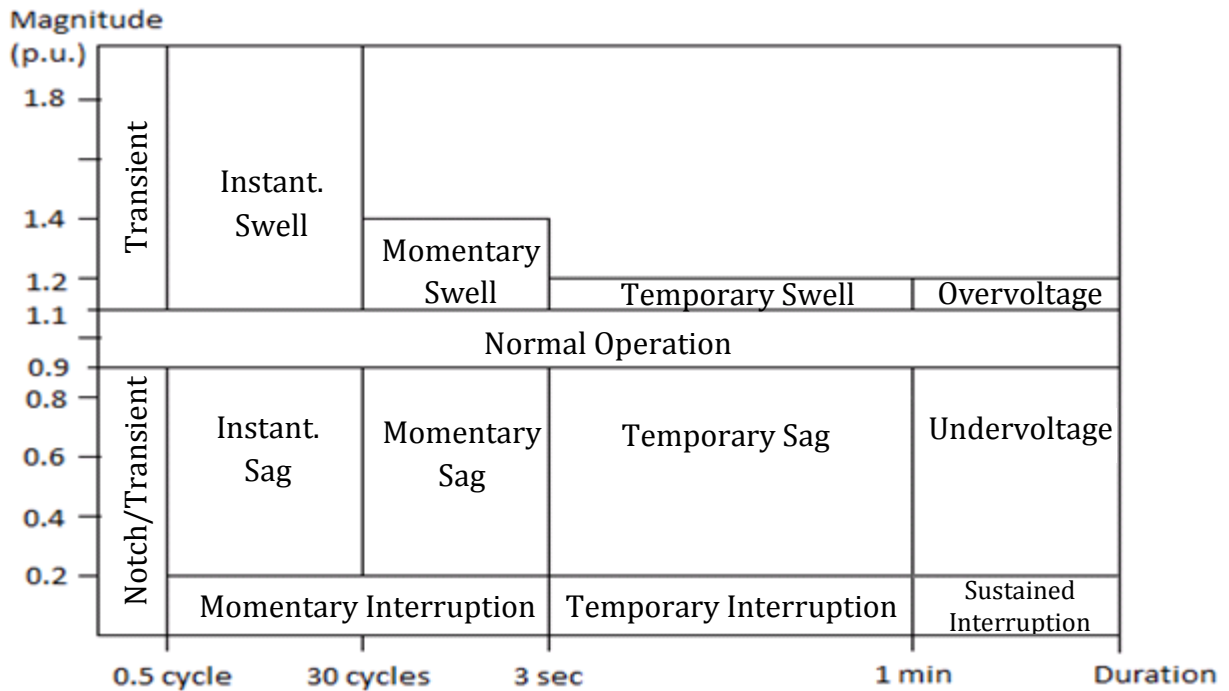


Figure 21: Definitions of PQ events magnitude and duration according to IEEE Std.

1195-2009. Adapted from [32]

A more comprehensive description and characterization of magnitudes, duration, and spectrum content ranges for PQ voltage events, as proposed by the IEEE Std. 1195-2009, is shown in Table 3. In addition to the events already represented in the magnitude-duration plane, voltage and current imbalance typical magnitudes are also identified. Other PQ events such as waveform distortion (harmonics and interharmonics) and DC offset are also defined with respect to their spectral content and magnitude. Defined thresholds are needed for monitoring purposes, to distinguish between the different events.

Table 3: Categories and typical characteristics of power system EM phenomena according to IEEE Std. 1995-2009 [34]

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 μ s rise	50 ns – 1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3–50 ms	0–4 pu ^a
1.2.2 Medium frequency	5–500 kHz	20 μ s	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μ s	0–4 pu
2.0 Short-duration root-mean-square (rms) variations			
2.1 Instantaneous			
2.1.1 Sag		0.5–30 cycles	0.1–0.9 pu
2.1.2 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles – 3 s	< 0.1 pu
2.2.2 Sag		30 cycles – 3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles – 3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		>3 s – 1 min	< 0.1 pu
2.3.2 Sag		>3 s – 1 min	0.1–0.9 pu
2.3.3 Swell		>3 s – 1 min	1.1–1.2 pu
3.0 Long duration rms variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8–0.9 pu
3.3 Overvoltages		> 1 min	1.1–1.2 pu
3.4 Current overload		> 1 min	
4.0 Imbalance			
4.1 Voltage		steady state	0.5–2%
4.2 Current		steady state	1.0–30%
5.0 Waveform distortion			
5.1 DC offset		steady state	0–0.1%
5.2 Harmonics	0–9 kHz	steady state	0–20%
5.3 Interharmonics	0–9 kHz	steady state	0–2%
5.4 Notching		steady state	
5.5 Noise	broadband	steady state	0–1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1–7% 0.2–2 P _{st} ^b
7.0 Power frequency variations		< 10 s	± 0.10 Hz
NOTE—These terms and categories apply to power quality measurements and are not to be confused with similar terms defined in IEEE Std 1366™-2003 [B27] and other reliability-related standards, recommended practices, and guides.			

^a The quantity *pu* refers to *per unit*, which is dimensionless. The quantity 1.0 pu corresponds to 100%. The nominal condition is often considered to be 1.0 pu. In this table, the nominal peak value is used as the base for transients and the nominal rms value is used as the base for rms variations.

^b Flicker severity index P_{st} as defined in IEC 61000-4-15:2003 [B15] and IEEE Std 1453™-2004 [B28].

Standards on PQ set limits and ranges to these power quality phenomena in order to reduce deviations from a nominal range of operating conditions and guarantee normal system operation. As EVs and DER present either a load or a power source, which can actively modify these metrics, they are subjected to similar requirements. The main current standards applied to Power Quality in the U.S. are the IEC 61000 series, which have been developed on Electromagnetic Compatibility (EMC), i.e., “the ability of an equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment”, and also the IEEE standards below [35]:

- IEEE 519 (1992): Recommended Practices & Requirements for Harmonic Control in Electrical Power Systems.
- IEEE 1346 (1998): IEEE Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment.
- IEEE 1159 (2009): Recommended Practice for Monitoring Electric Power Quality.
- IEEE 1547 (2003): Standard for Interconnecting Distributed Resources with Electric Power Systems.
- IEEE 1250 (2011): Guide for Identifying and Improving Voltage Quality in Power Systems.
- IEEE 1409 (2012): IEEE Draft Guide for the Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV through 38 kV.

Although it is mostly used in Europe, the European Norm EN-50160 also sets limits to the supply voltage characteristics including power quality aspects.

A summary and comparison between two of the most applicable standards, IEC 6300 series and EN-50160, is given in Table 4. When interpreting each standard, it is important to understand its individual scopes. The IEC standard sets maximum limits for emissions (the maximum level of electromagnetic disturbance an equipment can produce) and immunity (the minimum threshold an equipment should be able to withstand in an electromagnetic environment). On the other hand, the European standard 50160 presents the characteristic values at the customer terminals for both low voltage (LV) and medium voltage (MV) networks under normal operation — therefore, they are not targets or limits. The harmonic voltage percentages presented are the high values identified by a survey made in the European power system (CIGRE), which caused equipment failure. Hence, these values are rarely exceeded anywhere in Europe [32].

Therefore, even though the direct comparison between the standards mentioned above may seem straight-forward from Table 4, one should mind the differences between the two standards methodologies, more details are given in references [32], [35]

In addition, there are specific IEC standards for EVs. The ones that reference power quality issues are [35]:

- IEC 61851-21 (2001): Electric vehicle conductive charging system — Part 21: Electric vehicle requirements for conductive connection to an AC/DC supply. It gives the EV requirements for conductive connection to an AC or DC supply, for AC voltages up to 690 V and for DC voltages up to 1,000 V, when the electric

vehicle is connected to the supply network. It has references to EMC standards, specifically, IEC 61000 2-2, 3 (all parts), 3-2, 4 (all parts), 4-1, 4-2, 4-3, 4-4, 4-5, 4-11. Its contents include EMC issues and, specifically, immunity to generated electromagnetic disturbances.

- IEC 61851-22 (2001): Electric vehicle conductive charging system — Part 22: AC electric vehicle charging station. This part of IEC 61851, together with part 1, gives the requirements for AC electric vehicle charging stations for conductive connection to an electric vehicle, with AC supply voltages up to 690 V. It has references to IEC 61000- 2-2, 3-2, 4-1, 4-2, 4-3, 4-4, 4-5, 4-11 and includes EM environmental tests. Specifically, immunity to EM disturbances and to emitted EM disturbances.

Table 4: Summary and Comparison of applicable standards in Power Quality (EN 50160 and IEC 61000) [35] and [32]

	EN 50160	IEC 61000-x-y
<i>Frequency Variations</i>	LV, MV: Mean value of fundamental measured over 10s 1.Interconnected systems: $\pm 1\%$ for 95% of a week -6%/+4% for 100% of a week 2.Non-interconnected systems: $\pm 2\%$ for 95% of a week $\pm 15\%$ for 100% of a week	IEC 61000-2-2: LV: 2% (emission and immunity limits)
<i>Voltage Variations</i>	LV, MV: $\pm 10\%$ of nominal voltage (U_n), for 95% of week, 10-min mean rms values	$\pm 10\%$ applied for 15 minutes
<i>Rapid Voltage Changes (Voltage Fluctuations)</i>	LV: generally $< 5\%$ of U_n , but 10% might occur MV: generally $< 4\%$ of U_n is normal, but 6% might occur	IEC 61000-2-2 (Compatibility levels): 3% normally, 8% infrequently IEC 61000-3-3: 3% normal, 4% max. IEC 61000-2-12: 3% IEC 61000-3-7: Planning levels IEC 61000-3-11:

		Emission limits IEC61000-4-14, 4-15 (Immunity levels and measurements)
<i>Flicker</i>	LV, MV: $P_{lt} \leq 1$ for 95% of a week	IEC 61000-2-2: $P_{st} < 1.0$, $P_{lt} < 0.8$ IEC 61000-3-3: $P_{st} < 1.0$, $P_{lt} < 0.65$ IEC 61000-3-7 (Planning levels) IEC 61000-4-14, 4-15 (Immunity levels and measurements)
<i>Harmonic voltages</i>	LV, MV: Limits for harmonics up to the 25 th are given and should not be exceeded in 95% of the time. 5% - 3 rd , 6% - 5 th , 5% - 7 th , 1.5% - 9 th , 3.5% - 11 th , 3% - 13 th , 0.5% - 15 th , 2% - 17 th , 1.5% - 19 th , 0.5% - 21 th , 1.5% - 23 th and 25 th . THD < 8% (harmonics up to the 40 th)	IEC 61000-2-2: 6% - 5 th , 5% - 7 th , 3.5% - 11 th , 3% - 13 th , THD < 8% IEC 61000-3-2: 5% - 3 rd , 6% - 5 th , 5% - 7 th , 1.5% - 9 th , 3.5% - 11 th , 3% - 13 th , 0.3% - 15 th , 2% - 17 th
<i>Interharmonics</i>	-	IEC 61000-2-2: 0.2% (Indicative value)
<i>Unbalance</i>	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some areas	IEC 61000-2-2 (Compatibility levels): 2% IEC 61000-2-12 (Compatibility levels): 2%, IEC 61000-4-27 (Immunity requirements and measurements)
<i>Voltage Dips (Sags)</i>	LV, MV: Duration < 1s, depth < 60% (majority of dips)	IEC 61000-6-1, 6-2 (Immunity levels): up to 30% for 10 ms, up to 60% for 100 ms IEC 61000-6-2 (Immunity levels): up to 60% for 1000 ms
<i>Short Interruptions</i>	LV, MV: (up to 3 minutes) few tens to few hundreds events/year. Duration (70% of them) < 1 s	IEC 61000-6-1, 6-2: 95% reduction for 5 s
<i>Long Interruptions</i>	LV, MV: (Longer than 3 minutes) <10-50 events per year	-
<i>Temporary Overvoltages (Swells)</i>	LV: $< 1.5 U_n$, MV: $1.7 U_n$ (solid or impedance earth) $2.0 U_c$ (unearthed or resonant earth)	-
<i>Transient Overvoltages</i>	LV: generally < 6kV (occasionally higher), rise time: ms - μ s. MV: not defined	IEC 61000-6-1, 6-2: ± 2 kV, line-to-earth, ± 1 kV, line-to-line, 1.2/50(8/20) Tr/Th μ s
<i>Mains Signaling</i>	LV, MV: Over 99% of a day, the 3 second mean of signal voltages must be less than or equal to defined values (in a figure). In LV networks, 5% of U_n for frequencies between 1 and 10 kHz.	IEC 61000-2-2 (Compatibility levels)

3.3.1.1. Harmonics

For linear loads, where the current is proportional to the applied voltage, the waveform of current drawn is a pure sinewave. Non-linear loads, however, can distort this waveform, which can be analyzed by Fourier analysis to separate each of the contributions to this distortion into periodic integers multiple of the power system fundamental frequency. This phenomena is the so called harmonic distortion [36]. Figure 22 shows how a perfect sinusoidal voltage $V(t)$ when applied to a non-linear resistor, produces a distorted current $I(t)$. The non-linearity of the device can be observed in the I-V curve show in the right. For this non-linear resistor, a slight increase in voltage causes the current to increase sharply, taking on a different wave shape. A fixed resistance (linear load) would not distort the waveform.

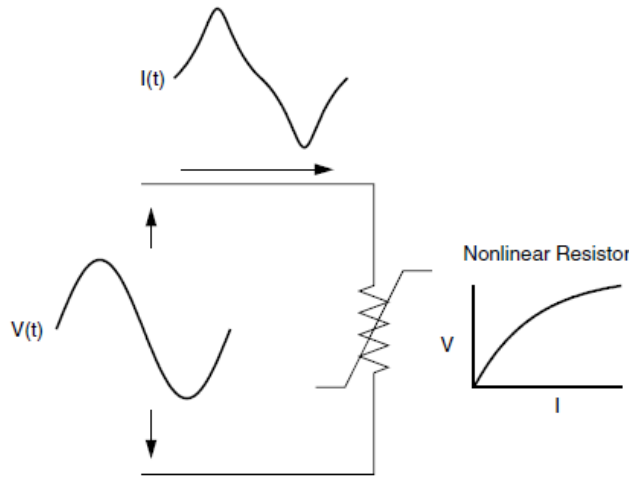


Figure 22: Current Distortion caused by non-linear device [36]

Harmonics are still considered the major power quality problem in the grid. Accounting for and dealing with harmonics changes, many of the conventional rules for

power systems design, analysis, and operation that usually only account for the fundamental frequency.

By Fourier analysis any periodic distorted waveform can be expressed as a sum of pure sinewaves of various magnitudes in which the frequency of each sinusoid is an integer multiple — the so called harmonic — of the distorted wave's fundamental frequency [36]. Fourier series are used to express the sum of sinusoids, and used to decompose a distorted waveform into its harmonic components, or orders, as shown in Figure 23. Analyzing the system at each individual harmonic order is much more straight forward than analyzing the distorted waveforms themselves [36].

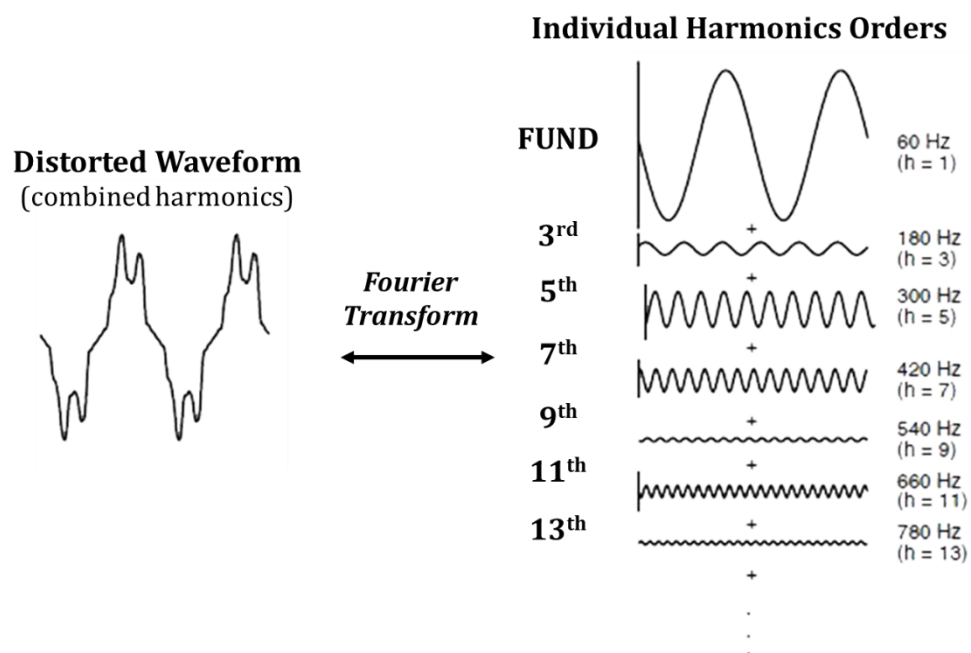


Figure 23: Fourier Transform decomposition of distorted waveforms into individual harmonic orders. Adapted from [36]

As most non-linear loads produce identical distortion in both polarities, the distorted sinusoids will look identical in the positive and negative halves. This leads to a useful

simplification: only odd harmonics are of concern. Moreover, high harmonic orders (from the 25th order up until the 50th) are usually negligible.

Yet, using the specific term “harmonics” by itself without further qualification to describe a PQ problem lacks on necessary details “Voltage harmonics” and “current harmonics” are preferable descriptors, which better indicate the specific cause of the PQ problem. Voltage and current harmonics — distortions in the current and voltage waveforms — can cause electronic device malfunctions or equipment overload. Distorted voltages are the result of distorted currents (injected in the system by non-linear loads) flowing through the system’s impedance (Figure 24).

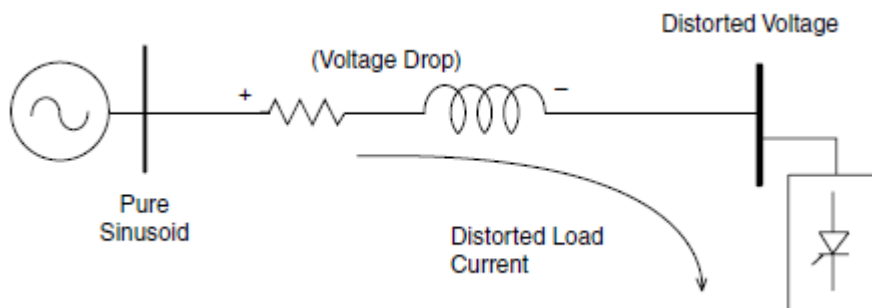


Figure 24: Distorted voltage originated by a distorted current [36]

The total harmonic distortion (THD) is a single quantity that characterizes the magnitude of the effective harmonic distortion level in a power system [37]. This index can be calculated for both current (Equation (1)) and voltage (Equation (2)) and are simply the root mean square (RMS) averages, i.e., the square root of the sum of the individual harmonic orders(h) magnitudes squared, divided by the fundamental (I_1 or V_1)

$$THD_i(\%) = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_1} \quad h = 2, 3, \dots h_{max} \quad (1)$$

$$THD_v(\%) = \frac{\sqrt{\sum_{h=2}^{h_{max}} V_h^2}}{V_1} \quad h = 2, 3, \dots h_{max} \quad (2)$$

Since THD indexes are calculated as a percentage of the fundamental, they may not be a good parameter to quantify distortion. Current magnitudes change constantly during operation, therefore, a lower fundamental value will reflect on a higher THD_i . As a result, a high THD_i may not always indicate that the harmonic content is increased, but in reality, only the fundamental that was reduced.

For the reason stated in the power quality background, the TDD index will be used here to represent current distortion. The TDD considers the RSS (Root Sum Square) of the distortion value as a percentage of a maximum demand load current I_L , measured at the point of common coupling PCC, which serves the basis for the recommendations of IEEE Standard 519-1992 [37].

$$TDD_i(\%) = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L} \quad h = 2, 3, \dots h_{max} \quad (3)$$

3.3.1.2. Harmonics Cancellation

Harmonic distortion in a power system is completely defined only if, for each individual harmonic order, both the magnitude and phase angles are well known.

In a power system, the sources of harmonic distortion are numerous. Moreover, a different harmonic input is produced according to the non-linear load type, thus each individual harmonic order present in the system has different (randomly distributed) phase angles, which most times constantly change during operation [38]. For mixing and matching these non-linear loads in a realistic way, vector summation should be used instead of linear summation. Therefore, phase angle diversity needs to be considered so that the summation of harmonic vectors (phasors) at the same frequency is accurate.

Harmonic cancellation occurs when the harmonic current or voltage phasors (vectors) are displaced 180 degrees apart (180 degree phase shift). Thus, an angular displacement between two three-phase outputs of:

- 60° is required to cancel the 3rd and 9th harmonic currents
- 30° is required to cancel the 5th and 7th harmonic currents
- 15° is required to cancel the 11th and 13th harmonic currents

Illustrating the above, consider the two different loads A and B with fundamental current and 7th harmonic current, shown in Figure 25 . In the 7th harmonic waveform, each half-wave occupies $180/7 = 26$ degrees, thus, a phase shift of 30 will cancel this harmonic order. Any displacement $n*30$ will produce the same result, n being an odd number. [38]

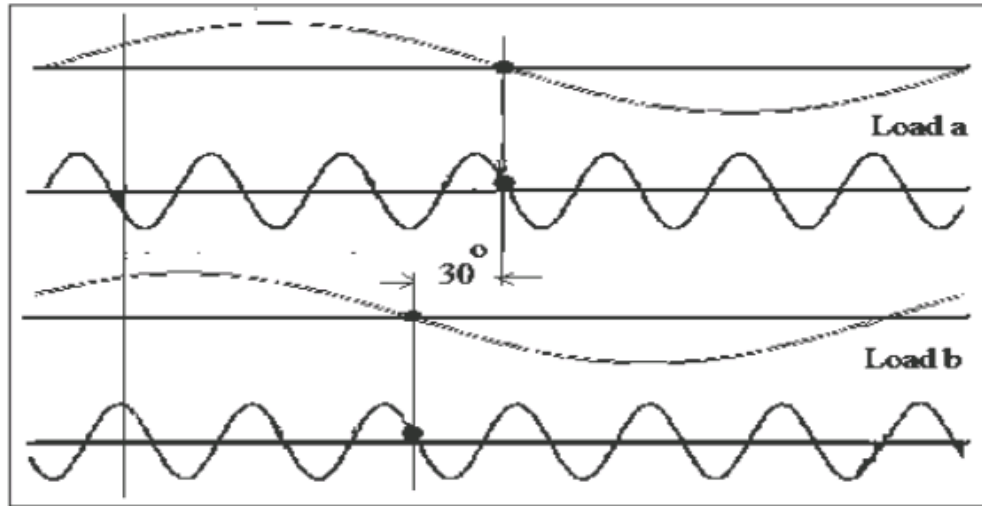


Figure 25: Mitigating the 7th harmonic current waveform by phase shifting [38]

3.3.1.3. Transients

Transients are very short-timescale (in the range of microseconds to milliseconds) changes in the voltage or current waveforms of a power system. When analyzing transients, the system's fundamental frequency magnitude does not offer important information, thus the signal's higher frequency components must be considered for a thorough characterization and classification. Typically, transients are originated by switching [39]. There are two types of transients, Impulsive and Oscillatory:

- **Impulsive transient**: a transient with a unidirectional polarity (positive or negative), as shown in Figure 26, usually characterized by their rise and decay times and typically caused by switching and lightening. Low frequency impulsive transients rise in 0.1 ms and lasts more than 1 ms. Mid-frequency events last between 50 ns to 1 ms. High-frequency types last for about 50 ns. Mid-to low frequency impulsive transients propagate very easily on the system. High frequency types, however, are usually only

seen near the source. Impulsive transients can excite power system resonance circuits and produce oscillatory transients [34].

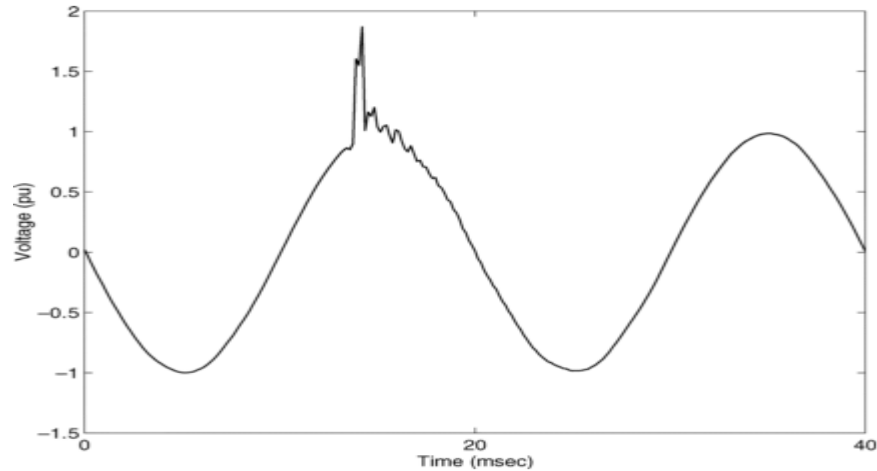


Figure 26: Voltage impulsive transient of a 132 kV line [39]

- Oscillatory transients: a transient with a damped oscillation, including both positive and negative polarity values, typically caused by power electronics circuits or capacitor banks or line energizing. Low frequency oscillatory transients contain frequency components up to 5 kHz (0.3 – 50 ms duration), which can be easily propagated. These transients occur when the system resonance magnifies low-frequency components in the transformer inrush current (e.g., 2nd and 3rd harmonic). Oscillatory low-frequency transients contain frequency components up to 5 kHz, also easily propagated. Mid-frequency events contain 5 to 500 kHz components, and tens of microseconds of duration, thus they are less frequent but have a higher amplitude. High frequency types range between 0.5 and 5MHz, and microseconds duration, and usually are only detected near the source and as a response to a local system impulsive transient. Loads

containing power electronic circuits produce oscillatory voltage transients as a result of commutation and RLC snubber circuits [34].

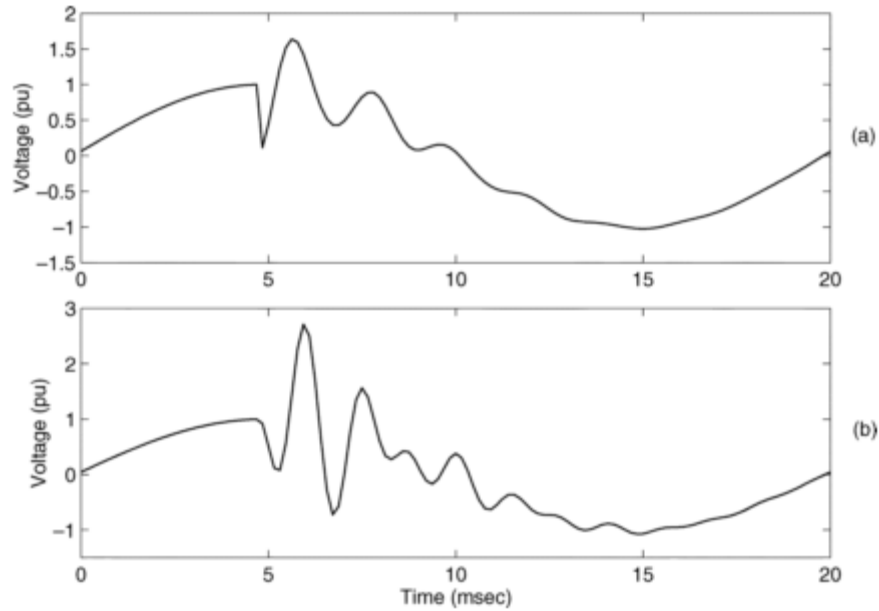


Figure 27: Oscillatory transient in the voltage waveform due to capacitor energizing [39]

3.3.2. EV Charging and Power Quality

EV battery chargers can be classified as on-board (integrated into the EV) or off-board (external to the EV), with unidirectional (Grid to Vehicle, or G2V) or bi-directional (Vehicle to Grid, or V2G) enabled power flow. On-board, conductive, and unidirectional configurations are the most common, due to simplicity and low-cost hardware. Different EV charging systems configurations are illustrated in Figure 28, where the three conventional charging power levels are shown along with the typical electrical infrastructure, connector type, rated voltage, and number of energized phases. Level 1 and Level 2, according to the

SAE J1772 standard, should be located on the vehicle (on-board), while for Level 3, the electric supply equipment is typically off-board. The connector type for Level 1 is the same as the conventional 120 V grounded outlet, such as a NEMA5-15R, so no additional infrastructure is technically necessary for a home garage or a business with an accessible receptacle. Level 2, on the other hand, requires a dedicated EVSE (or a dedicated 240V outlet) and a SAE J1772 connector. Lastly, Level 3 requires a dedicated off-board (for the additional power electronic equipment used for rectification) 3-phase/480 V EVSE. For rectifying the AC power in order to charge the battery, an onboard (or off-board) converter uses a combination of power electronic circuits, typically, but not restricted to, an AC/DC rectifier followed by a DC/DC boost converter with active power factor correction (PFC). The following section will present other topologies will be presented in in more detail. Inside the EV, a DC bus ties a bidirectional DC/DC converter that regulates the battery charge/discharge, and a bi-directional DC/AC converter, which integrates the electric motor. A unidirectional DC/DC converter is used for the auxiliary electronic loads.

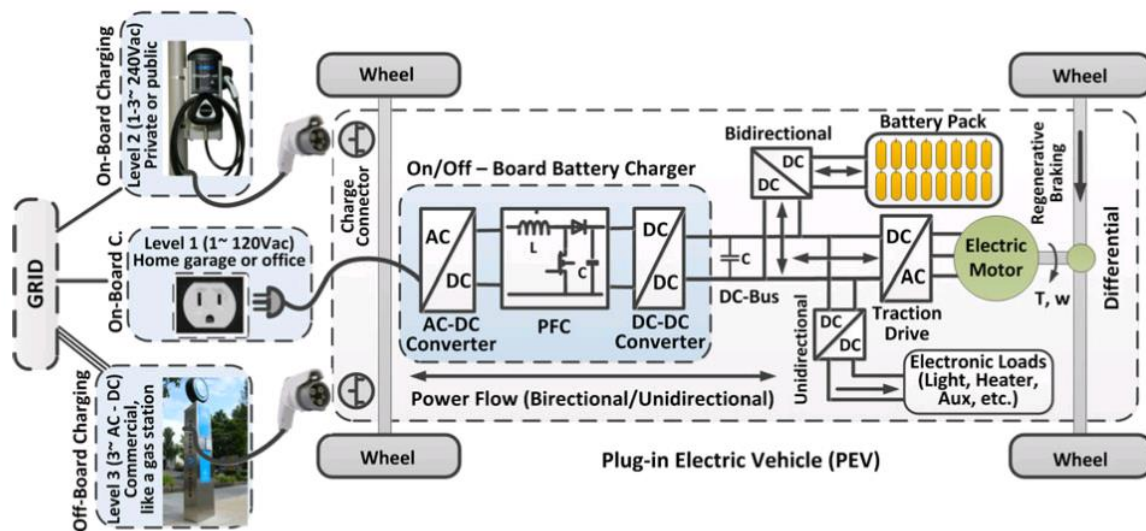


Figure 28: EV charging possible configurations [40]

As described above, EV chargers contain a significant amount of power electronics elements, which are responsible for converting the AC waveform into DC for the batteries. The most common charger topologies use semiconductor based single (4-pulse) or three-phase (6-pulse) bridge rectifiers. Some other topologies are Pulse Width Modulated (PWM) or Square Wave techniques. The DC power thus produced can be electrochemically converted in the EV battery for energy storage. The high non-linearity of these components, due mostly to semiconductor switching during the charger operation, produces current harmonics that can severely degrade the PQ aspects of the network [16]. Figure 29 illustrates the distorted waveform on the AC side (AC distribution network) caused by the AC/DC conversion process in a rectifier circuit during EV charging.

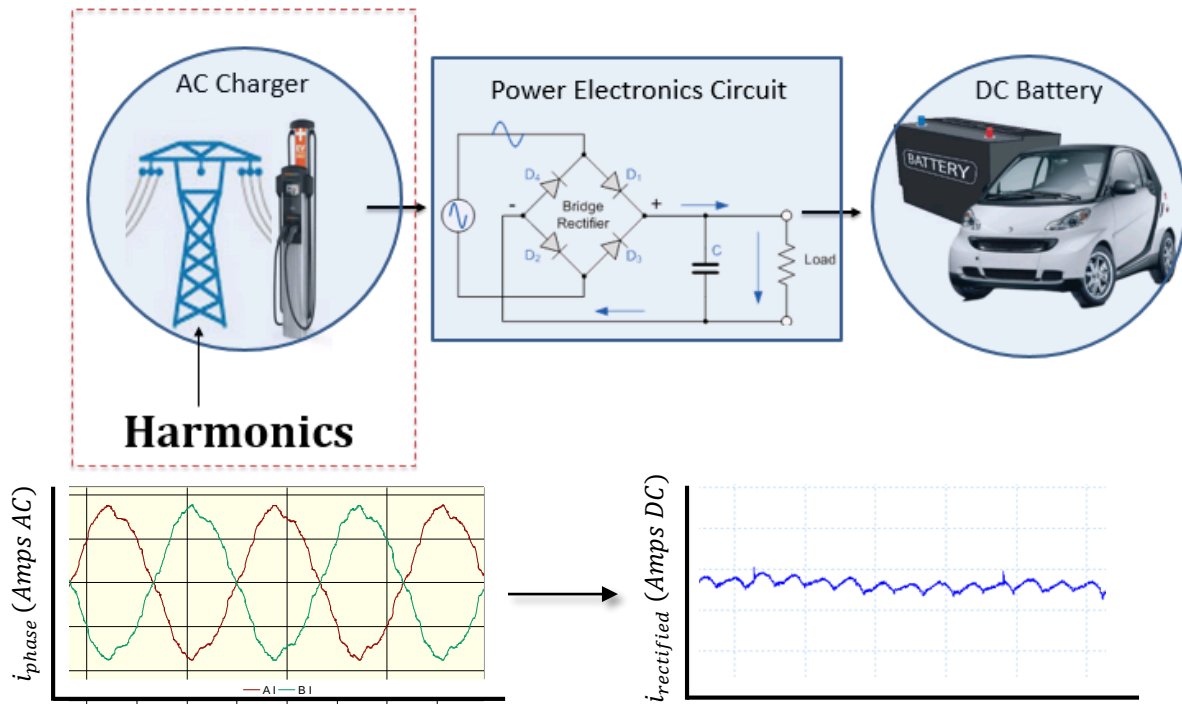


Figure 29: AC to DC conversion for EV Charging

3.3.2.1. EV charger Topologies

The charger topology, i.e., its circuit components and design, defines the power quality events produced that can affect the supply grid. Most chargers' topologies are based on rectifier circuits, mostly because of their low cost and simple design. As a drawback, these types of circuits cause low-order and high-amplitude harmonics in the current and voltage waveforms. Topologies based on controlled power switches also cause PQ degradations such as voltage drops, due to switch commutations, higher current consumption, harmonics with higher absolute values, and a lower power factor [16].

The most common EV Charger topologies, as suggested by manufacturer's literature, are:

1. Single-Phase Bridge Rectifier

This is the most commonly used topology for battery charging. To provide a constant path for the inductor current, two of the rectifier diodes must conduct at a given time. In the circuit schematics of Figure 30, diodes D_1 and D_3 conduct when the AC source line voltage $v_g(t)$ is positive and D_2 and D_4 conduct when it is negative [41].

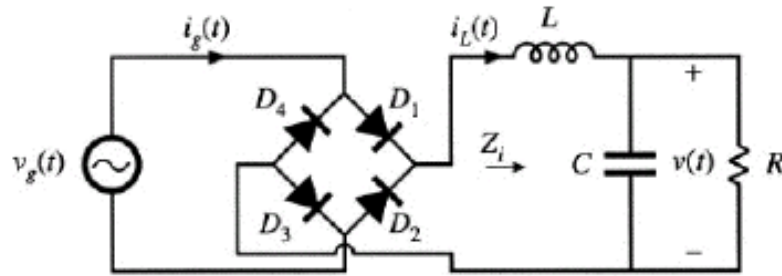


Figure 30: Basic structure of single-phase full wave rectifier with a DC-side L-C filter [41]

Therefore, in continuous conduction mode (CCM), the AC line current drawn is a square-wave that is positive ($i_g = i_L$) when the source voltage is positive and negative ($i_g = -i_L$) when the source voltage is negative. In Discontinuous Conduction Mode (DCM), that is, the inductor current is zero at least once during the switching period (when all diodes are reverse biased), the diodes conduct for less than one-half of the AC line period. The typical current waveforms drawn in CCM and DCM operation are shown in shown in Figure 31 [41].

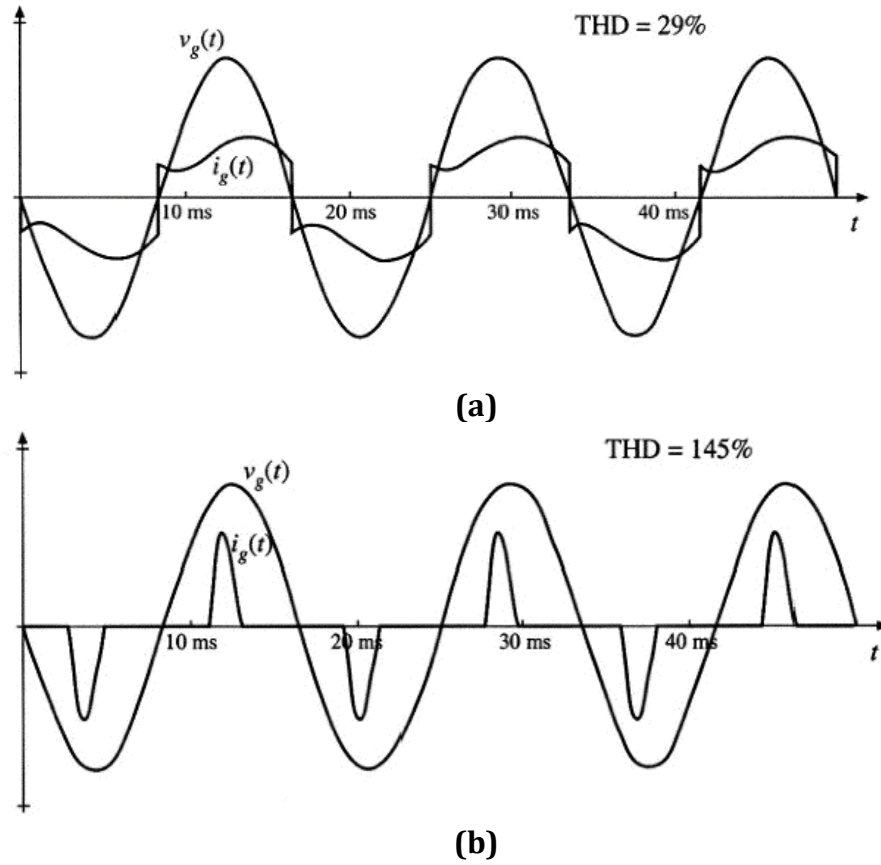


Figure 31: Typical line voltage and current drawn by Single-phase bridge rectifier in (a) CCM (b) DCM [41]

In this topology, an L-C filter is necessary to filter the conducted electromagnetic interference (EMI) generated by the converter, the L-C filter also smooths the DC output. However, the presence of a filter degrades the AC line current harmonics, since addition of reactive elements make the rectifier no longer behave like a pure resistive load to the AC input, producing high levels of odd-harmonics (1st, 3rd, 5th, 7th, 9th, 11th and so on) order distortion [41].

2. Three-Phase Bridge Rectifier

This topology operates akin to the Single-phase configuration, allowing both CCM and DCM modes. This configuration produces odd non-triplen harmonics in the line AC current (1st, 5th, 7th, 11th, and 13th). In this configuration, no more than 2 diodes can conduct simultaneously, thus, the line current must equal zero during part of the rectifier operation [41].

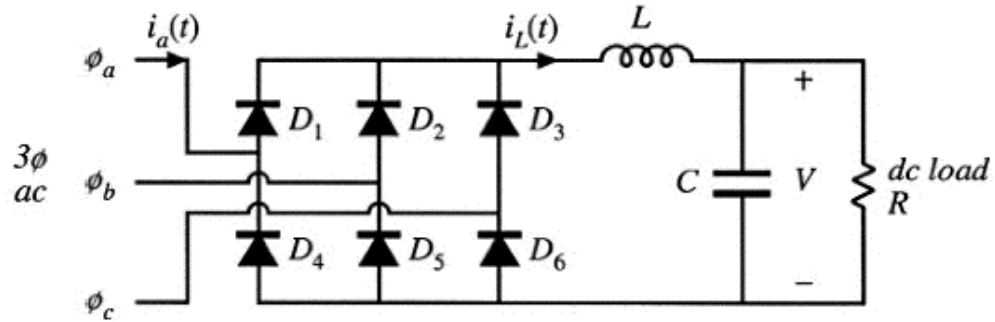
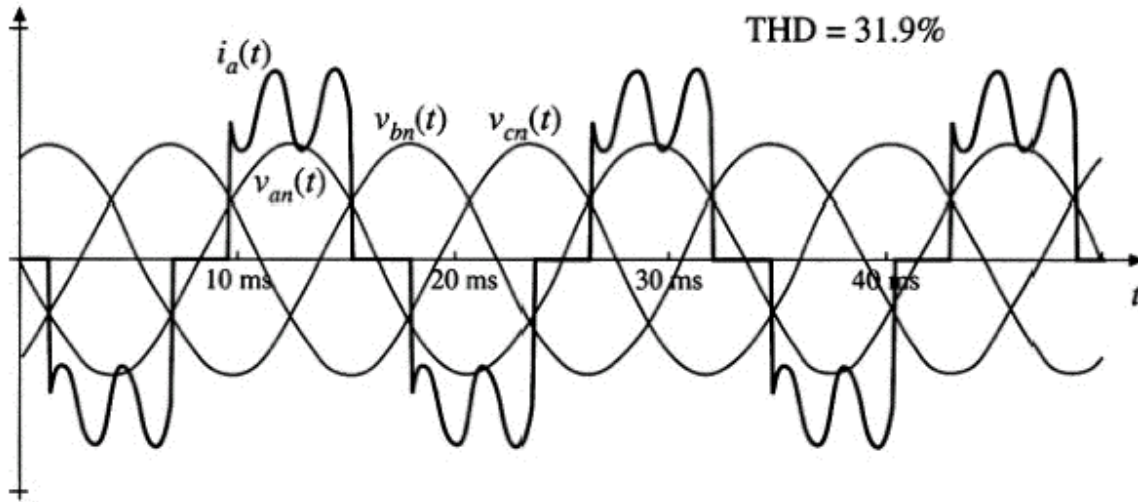


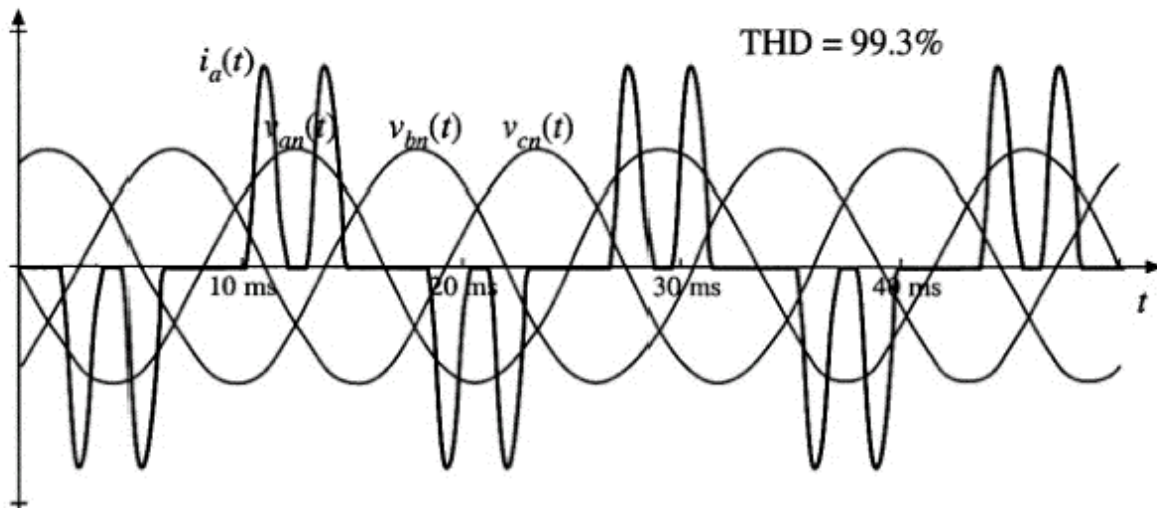
Figure 32: Basic structure of three-phase full wave rectifier with a DC-side L-C filter [41]

In CCM operation, the inductance L must either be very large, or the filter components L and C must be zero. Each line current is zero during 60 degrees out of each line half-cycle. This produces a square wave in each input AC line current, similarly to the single-phase

case. The absence of triplen harmonics in this topology improves the overall THD and power factor. In DCM, the AC line current drawn become narrow pulses occurring with line voltage peaks. In phase a, for instance, the line current $i_a(t)$ peaks twice in the positive and negative cycles, at the positive and negative peaks of $v_{ab}(t)$ and $v_{ac}(t)$ [41].



(a)



(b)

**Figure 33: Typical line voltage and current drawn by three-phase bridge rectifier in
(a) CCM (b) DCM [41]**

3. Pulse Width Modulated (PWM) Charger

This converter uses active PWM techniques with high switching frequencies (typically 10 - 50 kHz) which are much greater than the AC line frequency. A control network varies the duty cycle of a PWM DC-DC converter as necessary to cause the converter's input current to be proportional to the applied input voltage [41]. This topology behaves as ideally as possible, producing low THD and harmonic distortion. It is also possible to produce harmonic currents at specified phase angles that would allow for harmonic cancellation [42]. An example of the voltage and current waveforms drawn on the AC side of a voltage source PMW rectifier are given in Figure 35.

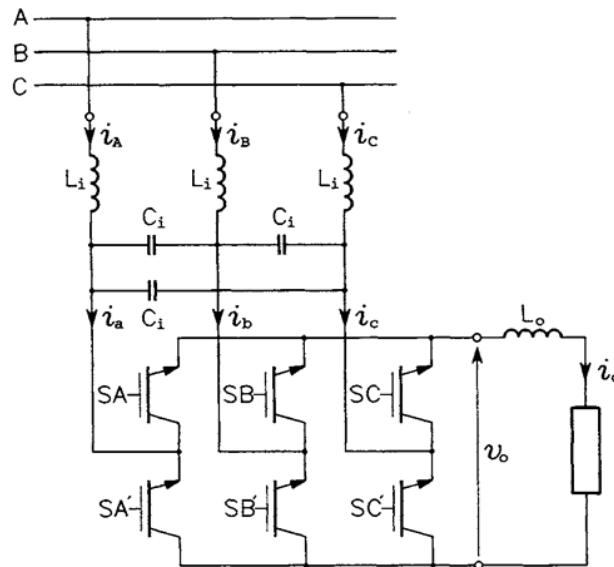


Figure 34: Ideal PWM rectifier [43]

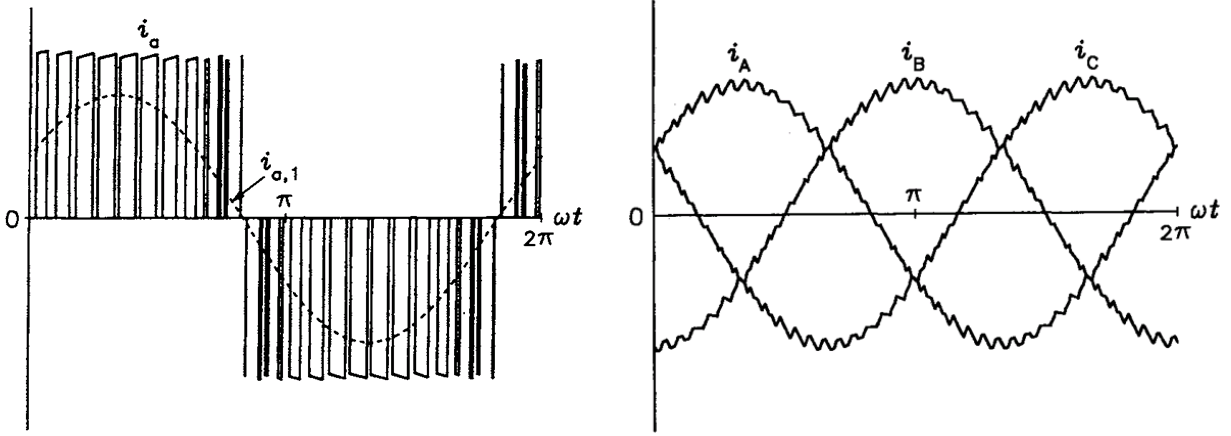


Figure 35: Typical voltage input and current drawn by PMW rectifier [43]

3.3.2.2. Power quality aspects of EV charging

The newer commercially available EVs are equipped with sophisticated charger topologies, which generate very low current harmonics. From 1994 to 1995, the EV commercial chargers THD_i improved from an average 45.17% to 6.12%. Thus, the increase in THD_v due to modern EV charging has been found rather negligible, not representing a major concern for the electric grid operation, even though existing standards don't give room to excessive THD_v on the transformer's secondary circuit. Yet, chargers without any form of active power correction will most definitely be unacceptable in the market [44].

In addition, one must consider the combined effects of charging multiple EVs simultaneously, which might completely cancel, accentuate, or attenuate certain harmonic order magnitudes. For EV charging loads, the phase angles of the various harmonic orders produced vary randomly. It has been observed that harmonic phase angles produced are related to the charger topology and the battery terminal voltage, as it is the case for the single-phase and three-phase bridge rectifier topologies [42]. Thus, in EV charging, phase

angles of the harmonic inputs are random and also vary with operation, as the battery voltages constantly increase during charging, giving room for harmonic cancellation.

Although many efforts in harmonics reduction have been made so far, recent literature identified THD in the current and voltage waveform values above the limits in IEEE Std. 519 for worst-case scenario simulations (high EV and renewable energy resources penetration during peak loads) when no harmonic filter is used downstream the inverter connection point [9]. Charging power rates and scheduling can also affect PQ in a smart-grid. Higher charging powers implied in an increased PQ deterioration, and therefore additional power losses [18]. DC Fast charging (50 kW) can also potentially exceeded the regulated harmonic voltage and current in a DC low voltage Microgrid [12].

In addition to the harmonic distortion phenomena, several other PQ issues that have been pointed out in the recent literature that need to be addressed when charging EVs. The local bus voltage profile is affected by charging a large number of EVs, unless the system has a large capacity reserve, where a possible overload can cause unacceptably low bus voltage values (below 0.98 p.u.) at high EV penetration and especially in high-impedance networks [6].

In addition to the voltage drop caused by the sudden active power consumption by EV loads (especially in buses placed within the vicinity of the EVs with any type of reactive compensation), uncontrolled EV loads can also negatively influence the network designed Power Factor [9].

Phase unbalance is another issue. Due to the use a single-phase charging to charge a number of EVs in the same network, three-phase networks may show unbalanced phase

voltage and current magnitudes [5]. High currents in the neutral conductor can result from an association of harmonics and phase unbalance [11].

Lastly, additional stress and losses on network components, mostly in the network transformers, may also result from high harmonics in the current and voltage waveforms [8]. Derating the transformer may be an option to overcome these effects if no filters are used downstream from the chargers. Hence, the main issue regarding the impacts on the transformer is the overloading, but one should also consider reduction of its lifespan [35].

