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Modeling of a Battery Storage System on a Distribution Feeder

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**MODELING OF A BATTERY STORAGE SYSTEM ON A
DISTRIBUTION FEEDER**

By

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B.S., Electrical Engineering, University of New Mexico, 2013

THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

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DEDICATIONS

This thesis is dedicated to my wife Elizabeth Griego, who has supported me and has been my driving force to finish my thesis.

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Modeling of a Battery Storage System on a Distribution Feeder

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Abstract

Driven by the need to reduce harmful emissions and the desire to move away from our dependency on fossil fuels, we have seen a sharp increase in alternative energy research and development within the last decade. Amongst the many alternative energy sources, photovoltaics (PV) is becoming more commonplace on the power utility system.

With these new sources of renewable energy being widely adopted, there are causes for concern that power utility companies must address. One of the more present issues that has been noted is the reliability of the power being delivered; in particular with PV systems. Studies have shown sharp changes in the power output of PV systems during cloudy and partially cloudy weather. With larger PV sites, this can lead to power quality issues, making solar less reliable for dispatch. To increase both power quality and reliability, various storage systems, such as batteries, are used in conjunction with PV systems. This has led researchers and utilities to see how these storage systems can aid in other reliability concerns.

The study outlined in this document is concerned with the siting and commissioning of a 1MW/1MWh battery storage system connected to a distribution feeder. While PV shifting and smoothing with storage systems was modeled, this study will focus on voltage regulation, which has not been a focus for storage units. To assist with this study OpenDSS, an open source electric power distribution system simulator, was utilized.

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Chapter 1

Introduction

1.1 Background

With the increasing concern of harmful emissions being released into our atmosphere, there has been a focus on shifting away from our current dependency on fossil fuels and searching for alternative, clean, and renewable forms of energy. This has led to a sharp increase in the research and development of these sources over the past decade. Amongst these sources, utilities have seen a rise in the amount of PV and wind generation being added to their systems.

A contributing factor that has increased the rate of renewable energy sources has been government incentives. Within the United States, government agencies at both the state and federal levels have been offering homeowners and companies tax incentives to install renewable generation. As an example, and according to the Energy Conservation and Management Division (ECMD) website, the state of New Mexico offers the New Mexico Solar Market Development Tax Credit, or Solar Tax Credit (STC). This tax credit will pay up to 10% (up to \$9,000) for a solar PV or solar thermal system. In addition to the STC, the federal government will pay 30% in tax credits for a solar system. [1]

In addition to customer and developer incentives, government agencies are also mandating utility companies to increase the percentage of renewable generation that are interconnected to their system. In accordance with the New Mexico Public Regulation Commission's (NMPRC) Renewable Energy Act (REA), Chapter 62, Article 16 section 4 (Renewable Portfolio Standard), Public utility companies in New Mexico must meet

timelines of increasing percentages of renewable energy. According to the REA, no later than January 1st 2020, utilities shall comprise of no less than 20 percent in renewable energy of the total retail sales to New Mexico customers. [2]

Figure one illustrates the solar growth in the United States over the past fifteen years. The provided data shows a drastic increase in both the residential and non-residential use of PV, as well as a sizable growth in the utility as a whole.

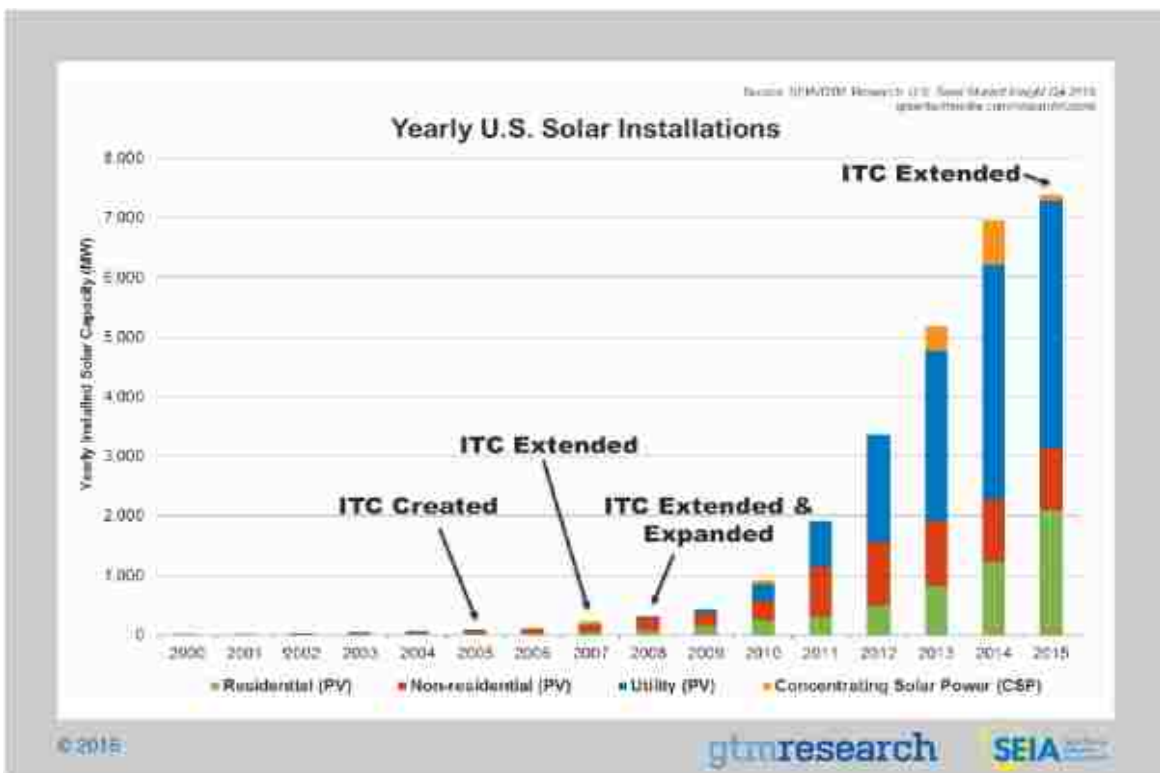


FIGURE 1: SOLAR GROWTH IN THE UNITED STATES PER YEAR INTERCONNECTED INTO THE BULK ELECTRIC AND DISTRIBUTION SYSTEMS [3]

As PV technology improves and costs for production and installation of these systems continue to decrease, we will see a growing percentage of PV on the utility system, especially in the southwestern United States.

However, solar power's inherent intermittency poses challenges in terms of power quality and reliability. Weather conditions throughout the day can fluctuate, taking a PV system's output from nominal to negligible levels within a very short period of time. These fluctuations can adversely affect the grid in the form of voltage sags unless steps are taken to quickly counteract the change in the power generation. In small power systems, system frequency can also be adversely affected [4].

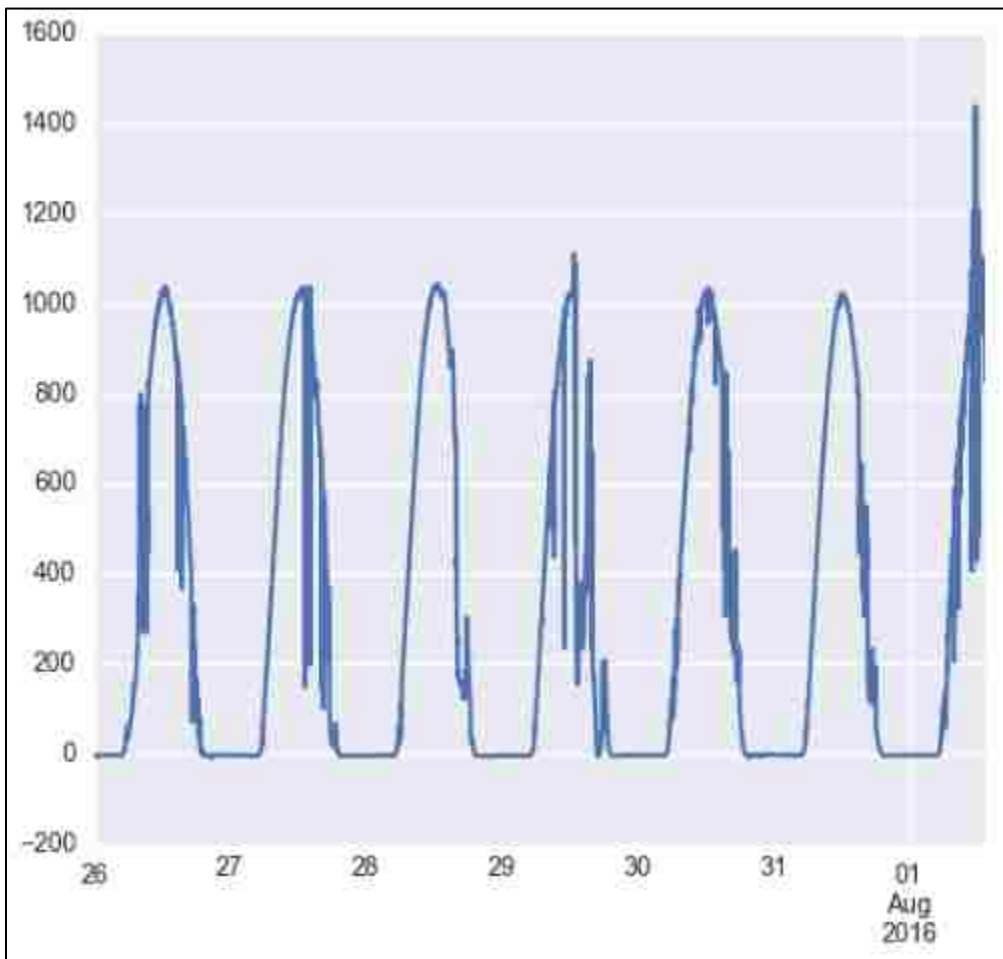


FIGURE 2: MEASURED SOLAR IRRADIANCE DATA IN ALBUQUERQUE TAKEN DURING THE LAST WEEK OF JULY [4]

The effect of clouds on PV production can be significant. Figure 2 shows local solar irradiance in Albuquerque during the last week in July collected by Fraunhofer USA. For example, on July 27th and July 29th, with no cloud cover, solar irradiance can produce up to 1100 W/m², allowing the maximum solar output from a PV panel. However, on these days, sharp drop off and sudden rise in the solar irradiance indicate the passing of clouds and result in associated spikes in PV power output, leading to fluctuations in the distribution system.

