ELEX 7890: Capstone Project Completion
OPC Server Setup Manual

Volt Var Optimization

Abstract

This report details of the results of our Capstone project that spanned the period from September 2014 to May 2015. Our Capstone deals with designing and implementing a Volt Var Optimization (VVO) controller for the BCIT Battery Energy Storage System (BESS). In addition the designing and performing a series of power quality tests requested by BC Hydro. Our VVO control algorithm was implemented using a Siemens PLC. Our controller was then connected to our BESS MATLAB model to demonstrate functionality. Through our completed BC Hydro tests, we were able to gather useful data and make conclusions about the BESS's operation and efficiencies. Carrying on into the future, there are many aspects of this BESS system that can still be investigate and we have made recommendations on what to investigate further.

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Submitted as part of a BCIT electrical engineering Capstone project: 2014-2015	
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1 Introduction

VVO is a method of operating the distribution system that utilizes supervisory control, data acquisition and distribution automation [1]. The two facets of VVO are the maintenance of the lowest constant voltage across the system while keeping the power factor as close to unity as possible. To accomplish this reactive power is injected or absorbed as needed to maintain the voltage at the local bus to the reference value. This capstone project focused on the implementation of VVO using a four quadrant inverter with a closed control loop. Closing the control loop on an inverter controlled VVO is a challenging new design problem not yet undertaken in this area.

Some of the advantages of implementing VVO are energy conservation, peak load shaving in areas where the infrastructure is at maximum capacity, voltage regulation and losses reduction. By maintaining a minimum voltage level, thereby flattening the voltage profile along a distribution feeder and lowering the voltage set point of the substation transformer, energy savings can be achieved [1].

Distributed generation (DG) systems also make use of four quadrant inverters, therefore our project was well suited to performing testing in this area for BC Hydro, our sponsor. The three areas of testing that were of interest to BC Hydro were peak shaving, battery energy conversion efficiency, and islanding a DG system with BCIT's steam generator to see how these systems affect the voltage stability of the grid.

This report will cover the application and need concerning VVO and discuss, via the state of the art, why we chose the four quadrant inverter as our means of implementing VVO. The report will then discuss our controller's design and implementation. Finally the report will state the testing undertaken and the results of those tests. Please refer to the project proposal document titled, "VVO*_Capstone_Proposal_20141230v13*" for further insight into background on the planning of the project.

The people who would gain benefit from this report would include, but not limited to those who have an interest in power quality as it pertains the electrical distribution, DG, including both energy generation and storage. This could include homeowners as well as the electrical utility companies.

This capstone project was carried out by three fourth year Electrical Engineering students at the BCIT Burnaby campus. The time frame for this project was about 9 months between September of 2014 and May of 2015.

1.1 Participants and Stakeholders

The people involved in this project were three fourth year BCIT Electrical Engineering students, two BCIT School of Energy faculty members, and the project course instructor. BC Hydro is the project's industry sponsor.

The three students involved in the project are James Vlasblom, Kevin Fletcher and Maninder Badial. These students have a keen interest in the power quality and controls aspect of the industry.

The two faculty members involved with this project are Ali Palizban and Kathy Manson. These faculty members are experts in the power industry and acted as mentors for this project.

The project course instructor was Neil Cox. This instructor oversaw all the projects worked on for the ELEX 7790 and ELEX 7890 courses. He made himself available to all the project groups as an extra mentor and provided suggestions as required.

Our industry sponsor for the project was BC Hydro. BC Hydro is one of the leaders in North America in the implementation of VVO in distribution systems. They were committed to lend support in both the financial and technical areas of the project.

1.2 Acknowledgements

A project of this magnitude has many more people involved than just the project mentors and sponsors. We would like to take this opportunity to give credit to some of the other people who were instrumental in the success of our project. They are all equally valuable in their respective areas of expertise, and so are listed alphabetically.

Jim Armstrong - Assistant Chief Engineer, BCIT Steam Plant. Jim provided access to the STG lab in SE8-215 and operated the steam turbine generator for our testing.

Lin Brander - Reference Librarian. Lin provided assistance in the research for our project and assisted us with the formatting and structure of our final capstone report.

Kelly Carmichael - Research Analyst, Group for Advanced Information Technology. Kelly provided networking advice and expertise to facilitate the interconnections we required with the project.

Frank Cichon - Instructor, Power Engineering Group. Frank also provided access to the STG lab in SE8-215 and operated the steam turbine generator for our testing.

Chris Cuthbert - Greensmith Energy Management Systems. Chris provided technical assistance with software and hardware areas involving the Greensmith DESS (distributes energy storage system).

Chris Goetz - Assistant Instructor, Electrical and Computer Engineering Technology. Chris provided expertise with communication issues involving PLCs.

Katherine Golder -Faculty, Communication. Katherine played a pivotal role in the all aspects of the communicating our project. Katherine provided us with assistance in the areas of report writing, presentation poster design, and presenting.

Kent Johnson - Intermediate Systems Analyst, Client Services. Kent liaised between our project's network needs and the network at BCIT. Kent also provide the communication hardware we needed for the success of our project.

Joubin Moshrefzadeh - Senior Systems Analyst, Technical Infrastructure Services. Joubin also provided networking solutions for our project to succeed.

Elena Underhill - Graphic Artist, Learning and Teaching Centre. Elena provided creative advice and assistance in our presentation poster design.

Thank you all for your time and assistance.

2 Context and Background

The following sections of this report will provide the reader with a thorough understanding of why our project is important and the motivations for choosing VVO as our project. We will examine the application and need of VVO, the background science behind it as well as how it is currently being implemented in industry. This information will set the stage for the subsequent sections and can be used for reference while examining the rest of the report.

2.1 Application and Need

VVO plays an important role in the future of distribution systems. VVO enables energy savings for the power producer and defers infrastructure costs. Maximizing the current infrastructure reduces the overall energy consumed, reducing the need for more generation capacity.

In July of 2013, BC Hydro, along with Natural Resources Canada, created a Battery backup Energy Source and Storage project (BESS) in the community of Field, BC [2]. This system allows the community of Field to meet the area's electricity needs in the event of a power outage (islanding) and to reduce system load during periods of high demand (peak shaving). Improving the power quality of the feeder lines for these remote communities would lessen the demand on the feeder lines and ultimately extend the lifetime of the infrastructure. This in turn would be a cost savings for BC Hydro.

The infrastructure that connects these remote communities is running close to maximum capacity. By improving the power quality, the demand on feeder lines, transformers, and switchgear can be reduced thereby extending their lifespans and deferring capital costs of upgrades.

In order to operate the BESS in both islanding and peak shaving modes, the battery storage capacity has to be shared, which could cause conflicts. For example, if the battery storage is coming off a depletion cycle after supplying the community during a high demand period, there would be no battery storage capacity available in the event of a power outage. In order for both modes of operation to coexist, a depletion limit must be set on the battery storage. This would limit the amount of backup power and peak shaving power available. Improving power quality can decrease the overall demand making the battery storage last longer without the need for increasing the battery storage capacity.

BC Hydro completed its first VVO project in 1996 with the objective of minimizing the distribution substation peak load demand and relieving transmission capacity constraints [1]. This project resulted in significant energy savings. During the five years of operation in winter periods, there were significant benefits as the winter energy was reduced by an average of 1.3 GWh/yr including two years at 1.8 GWh/yr, and the winter peak demand was reduced by an average of 1.6 MW (or 1.1%) [3]. These results were achieved using a demand reduction strategy where the VVO system was only put into play during times of peak energy demand. This was limited to the winter months. In 2006 the objective was changed from demand reduction energy conservation and the system was operational through the whole year. In 2007 the installed system provided around 7 GWh of energy savings or about 1% of the total energy throughput. The anticipated energy savings are estimated at 300 GWh/yr by 2020 when the program is fully deployed at 65 substations.

This data shows the great potential of implementing VVO to achieve economic benefit.

Financial value can be evaluated through:

1. Energy savings.
2. Deferral of capital expenditures for the transmission system supplying the selected substation, especially if improved efficiency in distribution system directly is reflected through voltage quality improvements and losses minimization.
3. Improved efficiency in distribution system.

The future of the electrical grid is the microgrid, with this topology more distributed generation (DG), such as photovoltaic (PV), wind and biomass generation will be coming on line. PV and wind rely on environmental conditions to generate their power and are therefore unstable. There are many unknowns and therefore, much interest into how these new DG sources affect the voltage levels of the grid. A VVO project plays an active role in determining how these new DG sources will affect the current electrical networks by providing a testing mechanism for new electrical topologies such as microgrid. BC Hydro has expressed interest in using a VVO system to investigate the following:

- How adding PV to the utility grid affects voltage stability and power quality.
- How a battery energy and storage system BESS, can be used for peak shaving at a community level.
- Test battery performance with regard to:
    - Discharge/charge cycle
    - Islanding mode
    - Load pick up
    - Over voltage compensation

Through research projects like this one, which implements VVO by using the BESS, we can make the most of our precious energy resources. By maximizing the efficiency on remote feeder lines BC Hydro can defer infrastructure replacement costs, saving money and also reduce the impact on the environment in the process. The consumer at the end of these feeder lines also benefits. They gain reliability and security from the backup power the BESS provides when operated in islanding mode. Also, because VVO utilizes a four quadrant Satcon inverter which is also a fundamental component of DG, testing can be done with our VVO system to gain a better understanding of how a DG system affects grid stability, when connected to it.

2.2 Background Science and State of the Art

In the following section our group will present the science behind our proposed Capstone project as well as the state of the art that already exists with respect to VVO. This information will serve as a foundation for understanding why our project is important and the opportunities that our group sees in the current power quality market.

2.2.1 Background Science

Optimizing power factor and regulating voltage is the focus for our Capstone project. In order get a thorough understanding of our intention with this project some background information is needed on what a power factor is and how it is corrected and why voltage regulation is needed and how it can be regulated.

2.2.1.1 Power Factor

Power factor is a measure of how much useful or real power is converted from the total apparent power supplied to a system. Apparent power is defined as being equal to the voltage times the current of a system and is recorded in Volt Amps (VA). Active power is defined as apparent power times the cosine of the power factor and is recorded in Watts (W). Reactive power is the portion of the apparent power that reduced the power factor rating, it is defined as the apparent power times the sine of the power factor. It is recorded as Volt-Amps reactive (Var). The relationship between these three types of power can be seen in Figure 1.

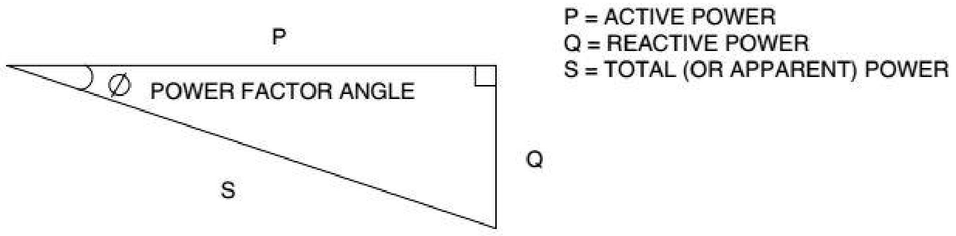

Figure 1 - Power triangle [4]

Depending on the type of reactive load, the current phase angle with respect to the voltage phase can swing. If the load is entirely capacitive, the current will lead the voltage by 90 degree while a purely inductive load with lag the voltage by 90 degrees.

There are two different power factors, displacement and true power factor. Displacement power factor is simply the ratio between the reactive and active power. The true power factor is the ratio that the utility companies base their penalties on. True power factor takes into consideration the harmonics present in the system, the ratio is then between reactive power (including harmonics) and active power (including harmonics).

There are two basic ways to improve the power factor of a power system, reduce the reactive power consumption or compensate the reactive power consumption with power factor correction equipment.

Compensating for the reactive power consumption requires calculations to determine how much compensation is needed in the power system. Capacitor or inductor banks are often used to correct the power factor ratio in order to negate the leading or lagging phase shift introduced by the different loads on a system.

Improving power factor ratings can save customers money, not only by avoiding penalties, but buy by increasing the life of their equipment, reducing energy loss and by reducing the heat of their equipment [5].

