University of Southern Queensland

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VAR Controller for STATCOM Solar Inverter

A dissertation submitted by

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In fulfillment of the requirements of

Courses ENG4111 and ENG4112 Research Project

Towards the degree of

Bachelor of Electrical and Electronics Engineering

Submitted: October, 2014

Abstract

In the past five years over 1.2 million PV installations were made in Australia which has had a detrimental effect on the overall power quality of the system. Utilities now provide a higher level of system harmonics as well as having to cope with unintentional DC current injection into the grid. At the same time, these PV installations have not helped the utilities at peak periods, or for localized loads such as starting of induction machines. Thus there is clearly a need for a more dynamic inverter system which can help improve system efficiency and maintain power quality standards.

In order to help improve the power quality of the grid, the existing STATCOM inverter would be adapted to monitor grid conditions with a smart energy meter and interfaced to a PLC to either bring voltage within limits or improve power factor to a desired level. The PLC will utilize both power factor information and voltage and current information from the smart energy meter to allocate an active power and a reactive power of either a capacitive or inductive reactive power in order to maintain power factor levels. Weak networks suffer from a range of problems depending on conditions. Typically when they are heavily loaded, they require additional capacitive reactive power to be injected into the grid. On SWER networks, due to the high X on R ratio they also require at peak times the injection of active power. When lightly loaded by comparison, they require the injection of reactive power in order to bring the voltage within limits due to the Ferranti Effect. In order to accommodate all of these functions, the power factor and the voltage conditions from the smart energy meter were read into the PLC where the decision was made as to what level of active, capacitive reactive or inductive reactive power was required to be injected into the grid. A set of SIMULINK models were developed to analyze a range of switching strategies in order to minimize injected harmonics and maximize STATCOM efficiency. The key outcome of this project was that the implementation of a PLC based system which provided active and reactive power support and was able to react to localized load changes rapidly. The broad application of this technology to existing PV systems will ultimately allow in system power quality and efficiency improvements throughout the state.

Keywords: Power Quality ,Bipolar switching, Unipolar Switching, Multimodal Switching, Power factor correction, VAR controller, Printed Circuit Boards, STATCOM inverter, Solar Inverter, Smart Energy Meter, UM100, UM72, PCB Profiles.

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Certification of Thesis

I certify that the experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own efforts, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

Akshay Jaishil Sahay

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Signed: ______________________

Dated: ______________________

Supervisor endorsement: ________________________

Dated: ____________________

Acknowledgment

I would like to take this opportunity to express my sincerest and deepest gratitude to the following people, without whom the completion of this research project would not have been possible.

1. My Supervisor, Dr. Leslie Bowtell for all his patience, support and the skillful and tactful guidance during the course of my research project.

2. The University of Southern Queensland Technical staff, in particular Mr. Graham Holmes, Mr. Brett Richards and Mr. Terry Byrne for their help in providing resources.

3. The staff at Futurlec Australia Pty Ltd, in particular their sales manager Alan, for all his help in providing the components and the prototyping of a printed circuit board (PCB) at very affordable prices and in a timely manner.

4. The staff at Bayarea Circuits for printing my PCB boards at student rates with a very fast turnaround time.

5. The staff at BEC Manufacturing Australia for their help with the production of my PCB boards at a very short notice.

6. Mr. Peter Taylor of PT Automations Gold Coast for his guidance and advice with regards to the Energy Meter section of my project.

7. I would also like to acknowledge my family, especially my parents and my sibling, for their continuous emotional, financial support and also for providing the continuous motivation through the course of this research project.

Last but not least, I would like to acknowledge everyone that has contributed to this project in general.