During the summer months, a utility would expect to see higher peak loads due to air conditioning and evaporative cooling units. With the load demand being high, power fluctuations can have negative impact on system reliability and utilities may not count on renewables as a stable source of power during this time. Because of these fluctuations in renewable energy generation Battery Energy Storage Systems (BESS) can quickly provide power in such scenarios to minimize customer interruptions. [5]

1.2 History of the Electrical utility in America

The modern electric utility system can be traced back to the invention of the light bulb in 1879 by Thomas Edison. For Edison to take his invention to the marketplace, he would have to develop a means to supply electrical power to the public. With this, he developed the first system in 1882 that generated and distributed electrical power. Edison's first power plant was located on Pearl Street in New York City's financial district and provided Direct Current (DC) electricity to businesses and shop owners who were using the light bulb. At that time, DC electricity had an inherent constraint that it could not deliver power over long distances. Due to this limitation, the DC power system was only

able to supply power to customers within a one mile radius and having multiple power stations serving a city was common. [6]

The electrical power system in America was being designed and built around DC power. While in Europe, several Alternating-Current (AC) Systems were being developed. George Westinghouse, an American inventor and industrialist, imported a set of Gaulard-Gibbs transformers and a Siemens AC generator in 1885. Along with the AC technology from Europe, Westinghouse also purchased Nikola Tesla's AC motor patents and hired Tesla to help improve and modify the motor for use in his power system. The benefit to the AC system over DC is its ability to deliver power over long distances.

With the emergence of the AC power system, Edison and other advocates of the DC power system began a campaign to discredit the AC system and to try and convince the public that AC was a dangerous power source which should not be used. In a show to the public of the dangers of AC, Edison arranged for the first execution by electric chair in 1890 of the convicted murderer William Kemmler. The power supplied for the Electric execution was a Westinghouse AC generator. However, all the efforts made against AC would fail. In 1893 Westinghouse won the bid to supply the World's Fair in Chicago with power, leading to our current AC electrical distribution system we know today.

1.3 Current Utility Distribution overview

The current electrical distribution system can be separated into three sections: generation, transmission and distribution. Power plants are typically located in remote areas and generate power to feed a large area. The powers generated at these stations are at a lower voltage level than what they are transmitted at. The power will normally be passed through a step-up transformer and connect to the transmission system. The Bulk Electric

System (BES) is the name designated for the vast majority of the electric power system in the United States. The BES consists of power generating plants, the majority of the high voltage transmission lines, and any facility directly connected to the BES that is responsible for maintaining system reliability and stability. The BES, for simplicity, can be defined as any generator, transmission line, or facility that is rated for 100kV or above. To deliver power to the customer, the power transmitted through the BES is then stepped down to a lower voltage at substations. These substations can be noted as the point of demarcation between transmission and distribution. From the substation, the power is distributed throughout a smaller area for residential, commercial and industrial use. For most cases, the distributed power will have another step down in voltage.

As an example, power delivered to the Albuquerque area comes from the San Juan generating facility, located in the “Four Corners” where New Mexico, Colorado, Utah and Arizona meet. The majority of the power delivered to Albuquerque is an amplitude of 345kV and switching stations within Albuquerque convert the voltage to 115kV for transmission within the city. These transmission lines have radial feeds to substations and are stepped down once again to 12.47kV for distribution around the city. The voltage level is stepped down one more time to 120/240/480V, depending on the customer’s needs. Figure 3 shows a simple representation of the electric power system.

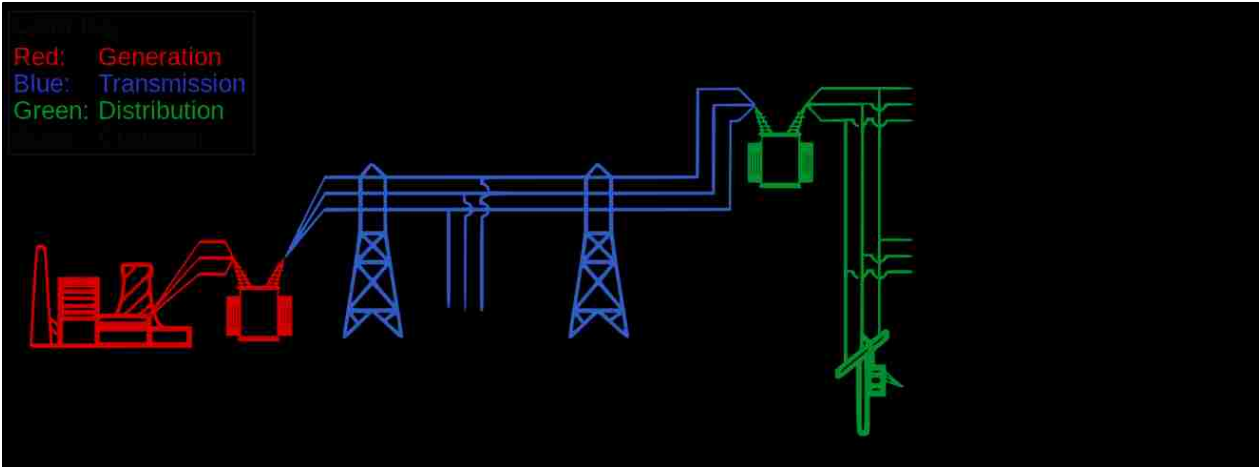


FIGURE 3: REPRESENTATION OF THE TRANSMISSION AND DISTRIBUTION OF ELECTRICAL POWER THROUGH THE BES FROM THE GENERATING STATION TO THE CUSTOMER

Our current power grid is based on Alternating Current (AC) power. While AC proved to be superior at delivering power over a larger distance, due to the impedance of transmission lines, AC still experiences power losses. The conductor spacing, types, and sizes determine the series impedance and shunt admittance of the transmission line. Series impedance affects line-voltage drops, I^2R losses and stability limits. Shunt admittance, which is primarily capacitive, affects line-charging currents which injects reactive power into the system. To help counteract these effects in the power system, shunt reactance and capacitors are placed on the system and switched into service whenever an over- or under-voltage occurs.

1.4 Objective

An electric power utility will install a 1MW/1MWh battery storage system to support an existing 1 MW PV solar system. This study concerns the commissioning of this battery energy storage system, to be located near the PV installation.

At the request of a utility, the University of New Mexico and the Electric Power Research Institute (EPRI) use OpenDSS, an open source power distribution system simulator developed by EPRI, to model the capabilities of the battery storage system to supply voltage support. Other aspects of PV support have already been modeled in OpenDSS, such as PV smoothing (to assist with the intermittences caused by passing clouds) and peak shaving to reduce the load seen by the utilities generation. Voltage support, however, is not currently modeled in OpenDSS, requires the development of a controller outside of the OpenDSS power flow engine. These results will be used in comparison with gathered field data after commissioning.

Chapter 2

Energy Storage

Electrical energy storage can be defined as the methods and techniques used for storing generated electrical energy from a primary source in a form that may be used at a later time [7]. Energy storage can be categorized based on the method or medium in which the energy is being stored. A few of the types of storages systems used today are mechanical, thermal, and electrochemical.

2.1 Mechanical Storage

There are a few different technologies being used today that can be categorized as mechanical storage. Pumped hydro-electric storage uses off-peak power to pump large amounts of water to an elevated reservoir. When the energy is needed, the pumped water is then discharged through turbines which generate electricity that can be used for grid support. As an advantage, pumped hydro-electric storage has the capability of storing massive amounts of energy. However, this technology is limited to the environment in which it can be placed. Even with the physical limitations of pump hydro-electric, nearly all of the current U.S. storage capacity (20.38 GW of 21.39 total) is in the form of pumped hydropower storage. In addition of pumped-hydro being limited to certain geographical sites, there is also an initial high cost associated with it.

Flywheels are another form of mechanical storage. Flywheel technology takes advantage of Newton's first law of motion. Off-peak electrical power is used to speed up the rotation of a heavy weight around an axel. The energy can be collected by using the momentum of the rotating mass to generate electrical or mechanical power. To increase

the performance of the flywheel, the spinning weight is kept in a vacuum and uses low friction bearings.

Compressed air technology also falls under the mechanical storage category. It uses off-peak energy to pump air into a containment area such as an underground mine, then when needed, the compressed air is released through a combustion engine to generate electricity.

2.2 Thermal Storage

The process of thermal storage involves the heating of a substance which will retain its temperature until the heat is needed. A well-known technology for thermal energy storage is the use of hot water tanks. Another form of thermal storage is “molten salt.” Molten salt is currently being used in Nevada. The heat stored in the molten salt is used to produce steam to generate electricity when the demand for additional power is needed.

2.3 Electrochemical

Battery storage technology is part of the electrochemical storage classification. Battery storage technology includes sodium sulfur (NaS), Lithium-ion (Li-ion), and Lead acid (Pb-acid). Due to the flexibility of location placement, this makes an ideal storage choice for solar energy.

With an established BES, battery storage systems provide greater flexibility for integration. Since battery systems do not require a specific geography, but rather a reasonable size of space to accommodate all equipment associated with the storage unit, battery storage can be placed in areas that will better accommodate the utility company. This makes it ideal for use with wind and solar sites that are located in rural areas.

Chapter 3

Simulation and Results

This chapter will cover the simulation efforts involved in modeling a 1MW battery storage system. Discussed herein is the simulation of the battery storage system that was performed using OpenDSS and MATLAB.

3.1.1 OpenDSS

OpenDSS is an open source distribution system simulator provided by the Electric Power Research Institute (EPRI). The OpenDSS program is a comprehensive electrical system simulation tool used for electrical utility distribution systems. OpenDSS is can perform multiple types of studies for electrical distribution. These studies include distribution planning analysis, general multi-phase AC circuit analysis, solar PV system simulations, storage modeling, harmonic and inter-harmonic distortion analysis, and neutral-to-earth voltage simulations.

OpenDSS varies from other power flow tools that are used in the utility industry.

Proprietary programs, such as CYME and Synergi, are widely used for distribution power flow and protection studies and use a graphical interface for creating models and performing power flow solutions. OpenDSS uses a text interface. Each piece of equipment must be typed on an individual line in a text editor. This can be quite the task when developing a full distribution feeder. With each line, or piece of equipment, that must be added, the correct connection configuration must be verified. If a conductor is not correctly connected to the appropriate node in a circuit, the solution will fail. Care must be taken when organizing feeder equipment and connections. OpenDSS provides a

means of plotting a created circuit which depends on the information added in by the user. Users must also create scripts for performing studies. This leads to creating a master file to perform the study.

To gather power flow data, meters are also required to be added to the circuit. These meters are passive devices that do not add any additional load loss or impedance to the system, but are required for reading data from the circuit. Meters can be placed throughout the feeder as the user desires.

OpenDSS also has several built-in solution modes. In this study; the Snapshot power flow, Daily power flow and Yearly power flow solution modes were used. The Snapshot mode is a one-time simulation that calculates the power flow throughout the circuit. The daily and yearly solution modes can provide a system simulation over a period of time, taking into account the load profile of the circuit being simulated. The Yearly power flow solution mode was used in this study and will provide a better representation of the interaction of the battery storage system on the utility's distribution feeder.