2.2.1.2 Voltage Regulation

Voltage regulation is the change in voltage at the receiving end of a line when the load changes between loaded and no-load conditions, while keeping the sending voltage the same. The bigger the difference in voltage the higher the percent voltage regulation. The difference in voltage between the sender and receiver is caused by losses that take place during the transmission of power. The transmission losses mainly consist of losses in the distribution transformer and the distribution line losses [6].

The distribution transformer losses are comprised of the losses from the I^2R losses in the windings of the transformer, and the real and reactive power losses in the core [7]. Ideally the windings in the transformers would have zero resistance but practically this cannot currently be achieved. The resistance in the windings cause there to be heat emitted when current flows, which contributes to a loss in energy. The amount energy lost in the windings is not constant because it varies by the square of the flowing current. The real and reactive losses in the core of the transformer are results of hysteresis and eddy current loss. Hysteresis losses are a direct result of using specific materials for the core of a transformer. Depending of the material, it could require more or less energy to reverse the magnetic field in the core. In Figure 2 there are examples of hysteresis curves that require more and less energy to reverse their magnetic field. The more energy required to reverse the field, the greater the hysteresis loss.

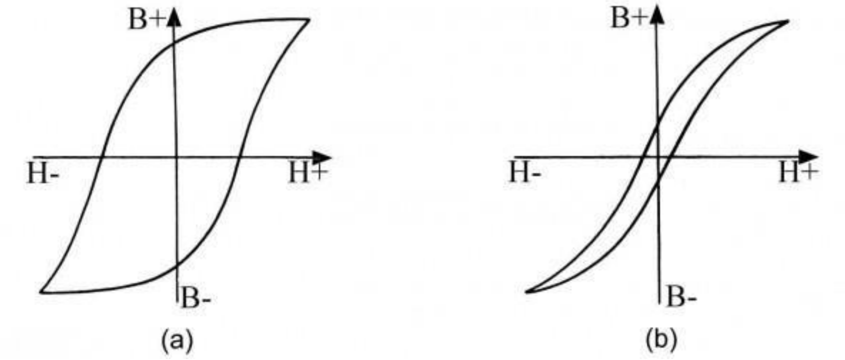

Figure 2 - Hysteresis Curves [8]

Eddy currents are produced by the changing magnetic field within the transformer. The currents circulate within the core material of the transformer and oppose changes in the flux density in the material. The current produced in the core will cause energy losses because of the resistivity and heating in the material [9]. The core losses in a transformer are usually taken to be constant since they rely on the frequency and intensity of the magnetic field passing through the material.

Transmission line losses mainly consist of I^2R losses and corona losses. The I^2R losses in transmission lines are the same as the losses found in the transformer windings. When current flows through the conductors that make up the transmission lines, heat is produced and energy is lost. The amount of energy lost is relative to the amount of current flowing squared. Corona losses compared to the I^2R losses are small but are worth mentioning. Corona occurs when the electric field at a conductor's surface causes the surrounding air to conduct. The conduction results in a flow of energy that is accountable for a loss of energy [7].

These two sources of losses, distribution transformer and distribution lines, play a significant role in the energy loss between the source and receiving end of a distribution line. In order to account for these losses, utilities must compensate by increasing their voltage output at the source so at the receiving end of the link the customer receives a voltage within the guaranteed voltage range.

2.2.2 State of the Art

There are two approaches of VVO, independent voltage optimization and Var optimization, and integrated VVO. In the following section we will discuss the state of the art information about both of these approaches. We will includes different methods, market products, technology and research for these different VVO approaches.

2.2.2.1 Independent Voltage Optimization and Var Optimization

One approach for optimizing voltage and Var is to optimize them separately. The benefit of taking this approach is that it is relatively simple in comparison to the integrated method. The simplicity comes from not having to worry about designing the optimization with both the voltage and Var in mind. This can however lead to problems because the optimization for one factor can affect the optimization for the other. A typical consideration for the independent optimization approach is to leave one optimization static and the other dynamic. This allows the optimizations to be independent but adjustable at the same time.

Below we will talk about the different methods used for independent voltage optimization and Var optimization.

2.2.2.1.1 Independent Voltage Optimization

Below are the different methods for independent voltage optimization. These methods all ensure that the voltage on the receiving end of the distribution line is within the guaranteed voltage range set by the utilities. These methods have their advantages and disadvantages, and we will compare them in this section.

2.2.2.1.2 Load Tap Changer

This method of voltage optimization can be made dynamic with the use of a controller. Load tap changers have been successfully utilized in industry for many years. Using signals outputted by a voltage monitoring controller, taps are changed on a three phase transformer found at distribution substations to adjust the winding ratio of the transformer [10] to compensate changing customer loads, Figure 3has an illustration of how a load tap changer would operate.

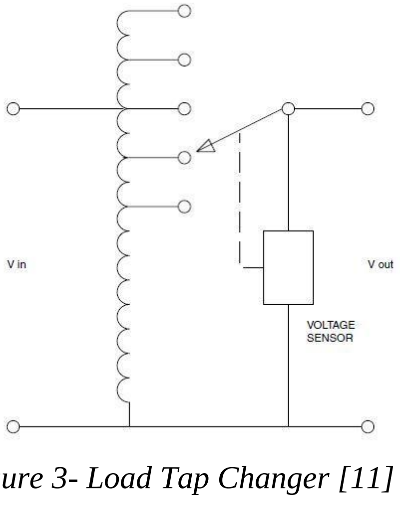

Figure 3- Load Tap Changer [11]

The advantage of this method is that it is simple to conceptualize and does not require various pieces of equipment. The disadvantages for this method is that it is difficult to make subtle voltage changes because of the defined tap winding ratios. Also, the mechanical aspect of the device increases maintenance cost and decreases reliability. And finally, the voltage adjustment is relatively slow compared to the quick changes of line voltage [12]. The market currently contains many LTCs that can be installed at substations [13].

2.2.2.1.3 Inline Voltage Regulators

Inline voltage regulators work in a way that is similar to load tap changer transformers in that they have adjustable windings ratios that allows for voltage regulation. The difference here is that the regulators are often installed further down the distribution line rather than just at the distribution substation. These regulators can be used for one, two or three phases [14]. The advantage of this method is that these regulators can be installed further down the distribution line to boost the voltage up to the utility guaranteed value when significant voltage loss has occurred. The disadvantage of this method is similar to the load tap changer in that the rate of regulation is much too slow to compensate for quick load and voltage changes. There are many three phase voltage regulators on the market that can be used to regulate voltages in a distribution system [15].

2.2.2.1.4 Voltage Regulating Capacitors

Capacitors, in optimization designs, are typically used in power factor correction which will be explored in the next section of the state of the art. Shunt capacitors can be used to bring the power factor of a line close to one so there is less reactive power on the line. By reducing the reactive power on the distribution line, the total current flowing on the line also reduces. Since the largest cause of energy loss in a distribution line is I^2R losses, the losses are reduced. The advantage of this method is that capacitors are easy to install and can be applied throughout the distribution system. The disadvantages of this method is that capacitors, especially switching capacitors, can cause dangerous transient effects and are restricted to the capacitor values in their capacitor banks [12].

These methods of independent voltage optimization work well in cases when the change in voltage on the distribution line are relatively slow and shallow. They also are restricted to their optimization level due to their set tap and capacitors levels. Also, the mechanical aspects of these methods leads to increased maintenance costs. With respect to VVO, these methods independently do not prove to be effective in dynamically optimizing voltage levels.

2.2.2.2 Independent Var Optimization

There are two main strategies of Var optimization of a system, a static strategy and an active strategy. The static strategy is based around the idea of calculating the exact amount of Var correction needed and installing a capacitor bank in series or parallel with a load. This correction reduces the amount of reactive power in the system and brings the power factor closer to 1. The active strategy is based on the idea of continuously monitoring the power consumption of a system and making slight changes to the load of a system to compensate for a changing power factor. Below, our group will outline the strengths and weaknesses of a few of the most popular methods.

2.2.2.2.1 Fixed Capacitor Banks

This method of Var optimization is a static strategy. Fixed shunt capacitor banks are installed to offset inductive loads in a system. If the inductive loads are always the same, this method will be effective in reducing the amount of reactive power in the system. However, if the inductive loads change over time, a fixed shunt capacitor bank will not always provide adequate power factor correction. Also, since the capacitor banks are a fixed values, there is a high chance that resonance can occur within the power factor correction circuit [16]. Resonance is a very important issue and can cause damage if not accounted for. Fixed capacitor banks are also easy to install and maintain, but may be expensive to replace. There are currently many fixed capacitor banks solutions that offer static power factor correction to industrial customers [17].

2.2.2.2.2 Switched Capacitor Banks

This method of Var optimization is a dynamic strategy. This method is based around the idea of having switches (relays or mechanical switches) connected to various capacitor values to allow for freedom in Var compensation. These capacitors can then be adjusted manually or connected to a controller to be adjusted automatically as loads change. The advantage of this method is that it is dynamic and can adapt to changing loads. Its disadvantages are that during the switching of capacitors dangerous voltage transients are produced which can be very harmful if not mitigated [18]. Also, the fixed capacitor steps makes it difficult to fine tune the power factor of a system. Automatic capacitor switching device are often wall mounted and uses a built in controller to switch in and out capacitors to compensate the power factor in the system [19].

2.2.2.2.3 Synchronous Condensers

This method of Var optimization is a dynamic strategy. This method is mainly used in large industries to correct their power factors. This methods works by operating a motor that is over-excited to act as a reactive load. This method is good because it does not generate or is affected by any harmonics and can be adjusted to offer a variable level of power factor compensation [20]. The disadvantages of this method is that a synchronous condenser is a heavy piece of equipment and would have a high cost.

2.2.2.2.4 Thyristor Switched Capacitor

This method of Var optimization is a dynamic strategy. This method involves controlling many different branches of capacitor banks with a controller using thyristors as switches [21]. The thyristor soft switching method allows quick insertion and removal of capacitors into the power system without any harmful switching transients [22], and produces very little harmonics. A disadvantage of this system is that power factor correction is done with steps of capacitance which makes fine tuning of the power factor very difficult.

These methods of independent Var optimization are effective in improving the power factor on a distribution line. With respect to VVO, the dynamic methods are the most effective methods in trying to optimize Var levels. However, even the dynamic methods have disadvantages. With the dynamic switched capacitor methods the common problem is that the Var optimization is restricted to the levels of capacitors available in the capacitor banks. Also the mechanical switching method is not quick enough to adapt to quick load changes on the distribution line.

2.2.2.3 Integrated Voltage Var Optimization

Integrated VVO is when both the voltage and Var levels are optimized to achieve specific set points set usually an adaptive system controller. VVO has been around for many years and its methods have been evolving as new technologies are developed. Below we will discuss the current methods for achieving integrated VVO and some of the new ideas that are coming into industry.

2.2.2.3.1 Series Var Compensator

With this method, the series Var compensator (SVC) operates in a similar way that switched capacitor systems operate. A controller controls reactive loads to compensate for varying Var levels on a distribution line. The difference between these two methods is that switched capacitors are usually done with mechanical switching while in the SVCs, reactors are controlled using thyristors. Using the reactors, Var levels can be optimized and voltage variations can be mitigated. The benefits of this method is that the thyristor switching enables VVO and adapts to changing conditions relatively quickly with a decreased amount of transients. The disadvantage of this method is that the fixed Var compensation steps in the reactor and capacitor banks restricts the controller’s ability to make slight, subtle adjustments to voltage and Var levels [23].

2.2.2.3.2 Static Synchronous Compensator

The static synchronous compensator employs a series, specially designed magnetically coupled device. A voltage sourced inverter is used to supply the inductor with a suitable field supply current to set up a voltage that will compensate for the harmonics present in the line. This kind of inverter draws its source from DC, meaning that it is only capable of delivering active power to the grid. For it to have the ability to supply the required reactive power a small capacitor must be employed at the output of the inverter source. This capacitor is relatively small in comparison to the amount of compensation that it offers.