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List of Symbols

D_{A-}	Inverter H-Bridge freewheeling diode
D_{A+}	Inverter H-Bridge freewheeling diode
D_{B-}	Inverter H-Bridge freewheeling diode
D_{B+}	Inverter H-Bridge freewheeling diode
i_c	DC offset correction current
i_{comp}	component of i_{ref} to compensate for switching delay
i_i	inverter output current
i_o	inherent DC offset current of the inverter output
i_p	output current from PV panels
i_{pr}	active power component of current reference
i_{qr}	reactive power component of current reference
i_{ref}	current reference to hysteretic current controller
i_s	Mains current
k_c	DC bus voltage sensor constant
k_e	proportional gain of analogue PI controller
k_h	Hall effect current sensor constant
k_m	coupling factor of 1:1 inductor pair
k_p	Hall effect current sensor on DC side
$k_z v_z$	$=k_{d1}$ or k_{d2} = constant integration rate of the integral element of the digital DC offset PI controller
T_{A-}	Inverter H-Bridge IGBT
T_{A+}	Inverter H-Bridge IGBT

T_{B-}	Inverter H-Bridge IGBT
T_{B+}	Inverter H-Bridge IGBT
T_{bi}	Mixed-mode current controller bipolar operation time
t_{df}	switching delay on current fall
t_{dr}	switching delay on current rise
v	Inverter output voltage
v_1	output of first stage of dual stage RC DC offset sensor
v_c	PV array bus voltage
v_f	input voltage across dual stage RC DC offset sensor
v_i	integrator output voltage in analogue PI controller
v_L	AC component of v_f
v_m	digitally filtered PV array bus voltage for MPPT
v_o	output voltage of dual stage RC DC offset sensor
v_{ref}	reference DC bus voltage
v_s	Mains (grid) supply AC voltage
v_z	output voltage of digital filter in digital DC offset controller
τ_d	time constant of first order digital filter used in the digital DC offset sensor
τ_f	time constant of each nominally identical stage of the dual RC DC offset sensor
τ_i	analogue PI controller integration time constant
τ_m	time constant of the DC bus voltage sensor for maximum power tracker
τ_p	L/R ratio of each inductor making up the RLLC DC offset sensor

List of Acronyms

AC	Alternating Current
DC	Direct Current
EMC	Electromagnetic Compatibility
FFT	Fast Fourier Transform
Hz	Hertz
IGBT	Insulated Gate Bipolar Transistor
MPPT	Maximum Power Point Tracking
PLC	Programmable Logic Controller
PV	Photo-Voltaic
PWM	Pulse Width Modulation
RFI	Radio Frequency Interference
RLLC	DC offset sensor based on 1:1 coupled inductor
SCADA	Supervisory control and data acquisition
STATCOM	Static Synchronous Compensator
THD	Total Harmonic Distortion
UPS	Uninterruptable Power Supply
VAR	Reactive Power
VSCC	Voltage sourced current controlled inverter
VSVC	Voltage sourced voltage controlled inverter

Chapter 1:

INTRODUCTION

1.1 Background and Justification

Due to the continuous increase in demand for electrical energy worldwide and the rapid depletion of fossil fuels, the need for efficient renewable energy sources has become paramount (Suganthi & Samuel 2012). Generation of electrical energy using photovoltaic (PV) and windmill systems in conjunction with static synchronous compensator (STATCOM) inverter is increasing rapidly worldwide. The generation of electricity using photovoltaic (PV) and windmill system in conjunction with static synchronous compensator inverters form Microgrids. It also gives the energy providing utilities the flexibility of sharing the electrical load between various Microgrids to help improve the power quality on the main electrical grid (Fathi & Hassan 2013).

Figure 1.1 shows the most common configurations used with STATCOM inverters. However, the inverters are not limited to this configuration and can either be connected directly to the generation source or through the use of battery banks. A grid connected photovoltaic (PV) system usually has a battery bank connected to the STATCOM inverter. The photovoltaic panels convert the light energy from the sun into direct current (DC) which is stored in the battery banks. A battery bank is used to store the electrical energy for when the PV panels are not generating the energy. Since the electrical grids can only accommodate alternating current (AC), the DC current from the battery banks has to be converted into AC, in order for it to be used to supply to the electrical network. The inverter works as a DC to AC converter where it converts the DC current from the battery banks into an AC current of 50Hz which is then injected into the electrical network.