While OpenDSS is the main power flow analysis tool for this study, there are features that are not developed in the main simulation engine. For this, OpenDSS includes a COM interface that allows for external software such as MATLAB, Visual Basic for Applications (VBA) and C#, to run the main simulation engine. This feature allows the user to design and execute custom solution modes and features in a language that is familiar to them without having to manipulate the main structure of the OpenDSS engine or create DLL's. Through the COM interface, users can directly access the text-based command interface to create and edit OpenDSS scripts using a third-party program. The COM interface also allows users to extract results calculated by OpenDSS to be used in

external scripts. OpenDSS also has a report generator that will export the data into a Microsoft Excel (.CSV) formatted file if the user would prefer to present the data using Excel. This is a feature that doesn't require the use of the COM interface. Figure 4 is a representation of the interface between OpenDSS and various interfaces. [8]

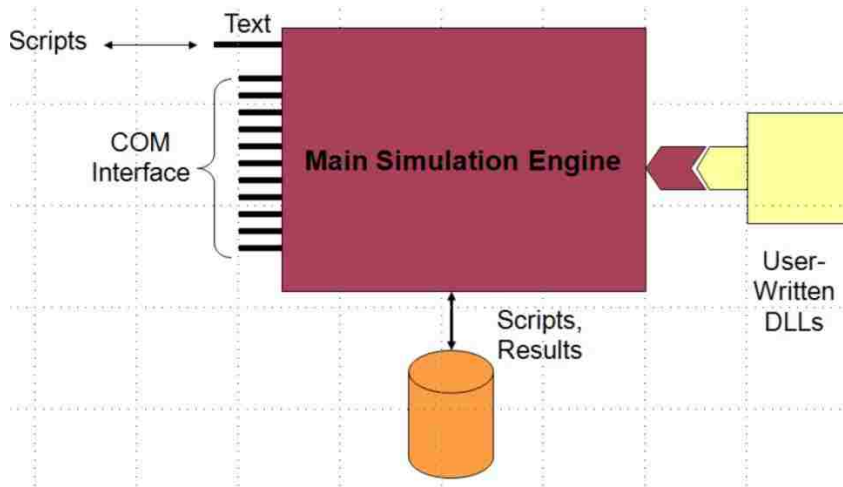


FIGURE 4 VISUAL REPRESENTATION OF THE COM INTERFACE WITH THE OPENDSS MAIN SIMULATION ENGINE

3.1.2 MATLAB

MATLAB is a high-level programming language with an interactive environment for numerical computation, visualization, and programming that is used throughout the professional and academic environments. MATLAB can be used to analyze data, develop algorithms, and create models and applications. MATLAB is also capable of performing various mathematical functions such as linear algebra, Fourier analysis, numerical integration, and solving ordinary differential equations

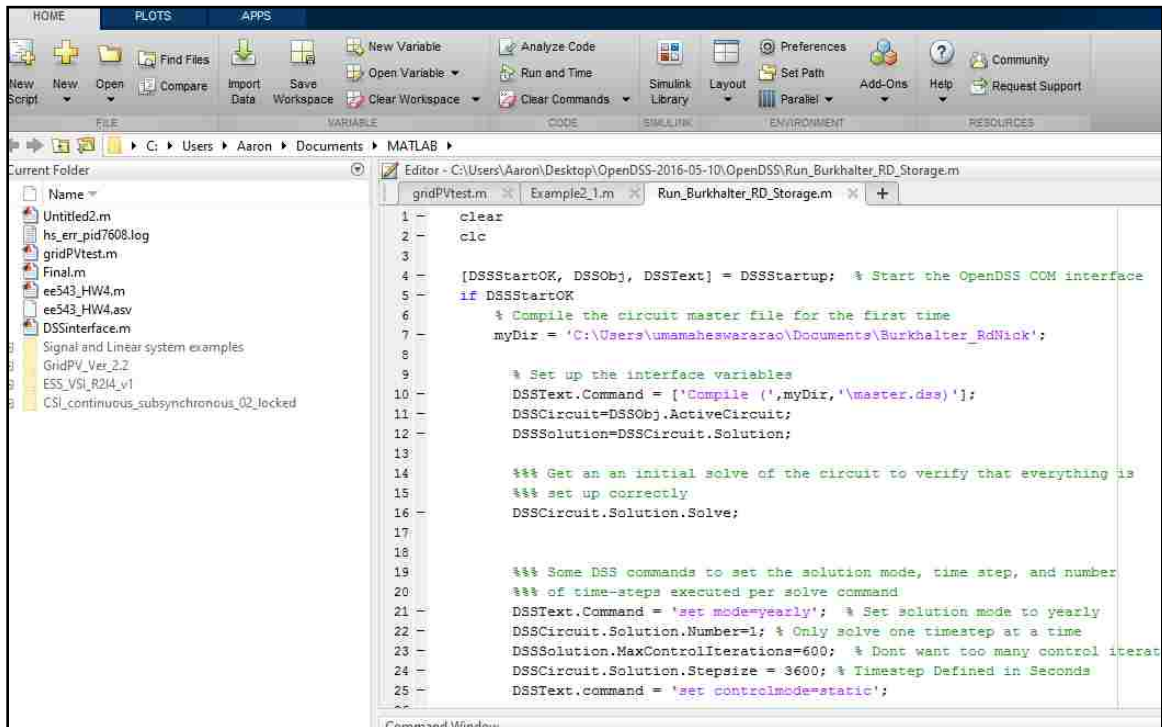


FIGURE 5 MATLAB GRAPHICAL USER INTERFACE

To gather the data required for the battery storage system, additional controls used outside of the OpenDSS program were necessary. As mentioned in the previous section, other programs such as MATLAB and Visual Basic have the capability to run OpenDSS through its COM interface. This allows for greater flexibility in system modeling.

Outlined in the OpenDSS user's manual, there are several 3rd party software that are compatible with the OpenDSS COM interface. MATLAB was chosen as the 3rd party software for several different reasons; 1) MATLAB is a software that is widely used throughout UNM's Electrical Engineering curriculum in both course work and research, and in the engineering industry, 2) Programming with MATLAB's interactive environment is easy to use, 3) MATLAB can handle complex numbers, making the software compatible for use with the power utility industry, and 4) with experience in programming in the MATLAB environment, time during the study can be focused on developing the algorithm and learning to use the OpenDSS COM link, rather than learning a new programming language.

3.1.3 Microsoft Excel

While MATLAB and OpenDSS are both capable of presenting and graphing the recorded data, Excel was chosen for analyzing the data. OpenDSS is capable of exporting its data into an Excel spreadsheet, we found this program would be the best method in analyzing our results. Excel is more flexible in organizing the data exported from OpenDSS and can easily be used to create graphs for visual representation of the data.

3.2.1 Study Overview

In conjunction with the Electric Power Research Institute (EPRI), this study will address the concerns regarding the siting and commissioning of a proposed 1MW/MWh battery energy storage system (BESS) on a distribution feeder. The proposed BESS site will be located near a 1MW photovoltaic (PV) installation. The load profile for this feeder consists of mainly a large industrial customer.

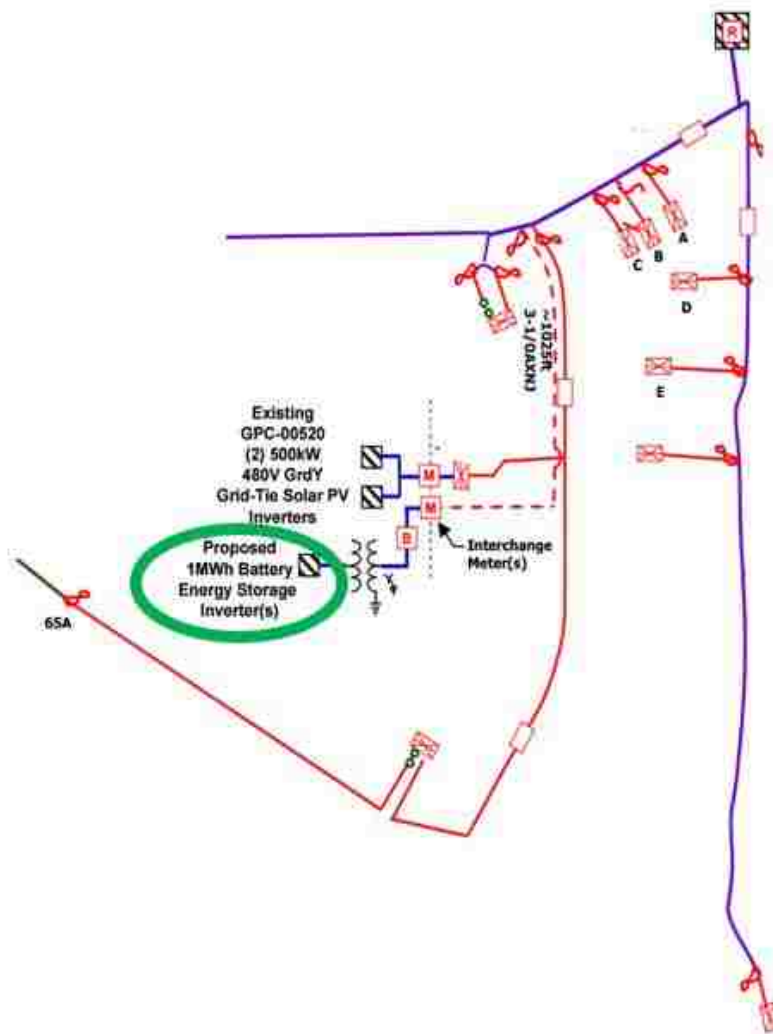


FIGURE 6 ONE-LINE DIAGRAM OF THE FEEDER AND STORAGE UNIT BEING MODELED IN OPENDSS.

Figure 6 is the one-line diagram of the feeder that was used for the study. In this , transformers labeled A thru E provide the power to the large industrial load. This customer's load accounts for approximately 90 percent of the total load on the feeder, with the location of the load located near the substation and both the PV and battery storage systems being further downstream.

The BESS is intended to provide shifting of the PV resource as well as voltage regulation to the associated feeder.

3.2.2 Feeder Model Setup

OpenDSS is a text based interface that requires users to create models using scripts and a text editor rather than a graphical interface that allows users to draw out and place elements into a model. To create the model in OpenDSS, users must define an infinite source, all of the elements that make up the model, including all of the element's parameters and terminal connections, and all nodes used for connecting all of the elements within the modeled feeder.

Utilities commonly use proprietary software, such as CYME and Synergi, to perform loading, power flow, and fault calculations. One of the benefits in using these programs is the graphical user interface (GUI); the GUI allows the user to draw out the model while automatically connected all of the elements when drawn correctly. The feeder provided for this study was originally modeled in CYME. Rather than creating the entire feeder model in OpenDSS, the original CYME model was translated into OpenDSS using an automated system. Both voltages and fault currents from CYME and OpenDSS were compared to validate the initial conversion process.