2.2.2.3.3 Dynamic LTC and Capacitor Controlled VVO

Using a voltage controller at a substation that receives near real-time voltage information from distribution lines, set points are determined to optimize voltage and Var levels on the distribution lines. The voltage information is received periodically and the optimal LTC, voltage regulator and switching capacitor values are derived using power flow analysis. The power flow model is built on real-time connectivity, nodal load and secondary circuit models [24]. Advantages of this method is that it utilizes both the VTC and capacitors to adjust the Var, and voltage of a changing load distribution line to achieve VVO. The major disadvantage of this method is that the modeling and computations done for the power flow analysis have to be very accurate and fast for the VVO to be effective. In order for the power flow analysis to be done effectively the processor speed of the controller has to be very high, and the modeling used in the controller has to be accurate.

2.2.2.3.4 Voltage Source Inverter

Voltage source inverters have been used for many years as a way of controlling industrial motors through the use of pulse width modulation (PWM) techniques. Utilizing PWM and a feedback controller, a four quadrant VSI is able to convert DC voltage from battery storage to AC voltage that can be injected into a distribution line to regulate voltage. The VSI can also utilize the battery storage to compensate for Var levels. By injecting or absorbing reactive power into or from the distribution line, the level of Var on the line can be optimized to reduce the total amount of current flowing on the line and improving power factor. There are many advantages of this method, one being that the optimization can be done very accurately due to the flexibility in compensation by injecting and absorbing reactive power [10]. Another advantage is that the optimization can be done very quickly because there is very little delay between the controller and the output. Another advantage is that there are very little transients given off by this method because no switching takes place during compensation. The downside to this method is that an energy supply must be attached to the VSI in order for it to be able to supply power to the distribution line. This can restrict the VSI to be installed at either the distribution or receiver end of the distribution line where energy can be supplied as opposed to somewhere in between where replenishing energy supplies could be difficult. Also another downside is that the controller for this method is more complex given that the optimization is completely reliant on feedback controls.

2.2.2.3.5 Multi-Agent Systems

The method of Multi-agent systems (MAS) is a new method that is currently being explored and has emerged because of new smart power distribution technologies coming into the market. The idea of MAS is that different smart technologies, equipment and controllers communicate with each other and automatically correct for changing conditions in a distribution network. This method relies heavily on new smart technologies and requires smart power measurement equipment to be installed at each node of the power distribution network. The advantage of this method is that the system would adapt automatically to changes in a network in an efficient and effect manner. The disadvantage of this method is the amount of infrastructure that needs to be installed throughout the distribution network and the reliability of the current smart technologies in the current market [25]. This method is very promising but without the mature and proven smart technologies, the idea may be too early to implement in the field. Also, further testing should be done.

2.2.2.3.6 Advanced Metering Infrastructure

The advanced metering infrastructure (AMI), utilizes smart meters that are currently installed within a distribution system to get more reliable and frequent distribution information. This information can then be utilized by VVO system controllers to produce more accurate feedback calculations and set point estimations to better achieve optimization objectives [24].

The above integrated VVO methods have many strong advantages over the independent voltage and Var optimization solutions. The dynamic and adaptable aspects of them prove to provide adequate optimization in both voltage and Var levels. The difference between these methods is the speed in which they can optimize, the control methods, and ability to provide continuous vs discrete levels of VVO. With respect to VVO, the VSI method is the most promising. The ability to quickly adapt to voltage and Var levels, the continuous levels of optimization, and the lack of operational transients makes this method very appealing for distribution systems. The only real disadvantage is that the use of these bi-directional inverters for VVO is relatively new and does not have a lot of industry application yet. This means that the idea has not been tested long term in the field and still needs exploration. Despite the lack of testing, this method shows promise especially with the new emerging research of multi-agent systems and AMI.

Based on the state of the art research our group did, we concluded that the integrated VVO methods have many strong advantages over the independent voltage optimization and Var optimization. The main advantage being the integrated controller’s ability to control equipment to meet both voltage and Var set point levels at the same time. This enables the objectives of the optimization to be met in a more efficient manner without the complexity of interactivity.

3 Project Definition

The following section will cover the specifics of what our objectives were for this project, and what we were able to deliver by the end of our course. Additionally, for each objective we have stated its scope in order to clarify what aspects we addressed, and did not address, during our project. By setting these boundaries we were able to meet most of our requirements and successfully complete our project.

3.1 Objectives

For our proposed Capstone project we partnered with BC Hydro to establish an automatic voltage and Var compensation system using the BESS installed on the BCIT Burnaby campus. From this we have set our project objectives as follows:

1. Create a closed loop controller algorithm that will constantly monitor the flow of reactive power the electric utility supplies to the grid. In doing so we aim to achieve a unity power factor, while regulating the voltage of distribution feeder lines. It will also supply power to the loads, via islanding, during a grid outage.
2. Provide BC Hydro with a test microgrid that can be used to test BESS related scenarios that can be implemented into full scale grid solutions.
3. Complete the power quality testing requested by BC Hydro.

After gaining access to the Greensmith operation portal, we found that they provided an online interface, which could be used by operators, to view the health of the batteries used in the BESS. The portal also provided access to power, Var, and energy data which can be exported into Excel. Our group, therefore, removed the objective of designing a monitoring interface for the BESS, which was earlier stated in our proposal, as this can be accomplished with Greensmith portal.

3.2 Deliverables

In this section of the report we will discuss the deliverables our group provided at the end of our project.

At project completion in May 2015, our group achieved the following deliverables:

1. MATLAB model of the BESS installed on the BCIT Burnaby campus.
2. A closed loop PLC program that controls that MATLAB model of the BESS.
3. Analysis of completed BC Hydro power quality tests.
    a. Peak shaving test.
    b. Partially completed battery energy conversion efficiency.
4. Documentation of the work and programing required to create the closed loop controller.
5. Project poster and PowerPoint presentation summarizing the progress of our project.
6. This final report.

Due to the issues that we faced throughout our project, the above deliverables are somewhat different from the ones that were stated in our proposal [26]. The issues that we ran into included a lack of cooperation with Greensmith, the designers of the BESS, and a passive hardware failure that occurred in the Samsung Battery Management System (BMS). These issues forced our group to adjust our project, which resulted in a different set of deliverables. The elements of our project that had to change were the operation of our closed loop controller and our BC Hydro power quality testing.

The closed loop controller was originally proposed to control the real Satcon inverter via Modbus. However, Greensmith did not feel comfortable providing us with the Modbus register addresses that controlled the Satcon inverter. This meant that our PLC could not directly issue commands to the Satcon inverter which forced us to adjust our project. The next best alternative was to connect the PLC program with our MATLAB model through an OPC server to simulate its operations.

The three tests that BC Hydro requested included a peak shaving test, a battery energy conversion efficiency test, and a transient test. Due to the hardware error that occurred in the BMS, we were unable to totally complete the battery energy conversion efficiency test, or complete any of the transient test. We were able to complete the peak shaving test and one full cycle of the battery charge/discharge test. In order to better determine the battery energy conversion efficiency, more cycles of the battery charge/discharge test will need to be performed, once the hardware issue in the BMS it resolved.

3.3 Scope

The scope of our proposed work for this Capstone project was limited to a closed loop control algorithm for the BESS four quadrant Satcon inverter that is installed on the BCIT Burnaby campus. This algorithm will be able to regulate the voltage, provide peak shaving, and adjust the Var being injected into the microgrid installed on the BCIT Burnaby campus. The controller design will assume that the three phases are balanced and will be limited to a Satcon inverter of the same make and model as the one employed in the BCIT BESS.

Fortunately the lack of real time control over the Satcon inverter did not affect the testing requirements of BC Hydro. In mid-April a meeting took place with a BC Hydro technical representative. In that meeting they informed us of the specific tests they were interested in exploring. These tests are as listed below.

The scenarios and tests that BC Hydro wants to perform on the BESS microgrid are:

1. Peak shaving
2. Battery Energy Conversion Efficiency
3. Steam generator islanding and transient

3.4 Requirements

Please refer to attached excel document for our list of requirements.

"*VVO_Requirements_Table_20150517v3_0.xlsx*"

4 Project Implementation and Results

In this section of the report we will provide a detailed description of our implementation methods as well as the results we found throughout our project. The detailed description includes a high-level summation of our system, an explanation of our design choices for both our VVO controller and our BC Hydro power quality test plan, our implementation decisions, and lastly a look at our testing methods and results.

4.1 High-Level Description

Below is a simplified block diagram of the controller portion of our project. It can be seen in Figure 4 that there are two major sections in our system: the PLC program and the MATLAB model. Below we will discuss these two sections and how they interact with each other.

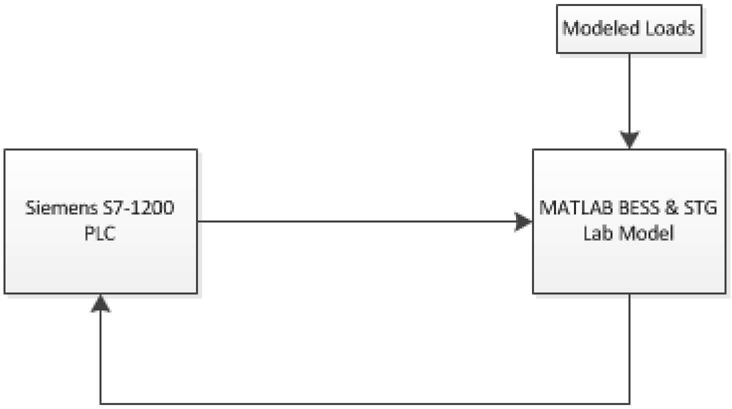

Figure 4 - High-Level block diagram of VVO controller

4.1.1 MATLAB Model

In this section of the report we will be breaking down the different modules that are included in our MATLAB, BESS, and STG Lab model. A simplified block diagram can be seen below in Figure 5 which highlights the modules of our model. The different modules of our model include the BC Hydro supply, the Satcon inverter, the STG lab loads, and the ION 7330 power meters.

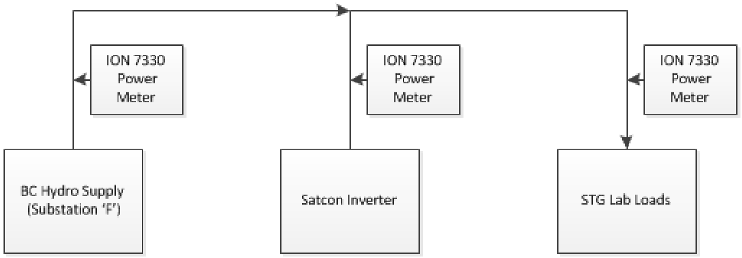

Figure 5- High-Level block diagram of MATLAB Model

Please see Appendix A to view the single line diagram represented by our model. By using a model of a power system, tests can be run without ever having to disrupt the real system. Our model mimics how the electrical distribution system would react to different power system scenarios. In our model we have set the BC Hydro supply to be a slack bus because it has the ability to supply the balance of the real and reactive power required by the STG lab loads. The Satcon inverter is a grid tied Satcon inverter which operates in all four quadrants of the power plane (Figure 6). This means it can consume and provide both reactive and real power at the grid voltage. The Satcon inverter is connected in parallel with the BC Hydro supply which allows it to safely generate or draw current due to its four quadrant abilities. The STG lab loads are characterized as being both real and reactive loads. Lastly, the ION 7330 meters display the voltage, current, real power, reactive power, and the power factor, all at specific points in the distribution system.

As the STG lab load's increase, BC Hydro supplies more current in order meet the demands of the system. The four quadrant ability of the Satcon inverter allows it to consume current from, or supply current to, the distribution line. This means it can act as a source or a load. By acting as a source or a load the Satcon inverter can be used to peak shave, power factor correct, and voltage regulate (please refer to Background Science section of this report for an explanation of these actions).