4. Approach

4.1. Task 1: Analyze BESS dynamics for different operation modes

This task firstly addresses the analysis and verification of data from the experimental platform in order to establish its quality and suitability. Ideally, the data will include power profiles for rooftop solar, EV charging for each EVSE, and battery storage performance in consistent 15-minute intervals. It ultimately analyzes the dynamics of the different battery operation modes tested on site during the project timeframe, as well as the renewable contribution/penetration for each mode.

4.2. Task 2: Develop and verify the Car Shade real-time power flow model

This task addresses (1) the development of a steady-state model to simulate the effect of adding rooftop solar panels, a battery energy storage system, and electric vehicle charging on the secondary circuit of a microgrid, and (2) the verification of the model. The combination of Melrok database high-resolution data and SCE data (from Task 1) provides

a rich resource for model verification. The verification strategy is to compare actual metered data against the model state-load estimator results, the modeling platform used in this study enables it through the “Real-Time” simulation feature.

4.3. Task 3: Analyze model outputs

This task aims to evaluate the model outputs, comparing different BESS dispatch modes, looking for preferred dispatch strategies that will improve the overall system power quality during operation.

4.4. Task 4: Characterize power quality aspects of EV charging

This task involves the acquisition of high-resolution power quality data on the experimental platform through site monitoring during a 2-week period, using a *Dranetz*® PowerXplorer PX5 meter. The system’s power quality aspects are studied, with focus on the harmonic distortion caused by the EV chargers. The IEEE 519-1992, currently the most industry-applied power quality standard, is used as a reference. The power flow model is the base for the development of a harmonic power flow simulation. The model is verified against the survey data and harmonic cancellation is assessed.

4.5. Task 5: Optimal economical BESS and PV sizing for Car Shade + AIRB nanogrid

Lastly, this task proposes an expansion of the Car Shade nanogrid by adding a classroom/laboratory building load, the Anteater Research and Instruction Building (AIRB), and ultimately, optimally sizing the old and new system components, BESS and PV, to minimize system total cost based on actual technology prices.

5. Results and Discussion

5.1. Task 1: Analyze BESS different operation modes dynamics

5.1.1. Analyze metered data from SCE

Before taken as appropriate, the Car Shade data acquired from SCE were analyzed for consistency and accuracy. These data are comprised by 5-minute resolution voltage, current, active power, reactive power, and power factor measurements obtained by Smart Meters installed throughout the experimental platform. The locations where meters are installed in the system as well as the adopted sign convention (generation/load and also charge/discharge) for power flows are shown in Figure 15.

5.1.1.1. DC measurements

A typical day of operation (August 11, 2014) was chosen to verify the DC voltage and current for both the Battery Energy Storage System (BESS) and the solar PV system (Figure 36).

The BESS voltage increases during the charging window (6 AM to 12 PM) and decreases when the battery is set to discharge (at 12 PM). The voltage drops at rates dictated by the discharging current. The BESS DC voltage ranged between 449-530 VDC during this day. The DC voltage and current profiles at the PV Array vary with weather conditions. The weather history for August 11, 2014 documented cloudy conditions for most parts of the day, justifying the fluctuations in the PV output current. The maximum measured current output was 107 A. The DC Voltage varies according to the Maximum Power Point Tracking (MPPT) controls in the inverter to maximize the PV array power output, and ranged from 418 - 458 VDC.

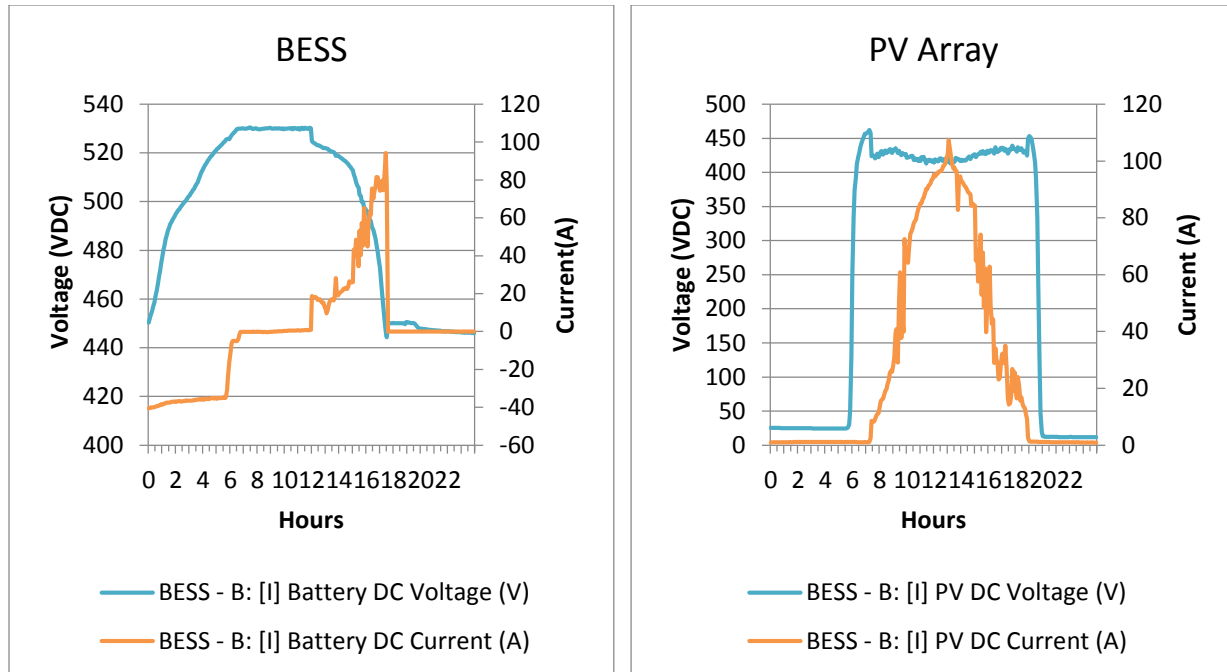


Figure 36: BESS (left) and PV (right) DC current and voltage profile. August 11, 2014

From the observation above, both the BESS and PV system measurements as taken are deemed appropriate for use in verifying the model.

5.1.1.2. AC measurements

Here, the same day of operation (August 11, 2014) was chosen to verify that the 3-phase AC measurements were accurate. For this, three measuring points in Figure 15 were observed, and the line voltages and line current profiles are plot in Figure 39.

All AC voltages and currents can be observed to be within an acceptable range, with dips during high EVSE demand periods. The phase current curves at EVSE and EVCS measurement points show a reasonable unbalance caused by the 2-phase connections of the EVSEs. Phase unbalance depends upon which chargers are being used at a given time and to which two phases they are connected.

The EVSE currents are directly proportional to power consumption, peaking in the morning and afternoon, depending on EV charging behavior. The inverter output current gradually increases during the day with higher PV output and peaks when the BESS is set to discharge. EVCS currents peak in the afternoon when the system is exporting power. It is important to notice that measured AC currents are always positive. Thus it is determined that the AC currents and line voltages as measured are sufficient for use in verifying the model.

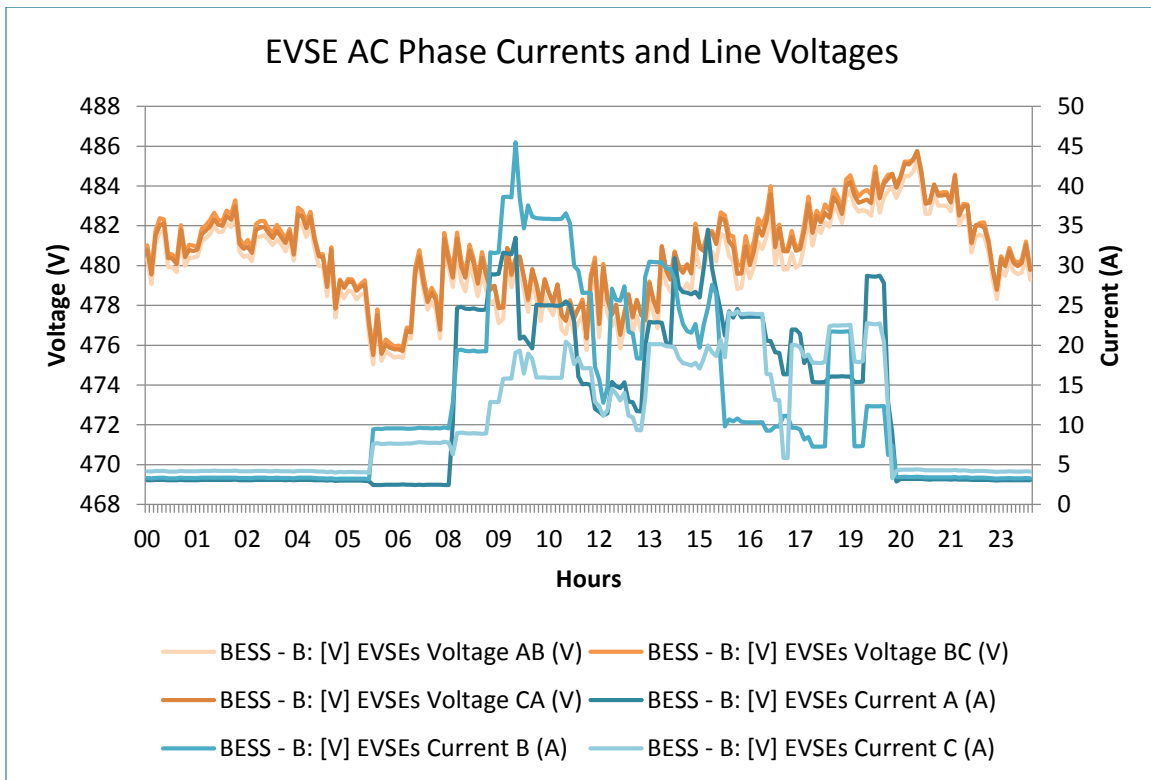


Figure 37: EVSE AC Phase currents and Line Voltages

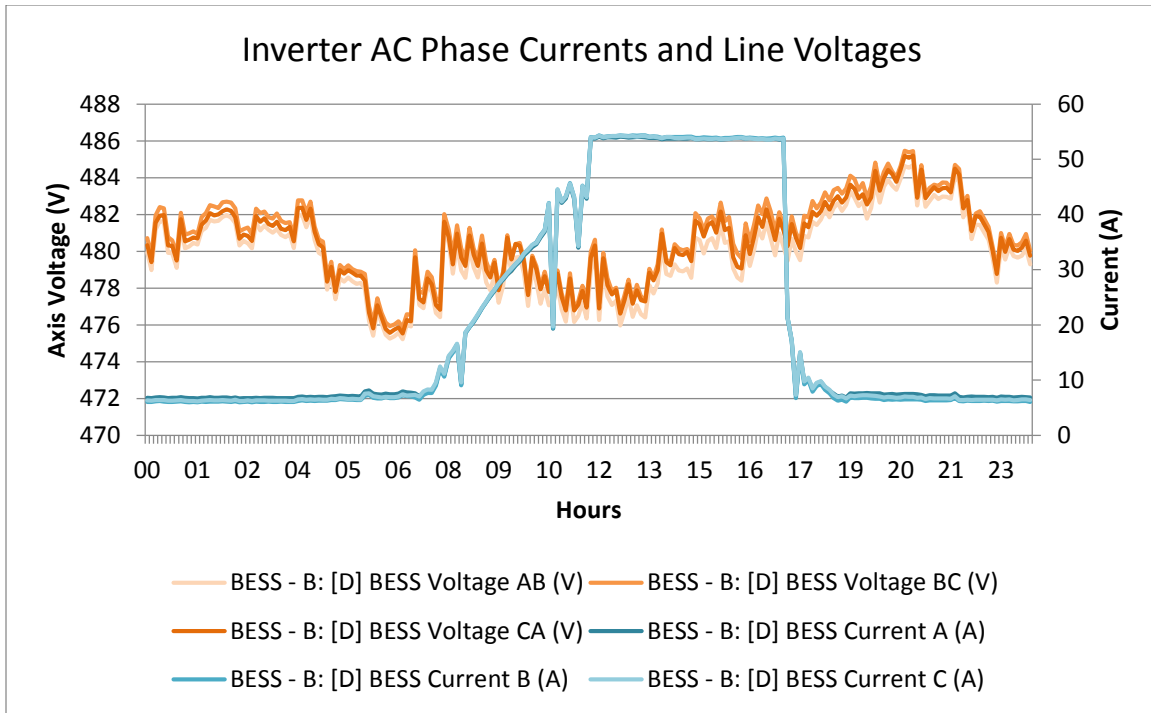


Figure 38: Inverter AC Phase Currents and Line Voltages

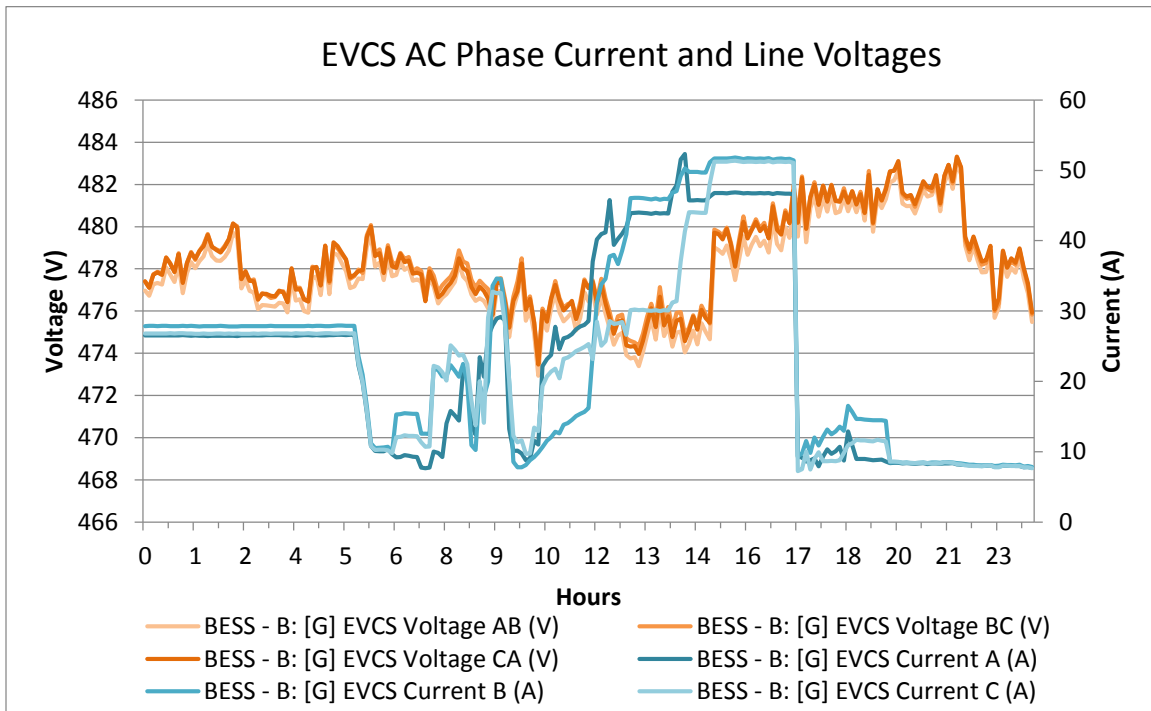


Figure 39: EVCS AC Phase Currents and Line Voltages

5.1.1.3. Non-Uniform timestamp intervals

Smart Meter technology enables high resolution data acquisition, however, if the communications system responsible for wirelessly transmitting Smart Meter data to the final storage database presents any issues that might result in data loss during the process (recording time delays, lack of communication, for instance) it will produce non-uniform interval data. That was the case observed for a few meters at the Car Shade. Comparable issues can be observed in many other practical systems with similar communication topologies. A sample of this data is presented in Table 5, where the timestamps are unevenly spaced 5 or 10 minutes, in a random fashion.

Table 5: Non Uniform Timestamps for Car Shade data

TIMESTAMP	YEAR	MONTH	DAY	READING TYPE	VALUE
1/13/2015 0:00	2015	JAN	13	B: [D] BESS Total Power (W)	20610.5449
1/13/2015 0:10	2015	JAN	13	B: [D] BESS Total Power (W)	20355.0625
1/13/2015 0:15	2015	JAN	13	B: [D] BESS Total Power (W)	20359.0644
1/13/2015 0:20	2015	JAN	13	B: [D] BESS Total Power (W)	20629.9804
1/13/2015 0:30	2015	JAN	13	B: [D] BESS Total Power (W)	20543.5273
1/13/2015 0:35	2015	JAN	13	B: [D] BESS Total Power (W)	20365.625
1/13/2015 0:40	2015	JAN	13	B: [D] BESS Total Power (W)	20276.1171
1/13/2015 0:50	2015	JAN	13	B: [D] BESS Total Power (W)	20539.541
1/13/2015 0:55	2015	JAN	13	B: [D] BESS Total Power (W)	20531.9687
1/13/2015 1:00	2015	JAN	13	B: [D] BESS Total Power (W)	20350.7109
1/13/2015 1:10	2015	JAN	13	B: [D] BESS Total Power (W)	20445.373
1/13/2015 1:15	2015	JAN	13	B: [D] BESS Total Power (W)	20628.3398
1/13/2015 1:25	2015	JAN	13	B: [D] BESS Total Power (W)	20449.6425
1/13/2015 1:30	2015	JAN	13	B: [D] BESS Total Power (W)	20451.8828
1/13/2015 1:35	2015	JAN	13	B: [D] BESS Total Power (W)	20536.6582
1/13/2015 1:45	2015	JAN	13	B: [D] BESS Total Power (W)	20531.7167

Considering the simulation purposes of this study, non-uniform timestamps are a potential issue, since the missing timestamps could trigger errors in the algorithms used

for power flow calculations. For this, a script developed in MATLAB was developed to interpolate all data in 15-minute intervals, using the linear interpolation method (table lookup) of the one-dimensional “interp1” MATLAB function. Figure 40 shows how the interpolated data (uniform 15 minute resolution) matches the raw data (non-uniform time resolution). It is expected that this interpolation process would produce a small error in the results that are produced in the model, however, it is still considered suitable and accurate enough for the purposes of this study.

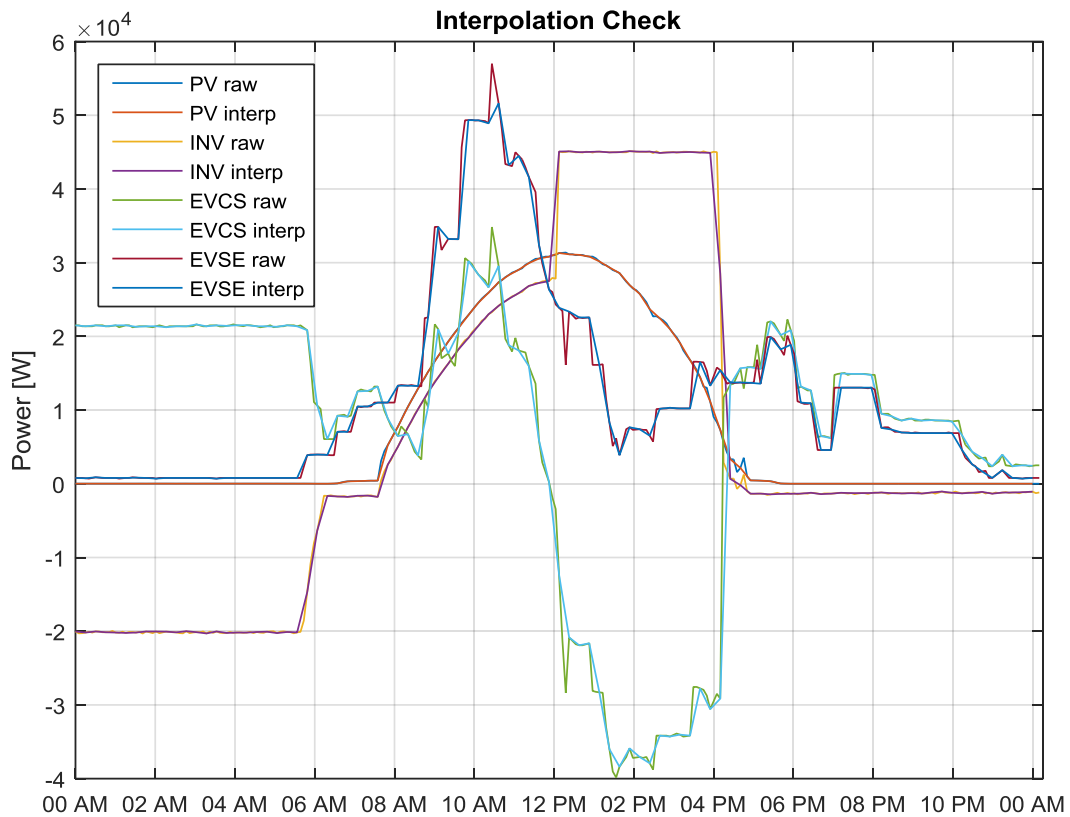


Figure 40: Raw and interpolated 15-minute data

5.1.2. BESS operation dynamics: different dispatch modes

Here, each BESS operation mode is characterized in terms of operation goals, controls, and dynamics. One important outcome of this analysis is the typical EV charging profile observed at the Car shade (EVSE curve), which closely matches student and faculty arrival/departures times for classes. The peak EVSE load occurs around 10:30 AM, when most students have already plugged-in their EVs. A second smaller peak occurs in the evening, likely due to arrivals for night classes. The solar generation peaks from 12PM to 2PM, typical of any PV system.

5.1.2.1. Peak Load Shifting (PLS)

In PLS mode, the battery energy storage is used to shift load from a congested on-peak period to an excess-generation off-peak period. Known substantial benefits to the electric grid are inherent in this strategy, including a reduction in the use of added capacity of peaking plants, which produce expensive energy with higher GHG emissions, increase the cost of energy, and deteriorate local air quality.

Thus, in PLS mode, beginning at midnight the battery is set to charge overnight at a constant 20 kW using grid power until it is fully charged. At noon, the battery is set to discharge enough power to maintain a constant 45 kW output at the inverter's AC side (point 3 in Figure 15) until it is fully discharged or reaches the end of the discharge period, (at midnight), when the overnight charging period begins. Thus, it takes into account any/all PV generation and discharges the remainder until a 10% SOC is reached. This operation is set on a time-schedule basis and is not affected by the EV charging loads' dynamic behavior. However, it is affected by the PV generation, which extends the battery

discharge time, since it reduces the amount of battery discharge power needed to reach the constant 45 kW output.

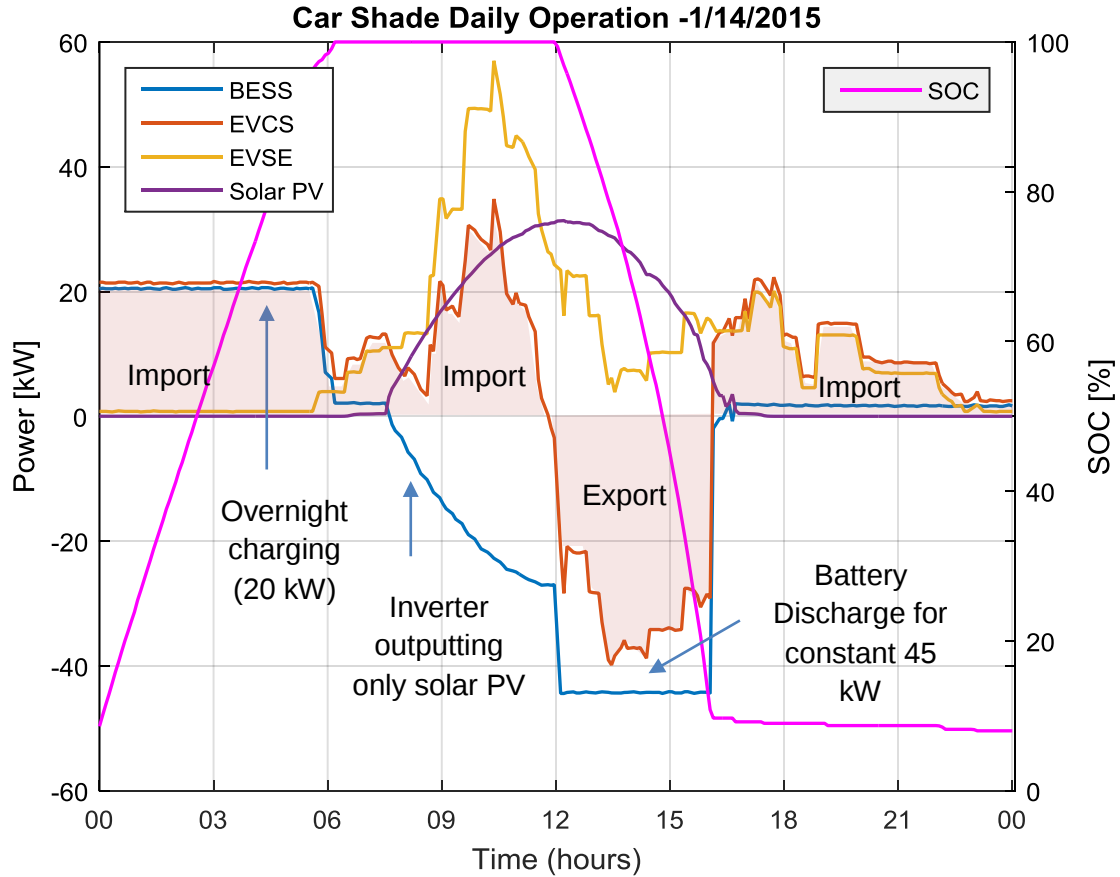


Figure 41: BESS PLS operation (Jan. 14, 2015)

The net power consumed or generated by the Car-Shade/UCI Microgrid interface is shown by the EVCS curve in Figure 41. In the early morning, when solar irradiation is low, the system imports grid power, but as soon as the BESS starts discharging, the system starts to export excess PV generation. In the late evening, when the PV generation is reduced, the system starts importing grid power again to meet EV loads.

This mode effectively shifts most of the afternoon EV charging demand to nighttime. Ideally, the morning EV loads would also be shifted, this goal, however, was not included in the project modes tested.

Excess PV generation export in the afternoon is beneficial to the UCI Microgrid, since it can be immediately used to power neighbouring loads, such as the AIRB building. However, it is also known that excess power export may be undesirable; Difficulties in absorbing excess power can exceed thresholds set in interconnection agreements, for example, or simply cause overvoltage issues.

Table 6 summarizes the PLS algorithm, and Figure 42 shows the system operation over a week using the PLS algorithm. During weekdays, the system follows the same pattern as described in Figure 41, importing in the morning and exporting in the afternoon exports. On the weekends, the BESS does not cycle and remains fully charged. The peak system import and export are determined by the instantaneous PV generation and EVSE demand, thus, the system's peak import occurs in the morning (low PV generation and high EVSE demand) and the peak export occurs around noon (high PV generation and low EVSE demand).

Table 6: BESS PLS Control settings

BESS mode	Time	Constraints
Discharge	Mon-Fri 12:00 PM to 18:00 PM	while SOC > 10% BESS_DischPower = 45 kW – PV_Gen
Overnight Charge	Tue-Fri 12:00 AM to 06:00 AM	while SOC < 100% BESS_ChPower = 20 kW
BESS_DischPower = BESS discharge power setting BESS_ChPower = BESS charge power setting PV_Gen = PV power output		

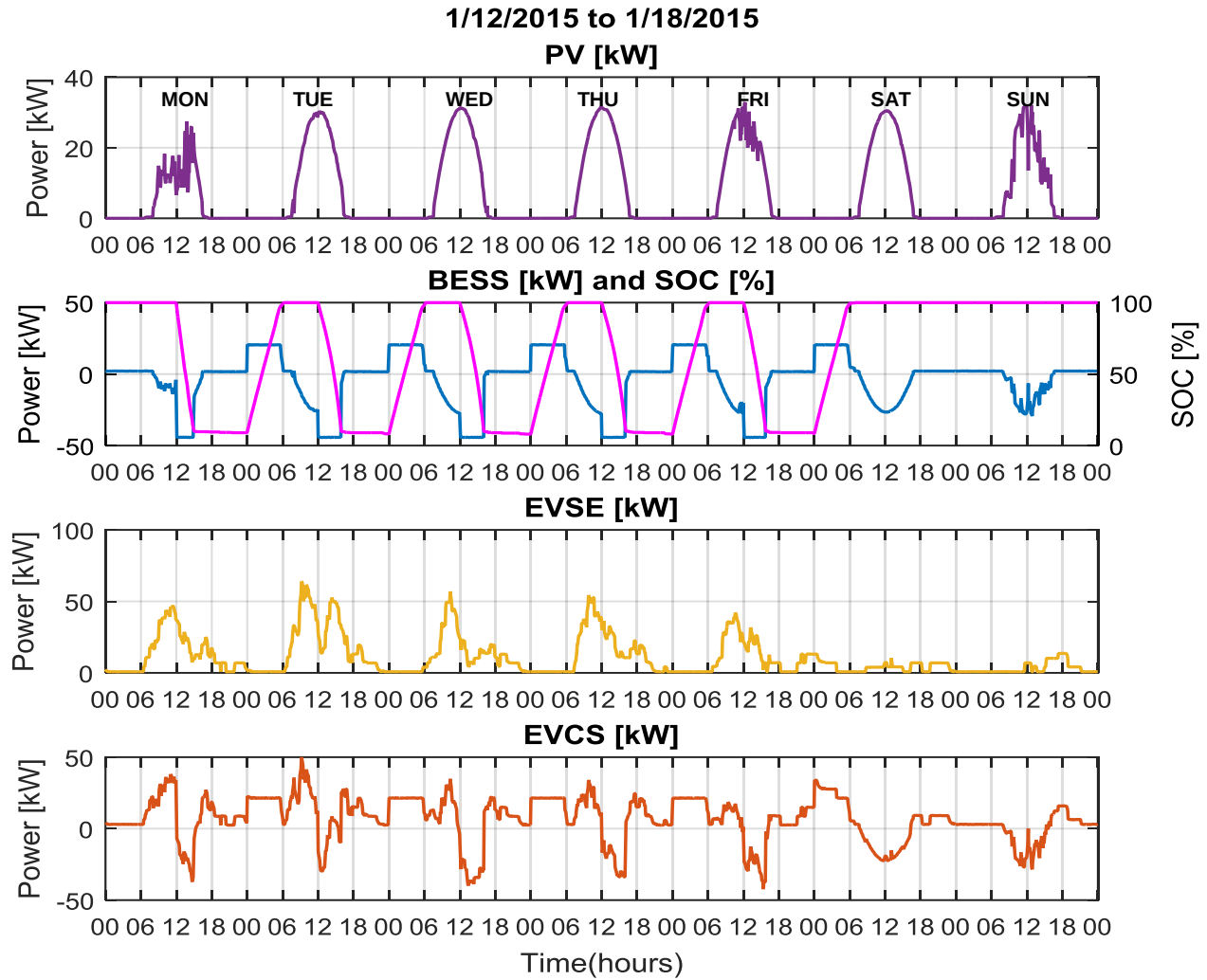


Figure 42: BESS PLS operation (Jan. 12, 2015 week)

5.1.2.2. Maximize Peak Period Impact (MPPI)

A typical concern around EV charging stations is the excessive local electric demand, which could translate into increased peak loads (depending upon the charging time) that will require a greater generation capacity and may cause stress in the distribution system. In the MPPI mode, the BESS will discharge to offset EV demand completely during the period where the UCI Microgrid is most stressed (highest load demand period). Observing

historical data on the UCI Microgrid weekday demand (Figure 43), the major demand occurs from 9:00 AM to 4:00 PM, typically peaking at around 1:00 PM.

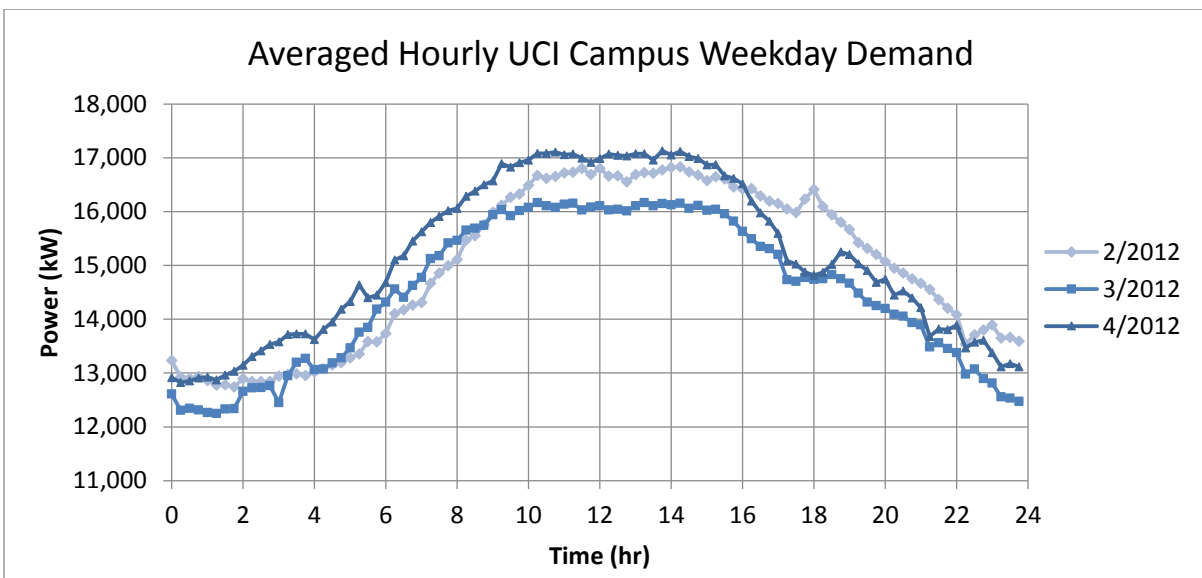


Figure 43: Averaged hourly campus weekday demand for Feb., Mar., and Apr. 2012.

In parallel, the maximum EV charging demand at the Car Shade happens around 10:00 AM (Figure 44), when the Campus load is already substantial.

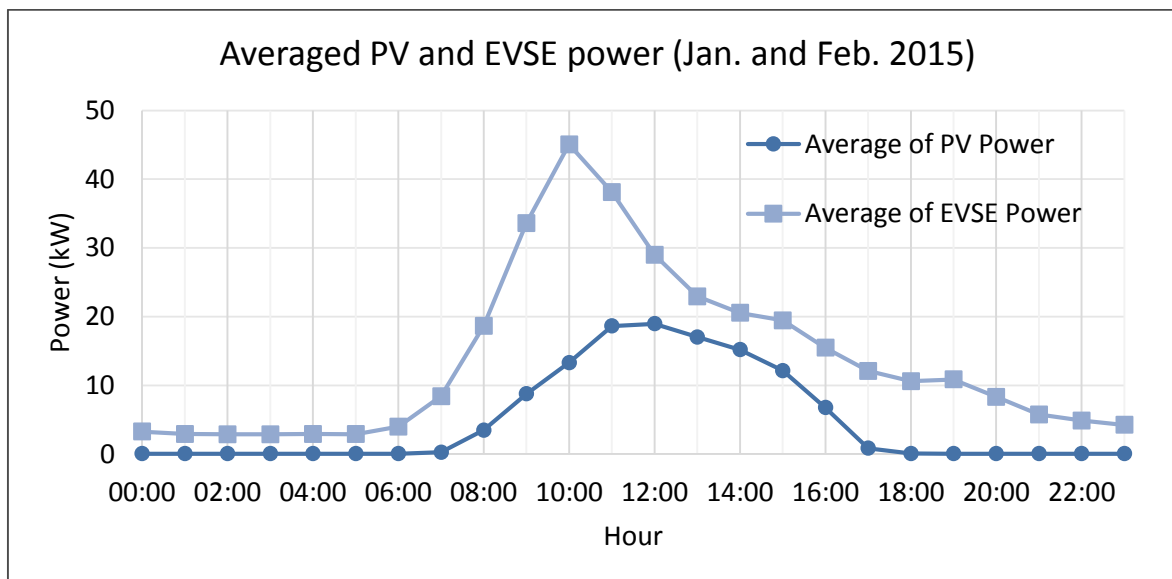


Figure 44: Average PV and EVSE power (averaged though Jan. and Feb. 2015)

Thus, in MPPI mode, from 9:00 AM to 12:00 AM, the BESS will aim to completely offset (cap to zero) the power flows in the interface of the Car Shade nanogrid/UCI Microgrid (EVCS demand/generation). Thus, it will discharge the power to meet the EVSE loads unless (1) the EVSE load is greater than 75 kW or (2) the EVSE load is greater than the available PV generation plus the available battery power. If (1) or (2) occur, the EVCS demand will be the amount of EVSE excess load.

In this mode, the BESS will also day-charge whenever PV power exceeds EVSE loads, until a 100% SOC is reached, and will charge overnight as in the PLS mode. PV will always be curtailed to prevent export.

Table 7 presents a summary of the MPPI algorithm.

Table 7: BESS MPPI control settings

BESS mode	Time	Constraints
Discharge	Daily 9:00 AM to 12:00 AM	if EVSE_Load > 75 kW BESS_DischPower = 75 kW else if EVSE_load – PV_Gen > Battery_kW BESS_DischPower = Battery_kW else BESS_DischPower = EVSE_Load
		while SOC < 100% if PV_Gen > EVSE_Load BESS_ChPower = PV_Gen – EVSE_Load if SOC > 100% PV_Gen = 0 (curtailed)
Overnight Charge	Daily 12:00 AM to 06:00 AM	while SOC < 100% BESS_ChPower = 20 kW
PV_Gen = Solar PV output Battery_kW = Maximum Battery discharge power		

The daily (Figure 45) and weekly (Figure 46) operation at MPPI mode shows the ability of limiting EVCS demand to zero kW from 9:00 AM to 4:00 PM, thus all EV charging during this window occurs with virtually no impact to the grid. This is a particularly important achievement to obtain a seamless integration of EV charging into the microgrid.

It is important to notice, however, that in the early morning and late evening, there is EVSE demand that still needs to be met by the grid, requiring an average peak power of about 40 kW (Figure 46). The “PV Capture” operation mode attempts to address this issue.

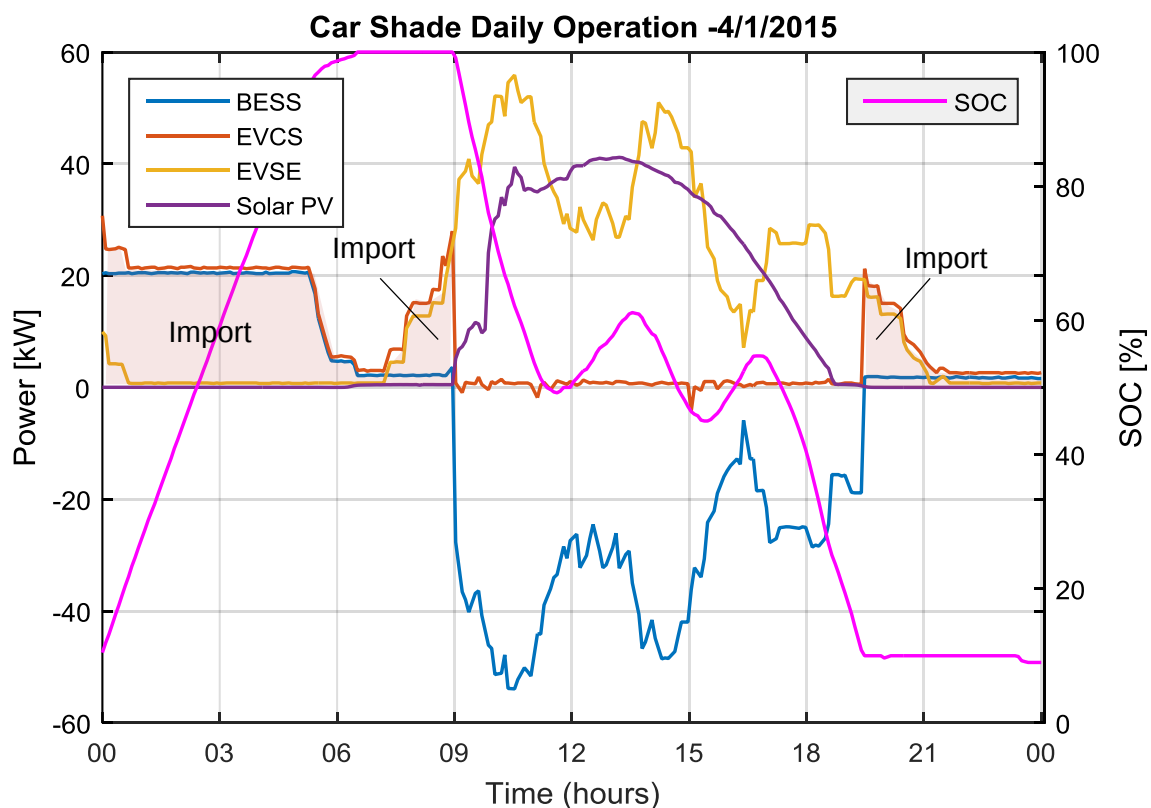


Figure 45: BESS MPPI mode (Apr. 1, 2015)

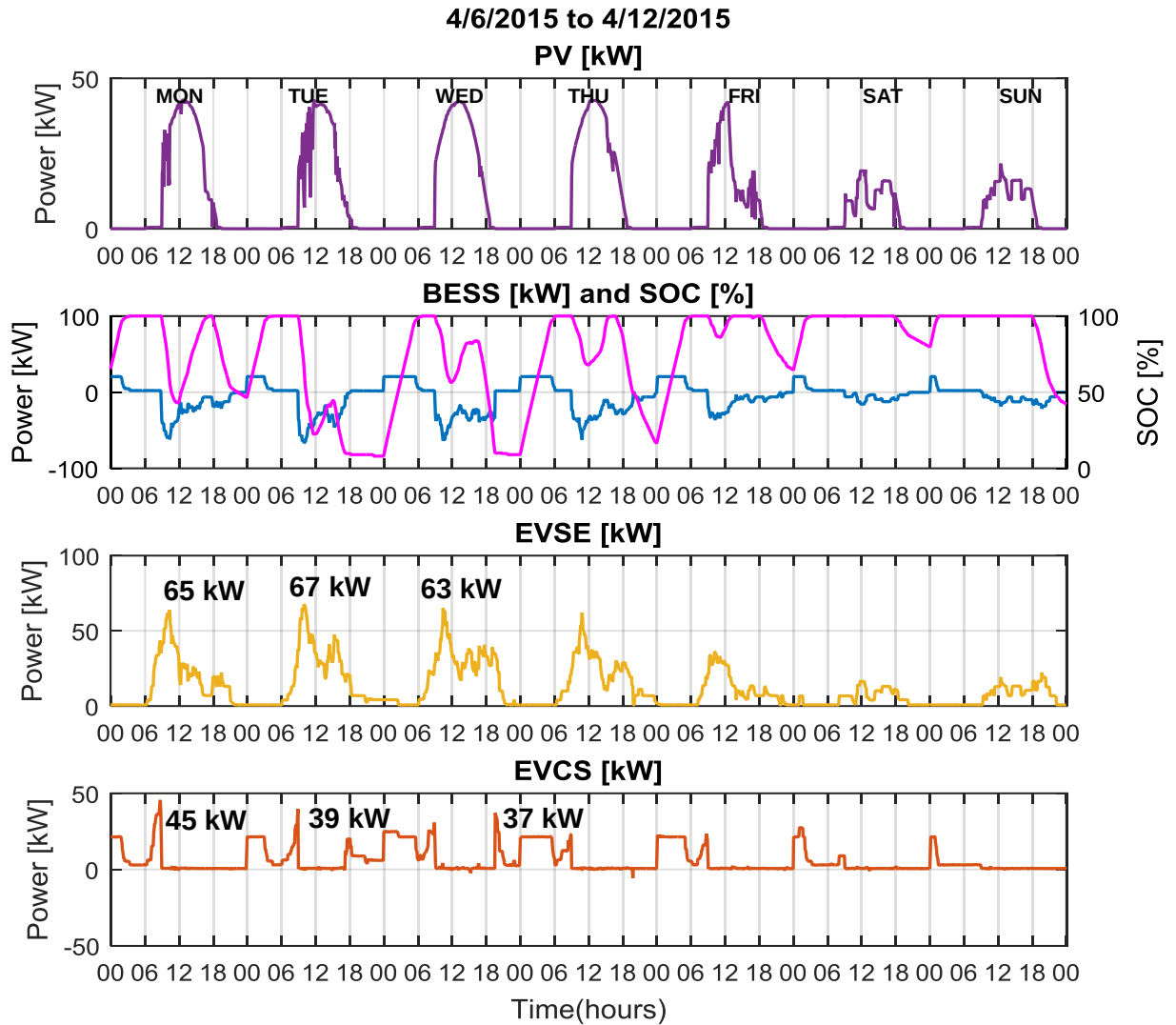


Figure 46: BESS MPPI mode (Apr 6, 2015 week)

5.1.2.3. UCI Cap Demand: 10, 15 and 20 kW (CAP 10, 15, 20)

This mode will cap the Car Shade EVCS demand imposed to the UCI Microgrid. This mode is particularly interesting because it enables the use of the BESS as a buffer to prevent demand charges in typical applications. The threshold can be set to any desired value. In this study, three thresholds were implemented and tested: 10, 15, or 20 kW. Similar to the MPPI mode, if the EVSE load exceeds 75 kW or the sum of the available PV

and battery power, the demand at the interface (EVCS) will be the amount of EVSE load excess.

The Cap Demand mode will also perform BESS day-charge whenever PV power exceeds EVSE loads, until a 100% SOC is reached, when then PV power will be curtailed. The BESS will also charge overnight as it did in previous modes. Table 8 presents a summary of the Cap Demand algorithm.

Table 8: BESS CAP demand control settings

BESS mode	Time	Constraints
Discharge	Daily 9:00 AM to 12:00 AM	if EVSE_Load > 75 kW
		BESS_DischPower = 75 kW
		else if EVSE_load - PV_Gen > Battery_kW
		BESS_DischPower = Battery_kW
Day Charge	Daily 9:00 AM to 12:00 AM	else
		BESS_DischPower = EVSE_Load - CAP_kW
		while SOC < 100%
		BESS_ChPower = PV_Gen – EVSE_Load + CAP_kW
Overnight Charge	Daily 12:00 AM to 6:00 AM	if SOC > 100%
		PV_Gen = 0 (curtailed)
		while SOC < 100%
		BESS_ChPower = 20 kW
CAP_kW = Cap threshold (kW)		

In Figure 47, the system dynamics is shown for 20, 15 and 10 kW CAP settings. The EVCS demand was successfully capped for the first two thresholds. At 10 kW, the BESS was fully depleted at around 6PM, causing the system to import more than 10 kW at the interface, as to meet the evening EVSE demand. Moreover, it is visible that when the

threshold is lowered (1) the BESS cycles more in order to buffer the system and (2) more PV power is curtailed.

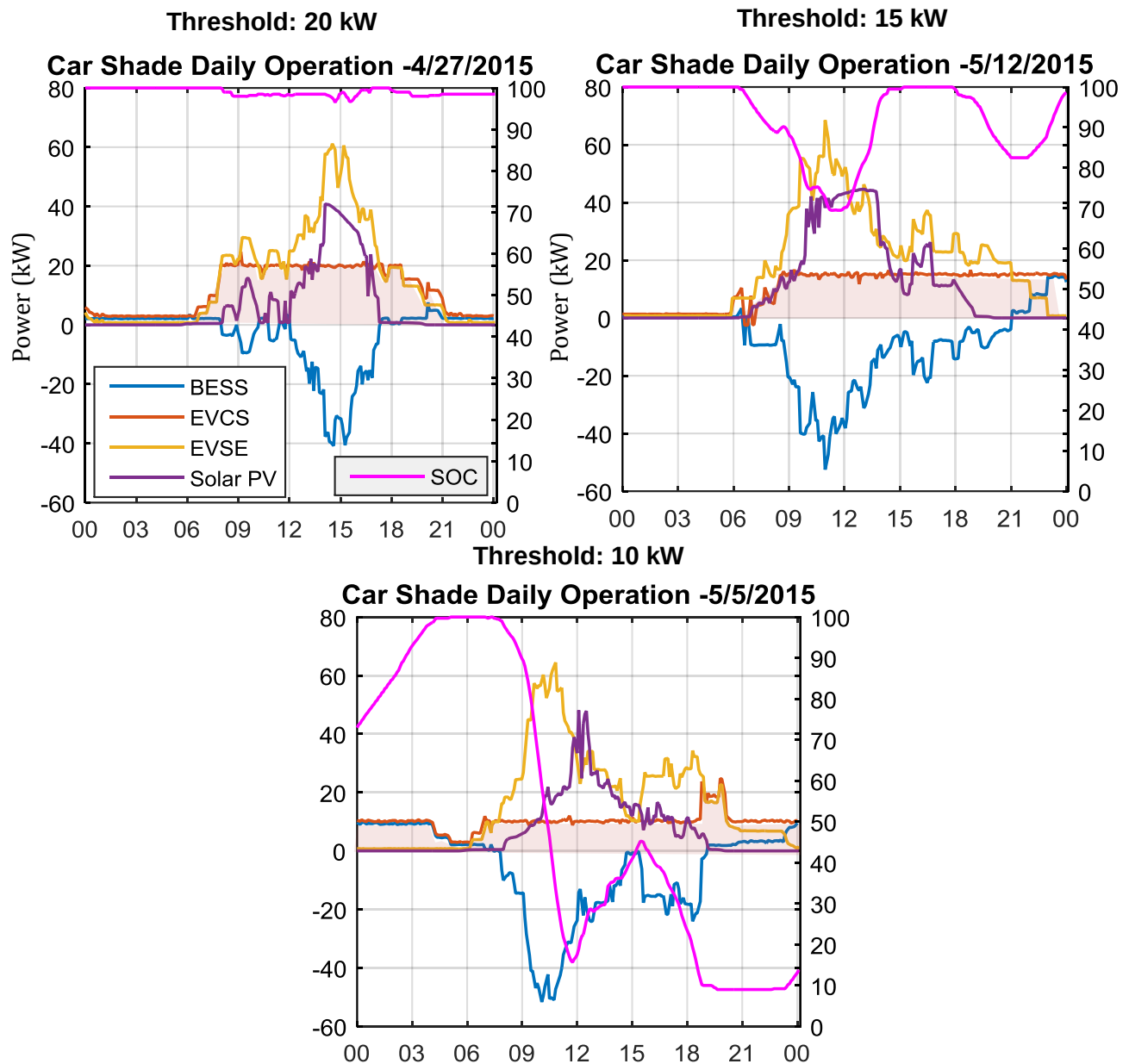


Figure 47: CAP 20, (top left) CAP 15, (top right) and CAP 10 (bottom)

Looking at the weekly profile for the 20 kW threshold (Figure 48), a significant amount of PV is curtailed during the week, and on weekends it is completely curtailed, since the EVSE demand was always far below 20 kW and could be met by grid power. In addition, the SOC always remains above 65%, and the BESS was rarely cycled. Here, all week was effectively capped to a maximum 20 kW EVCS power. Short duration spikes in the EVCS demand that exceeded 20 kW occurred due to BESS discharge response time.