To provide more accurate modeling data to the utility, high resolution measurements of voltage (V), real power (P), and reactive power (Q) were taken at the substation using a DRANETZ power explorer PQ meter. With the utility-provided real time measurements, taken at one second intervals, load-shapes were developed for a time series analysis. The power flow model was validated with the measured data. The close match in both real and reactive power indicated the feeder topology and loading characteristics are accurately represented in the OpenDSS model.



FIGURE 7 REAL POWER SIMULATION VALUES COMPARED TO THE METERING DATA GATHERED FROM THE FIELD.

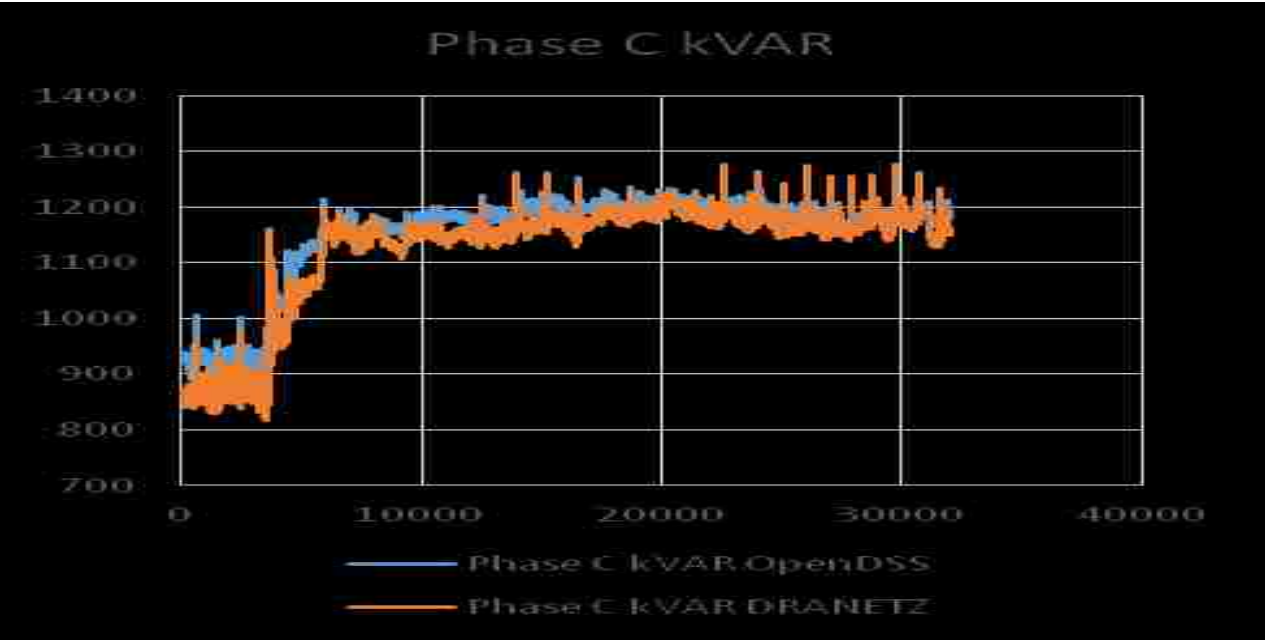


FIGURE 8 REACTIVE POWER SIMULATION VALUES COMPARED TO FIELD GATHERED VALUES.

However, voltage did not match the metering data gathered from the substation.

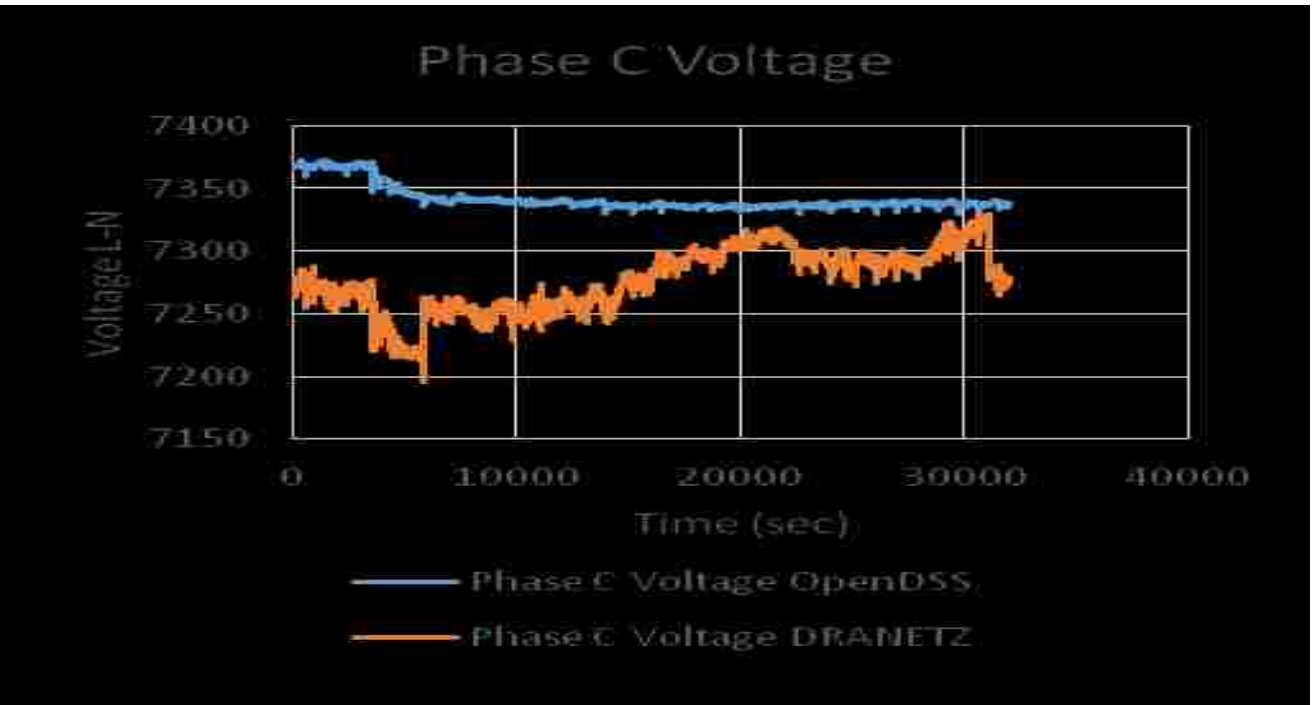
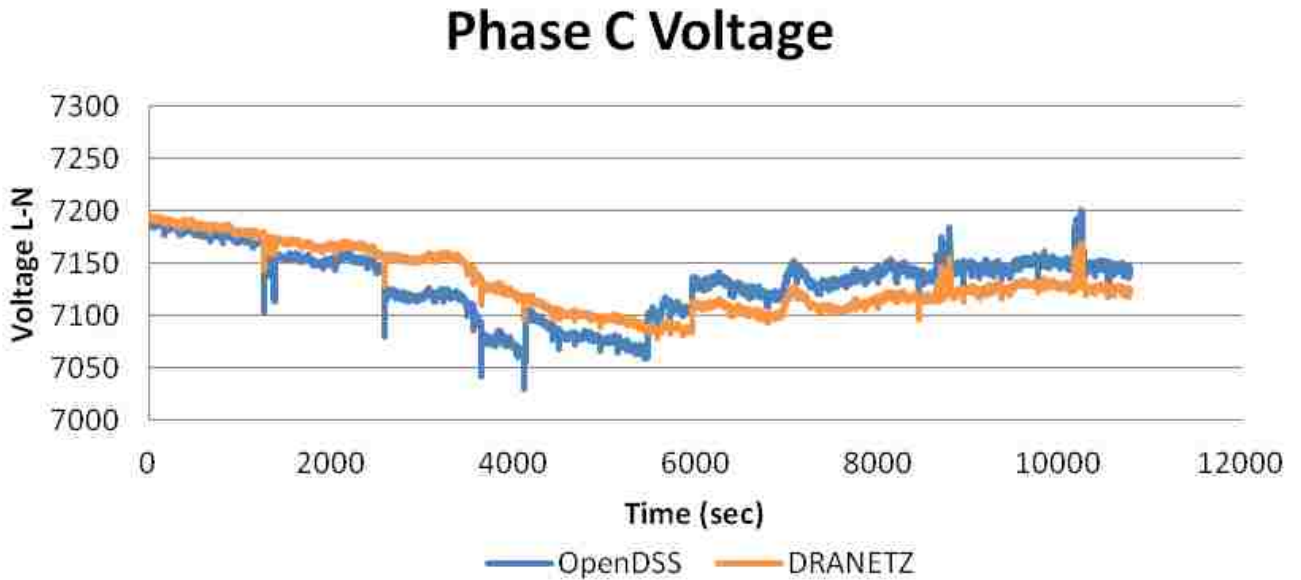


FIGURE 9 COMPARING VOLTAGE VALUES BETWEEN THE OPENDSS MODEL AND THE ACTUAL READINGS SHOWS THE MODEL NEEDS TO BE RE-EVALUATED.

Possible sources of error include parallel feeder loading or sub-transmission instability. To correct for the voltage mismatch, a parallel feeder load was used to mimic the voltage variability in the model while maintaining correct power flow.



1.2.2. Battery and Battery Energy Management System (BEMS)

For this study, ABB's PCS100 ESS, grid connected interface for energy storage systems, was used as the interfacing device for the 1MWh/1MW battery storage to the utility distribution feeder. The PCS100 ESS allows control of both real and reactive power based on the system requirement. The converter behaves together with the power system like a traditional synchronous machine. This is achieved through power electronic control since there are no large spinning masses. Inertia is modelled with the system enabling it to deliver or to draw power from the grid dependent on the rate of change of system frequency [9]. A demand controller, Programmable Logic Control (PLC), can be used for overriding control for specific applications and may contain both a battery management system and an application control. Other features include high and low voltage ride through, black start option, and grid stabilization features,

such as synthetic inertia and active damping. Figure 10 provides a system diagram of the PCS100 interconnecting a BSS to the utility feeder.

The PCS100 provides the user with the ability to provide power system load leveling as well as increase network stability and transmission capacity, and allows for multiple energy storage devices to be coupled to the grid. . The PCS100 delivers grid compliance for renewable generation systems and dampens disturbances and oscillations in critical system configurations. The PCS100 can be configured to operate in various modes depending on the applications. These operating modes include Current source and Voltage source modes.