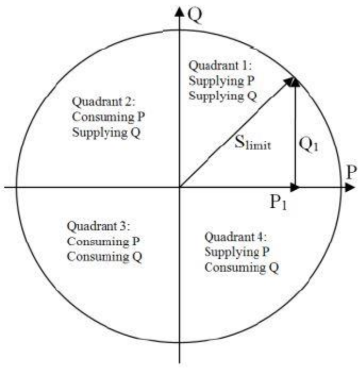

Figure 6 - Four Quadrant Inverter Operations [27]

4.1.2 PLC Implementation

In this section we will briefly describe how our Programmable Logic Controller (PLC) operates. Below in Figure 7 is a simplified block diagram of our PLC implementation.

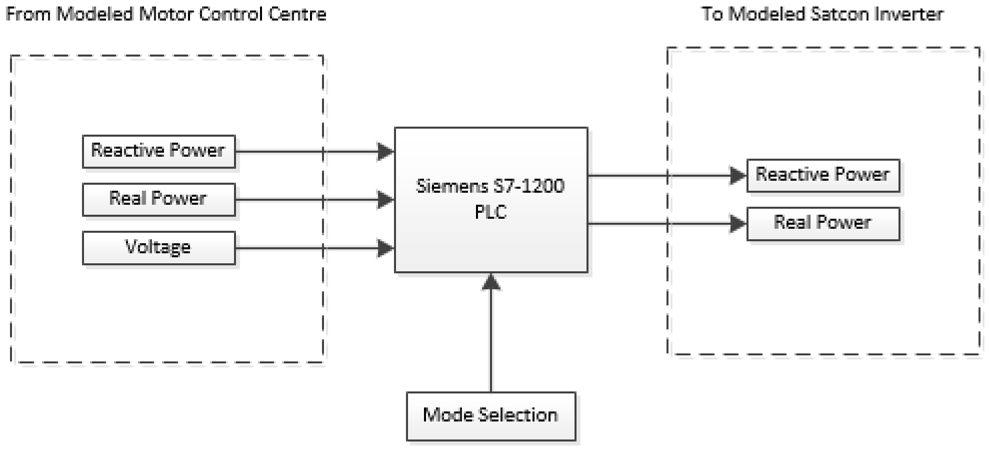

Figure 7- High-Level block diagram of PLC program

The inputs of the PLC include real and reactive power and voltage measurement data from the Motor Control Centre. The outputs of the PLC include real and reactive power and voltage control data to the modeled Satcon inverter which are based on the control mode selected by the user. We have designed our PLC program to operate in three automatic modes: power factor correction, peak shaving and voltage regulation. A manual mode is also available to allow fixed values of Power and Var to be set with the PLC.

Using the power factor correction mode, the PLC will read the reactive power input and output a command to the modeled Satcon inverter. The PLC will issue a command to output the opposite reactive power within the capabilities of the Satcon inverter in order to negate the reactive power on the grid. In doing so the power factor on the distribution line will be greatly improved.

The peak shaving mode will configure the PLC to command the modeled BESS to shoulder as much of the load from BC Hydro as it can based on its rated capabilities. It does this by using the real and reactive power inputs from the distribution line and calculates how much load to offset with a bias toward power factor correction. Once the calculations are complete, the PLC will issue the calculated reactive and real power commands to the modeled Satcon inverter and decrease BC Hydro’s load.

Lastly during the voltage regulation mode, the PLC reads the voltage input and decides if there is an under voltage or overvoltage condition based on a nominal voltage set point. If there is an under voltage condition at the STG lab, the PLC will command the modeled Satcon inverter to cancel out the reactive power seen from the reactive power input and inject as much real power as possible to reduce the current supplied from BC Hydro. In doing this the Satcon inverter will reduce line losses and increase voltage. If there is an overvoltage condition the PLC will command the Satcon inverter to start charging. This acts as a load and increases the current supplied from BC Hydro. By consuming real power the Satcon inverter can reduce the voltage at the STG lab.

4.1.3 System Connectivity

In order for the Siemens PLC to communicate with MATLAB model we needed to set up an OPC server. OPC stands for OLE (Object Linking and Embedded) for Process Control [28]. OPC allows industrial hardware devices such as PLCs to communicate with programs such as MATLAB. Our OPC server is set up in server/client pair system where devices act as clients and read and write to the server. Below in Figure 8 is a block diagram showing the information flow between the PLC, OPC server and our MATLAB model.

Figure 8- High-Level block diagram of OPC server

Using this OPC server we are able to exchange commands and metered information between the MATLAB model and the Siemens PLC. This allowed our group to create a closed loop system.

4.2 Design and Implementation

In this section of the report we will provide a description of what we designed and how we implement specific elements of our project. The elements that we will explore include the BESS and STG lab MATLAB model, our Siemens PLC program, our OPC server, and our BC Hydro power quality test plan.

4.2.1 VVO Closed Loop Controller

Below we will discuss the design and implementation decisions we made with regards to our VVO controller. We will examine different aspects of our BESS and STG lab MATLAB model, Siemens PLC program and the OPC server.

4.2.1.1 BESS and STG Lab MATLAB Model

In order for our MATLAB model to mimic the behaviour of the real system, we needed include as many aspects of the real system as we could into our design. We split our model into the following modules: the Satcon inverter, line losses, the BC Hydro supply and the STG lab loads. Below we will discuss how we designed each of these modules and what the trade-offs were when we were making our decisions. In Appendix B there is a screenshot of the full MATLAB model within Simulink.

4.2.1.1.1 Modeling Platform

Before we could start modeling our system we had to select a program to use. The two graphical programming environments our group were the most familiar with were National Instrument's LabVIEW and MathWorks' Simulink within MATLAB.

At the time of making the decision, we were unsure how effective LabVIEW would be for modelling a power system, because we did not have any experience using it in that respect. However we did have experience with SimPowerSystems design module for MATLAB's Simulink. Therefore, based on our previous design experience using SimPowerSystems and Simulink, we decided to use it to design our BESS and STG Lab MATLAB model.

4.2.1.1.2 Satcon Inverter

The Satcon inverter was the most important module in our MATLAB model. In 0 there is a screenshot of the Satcon inverter block made within Simulink. The elements that we took into consideration when designing this module were the delay timing between when an event was scheduled and when the Satcon inverter was able to act on the command, the design of the actual Satcon inverter block and how it was able to supply and draw current and lastly how the Satcon inverter was given commands.

The amount of delay we introduced to the model as part of our design choices in order for the Satcon inverter to represent the physical system was 3ms between when it receives an output request and when that request is fulfilled. A "Time On delay" of 20ms was also added to allow the voltage to stabilize in the model before any requested levels are output from the inverter. Without this delay the inverter tries to output an infinite current and does not stabilize, breaking the model.

The inverter was modeled as a controlled current source, this allows the amplitude, frequency and phase angle of the output to be changed. With these parameters our modeled inverter can operate in all four quadrants of the power plane. Based on the Power (P) and Var (Q) request inputs the required phase and current amplitude are calculated using Eqn 1 and Eqn 2.

$$|current| = \frac{\sqrt{Q_{Request}^2 + P_{Request}^2}}{V_{grid}} \qquad \text{(Eqn 1)}$$

$$phase = tan^{-1}\left(\frac{Q_{Request}}{P_{Request}}\right) \qquad \text{(Eqn 2)}$$

A shunt resistor was placed at the output of the current source. This effectively converts the current source into a voltage source and makes it compatible with the voltage level of the simulated grid.

4.2.1.1.3 Line Losses

In order for our modeled system to react similarly to the physical system we can had to introduce line losses between the BC Hydro supply and the STG lab. This value was calculated by measuring the voltage and current both magnitude and phase in the STG lab with a light load applied and then again with a heavier load. This created two equations that could be used to solve for the element values of the line loss. We made an assumption that BC Hydro was a fixed voltage. From this we arrived at values of 0.01347ohms and 2.0717uH.

4.2.1.2 BC Hydro Supply

During power system analysis, there always has to be a slack bus that picks up the balance of the load to ensure the system operates properly. In our modeled system, the BC Hydro supply at Substation 'F' acts as the slack bus. This used a controlled voltage supply, which has the inputs similar to the current supply used in the inverter model. The model elements used in Simulink can be configured to have internal elements of resistance, inductance, and capacitance. In order to simulate the slack bus it is treated as an ideal source. This way the voltage that is required stays fixed. The elements also do not have any limitations on the amount of current they output, so this allows the source to supply any power to the modeled grid that the inverter is not picking up.

4.2.1.2.1 STG Lab Loads

The loads within the STG lab are not fixed or predictable. The different loads that exist are generated through the daily use of the steam plant in the SE8 building. These loads include the various pumps, fans, and lighting located in this building. In our model a second "inverter" block was used to act as these building loads. This block can either be controlled through a SimIn block that takes input from a matrix created from CSV data collected from Modbus Poll. Through the use of an OPC read block data can be read in real time from the ION 7330 meters located at the Motor Control Centre. This allows the model to react to real world conditions.

4.2.1.3 Siemens PLC Program

Below we will discuss the design and implementation decisions we made with regards to our PLC program. We will examine our design decisions behind our controller selection, control methods, control modes and methods of communication.

4.2.1.3.1 Controller Programming Method Selection

Throughout our project we examined three ways of programming our control algorithm: a Linux based program, a multifunction DAQ based program and a PLC ladder logic based program. The Linux program would update the constant power commands of the Greensmith control portal after collecting and analyzing measurement data through networked meters. The DAQ would accept and process measured distribution line data and issue inverter commands through a manually programmed Modbus protocol via an output pin. Lastly connecting a PLC to the STG lab and BESS systems we could collect measurement data and issue inverter commands through a Modbus communication PLC module.

We determined that the Linux based method would be too slow in updating the output of the inverter through the Greensmith control portal due to its scheduling requirement. Also attaining the measurement data from the private STG lab network would be very difficult to attain for network security reasons.

When comparing the DAQ and PLC methods we decided that the PLC method was the most viable because of the Modbus communication modules and the pre-existing networking blocks available within the Siemens programming software.

The PLC we used was a Siemens S7-1200 which was provided to us by our mentors. This specific PLC is heavily used in the BCIT technology programs which gave us assurance that we had support if we ran into any programming problems.

4.2.1.3.2 Control Methods

Our PLC had an RS485 communications module installed in it which allowed it to communicate with the meters that were installed in the STG lab. This allowed easy integration with our intended control algorithm, which would take power and voltage measurements in real time and process the necessary output commands for the inverter which would be output through Modbus TCP to the Greensmith inverter control system. The adjustments to the inverter happen continuously in real time, this allows for sudden changes in the network to be compensated for.

4.2.1.3.3 Control Modes

We have designed our PLC program to operate in three automatic modes: power factor correction, peak shaving and voltage regulation. A manual mode is also available to allow fixed values of Power and Var to be set with the PLC. Below we will discuss how each of these were implemented in our PLC program.

The Power Factor Correction (PFC) mode of our PLC program takes a measurement of the loads Var requirements and tries to match it with an equal, but opposite magnitude. This is limited by the maximum kVA rating of the Satcon inverter. A higher priority bias is set toward this mode when it is activated.

Peak shaving mode takes measurements of the current load demands and tries to supply them taking the demand away from BC Hydro. This mode works in a similar manner to PFC, but supplies real power. When the PCF mode is active the maximum output of power is limited by the balance of kVA left after Var contributions.

Voltage regulation mode uses the inverter as either a load or a source depending on the direction that the voltage needs to be adjusted toward a predetermined set point. This mode can help stabilize the voltage at the end of a long feeder, but is limited to the kVA rating of the inverter. This made the range of voltage that could be regulated quite small.

4.2.1.3.4 Communication Methods

In order for our PLC work as a VVO closed loop controller, it needs the ability to communicate with meters and an OPC server for our system model. The communication can be done using Modbus RTU and Modbus TCP/IP. Below we will discuss these methods and where we implemented each type.

Modbus RTU is a serial communications protocol that allows either point to point connections between master and slave devices when used with RS-232 or a bussed network with RS-485. The advantages of this protocol is that it allows for up to 247 devices to be addressed. Each device then has multiple registers that can be accessed by the master. The slaves do not broadcast the values of the registers unless specifically requested. This saves a lot of needless transmission wasting bandwidth. In the case of RS-485, multiple clients (up to 32) can be connected to the same bus without the use of repeaters.