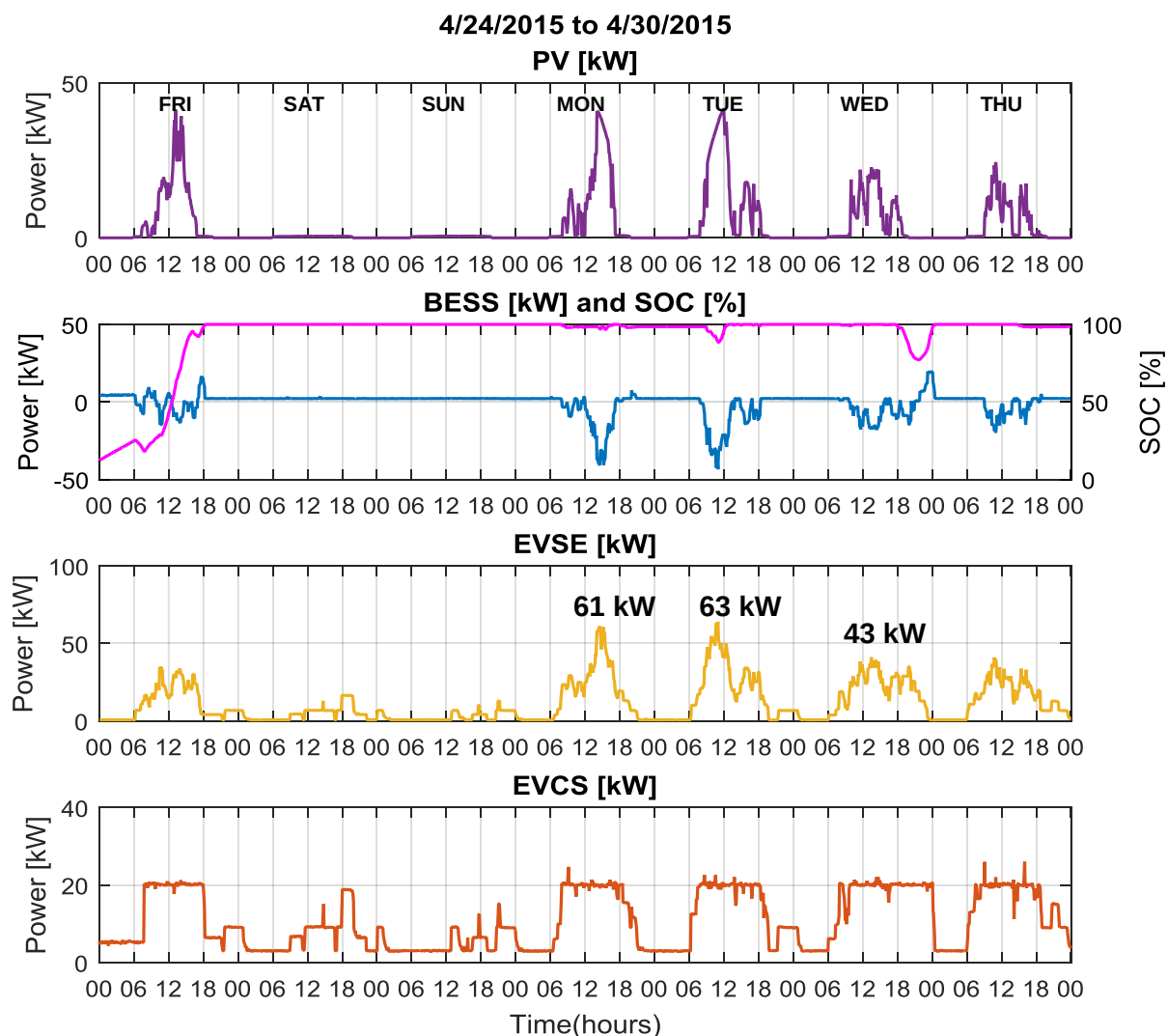


Figure 48: BES Cap 20 mode. Apr 24, 2015 week

Reducing the CAP threshold to 15 kW (Figure 49), as previously mentioned, will cause less PV curtailment and higher BESS cycling. The 15 kW threshold was not met only at one day during the week testing frame (05/26/2015), when the EVSE load exceeded the sum of available PV + Battery power + 15 kW.

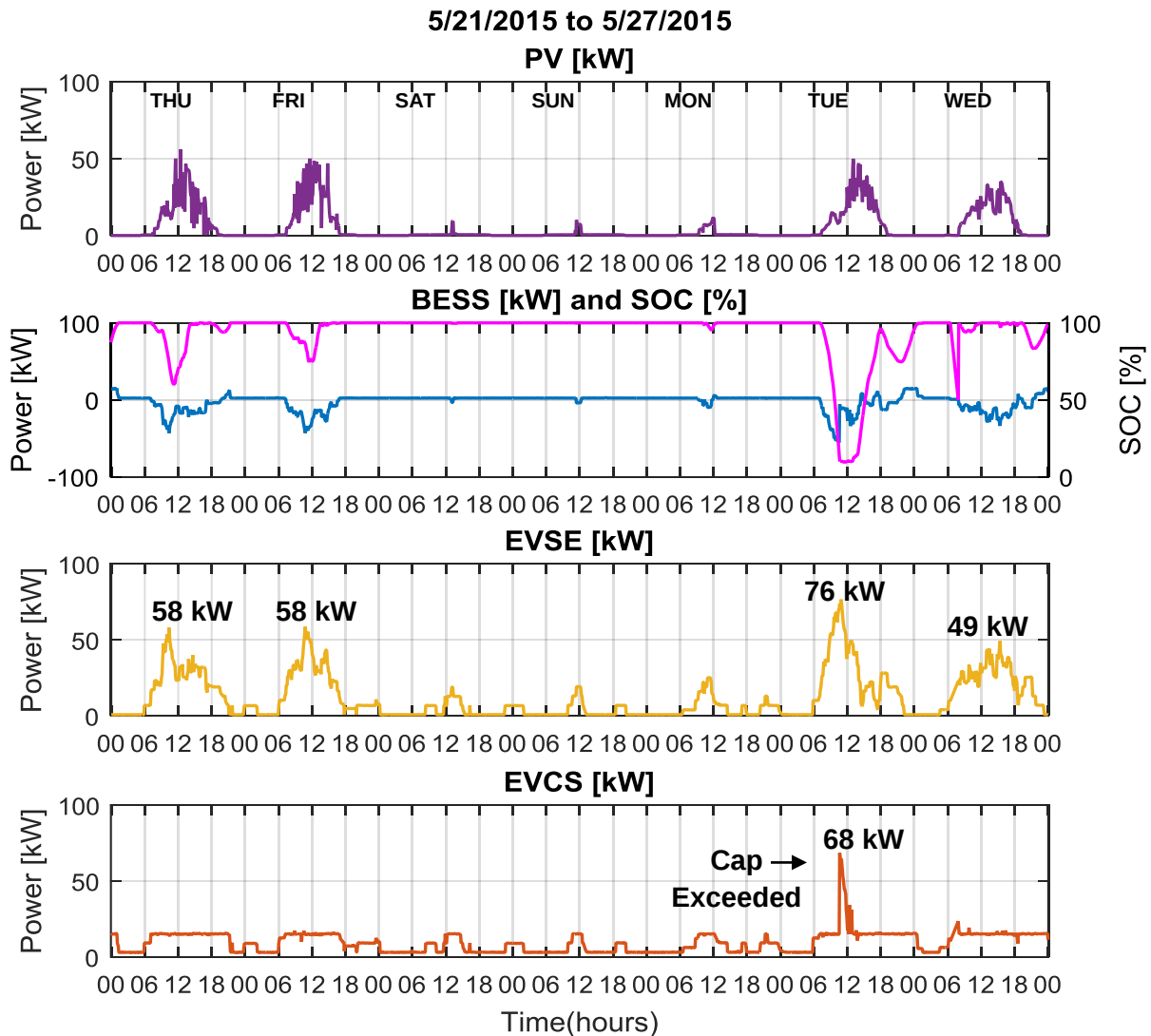


Figure 49: BES Cap 15 mode. May 21, 2015 week. OBS: Memorial Day Holiday on Monday 05/25

The same observations mentioned above can be made if the threshold is reduced further to 10 kW (Figure 50). Little PV power was curtailed, however, during almost all weekdays, the EVCS demand was not effectively capped since the EVSE load would always exceed the amount of available PV + Battery power + 10 kW. Also, at most times, the 10 kW constant overnight charging power was not enough to restore the Battery SOC for the next day's EVSE loads.

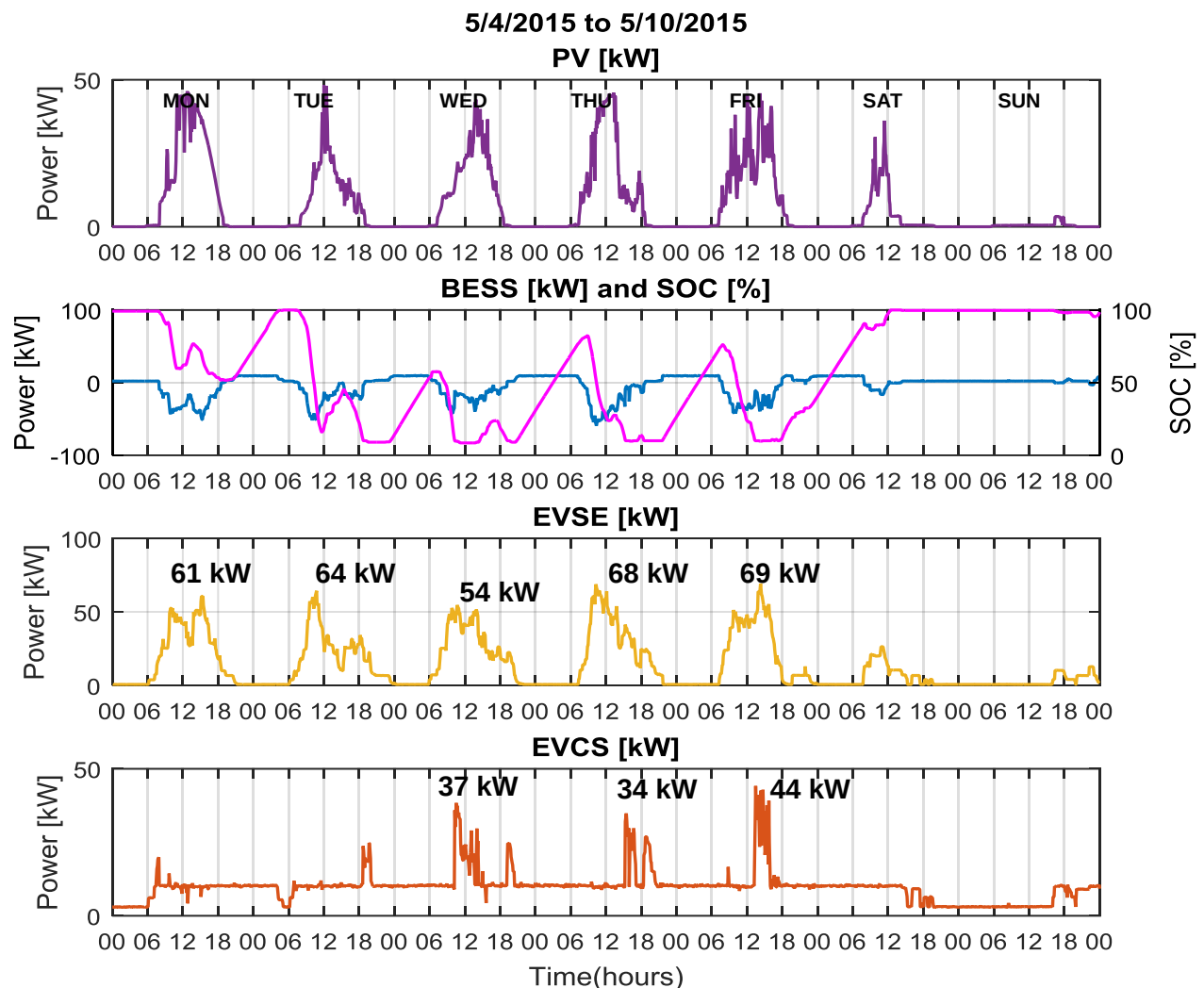


Figure 50: BES Cap 10 mode. May 4, 2015 week.

Summarizing, in the CAP mode:

- The BESS effectively capped the Car Shade nanogrid to a 20 kW threshold.
- When the threshold was lowered, there were times when the EVCS demand exceeded the imposed limit, and BESS SOC was not fully restored.
- On CAP 20 and CAP 15, there is a reasonable amount of curtailed PV power, which can be noticed by the narrow PV curves; on CAP 10, however, almost no PV was curtailed.

From an operation perspective, it is preferable to allow PV export rather than curtailing. Unfortunately, a cap mode that would allow export was not tested during the project timeframe. To predict how the system would have operated without PV curtailing, a model that simulates the BESS dynamic dispatch was developed and verified against Car Shade historical data. The result is shown in Figure 51, which shows an amount of 20 kW peak of PV was curtailed in this particular day. In section 5.3.1, the amount of PV curtailed/exported is quantified for all BESS modes.

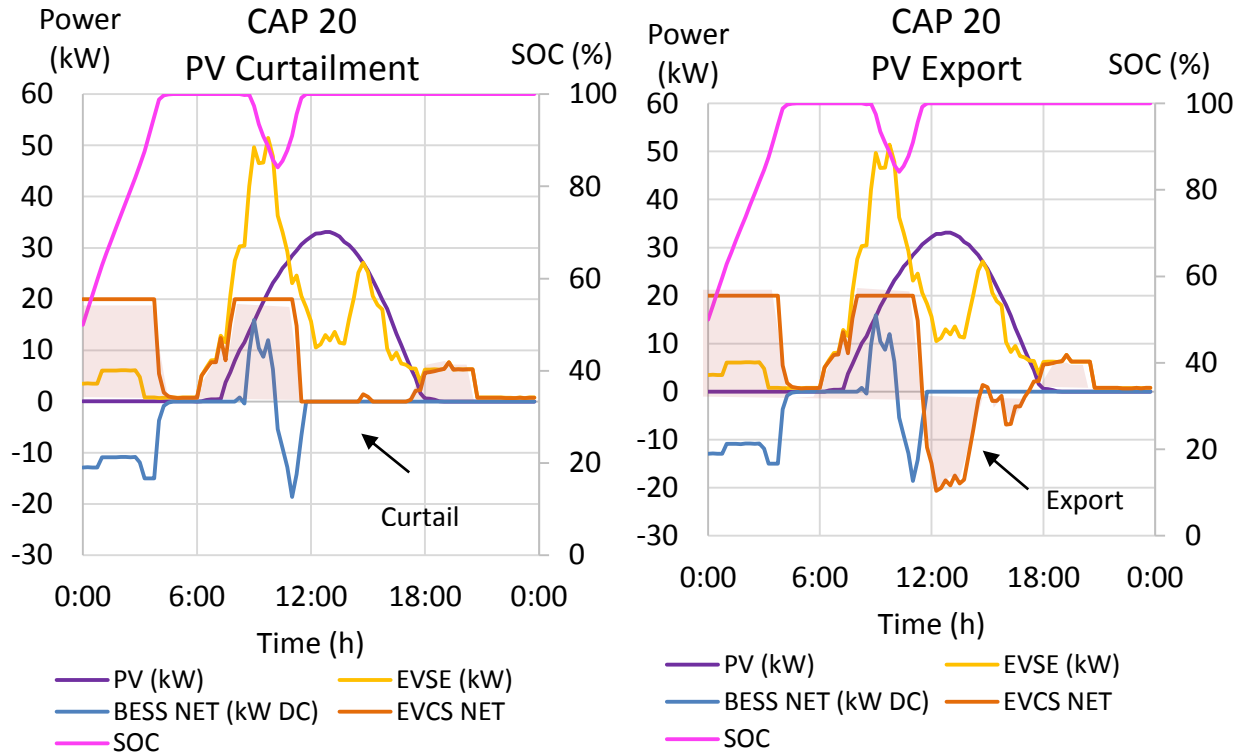


Figure 51: CAP 20 –With curtailment (SCE data set) and without PV curtail (simulation)

5.1.2.4. PV Capture

As previously observed in Figure 44, at the Car Shade the EVSE loads morning peak does not coincide with the solar PV generation peak. Besides, evening EVSE loads also do not coincide with the solar PV generation window. Hence, in this mode, the BESS is used as a buffer to promote a seamless integration of the nanogrid to the microgrid, and most important, to maximize the amount of solar renewable contribution to EV charging.

As a result, the net load on the system was effectively met by the PV + BESS combination, as it can be observed in Figure 52. Since this mode was implemented during the Summer Quarter, when most students are off campus, the EVSE loads were significantly

reduced, making it easier for the BESS to act as a buffer given its designed energy and power ratings of 100 kWh/100 kW. For this particular day, the minimum SOC was 50% before the system started to recharge from excess PV, indicating that when the system is under light load conditions and a good PV generation, the BESS capacity was only 50% used. Also, in this mode, the BESS output is essentially the EVSE demand, as it can be observed that the blue curve (BESS output) is the mirror image of the yellow curve (EVSE demand). As the SOC reached 100%, PV power was gradually curtailed to match the EVSE evening demand.

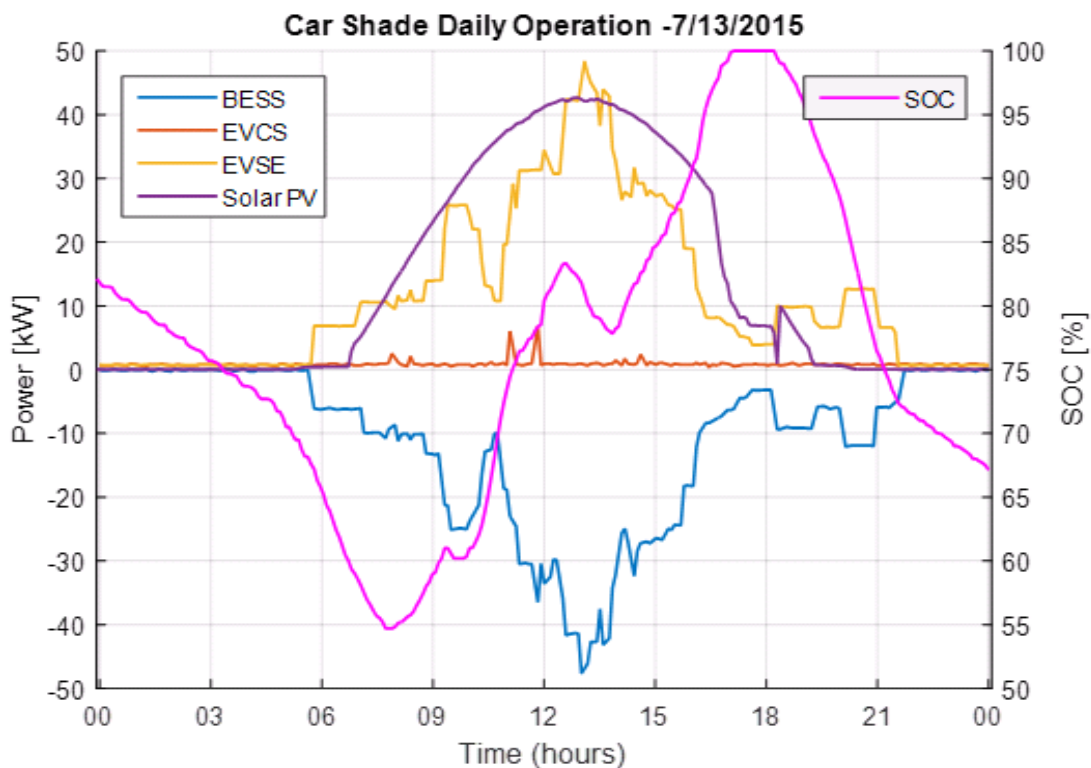


Figure 52: BESS PV Capture mode (July 13, 2015)

In this mode, most of the same MPPI control parameters are used, except for the BESS discharge and charge time settings, which are now extended to the entire day. The full settings are shown in Table 9.

Table 9: BESS PV Capture control settings

BESS mode	Time	Constraints
Discharge	Daily 12:00 AM to 12:00 AM	if EVSE_Load > 75 kW BESS_DischPower = 75 kW else if EVSE_load > PV_Gen + Battery_kW BESS_DischPower = PV_Gen + Battery_kW else BESS_DischPower = EVSE_Load
		while SOC < 100% if PV_Gen > EVSE_Load BESS_ChPower = PV_Gen – EVSE_Load if SOC > 100% PV_Gen = 0 (curtailed)
Day Charge	Daily 12:00 AM to 12:00 AM	
Overnight Charge	Daily Only in Overnight charging mode 12:00 AM to 6:00 AM	while SOC < 100% BESS_ChPower = 10 kW

During a week operating in PV Capture mode (Figure 53), the BESS was successfully charged during the afternoon and discharged throughout the evening and the following morning. The Car Shade demand (EVCS) was reduced to zero for two consecutive days. On the following days, the SOC was not fully restored due to low PV generation and a higher EVSE usage in the early morning, creating an EVCS demand, which remained below 20 kW. The average weekday SOC at 6:00 AM was 50%, as seen in Figure 53.

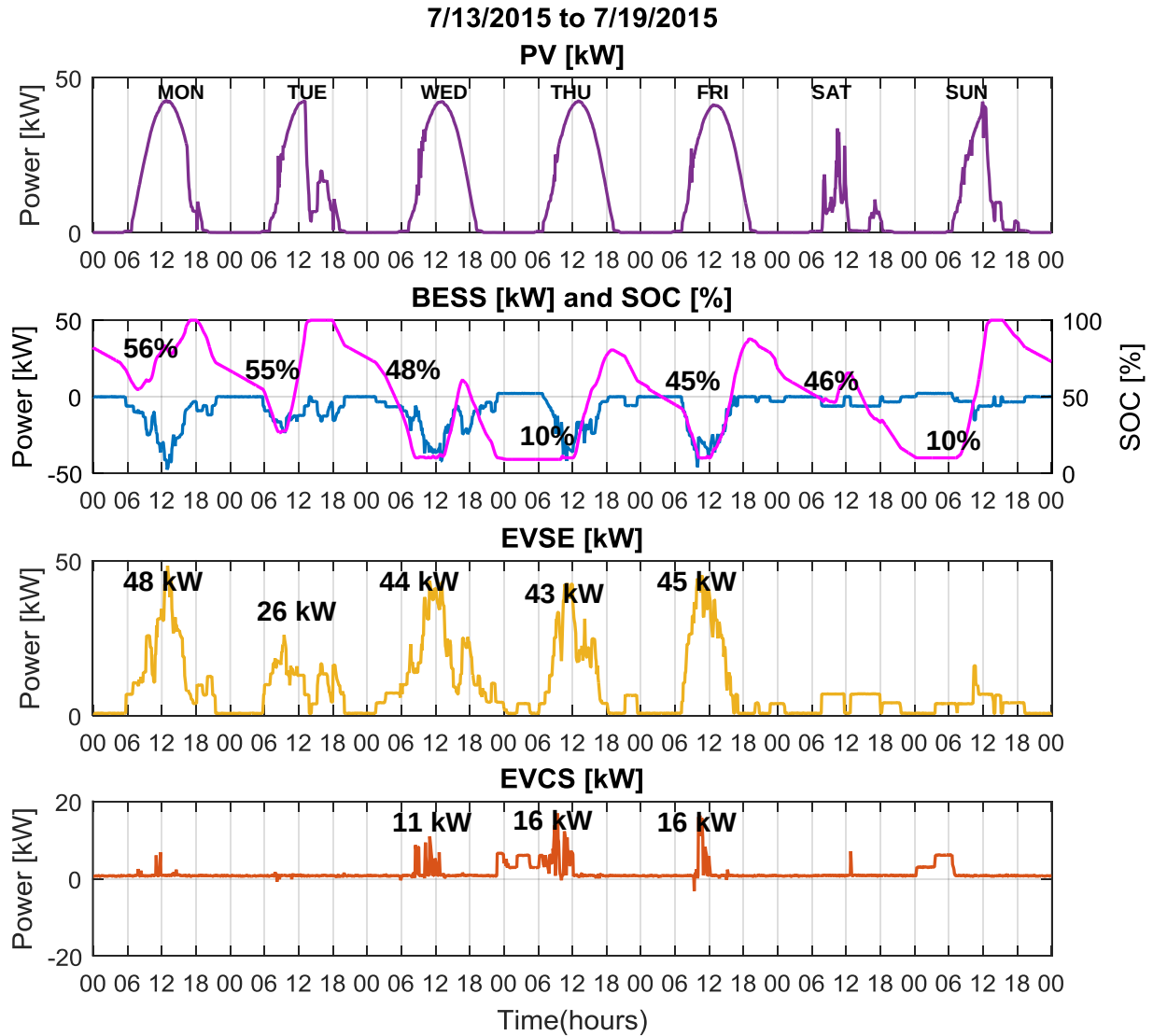


Figure 53: BESS PV Capture mode. (Jul. 13, 2015 week).

To counteract this problem, a constant 10 kW overnight charging strategy was implemented — this way, the battery will not be depleted in the early morning, and the BESS will be able to shift the EVCS load to the off-peak nighttime.

With overnight charging (Figure 54), the average SOC in the early morning increased to 82%. During the first two days of testing, however, the morning PV generation was affected by cloud coverage, which quickly depleted the battery in the early morning and

was also not sufficient to restore the battery SOC in the afternoon, since EVSE usage was also unusually high (62 kW peak), which required additional EVCS power. The SOC was only able to recover on the third day, since in the following days, the weather was clear and the PV generation was enough to allow the BESS to buffer the system and zero out the EVCS demand during the day.

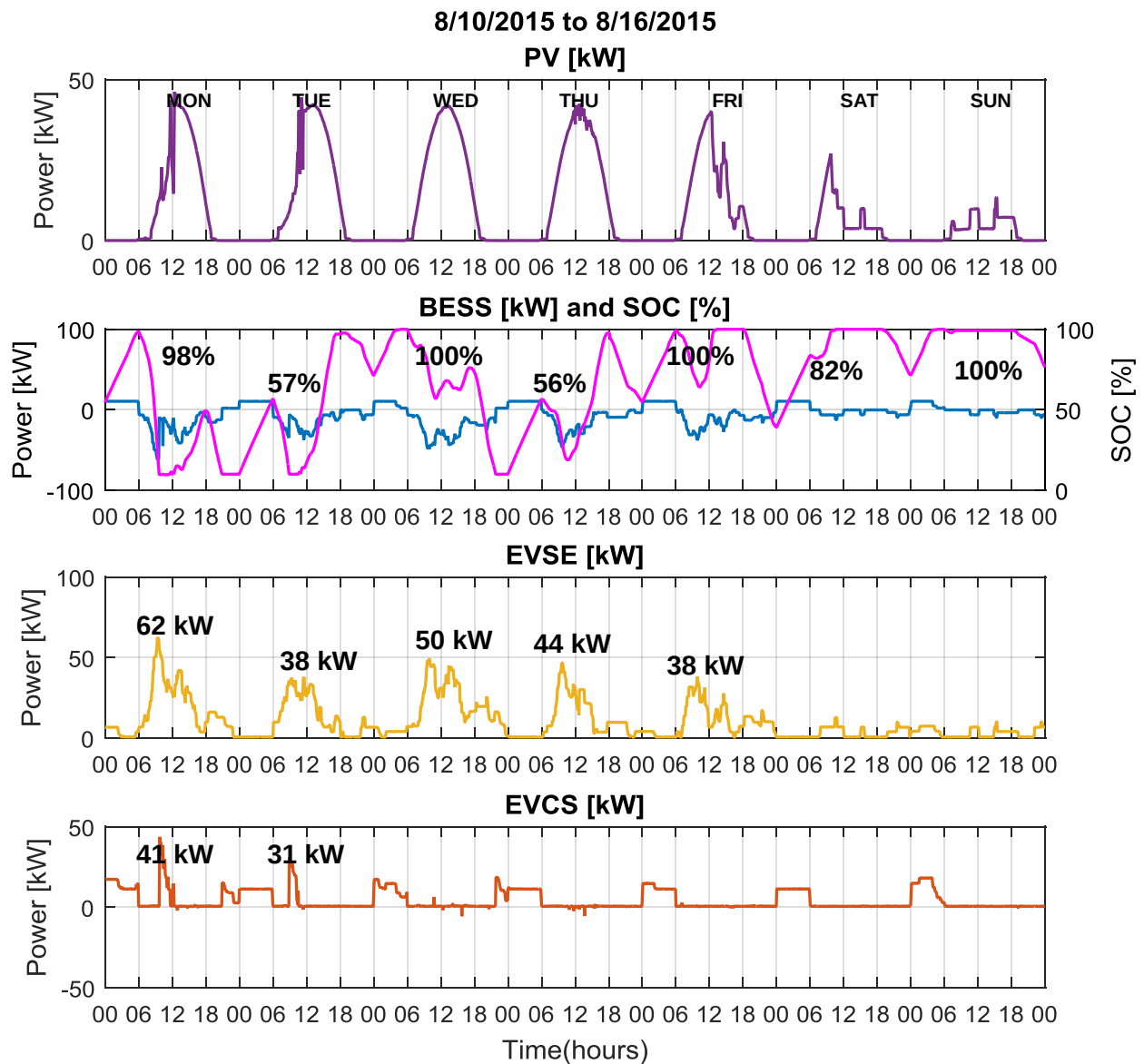


Figure 54: BESS PV Capture (with overnight charging) mode. August 10, 2015 week.

Summarizing, for the PV Capture mode:

- Both strategies: with and without overnight charging, did not fulfill their goals under poor weather conditions. Overnight charging helps increase the average morning SOC, which in turn helps the BESS to buffer the system completely.
- While this mode enables more renewable penetration — as will be discussed in the next section — the EVCS demand curve showed significant fluctuations caused by high EVSE loads' variability when the BESS is already depleted. These fluctuations are not ideal in the case of a bigger EVSE load as increased ramping is not desirable in any power system. This problem could be further addressed with higher capacity BESS.
- This results show how undersized the BESS + PV system combination is for the designed 20 EVSEs rated power (132 kW, or 144 kVA). Currently, the system would not be able to perform as an islanded nanogrid. Section 5.5 will present a strategy for optimally sizing the PV and BESS assets in the nanogrid.

Here, again, the excess PV was set to be curtailed during the modes testing timeframe. However, in PV capture, curtailment was only significant during the weekends since during the week the BESS was rarely 100% charged. Ideally, the system should always be able to allow PV export in order to maximize PV electricity use. The same way as was done previously, the system was simulated as if PV power was not curtailed. The chosen day was a Saturday and a comparison between modes is made in Figure 55. If no curtailment is set, the export will be almost all the PV generation.

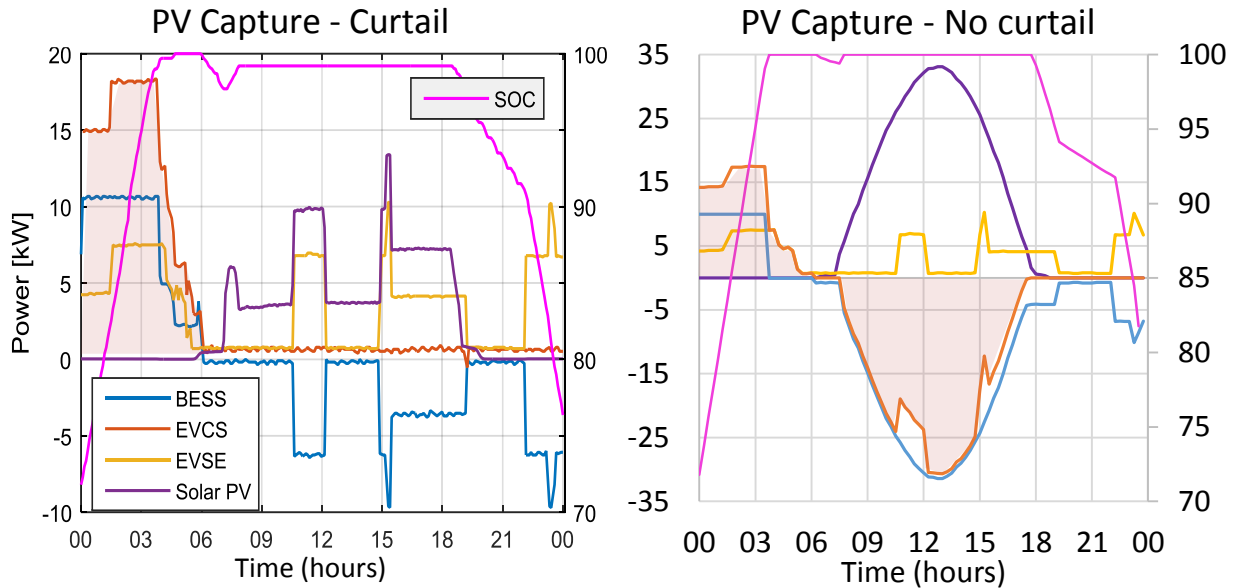


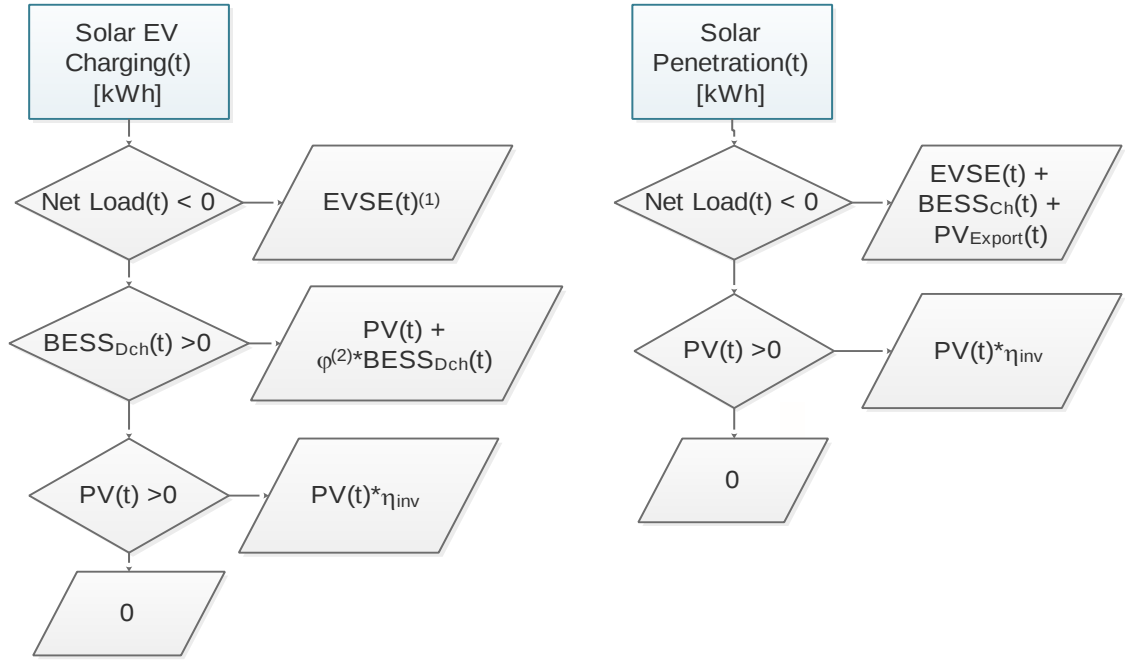
Figure 55: PV Capture weekend operation — With PV curtail (SCE data-sets) and without PV curtail (simulated)

5.1.3. Solar EV Charging and Solar Penetration

Although different BESS operation modes have clear distinct goals, one of the Car Shade’s main goals as nanogrid is to ultimately charge EVs using 100% renewable energy, and in turn, to increase EV’s environmental benefits. Here, different BESS operation modes are compared in their ability to allow renewable solar PV penetration and contribution to EV charging.

Two metrics were used to determine renewable penetration. The first one, “Solar EV Charging”, determines how much of the daily EVSE load (kWh) was met from PV generation. The second one, “Solar Penetration”, is a ratio of how much PV generation was effectively used in the system (EVSE load + BESS charging + exported to the grid), in other words, all PV generation not curtailed.

The flowcharts of Figure 56 describe how these metrics are calculated. First, the energy values in kWh *Solar EV Charging(t)* and *Solar Penetration(t)* are evaluated at each time-step t .



⁽¹⁾In PLS mode, subtract also BESS_{Dch}(t)

⁽²⁾ ϕ is the % of energy in the BESS charged by solar PV. In PVSOURCE, $\phi = 1$

⁽³⁾ $\eta_{inv} = 97\%$

Figure 56: Flowcharts for Solar EV Charging and Solar Penetration metrics

The metrics, denoted as percentages, are a ratio of the sum of the kWh values to the total daily EVSE load or PV generation.

$$\text{Solar EV Charging (\%)} = \frac{\sum_{t=1}^T \text{Solar EV Charging}(t) [\text{kWh}]}{\sum_{t=1}^T \text{EVSE Load}(t) [\text{kWh}]}, t = 1, 2, 3, \dots, T \quad (4)$$

$$\text{Solar Penetration (\%)} = \frac{\sum_{t=1}^T \text{Solar EV Charging}(t) [\text{kWh}]}{\sum_{t=1}^T \text{PV}(t) [\text{kWh}]}, t = 1, 2, 3, \dots, T \quad (5)$$

A dynamic dispatch model of the Car Shade was developed for each BESS operation mode, and verified against real-world system dispatch profiles. A given EVSE load and PV generation profiles (taken from the Car Shade historical data) were used as inputs, using a 15-minute resolution. A daily total of 279 kWh of EVSE load and 224 kWh PV generation were registered for these days. An initial 50% SOC was assumed for all modes. The renewable penetration metrics were calculated, as a function of different BESS dynamics as a response to these profiles. Table 10 summarizes the results.

The following figures present a comparison of the dynamics of the system for various operation modes under the same EVSE load and PV profile, and in some cases, with and without PV curtailment (if applicable). In Figure 57, the two modes that do not curtail excess PV (PLS and MPPI) show very different dynamics in terms of export. While PLS exports all excess PV power, the MPPI mode uses it to recharge the BESS during the day.

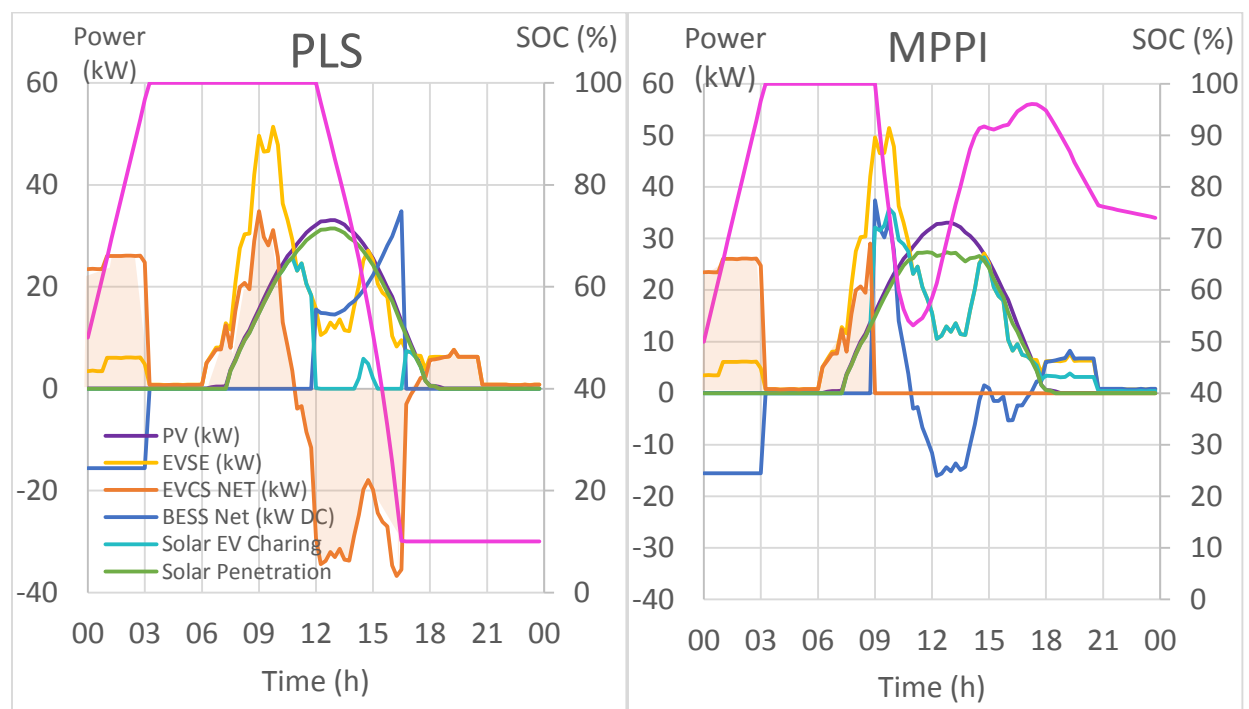


Figure 57: PLS and MPPI — Renewable contribution

In Figure 58, the CAP 20 mode dynamics are shown on the right, when PV was allowed to be exported, and on the left, when PV was curtailed. In the PV-export case, an average of 20 kW of solar PV were exported for about an hour and a half starting near 12:00 PM, which was curtailed on the PV-curtail mode. In contrast to the previous modes shown above, this mode utilizes very little of the battery system as a buffer. In both cases, after fully charged, the battery's SOC is discharged to only 85% of its full capacity.

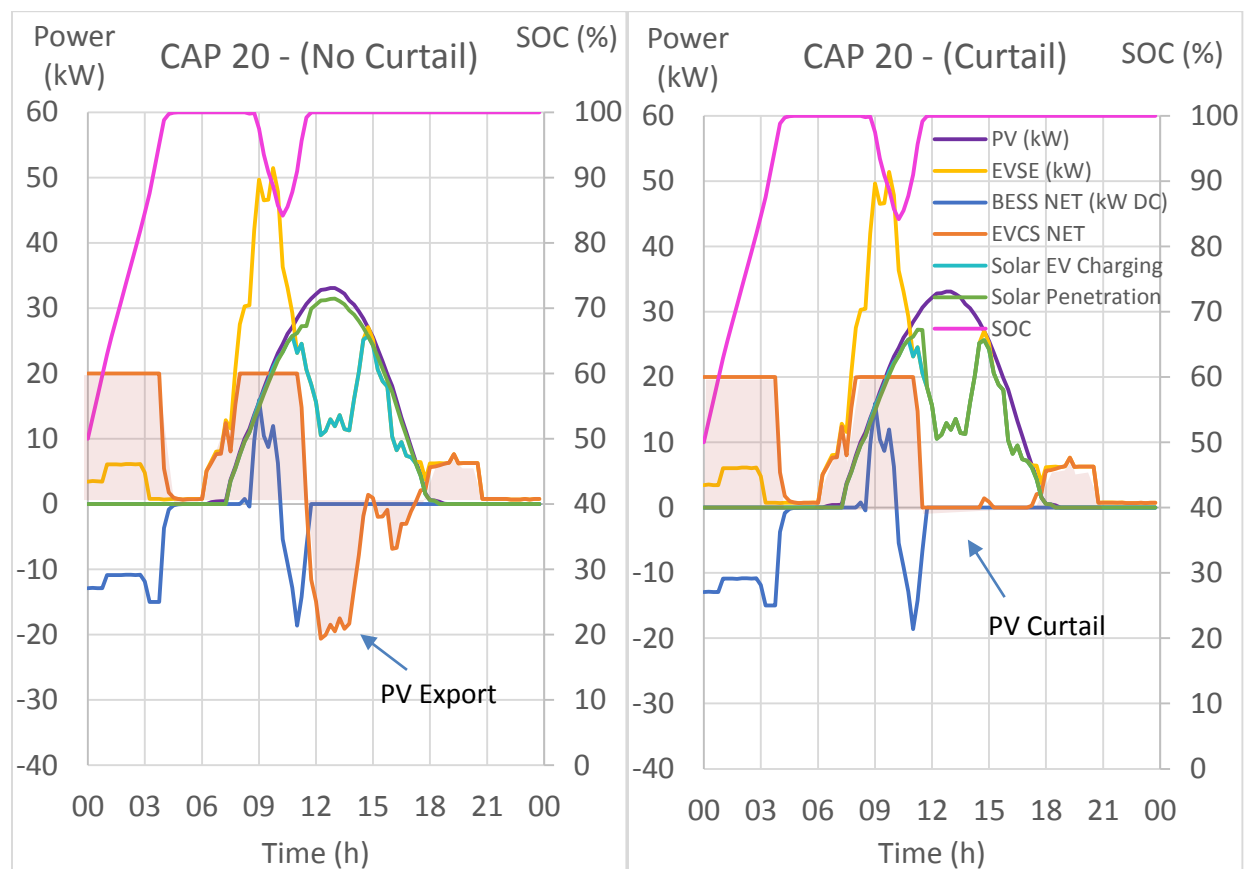


Figure 58: CAP 20 with and without curtail — Renewable contribution.

The lower threshold CAP modes are shown in Figure 59. Naturally, in these modes the total PV export is lower, since the BESS is discharged to a lower SOC as with the 20 kW CAP due to reduced grid power to meet EVSE demand. Hence, the battery will reach full SOC after its daytime recharge later in the day, and only then will PV export begin.

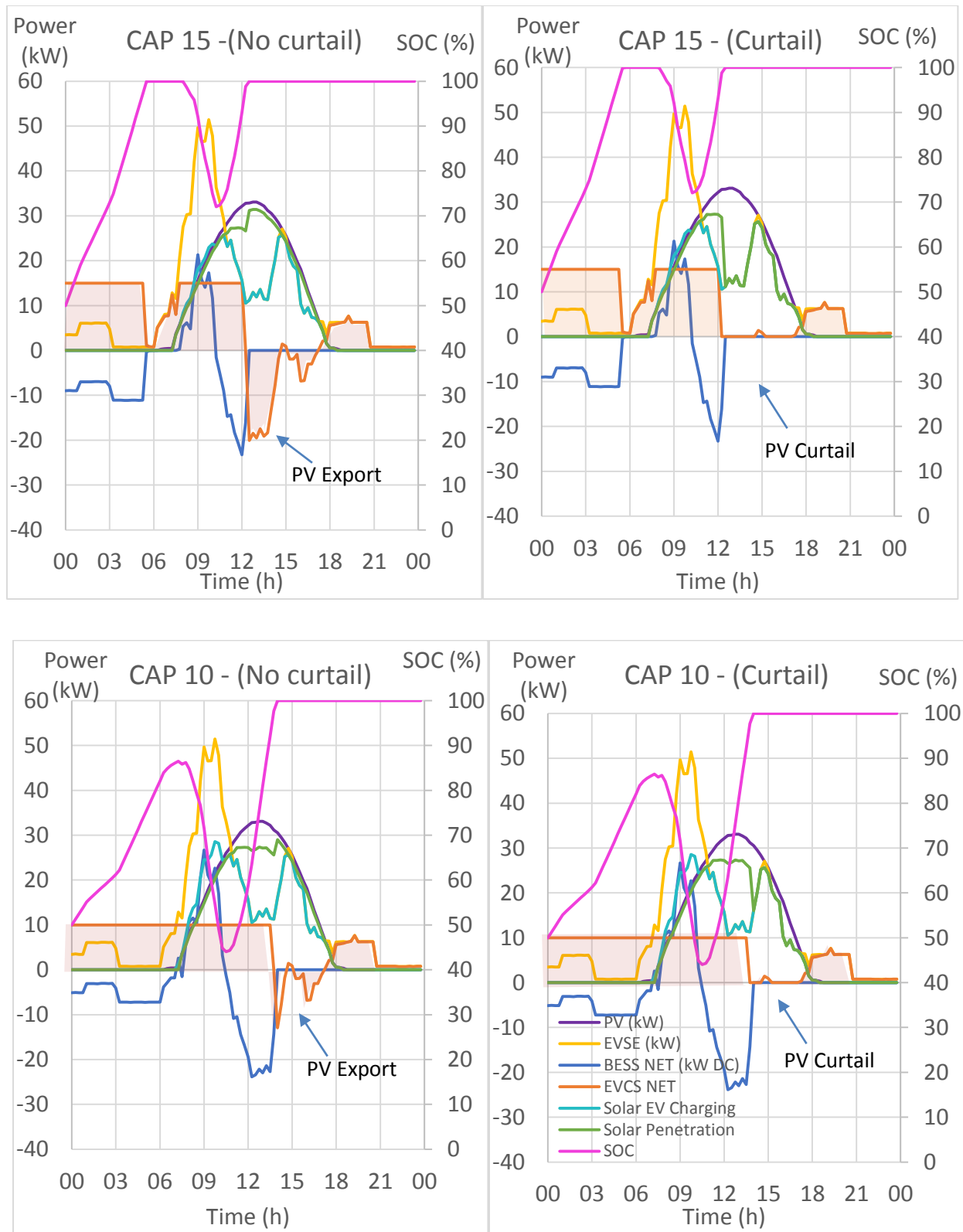


Figure 59: CAP 15 and CAP 10, with and without curtail — Renewable contribution.

The PV Capture mode (Figure 60) operates identically regardless of whether or not export is allowed since the BESS had not reached full charge. Hence, only one dynamics is illustrated in Figure 60 for this mode.

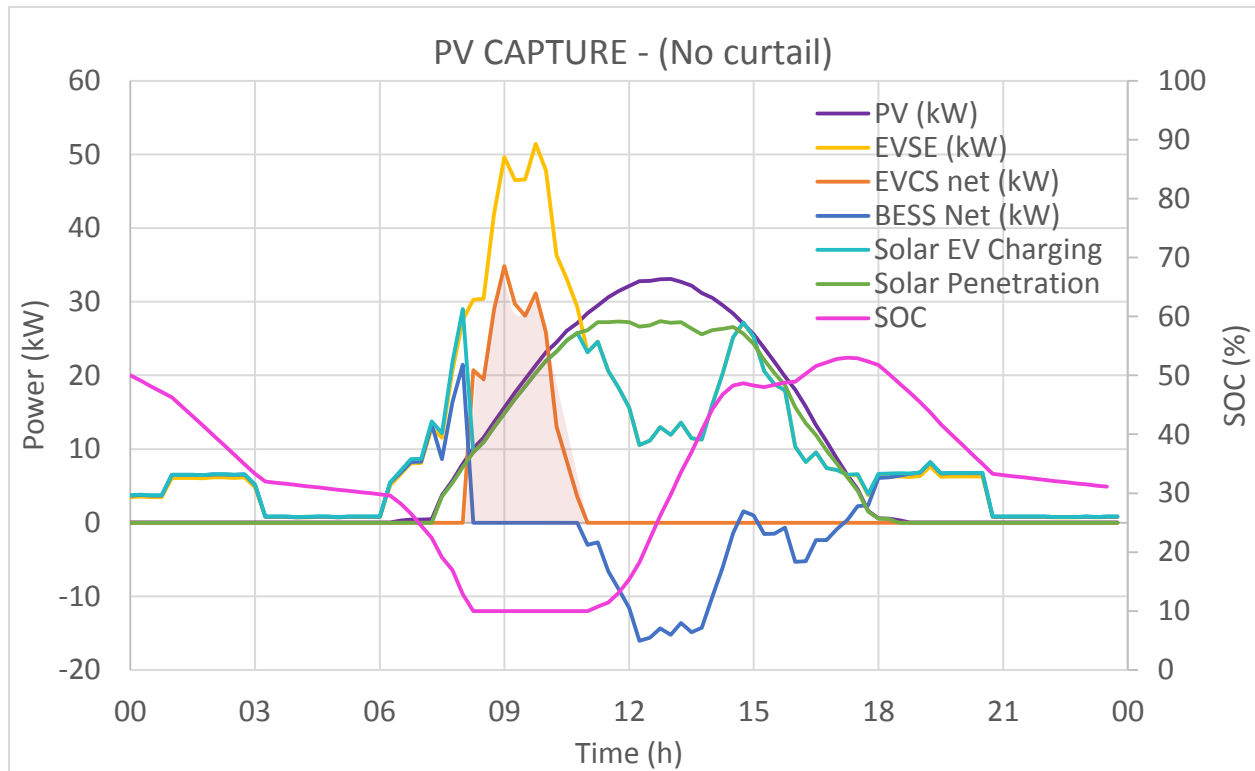


Figure 60: CAP 10 and PV Capture, without curtail — Renewable contribution.