The second configuration shown in Figure 1.1 are for small scale windmills. However, large windmills can come as standalone generators which can inject electricity directly into the grid. The windmills generates kinetic energy when the wind blows and causes the turbines to move, which in turn generates alternating current. This alternating current is then converted into direct current through a charging circuit which is connected to a battery bank. The battery bank is an integral part of a small scale windmill setup as it stores the electricity for when the wind is not blowing. The battery bank is then connected to a STATCOM inverter which converts the DC back into alternating current of 50Hz and injects it into the electrical network (US Department of Energy 2014).

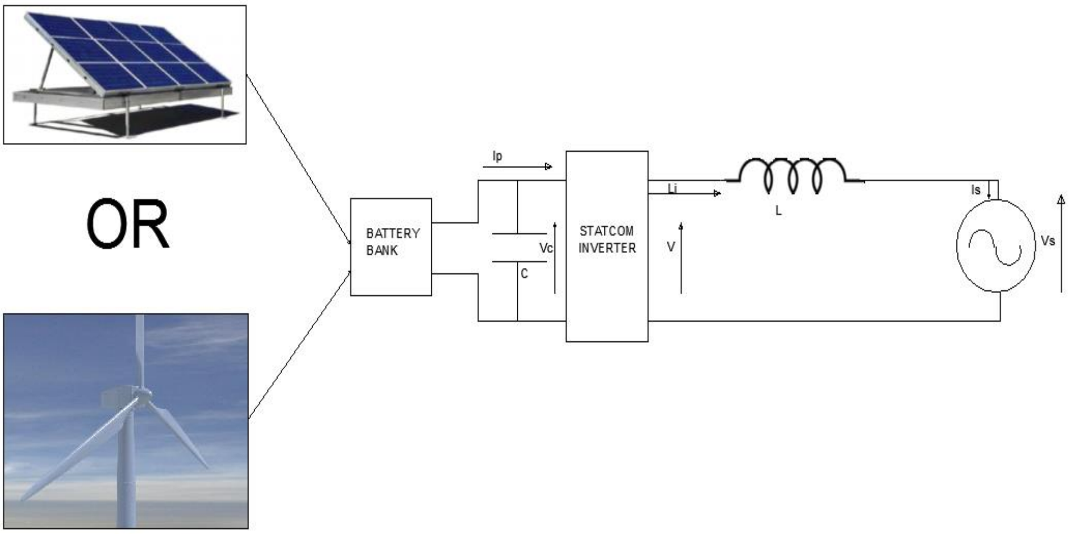


Figure 1. 1: Essential Components of a Grid-Connected STATCOM Inverter

The optimal quality of alternating current that could be injected into an electrical network would be a purely sinusoidal alternating current. However this is not possible with even the highest quality or the most expensive inverters available on the market due to electronic limitations. Electricity utility companies specify limits on the direct current (DC) of the inverter output and the lower and higher harmonic contents of the inverter. This helps limit the distortion of the alternating current (AC) in the electrical network and also prevents damage to the electrical network devices. Harmonic currents causes electrical network equipment to generate heat and hence minimizes the lifespan of these devices (Wodrich 2007). The lower level harmonics comprises of current frequencies between the standard 50Hz and the 1 KHz frequency range (Wodrich 2007), whereas the higher level harmonics comprise of switching frequencies from inside the inverter. The electromagnetic interference (EMI) caused by the rapid switching inside the inverter also has to be limited due to the effect they have on other electronic devices (Kaur, Kakar & Mandal 2011).

Apart from the AC current, amount of harmonics and electromagnetic interference which are injected into the electrical network, there are other factors that need to be considered. These factors include power factor correction, the efficiency of the inverter and the cost.

1.2 Development of the Project Topic

This research and implementation project was made available by Dr. Leslie Bowtell, lecturer for Electrical and Power Engineering at the University of Southern Queensland. Dr. Bowtell had initially started the research and implementation of this project during his PHD course and was able to implement an efficient bread board version of a four quadrant static synchronous compensator (STATCOM) inverter. During his PHD, Dr. Bowtell was constrained by time and was unable to implement a power factor correction unit and was unable to convert the inverter into a printed circuit board (PCB) form. The current bread board version of the STATCOM was lab tested and was found to be working as required, but without any power factor correction. It is because of this, the need for the project arose.