Modbus TCP encapsulates the Modbus data packet into a standard TCP/IP packet. This allows it to transfer data over greater distances and at higher speeds. The devices are addressed using network IP addresses.

For our project the meters in the STG lab communicated through Modbus RTU using RS-485. The Greensmith inverter would utilize Modbus TCP/IP to accept user input, but this function was not implemented in Greensmith's control interface during the time we had with the inverter. We also discovered that in order to communicate from the PLC in client mode the data base for the MB_Client block had to have the MB_UNIT_ID changed from its default of 255 to 1 so that it aligned with the default address of all other Modbus TCP devices.

4.2.1.3.5 HMI Control for PLC

The PLC program that we developed has three different operating modes and different interactions with Modbus interfaces. In order to access these modes a Human Machine Interface (HMI) was developed with multiple screens:

1. Automatic mod controls (Figure 9)
2. Manual controls(Figure 10)
3. Modbus and set point(Figure 11)

These screens also present the user with access to the input measurement values that the PLC is monitoring and the output commands it is sending to the inverter. The HMI screen could be placed anywhere there is a network connection to the PLC available for greater convenience. Our suggestion would be to mount it in the STG controls cabinet located in the SE8 STG lab.

Figure 9 - HMI Automatic Controls Screen

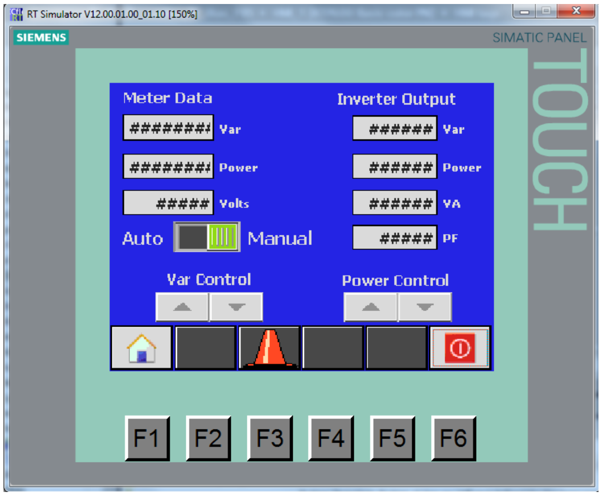

Figure 10 - HMI Manual Controls Screen

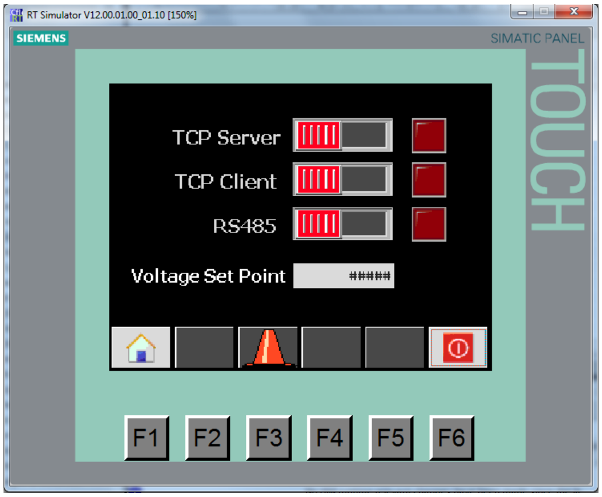

Figure 11 - HMI Modbus and Set Point Control Screen

4.2.1.4 OPC Server

Below we will discuss the design and implementation decisions we made with regards to our OPC server. In order to allow testing of our PLC program in our lab we required a way of interconnecting our PLC with MATLAB. This would allow testing without having to connect with the real inverter and a live power grid. An industry standard way of interfacing Windows applications with industrial instrumentation devices is through an OPC server. We chose to use Matrikon's OPC server because it was available for free and had a plug in for our specific Siemens PLC. Matrikon is also a subsidiary of Honeywell Controls, so we felt it would be a quality product.

For more information on the setup and use of the Marikon OPC server please refer to the accompanying manual '*VVO_OPC_Setup_Manual_20150516v1_1*'.

4.2.2 BC Hydro Power Quality Test Plan

In order to systematically perform the tests that BC Hydro requested we designed tests plans for each test. The test plans include, for each test, a list of needed equipment, a setup and test procedure and the measurement locations. Below we will outline our decisions while designing each of the three tests with regards to the above elements.

Please refer to the '*VVO_Test Plan for BC Hydro Steam Turbine Test_1.0*' document, in folder of accompanying documents, for the complete testing plan.

4.2.2.1 Peak Shaving

The peak shaving test requires us to make measurements at the Motor Control Centre while injecting power into the distribution line. By injecting real power, the Satcon inverter could offset some of the STG lab's loads and allow BC Hydro to supply less power.

To monitor this effect we decided that we would need to access to the measurement data from the ION 7330 protection relay that is located at the Motor Control Centre. By accessing this protection relay we could capture data that represents how BC Hydro views the STG lab loads.

The equipment needed to run these tests included a Modbus utility software called Modbus Poll, a laptop to install and run the software on and an Ethernet cable to connect the laptop to the STG meter network.

Modbus Poll a free piece of utility software that acts as a Modbus master and has the ability to poll Modbus servers to gather information and log in a .CSV file. We configured it to poll the SEL-751A protection relay every 2ms and gather 3 phase voltage and current data as well as power measurement information.

The procedure for conducting this test includes outputting real power from the Satcon inverter and logging its effect on the distribution line. The logging would be done using the Modbus Poll software using a laptop connected to the STG metering network. The Greensmith portal would be used to schedule a constant -25 kW and 3 kVar output for 3 minutes. The software would then begin polling the relay and log measurement data when the event was scheduled and finish polling when the constant power event is completed. By plotting this captured data the effects of peak shaving can be seen which include a change in current supplied by BC Hydro.

A constant -25 kW and 3 kVar output was selected to perform the peak shaving test because its effect would be easily located within the measurement log data. Synchronizing the output of the Satcon inverter and the logged data was very difficult because of the inconsistent scheduling system used by the Greensmith control portal. The Greensmith control portal was not very effective in scheduling events, the start times and event durations did not usually match the user input. This control behaviour made it very difficult to correlate the Satcon inverter's output with what was being seen on the logged data especially because of the unpredictability of the STG lab loads. One thing that we noticed in the STG lab loads was that there was very little reactive load. Therefore by injecting a few kVar as well as kW we could easily identify when the Satcon inverter was and was not injecting power.

4.2.2.2 Battery Energy Conversion Efficiency

In order to measure the energy conversion efficiency of our BESS, we would have to compare the total amount of energy that would be stored during a full charge cycle and how much energy that would be injected into the grid during its full discharge cycle. Ideally these values would be the same but due to losses within the conversion process, energy would be lost. There are two tests BC Hydro requested us to do with regards to energy conversion efficiency. They wanted us to complete the charge and discharge cycle in two ways, one being at a fixed 25 kW charge and discharge rate and the other being a varying charge rate that mimics the charge rate while using a solar panel and a fixed 25 kW discharge rate.

The equipment needed to complete this test includes a PowerPad III Model 8333 power quality meter and a laptop.

The PowerPad III Model 8333 power quality meter would be used because had the ability to record the generated and consumed energy, sampled at a rate of once per five seconds for up to one month and had was rated for 1 kV_{RMS} and 10 kA_{RMS}. These features made it perfect for our battery energy conversion efficiency testing.

To record the amount of energy consumed and generated we would install the PowerPad III power quality meter at the input to the Satcon inverter. The measurement mode used to capture this energy data would be the trend mode on the PowerPad III. The data can then be downloaded to the laptop once the testing is completed.

The fixed charge and discharge rate test would be conducted as follows:

After the meter is installed, the trend monitoring on the PowerPad III would begin once a 100% state of charge event at a charge rate limited at 25 kW is scheduled using the Greensmith control portal. Once the battery is 100% charged, the battery will be depleted using a 0% state of charge event at a discharge rate limited at 25 kW, again using the Greensmith control portal. After the charge and discharge cycles are completed, the trend monitoring on the PowerPad III would be stopped. The logged data stored on the PowerPad III would be then extracted via USB onto a laptop. This logged data can then be used to determine the difference between the charged and discharged energy.

The varying charge rate and fixed discharge rate test would be conducted as follows:

The charging will start at 6AM and complete at 6PM. The charging rate start at 1 kW and increases by a 1 kW every three hours till 2PM. After 2PM the charging rate will decrease every three hours by 1 kW till 6PM. After 6PM the battery will then be discharged at a rate limited at 25 kW. The PowerPad III will start logging at 6AM and will stop logging when the battery discharge is completed. The logged data stored on the PowerPad III would be then extracted via USB onto a laptop. This logged data can then be used to determine the difference between the charged and discharged energy.

This charging schedule would be used to mimic the charging rate of the sun when using a solar panel system [29]. The output of a solar panel system is dependent on the time of day. The output of a solar panel system starts off low when the sun first rises, but as the sun moves throughout the day the output increases. The output rate peaks at early noon and begins to decreases as the sun continues to move. The peak output for a typical solar panel system is 3 kWh.

4.2.2.3 Steam Generator Islanding and Transient

One elements of the BESS's operation that was of the most interest to everyone involved with this project was how the apparent step power output of the Satcon inverter affected the power quality on the distribution line. The purpose of this test would be to inspect what sort of transients the Satcon inverter would generate on the BC Hydro feeder line when the inverter injects power. To get a sense of how these transients would affect a more realistic distributed generation system, this test will include islanding the Satcon inverter with the steam turbine. During this test, the only loads available to the turbine would be the load bank installed on top of the STG lab and the Satcon inverter itself.

The equipment needed to complete this test includes a PowerPad III Model 8333 power quality meter, a RIGOL DS1054Z digital scope with isolation probes and a laptop.

The PowerPad III Model 8333 power quality meter would be used to record the V_{RMS} and A_{RMS} during the tests because it is rated for 1 kV_{RMS} and 10 kA_{RMS}. These features would allow us to get a snapshot of conditions that were present on the distribution line when a transient would occur.

To get a more detailed look at the transient generated by the Satcon inverter, we would use the RIGOL DS1054Z. The RIGOL DS1054Z samples at a rate of 1 GHz samples per second. Using the single waveform mode and trigger level we could detect the transients on the voltage and current with a lot higher time resolution than the PowerPad III.

Both the PowerPad III power meter and the RIGOL scope will be connected to the Satcon inverter side of CB1, located in the panel in SE8-215. These will be installed, prior to testing, by a certified technician. The measurement mode on the PowerPad III that would be setup using the trend mode of the meter during the tests. The RIGOL scope would be set up using the single waveform capture and set the trigger level slightly above the nominal voltage level.

The steam generator islanding and transient test will be composed of performing twelve two minute tests. The procedure for conducting these test would include turning on the steam generator and waiting for it to reach 1800 rpm. Then we would apply the external loads required for each test to the system. Then for each test we would start recording the trend data on the PowerPad III and setup the RIGOL scope for single waveform capture. We would then use the Greensmith control portal to schedule the constant power event required for the test. Once the event is completed, the transient waveform detected by the scope would be saved onto a USB drive and the PowerPad III trend would be stopped and downloaded onto a laptop. For the next of the following tests we would perform the above procedure to capture transient information.

The twelve test mentioned above are as follows:

1. No external load, steam generator used to charge Satcon inverter at + 5 kW.
2. No external load, steam generator used to charge Satcon inverter at + 20 kW.
3. 20 kW external load, Satcon inverter outputs - 5 kW.
4. 20 kW external load, Satcon inverter outputs - 19 kW.
5. 20 kW external load, Satcon inverter outputs + 5 kVar.
6. 20 kW external load, Satcon inverter outputs + 15 kVar.
7. 20 kW external load, Satcon inverter outputs -5 kVar.
8. 20 kW external load, Satcon inverter outputs -15 kVar.
9. 20 kW external load, Satcon inverter output 5 kVar and - 5 kW.
10. 20 kW external load, Satcon inverter output -5 kVar and - 5 kW.
11. 20 kW external load, Satcon inverter output +14.25 kVar and - 19 kW.
12. 20 kW external load, Satcon inverter output – 14.25 kVar and - 19 kW.