For the overnight charging case, shown in Figure 61, there is a small amount of PV export of an average 20 kW for about one hour around 13:30 PM, since now, the BESS started buffering the system from a full charge, and thus, was fully recharged during the day.

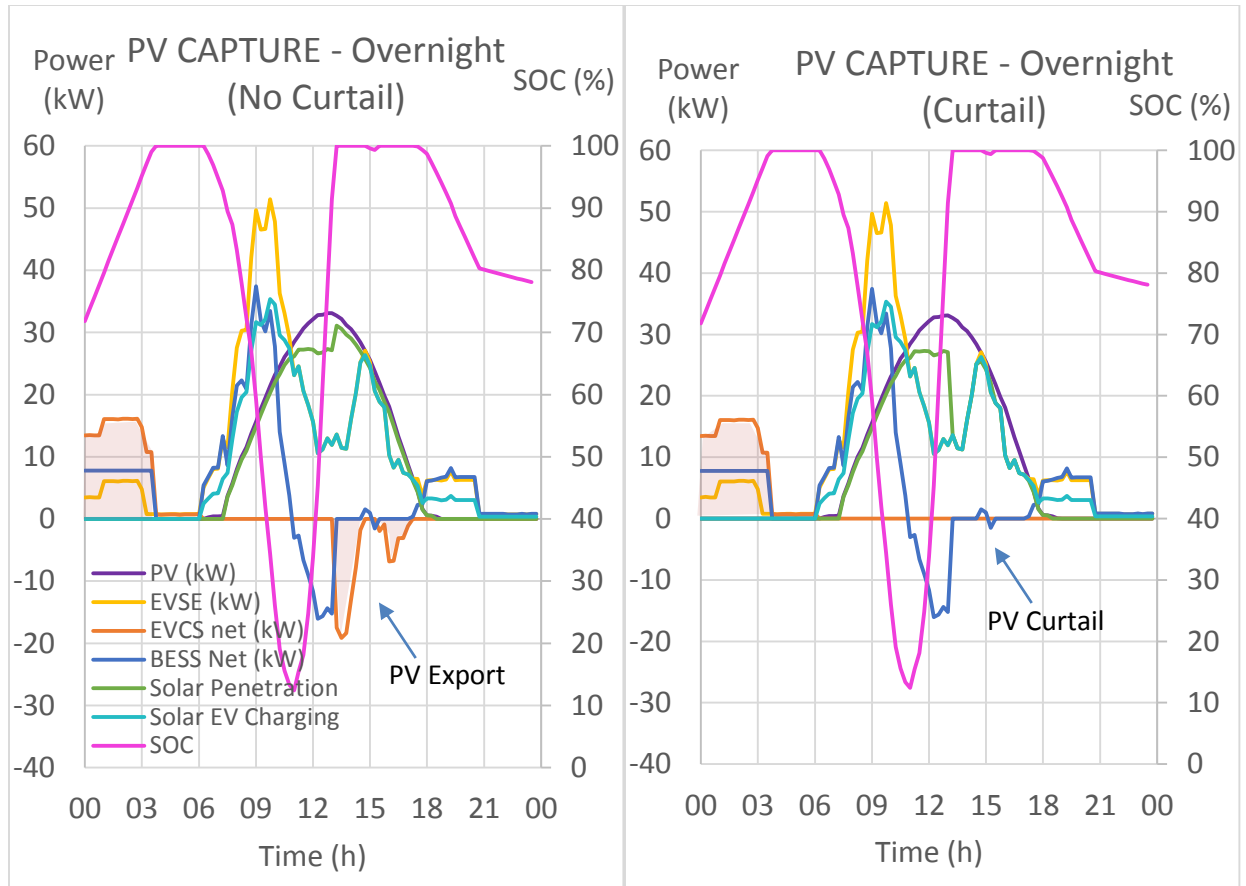


Figure 61: PV Capture with Overnight Charging, with and without curtail — Renewable Contribution

Table 10: BESS modes — Renewable penetration study

Mode	Solar EVSE Charging (%)	Solar Penetration (%)	ϕ^1 (%)
PV CAPTURE (curtailed)	80	89	100
PV CAPTURE (not curtailed)	80	89	100
PV CAPTURE (Overnight charging)	74	92	29
MPPI	68	89	46
CAP 10 (curtailed)	62	85	36
CAP 15 (curtailed)	58	75	15
CAP 20 (curtailed)	56	71	5
CAP 20 (not curtailed)	56	94	5
PLS	31	95	0

(1) ϕ is the % of solar energy in the BESS total energy

The following observations can be drawn from these analyses:

- As expected, the PV Capture mode allowed for the biggest EV charging from renewable solar, followed by the MPPI, then CAP 10, 15, and 20, and lastly, the PLS mode.
- CAP demand modes have an increased renewable contribution as the threshold is decreased, since less PV is curtailed. Yet, more grid power is used to charge the battery, since significant charging occurs overnight.
- For the PV Capture mode (without overnight charging), the battery was solely charged by solar energy ($\varphi=100\%$). On the other hand, in PLS mode, the battery was entirely charged with grid power ($\varphi=0\%$).
- PV Curtailment does not have an effect on increasing Solar EV Charging, but definitely an effect in increasing Solar Penetration.

5.1.4. Monthly Energy Summaries

The Car Shade project was completely installed and operational from December 2013 to July 2015. The BESS was installed in September 2013, followed by the PV array in November 2013 and the EVSEs in late November/December 2013. The system energy totals at three different metering points on the system have been recorded by SCE's Shark Meters (Figure 15). Table 11 below shows the monthly energy totals through July 2015.

Table 11: Car Shade Monthly energy summaries [45]

Year	Month	EVSE Load [2] kWh	BESS Net [3] kWh	EVCS [1] kWh
2013	September	0	1,398	1,382
	October	0	1,669	1,690
	November	289	-424	-116
	December	1,539	-1,023	571
2014	January	2,977	-1,356	1,662
	February	2,893	-2,973	-45
	March	3,164	-3,405	-306
	April	4,363	-4,464	12
	May	3,946	-5,935	-1,964
	June	3,779	-6,731	-2,994
	July	3,624	-6,234	-2,572
	August	4,237	-6,711	-2,414
	September	4,942	-5,232	-397
	October	7,097	-3,805	3,520
	November	492	-2,701	-2,190
	December	1,432	-1,959	-565
2015	January	7,216	-1,762	5,492
	February	7,699	-2,158	5,693
	March	7,880	-2,486	5,141
	April	9,108	-3,642	5,796
	May	9,687	-2,264	7,519
	June	7,941	-1,109	6,771
	July	6,605	-2,679	3,980
TOTAL		100,910	-58,146	35,666

The negative sign convention shows energy exported to the grid and positive means energy consumed by the system. The monthly energy total (absolute values) at the EVCS is not the direct sum of the inverter energy output and EVSEs load, as it might seem from the diagram in Figure 15. This occurs because the power required to maintain the BESS itself averages at 2 kW, this energy is therefore not computed in the energy totals.

The monthly energy totals are plotted in Figure 62.

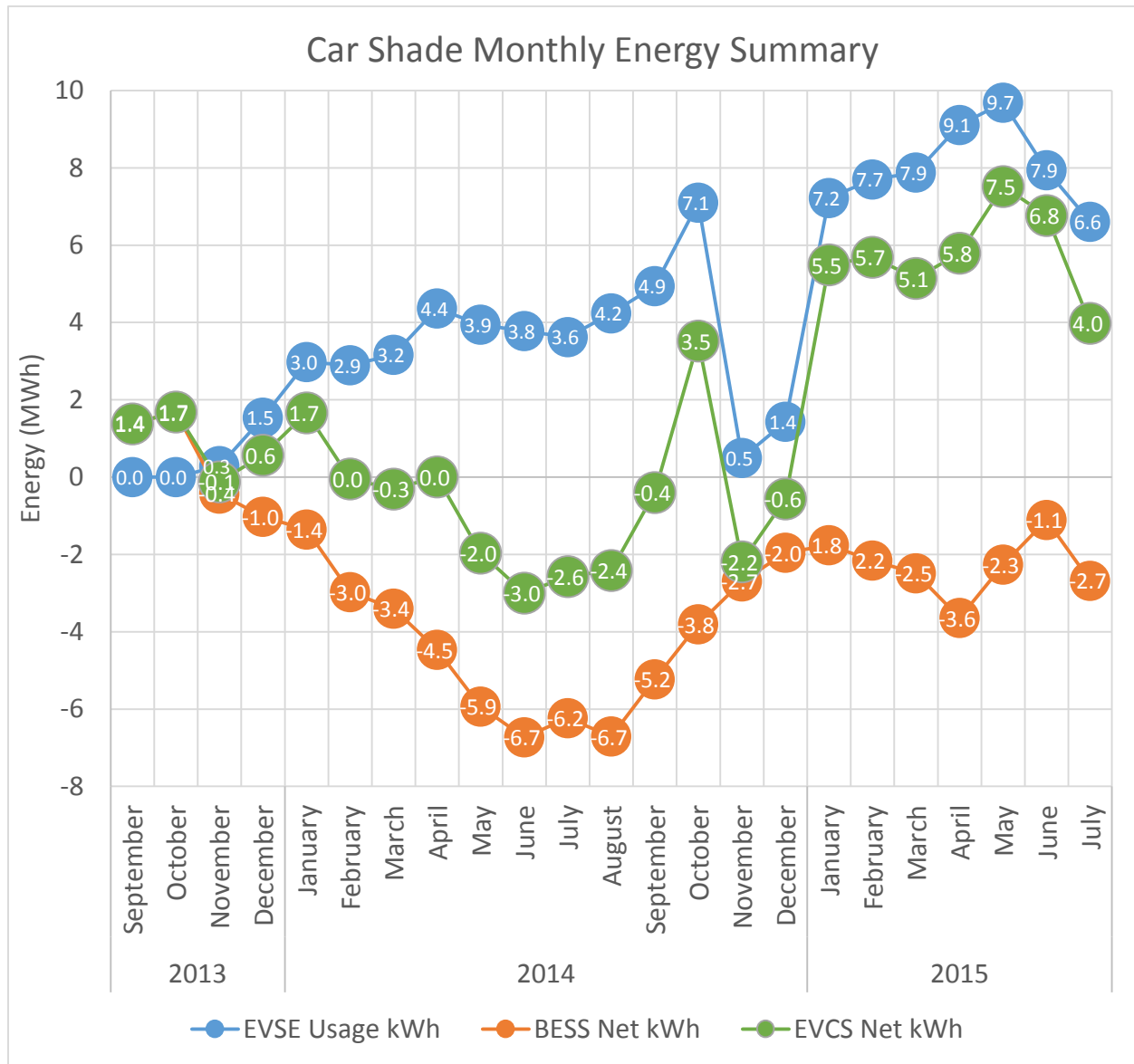


Figure 62: Car Shade monthly energy totals [45]

During its first operation months (November through February), the Car Shade nanogrid reached a peak of 1.7 MWh net import in January due to low PV generation during winter. Over the summer of 2014, the inverter output increased gradually, reaching a peak of 6.7 MWh in June and in August. There was a slight but perceptible decrease in load

during the UCI summer break, June through August. Later in summer, once the Car Shade became more popular and known within UCI, especially because of its free charging, the total EV load progressively increased.

With the beginning of fall quarter in late September 2014, an increased campus activity kept the rising trend for the EVSE usage, so the nanogrid net-imported again. However, in late October, the EVSEs on site needed to be replaced and the system was made unavailable to the public. The Car Shade was back in operation only on December 18th, which explains the low usage during the previous 3 months.

From December on, the EVSE usage continued to increase progressively, also increasing the net import. The inverter output was reduced compared to the previous year due to testing of BESS algorithm modes that curtailed PV generation. Both facts contributed for the Car Shade nanogrid to become a net-importing system since December 2014.

Overall, during the 23 months of operation observed here, the EVSEs consumed a total of 101 MWh. Assuming an average EV battery size of 20 kWh, this represents about 5,000 fully charged units. The net import was about 35 MWh.

5.2. Task 2: Develop and verify the Car Shade nanogrid real-time power flow model

5.2.1. Power flow model development

The Car Shade is a unique system that needs to be analyzed using a load flow model for overall performance and scenario evaluation. The software platform used for developing the Car Shade load flow model was the Electrical Transient and Analysis Program (ETAP). The model's main objective is to perform steady-state power flow

simulations to analyze active and reactive power flows as well as bus voltages across the system, to ultimately compare different BESS operation modes.

All equipment specifications used were received from SCE, or equipment specification sheets.

The modeled nanogrid includes:

1. The 12 kV UC-9 branch circuit;
2. A 1MVA 12 kV/480 V step down transformer (T-131) located at the Anteater Parking Structure;
3. A 48 kW rooftop solar array (8 modules in series per string with 18 strings in parallel, totaling 144 panels);
4. A 100 kW/100 kWh battery energy storage system;
5. A 100 kVA Inverter that connects the DC elements (solar panels and battery storage) to the AC part of the circuit (EVSEs and UCI Microgrid);
6. Two 75 kVA 480 V/208 V step down transformers, connected to the AC side of the inverter (on primary side) and to 10 EVSEs each (on secondary side);
7. 20 Level 2 (7.2 kVA) EVSEs;
8. Anteater Instruction & Research Building (AIRB) loads (General classroom/ laboratory, office, elevator, and lighting loads);
9. Anteater Parking Structure 50 kVA loads (Elevator and lighting loads);

A schematic of the ETAP model and the ETAP simulation environment are shown in Figure 63 and Figure 64, respectively.

The model assumptions are:

- The 12 kV UC-9 circuit is considered a voltage source (swing power grid);
- The inverter was modeled as a regular two-port inverter rather than a three-port configuration (two DC separate ports for PV and BESS, and one AC port) because ETAP does not support an AC/DC power flow integration, the DC power flow is not simulated nor considered in this study;
- AIRB and APS load ratings were obtained from the yearly average of the historical data on the Melrok system;
- A load diversity factor of 70% for all buses was assumed to reflect the random EV charging behavior observed at the Car Shade.

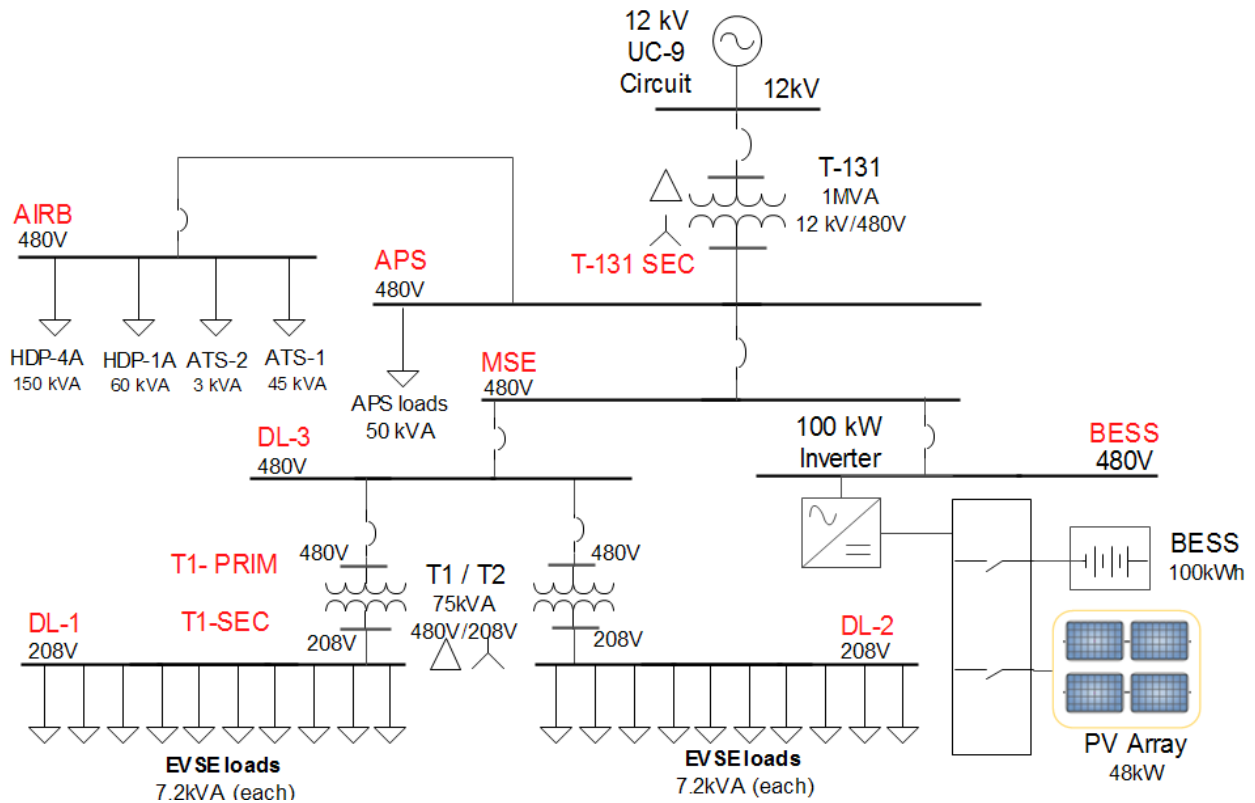


Figure 63: Car Shade nanogrid ETAP model schematic

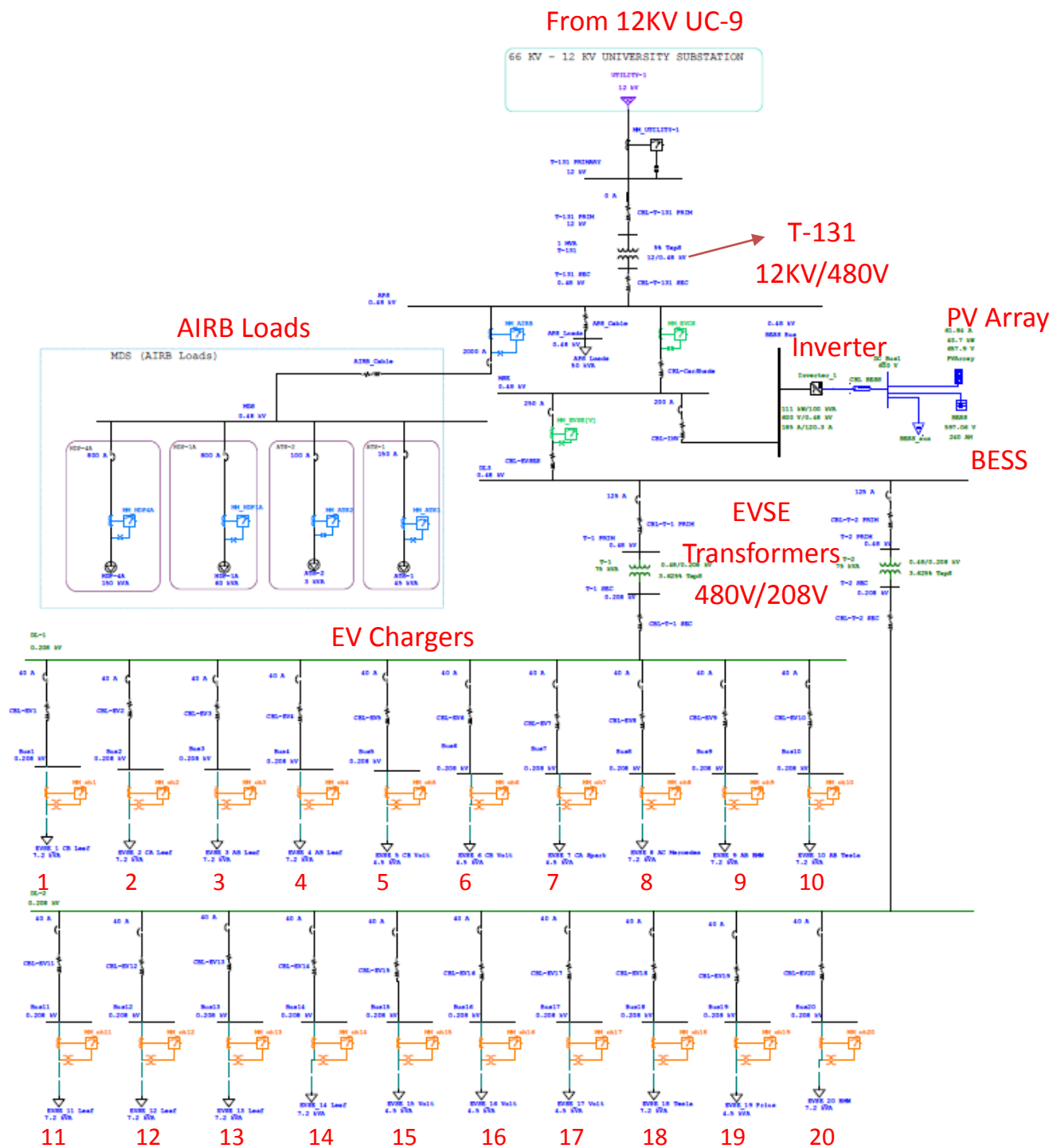


Figure 64: Car shade model (ETAP simulation environment)

5.2.2. Power flow model verification

The state load estimator (SLE) feature of ETAP Real-Time was used here for model verification. The SLE uses known system metered data to compute estimated voltage magnitudes and phase angles at all buses in the system for each snapshot of operation, the SLE uses:

- Field measurements (active and reactive power, voltage, and power factor);
- Equipment ratings and loading categories;
- Manually pinned data and calculated data;
- Various measurement weighting factors.

To avoid ambiguity, the RT module is only used for model verification purposes and will not perform a truly real-time simulation — the terminology “Real-Time” simulation is not to be interpreted literally.

The simulation input/output data resolution is 15 minutes, which allows for a good sampling in observing the model dynamics when changing BESS operation modes. The SLE checks the metered versus calculated data for any major mismatches, and creates artificial measurements for any unknown loads.

A typical day of operation (Wednesday, 01/14/2015) was selected to carry on the RT simulation. Meter data at the Car Shade were gathered from SCE and UCI’s central metering cloud database, the Melrok System. However, to feed the metered historical data in ETAP without having a SCADA (Supervisory Control and Data Acquisition) system was a rather complex process and required some non-conventional methods.

Ideally, ETAP RT simulations are integrated with a SCADA system, using communication protocols that automatically feed meter data into the ETAP Server in a truly real-time manner. However, since there is still no SCADA system in place in the UCI Microgrid, the SCE and Melrok meter data needed to be manually fed into ETAP. For this, an input file (.txt file), which links the metered points in ETAP to the meter data was created. A MATLAB script was developed for this purpose.

The workflow chart on how the RT simulation was performed in this study is shown in Figure 65. The data pre-processing starts with using a MATLAB script to interpolate the metered data in order to obtain evenly spaced 15-minute intervals. Next, a “Tag File”, which is essentially a database file, is generated using ETAP. The tag file attributes tags to each input or output signal in the model (voltage, current, power, etc.) and equipment components (meter, transformer, breaker, etc.). After the Tag File is created, a second MATLAB script is used to create a “.txt File”. This file contains the interpolated data associated with the respective ETAP tags. The Tags will identify the type of signal and the location where this signal belongs within the ETAP model. The system configuration (step 2) involves specifying the location of both these files in the server using the *ETConfig* Tool. Once these steps are completed, the simulation can be performed in the ETAP RT Server, which will perform the SLE calculations and display any user-pre-set alarms (in case of an over-voltage, for instance).

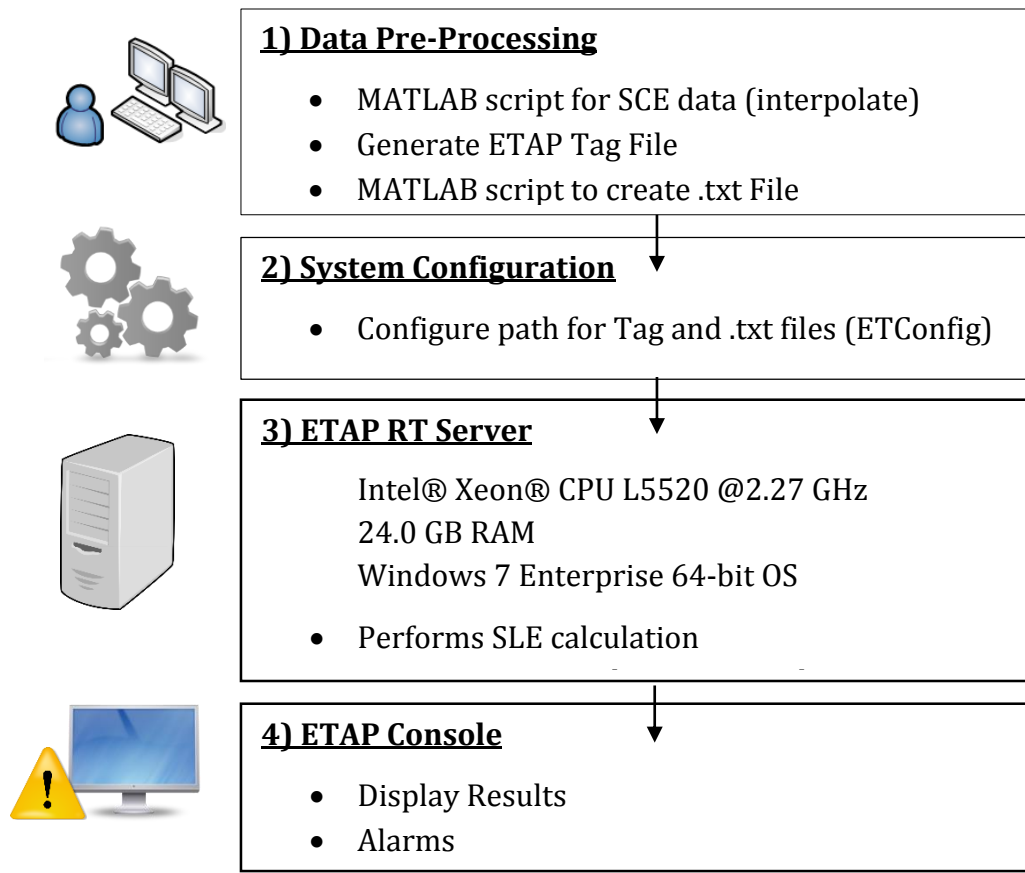


Figure 65: ETAP RT simulation workflow

Once the data were properly fed into ETAP, the RT simulation was carried out for an entire day (24 hours). Figure 66 is a screenshot of the ETAP RT simulation environment. The numbers in green, next to the meters, represent the actual meter data that are input into ETAP meter points. The numbers in red, next to the buses, are the data that the ETAP software estimates through the SLE feature: bus voltage, real and reactive power.

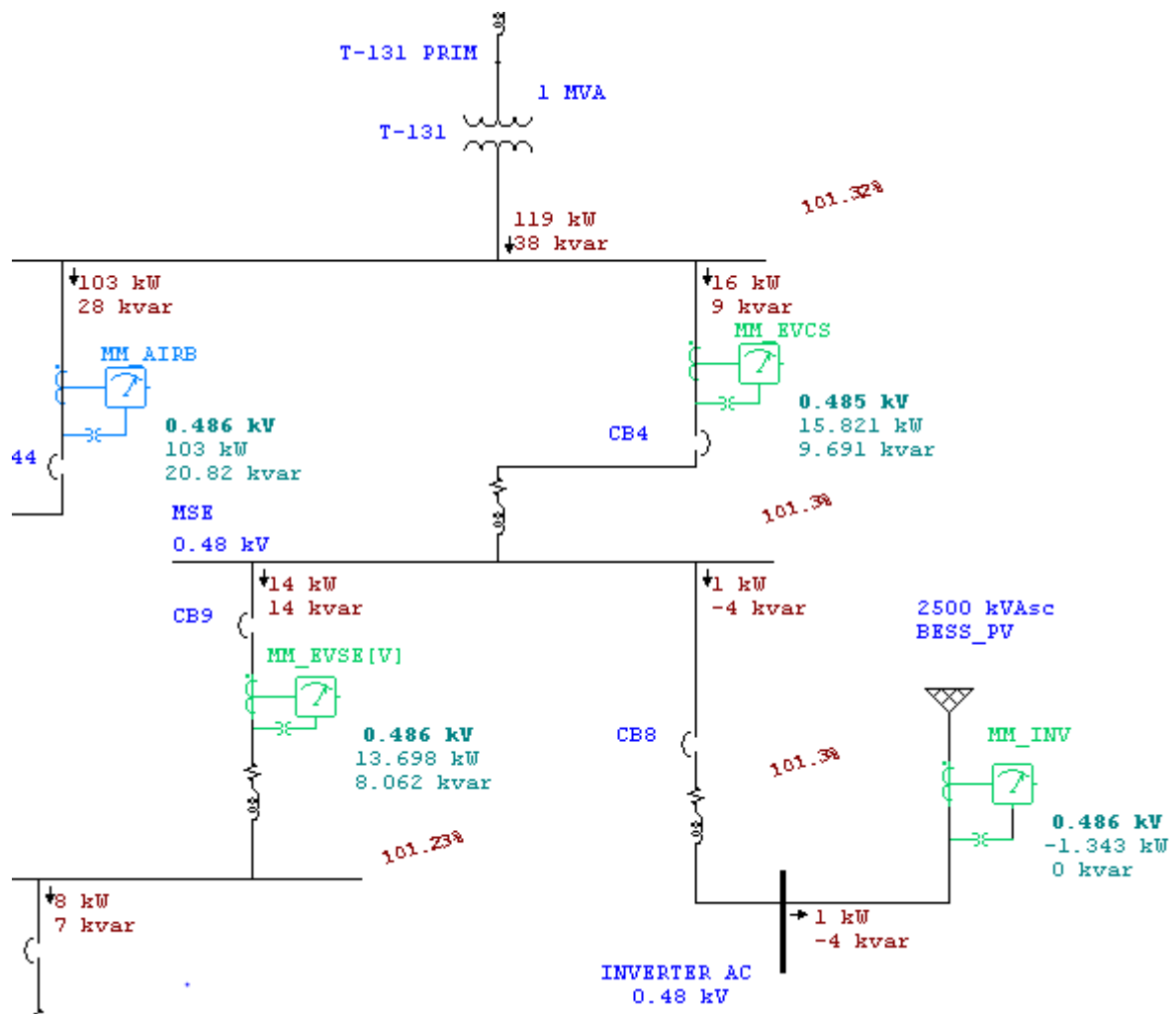


Figure 66: ETAP RT simulation environment

5.2.2.1. SLE comparison reports

After the RT simulation converges, a comparison report is generated for each 15-minute snapshot, showing the errors in the simulation results.

Table 12 shows the report for a given snapshot taken at 10:00 AM. The voltage differences were found to be less than 0.01% at all metered locations. Active power mismatches were below 30%. This error might seem high, but the small power flows (in

the order of 4–6 kW) compared here contribute to a high percentage error. The absolute magnitude of the power mismatches for the 30% deviation case is actually only 1 kW. EVSEs not being used at that moment, mostly with a power usage below 1 kW, appear grayed in the table since their high percentage errors should not be considered.

The major mismatches were found to be in the reactive power flows. This most likely occurred because a fixed power factor of 92% was assumed for all EVSE charging events, since reactive power meter data were not available for each individual EVSE. In reality, the EV charging power factor will vary in the range of 90% to 98%. Nevertheless, the biggest absolute mismatch for real power was only 17 kVAR, calculated at the branch that powers the EVSEs. This magnitude of mismatch is acceptable for the current model purposes.

Likewise, the remaining snapshots showed errors in a similar range. These mismatches were considered acceptable for the purposes of this study, and the ETAP power flow model was therefore verified.

Table 12: SLE Comparison Table (01/14/2015 @ 10AM)

ID	Type	Variable	Meter	SLE	Delta	Deviation
MM_EVCS	Branch	kV	0.485	0.485	0	-0.029
MM_INV	Source	kV	0.486	0.486	0	0.002
MM_AIRB	Branch	kV	0.485	0.485	0	0.033
MM_EVSE[V]	Branch	kV	0.485	0.484	0.001	0.163
MM_AIRB	Branch	kVar	14	23	-8	-58.627
MM_UTILITY-1	Source	kVar	21	31	-9	-42.48
MM_EVCS	Branch	kVar	7	7	0	3.848
MM_INV	Source	kVar	0	7	-7	100
MM_EVSE[V]	Branch	kVar	-3	14	-17	582.782
MM_ch19	Static Load	kW	3	4	-1	-44.063
MM_ch15	Static Load	kW	3	4	-1	-44.024
MM_ch2	Static Load	kW	3	3	0	-6.552
MM_INV	Source	kW	21	22	0	-2.285
MM_EVSE[V]	Branch	kW	49	50	-1	-1.302
MM_ch5	Static Load	kW	4	4	0	-1.162
MM_AIRB	Branch	kW	101	102	-1	-0.858
MM_UTILITY-1	Source	kW	129	130	-1	-0.593
MM_ch4	Static Load	kW	0	0	0	0
MM_EVCS	Branch	kW	28	28	0	0.948
MM_ch1	Static Load	kW	6	5	0	6.946
MM_ch7	Static Load	kW	6	5	0	7.108
MM_ch8	Static Load	kW	6	5	0	7.45
MM_ch17	Static Load	kW	3	2	0	16.072
MM_ch12	Static Load	kW	6	5	1	18.986
MM_ch10	Static Load	kW	4	2	2	48.114
MM_ch9	Static Load	kW	4	2	2	48.447
MM_ch11	Static Load	kW	0	0	0	100
MM_ch13	Static Load	kW	0	2	-2	100
MM_ch14	Static Load	kW	0	2	-2	100
MM_ch16	Static Load	kW	0	2	-2	100
MM_ch18	Static Load	kW	0	0	0	100
MM_ch20	Static Load	kW	0	2	-2	100
MM_ch3	Static Load	kW	0	0	0	100
MM_ch6	Static Load	kW	0	1	-1	100

5.3. Task 3: Analyze Model Outputs

Here, different BESS operation modes are compared on their impact on the Car Shade nanogrid circuit voltages up to the point of connection with the UCI Microgrid.

Each operation mode was simulated in ETAP RT for an entire day (12:00 AM to 11:59 PM). Again, here, the term “real time simulation” should be interpreted rather as “continuous steady state simulation” of 96 snapshots in time every day, in 15-minute resolution. A typical historical day of operation in each mode was chosen to be simulated, taking into consideration the need for a comparable PV generation and EVSE demand. In addition, an averaged AIRB load profile was considered for all days simulated.

According to ANSI standard C.84.1–R2005, for a 12 0V single-phase system, nominal voltages are 126 -114 V and for a 480 V 3-phase system, 504 – 456 V (5% above and below nominal). Thus, voltage thresholds of 98% and 95% were set in ETAP alarm settings. If SLE calculated values exceeded these thresholds, an alarm was generated indicating marginal or critical under-voltage events respectively.

During the simulations, most under-voltage alarms generated indicated that the buses affected were mostly EVSE terminal buses, and, under more severe loading conditions, T1 and T2 secondary and primary buses, and often DL buses would also be affected.

It is important to notice here that ETAP alarms generated in the simulation are highly dependent upon the system configuration modeled and daily dynamics being simulated. Of course, real life system operation differs slightly from simulation since models are not perfect. Thus, the alarms indicated here are not a reflection of what would exactly happen

in real operation, but still are a good indicator for weak points in the system that are subjected to higher power flows, higher currents and higher voltage drops, and consequently under-voltages. Hence, the results presented next are to be used more as a comparison between BESS modes and their impacts in the system rather than as isolated events.

In general, the under-voltages were observed to be caused by three main reasons:

1. High nanogrid total load (AIRB + EVSE), which lowers the upstream source voltage at T-131 Primary bus
2. High inverter AC (BESS + PV) output power: The conductor used for the inverter (AWG 3/0) is much more resistive compared to the one used for the EVCS connection (350 kcmil). Thus, the more PV and BESS power outputted to supply the EVSEs, the bigger the voltage drop at its interconnection bus.
3. High EVCS load: When EVCS demand is high, a more severe voltage drop is caused at T-131 PRIM, the most upstream bus in the system, where the 12 kV source (UC-9 from UCI Microgrid) is connected. This voltage drop further deteriorates at the buses downstream due to normal conductor voltage drop.

In PLS mode, no under-voltages occurred. This can be explained by two main reasons:

1. Neither inverter nor EVCS outputs exceeded 45 kW (Figure 67). Recall that until 12:00 PM, the inverter only outputs the PV generation (40 kW peak), while the remainder EVSE demand is met by EVCS grid power (30 kW peak). The peak EVSE occurred before the battery discharge, at 10:45 AM (56 kW), thus the inverter did not try to match the EVSE demand at this time. After

12:00 PM, when the BESS starts to discharge, the EVSE usage is already reduced. Lower simultaneous (EVSE, EVCS and INVERTER) high power flows in the system means lower conductor voltage drops that will not cause a voltage problem.

2. The PV export in the afternoon reduces the nanogrid total load in this time (AIRB peak load), increasing the voltage at T-131 SEC.

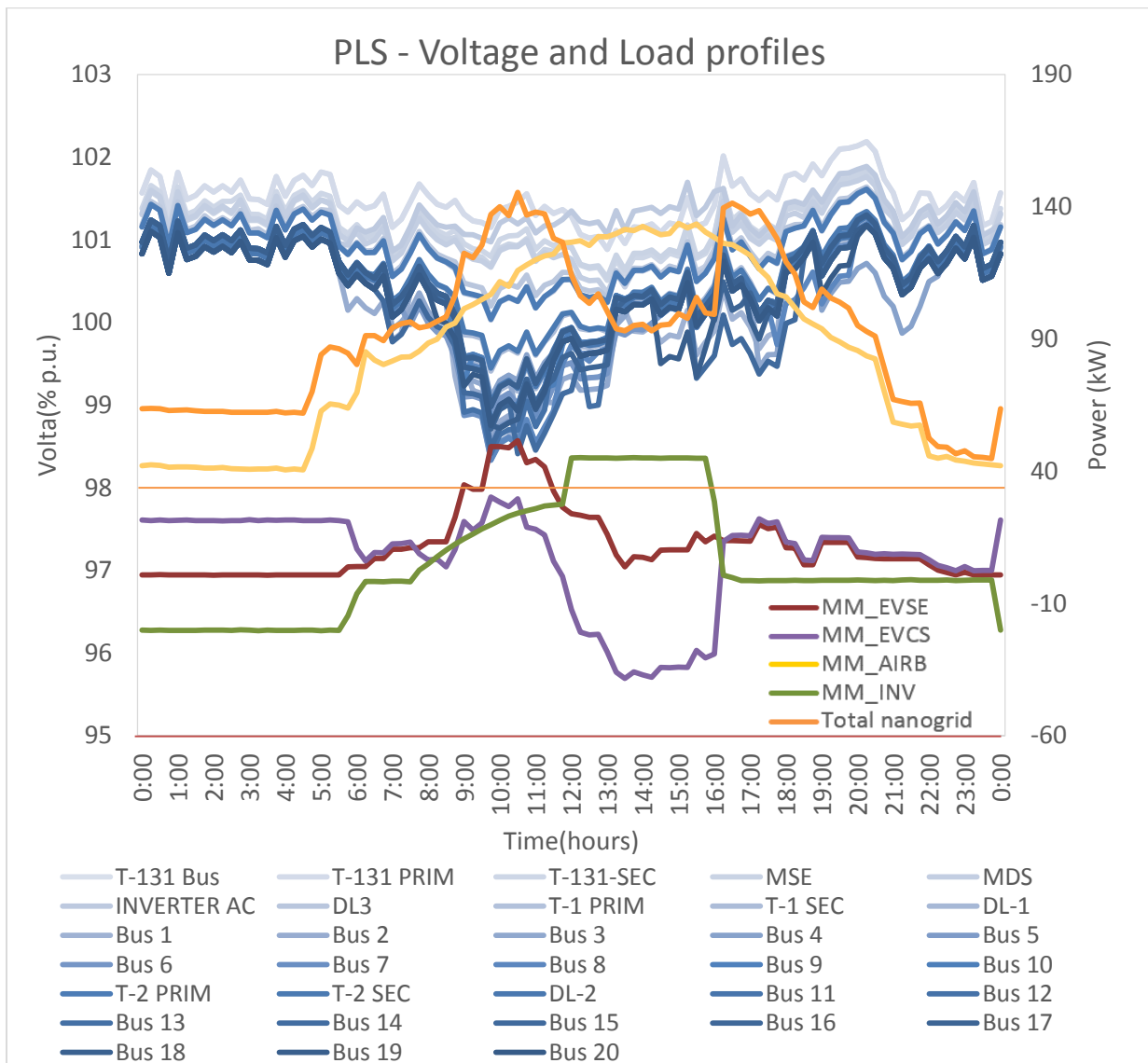


Figure 67: PLS voltage and load profiles

In MPPI mode, the BESS will discharge to meet all EVSE demand and zero-out EVCS. Noticing how in Figure 68 MM_EVSE and MM_INV curves overlap. These high simultaneous power flows lowered the voltage at the upstream MSE bus. Marginal under-voltages were detected (from 10:00 AM to 1:30 PM) in almost all EVSE terminal buses feeding EVSEs that were used. The nanogrid total load matches AIRB load after BESS starts discharging at 9AM

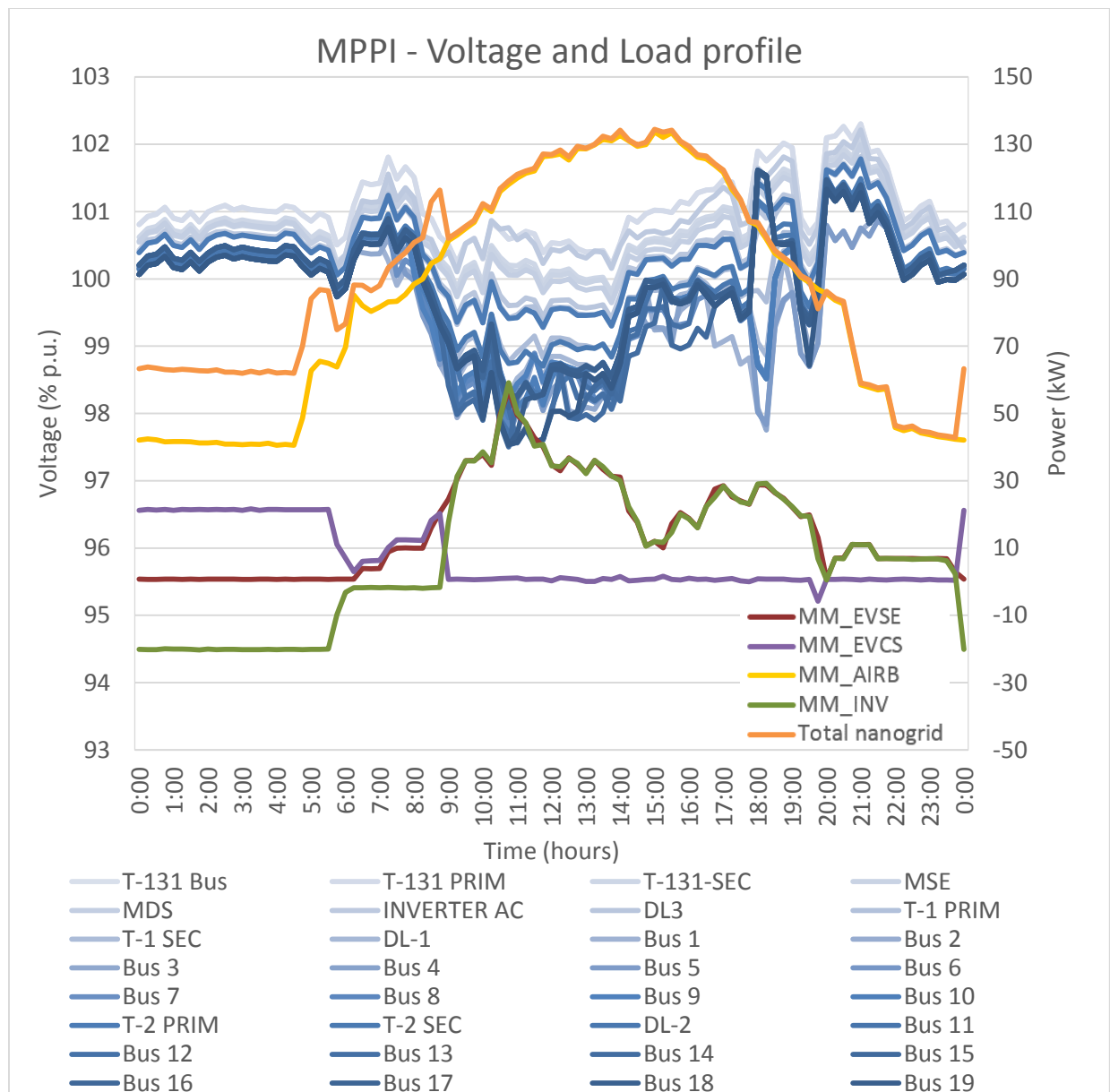


Figure 68: MPPI voltage and load profiles

In CAP demand 20 kW, the under-voltage problem is the most severe. Under-voltages extended to bus DL-3. The voltage at terminal EVSE buses was less than 95% in four buses for 15 minutes, coinciding with peak nanogrid load. Recall that in this mode, EVCS will always consume 20 kW, increasing the total nanogrid load to AIRB + 20 kW. Higher nanogrid total load lowers the upstream source bus voltage. Progressive conductor voltage drops downstream caused under-voltage problems from 9:15 AM to 4:00 PM.

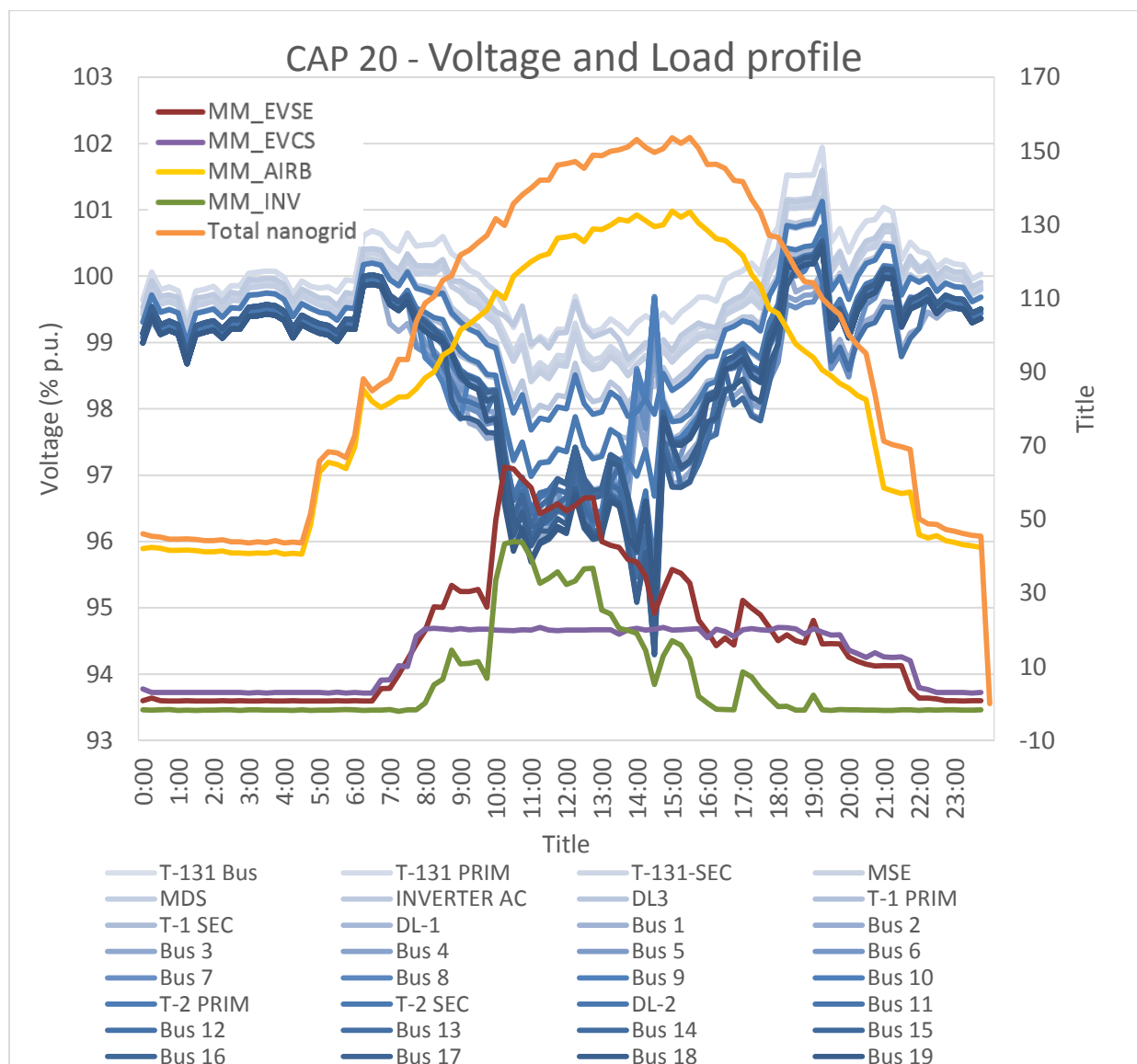


Figure 69: CAP 20 voltage and load profiles

CAP 15 and 10 showed less severe voltage drops, reinforcing the previously observed relationship between nanogrid total load and source voltage. In CAP 15 mode, the nanogrid load is AIRB + 15 kW, and CAP 10 mode, AIRB + 10 kW. However, results show that CAP 10 mode showed more under-voltages due to a slight higher EVSE load on that particular day simulated. Usually, since in CAP 10 nanogrid loads are smaller, fewer under-voltages are expected.