1.3 Issues with the current design

The current version of the STATCOM inverter is breadboard based, therefore increasing the susceptibility of the electronic components to noise. There are also some safety concerns, due to exposure of high voltage live wires during the testing of the device. The device also does not have the ability to do power factor correction. Another problem associated with the STATCOM is that the wires used to connect the components to each other can be accidentally pulled out during the testing and probing process.

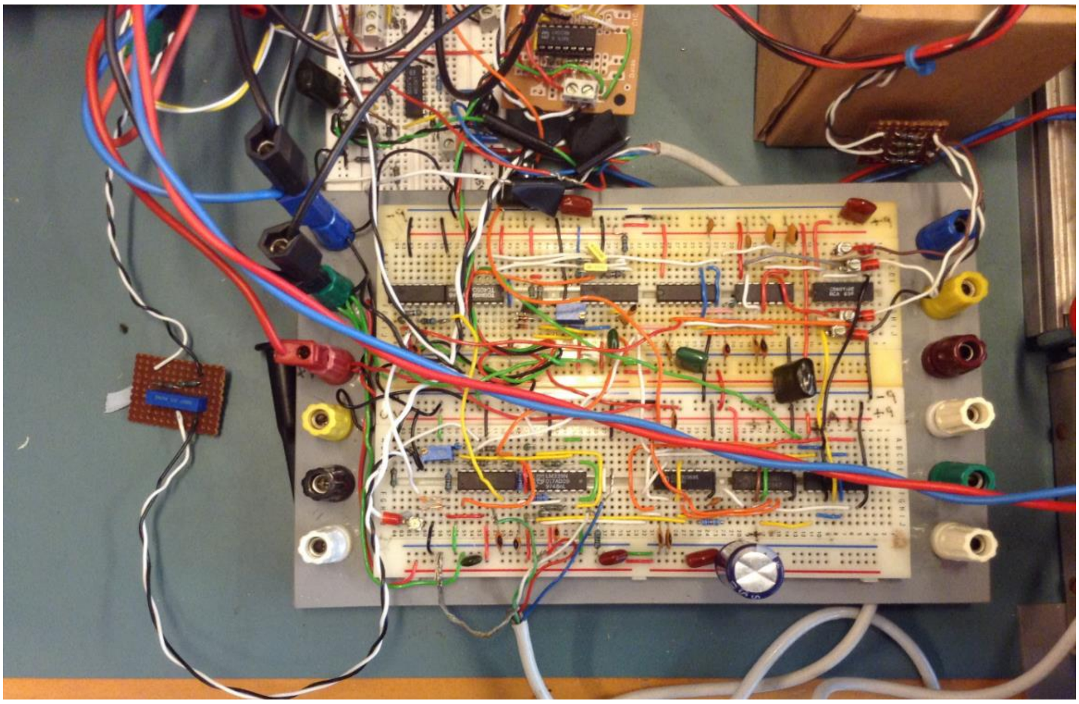


Figure 1. 2: Breadboard version of STATCOM inverter

In order to significantly increase the safety for testing and probing purposes, and to avoid any of the wires connecting the components from being disconnected, it is essential that that the STATCOM inverter be converted into a printed circuit board (PCB). The device has to be redesigned, in order to include a power factor correction module so that the STATCOM inverter can be used to help improve the power quality in the grid.

1.4 Problem Statement

The current STATCOM inverter was tested in the laboratory and was found to be highly efficient with all four quadrants working properly. However, the current design posses' safety risks due to high voltage wires being exposed. The STATCOM inverter also has capabilities to improve the power quality being provided which is not being utilized. This project will attempt to design a STATCOM inverter which eliminates the safety risks and will help improve the power quality by utilizing the power factor capabilities of the STATCOM inverter.

1.5 Project Aim

The aim of this project is to conduct research and implement a static synchronous compensator (STATCOM) inverter with a VAR controller which will enable power factor correction through the control of the reactive power of the inverter.