The data gathered from the tests stated above would then be analyzed until a conclusion was formed.

4.3 Results, Testing and Verification

Our project is comprised of two types of testing. The first is the testing of what we designed and built. This includes the controller utilizing the PLC, which was to command the Satcon inverter in real time. Because the controller was not able to the command the Satcon inverter in real time, the controller was relegated to interact with the MATLAB model only. The second test is comprised of the testing which was requested by BC Hydro.

4.3.1 Controller Testing

The controller was implemented inside of a MATLAB model, and as such, the values it was commanded to output were easily verifiable by simply observing if the outputs matched what was requested. This verification was accomplished with two main meter blocks within the Simulink / MATLAB model. These are the meter block on the output of the inverter and another meter block connected to the load. Inside the MATLAB model, the load was put into manual mode which meant the user can enter, via a slider control, how much reactive or real power the load would draw. By manipulating the amount of real and reactive power requested by the load, we can determine what the inverter should be outputting, depending on the operating mode selected. What follows are the three operating modes.

4.3.1.1 Peak Shaving Mode

In peak shaving mode, the controller commands the modeled inverter to output real power to match that which is requested by the load, up to point of the Satcon inverters capacity. This capacity is 25 KVA, and since in peak shaving mode the modelled inverter only outputs real power, this limit is 25 kW. This means if the load is set to a value greater than 25 kW, the modelled inverter will only put out a maximum of 25 kW.

The verification for peak shaving mode is simply observing that the meter connected to the modelled inverter matches the meter connected to the load, up to a maximum load input of 25 kW. This was done and it was verified that the peak shaving mode was working correctly.

4.3.1.2 Voltage Regulation

The voltage that is regulated is the voltage at the load end of the distribution line, which is also the same as the load’s voltage. In voltage regulation mode, the controller commands the modelled inverter to output or absorb only real power in accordance to an algorithm which tries to reach a voltage set point. This set point is programmed into the controller HMI. The amount of real power the modelled inverter is commanded to output or absorb, by the algorithm, depends on the line loss and the amount of the load present. Once again, the maximum the inverter can produce is 25 kVA. If the current voltage is above the set point, the controller algorithm commands the modelled inverter to absorb real power, effectively charging the batteries. This causes more current to flow through the line which causes the voltage to sag. If the current voltage is below the set point, the controller algorithm commands the modelled inverter to output real power, effectively shouldering some of the load which is fed from BC Hydro, reducing the current flowing through the line. This reduces the voltage sag and increases the voltage.

The voltage regulation test can be verified by first turning off the voltage regulation feature and confirming that the load voltage is some value above or below the voltage set point. This can be viewed with the voltage meter connected to the load. Next, turn on the voltage regulation feature and verify that the load voltage has been regulated to the voltage set point. Remember that the maximum real power the modelled inverter can output or absorb is limited to 25 kW. If the voltage regulation set point is not met, this is the problem.

An alternative way to verify the voltage regulation mode, is under the current conditions, calculate the amount of power that needs to be outputted or absorbed to raise or lower the current voltage to hit the voltage set point. Monitor the meter on the output of the modelled inverter and verify that this power value matches the calculated value.

Both of these test were tried and it was verified that the voltage regulation mode was working correctly.

4.3.1.3 PF (Power Factor) Correcting Mode

The power factor correction mode is identical to the peak shaving mode, except instead of absorbing or outputting real power, the modelled inverter outputs and absorbs reactive power, opposite to that of the load. Once again, the maximum the inverter can produce is 25 kVA.

The verification for power factor correction mode is simply observing that the meter connected to the modelled inverter matches the meter connected to the load, up to a maximum load input of 25 kVar. Keep in mind that this value will be of opposite sign. This was done and it was verified that the power factor correction mode was working correctly.

4.3.2 BC Hydro Testing

Due to a passive hardware failure within the Samsung battery energy management system, our team was unable to complete all the designed BC Hydro testing. Therefore in this section of the report we will discuss the results of the tests we were able to complete before the hardware failure occurred. The tests that we were able to complete included the peak shaving tests and the constant charge and discharge battery energy conversion efficiency test. We were unable to conduct the variable charge rate and constant discharge rate battery energy conversion efficiency test and the steam turbine islanding and transient test.

Please refer to the document, ‘*VVO_Test Plan_for_BC_Hydro_Steam_Turbine_Test_20150501v1.0*’ for detailed test plan procedures.

4.3.2.1 Peak Shaving Test

Below are the results from our peak shaving test. In Figure 12 we can see the effect of the inverters power injection.

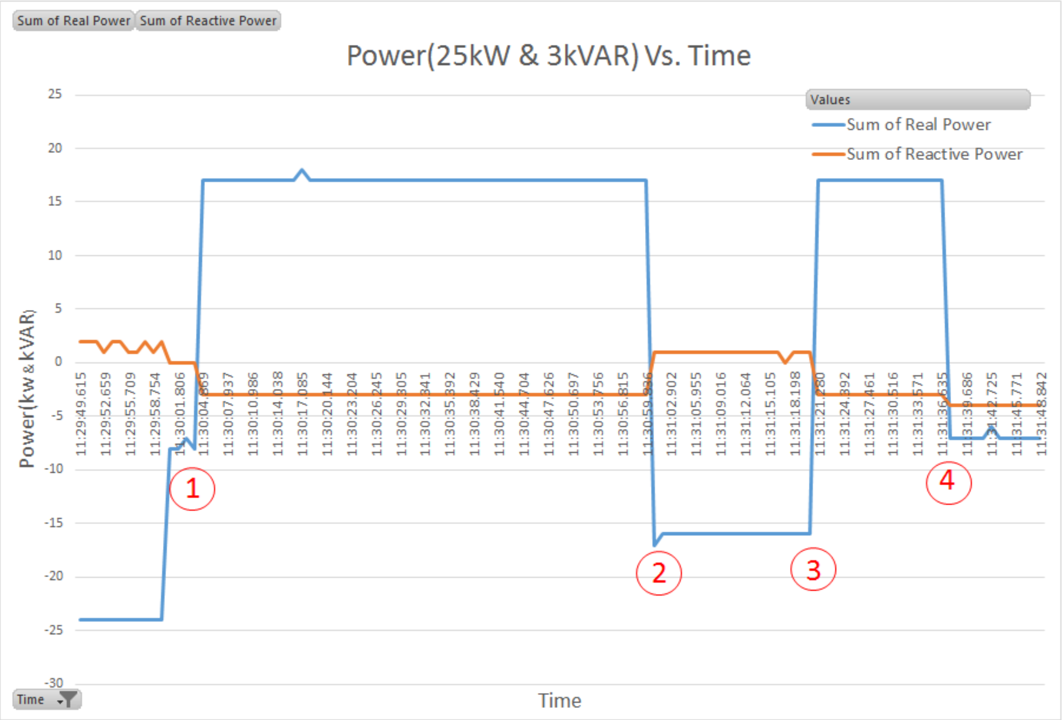

Figure 12- Peak shaving test results

At point 1 on the graph we can see the inverter comes online and injects 25 kW and 3 kVar into the distribution system. Then in between point 2 and 3 on the graph a 34 kW and 4 kVar STG building load comes online and offline. At point 4 on the graph the inverter finishes injecting power into the distribution system.

The effect of peak shaving can be seen between points 2 and 3 in Figure 12. In between point 2 and 3 BC Hydro only supplies 17 kW instead of the full 34 kW that the building loads require.

4.3.2.2 Battery Energy Conversion Efficiency

Below are the results of our constant charge and discharge rate battery energy conversion efficiency test. Figure 13 shows the charge level as we charged and discharge the battery.

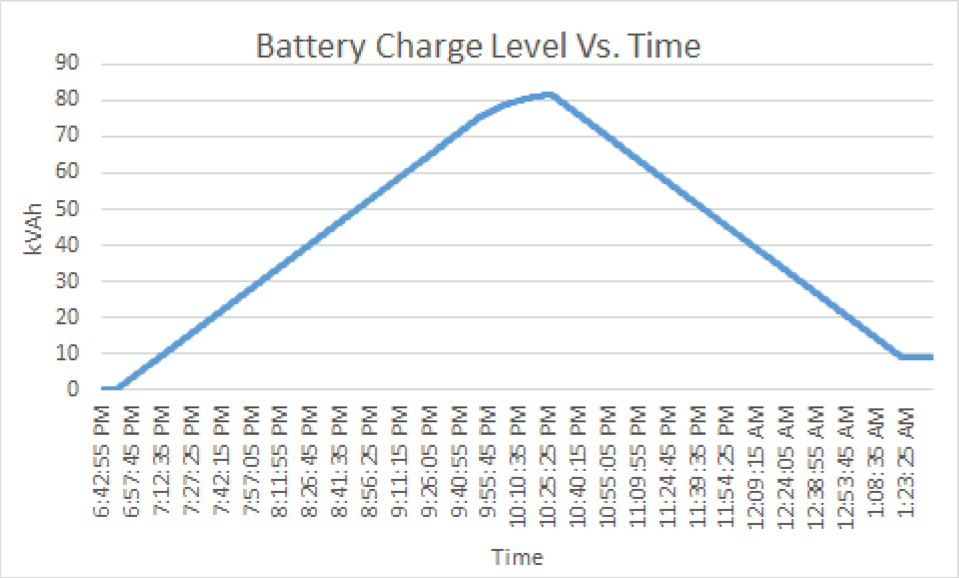

Figure 13- Battery energy conversion efficiency test

The full test took roughly six hours to complete. As we can see from Figure 13 the amount of apparent power that was stored in the battery during the full charge cycle was 81.4kVAh. The amount of apparent power that was injected during our full discharge cycle was 72.6 kVAh. Thus the energy conversion efficiency based on a single battery cycle is 89.2%.

5 Discussion and Directions for Future Work

In this section we will interpret the results of the project and make recommendations for follow-up projects and future work. We will relate them to our project's original objectives and provide a critical analysis of how they might play out in future iterations of this project.

5.1 Interpretation of results

The results of this project are slightly different than when we originally set out, due to two distinct circumstances that were beyond our control.

First, we were originally informed that the Greensmith software package controlling the BESS on the BCIT Burnaby campus was capable of outputting both real and reactive power in real time. Since the BESS was not a piece of equipment that was frequently used, and no one had any information to the contrary, this information was taken at face value. After beginning to use the BESS, it was soon realized that the BESS was not capable of outputting real or reactive power in real time. The only way we knew to make this happen was to acquire Modbus register addresses for the Satcon inverter and circumvent Greensmith's web portal scheduler. Greensmith actually provided a means for doing this in the *Operations/Dispatch/User Input* tab. They did not, however, want to provide support for this feature despite several attempts at reaching out to them. This would eventually affect how we implemented the controller design.

The second area beyond our control was a hardware malfunction in the middle of our BC Hydro testing schedule. Specifically, this was a failure of one of Samsung's battery management cards. This eliminated the steam generator test and cut short the battery energy conversion efficiency tests.

5.1.1 Recap of our Project Objectives

The stated objectives of our project are the following:

1. Create a MATLAB model of the BESS on the BCIT, Burnaby campus. This model was to include the SATCON inverter, the line loss between the STG lab, SE8-215, and substation F on the BCIT Burnaby campus, and the STG lab building load. Refer to the Appendix A for the single line diagram.
2. Create a controller using a PLC to control the Satcon inverter in real time. This controller would have three areas of function:
   a. Peak shaving
   b. Power factor correction
   c. Voltage regulation
3. Provide a testing platform for BC Hydro and run the following tests:
   a. Peak shaving test using the STG lab building as our load
   b. A battery energy conversion efficiency test to determine the energy efficiency of the BESS
   c. A test which islands the BESS with the steam turbine generator in SE8-215 to see the affects a DG system has on the grid.

5.1.2 Analysis of Results

Below we will discuss the results of our completed BC Hydro testing. Due to a passive hardware failure, we were only able to complete the peak shaving test and one complete cycle of the constant charge and discharge rate battery energy conversion efficiency test.