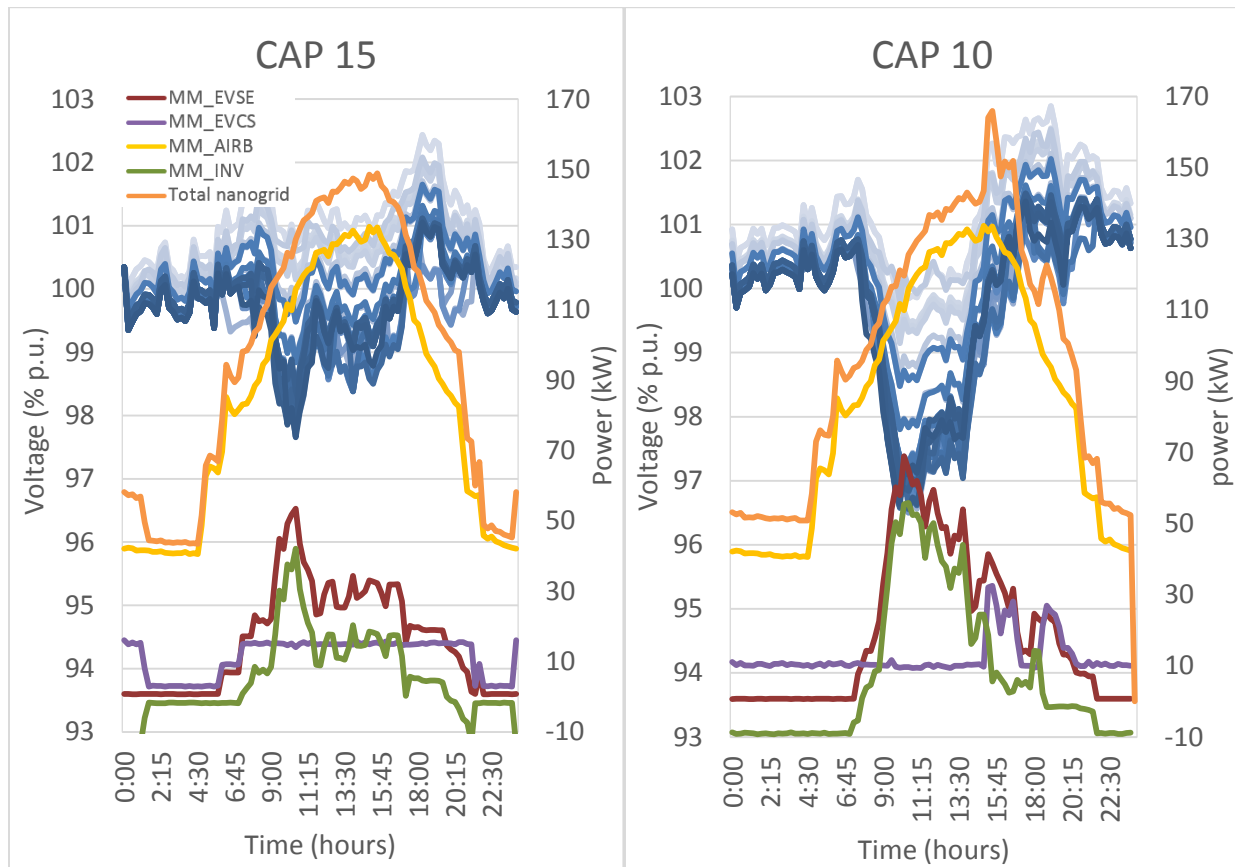


Figure 70: CAP 15 and CAP 10 voltage and load profiles

In PV Capture mode, recall that the EVCS demand will be always zero-out throughout the day, thus, the nanogrid load is solely AIRB loads. Thus, it is expected that under-voltage problems are not severe. However, since the EVSE peak loads matched AIRB peak loads in

this particular day, the source voltage (already low because of high nanogrid loads) was further dropped by simultaneous high inverter outputs and EVSE usage (conductor voltage drop).

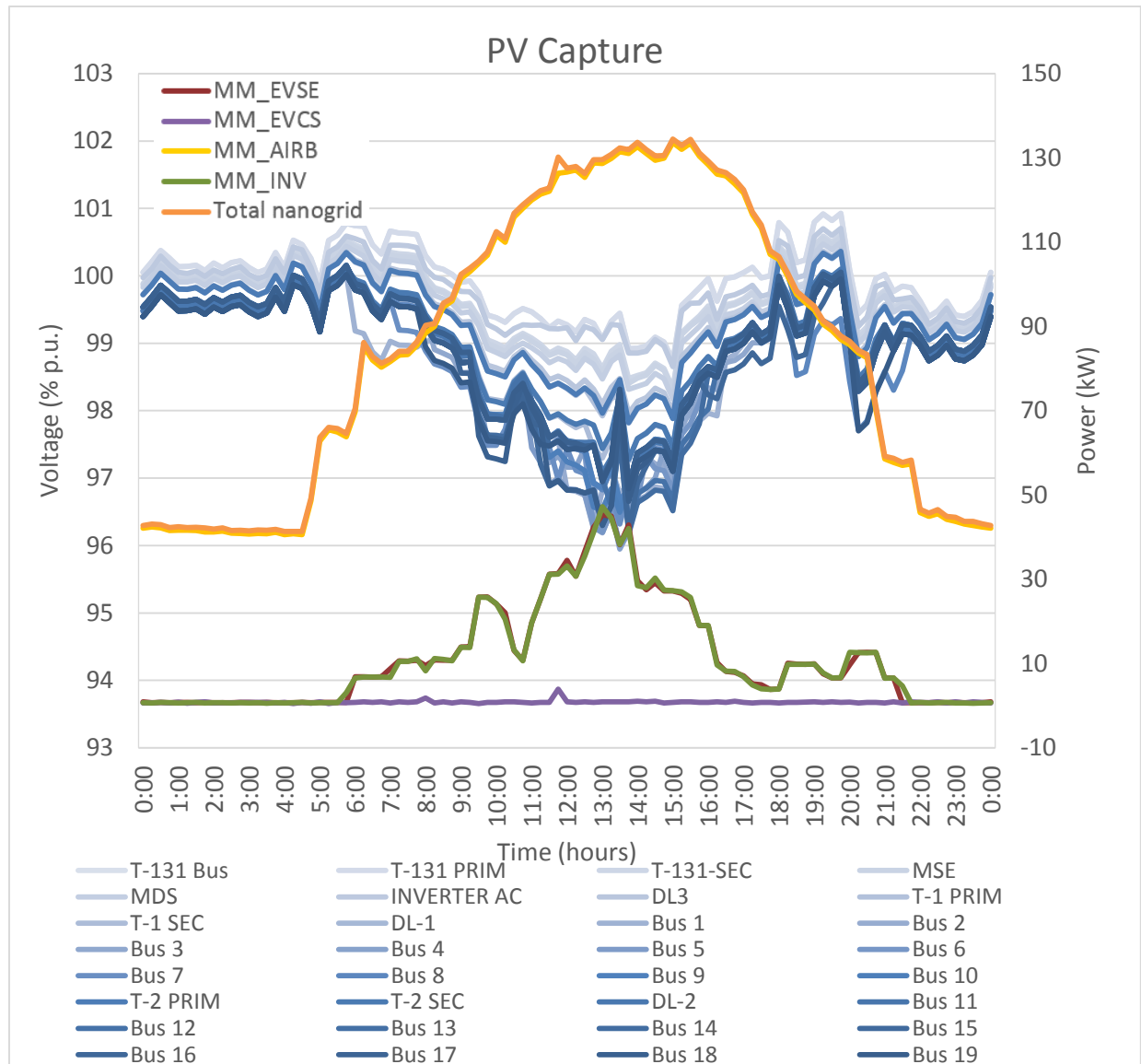


Figure 71: PV Capture voltage and load profiles

5.3.1. Preferred BESS dispatch modes

Here, BESS modes were compared in four distinct figures of merit: (1) impacts on the nanogrid voltage, (2) ability to net-zero the daily EV charging demand, (3) curtailed PV, and (4) renewable penetration (results from Section 5.1.3). Table 13 compares the modes using the criteria mentioned above. Ideally, the operation modes should not cause voltages below 95%, operate seamlessly in the UCI Microgrid (net-zero) and promote PV integration, with small or no curtailment. Under-voltage daily time indicates the percentage of the time during the day that the system presented at least one under-voltage bus (95% p.u. or 98% p.u.) for any given 15-minute period.

In terms of impacts in the system, the PLS mode had best performance; this can be attributed to non-simultaneous high power flows in the system. The worst performance observed was during CAP 20.

Table 13: BESS operation modes figures of merit results

Mode	Under-voltage Daily time (%)		Solar EV Charging (%)	Solar Penetr- ation (%)	Net EVCS demand (kWh)		PV Curtailment (kWh)
	98% p.u.	95% p.u.			Curtail	No Curtail	
PVCAP	30	0	80	89	-	61	0
MPPI	14	0	68	89	-	116	0
CAP 10	21	1	62	85	159	147	12
CAP 15	2 ⁽¹⁾	0	58	75	184	143	40
CAP 20	35	2	56	71	188	137	52
PLS	0	0	31	95	-	33	0

⁽¹⁾ During this day, a slightly reduced load caused the results not to follow the trend.

In terms of Solar EV charging, PV Capture ranks first with 85% of the EVSE load met entirely by solar. When in CAP mode, the higher the kW threshold, the smallest the EV charging contribution, since more power will be taken from the grid. Overall, the worst performance was PLS mode (31%), since most of the EVSE demand is met with grid power, shifted from the nighttime to the afternoon.

However, in terms of Solar Penetration, PLS showed the best performance (95%) since, instead of charging the BESS with excess solar during the day, it allows a high PV export in the afternoon (which saves the BESS round trip efficiency losses). PV Capture and MPPI tied in second (89%) since they use the same day-charging algorithm; here, BESS roundtrip efficiency plays an important role. The worst performance was produced by the CAP 20 mode (71%) since the BESS remains mostly fully charged and shows the highest amount of PV curtailed (52 kWh). Again, a high CAP threshold decreases renewable contribution.

In terms of NET EVCS demand, PLS mode ranked first, since all PV export contributed to the lowest net-import of 33 kWh. It is important to observe that the modes' SOC in the end of the day was 10%. This plays an important role in this figure of merit: the BESS was fully charged in the middle of the day and was able to buffer the evening loads completely, reducing grid import. PV Capture comes in second, where the SOC behavior is the complete inverse of PLS mode: without overnight charging, the SOC progressively drops during the morning and in the later morning though the afternoon, the BESS stays fully depleted for 2.5 hours. Only then, it starts charging with excess PV, which was mostly exported on PLS and this does not contribute to offsetting net-imports.

One last interesting observation is that the option of curtailing PV in CAP modes determines whether low or high thresholds are more efficient for a lower net import.

5.4. Task 4: Characterize Power Quality aspects of EV Charging

5.4.1. Power Quality Survey

The objective of the power quality survey was to characterize the power quality at the Car Shade and to both verify and refine the ETAP PQ model. During two weeks in May 2015, the system was monitored using two Dranetz© PowerXplorer PX5 (256 samples/cycle) power quality meters. The instruments were installed to monitor two EVSEs individually: EVSE 6 (point 1) and EVSE 8 (point 2), and to monitor the secondary of transformer T1 (point 3), which feeds 10 EVSEs. The installation locations are shown in Figure 72. Pictures taken during the installation are displayed in Figure 73.

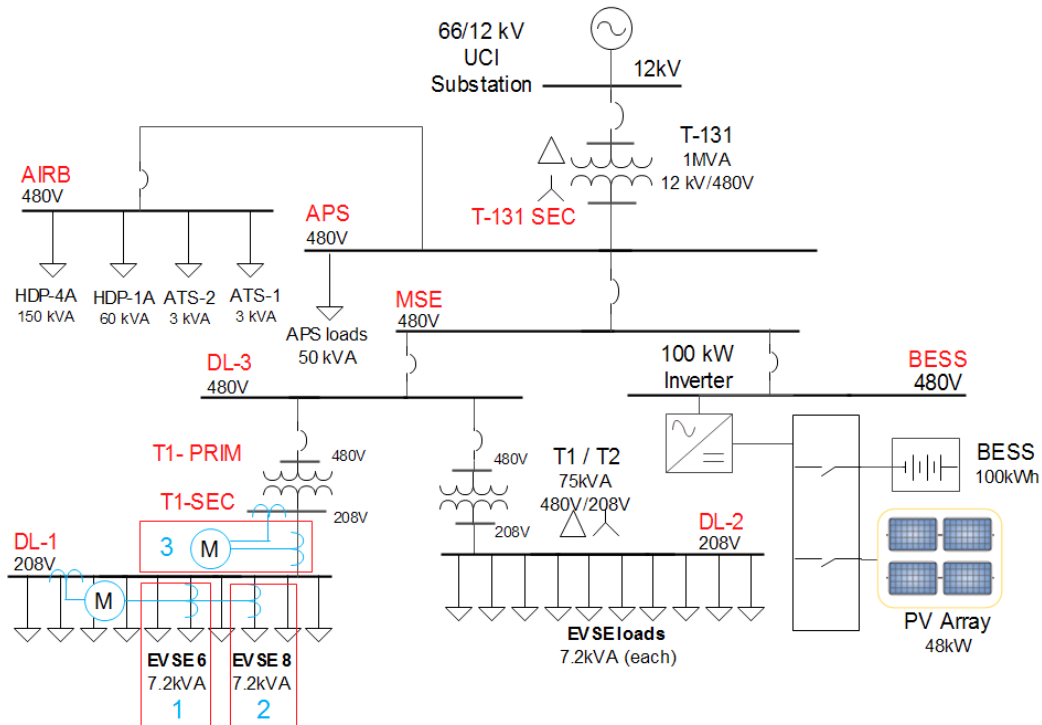


Figure 72: PQ Meter installation points: EVSE 6(1), EVSE 8(2), and T1-SEC (3).



Figure 73: Power quality equipment installation by SCE Field Engineer.

According to IEEE 159-1992, a system's power quality should be evaluated at the PCC. In this study, due to limited PQ meter availability, the most upstream monitoring point was not the actual PCC, which is at bus MSE, but at the secondary side of transformer T1. However, since most of the non-linear loads are located downstream of bus T1-SEC, it is still a good location to monitor and identify most of the PQ problems that could be associated with EV charging. The programmed trigger thresholds are listed in Table 14.

Table 14: Dranetz® PowerXplore Trigger Thresholds

Current probes							
Chan A, B, C, and D	TR2021, 1A-30A RMS (Scale=20.00)						
Voltage scale factors							
Chan A, B, C, and D	1.000						
Current scale factors							
Chan A, B, C, and D	1.000						
Limit Setups							
Voltages	A	B	C	D	A-B	B-C	C-A
RMS High:	126.0	126.0	126.0	132.0	0.0	0.0	0.0
RMS Low:	114.0	114.0	114.0	108.0	0.0	0.0	0.0
RMS Very Low:	12.0	12.0	12.0	12.0	0.0	0.0	0.0
Crest:	255.0	255.0	255.0	255.0	0.0	0.0	0.0
Wave:	24.0	24.0	24.0	24.0	0.0	0.0	0.0
DC:	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DEG:	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WAVE Window Mag:		24.0	24.0	24.0	24.0	0.0	0.0
	0.0						
WAVE Window Dur:	15.0	15.0	15.0	15.0	0.0	0.0	0.0
HF:	200.0	200.0	200.0	0.0	0.0	0.0	0.0
Periodic Journal Intervals							
Voltage	10.0 minutes						
Current	10.0 minutes						
Power	10.0 minutes						

For analyzing harmonic distortion levels during the survey, the 95% probability value (a value that is a threshold that will not be exceeded for 95% of the time) commonly used in industry to process measured harmonic data over an extended period, is adopted here to determine harmonic distortion problems. This will exclude the outlier high THD_i values. When the maximum distortion value recorded is to be considered, it will be indicated.

5.4.1.1. Power Quality Events

Transients in the phase voltage waveforms were the most significant power quality event. These transients were both impulsive and oscillatory in the low and mid-frequency range. The events could be precisely associated with EVs plugging into the system. Such transients are caused by the power electronics (switching and capacitor charging) on the on-board charger of the vehicles.

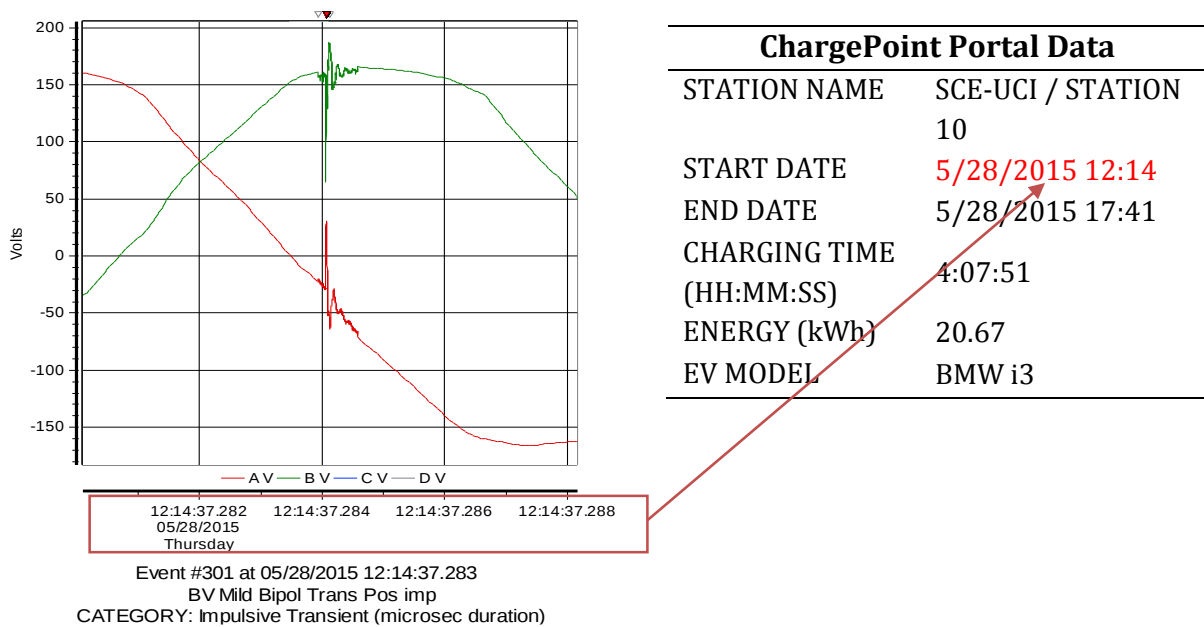


Figure 74: Impulsive Transient Event at EVSE 8

For impulsive transients, taking an average of all events observed, the rise time was 5.66 microseconds (μs), and the worst peak-to-peak was 119 % p.u. For oscillatory transients, the average frequency was 14.7 kHz. These types of transients are in the voltage tolerance envelope applicable to single-phase 120 V equipment, the "no interruption in function" region of the ITIC CBMA curve [46]. Thus, they do not pose a threat to either

sensitive electronic equipment operation, equipment degradation or insulation failure, as higher magnitudes and faster rise time transients would (IEEE 1159-2009).

Moreover, propagation of transients across the system was observed since EVSE 6 and 8 were the ones being monitored and the events were mostly originated at EVSE 1 and 10 (as times that transients occurred matched with cars being plugged-in to these EVSEs). The low frequency range of these transients allows for propagation even further upstream in the system. A propagation event can be observed in Figure 75, where an impulsive transient detected first at T1 secondary in Figure 75 (a) propagated to EVSE 8 terminals in Figure 75 (b).

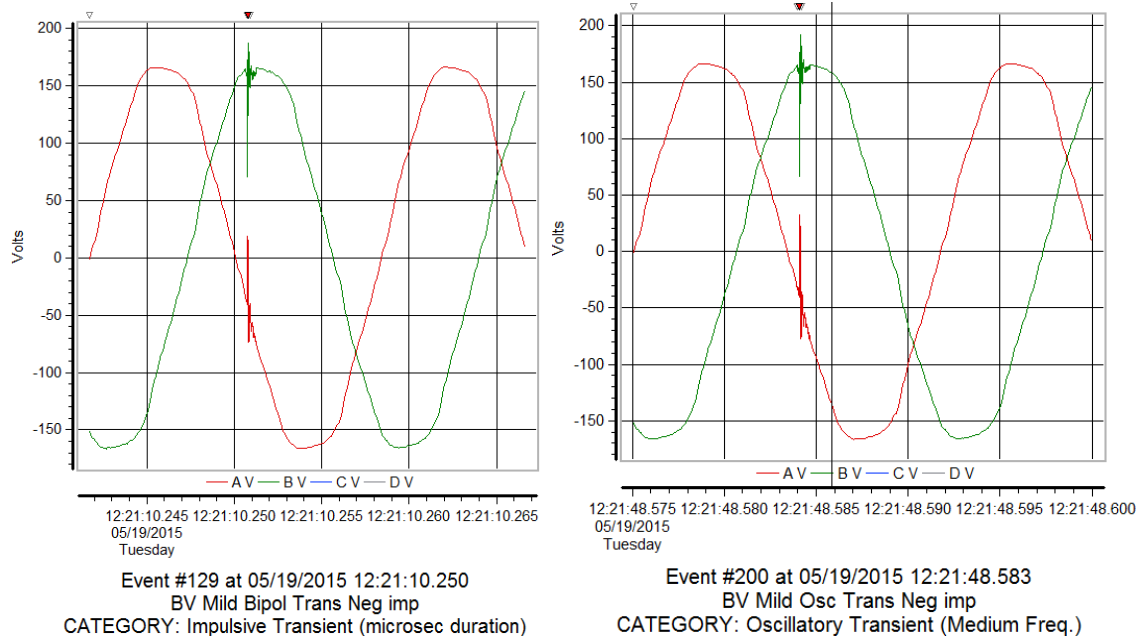


Figure 75: Transient propagation on Phase B (left) Impulsive transient at T1 secondary (right) Oscillatory transient at EVSE 8 terminals

A couple other transient events were detected that could not be associated with any EV plug-in event. These events are most likely associated with the capacitor bank

switching on the utility network side, or some unknown dynamic associated with the onboard vehicle chargers.

5.4.1.2. Current Total Demand Distortion (TDD_i) and Individual Harmonic Distortion (IHD_i)

Here, the total and individual current distortion TDD_i and IHD_i at the Car Shade's most upstream monitored point, T1-SEC, is characterized.

For practical purposes, only harmonic magnitudes up to the 15th order were taken as significant (

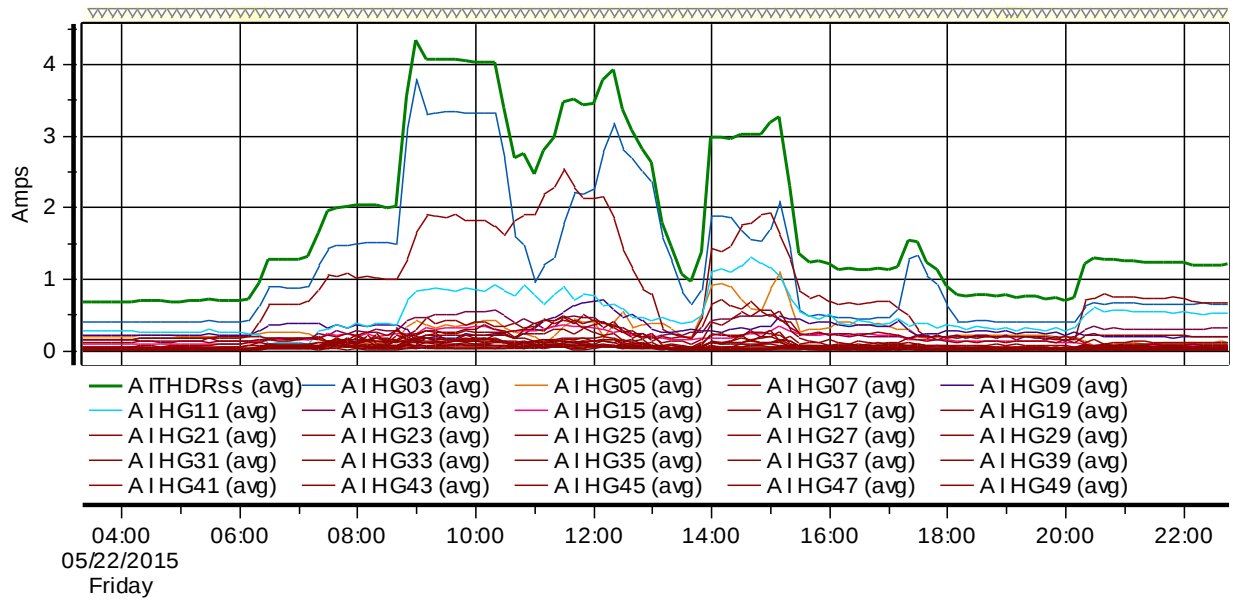
From Figure 77 it can also be observed that above the 15th harmonic order (curves in red) the current magnitudes are so reduced that they can be disregarded to simplifying the analysis.

). Higher frequency harmonics (monitored up to the 50th order) occur, but with a much reduced magnitude, mostly below 0.5 A.

The harmonic current profile in Amps can be observed in

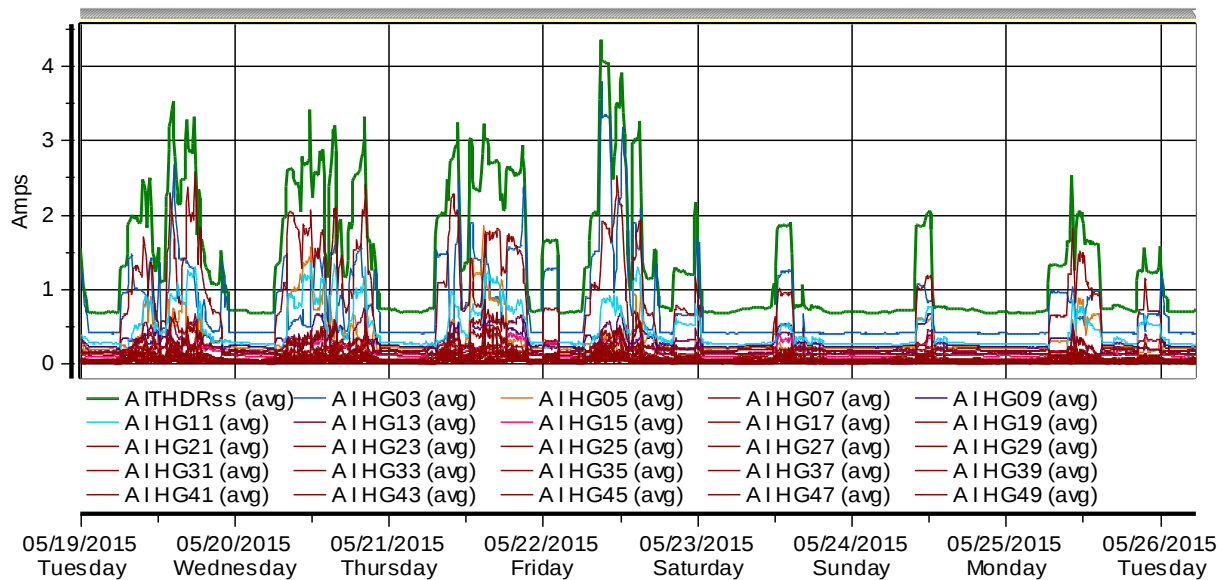
From Figure 77 it can also be observed that above the 15th harmonic order (curves in red) the current magnitudes are so reduced that they can be disregarded to simplifying the analysis.

for a single day and in Figure 77 for the whole week. The direct relationship between EV charging and harmonic inputs is clear from observing that the harmonic currents are proportional to the fundamental current drawn by the EV chargers.



**Figure 76: T1-SEC Phase A Current Harmonics (Amps) (H03 to H49)
(Friday 05/22/2015)**

From Figure 77 it can also be observed that above the 15th harmonic order (curves in red) the current magnitudes are so reduced that they can be disregarded to simplifying the analysis.



**Figure 77: T1-SEC Phase A Current Harmonics (Amps) (H03 to H49)
(Tuesday 05/19/2015 to Tuesday 05/26/2015)**

Hence, the average values for the harmonic currents up to the 15th order, over a week timeframe, are shown in Table 15. The minimum, average, maximum and 95% statistical value listed were calculated using the PQ software *Dranview*©.

Table 15: T1 –SEC Phase A Current IHD_i (Amps) and THD_i Rss (Amps)
(Tuesday 05/19/2015 to Tuesday 05/26/2015)

	Min	Avg	Max	95%
AITHDRss	0.67	1.32	4.34	2.92
AIrms	0.98	19.75	102.80	68.47
AI HG01	0.71	19.75	102.70	69.51
AI HG03	0.33	0.75	3.80	1.58
AI HG05	0.05	0.32	1.86	0.91
AI HG07	0.14	0.64	2.59	1.86
AI HG09	0.02	0.28	0.72	0.53
AI HG11	0.10	0.44	1.37	1.03
AI HG13	0.09	0.23	0.76	0.52
AI HG15	0.02	0.15	0.41	0.31

From the 95% data, the TDD_i and IHD_i , as a percentage of I_L were calculated (Table 16). Here, for simplicity, I_L was assumed to be the maximum RMS value of Phase A current recorded during the survey, thus $I_L = 102.7 A$. In addition, to determine the I_L/I_{SC} ratio, the system short circuit current was calculated (using ETAP Short Circuit module) to be $I_{SC} = 19 kA$, thus the system's $I_L/I_{SC} = 0.005$, so the standard Table 10.3 row for $I_L/I_{SC} < 20$ is to be used here which limits:

- **IHD_i** : 3rd - 11th order < 4% and 11th - 17th order < 2%
- **TDD_i** < 5%

Table 16: T1-SEC Phase A Current IHD_i and TDD_i (% I_L)

IHD (% I_L)	
AI HG03	1.53
AI HG05	0.89
AI HG07	1.81
AI HG09	0.52
AI HG11	1.00
AI HG13	0.50
AI HG15	0.30
TDD	2.84

It was observed that no individual harmonic orders registered IHD_i magnitudes above those recommended by IEEE 519-1992 (Figure 78). Moreover, since measurements were taken at the secondary of T1, which has a delta-wye grounding scheme, the triplen harmonics would not propagate upstream in the system and thus it is expected that the TDD upstream in the system will be even lower.

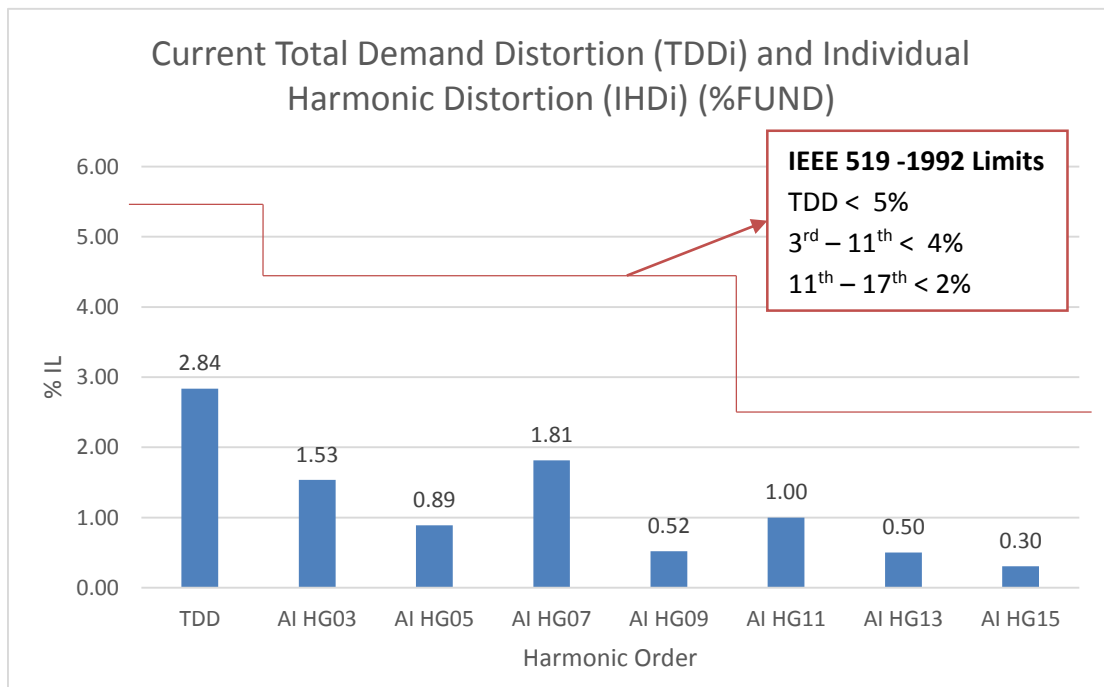


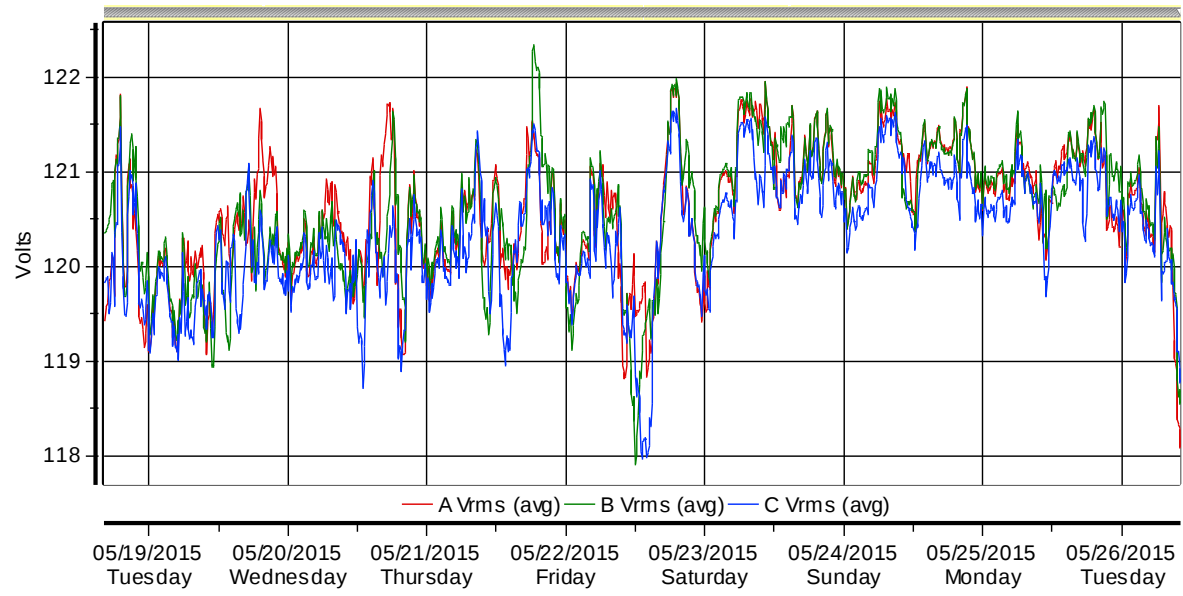
Figure 78: T1-SEC –Phase A TDD_i and IHD_i (% I_L) 95% values

The distorted current waveform does not have a typical shape or pattern since during operation, the random phase unbalances of EV charging create different levels of waveform distortion and THDs. To illustrate the last statement, the phase RMS current and THD are shown for six snapshots in time in Appendix A. As expected, the largest harmonic distortion (THD) occurs when EVSE usage is maximum, i.e., when the current RMS values are also maximum.

5.4.1.3. Voltage Total Harmonic Distortion (THD_v) and Individual Harmonic Distortion (IHD_v)

Here, the total and individual voltage distortion THD_v and IHD_v at the Car Shade's most upstream monitored point, T1-SEC, will be characterized.

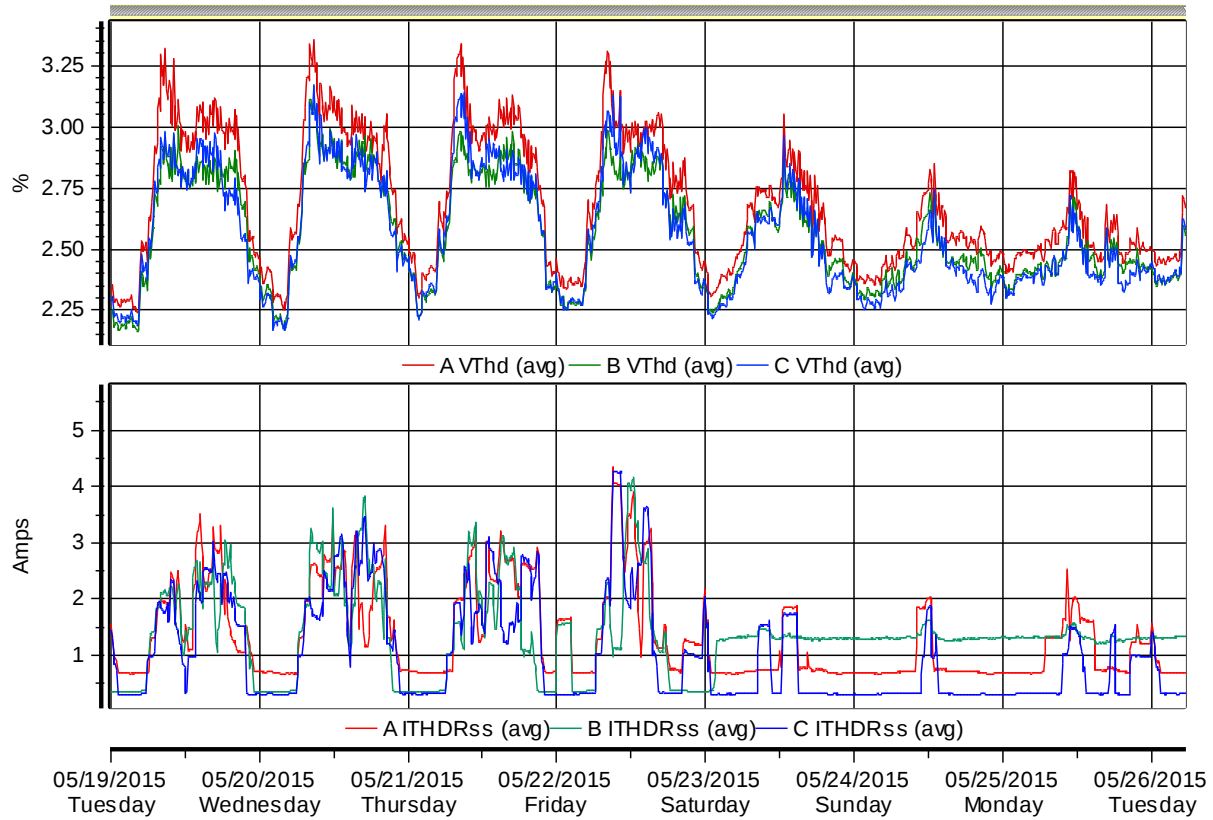
First, the system RMS voltage profile needs to be described. During a week observation timespan (Tuesday 05/19/2015 to Tuesday 05/26/2015), the recorded RMS voltage (Figure 79) remained within the acceptable range of 114 V – 126 V, established in the ANSI Standard C84.1-1995.



	Min	Average	Max	95%
A Vrms	118.8	120.6	122	121.6
B Vrms	117.9	120.6	122.3	121.7
C Vrms	118	120.4	121.7	121.4

Figure 79: T1-SEC Phase A, B, and C RMS Voltages

The THD_v (percentage of fundamental, FUND) at phases A, B and C was recorded Figure 80 (top) during the same week. The voltage distortion is directly related to EV charging, as can be observed in Figure 80 (bottom); the THD_v increases when the system current distortion THD_i increases as well, i.e., when the EVSEs usage increases. Therefore, the THD_v is higher during the weekdays and lower during weekends.



	Min	Avg	Max	95%
A VThd	2.24	2.70	3.35	3.21
B VThd	2.16	2.57	3.11	2.91
C VThd	2.17	2.57	3.17	2.94

	Min	Avg	Max	95%
A ITHDRss	0.67	1.75	4.34	3.26
B ITHDRss	0.34	1.55	4.15	3.18
C ITHDRss	0.30	1.49	4.28	3.09

Figure 80: T1-SEC Phase A, B, and C THD_v (top) THD_v and THD_i correlation (bottom)

The worst 95% THD_v (3.21%) occurred in Phase A, since the system is unbalanced. According to IEEE 519-1992 standard Table 11.1, systems up to 69 kV should not exceed

5%. Thus, the THD_v is not a concern with regard to IEEE standards at this point in the system.

A typical voltage waveform recorded during maximum THD_v (3.35 % at Phase A) is displayed in Figure 81, where not only Phase A, but also phase C are visually more distorted. This uneven distortion between phases occurred since EVSEs are single-phase loads; therefore, phases A, B, and C are subjected to different harmonic inputs. At that moment in operation, all EVSEs being used downstream were EVSE 1 (CB), charging a Nissan Leaf, EVSE 7 (AC), a Chevrolet Volt, and EVSE 10 (AB), a Chevrolet Spark. Among these EVs, the Volt produces higher THD_i (7.5%) (individual EV THDs is assessed in the next sections), which translates into a greater distortion in the voltage waveform of phases A and C.

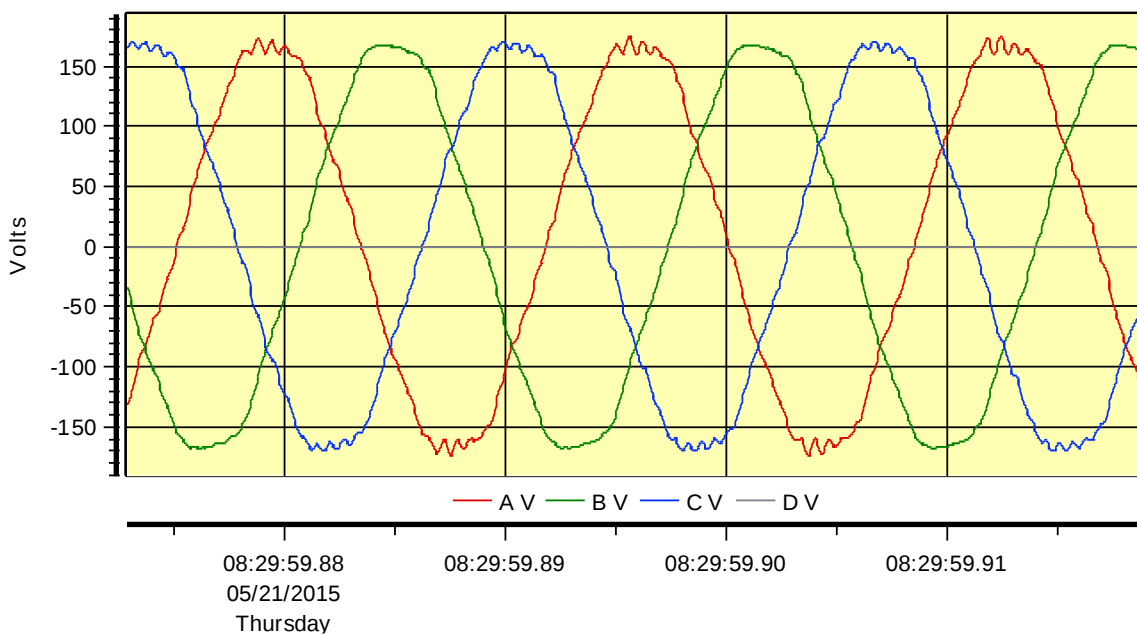
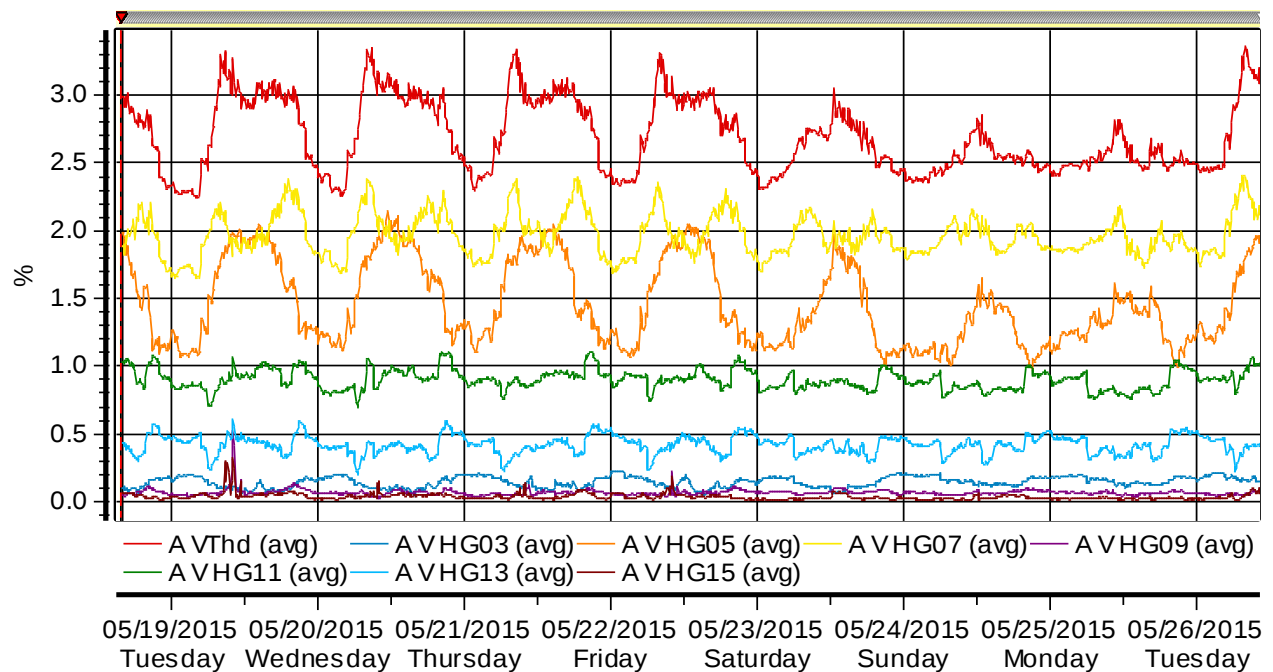


Figure 81: T1-SEC Phase A, B and C Voltage Waveforms at maximum THD_v (3.35 % Phase A) (Thursday 05/21/2015)

The IDH_v (Figure 82) was also monitored to determine the system's voltage harmonic spectrum (Figure 83). In the Car Shade, the major contributions to distortion come from the 7th and 5th orders. Recalling IEEE 519-1992 recommendations of keeping a $IDH_v < 3\%$, (standard Table 11.1) we can observe that none of the individual harmonic orders exceed this desirable limit. In fact, an isolated excessive IDH_v is not a major concern, since individual orders are limited with the main aim to control the total distortion THD_v , which was already observed to be within allowed limits.

These results prove the ability of the Car Shade system to absorb the harmonic currents without exceeding voltage distortion limits.



	Min	Avg	Max	95%
A VThd (%)	2.24	2.68	3.35	3.12
AV HG03	0.04	0.14	0.23	0.20
AV HG05	0.96	1.45	2.15	1.98
AV HG07	1.64	1.96	2.39	2.24
AV HG09	0.02	0.07	0.52	0.10
AV HG11	0.70	0.90	1.11	1.03
AV HG13	0.20	0.42	0.61	0.52
AV HG15	0.01	0.04	0.32	0.07

Figure 82: T1-SEC Phase A IHD_v

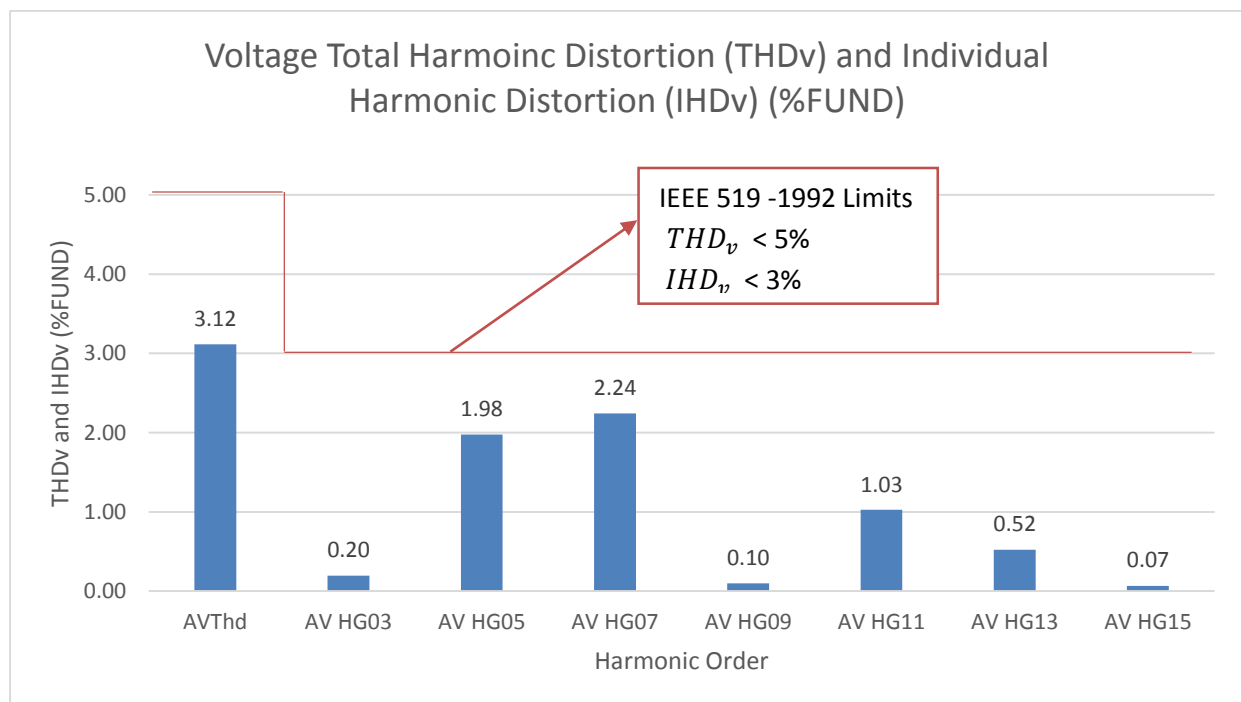


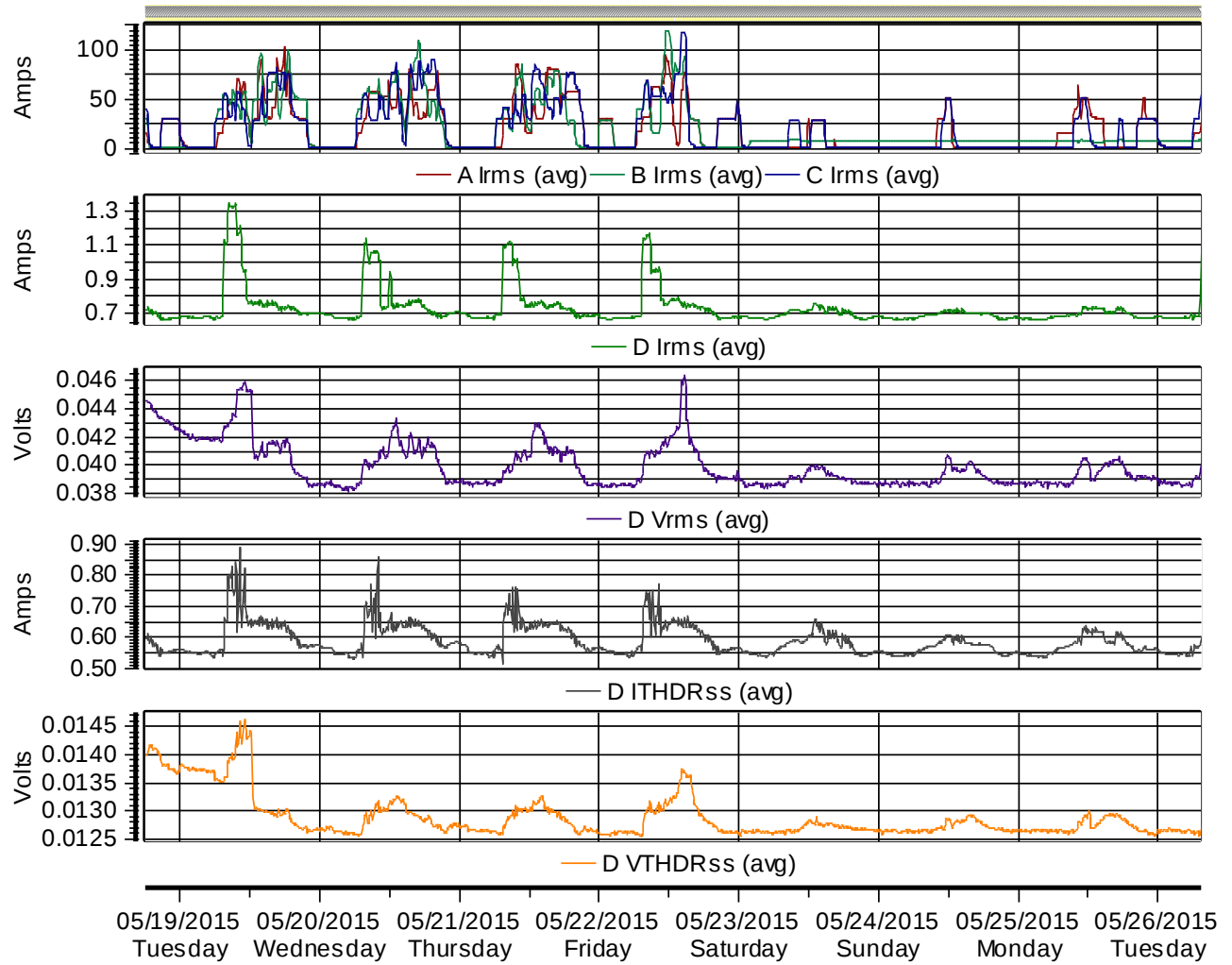
Figure 83: T1-SEC Phase A THD_v and voltage harmonic spectrum (95% values)

5.4.1.4. Neutral Conductor

The neutral conductor was monitored during the survey using Phase D probe on the PQ meter. Since EVSEs are dual-phase loads, the Car Shade is an unbalanced system where fundamental phase currents are not the same and do not cancel in the neutral. Thus, it was expected that a 60Hz current could be detected on the neutral conductor. Furthermore, dual-phase connected EVSEs inject the same harmonic in only 2 phases; therefore, harmonic currents in the neutral wire that do not get cancelled were also expected to be observed — especially triplen harmonics, which are naturally additive in the neutral. It is important to recall that even when charging at Level 1, the EVSEs uses a dual-phases connection (not phase-neutral), in which both phases draw a reduced current.