1.6 Project Objectives

The specific objectives of this project are:

1. Conduct a literature review in order to study and understand the current static synchronous compensator (STATCOM) inverter and their flaws. Using the literature review redesign a STATCOM inverter with greater efficiency and a VAR controller to improve the power factor using the reactive power of the inverter.
2. Using the information from the literature review design the printed circuit boards (PCB's) using the UM 72 profile standard and the UM 100 profile standards.
3. Implement the printed circuit boards and do a laboratory setup of the hardware for testing purposes.

4. Interface the static synchronous compensator (STATCOM) inverter with a programmable logic controller (PLC) for control purposes and for power factor correction purposes.
5. Interface an energy meter with the programmable logic controller (PLC) to read the power factor from the main grid and to help in the power factor correction.

1.7 Limitations

This project will mainly focus on the redesign and the implementation of the four quadrant STATCOM inverter and the implementation of the VAR controller to enable power factor correction. In order for the device to be in compliance with the Australian Standards and International Organization Standards further work will need to be done. Once it is compliant with the Australian Standards, the device has some commercial value and would be beneficial in helping improve the power quality in the grids. Some of the work that has to be done for the device to be compliant with the standards include:

- Design of a suitable equipment enclosure.
- The design of a secure communications protocol

The two things listed above is out of the scope of this project and can form the basis of yet another Thesis for future Research students.

1.8 Thesis Overview

Chapter one of this dissertation introduces the reader to the rationale of the project and outlines the project aims and objectives.

To achieve the objectives of this project, chapter 2 contains the literature review which helps justify some of the techniques and parts used in this project for the switching between the bipolar and the unipolar modes and for the power factor correction of the STATCOM. Chapter 3 of this dissertation outlines the methodology that was adopted for the completion of this project, while chapter 4 has an in depth discussion about the inverter switching and a detailed comparison of unipolar and bipolar switching operations. Chapter 4 also contains the methods and the results for the reactive power control (VAR controller) for the static synchronous compensator (STATCOM) inverter.

The final results and an in depth discussions of the shortcomings are also provided in this chapter.

Finally, chapter 5 gives a list of recommendations keeping in mind the results that were obtained from the testing process and also suggestions for the further development of the technology to make it more efficient and commercially viable.