The current source mode provides balanced three phase sinusoidal currents to the grid, regardless of the grids conditions such as unbalance or harmonics. The current source mode also provides rapid sub cycle response to power commands for highly dynamic system requirements. Examples where current source mode would be used is together with wind parks where fast support for the grid is required in the event of a low voltage event. [9]

The voltage source mode is a unique operating mode for a power electronic converter whereby the converter mimics the behavior of regular rotary generators. For this mode, the PCS100 interfaces to the grid with a balanced three phase voltage. The benefit of this is a natural correction of grid unbalance and harmonics by the ESS. Physical inertia is also modelled into the PCS100 control system, providing a damping response to the frequency in the grid via the storage connected to the PCS100 ESS. [9]

System Overview: Example for a typical battery ESS

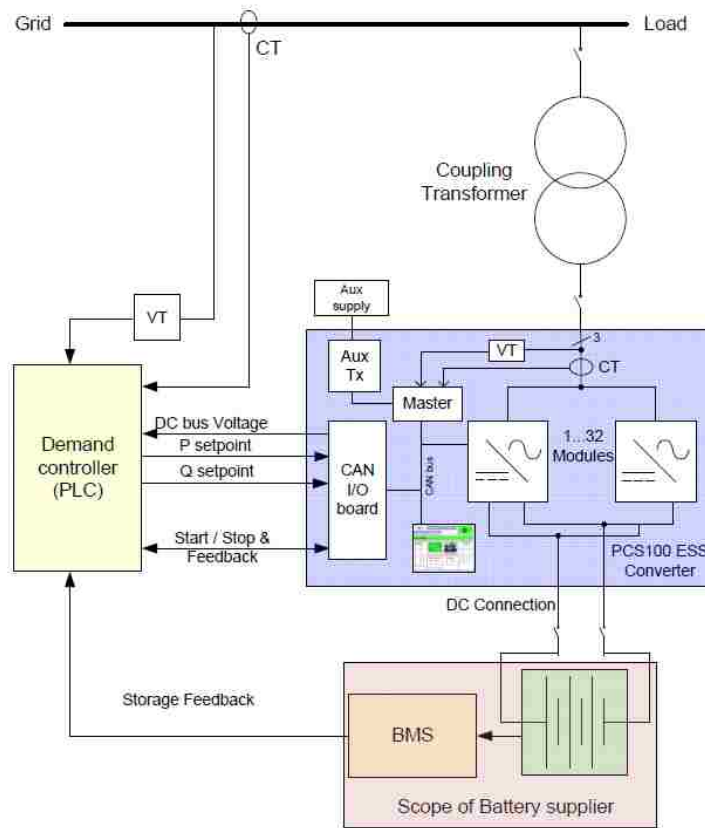


FIGURE 10 ONE-LINE DIAGRAM REPRESENTING A TYPICAL INSTALLATION SIDE FOR A BATTERY STORAGE SYSTEM

As mentioned, the PCS independently controls real and reactive power. This allows the system operator to use the reactive capacity during times where real power demand is low. This will provide voltage support or power factor compensations.

1.2.3. Energy Storage Modeling in OpenDSS

Open DSS has two built in elements, Storage and StorageController, for modeling battery storage systems. The storage element is designed from the Generator element and can be dispatched for either real power production (discharge) or real power consumption (charge).

The amount of power produced or consumed will be within the rating and energy capacity of the device. These values are set when creating the element. The Storage element can also deliver or absorb reactive power (var) within the kVA rating of the inverter. A storage controller can request a specific amount of kvar to provide to the system, as long as it's within the defined capacity of the Storage element. The storage element can either operate independently or be controlled using the StorageController element.

The storage element can be used in various solution modes; Snapshot, Daily, Yearly, and DutyCycle. During these modes, the storage element can be in one of the following operational states: IDLING, CHARGING, or DISCHARGING. While in the Snapshot mode, the state of the element can be selected prior to solving the circuit power flow. During the time-varying modes, Daily, Yearly, and DutyCycle, the storage element will change states as the storage controller requests dispatch. If there is available capacity within the controller, power will be dispatched, real or reactive. However, power will not be available for discharge if the power lever is lower than the specified reserve level. Also, the storage element will only take charge when the kWhStored value is less than the kWhRated. The rate of discharge and charge for the element can also be specified. [10]

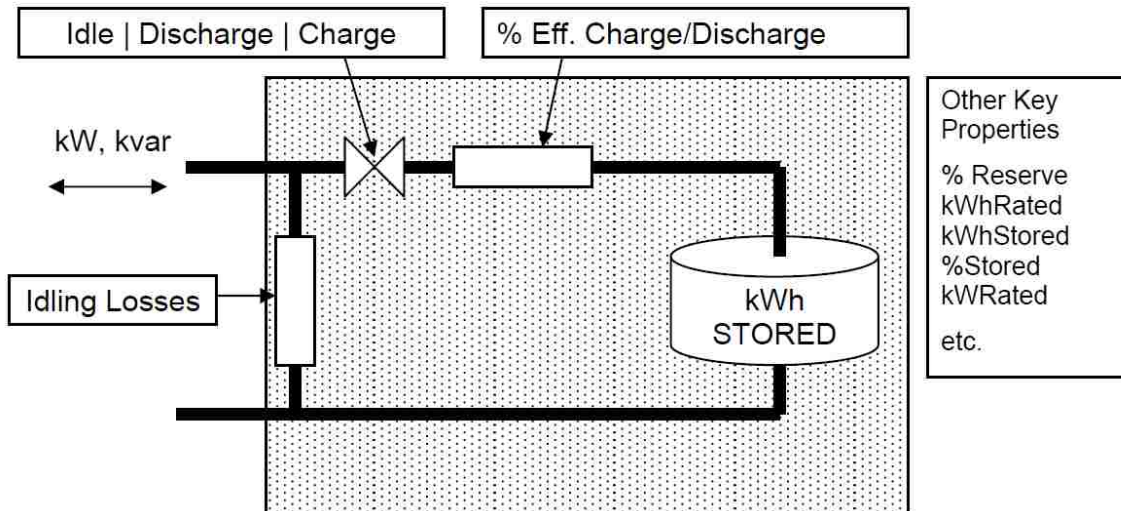


FIGURE 11: BASIC CONCEPT OF THE OPENDSS STORAGE ELEMENT.

The element also includes losses to help with evaluating storage schemes. Different efficiencies may be specified for charging and discharging. In addition, idling losses may also be specified. These losses may represent various equipment within a storage unit, such as control systems, heaters, coolers, and any other electrically powered piece of equipment required to maintain constant temperatures and overall battery performance and health.

The Storage element in OpenDSS has five dispatch mode; DEFAULT, FOLLOW, EXTERNAL, LOADLEVEL, and PRICE. There are also two triggers associated with these modes: ChargeTrigger and DischargeTrigger. The values applied to these triggers will interact differently depending on the mode selected.

Each mode has various operations for simulation. The DEFAULT mode dispatches power based on a load curve and the set trigger points. During operation, when the load curve goes above the specified DischargeTrigger, the storage device will deliver power until all of the stored energy is depleted, or until the load drops below the DischargeTrigger. The same applies for the ChargeTrigger. Once the load shape drops below the ChargeTrigger, the storage device will add

additional load by charging. Again, the charging mode will only be applicable until the Storage element is fully charged. A TimedChargeTrigger is also available. This trigger can be set to charge the Storage element at a specific time of day. This allows the unit to be at full capacity for the next high load event. This is beneficial for planning next day events.

In FOLLOW mode, the output of the storage element follows the loadshape multiplier. The element will continue to provide power until the storage element is depleted. During a positive multiplier of load the element will discharge. Likewise, when the loadshape multiplier is negative, the storage element will begin to charge. Both discharge and charge cycles will be limited to the capacity of the unit. For example, if the loadshape is positive and the storage element is depleted beyond the reserve limit, the storage element will be placed into an idling state. Similarly, if the unit reaches full capacity during the negative portion of the loadshape the Storage element will no longer be capable of absorbing power. While this dispatch mode is helpful for delivering power during rises in load, if the loadshape multiplier does not go below zero, the storage unit will not be able to absorb power (charge) and will not be able to produce energy when needed. [10]

LOADLEVEL and PRICE are both dispatch modes that can be set with a fixed value for discharging the storage unit. LOADLEVEL requires a daily or yearly loadshape file and a load multiplier value that is set as a global value. The same applies to the PRICE dispatch mode, with both Price signal and Price curve being a global define. [10]

EXTERNAL dispatch mode allows for the controller element to take control of the storage device. When a controller is used, the controller will provide the storage element with the state of which the controller will need to be in. As well as having a controller element, the COM

module can also be used to control the modes of the storage element, allowing for additional study functionality. [10]

The StorageController element may be used in conjunction with the Storage element. Its main purpose is to provide greater versatility when utilizing energy storage. The StorageController can be used to control a single storage element with more dispatch options or a fleet of storage elements. There are various limitations of the placement of a storage facility location:

accessibility, right of way, land limitations, and cost may play a role when selecting a location along a feeder's path. Given these reasons, a storage element may not be placed in a location where it can monitor load behavior and produce support at the desired location. The

StorageController element is one solution that has been developed to manage these types of situations. An example of this type of setup is the use of a storage element located near a large load customer to help reduce the load seen by the feeder during large or unexpected spikes. The controller can monitor the power being supplied at the feeder to determine when the feeder would require support and set the state of the storage element accordingly. With this concept, the controller's capacity for support may increase with a larger array of storage devices located throughout the feeder.