Since 1991, the National Electrical Code (NEC) considers the neutral wire as a current carrying conductor, recognizing unbalance issues and problems brought on by non-linear loads. At the Car Shade system, the neutral wire is a copper 1/0 AWG, which has a rated ampacity of 125-170 A (depending upon its temperature rating).

During the survey period, the RMS neutral current registered a maximum of 1.35 A (65% THD_i) and the maximum neutral RMS voltage was 0.05 V (20% THD_v), most likely when phase imbalance was highest due to strong EVSE usage. Although percentage values might seem high, they do not pose a threat of increasing the neutral currents above the recommended limit. According to [47], a 1.73 p.u. neutral current is accepted. As a result, a minimum of 70.7% line current THD is required to reach this maximum, and in practice, it typically takes 80–90% THD to achieve maximum neutral levels.



	Min	Avg	Max	95%
D Irms	0.66	0.73	1.35	1.02
D Vrms	0.04	0.04	0.05	0.04
D VTHDRss	0.01	0.01	0.01	0.01
D ITHDRss	0.51	0.59	0.89	0.67

Figure 84: T1-SEC Phases A, B, and C current (top), neutral current (middle), neutral THD_i (middle), and THD_v (bottom)

5.4.1.5. EV Charging Profiles Characterization

This section aims to determine the potential impact of different EV models available in the market as individual harmonic sources, and ultimately to characterize their signature current harmonic inputs based upon power quality measurements taken at the measurement point 1.

The highly dynamic profile of EV charging power is a function of many factors such as the charger-battery system topology, charging strategy, battery initial SOC and temperature, ambient temperature, and others [48]. A different impact on the AC side will be produced depending upon the charging current, in other words, depending upon the different stages in an EV charging profile [49].

Typical expected current profiles for a Li-ion based battery charging process are shown in Figure 85, for both uncontrolled and controlled (with additional tools to improve charging conditions, like power factor correction — PFC) charger topologies.

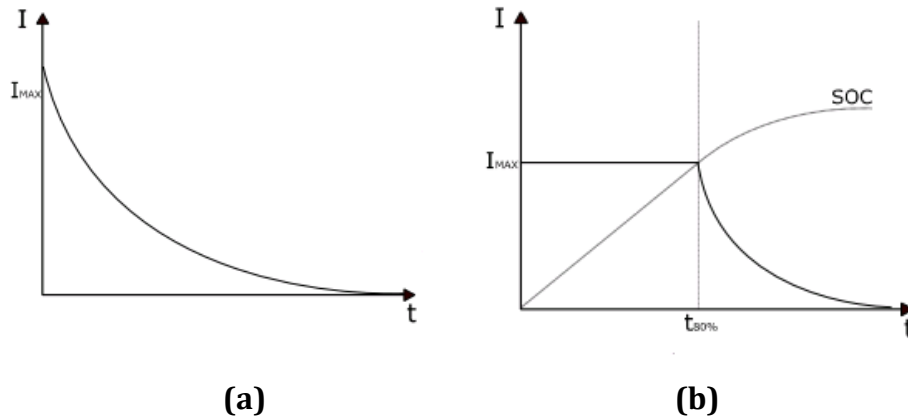


Figure 85: Current charging profiles for (a) uncontrolled and (b) controlled charging

The fundamental current clearly varies during charging. However, a higher fundamental current does not always mean a higher harmonic input. That is the case for

the Nissan Leaf charging profile (Figure 86), for instance. Its charging event can be divided into 3 clearly distinct regions: Region 1, where the fundamental current magnitude is at its maximum. Region 2, where the fundamental current progressively drops with time as the battery reaches its full SOC, and a simultaneous increase in the 3rd harmonic increases the $ITHD_i$ (Amps). Region 3, where both fundamental and harmonic currents drop with time. The maximum THD_i in Amps occurs in Region 2, but the maximum THD_i percentage occurs in Region 3 due to reduced fundamental magnitude.

In this study, the characteristic harmonic input for each EV model assumes the worst-case (maximum) recorded individual harmonic order magnitudes in Amps, averaged over all charging events that occurred for of each EV model during the survey observation time.

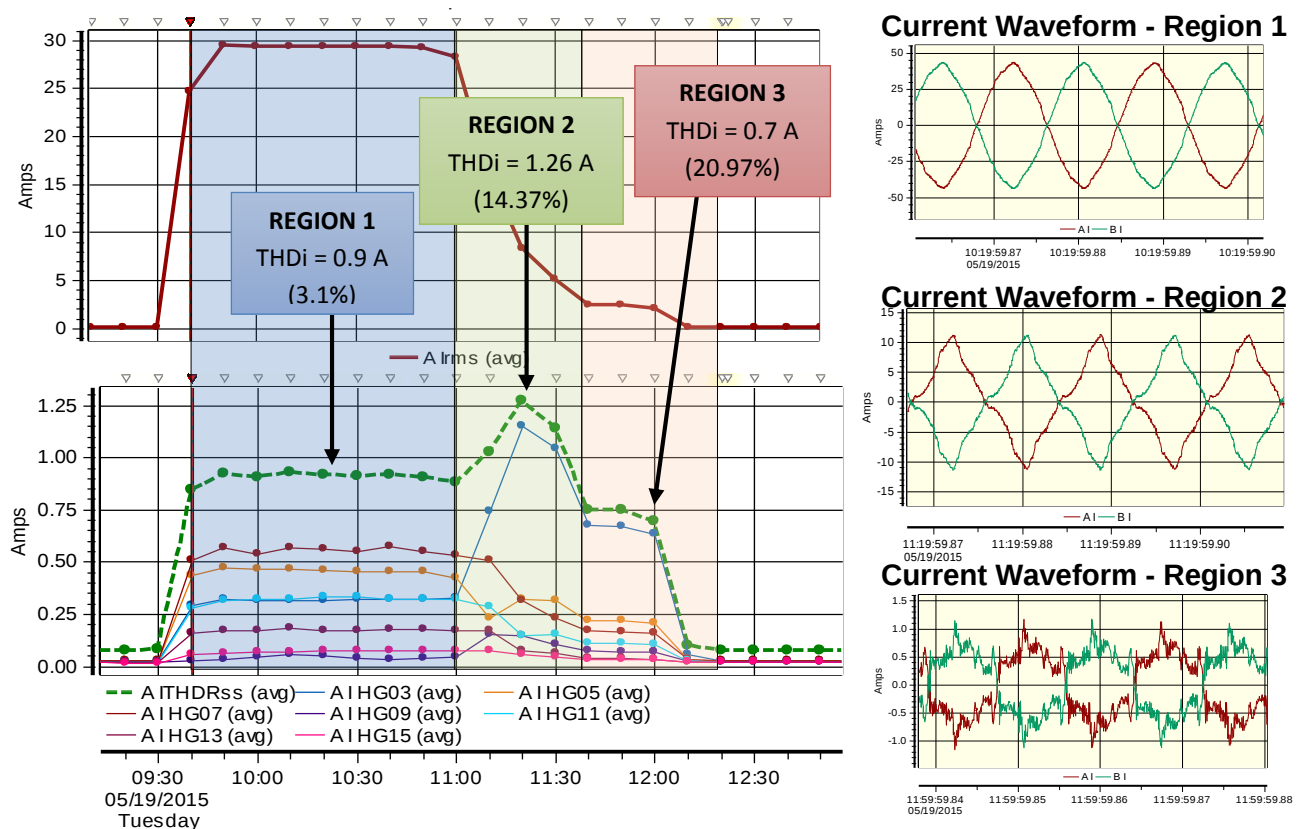


Figure 86: Nissan Leaf charging current profile and current waveforms

A similar profile can be observed for the Toyota Prius and BMW i3, whose illustrations were included in Appendix B.

For most other EV models, however, the charging currents (fundamental and harmonic) remain approximately constant during the entire charging event. That is the case for the Tesla model S (Figure 87). The illustration for the Volt, Kia Soul, and Mercedes EV are shown in Appendix B.

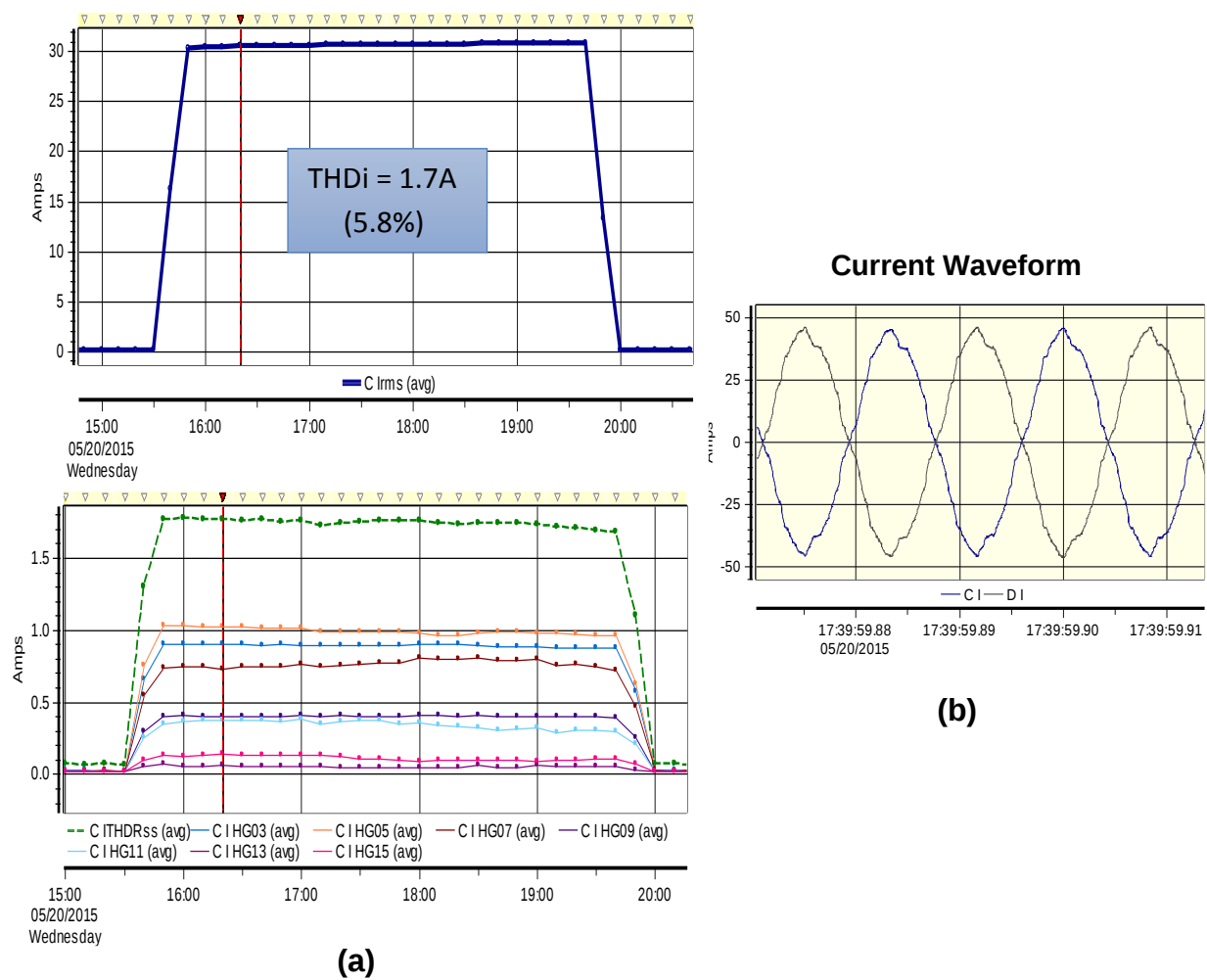


Figure 87: (a) Tesla Model S charging current profile (b) Current Waveform

Due to the diversity of charging profiles and on-board charger topologies, each EV model will produce a different. Considering worst-case IHD_i inputs, a signature harmonic input profile can be defined for each EV model. In Figure 88, for eight different EV models, the averaged harmonic input (from the 3rd to the 15th order) is presented in Amps. It is interesting to notice that harmonic magnitudes will not necessarily decrease with frequency, in other words, decrease in the ordered sequence: 3rd, 5th, 7th order. The Volt, for instance, has a dominant 3rd harmonic order (1.23 A), followed by the 7th (0.57 A). The Tesla, however, has a dominant 5th order (1.04 A), followed by the 3rd (0.9 A).

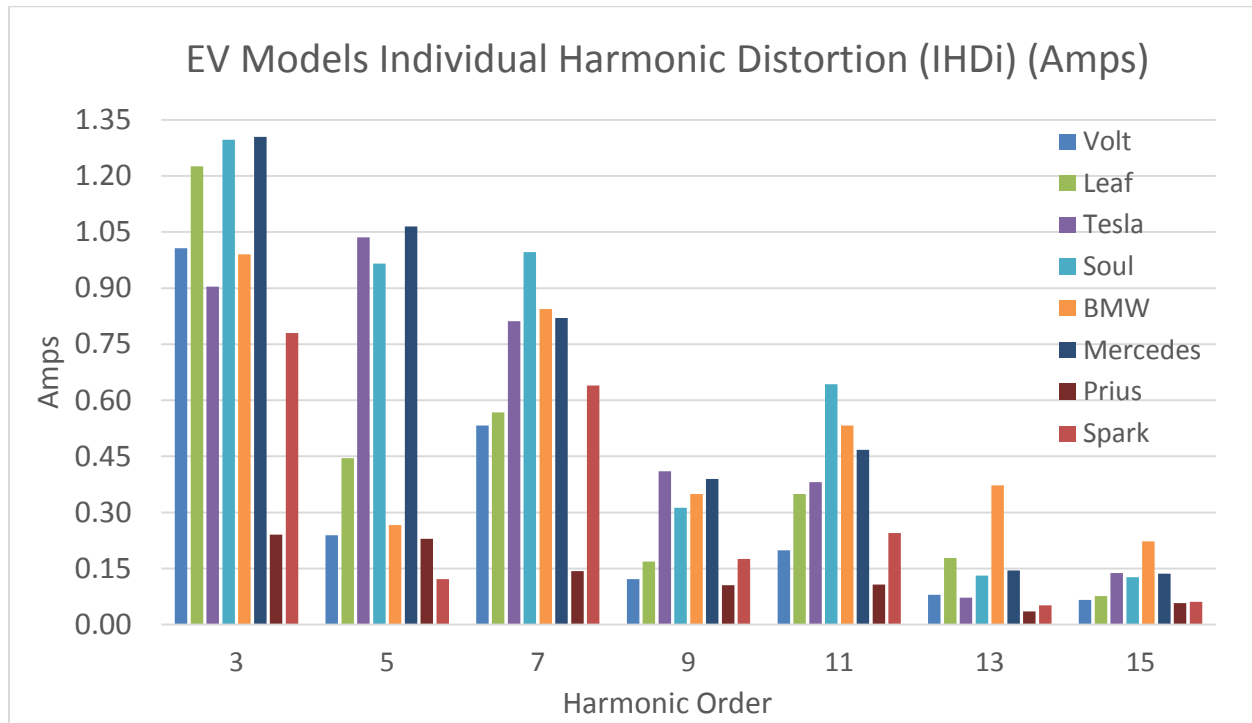


Figure 88: Individual Harmonic Distortion (Amps max) for different EV models.

In Figure 89, the same comparison is made, but now the results are expressed as a percentage of the fundamental current. Applying the limits recommended by IEE Std. 519

(4% for 3rd to 9th order and 2% for orders above 11th), we can notice that some EVs have orders that exceed these thresholds.

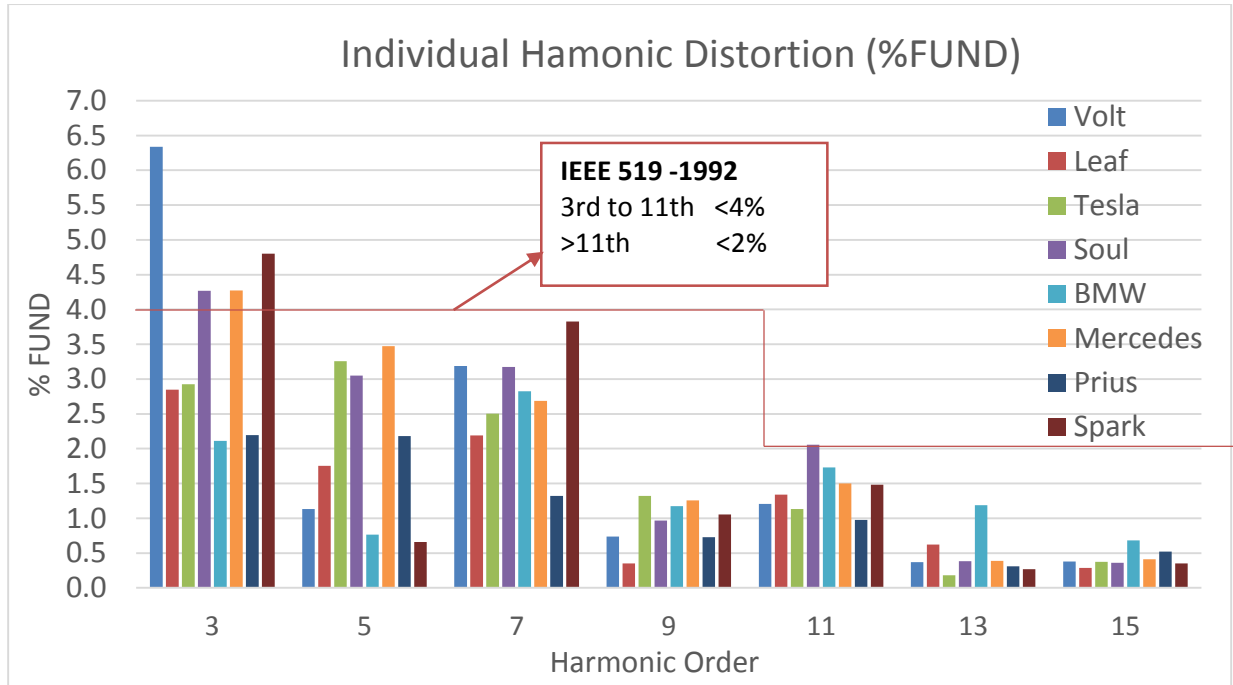


Figure 89: Comparison: Individual Harmonic Input (% FUND) for different EV models

The values graphed above are listed in Table 17 for clarity, and the values in red indicate the values exceeding IEEE 519 thresholds. If any sensitive loads were to be connected to the same bus as an EVSE, it would suffer from poor local power quality. However, the system power quality assessment should be evaluated at the PCC, which is far upstream in the circuit, where IHD_i magnitudes are significantly lower.

Table 17: Characteristic IHD_i inputs for each EV (a) Amps (max)

(b) % fundamental (FUND)

(a)

Harmonic Order	Volt	Leaf	Tesla	Soul	BMW	Mercedes	Prius	Spark
FUND	15.89	29.28	30.79	30.03	29.86	29.63	11	16.12
3rd	1.01	1.23	0.90	1.30	0.99	1.30	0.24	0.78
5th	0.24	0.45	1.04	0.97	0.27	1.07	0.23	0.12
7th	0.53	0.57	0.81	1.00	0.84	0.82	0.14	0.64
9th	0.12	0.17	0.41	0.31	0.35	0.39	0.11	0.18
11th	0.20	0.35	0.38	0.64	0.53	0.47	0.11	0.24
13th	0.08	0.18	0.07	0.13	0.37	0.14	0.04	0.05
15th	0.07	0.08	0.14	0.13	0.22	0.14	0.06	0.06

(b)

Harmonic Order	Volt	Leaf	Tesla	Soul	BMW	Mercedes	Prius	Spark
FUND	100	100	100	100	100	100	100	100
3rd	6.34	2.85	2.93	4.27	2.11	4.27	2.19	4.80
5th	1.13	1.76	3.26	3.05	0.77	3.47	2.18	0.66
7th	3.19	2.19	2.51	3.17	2.82	2.69	1.32	3.83
9th	0.74	0.35	1.32	0.97	1.18	1.26	0.73	1.05
11th	1.21	1.34	1.13	2.06	1.73	1.50	0.98	1.48
13th	0.37	0.62	0.18	0.38	1.19	0.39	0.31	0.27
15th	0.38	0.29	0.38	0.36	0.68	0.41	0.52	0.35

As a final comparison, the Total Current Harmonic Distortion produced by each EV model is shown in Figure 90. The Chevrolet Volt produces the maximum THD_i of 7.5%, followed by the Kia Soul (6.8%), the Mercedes EV (6.7%), the Spark (6.6%), the Tesla model S (5.5%), the BMW i3 (5.1%), the Nissan Leaf (5.1%) and lastly the Toyota Prius (3.6%).

Recalling that the THD_i (% FUND) is not limited by the IEEE 519-1992, note that it remains a good indicator of how much voltage distortion would be produced as a result of current harmonic inputs through the system impedances.

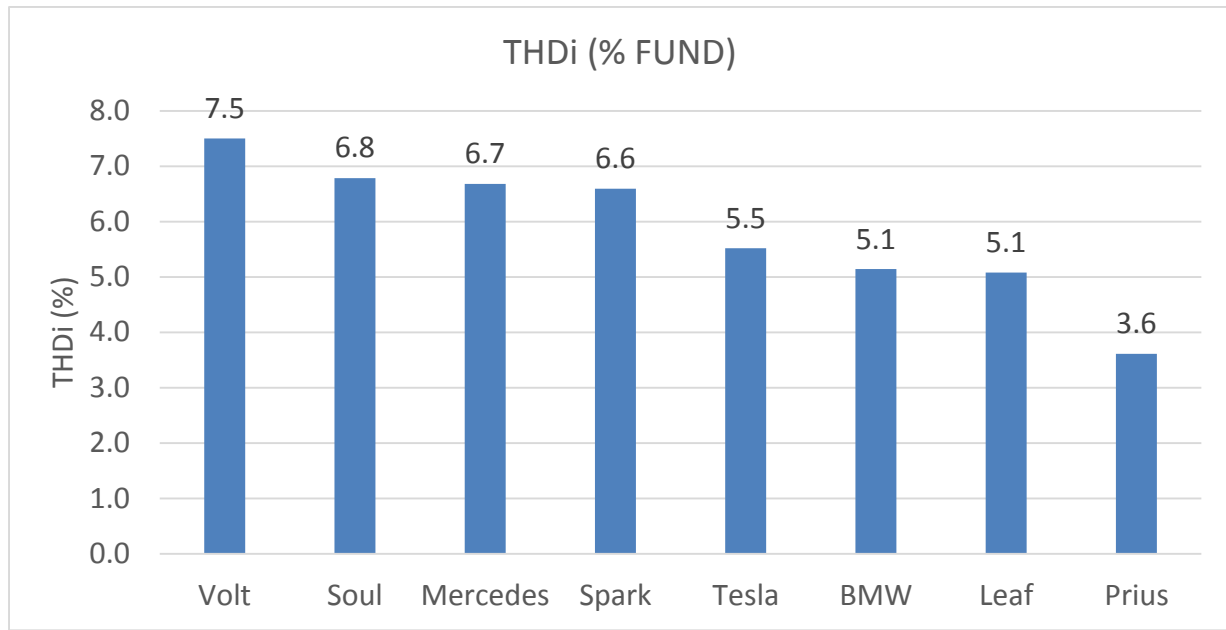


Figure 90: Current THD for each EV model

5.4.2. Power Quality Model Development

The ETAP Power Quality model is essentially the Load Flow model, which is able to simulate the harmonic power flows, using the Harmonic Analysis module on ETAP. This enables the user to define and attribute a harmonic spectrum to specific loads to be included in the harmonic power flow. The harmonic power flow is also a steady-state simulation, in other words, a snapshot of the system during a given moment in time, which calculates the currents and voltages fundamental and individual harmonic orders (IHD_i and IHD_v) as well as total harmonic distortions (THD_i and THD_v) throughout the systems buses and cables.

Modeling the different system components required the following assumptions:

- EV chargers were modeled as resistive static loads, as they are usually assumed in the literature [49], focusing on the analysis of the AC-side charging current.
- The harmonic inputs (magnitudes) for different EV models defined in Table 17 were attributed to each EVSE.
- The EV model population was defined to reflect the actual system EV population. Figure 91 shows the Car Shade EV population recorded during the power quality survey. Using these percentages and considering only the EV models that were characterized during the survey, the EV models attributed to the 20 EVSE are listed in Table 18.
- A load diversity factor of 70% was used to represent the random character of EV charging.

- The harmonics produced by the Inverter and parking structure loads are included.
- Harmonic distortion from the network supply side is assumed to be negligible.

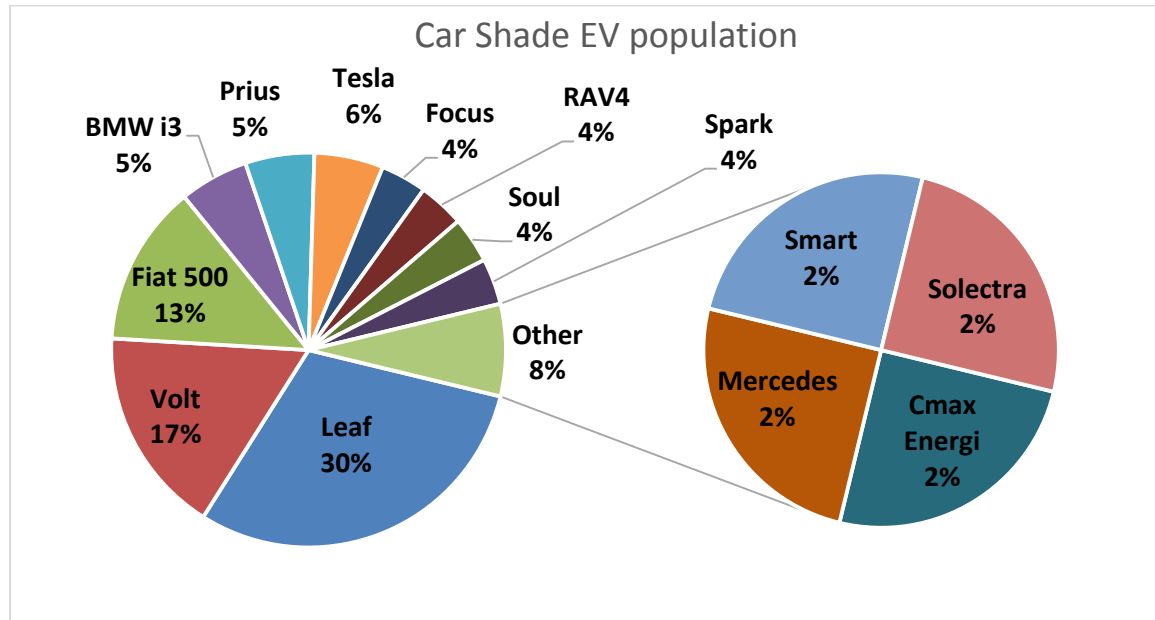


Figure 91: Car Shade EV population (May 18, 2015 to June 1, 2015)

Table 18: EVESE population in ETAP PQ model

	Count	%	EVSES in ETAP model
Leaf	16	41.0	8
Volt	9	23.1	5
BMW i3	3	7.7	2
Prius	3	7.7	2
Tesla	3	7.7	2
Soul	2	5.1	1
Spark	2	5.1	1
Mercedes	1	2.6	1
TOTAL	39	100	20

Harmonic input profiles for each EV model were created in ETAP's Harmonic Library Editor by defining each IHD_i as a magnitude. These harmonic profiles were then attributed to the desired loads in the Static Load Editor (Figure 92).

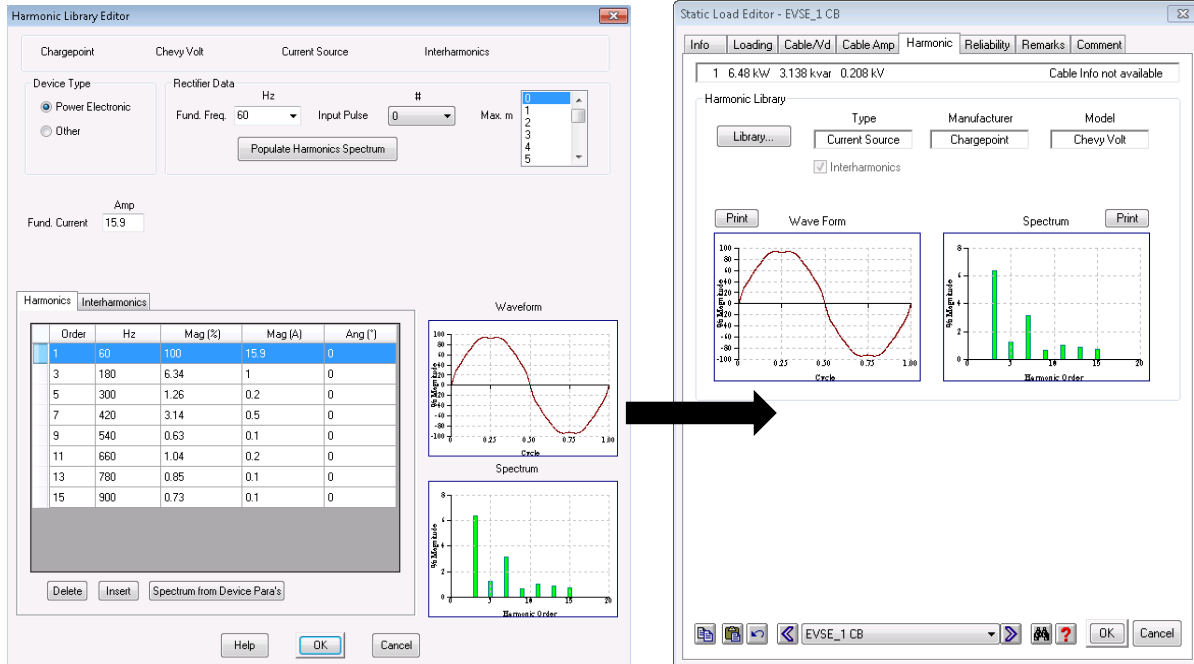


Figure 92: ETAP Harmonic Library Editor and Static Load Editor

5.4.3. Power Quality Model Verification

The strategy used to verify the results from the ETAP model is to compare $THD_i(\%)$ and $THD_v(\%)$ values from the PQ survey measuring points 1 and 3 with the values calculated by ETAP (harmonic power flow snapshot) at the correspondent buses, i.e., individual EVSE buses and T1- SEC bus. Table 20 shows the comparison between model vs. measured values and respective errors.

Initially, during verification, ETAP calculated values were always found to be lower than the actual measured values. As an example, the THD_v value was initially being calculated by ETAP at the EVSE buses to be 1.96%, which is 1.5 times lower than the value

recorded at the PQ survey the at EVSE 8 (3.13%) (Figure 78). Similarly, at bus T1-SEC the THD_i and THD_v values surveyed were always higher than the values produced by the ETAP model of the Car Shade system.

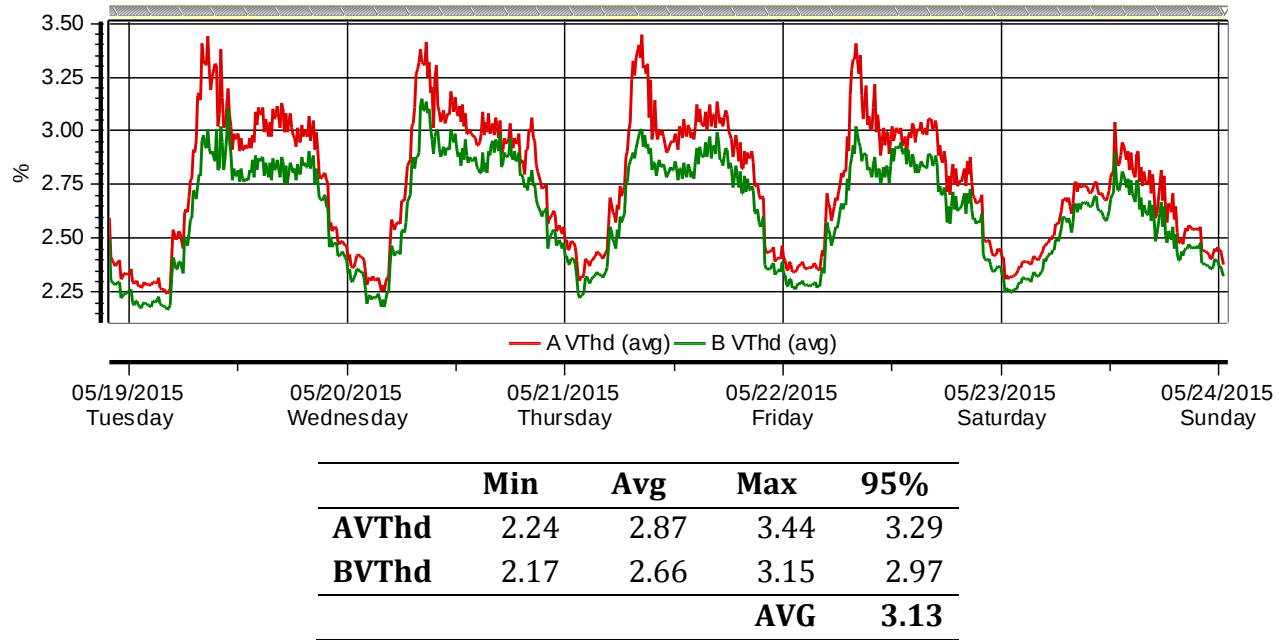


Figure 93: EVSE 8 THD_v

Further analysis revealed that the reason why ETAP values were lower was the fact that ETAP simulations always assume that the system is a three-phase system with balanced loads, and runs the power flow calculations for only one phase, since the other phases are assumed to produce the same results. Thus, ETAP harmonic flow does not support single/dual-phase loads such as the experimental EVSEs; instead, it considers each EVSE a 3-phase 7.2 kVA load. This way, the fundamental current for each phase will be lower to maintain the same load power. Since the harmonic inputs in ETAP are established as a percentage of the fundamental current, the harmonic injection in the system was also

lower than what it should be, explaining the lower distortion results produced by the ETAP model.

Knowing this, the harmonic inputs for each EV model needed to be scaled to account for the balanced phase assumptions of ETAP so that the right amount of harmonic distortion (Amps) could be simulated for an unbalanced 3-phase system. This scaling of inputs increased the percentages of the fundamental. A comparison between the previous (2-phase) and corrected (3-phase) harmonic inputs can be observed in Table 19: the percentage values needed to be increased since the fundamental went down from 29.28 A (dual-phase) to 14.20 A (3-phase).

Table 19: ETAP Harmonic input correction for the Nissan Leaf

	Old (2-phase)		Corrected for ETAP(3-phase)	
	Amps	%	Amps	%
FND	29.28	100.0	14.0	100.0
3	1.23	4.2	1.23	8.6
5	0.45	1.5	0.45	3.1
7	0.57	1.9	0.57	4.0
9	0.17	0.6	0.17	1.2
11	0.35	1.2	0.35	2.5
13	0.18	0.6	0.18	1.3
15	0.08	0.3	0.08	0.5

After all harmonic inputs were appropriately scaled, the results obtained by the ETAP model better represented those observed in the real system. The errors were mostly kept below 3%, with the exception of the THD_v at the individual EVSE buses, which reached a maximum distortion of 4.01 %, representing an error of 28%. This relatively high error is caused by the fact that a worst-case approach was used for harmonic inputs — in reality, the Car Shade system operation usually experienced lower harmonics.

The low errors indicate that the model is suitable to represent the real system harmonic inputs upstream bus T1-SEC for a worst-case scenario type of analysis. Although phase unbalance increases injection of non-characteristic harmonics, the use of a balanced model meets the goals of this study.

Table 20: ETAP PQ model validation

<u>Bus T1-SEC</u>				
	<i>THD_i</i> (%)	<i>THD_v</i> (%)	Voltage (V)	Current (A)
Measured	7.84 ¹	3.02 ¹	121.7 ¹	87.6 ¹
ETAP	7.92	3.08	121.2	120.0
Error	1.0 %	1.9 %	-0.3 %	³
<u>Individual EVSE buses</u>				
	<i>THD_i</i> (%)	<i>THD_v</i> (%)	Voltage (V)	Current (A)
Measured	3.6 – 7.5 ²	3.13 ¹	120.0 ¹	11 – 30 ²
ETAP	5.05 – 13.48 ²	3.20 - 4.01 ²	117.2	8.7 – 13.6 ²
Error	⁴	2.2 – 28.1 % ⁵	-2.3 %	⁴

(1) Measured values shown here are statistical 95% values averaged across the PQ survey period. EVSE buses *THD_v* from Figure 93.

(2) The *THD_i*, *THD_v* current and values at EVSE buses will vary with EV model

(3) The difference in current is not to be considered an error here because 87.6 is an averaged current value. Therefore, EVSE loads in ETAP will be always higher.

(4) Not an error, due to the expected difference in fundamental currents (3-phase vs. 2-phase) that will influence in the final percentage value.

(5) High errors occur because ETAP is considering worst-case harmonic inputs

5.4.4. Power Quality Model Results

Once the model was verified, the harmonic load flow simulations were performed. The THD values for 6 points in the system — buses T1-SEC, T1-PRIM, DL-3, BESS, AIRB, MSE (the actual Car Shade PCC) — are listed in Table 21 and illustrated in Figure 94.

As expected, the THD is highly dependent upon non-linear load location. Thus, stronger distortion effects are observed closer to the EVSEs and the Inverter. The THD also depends upon the system voltage. The majority of non-linear loads are located in the 208 V (low

voltage) part of the system, so the distortion levels gradually drop as the voltage is increased. Moreover, the delta-wye transformer connection prevents the triplen harmonics from flowing through T1 and T2, reducing the THD in the buses upstream.

Table 21: ETAP PQ model results: THD_v , THD_i , IHD_i and IHD_v

Bus		T1-SEC	T1-PRIM	DL3	BESS	MSE	AIRB
Harmonic	THD_v (%)	3.08	1.54	1.54	1.47	1.51	0.92
Distortion	THD_i (%)	7.92	3.66	3.33	0.51	5.95	0.62
Current IHD_i (%)	FUND (A)	119.6	53.7	105.1	75.6	59.9	258.8
	3	6.9	0	0	0.4	0.5	0.6
	5	2.8	2.7	2.4	0.1	4.3	0.2
	7	2.8	2.3	2.1	0.1	3.8	0.2
	9	2.4	0	0	0.2	0.2	0.1
	11	0.8	0.9	0.8	0.3	1.3	0.5
	13	0.5	0.2	0.4	0.1	0.6	0.2
	15	0.4	0	0	0	0	0
TOTAL (A RMS)		119.6	53.7	105.2	75.6	60.1	258.8
Voltage IHD_v (%)	FUND	100.9	101.9	105.1	103.5	102.7	81.5
	3	1.6	0.48	0	0.46	0.48	0.27
	5	0.97	0.18	2.4	0.22	0.22	0.21
	7	1.19	0.32	2.1	0.35	0.36	0.27
	9	0.56	0	0.59	0.57	0.59	0.55
	11	1.84	0.9	1.22	1.17	1.19	1.2
	13	0.92	0.2	0.51	0.48	0.49	0.2
	15	0.42	0	0.01	0.01	0.01	0
TOTAL (%RMS)		100.9	101.9	105.2	103.5	102.7	81.5

Table 22: IEEE 519-1992 Power Quality thresholds applicable to the Car Shade

Voltage Distortion	Current Distortion
Category: 69 kV and below	Category: General Distribution Systems 120 V through 69 kV and $\frac{I_L}{I_{sc}} < 20$
• $THD_v < 5\%$ (General Systems) • $IHD_v < 2.5\%$ (Dedicated systems: Short Circuit Impedance (SCR) at PCC=10)	• $IHD_i < 4\%$ for 3rd to 11th • $IHD_i < 2\%$ for 11th to 17th • $TDD_i < 5\%$

The relevant observations that can be made about the ETAP simulation results are as follows:

- The 5th harmonic $IHD_i = 4.3\%$ at bus MSE (PCC) is above the 4% limit, but it does not cause excessive THD_v problems.
- At the PCC, no THD_v or IHD_v values go above the limits.
- Since transformers feeding EVSEs (T1 and T2) are connected in a delta-wye grounding configuration, the triples harmonics are trapped, preventing them to propagate upstream
- A classroom/laboratory building (AIRB) adjacent to the Car Shade did not show excessive THD. This appears to be because it is separated by a length of cable, and that a non-linear load was modeled at the APS bus to account for the THD observed when no EVs were charging.

5.4.4.1. Harmonic Cancellation

Charging of multiple EVs from the same source is expected to bring a beneficial addition of harmonic currents at different phases that may cancel or diminish their

percentage in proportion to the fundamental. Here, harmonic currents addition and cancellation effects at the Car Shade are described.

The following observations can be made about EV charging phase angles:

1. Charging events at the same EVSE and with the same EV model charging current phase angles registered were close to a mean value.
2. Charging events at different EVSEs, however, showed different phase angles for the same EV model.
3. Different EV models present different phase angles of harmonic distortion.

To corroborate the statements above, the current phasors for two different Nissan Leafs charging at EVSE 6 are shown in Figure 95. For both EVs, current magnitudes vary during charging. Phase angles also vary (more significantly at the 5th and 9th orders), but can be assumed to be within one or two standard deviations around a mean value. This verifies item 1 mentioned above.

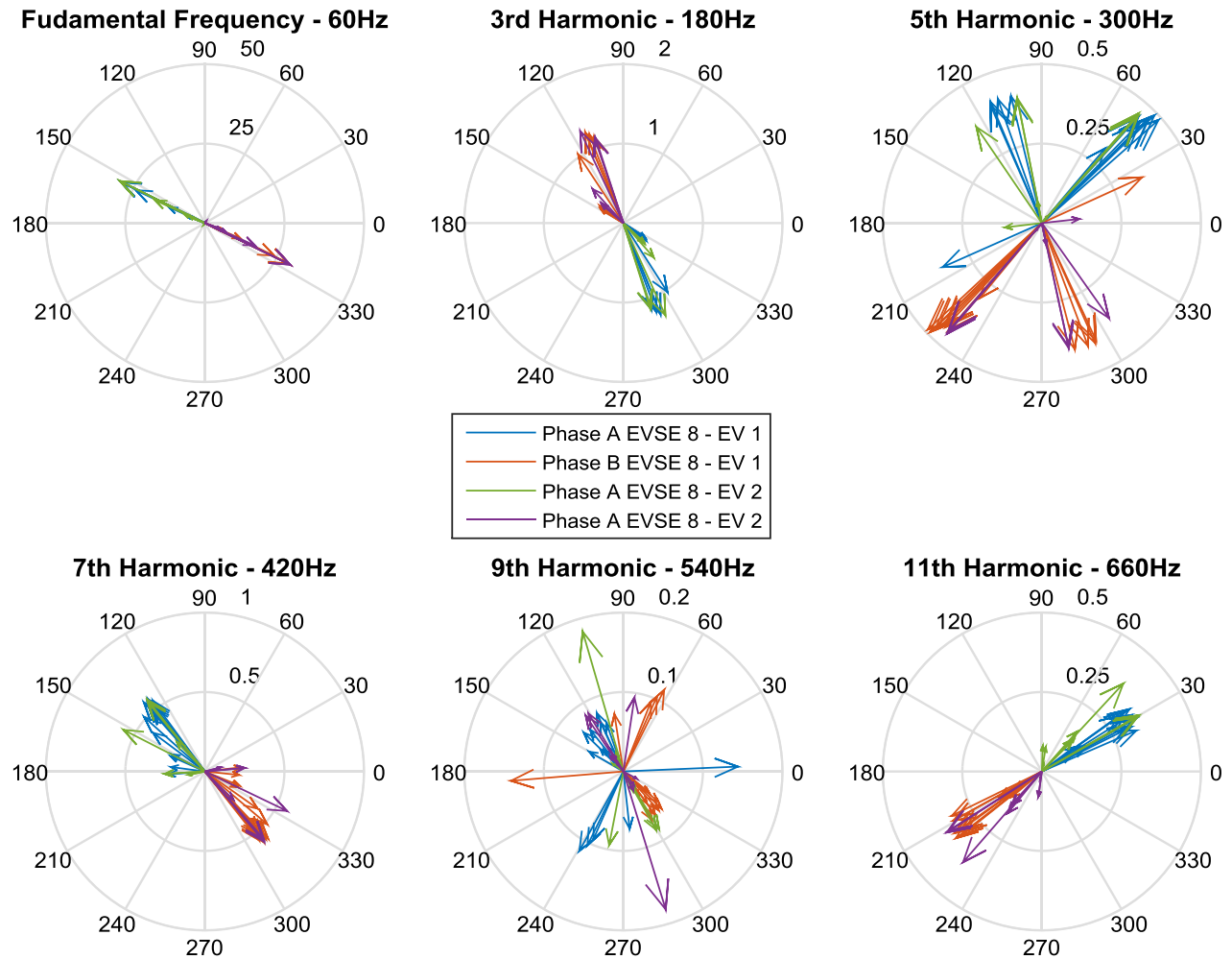


Figure 95: Charging event current phasors - Nissan Leafs (EV1 and EV2) charging at EVSE 8

However, when comparing charging events at different EVSEs, the phase angle difference starts to become too large and random, as observed in Figure 96. The same comparison is made in Figure 97, but now considering a different EV model, 2 Volts charging in EVSE 6 and EVSE 8.

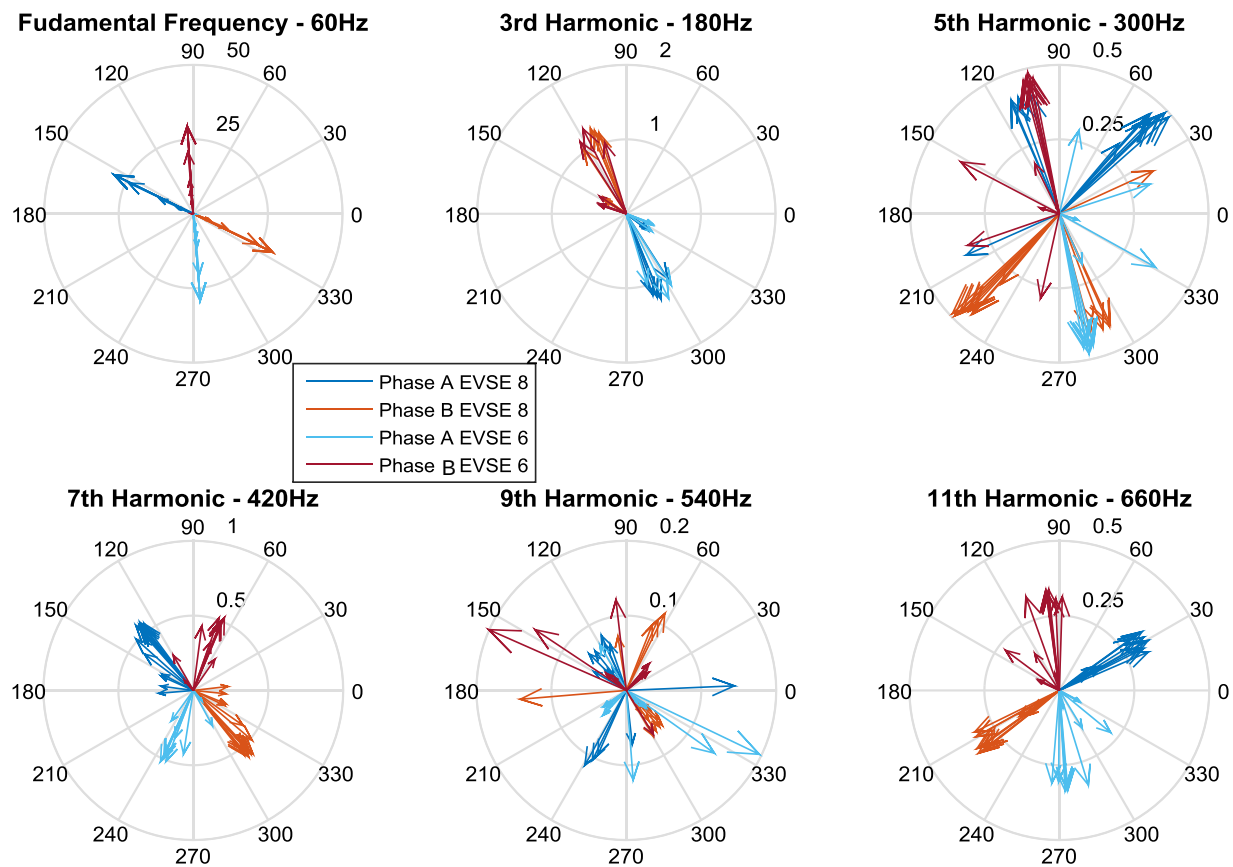


Figure 96: Charging event current phasors of Nissan Leafs charging at EVSE 6 and EVSE 8

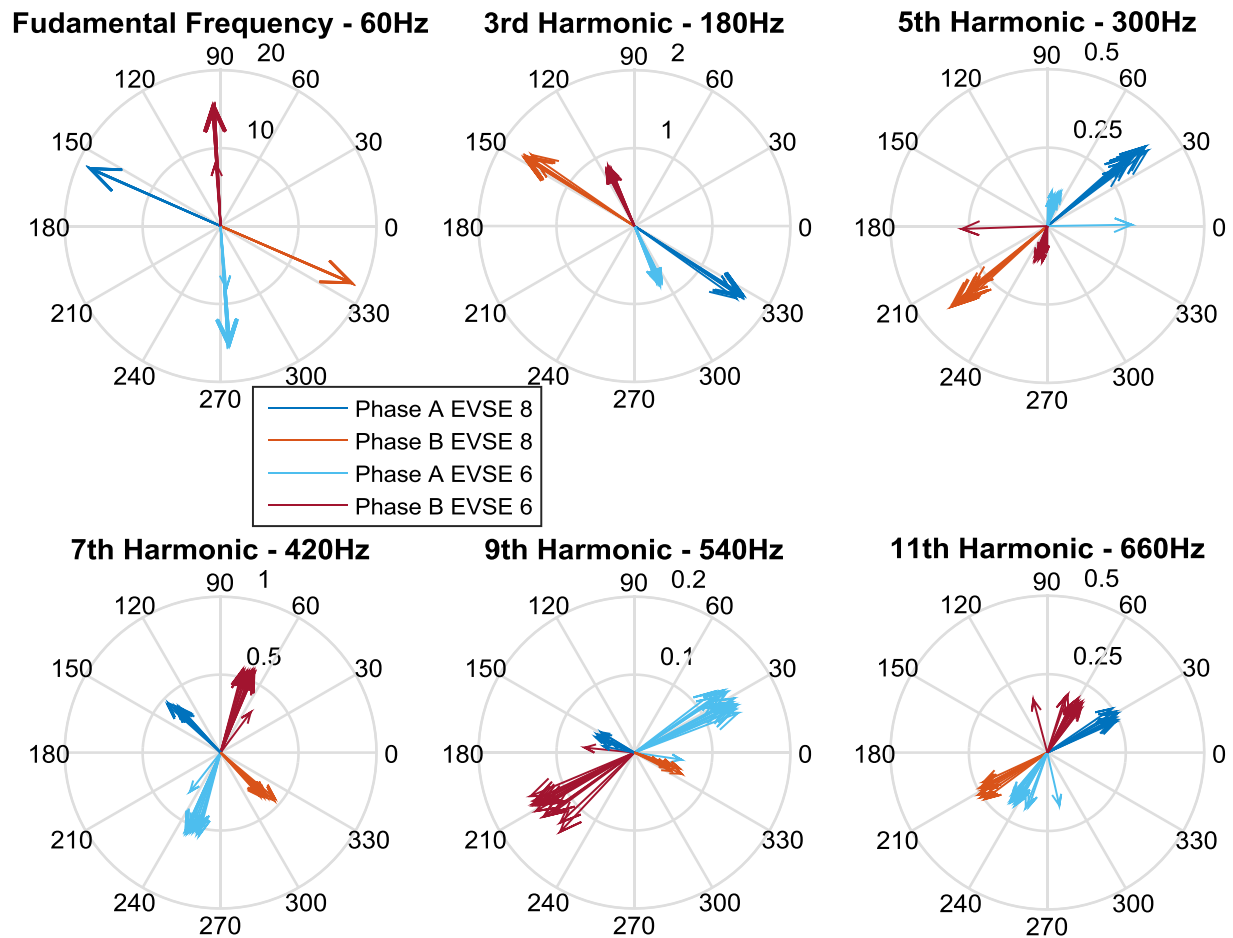


Figure 97: Charging event current phasors of Chevrolet Volts charging at EVSE 6 and EVSE 8

At first, one might think it is possible to correct the harmonic phase angles for the phase shifts for different EVSEs. By observing the phase shift from EVSE 6 (Phase A) to EVSE 8 (Phase A), we conclude that this is not possible. This verifies the second item mentioned above.