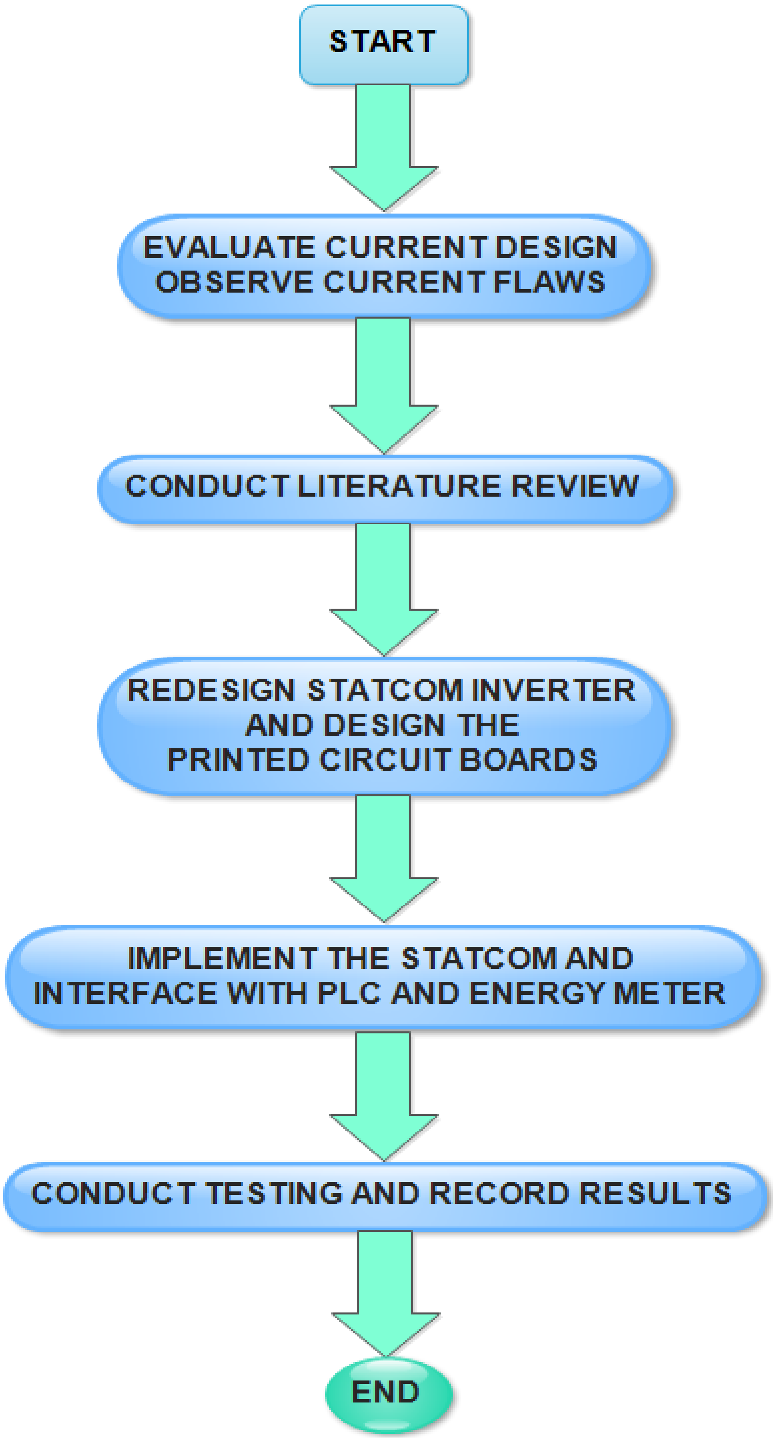


Figure 1. 3: Overview of Thesis

Chapter: 2

LITERATURE REVIEW

2.1 Overview

This chapter contains a summary of the reviewed literature that was required for the successful implementation of this project. It reviews inverter DC injection control techniques, power quality assurance measures, energy meter interfacing and VAR control systems. The theoretical knowledge from the literature review has been used for the practical implementation of the STATCOM inverter with a VAR controller.

2.2 DC Offset Control

The output current of the inverter which is part of a grid connected PV system will ideally be purely AC. However, in practice this contains small amounts of DC unless certain measures are taken. If excessive DC injection occurs in AC mains, predicaments such as corrosion in underground equipment (Masoud & Ledwich 1999), transformer permeation, transformer magnetizing current distortion (Ahfock & Hewitt 2006) and malfunction of protective equipment (Bradley & Crabtree 2005) occurs. Consequently, guidelines and standards have been set up to govern DC injection (Salas et al. May 2006) (Salas et al. 2008). The AS4777.2 (Austrailian Standards Commission 2005) standard limits DC injection to 5mA or 0.5% of rated output whichever one is greater in Australia.

The simplest way to eradicate DC injection from the AC network would be to use a grid frequency transformer between the inverter and the network. A number of commercial systems have adopted this method of DC injection eradication (Salas et al. May 2006) (Haeberlin, Ch.Liebi & Ch.Beutler 1997). The usage of grid frequency transformer has major disadvantages such as power losses, added mass and volume and most importantly, the added costs associated with it. There are some commercial systems that are transformer less or contain a small higher frequency transformer. The measurement of DC currents on the AC output of commercial systems is reported by Salas (Salas et al. May 2006). The measurements from Salas's report when compared against the limits that are imposed on DC currents in the Australian Standards AS4777.2 (Austrailian Standards Commission 2005) was found to be quite significant. Masoud (Masoud & Ledwich 1999), Sharma (Sharma 2005) and Armstrong (Armstrong et al. 2006) have proposed methods of alleviating the DC injection problem. Both Masoud (Masoud & Ledwich 1999) and

Sharma (Sharma 2005) have proposed the use of a feedback loop to eradicate the DC offset at the inverter output. The use of a voltage sensor at the inverter output with a differential amplifier and a low pass filter was proposed by Masoud (Masoud & Ledwich 1999) for the eradication of the DC offset. When using this method, any DC which may be detected at the output of the low pass filter is fed back to the controller which in turn operates the inverter in a way that reduces the DC offset. Although experimental results were not reported, a mathematical model was proposed for the control system and it is assumed that the inverter is voltage controlled.