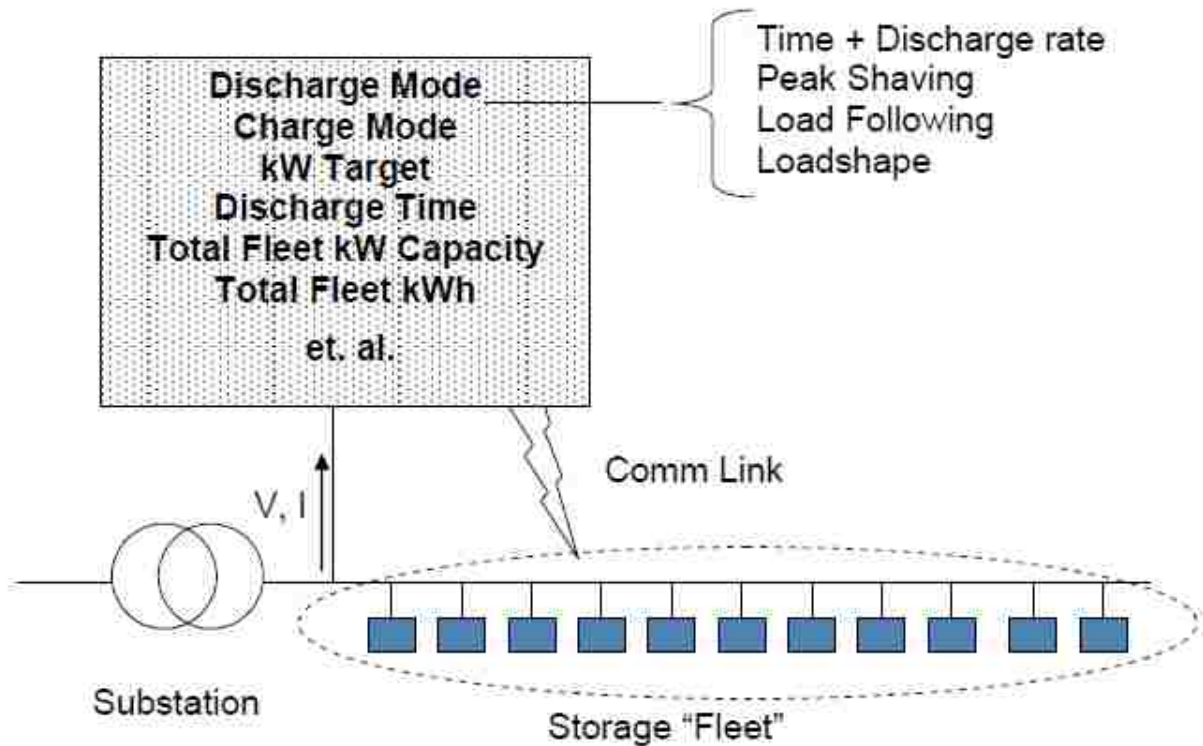


FIGURE 12: STORAGE CONTROLLER CONCEPT

Built in dispatch modes include Peakshave, Follow, Support, Loadshape, and Time; as well as Loadshape and Time for charging modes. Again, with the controller being in control of the storage devices, these will be the modes available for modeling use. For Peakshave, follow, and support modes, a deadband controller concept is used, where a target values is set and a band around the target value is specified. For example, a KWTarget may be set with a percentage variance from the target is given, two (2) percent by default. While Volt/VAR support has been developed into the OpenDSS software using s smart inverter module, this module is only available with the PV model and not currently available in the current StorageController element. [10]

For the purpose of this study, we need to be able to provide voltage control. This will require an additional controller. The created controller will need mimic the inverter controller already created for PV systems.

The Current inverter control element works with the PVSystem objects and can operate in the following modes: VOLTVAR, VOLTWATT, and DYNAMICCREACURR. In VOLTVAR (default) mode, the controller will attempt to dispatch the vars according to one or two volt-var curves, depending on the local terminal voltage, present active power output, and the capabilities of the PVSystem. VOLTWATT operates in the same manner, utilizing local terminal voltage and the PVSystem capabilities to dispatch watts according to a defined volt-var curve. [11]

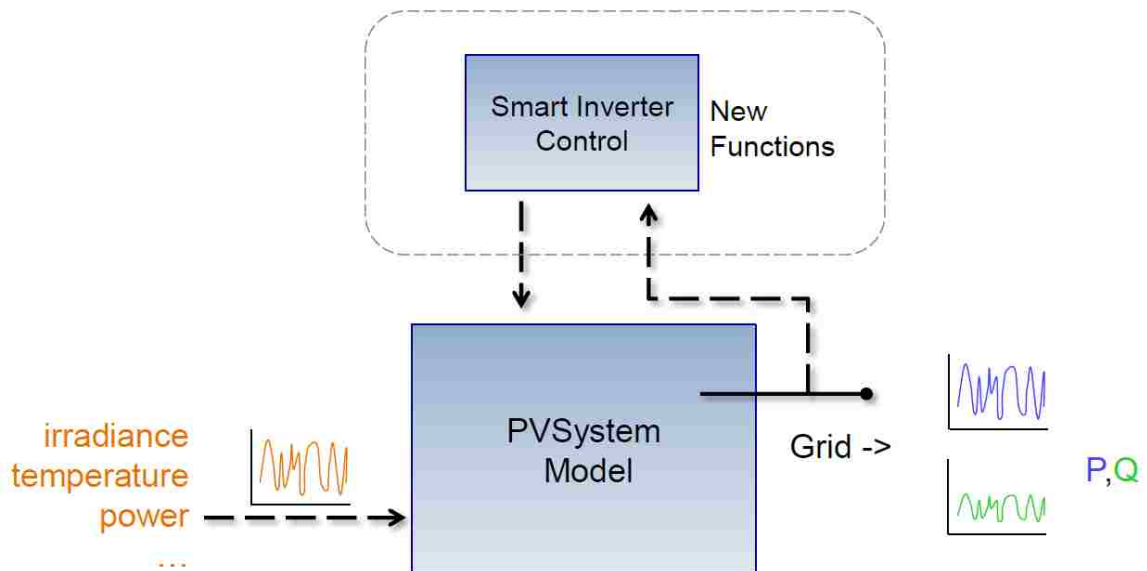


FIGURE 13 OVERVIEW OF SMART INVERTER FOR PVSYSTEM CONTROL WITHIN OPENDSS

For the purpose of this study, the development of the PCS controller was modelled after the smart inverter control used for OpenDSS’s PVsystems. As mentioned, using OpenDSS’s COM module as an interface into the OpenDSS software, we developed a control system within

MatLab that mimics the voltage support seen with the smart inverter, but focused on controlling the state of the Storage element. Creating the Storage element smart inverter using the MATLAB software allows for easier and faster integration with the OpenDSS software while having the flexibility to debug the new code before incorporating the code into the OpenDSS source code. All Circuit definitions and parameters were created using a text editor following the correct format required for OpenDSS's power flow calculations. A master file was created that established the main circuit parameters, to include voltage bases, sequence impedances, per unit, and base KV. The master file also contained the redirect commend. These commands were used to bring in, line parameters, line geometries, loads, regulators, capacitors, loadshapes, and monitors. The master file will also generate the map in powerbase for the feeder. [8]

1.2.4. The MATLAB Smart inverter with Voltage control program

There were two separate MATLAB programs created for this study. The first program, titled DSSStartup, establishes communications with the OpenDSS software. This program was created from the example program provided in the OpenDSS example documents. The second and main program houses the smart inverter with voltage control algorithm. On the initial run of the main program, the DSSStartup program is called to establish communications through the COM module interface. The DSSStartup passes back confirmation to the main program of successful communication. After successful communications, the program then uses the COM interface commands to compile the OpenDSS master file and set the parameters for the power flow study. The solution setup was established with MATLAB using the com interface commands. For the purposes of this study, the yearly solution mode was used. Since we are controlling the Storage element's mode based on voltage at a given instantaneous value, we set

the number of solutions to one so that only one time step is solved for each time the solve command is given. The control mode of the power flow was set to static. For voltage control, the algorithm is designed for PCS “clamping.” This mode provides a deadband around a specified voltage, which can be set based on user preference. With the voltage stabilization of this feeder the deadband was set to +/- .005 percent of 7.25 KV. This establishes the upper boundary at 7.28 kV and the lower boundary at 7.22kV.

During the control loop, an initial “solve” is performed. This initial power flow solution will set the bases for the system and allows for initial system voltages to be read as a comparison. During each iteration of the control loop, a “solve” command is performed and results are fed back to the control loop for voltage evaluation. The loop advances to the next iteration after a check on voltage is complete. During the first two iterations, the smart inverter will determine if the Storage element will remain in the idling state or be set to the discharging/charging state. The state will be changed as long as the storage capacity is capable of providing the needed support.

After these iterations, the controller will evaluate the current voltage and the previous state of the storage element to determine if the controller should place the storage element back into the idling state. The conditions of this check are the current iteration voltage and the state of the controller. If the monitored line voltage is within the bandwidth, and as long as the controller isn't already in the idling state, the controller will evaluate if the storage element should be placed in idle. A NoControl mode solution is run to suppress the time step from advancing. This allows the controller to determine if placing the controller into an idle state will cause the voltage to convert back to a condition of being outside the bandwidth. If the voltage appears to be out of bandwidth with the storage element in idle, the controller will keep the storage

element in its current state for an additional iteration of the control loop. This process will take place until the voltage has returned to a safe level within the bandwidth.

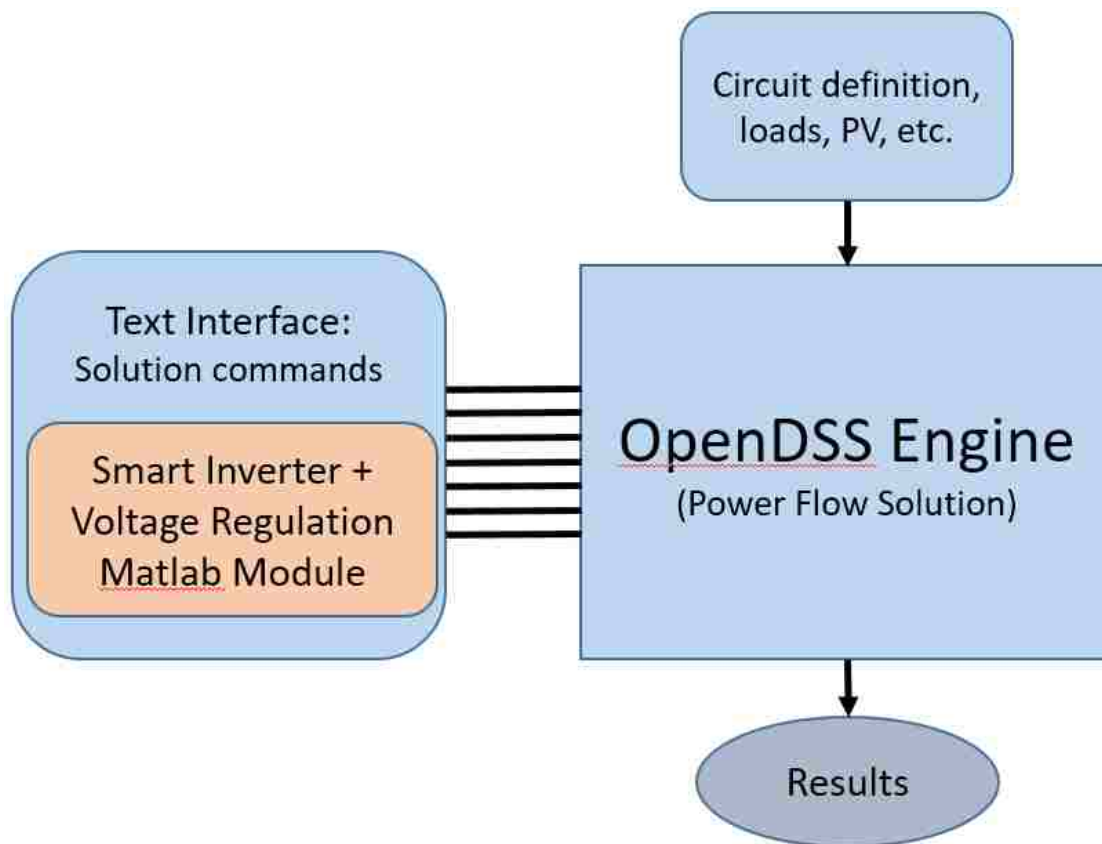


FIGURE 14 FLOW CHART OF SMART INVERTER VOLTAGE REGULATOR PROCESS

Once the controller checks for voltages within bandwidth, the controller will check to see if the storage element is needed for voltage support. Again, this check will require the current voltage input and the status of the storage element. If voltage is seen to be above the threshold, the capacity is available, and the device wasn't already in the charging state, the storage element will be dispatched as a load and be placed into the charging state. The same evaluation will continue through the subsequent iterations and the voltage will be evaluated to see if it has dropped below the threshold. If this is the case and the Storage element isn't already in the

discharging state, the Storage element will be dispatched and its state set to discharging. All the results from the study were exported to a .CSV file and compared using Microsoft excel.