Therefore, the only means of achieving a completely accurate cancellation model would be if high-resolution PQ measurements were installed for each one of the 10 EVSE loads connected together. Since only two EVSEs were being monitored, to quantify the

harmonic cancellation at the Car Shade, a current profile analysis was made to quantify the harmonic cancellation at the Car Shade. It is shown in Figure 98.

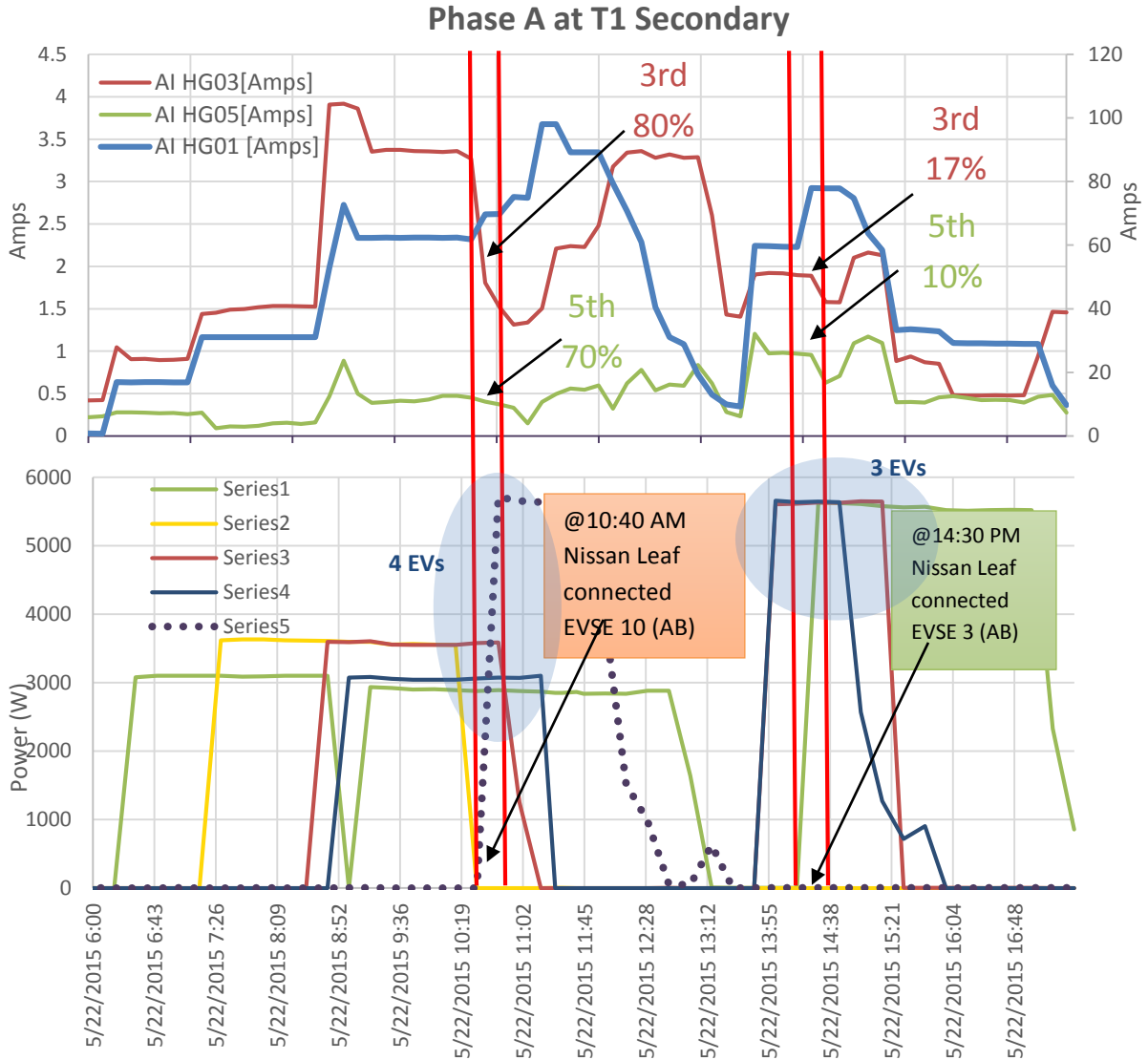


Figure 98: Harmonic Cancellation Phase A at T1 secondary

Every time there is an increase in the fundamental current (Figure 98 blue curve — secondary axis) due to EVs being plugged in, and a simultaneous decrease in the harmonic current (that is not caused simply by cars being disconnected) harmonic cancellation happened. Therefore, in Figure 98, one can notice that twice during the day, cancellation

on the 3rd and 5th orders happened on phase A. The harmonic magnitude drop precisely matches the time that Nissan Leafs were being plugged in and no other EV was being disconnected. Similar behavior was identified in other days of operation and in the remaining phases B and C. This verifies the third point made above regarding harmonic cancellation.

Cancellation of low-order harmonics (3rd and 5th) were also observed in [50], while it has been previously suggested that mostly high frequency harmonics would have significant cancellation.

It is interesting to notice that at the Car Shade, the more cars were connected at the time of cancellation, the greater the drop on the harmonic currents, i.e., the greater the cancellation.

5.5. Task 5: Optimal economical BESS and PV sizing for Car Shade + AIRB nanogrid

In spite of the benefits inherent in a PV/PEV/Storage nanogrid, sizing its assets is still a challenge due to affordability and reliability factors. In this section, an economical optimization is proposed for sizing assets in a PV/Storage nanogrid for EV charging, and ultimately, a classroom/laboratory building is added to the load mix of the optimization. For this optimization effort, a linear program (LP) was developed in MATLAB. The problem's mathematical formulations — equalities, inequalities, upper and lower constraints, as well as data inputs — are summarized in the following sections.

5.5.1. Parameters and variables

The parameters used in this model are presented in Table 23.

Table 23: Optimization Parameters and Variables

Name	Description	Units
$BESS$	Optimal size of the Battery	kWh
n_{PV}	Optimal size of the PV array	kW
$C_{BESS}, C_{PV}, C_{grid}$	LCOE for Storage, PV and Grid import respectively	\$/kWh
t	Simulation time steps (15 minute resolution)	$t = 1, 2, \dots, T$
$EVSE(t)$	EVSE load profile at time t	kWh
$PV(t)$	Normalized PV generation profile on site at time t	kWh/kW installed
$AIRB(t)$	Building load profile at time t	kWh
$Import(t), Export(t)$	Energy import and export from the grid respectively (always positive variables)	kWh
$BESS(t)$	Accumulated energy in the BESS at time t	kWh
	Energy amount charged/discharged at time t	kWh
$BESS_{dt}(t)$	Sign Convention: (+) $BESS_{dt} \rightarrow Discharging$ (-) $BESS_{dt} \rightarrow Charging$	

5.5.1.1. Cost assumptions

The costs assumed in this analysis were taken from a thorough comparative analysis of different Levelized Cost of Energy (LCOE) for various technologies [51].

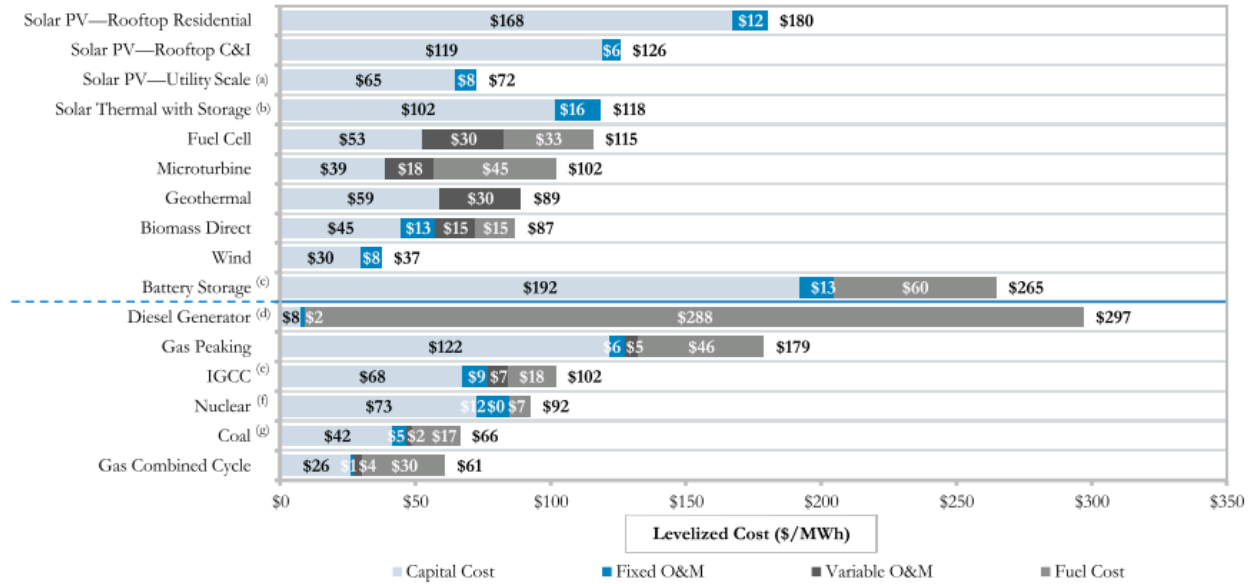


Figure 99: Levelized Cost of Energy for various technologies [51]

Thus, C_{PV} was assumed to be 0.126 \$/kWh, and C_{BESS} was assumed 0.205 \$/kWh (noting that the fuel cost was discarded since here our battery is considered to be charged with electricity from the grid). The electricity cost assumed was based on the local utility costs (SCE TOU-8, Option R), thus C_{grid} was assumed \$0.03147/kWh.

5.5.2. Data inputs and outputs

The inputs to the optimization are historical data of (1) a normalized PV generation profile, (2) an EV charging load demand, and (3) a UCI classroom building load demand (AIRB). The LP outputs are the required sizes for a PV and storage system combination

(required kW of the PV array, and BESS kW/KWh required capacities), the system optimal economic dispatch profile, and the monthly system cost.

In order to increase the system's reliability, a worst-case scenario approach was taken. The simulation length was chosen to allow a variety of load and generation combinations during system operation for its most stressful operating conditions. Such a methodology is essential to guarantee that the correct system capacity is dimensioned. Thus, the optimization is run for an entire month during winter 2015 (Jan 8 to Feb 6 billing cycle), when the PV generation was the lowest observed during the year and EV charging loads were considerably high.

The power (kW) profile of the data inputs are shown in Figure 100. The normalized PV generation comprises days where the PV output was considerably affected by typical low insolation during winter, while the EV charging loads follow a regular pattern of EV charging loads at a public charging station, with a high weekday demand (variable between 50 kW and 80 kW peak) compared to the weekend demand (less than 20 kW peak).

The Anteater Instruction and Research Building is a 160 kVA nominal lumped load. It is characterized by having lighting, elevator and some cooling loads, thus, its daily load profile follows a typical constant load pattern: afternoon peaks with a low and constant baseload during morning and evening.

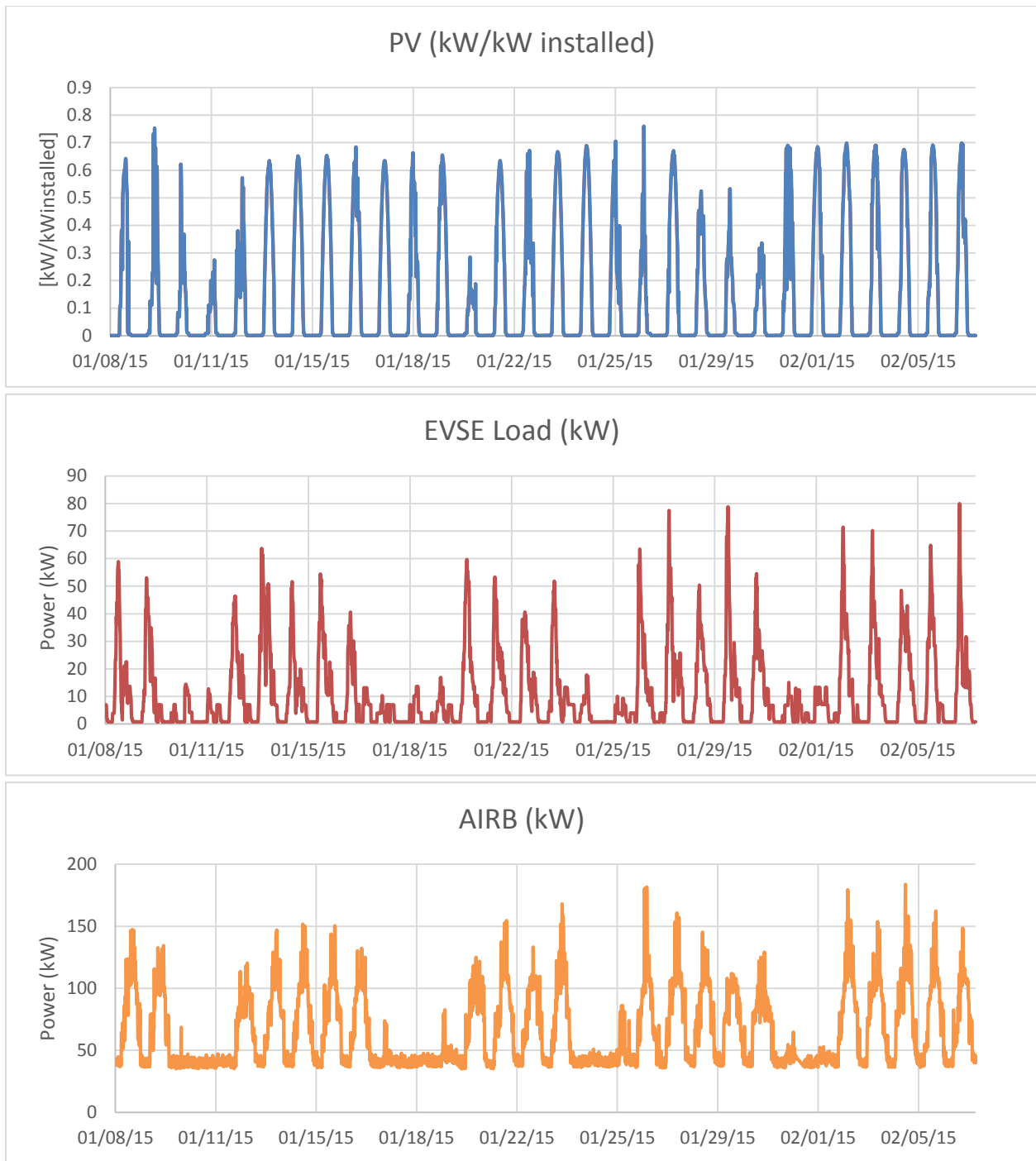


Figure 100: PV Normalized (top), EVSE (middle) and AIRB (bottom) power profiles.

5.5.3. Optimization formulation

The LP objective function includes three terms to be minimized: electricity, capital, and operation costs to the microgrid/nanogrid operator as follows:

$$\min f = C_{BESS} BESS + C_{PV} n_{PV} \sum_{t=1}^T PV(t) + C_{grid} \sum_{t=1}^T Import(t) \text{ [\$]} \quad (6)$$

Optimization Problem Constraints

- **Equalities**

1. Energy and demand should balance at all times.

$$\underbrace{EVSE(t)}_{kWh} = \underbrace{n_{PV} PV(t)}_{kWh} + \underbrace{BESS_{dt}(t)}_{kWh} + \underbrace{Import(t) - Export(t)}_{\substack{kWh \\ Grid(t)}} \quad (7)$$

2. The energy is accumulated in the BESS

$$BESS(t+1) = BESS(t) - BESS_{dt}(t) \quad (8)$$

3. Net import form the grid must be zero by the end of period T.

$$\sum_{t=1}^T Import(t) - \sum_{t=1}^T Export(t) = 0 \quad (9)$$

4. SOC = 50% at the beginning of the simulation

$$BESS(1) = 0.5 BESS \quad (10)$$

5. SOC = 50% at the end of the simulation

$$BESS(T) = 0.5 BESS \quad (11)$$

- **Inequalities**

1. Limits a 10% SOC for the battery

$$0.1 \text{ BESS} \leq \text{BESS}(t)$$

2. Limits a 100% SOC for the battery

$$\text{BESS}(t) \leq \text{BESS}$$

3. Limits BESS to discharge only when there is EV load

$$\text{BESS}_{dt}(t) \leq \text{EVSE}(t)$$

Matrix Formulation

Variables	Lower Bounds	Upper Bounds
$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{T+2} \\ x_{T+3} \\ \vdots \\ x_{2T+2} \\ x_{2T+3} \\ \vdots \\ x_{3T+2} \\ x_{3T+3} \\ \vdots \\ x_{4T+2} \end{bmatrix} = \begin{bmatrix} \text{BESS} \\ n_{pv} \\ \text{BESS}_{dt}(1) \\ \vdots \\ \text{BESS}_{dt}(T) \\ \text{BESS}(1) \\ \vdots \\ \text{BESS}(T) \\ \text{Import}(1) \\ \vdots \\ \text{Import}(T) \\ \text{Export}(1) \\ \vdots \\ \text{Export}(T) \end{bmatrix}$	$lb = \begin{bmatrix} -Inf^{**} \\ -Inf^{**} \\ -Inf \\ \vdots \\ -Inf \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$	$ub = \begin{bmatrix} Inf \\ Inf \\ Inf \\ \vdots \\ Inf \\ Inf \\ \vdots \\ Inf \\ Inf^* \\ \vdots \\ Inf^* \\ Inf^* \\ \vdots \\ Inf^* \end{bmatrix}$

(*) these bounds can be changed depending on amount of limit of import/export grid power in the system is wanted

(**) these bounds can be changed to force a minimum size for the BESS and PV array

These equality, inequalities and boundary constraints are translated into a matrix linear system as described below:

- **Equalities:** $A_{eq}x = b_{eq}$

1. $x_2 * PV(t) + x_{3+j} + x_{2T+3+j} - x_{3T+3+j} = \text{EVSE}(t), j = 0 \text{ to } T - 1$

$$A_{eq1} = \begin{bmatrix} BESS & n_{pv} & BESSdt(1) & BESSdt(2) & \dots & BESSdt(T) & BESS(1) & BESS(2) & BESS(T) & Import(1) & Import(T) & Export(1) & Export(T) \\ \widehat{0} & \widehat{PV(1)} & \widehat{1} & \widehat{0} & \dots & \widehat{0} & \widehat{0} & \dots & \widehat{0} & \widehat{1} & \dots & \widehat{0} & \widehat{-1} & \dots & \widehat{0} \\ 0 & PV(2) & 0 & 1 & \dots & 0 & 0 & \dots & 0 & 0 & \dots & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & 0 \\ 0 & PV(T) & 0 & 0 & \dots & 1 & 0 & \dots & 0 & 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix}$$

$$2. -x_{3+j} + x_{T+3+j} - x_{T+4+j} = 0, j = 0 \text{ to } T - 2$$

$$A_{eq2} = \begin{bmatrix} BESS & n_{pv} & BESSdt(1) & BESSdt(2) & \dots & BESSdt(T) & BESS(1) & BESS(2) & BESS(3) & \dots & BESS(T-1) & BESS(T) & Import(1) & \dots \\ \widehat{0} & \widehat{0} & \widehat{-1} & \widehat{0} & \dots & \widehat{0} & \widehat{1} & \widehat{-1} & \widehat{0} & \dots & \widehat{0} & \widehat{0} & \widehat{0} & \dots \\ 0 & 0 & 0 & -1 & \dots & 0 & 0 & 1 & -1 & \dots & 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & 0 & \dots \\ 0 & 0 & 0 & 0 & \dots & -1 & 0 & 0 & 0 & \dots & 1 & -1 & 0 & \dots \end{bmatrix}$$

$$3. \sum_{j=0}^{T-1} x_{2T+3+j} - \sum_{j=0}^{T-1} x_{3T+3+j} = 0, j = 0 \text{ to } T - 1$$

$$A_{eq3} = \begin{bmatrix} BESS & n_{pv} & BESSdt(1) & BESSdt(2) & \dots & BESSdt(T) & BESS(1) & BESS(2) & BESS(T) & Import(1) & Import(T) & Export(1) & Export(T) \\ \widehat{0} & \widehat{0} & \widehat{0} & \widehat{0} & \dots & \widehat{0} & \widehat{0} & \dots & \widehat{0} & 1 & \dots & 1 & -1 & \dots & -1 \end{bmatrix}$$

$$4. x_{T+3} - 0.5x_1 = 0$$

$$A_{eq4} = \begin{bmatrix} BESS & n_{pv} & BESSdt(1) & \dots & BESSdt(T) & BESS(1) & \dots & BESS(T) & Import(1) & \dots & Import(T) & Export(1) & \dots & Export(T) \\ \widehat{-0.5} & \widehat{0} & \widehat{0} & \dots & \widehat{0} & \widehat{1} & \dots & \widehat{0} & 0 & \dots & 0 & 0 & \dots & 0 \end{bmatrix}$$

$$5. x_{2T+2} - 0.5x_1 = 0$$

$$A_{eq5} = \begin{bmatrix} BESS & n_{pv} & BESSdt(1) & \dots & BESSdt(T) & BESS(1) & \dots & BESS(T) & Import(1) & \dots & Import(T) & Export(1) & \dots & Export(T) \\ \widehat{-0.5} & \widehat{0} & \widehat{0} & \dots & \widehat{0} & \widehat{0} & \dots & \widehat{1} & 0 & \dots & 0 & 0 & \dots & 0 \end{bmatrix}$$

$$A_{eq} = \begin{bmatrix} A_{eq1} \\ A_{eq2} \\ A_{eq3} \\ A_{eq4} \\ A_{eq5} \end{bmatrix} \quad b_{eq} = \begin{bmatrix} EVSE(1) \\ \vdots \\ EVSE(T) \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

- **Inequalities: $Ax < b$**

$$1. \quad 0.1 x_1 - x_{2T+3+j} \leq 0, j = 0 \text{ to } T - 1$$

$$A_1 = \begin{bmatrix} BESS & n_{PV} & BESSdt(1) & \dots & BESSdt(T) & BESS(1) & BESS(T) & Import(1) & Import(T) & Export(1) & Export(T) \\ \tilde{0} & \tilde{0} & \tilde{0} & \dots & \tilde{0} & -1 & \dots & \tilde{0} & \tilde{0} & \dots & \tilde{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & 0 & 0 & \ddots & 0 \\ 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}_{96 \times 386}$$

$$2. \quad -x_1 + x_{2T+3+j} \leq 0, j = 0 \text{ to } T - 1$$

$$A_2 = \begin{bmatrix} BESS & n_{PV} & BESSdt(1) & \dots & BESSdt(T) & BESS(1) & BESS(T) & Import(1) & Import(T) & Export(1) & Export(T) \\ -1 & \tilde{0} & \tilde{0} & \dots & \tilde{0} & 1 & \dots & \tilde{0} & \tilde{0} & \dots & \tilde{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}_{96 \times 386}$$

$$3. \quad x_{3+j} \leq EVSE(t), j = 0 \text{ to } T - 1$$

$$A_3 = \begin{bmatrix} BESS & n_{PV} & BESSdt(1) & \dots & BESSdt(T) & BESS(1) & BESS(T) & Grid(1) & Grid(T) \\ \tilde{0} & \tilde{0} & 1 & \dots & \tilde{0} & \tilde{0} & \dots & \tilde{0} & \tilde{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}_{96 \times 386}$$

$$A = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} \quad b = \begin{bmatrix} 0 \\ \vdots \\ EVSE(1) \\ \vdots \\ EVSE(T) \end{bmatrix}$$

- **Objective Function**

$$f = \begin{bmatrix} C_{BESS} \\ C_{PV} * \sum_{t=1}^T PV(t) \\ \vdots \\ C_{grid} \\ \vdots \\ C_{grid} \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2T+3} \\ \vdots \\ x_{3T+2} \\ x_{3T+3} \\ \vdots \\ x_{4T+2} \end{bmatrix}$$

5.5.4. Optimization Results

The optimization problem is solved using a MATLAB linear programming solver *linprog* (full code is included in Appendix C) in the context of minimum levelized cost of energy (LCOE). The system was optimally sized for two scenarios with different nanogrid components:

- **Scenario 1:** PV + storage + EV charging + grid
- **Scenario 2:** PV + storage + EV charging + grid + AIRB

The resulting optimal operation dynamics and sizing are presented in Figure 101 (scenario 1) and Figure 102 (scenario 2), and summarized in Table 24,

Table 24: Optimization Results

	Scenario 1	Scenario 2
PV	80 kW	558 kW
BESS	95 kWh/42 kW	1.1 MWh/320 kW
Total cost	1,065 \$/month	7,367 \$/month
Max. Grid Import	31 kW	49 kW

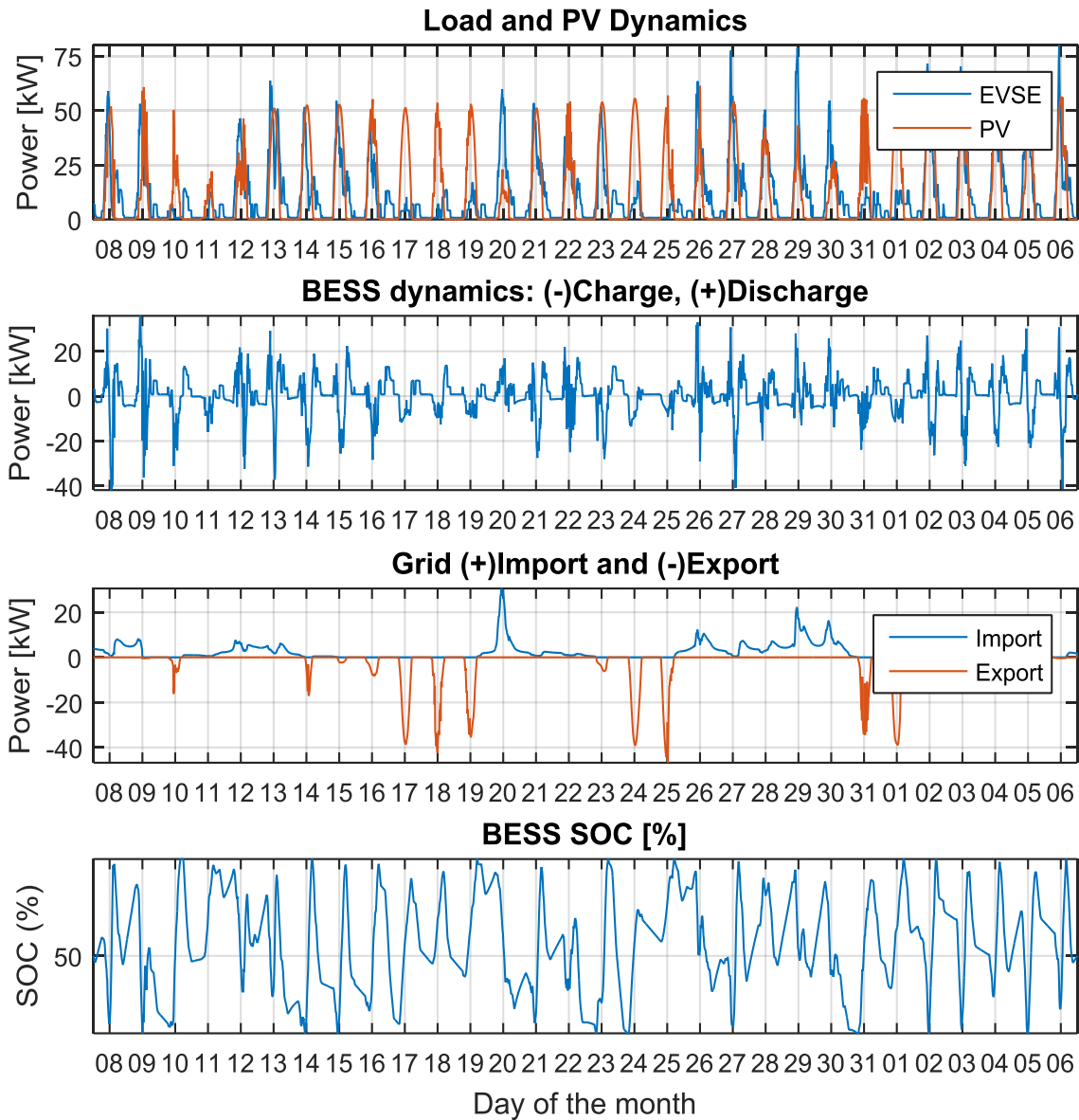


Figure 101: Scenario 1— EVSE load, PV generation, BESS dynamics, Grid import/export, and BESS SOC.

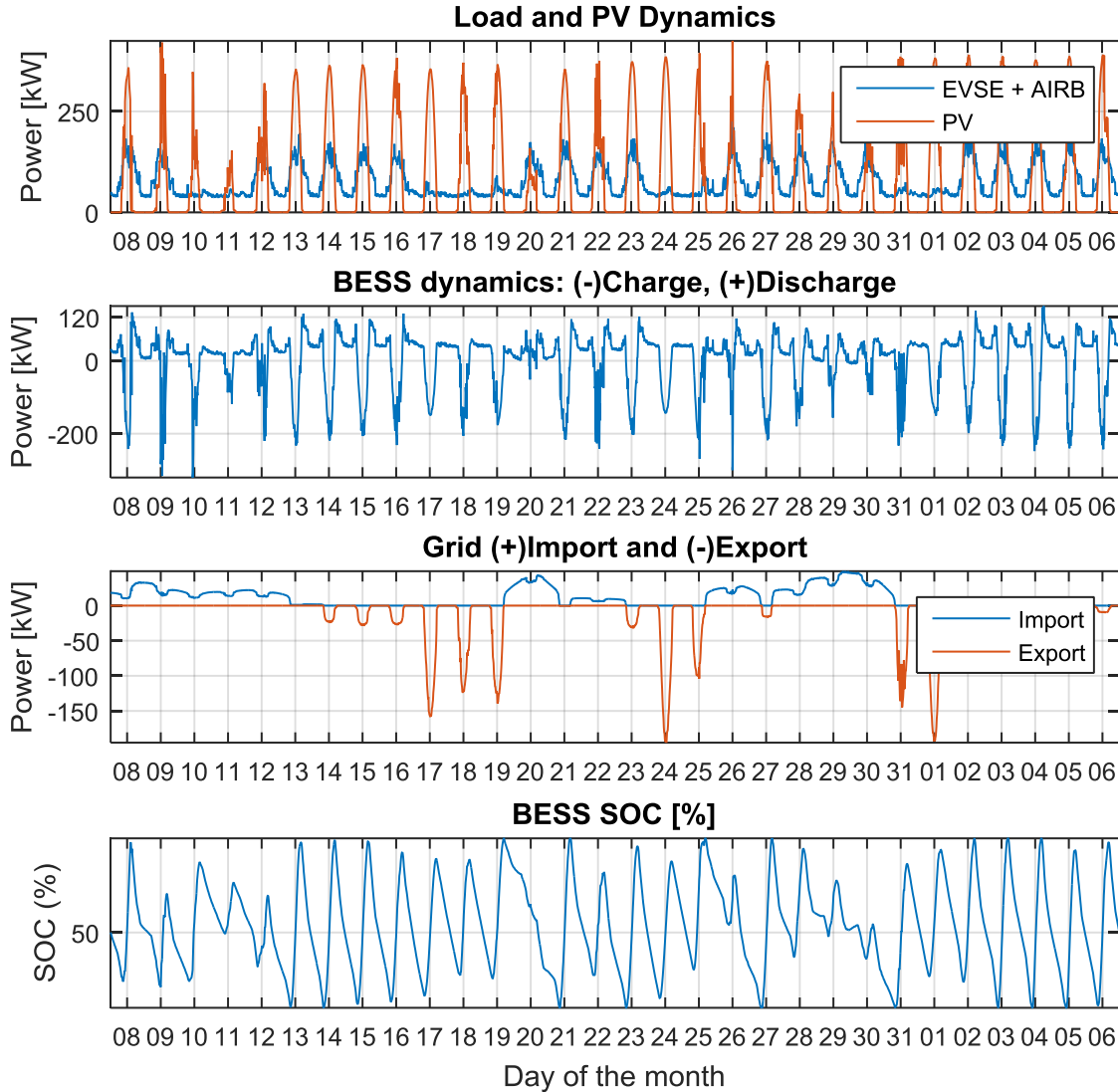


Figure 102: Scenario 2 — EVSE + AIRB load, PV generation, BESS dynamics, Grid import/export, and BESS SOC.

During system operation, the BESS always respects a 10% minimum SOC and assumes an initial and final SOC of 50% as a constraint for a guaranteed sustainable operation during the next billing cycles.

As expected, Scenario 2 requires a greater PV + Storage capacity than Scenario 1, and also presents higher grid imports and exports. The peaking nature of PV generation requires more storage capability as the PV array size is increased. This is because in Scenario 1, the PV and EVSE load peaks match relatively well, however, in Scenario 2, the PV peak is rather non-coincident with the building load, is much higher, and exceeds the total load peak. Consequently, the storage capacity required is higher and grid exports occur more frequently during peak PV hours.

In a general trend, higher grid imports follow days with low PV generation. Moreover, BESS storage capacity is mainly sized in order to buffer the system during such days of low PV and a considerable load demand. A statistical approach or a sensitivity analysis would better account for the stochastic nature of both of these variables, which is recommended for future work.

6. Summary

The first main observation drawn from the study of an EV charging station deployed at a university campus is that the typical EV charging profile observed closely matches student and faculty arrival/departure times for classes. The peak EVSE load occurred around 10:30 AM and a second smaller peak occurs in the evening around 6:00 PM.

The subsequent findings were presented in the following tasks:

In Task 1, each BESS operation mode was characterized in terms of operation goals, controls, and dynamics:

- PLS: Effectively shifts most of the afternoon EV charging demand to nighttime. Moreover, afternoon PV exports are beneficial to the microgrid as an additional supply to neighboring loads.
- MPPI: Successfully limits total system demand to zero kW from 9:00 AM to 4:00 PM, thus all EV charging during this window occurs with virtually no impact to the grid. This is an extremely important achievement to obtain a seamless integration of EV charging into power systems.
- CAP Demand: The BESS effectively capped the Car Shade nanogrid to a pre-set demand threshold. When the threshold was lowered, the total demand often exceeded the imposed limit, and the BESS SOC was not fully restored for the next day of operation. The higher the threshold, the more curtailed PV power.
- PV Capture: Under poor weather conditions, both strategies, with and without overnight charging, did not fulfill their goals. Overnight charging helps to increase the average SOC in the morning, which in turn helps the BESS to buffer the system

completely. While this mode enables more renewable penetration, the EVCS demand curve showed significant fluctuations caused by high EVSE loads variability when the BESS is already depleted. These fluctuations are not ideal in the case of a bigger EVSE load as increased ramping is not desirable in a power system.

Lastly, different BESS operation modes were compared in their ability to allow renewable solar PV penetration and contribution to EV charging. The following observations were made in this analysis:

- As expected, the PV Capture mode allowed for the most EV charging from renewable solar, followed by the MPPI, then CAP 10, 15, and 20, and lastly, PLS mode.
- CAP demand modes have an increased renewable contribution as the threshold is decreased, since less PV is curtailed. Yet, more grid power is used to charge the battery, as the threshold lowers, since more charging happens overnight.
- On PV Capture (without overnight charging), the battery was solely charged by solar energy ($\varphi=100\%$). On the other hand, in PLS mode, the battery was entirely charged with grid power ($\varphi=0\%$).
- PV Curtailment does not have an effect on increasing Solar EV Charging, but definitely an effect in increasing Solar Penetration.

In Task 2, an ETAP load flow model was developed and verified using meter data. The process anticipated the importance of a SCADA system to effectively store and archive meter data, and enable data manipulation and analysis by various commercially available software.

In Task 3, different BESS operation modes were simulated and compared concerning their impact on the Car Shade nanogrid circuit voltages up to the point of connection with the UCI Microgrid. Mostly EVSE terminal buses presented under-voltages. In general, observed to be caused by three main reasons:

1. High nanogrid total load, which lowered the upstream source voltage.
2. High inverter AC output power, which caused a significant conductor voltage drop.
3. High total nanogrid load: When this demand is high, a more severe voltage drop is caused at the most upstream bus in the system. This voltage drop is further deteriorated at the buses downstream due to normal conductor voltage drop.

In terms of impacts to the system, the PLS mode had best performance, which can be attributed to non-simultaneous high power flows. The worst performance observed was during CAP 20, where 98% and 95% under-voltages occurred during 35% and 2% of the time, respectively.

As mentioned above, in terms of Solar EV charging, PV Capture ranks first with 85% of the EVSE load met entirely by solar. However, in terms of Solar Penetration, PLS showed the best performance (95%) since, instead of charging the BESS with excess solar during the day, it allows a high PV export in the afternoon (which saves the BESS round trip efficiency losses). PV Capture and MPPI tied in second (89%). The worst performance was seen in CAP 20, which holds the highest amount of curtailed PV (52 kWh). Again, a high CAP threshold decreases renewable contribution.

In terms of NET EVCS demand, the PLS mode ranked first, since the mode only net-imported 33 kWh. PV Capture comes in second. The option of curtailing PV in CAP modes determines whether low or high thresholds are more efficient for a lower net import.

In task 4, power quality aspects of EV charging was characterized. A two-week survey revealed that transients in the phase voltage waveforms were the most significant power quality event. The transient events could be precisely associated with EVs plugging into the system. However, the transients observed (Average rise time of 5.66 microseconds (μ s), and average worst peak-to-peak was 119% p.u. for impulsive transients and an average frequency of 14.7 kHz for oscillatory transients) do not pose a threat to sensitive electronic equipment operation.

In terms of total voltage distortion, a clear direct correlation was observed for EV charging and harmonic distortion and the main contributions to distortion came from the 7th and 5th harmonic orders, yet, the 5% THD_v limit established by the IEEE 519 standard was not exceeded. Moreover, EV load diversity — different EV models with different on-board charger topologies — and EVSE phase diversity is beneficial for harmonic cancellation, which attenuates the harmonic distortion problem even more; cancellation was detected on the 3rd and 5th orders.

Lastly, to evaluate power quality at the Car Shade's PCC, different EV models available in the market were characterized as individual harmonic sources and a harmonic load flow was simulated in ETAP. The following conclusions were drawn:

- At the PCC, neither THD_v or IHD_v values went above the IEEE 519-1992 standard proposed limits;

- Since transformers feeding EVSEs are connected in a delta-wye grounding configuration, the triplen harmonics are trapped, preventing them from propagating upstream;
- The AIRB building connected to the same transformer did not show excessive THD.

In task 5, the optimal sizing of a nanogrid comprised of PV/Storage for EV charging with or without a classroom building added to the load mix using a linear program is demonstrated in the context of minimizing total system and operation costs.

A combination of an 80 kW PV array with a 95 kWh/42 kW BESS would be optimal for powering the 20 EVSEs, while a bigger system — 558 kW PV plus 1.1 MWh/320 kW BESS — would be required if a classroom/laboratory building (160 kVA average peak) was added to the nanogrid.

The proposed sizing methodology is suitable for use in various existing similar nanogrid configurations and can be extended to a more detailed analyses including stochastic behavior of PV generation and EV loads.

7. Conclusions

The following main conclusions can be drawn from this study:

- **Seamless integration of EV charging into power systems can be achieved with the right battery dispatch strategy**

In this specific system, both MPPI and PV CAPTURE modes were able to meet the daily EVSE demand while imposing no burden to the UCI Microgrid. Such achievement is important given the expected expansion for EV charging needs and grid-infrastructure planning.

- **A PV/battery nanogrid for EV charging enables renewable solar penetration in different levels**

The amount of PV power that will ultimately contribute to EV charging, or be exported, depends directly on the battery charging/discharging scheduling, i.e., the battery dispatch mode in place. Strategies where BESS recharging during the day — when PV generation exceeds EV loads — was always allowed, showed a higher renewable solar PV penetration.

- **EV charging will not cause power quality issues in a robust well-designed power system with delta-wye transformers.**

Voltage harmonic distortion was identified to be directly associated with EV charging. However, voltage distortion levels above IEEE Std. 519 were only identified at the bus connecting directly to the EVSE. The use of delta-wye transformers before neighboring loads prevents triplen harmonics to flow upstream the EV chargers, hence; it is an effective way to eliminate the problem of excessive voltage distortion.

- **Different EV models will produce a signature harmonic distortion, and this diversity contributes to harmonic cancellation or attenuation**

As different manufacturers will choose from a myriad of possible power electronic circuit topologies for power rectification, different EV models will cause a different impact in the AC side of the system. This is remarkably beneficial; harmonic currents are added using vector summation, and phase shifts will help attenuate the resultant distortion magnitude. At the Car Shade, cancellation was detected on the 3rd and 5th harmonic orders.

- **An optimal PV/battery combination for minimizing system cost can be established for a given EV charging load profile, and on-site solar insolation.**

The challenge of sizing the perfect combination of PV and battery for EV charging can only be addressed if the overall behavior of the EV charging loads is known (or can be predicted). This behavior will differ for different EV charging locations: at an office building, an apartment complex, a university campus, for instance.

It is also worth noting that batteries power and energy capacities are decoupled. For the specific system studied in this project, a combination of an 80 kW PV array with a 95 kWh/42 kW BESS would be optimal for powering 20 EVSEs.

8. Bibliography

- [1] R. W. McCarthy, C. Yang, and J. M. Ogden, "Interactions between electric-drive vehicles and the power sector in California," in *EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, 2009, pp. 1–14.
- [2] B. Tarroja, J. D. Eichman, L. Zhang, T. M. Brown, and S. Samuelsen, "The effectiveness of plug-in hybrid electric vehicles and renewable power in support of holistic environmental goals: Part 2 – Design and operation implications for load-balancing resources on the electric grid," *J. Power Sources*, Aug. 2014.
- [3] D. B. Richardson, "Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 247–254, Mar. 2013.
- [4] F. Mwasilu, J. J. Justo, E.-K. Kim, T. D. Do, and J.-W. Jung, "Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration," *Renew. Sustain. Energy Rev.*, vol. 34, pp. 501–516, Jun. 2014.
- [5] G. A. Putrus, P. Suwanapingkarl, D. Johnston, E. C. Bentley, and M. Narayana, "Impact of electric vehicles on power distribution networks," in *2009 IEEE Vehicle Power and Propulsion Conference*, 2009, pp. 827–831.
- [6] S. Avdakovic and A. Bosovic, "Impact of charging a large number of electric vehicles on the power system voltage stability," *Elektroteh. Vestnik/Electrotechnical Rev.*, vol. 81, no. 3, pp. 137–142, 2014.
- [7] P. Chen, S. Member, V. Malbasa, and M. Kezunovic, "Analysis of Voltage Stability Issues with Distributed Generation Penetration in Distribution Networks," in *North American Power Symposium (NAPS)*, 2013, pp. 1–6.
- [8] P. S. Moses, M. a S. Masoum, and K. M. Smedley, "Harmonic losses and stresses of nonlinear three-phase distribution transformers serving plug-in electric vehicle charging stations," in *IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT Europe*, 2011, pp. 1–6.
- [9] M. Farhoodnea, A. Mohamed, H. Shareef, and H. Zayandehroodi, "Power quality impacts of high-penetration electric vehicle stations and renewable energy-based generators on power distribution systems," *Measurement*, vol. 46, no. 8, pp. 2423–2434, Oct. 2013.
- [10] H. Farooq, C. Zhou, M. Allan, M. E. Farrag, R. A. Khan, and M. Junaaid, "Investigating the Power Quality of an Electrical Distribution System Stressed by Non-Linear Domestic Appliances," in *International Conference on Renewable Energies and Power Quality (ICREPQ'11) Las Palmas de Gran Canaria (Spain)*, 2011, pp. 2–7.
- [11] L. Kutt, E. Saarijarvi, M. Lehtonen, H. Molder, and J. Niitsoo, "A review of the harmonic and unbalance effects in electrical distribution networks due to EV charging," in *12th International Conference on Environment and Electrical Engineering, IEEEIC 2013*, 2013, pp. 556–561.
- [12] K. Kim, T. Yoon, and G. Byeon, "Power demand and power quality analysis of EV charging station using BESS in MicroGrid," in *2012 IEEE Vehicle Power and Propulsion Conference*, 2012, pp. 996–1001.

- [13] Q. Li, S. Tao, X. Xiao, and J. Wen, "Monitoring and analysis of power quality in electric vehicle charging stations," in *2013 1st International Future Energy Electronics Conference (IFEEEC)*, 2013, pp. 277–282.
- [14] C. Wenge, T. Winkler, M. Stotzer, and P. Komarnicki, "Power quality measurements of electric vehicles in the low voltage power grid," in *11th International Conference on Electrical Power Quality and Utilisation*, 2011, pp. 1–5.
- [15] V. Monteiro, H. Gonçalves, and J. L. Afonso, "Impact of electric vehicles on power quality in a Smart Grid context," in *Proceeding of the International Conference on Electrical Power Quality and Utilisation, EPQU*, 2011, pp. 660–665.
- [16] J. P. Trovão, P. G. Pereirinha, L. Trovão, and H. M. Jorge, "Electric vehicles chargers characterization: Load demand and harmonic distortion," in *Proceeding of the International Conference on Electrical Power Quality and Utilisation, EPQU*, 2011, pp. 694–700.
- [17] A. R. Boynuegri, M. Uzunoglu, O. Erdinc, and E. Gokalp, "A new perspective in grid connection of electric vehicles: Different operating modes for elimination of energy quality problems," *Appl. Energy*, vol. 132, pp. 435–451, Nov. 2014.
- [18] P. S. Moses, S. Deilami, A. S. Masoum, and M. A. S. Masoum, "Power quality of smart grids with plug-in electric vehicles considering battery charging profile," in *IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT Europe*, 2010, pp. 1–7.
- [19] Electric Drive Transportation Association (EDTA), "Electric Drive Sales," 2016. [Online]. Available: <http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952>. [Accessed: 12-Jan-2016].
- [20] California New Car Dealers Association (CNCDA), "California Auto Outlook," 2015.
- [21] G. G. B. Jr., "ZEV Action Plan. A roadmap toward 1.5 million zero-emission vehicles on California roadways by 2025," pp. 1–32, 2013.
- [22] O. Egbue and S. Long, "Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions," *Energy Policy*, vol. 48, no. 2012, pp. 717–729, Sep. 2012.
- [23] M. Honarmand, A. Zakariazadeh, and S. Jadid, "Integrated scheduling of renewable generation and electric vehicles parking lot in a smart microgrid," *Energy Convers. Manag.*, vol. 86, pp. 745–755, Oct. 2014.
- [24] O. Saadeh, "North American Microgrids 2015: Advancing Beyond Local Energy Optimization," *GTM Research*, 2015. [Online]. Available: <https://www.greentechmedia.com/research/report/north-american-microgrids-2015>. [Accessed: 16-Nov-2015].
- [25] C. Martin, "Brooklyn Plans to Avoid Blackouts With Utility-Disrupting 'Microgrids' - Bloomberg Business," 2015. [Online]. Available: <http://www.bloomberg.com/news/articles/2015-09-09/brooklyn-to-avoid-blackouts-with-utility-disrupting-microgrids>. [Accessed: 16-Nov-2015].
- [26] B. Nordman and K. Christensen, "Local power distribution with nanogrids," in *2013 International Green Computing Conference Proceedings, IGCC 2013*, 2013, pp. 1–8.