5.1.2.1 Peak Shaving

The results stated in section 4.3.2.1 suggest that the inverter is successfully able to peak shave and offset some of the STG lab load to decrease the amount of load BC Hydro has to support. This could potentially save BCIT money during periods of high energy demand. Also this would allow BC Hydro to decrease their maximum load during high energy demand periods and reduce their generation costs.

5.1.2.2 Battery Energy Conversion Efficiency

From the test results in section 4.3.2.2 it can be seen that the efficiency determined by our single full cycle constant charge and discharge rate battery energy conversion efficiency test was 89.2%. This mean that 10.8% of the energy is lost through the conversion process. The losses can be attributed to the heat generation that occurs through the process of converting and storing the energy.

5.1.3 How Results Apply to Objectives

In performing the above tests we have partially completed the tests requested by BC Hydro. Even though we have gained insight into our system, completing the remaining tests would allow us to further explore the relationship between the Satcon inverter operation and the BC Hydro supply.

5.2 Direction of future work

This section will include a discussion of outstanding development and what steps could take place to add value to the work completed thus far.

5.2.1 Outstanding Development

This project has two obvious outstanding developments items or tasks that will need to be completed.

First, we settled on designing the controller to command the modelled inverter because we did not have the means to access the real inverter in real time. Work needs to continue fostering a relationship with Greensmith so that we can obtain these Modbus register addresses. Once these addresses are acquired, work can continue with the implementation of the PLC program to command the Satcon inverter in real time.

Second, once the replacement battery management boards from Samsung are received, the remaining testing for BC Hydro can continue. This includes the variable charging and constant discharging of the battery energy conversion efficiency test, and the steam generator tests.

5.2.2 Other Possible Applications

Because of the physical installation of the BESS and the connection to the STG lab, other possible applications will have to be accommodate these features. This would include, but would not necessarily be limited to, various forms of testing. These could include:

- Testing of various control algorithms
- Testing of various new energy generation systems including:
    - solar voltaic arrays
    - mechanical flywheel
    - wind turbine
    - bio mass
- Testing of new battery technologies
- Investigate voltage regulation using reactive power instead of real power. It was noticed that when discharging the batteries with only reactive power, the batteries took a lot longer to discharge.
- Design of a whole new BESS system, eliminating Greensmith altogether

5.2.3 Recommendations and Next Steps

As mentioned in section 5.2.1, the next logical steps would be to repair the inverter and complete the required testing, and continue with the effort to implement the real-time controller of the Satcon inverter. This last step can be done one of two ways:

- Acquire real-time control of the Satcon inverter through Greensmith's software.
- Redesign the BESS controlling from scratch thereby eliminating Greensmith's involvement.

This last idea could be structured into many future capstone projects for both the Electrical Engineering program and BCIT's Computer Science program.

6 Conclusions

This project proposed to improve power quality through the implementation of VVO using a four quadrant inverter located on the BCIT Burnaby campus. The areas or power quality addressed were power factor correction and voltage regulation. The inverter was to be controlled using a PLC which would command the inverter in real time. However, the access necessary to control the inverter in real time was not obtainable in the time we had to complete this project. This resulted us in designing the controller for the modelled inverter instead. This modelled inverter was created in MATLAB at the beginning of the project to provide a safe environment to test the controller. Within this modelled environment, the controller was shown to perform both power quality tests within expectations.

Distributed generation (DG) systems also make use of four quadrant inverters, therefore our project was well suited to performing testing in this area for BC Hydro. The three areas of testing deemed important to BC Hydro were peak shaving, battery energy conversion efficiency and islanding a DG system with BCIT's steam generator to see how these systems affect the voltage stability of the grid. The peak shaving test showed the BESS to be well equipped to perform this function. The battery energy conversion efficiency test showed the BESS to be 89.2% efficient for the single test we were able to do. Islanding the BESS with the steam turbine generator, to investigate the effects of DG on the grid, could not be performed due to a hardware issue that developed with the battery management system of the Satcon inverter.

The next steps for this project would be to gain access to the real time control of the inverter and finish the controller so it can command the Satcon inverter in real time. Once the battery management system of the BESS is repaired, the remainder of the testing can be completed.

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Appendix A Single Line Diagram of STG Power Network

Below in Figure 14 is a single line diagram of the STG Power Network. The single line diagram includes the BC Hydro supply at Substation 'F', the Turbine Lab Motor Control Centre, the LOAD Bank, the Inverter & Battery Bank, the Turbine Generator, corresponding meters and circuit breakers.

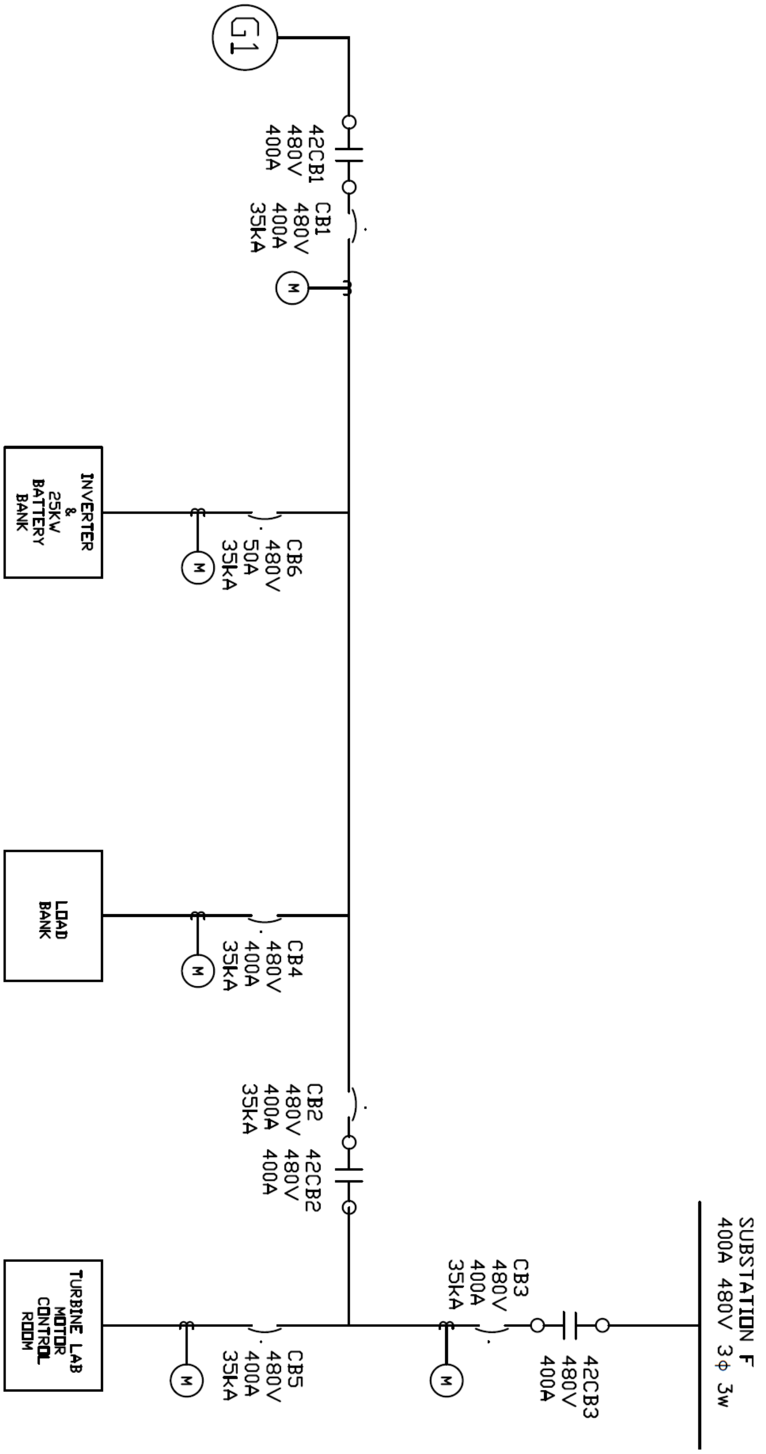


Figure 14 - Single Line Diagram of Power Distribution in SE8-215

Appendix B MATLAB Model

Below in Figure 15 is a screenshot of our MATLAB model within Simulink. The Screenshot include the different modules of our model. These modules include: the BC Hydro supply, the Satcon inverter, the STG lab loads, and the ION 7330 power meters.

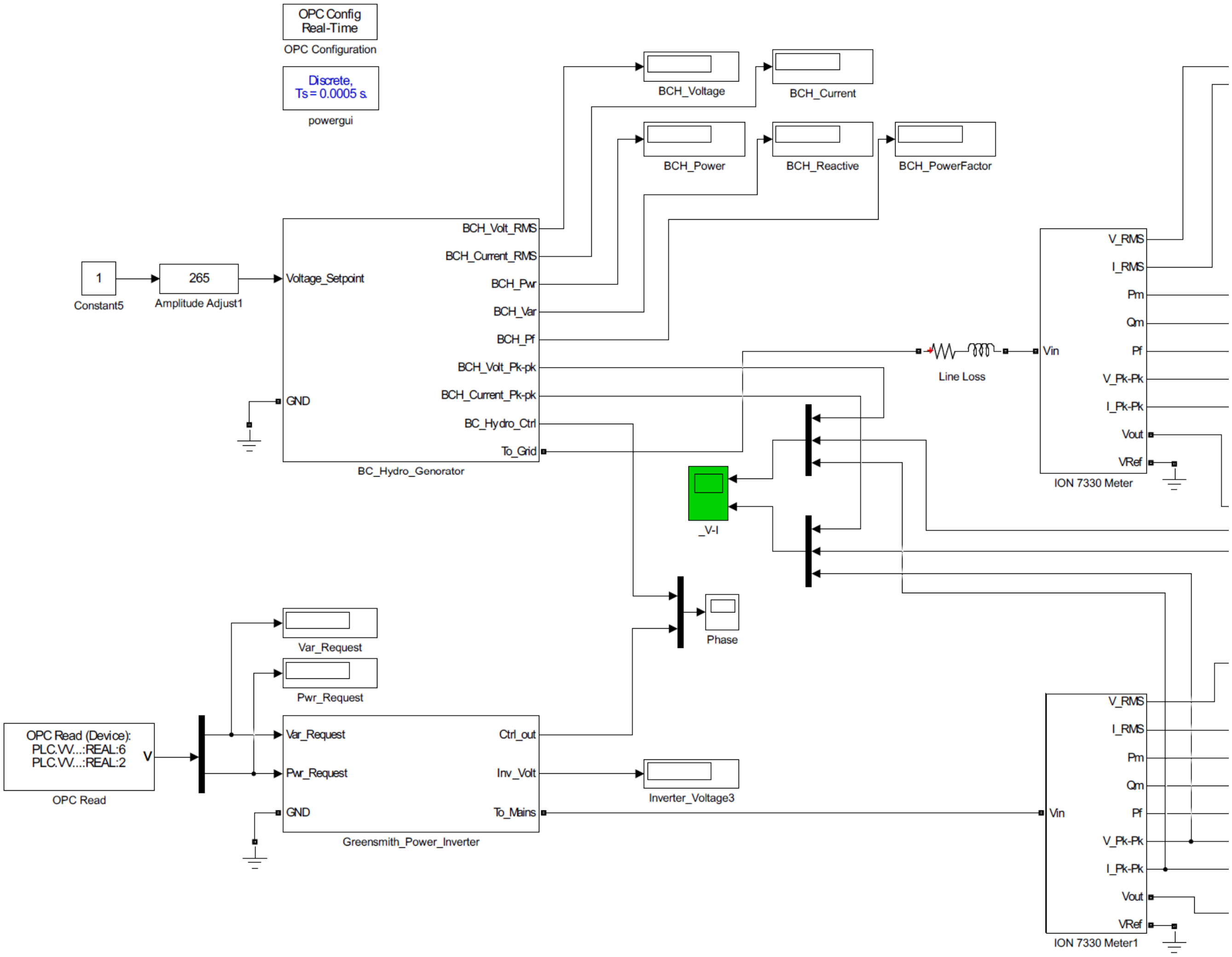
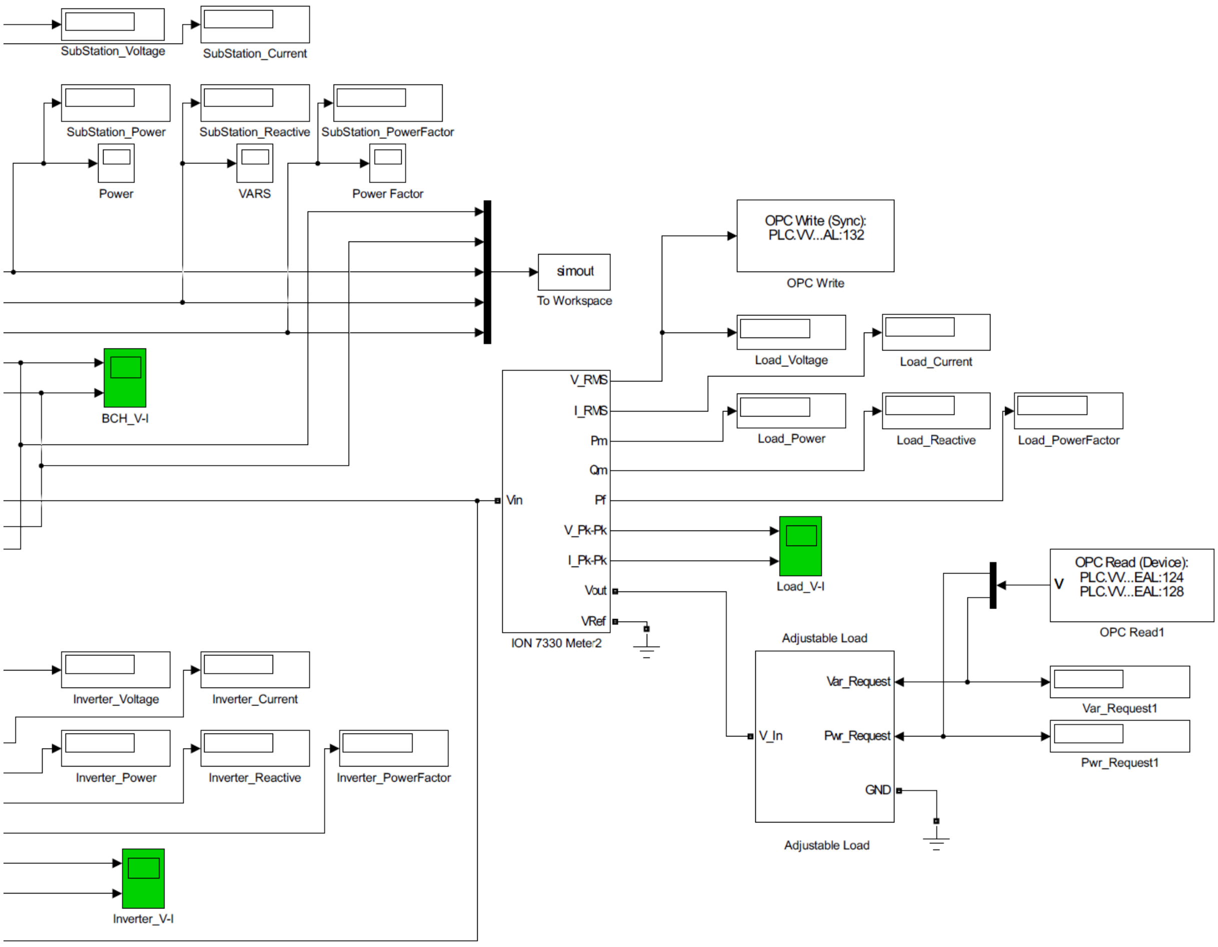