During the process of voltage adjustment, there were 4 different operating modes that were utilized for voltage “clamping.” The first mode was Volt/Watt control. The real power is determined by the voltage feedback and the reactive component is not actively adjusted. The second mode is Constant VAR: the real power is determined by the voltage feedback and the reactive component is set to a constant value. VAR support will be inductive when the storage element is charging and capacitive when it is discharging. Third mode is Volt/VAR. In this mode, the real power is determined by the voltage feedback and the reactive component is determined with a Volt/VAR curve. As with the constant VAR mode, the storage element is inductive during charge and capacitive while discharging. The fourth mode is constant power factor. The real power is determined by voltage feedback and the ratio of real power to reactive is constant, and will be inductive during charge and capacitive when discharging.

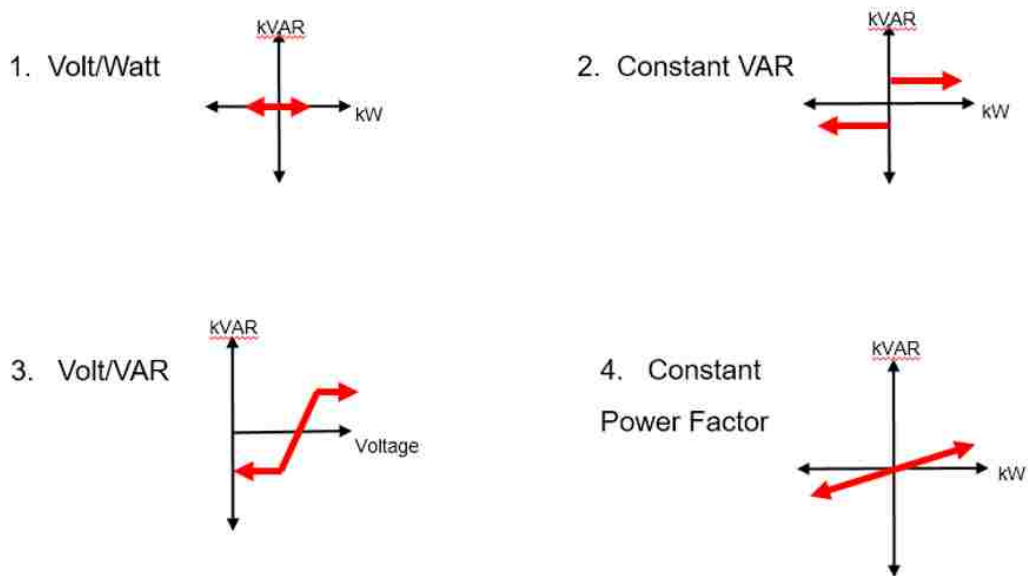


FIGURE 15 VISUAL REPRESENTATION OF THE FOUR OPERATING MODES OF THE SMART INVERTER.

1.2.5. Modeling Results

After various iterations with the PCS controller, the storage element was shown to be capable of providing voltage support. The following graphs show the feeder voltage and support for the various operating modes.

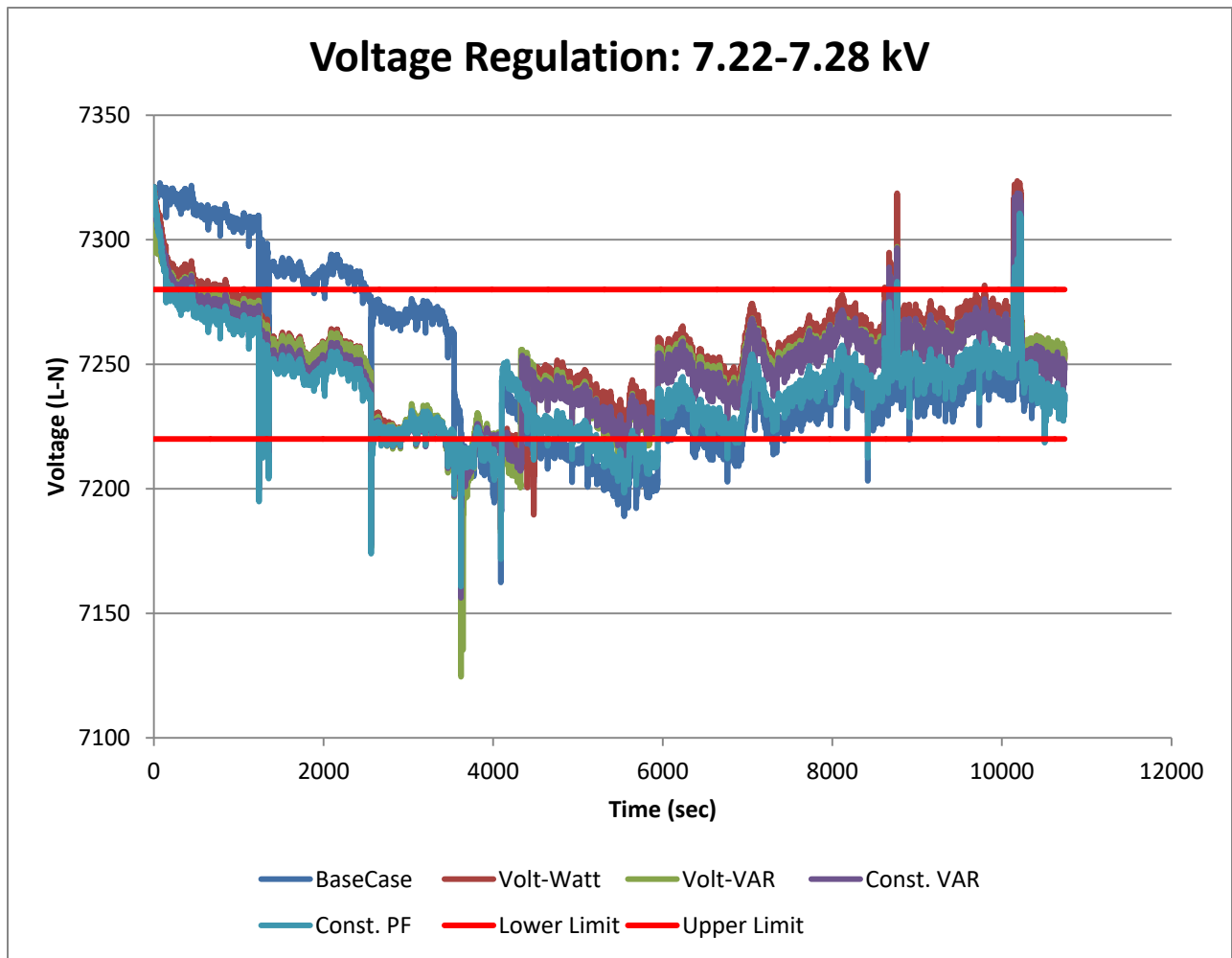


FIGURE 16 VOLTAGES OF THE DIFFERENT OPERATING MODES COMPARED TO THE BASE CASE OF THE FEEDER

kW Demand: 7.22-7.28 kV

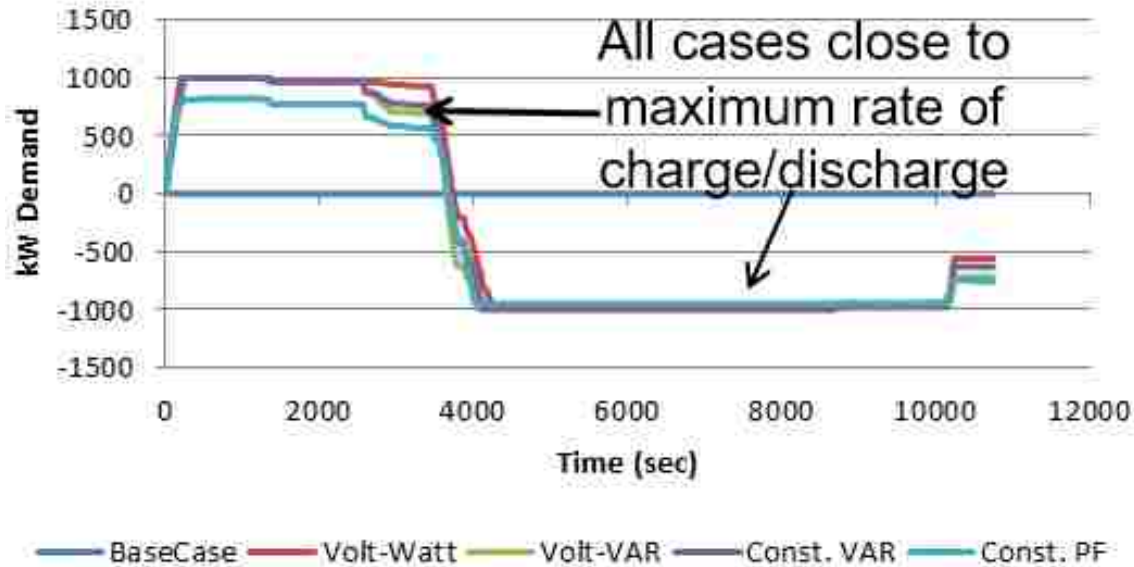


FIGURE 17 STORAGE DISCHARGE RATES DURING EACH OPERATING MODE.

kWh Stored: 7.22-7.28 kV

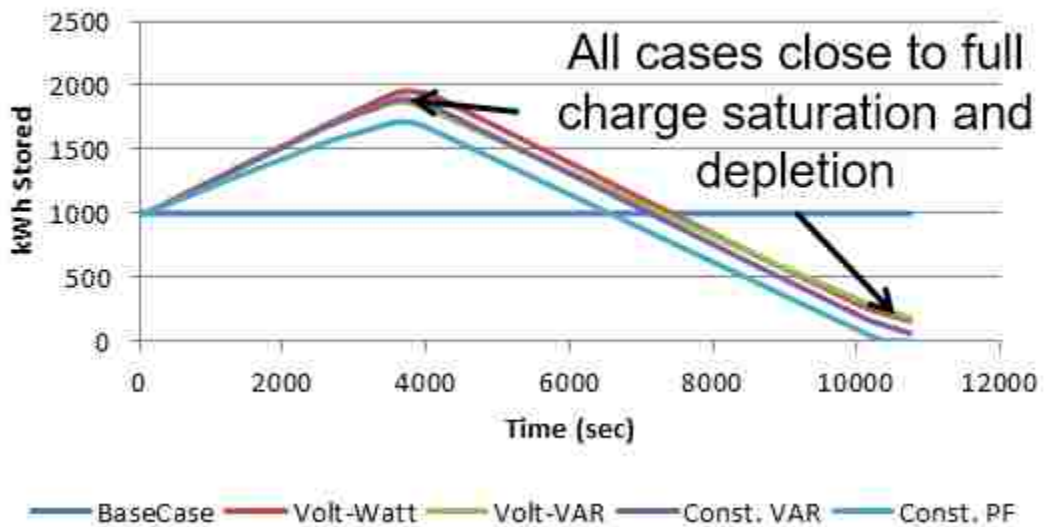


FIGURE 18 COMPLETE CHARGE/DISCHARGE FOR ALL OPERATING MODES.