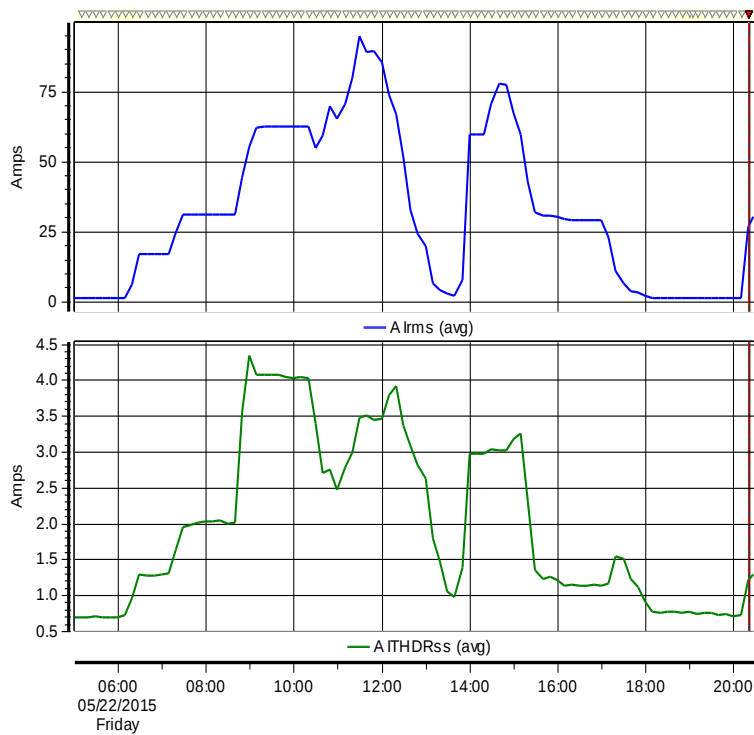
- [27] B. P. Shaffer, "UCI Microgrid Hardware Assets." Advanced Power and Energy Program, Irvine, California, p. 13, 2013.
- [28] Chargepoint, "CT1500 Family ChargePoint ® Networked Charging Stations Installation Guide." p. 78, 2014.
- [29] ChargePoint, "Chargepoint Portal DASHBOARD," 2015. [Online]. Available: <http://www.na.chargepoint.com>. [Accessed: 20-May-2010].
- [30] G. A. Luckjiff, J. W. Freeborg, and R. L. Hayes, "Case studies from operation of a nationwide PQ&R monitoring system," *IEEE Ind. Appl. Mag.*, pp. 0–5, 2005.
- [31] "IEEE Std 1100, Recommended Practice for Powering and Grounding Electronic Equipment," vol. 1999. 1999.
- [32] M. H. J. Bollen, "Understanding Power Quality Problems," *Underst. Power Qual. Probl.*, pp. 485–505, 1999.
- [33] T. Ise, Y. Hayashi, and K. Tsuji, "Definitions of power quality levels and the simplest approach for unbundled power quality services," in *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, 2000, vol. 2, pp. 385–390.
- [34] *IEEE Std 1159-2009, IEEE Recommended Practice for Monitoring Electric Power Quality*. 2009.
- [35] M. N. Moschakis, E. L. Karfopoulos, E. I. Zountouridou, and S. A. Papathanassiou, "On Adaptation of Electric Vehicle and Microgrid Issues to EMC-Power Quality Standards," *Electr. Electron. Eng. J.*, vol. 2, no. 5, pp. 249–257, 2012.
- [36] R. Dugan, "Electrical power systems quality, Second Edition," *New York, NY McGraw-Hill*, 1996.
- [37] *IEEE Std. 519, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*. 1992.
- [38] H. A. Attia, M. El-Metwally, and O. M. Fahmy, "Harmonic Distortion Effects and Mitigation in Distribution Systems," *J. Am. Sci.*, vol. 6, no. 10, pp. 173–183, 2010.
- [39] M. H. J. Bollen, E. Styvaktakis, and I. Y. H. Gu, "Categorization and analysis of power system transients," *IEEE Trans. Power Deliv.*, vol. 20, no. 3, pp. 2298–2306, 2005.
- [40] M. Yilmaz and P. T. Krein, "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013.
- [41] R. W. Erickson, *Fundamentals of Power Electronics*, Second Edi. Secaucus, NJ, USA: Kluwer Academic Publishers, 2000.
- [42] E. C. Bentley, P. Suwanapongkarl, S. Weerasinghe, T. Jiang, G. a. Putrus, and D. Johnston, "The interactive effects of multiple EV chargers within a distribution network," in *2010 IEEE Vehicle Power and Propulsion Conference, VPPC 2010*, 2010.
- [43] "Rectifiers." [Online]. Available: <http://what-when-how.com/induction-motor/rectifiers-induction-motor/>. [Accessed: 28-Feb-2016].
- [44] S. H. Berisha, G. G. Karady, R. Ahmad, R. Hobbs, and D. Karner, "Current harmonics generated by electric vehicle battery chargers," in *Proceedings of International*

- Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*, 1996, vol. 1, pp. 584–589.
- [45] J. Thode, “Car Shade Project Data - Monthly Energy Summaries.” 2015.
 - [46] Information Technology Industry Council, “ITI (CBEMA) Curve,” 1997.
 - [47] R. Arthur and R. Shanahan, “Neutral currents in three phase wye systems,” *Actas del IEEE*, 7th. ..., no. August, 1996.
 - [48] S. Bai and S. M. Lukic, “Unified active filter and energy storage system for an MW electric vehicle charging station,” *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5793–5803, 2013.
 - [49] O. A. Ruiz-Guzman, A. J. Ustariz-Farfan, and E. A. Cano-Plata, “Modeling of electric vehicle chargers by its characterization in charging stages,” in *2015 IEEE Workshop on Power Electronics and Power Quality Applications, PEPQA 2015 - Proceedings*, 2015, pp. 1–6.
 - [50] L. Kutt, E. Saarijarvi, M. Lehtonen, H. Molder, and J. Niitsoo, “Current harmonics of EV chargers and effects of diversity to charging load current distortions in distribution networks,” in *2013 International Conference on Connected Vehicles and Expo, ICCVE 2013 - Proceedings*, 2013, pp. 726–731.
 - [51] Lazard, “Lazard’s levelized cost of energy analysis—version 8.0,” 2014.

APPENDIX A

Car Shade distorted current waveforms: RMS and THD

Table A.1: Different Phase RMS current and THD on Friday 05/22/2015



7:59 AM			
Phase	A	B	C
RMS (A)	31.0	67.8	68.8
THD (A)	2.2	2.3	2.4
10:29 AM			
RMS (A)	64.4	61.1	50.5
THD (A)	2.8	2.3	2.7
11:29 AM			
RMS (A)	89.0	119.4	46.4
THD (A)	3.5	4.0	1.9
13:49 PM			
RMS (A)	55.2	70.2	108.7
THD (A)	3.0	2.6	3.6
14:49 PM			
RMS (A)	71.9	60.0	80.7
THD (A)	3.1	1.9	3.0
15:59 PM			
RMS (A)	29.2	29.8	3.1
THD (A)	1.2	1.4	1.0

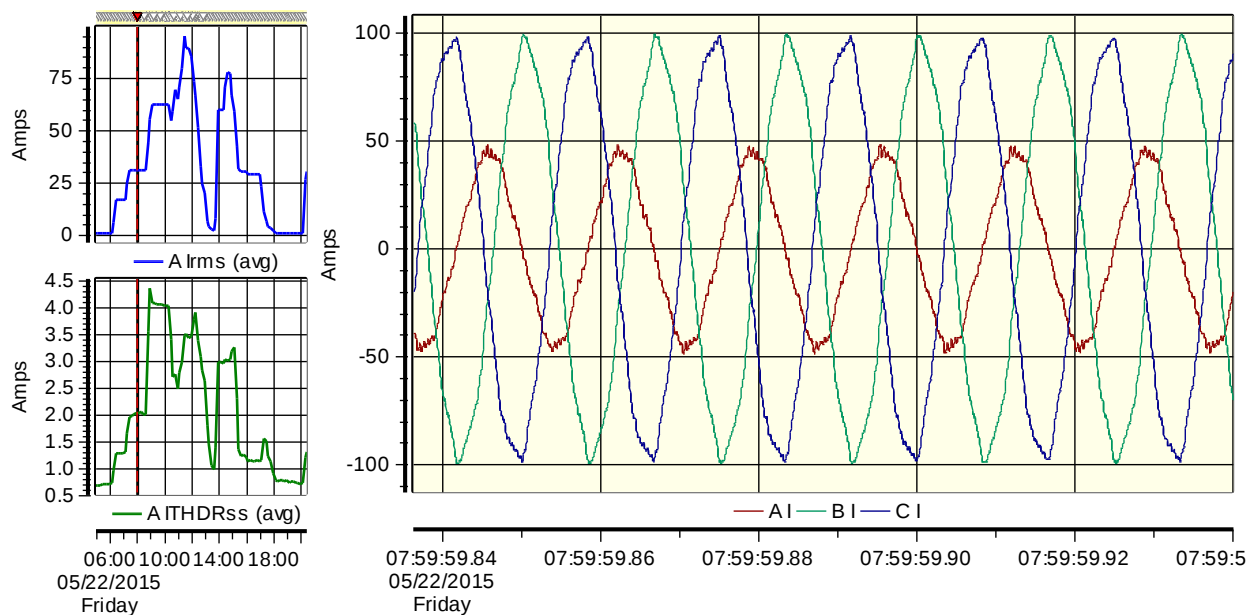


Figure A.1: T1-SEC Phase A, B, and C Current Waveforms (05/22/2015 - 07:59 AM)

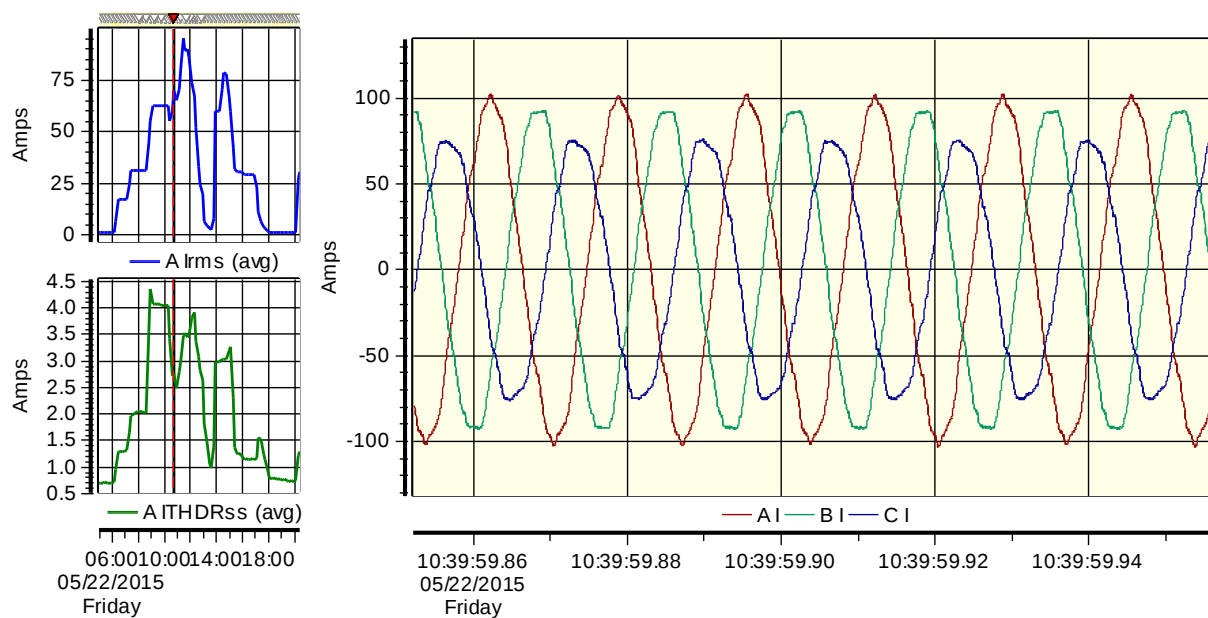


Figure A.2: T1-SEC Phase A, B, and C Current Waveforms (05/22/2015 - 10:39 AM)

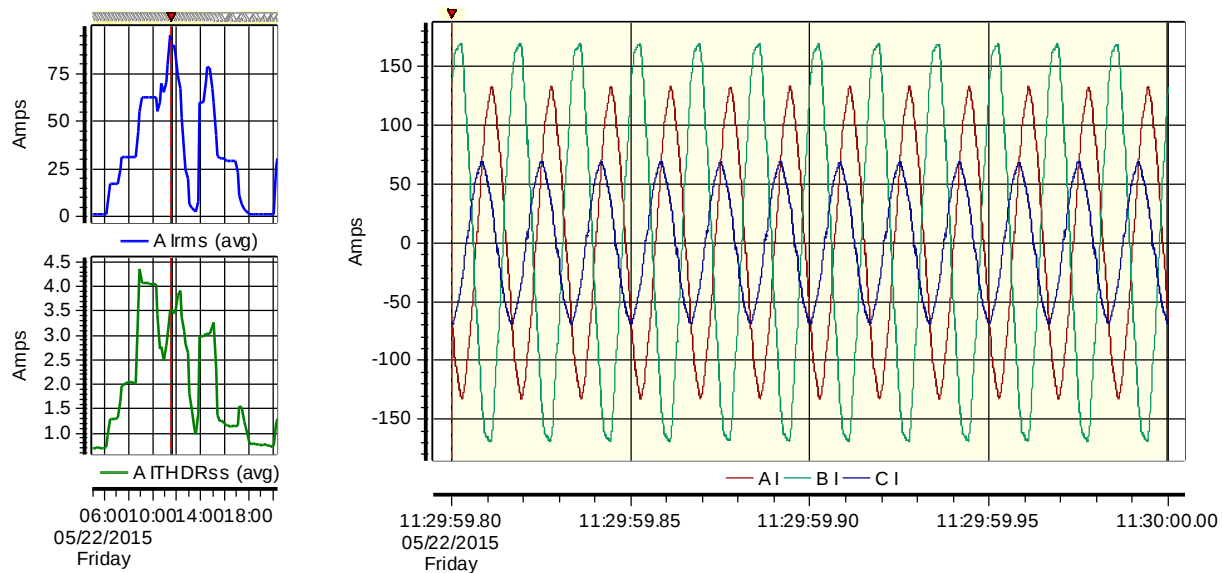


Figure A.3: T1-SEC Phase A, B, and C Current Waveforms (05/22/2015 - 11:29 AM)

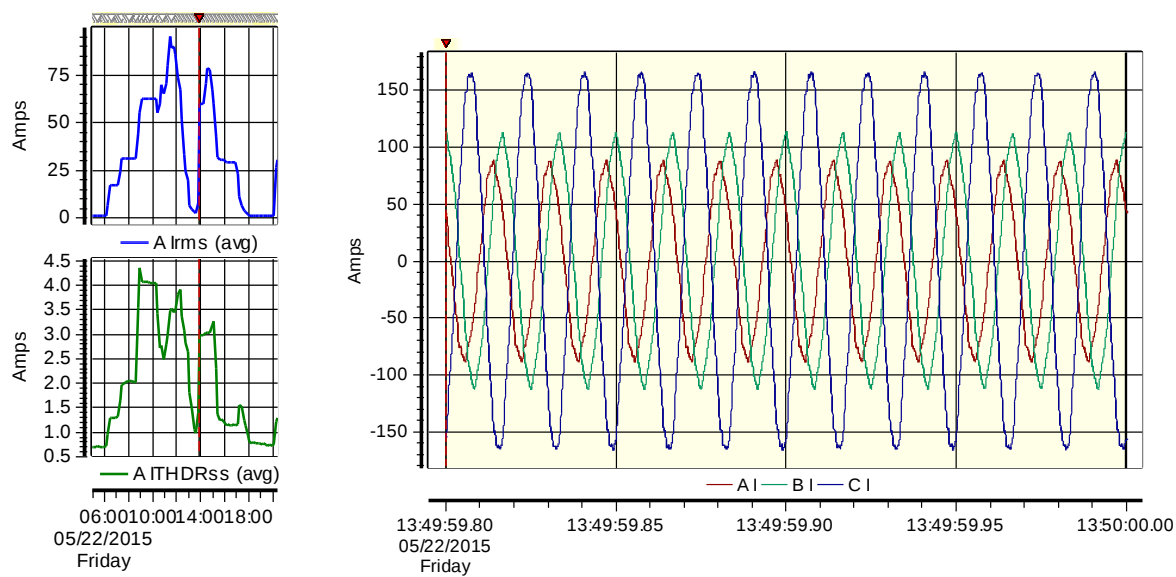


Figure A.3: T1-SEC Phase A, B, and C Current Waveforms (05/22/2015 - 13:49 PM)

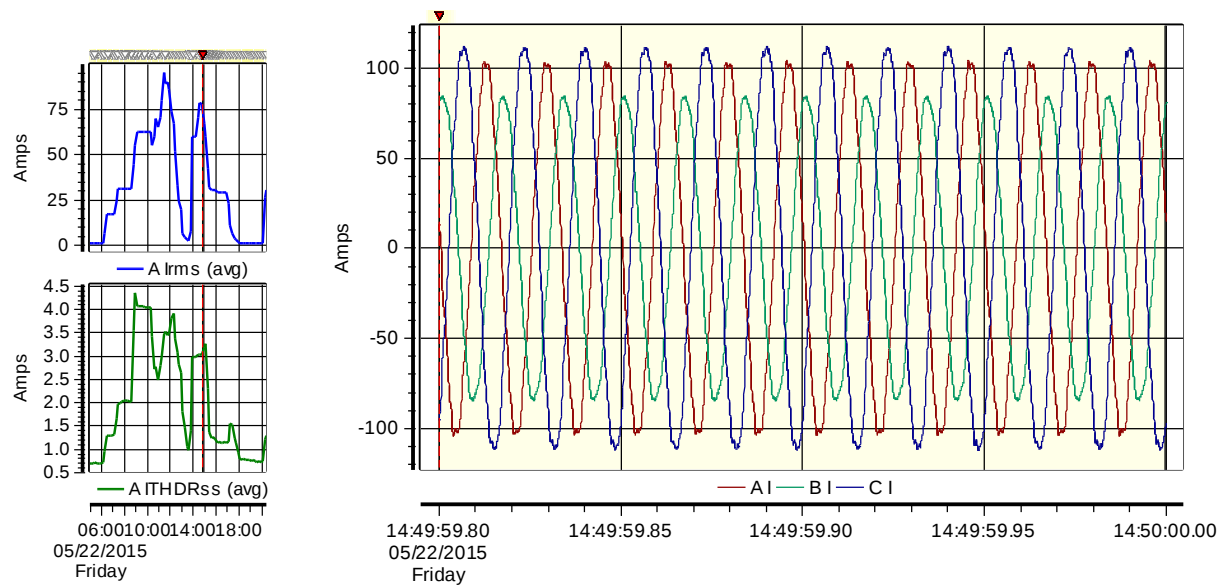


Figure A.4: T1-SEC Phase A, B, and C Current Waveforms (05/22/2015 - 14:49 AM)

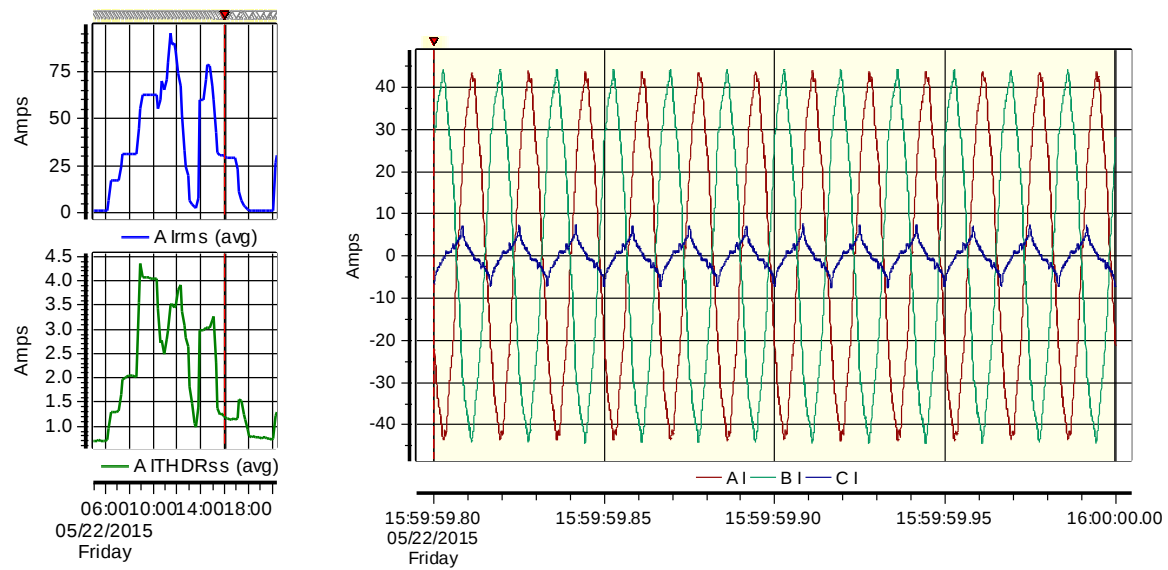
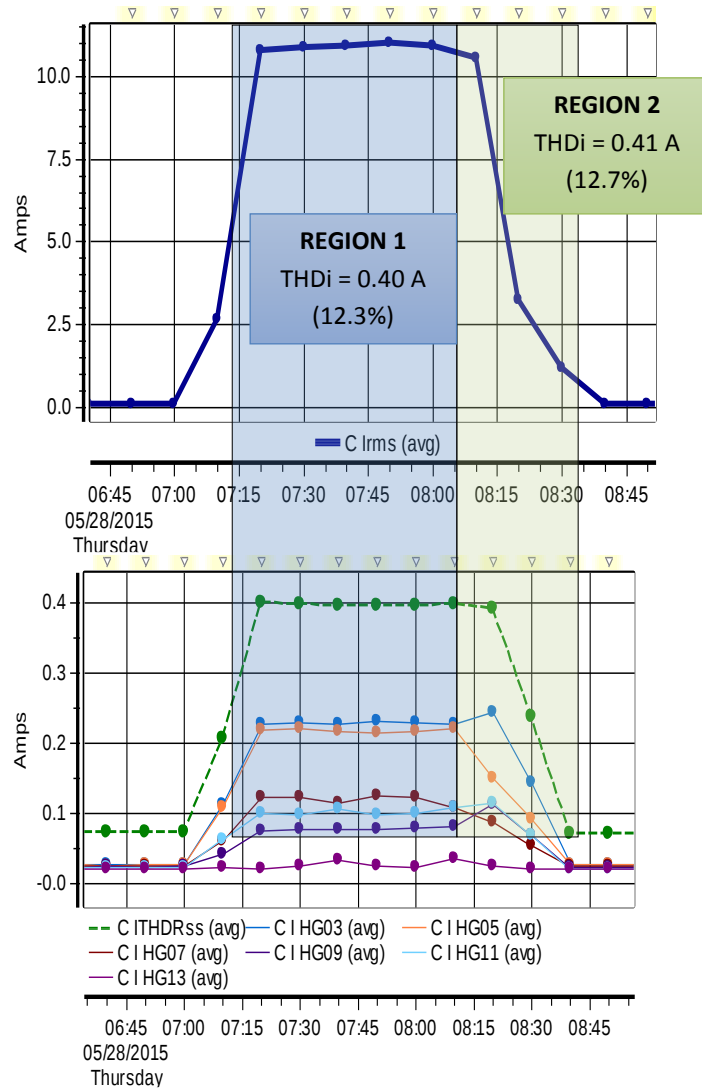


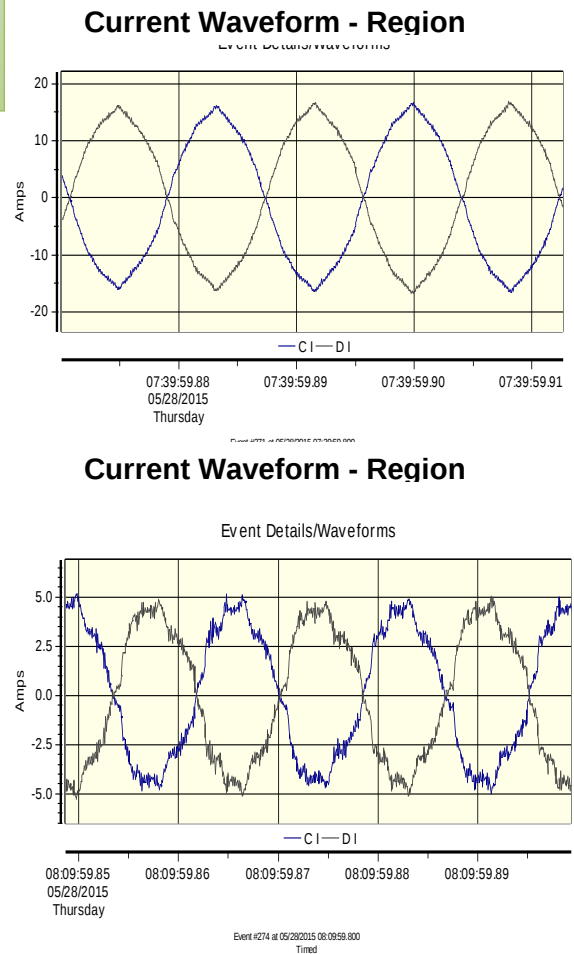
Figure A.5: T1-SEC Phase A, B, and C Current Waveforms (05/22/2015 - 15:59 PM)

APPENDIX B

Characteristic charging profiles for different EVs

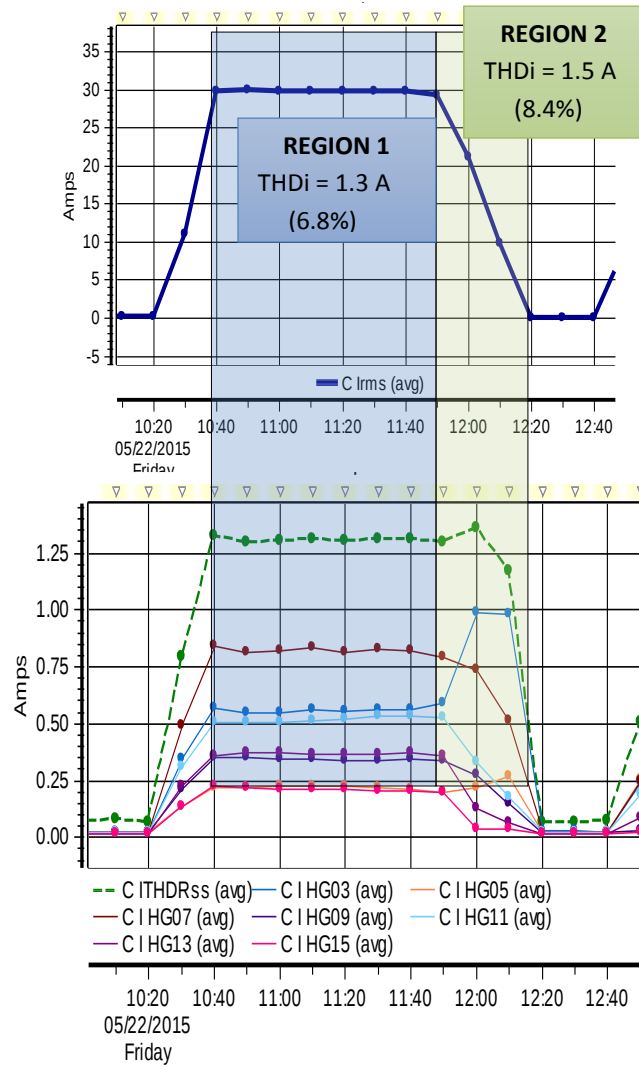


(a)

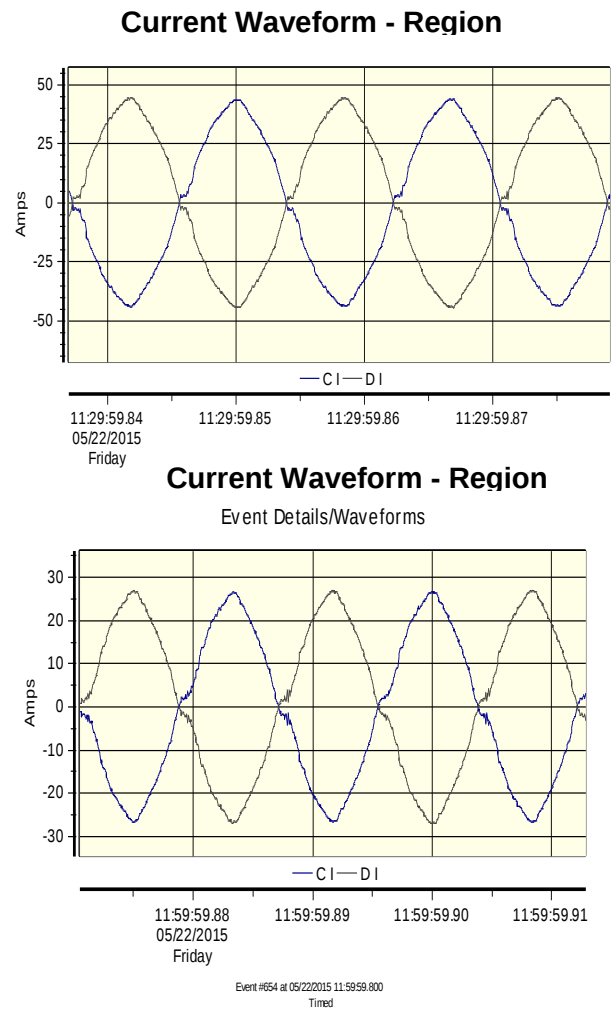


(b)

Figure B.1: (a) Toyota Prius charging current profile (b) Current Waveforms

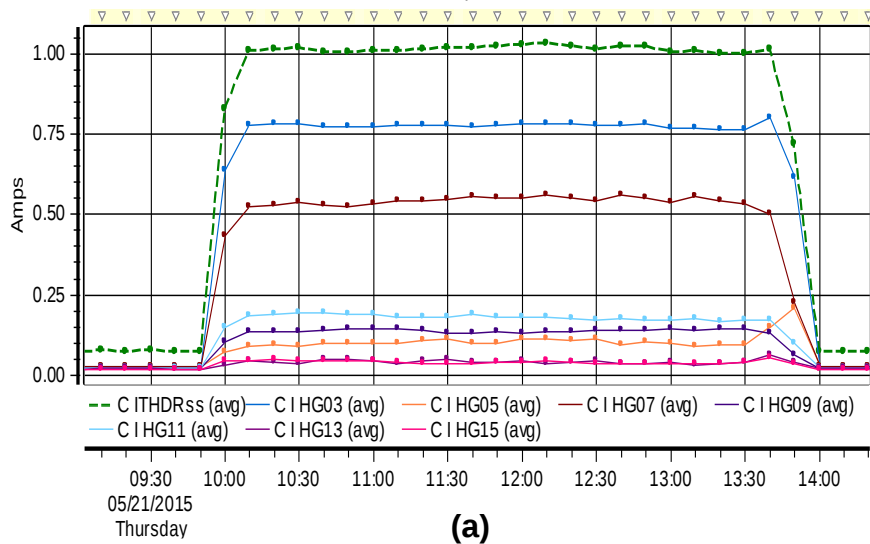
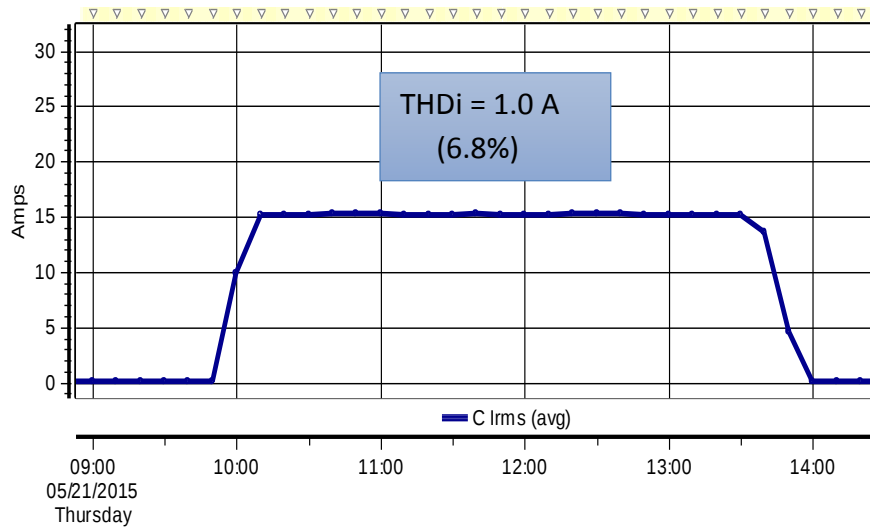


(a)

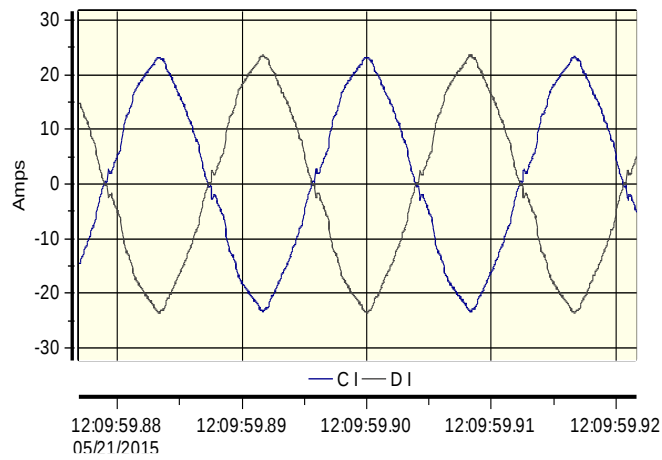


(b)

Figure B.2: (a) BMW i3 charging current profile (b) Current Waveforms

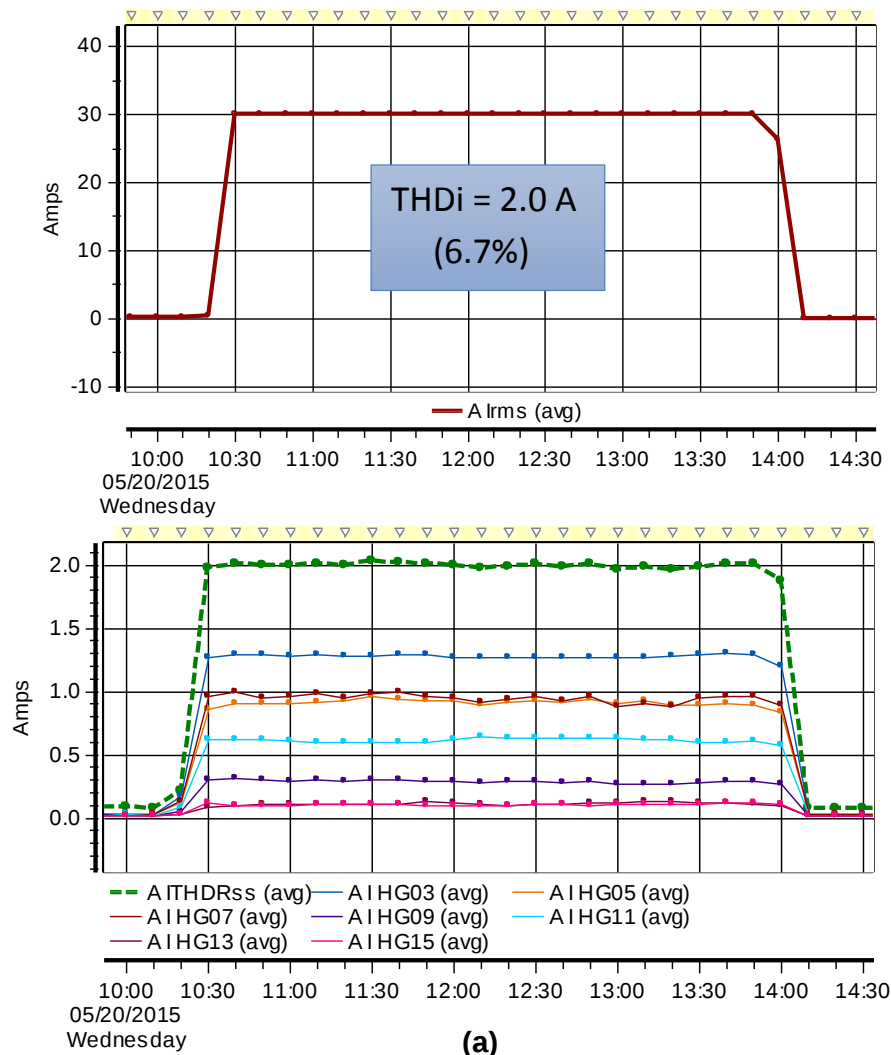


(a)
Current Waveform



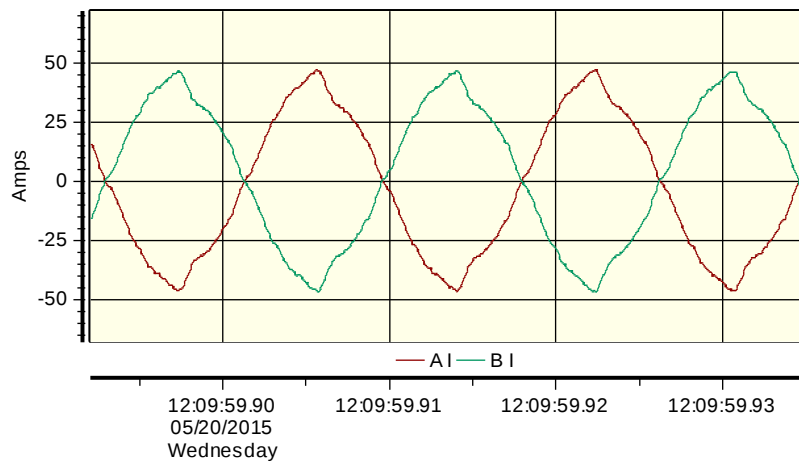
(b)

Figure B.3: (a) Chevy Volt charging current profile (b) Current Waveform



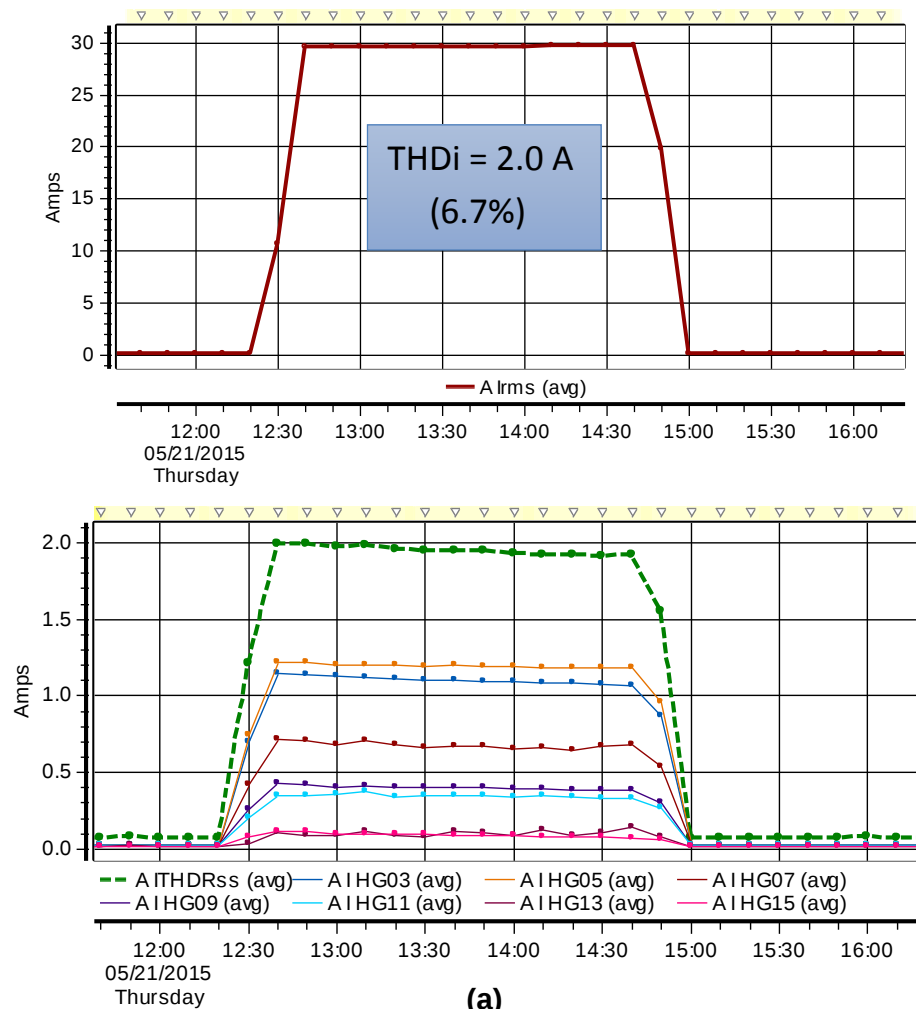
(a)

Current Waveform



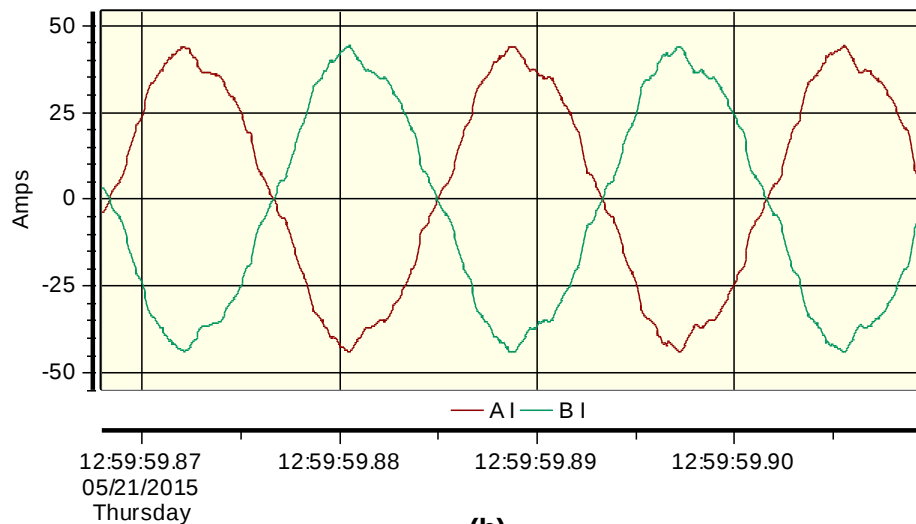
(b)

Figure B.4: (a) Kia Soul charging current profile (b) Current Waveform



(a)

Current Waveform



(b)

Figure B.5: Mercedes EV charging current profile (b) Current Waveform

APPENDIX C

Optimization LP: MATLAB source code

Contents:

- Known variables
- Linear Inequalities
- Linear Equalities
- Lower Bounds
- Upper Bounds
- Initial conditions
- Objective Function
- Subplots in kW
- Optimization Results

```
% Car Shade Nanogrid - BESS and PV sizing
% EVSE + ARIB (optional)
% Data inputs from 01/08/2015 to 02/06/2015
% Initial and final SOC = 50% -> for sustainable operation

clc
clear all
close all
```

Known variables

```
%Costs
C_bess = 0.205; % [$ / kWh]
C_pv = 0.126; % [$ / kW]
C_SCE = 0.03147; %Option R [$ / kWh] 0.03219

PV_raw_t = [];
PV_raw = transpose(PV_raw_t);

% Normalized PV [kWh/kW0]
PV = PV_raw ./ 48 * 0.25;

%EVSE [kW]
EVSE_raw_t = [];
EVSE_raw = transpose(EVSE_raw_t);

%EVSE [kWh]
EVSE = EVSE_raw * 0.25;

%AIRB [kW]
AIRB_raw_t = [];
```

```

AIRB_raw = transpose(AIRB_raw_t);

%AIRB [kWh]
AIRB = AIRB_raw.*0.25;

leg = 0;

%Nanogrid (EVSE + AIRB)
%EVSE = EVSE + AIRB;
%leg = 1; % ( 0 for w/o AIRB and 1 for with AIRB)

L = length(EVSE);

```

Linear Inequalities

```

A = zeros(3*L,2+4*L); % rows = (number of inequalities)*L , columns = 2 +(number of
variables)*L
b = zeros(3*L,1); % rows = (number of equalities)*L

for i = 1:L
    b(2*L+i) = EVSE(i);
end

%First inequality : 0.1*BESS <= BESS(t)
j=0;
for i = 1:L %from row 1 to 96
    A(i,1) = 0.1;
    A(i,3+L+j) = -1;
    j = j+1;
end

%Second inequality 1*BESS(t) <= BESS
%It will populate the second half of A
j=0;
for i = L+1:2*L %from row 97 to 192
    A(i,1) = -1;
    A(i,3+L+j) = 1;
    j = j+1;
end

%Third inequality BESSdt(t) <= EVSE(t)
%It will populate the third half of A
j=0;
for i = 2*L+1:3*L %from row 193 to 288
    A(i,3+j) = 1;
    j = j+1;
end

```

Linear Equalities

```

Aeq = zeros(2*L,2+4*L); % rows = #of equalities , columns = 2 + # of (t) variables*L

%First equality: npv*Pv(t) + BESSdt(t) + Import(t) - Export(t) = EVSE(t)
j=0;
for i = 1:L %from rows 1 to 3072
    Aeq(i,2) = PV(i);
    Aeq(i,3+j) = 1;
    Aeq(i,3+2*L+j) = 1;
    Aeq(i,3+3*L+j) = -1;
    j = j+1;
end

%Second equality: BESS(t+1) = BESS(t) - BESSdt(t)
%It will populate the second half of Aeq
j=0;
for i = L+1:2*L-1 %from rows 3073 to 6143
    Aeq(i,3+j) = -1;
    Aeq(i,3+L+j) = 1;
    Aeq(i,3+L+1+j) = -1;
    j = j+1;
end

%Third equality: SUM(Import(t)) - SUM(Export(t)) = 0
j=0;
for j = 0:L-1 % j = 0 to 3071
    Aeq(2*L,3+2*L+j) = 1; %row 6144
    Aeq(2*L,3+3*L+j) = -1; %row 6144
end

%BESS(1) = 0.5*BESS %SOC initial = 50%
Aeq(2*L+1,L+3) = 1; % BESS(1) = 1
Aeq(2*L+1,1) = -0.5; % BESS = -0.5

%BESS(L) = 0.5*BESS %SOC final = 50%
Aeq(2*L+2,2*L+2) = 1; %row 6145
Aeq(2*L+2,1) = -0.5; % BESS = -0.5

beq = zeros(2*L+2,1);

for i = 1:L
    beq(i) = EVSE(i);
end

```

Lower Bounds

```

lb = zeros(2+4*L,1);

%lb(1) = 100; %Min BESS
%lb(2) = 40; %Min PV

for i = 1:L

```

```

    lb(i+2)= -Inf; %BESSdt(t) limits - BESS can CHARGE with no limits
end

```

Upper Bounds

```

ub = Inf(2+4*L,1);

for i=2*L+1:3*L % Import limits
    ub(i+2) = Inf;
    %ub(i+2)= 50;
end

for i = 3*L+1:4*L % Export limits
    ub(i+2) = Inf;
    %ub(i+2)= 50;
end

```

Initial conditions

```

x0 = zeros(2+4*L,1);

%x0(1) = 100; % BESS = 100 kWh
%x0(99) = 200; % Initial BESS(0)

```

Objective Function

```

%f = C_bess*BESS + C_pv*npv*sum(PV(t)) + C_SCE*sum(Import(t))
f = zeros(size(x0));
f(1) = C_bess;
f(2) = C_pv*sum(PV);

for i=0:L-1
    f(3+2*L+i) = C_SCE; %Charges for the energy that is imported
end

%Solve linear program
x = linprog(f,A,b,Aeq,beq,lb,ub);

```

Subplots in kW

```

BESSdt_kW = BESSdt./0.25; %Battery charge/discharge dynamics
Import_kW = Import./0.25; %Grid Import power
Export_kW = Export./0.25; %Grid Export power
EVSE_kW = EVSE./0.25;

```

```

PV_kW = PV./0.25;
a = figure;
title('Optimization Results for Jan/Feb 2015')
subplot(4,1,1);
plot(t, EVSE_kW, t, x(2)*PV_kW)
title('Load and PV Dynamics')

if leg == 0
    legend('EVSE', 'PV')
    ticks_y = [0 25 50 75];
else
    legend('EVSE + AIRB', 'PV')
    ticks_y = [0 250 500];
    ticks_y_BESS = [ -400 -200 0 120];
end

axis ([-Inf +Inf -Inf +Inf]) % Fixing blank space after x axis
ylabel('Power [kW]')
grid on
ticks = linspace(length(EVSE)/(30*2),length(EVSE)-length(EVSE)/(30*2),30);
ticklabel = [ '08' ;'09' ;'10' ;'11' ;'12' ;'13' ;'14' ;'15' ;'16' ;'17' ;'18' ;'19'
;'20' ;'21' ;'22' ;'23' ;'24' ;'25' ;'26' ;'27' ;'28' ;'29' ;'30' ;'31' ;'01' ;'02' ;
'03' ;'04' ;'05' ;'06'];
ax = gca; %defines current axes handle
set(ax, 'XTick' , ticks)
set(ax, 'XTickLabel', ticklabel)
set(ax, 'YTick' , ticks_y)

subplot(4,1,2);
plot(t, BESSdt_kW)
title('BESS dynamics: (-)Charge, (+)Discharge')
axis ([-Inf +Inf -Inf +Inf]) % Fixing blank space after x axis
ylabel('Power [kW]')
grid on
ticks = linspace(length(EVSE)/(30*2),length(EVSE)-length(EVSE)/(30*2),30);
ticklabel = [ '08' ;'09' ;'10' ;'11' ;'12' ;'13' ;'14' ;'15' ;'16' ;'17' ;'18' ;'19'
;'20' ;'21' ;'22' ;'23' ;'24' ;'25' ;'26' ;'27' ;'28' ;'29' ;'30' ;'31' ;'01' ;'02' ;
'03' ;'04' ;'05' ;'06'];
ax = gca; %defines current axes handle
set(ax, 'XTick' , ticks)
set(ax, 'XTickLabel', ticklabel)
if leg == 1
    set(ax, 'YTick' , ticks_y_BESS)
end

subplot(4,1,3);
plot(t, Import_kW,t, Export_kW)
title('Grid (+)Import and (-)Export')
legend('Import', 'Export')
axis ([-Inf +Inf -Inf +Inf]) % Fixing blank space after x axis
ylabel('Power [kW]')
grid on
ticks = linspace(length(EVSE)/(30*2),length(EVSE)-length(EVSE)/(30*2),30);

```

```

ticklabel = ['08' ; '09' ; '10' ; '11' ; '12' ; '13' ; '14' ; '15' ; '16' ; '17' ; '18' ; '19'
; '20' ; '21' ; '22' ; '23' ; '24' ; '25' ; '26' ; '27' ; '28' ; '29' ; '30' ; '31' ; '01' ; '02' ;
'03' ; '04' ; '05' ; '06'];
ax = gca; %defines current axes handle
set(ax, 'XTick' , ticks)
set(ax, 'XTickLabel', ticklabel)

subplot(4,1,4);
SOct = 100*BESSt./x(1);
plot(t,SOct)
title('BESS SOC [%]')
axis ([-Inf +Inf -Inf +Inf]) % Fixing blank space after x axis
ylabel('SOC (%)')
grid on
ticks = linspace(length(EVSE)/(30*2),length(EVSE)-length(EVSE)/(30*2),30);
ticklabel = [ '08' ; '09' ; '10' ; '11' ; '12' ; '13' ; '14' ; '15' ; '16' ; '17' ; '18' ; '19'
; '20' ; '21' ; '22' ; '23' ; '24' ; '25' ; '26' ; '27' ; '28' ; '29' ; '30' ; '31' ; '01' ; '02' ;
'03' ; '04' ; '05' ; '06'];
ax = gca; %defines current axes handle
set(ax, 'XTick' , ticks)
set(ax, 'XTickLabel', ticklabel)
ticks_y = [ 10 50 100];
set(ax, 'YTick' , ticks_y)
xlabel('Day of the month')

a.PaperUnits = 'inches';
a.PaperPosition = [0 0 7.5 7.8]; % [ 0 0 width height]
a.PaperPositionMode = 'manual';
print(a, 'Optimization_1', '-dtiff', '-r150')

```

Optimization Results

```

%Calculating max Instantaneous power kW (charge or discharge)
max_kWh = max(max(BESSdt), abs(min(BESSdt)));
max_kW = max_kWh/0.25;

disp('Opimization Results:')
disp('PV Size kW')
disp(x(2))
disp('BESS Size kWh')
disp(x(1))
disp('BESS Size kW ')
disp(max_kW)
disp('Max Grid Import kW')
disp(max(Import_kW))
disp('Sum Import kWh')
disp(sum(Import))

```