Figure 15 - MATLAB Model of STG Lab Grid (spans to page 37)


SubStation_Voltage
SubStation_Current
SubStation_Power
SubStation_Reactive
SubStation_PowerFactor
Power
VARS
Power Factor
simout
To Workspace
OPC Write (Sync):
PLC.VV...AL:132
OPC Write
Load_Voltage
Load_Current
Load_Power
Load_Reactive
Load_PowerFactor
BCH_V-I
V_RMS
I_RMS
Pm
Qm
Pf
V_Pk-Pk
I_Pk-Pk
Vout
VRef
Vin
ION 7330 Meter2
Load_V-I
OPC Read (Device):
PLC.VV...EAL:124
PLC.VV...EAL:128
V
OPC Read1
Adjustable Load
Var_Request
Pwr_Request
V_In
GND
Adjustable Load
Var_Request1
Pwr_Request1
Inverter_Voltage
Inverter_Current
Inverter_Power
Inverter_Reactive
Inverter_PowerFactor
Inverter_V-I

Appendix C MATLAB Model (Satcon Inverter Module)

Below in Figure 16 is a screenshot of our modeled Satcon inverter module within Simulink. The screenshot displays the details of the algorithm we used for the modeled Satcon inverter's operation.

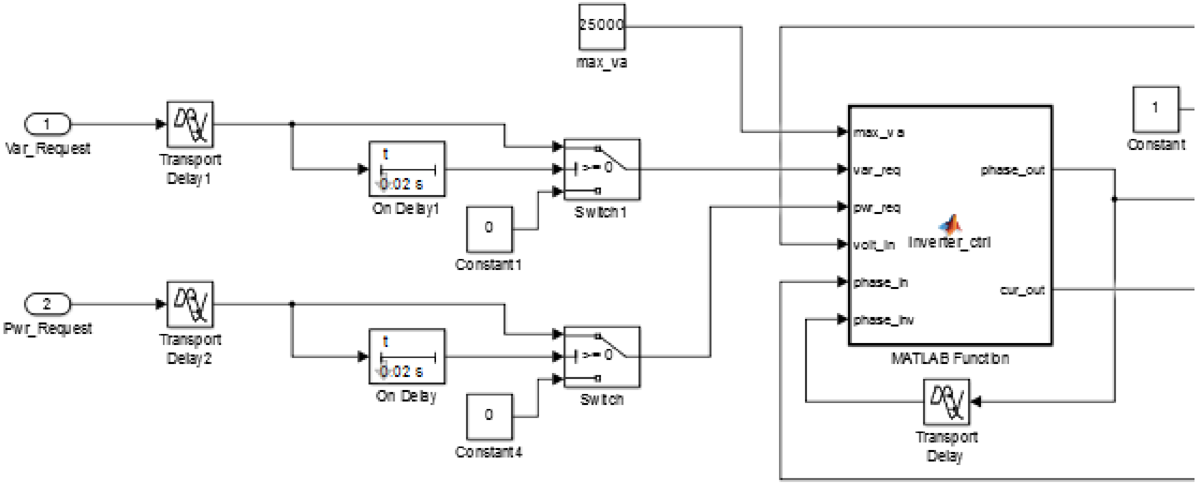
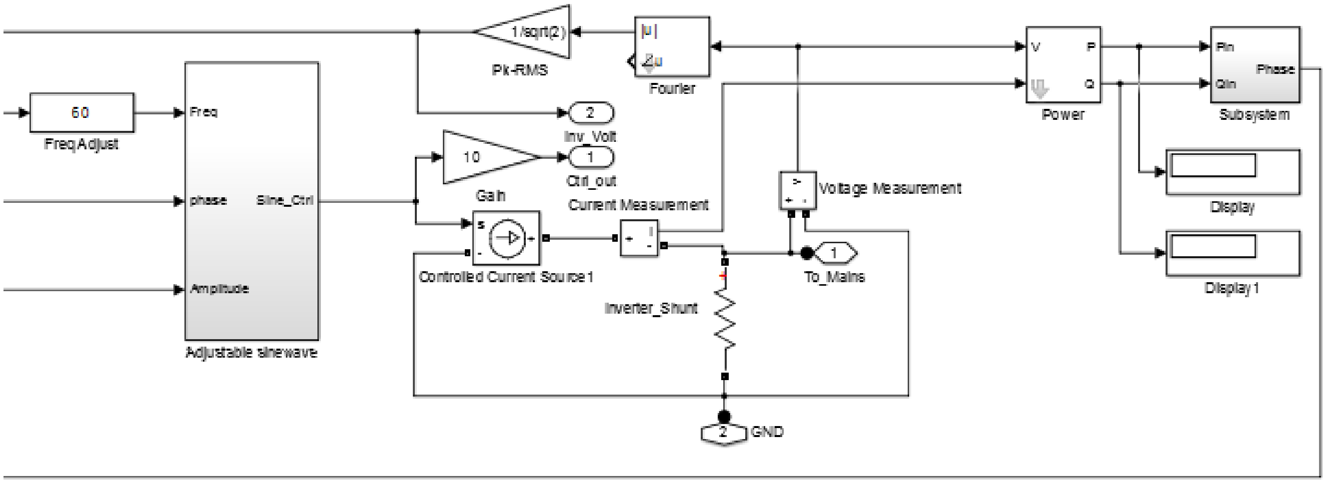


Figure 16 - MATLAB Model of the Internal Controls of the Satcon Inverter (spans to page 39)


1/sqrt(2)
Pk-RMS
|u|
∠u
Fourier
V
P
Q
Power
Pin
Qin
Phase
Subsystem
60
FreqAdjust
Freq
phase
Sine_Ctrl
Amplitude
Adjustable sinewave
2
Inv_Volt
10
Gain
1
Ctrl_out
Current Measurement
Voltage Measurement
Display
Display1
s
Controlled Current Source1
1
To_Mains
Inverter_Shunt
2
GND

Appendix D VVO Controller Connectivity Diagram

Below in Figure 17 is the connectivity diagram of our VVO controller. The diagram includes the connection details between our PLC, MATLAB model and the potential connections to the Saton inverter and ION 7330-2 meter.

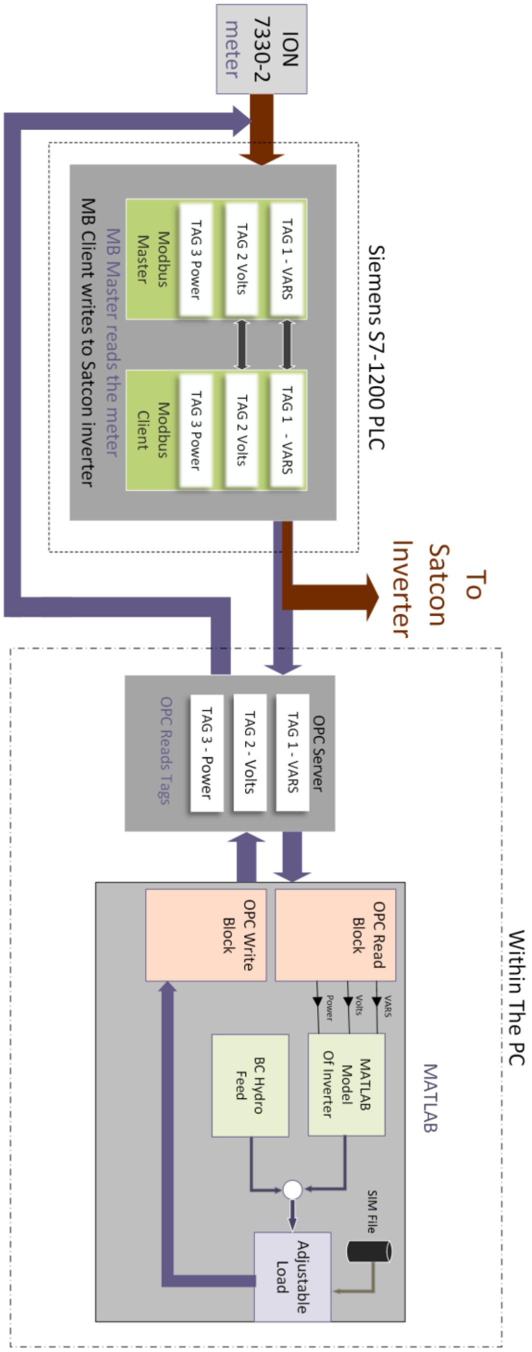


Figure 17 - Diagram Outlining the Control Interconnections of out PLC and MATLAB Model