The results show that the storage device is capable to provide voltage support. This also indicate that the size of the storage device and inverter will determine the extent of voltage regulation capabilities.

1.2.6. Commissioning Results

Prior to the commissioning of the Storage facility, a DRANETZ power explorer PQ meter was installed at the substations primary to monitor PQ attributes. The values were logged at one second intervals. This information was collected to analyze the baseline characteristics of the feeder. The following plots below show line voltages, currents, real and reactive power, voltage, and current unbalances. These values were taken for five days leading up to the commissioning.

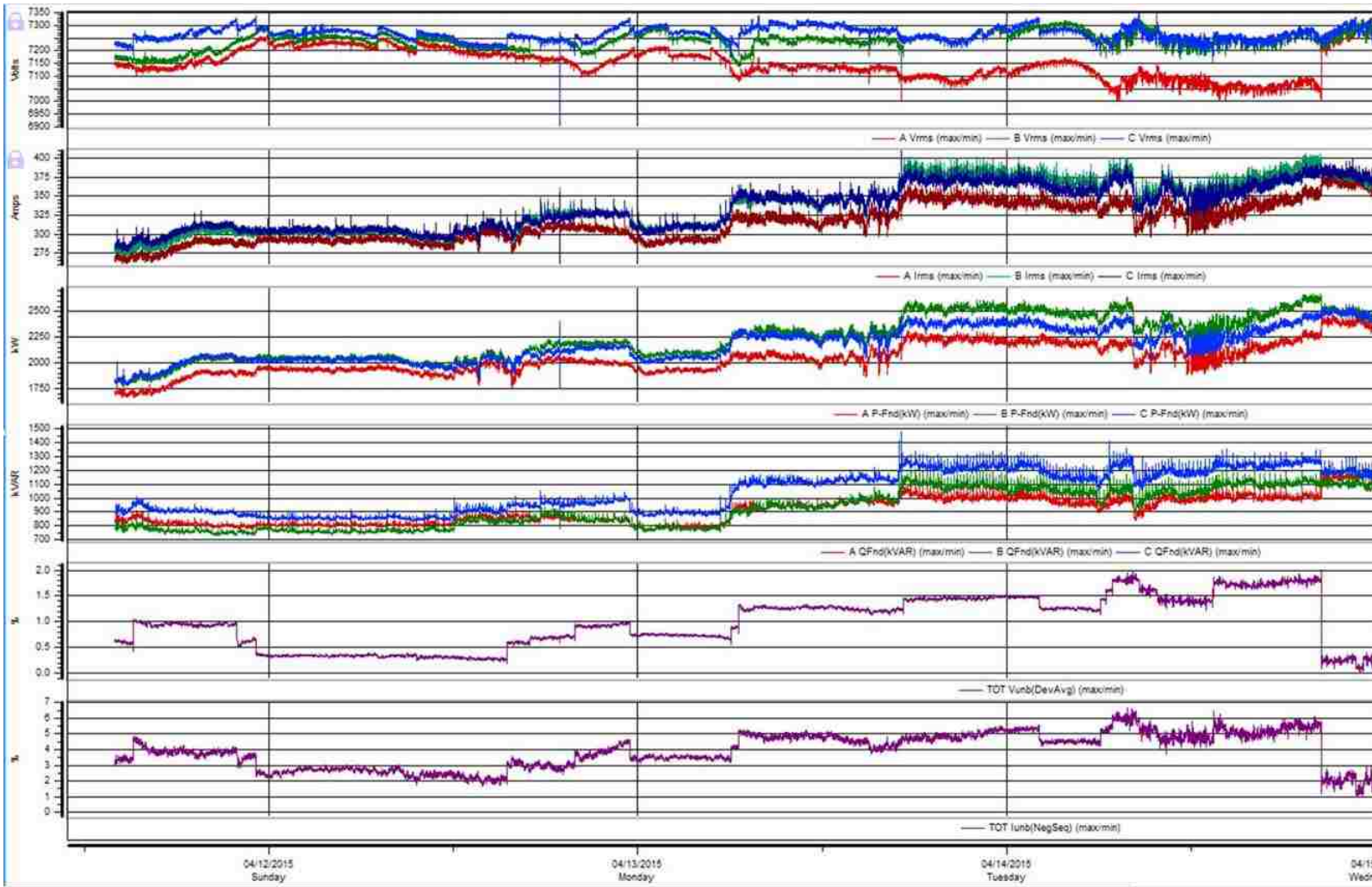


FIGURE 19 SAMPLE OF VOTAGE, CURRENT, AND REAL POWER FOR ONE DAY PRIOR TO COMSSIONING

The same data was collected after the commissioning of the site.

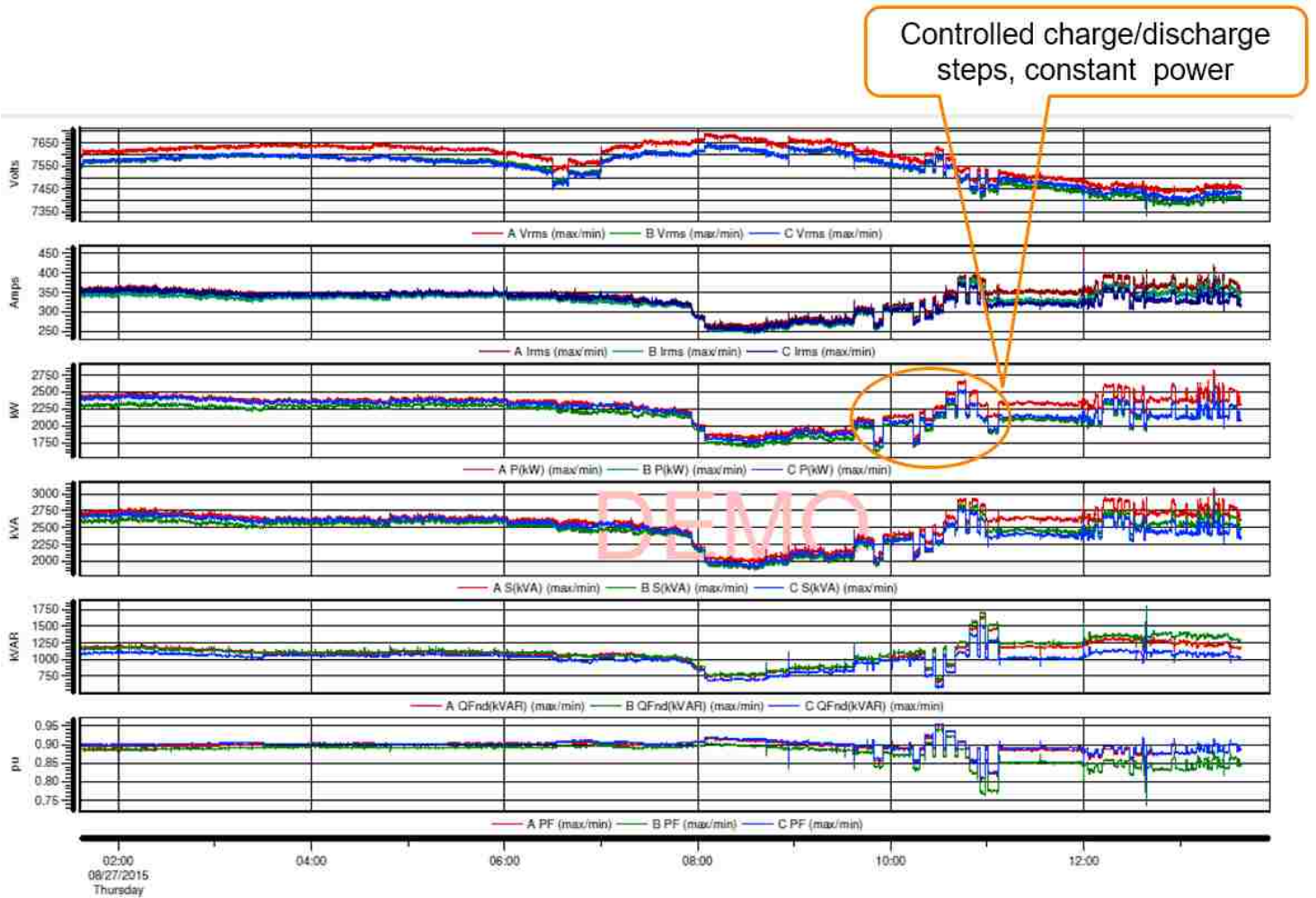


FIGURE 20 METER DATA GATHERED AFTER THE COMMISSIONING OF THE 1MW STORAGE SYSTEM.

The storage element is able to provide real and reactive power to provide support for voltage control. As shown in this study, support will only be supplied for the duration of the capacity of the storage unit. When the voltage drops below the threshold, the storage device is dispatched and constant power is applied to bring the voltage back into the threshold. This process repeats until the capacity of the storage device is reached. With this we can see that the size of the storage unit will have a significant role in its ability to provide voltage support.

1 Chapter 4

Conclusion

As demonstrated through both simulation and field verification, battery storage systems have the capability to provide additional utility reliability with voltage support. With the storage system having the ability to provide voltage support, the capacity in which they can provide this support is limited on the size of the battery storage and the inverter's specifications. Due to lack of operational experience of energy storage systems, additional research will be required to assist utilities with planning and analysis to understand the best practices and utilization of large-scale storage systems.

The development of this MATLAB program, along with the OpenDSS model, can assist utilities with sizing storage systems to best suit their needs for both PV generation stabilization and feeder reliability.

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