An automatic adjustment scheme to vitiate the effect of the DC offset contributions from the Hall-effect current sensor in series with the DC input was proposed by Armstrong (Armstrong et al. 2006). In this scheme, an algorithm is used to ensure that the current measurement made during the freewheeling process is subtracted from all the measured current values. The major flaw in using Armstrong's (Armstrong et al. 2006) technique is that it is limited to unipolar switched inverters, since the controls of the unipolar switched inverters enables easy measurement of the freewheeling intervals. Using large electrolytic capacitors in series to block any DC component in the current was proposed by Blewitt (Blewitt et al. 2010). When using this method, an additional fast control loop and a slower capacitor offset voltage control loop is required. Blewitt's (Blewitt et al. 2010) results indicate that a maximum of 5mA of DC is injected into the grid. The use of a sensor at the output of the inverter to detect DC voltage offset and a DSP to affect control was proposed by Buticchi (Buticchi et al. 2009). The flaws with Buticchi's (Buticchi et al. 2009) technique was that there were additional losses and hence it did not meet the requirements of the Australian Standards AS4777.2 (Austrailian Standards Commission 2005).

A current controlled inverter is considered by Sharma (Sharma 2005). Sharma (Sharma 2005) uses a sensor connected to the output of the inverter to detect the presence of any DC offset voltage. This sensor consists of an RC circuit and a 1:1 signal transformer. The DC signal which has to be removed is of the order of a few millivolts in comparison to the magnitude of the total signal which is greater than two hundred volts and is almost equivalent to the grid voltage. The RC circuit which forms the sensor is connected in series to the secondary side of the 1:1 signal transformer, with the series combination then being connected to the output of the inverter. The primary side of the 1:1 signal transformer is connected across the AC power supply, allowing the assumption that the signal transformer is perfect and that the secondary voltage from the transformer opposes the AC supply voltage. If the above assumptions hold true, only DC appears in the capacitor of the RC branch, allowing it to be fed back into the controller and hence adjusts the inverter current reference so that the DC offset is eliminated. For the method stated by Sharma, no quantitative experimental results were presented but a statement was made that the DC offset controller was found to be operating correctly (Sharma 2005). This method was then later validated by a mathematical model presented by Ahfock and Bowtell with quantitative experimental results (Ahfock & Bowtell 2006). The mathematical model that was presented by Ahfock and Bowtell was experimentally validated with results indicating that the 1:1 transformer is only effective if the primary winding time constant is sufficiently low, meaning that a relatively large core with low winding resistance is required (Ahfock & Bowtell 2006). This also indicates that the DC offset sensor is relatively large and expensive.

For the purpose of this project, a simple two stage RC filter will be used as the DC offset sensor. The DC sensor in this case would be connected across the ripple filter inductor at the output of the inverter bridge as proposed by Bowtell (Bowtell & Ahfock 2010) instead of it being connected across the AC supply terminal as proposed by Masoud (Masoud & Ledwich 1999) and Sharma (Sharma 2005). The advantage of connecting the DC sensor across the inverter bridge as opposed to connecting it across the AC supply terminal is that the offset sensor may sense offset currents which may not be related to the inverter at all and maybe from other sources when it is connected to the AC supply terminal, whereas when it is connected at the inverter bridge, it is only the inverter offset that is being sensed. The design of the DC offset controller that is being investigates the interaction between the DC offset control loop and the other control loops within the system similar to what was proposed by Bowtell (Bowtell & Ahfock 2010).

The three control loops that will be used in this project are:

- The Current Control Loop
- The DC Bus Voltage Control Loop
- The Maximum Power Tracking Loop

The use of these control loops are greatly simplified if they are all isolated and independent to each other. There are various authors such as Raoufi (Raoufi 2004) and Varjasi (Varjasi, Balogh & Halasz 2006) that have assumed either implicitly or explicitly that the DC Bus Voltage Control Loops do not interact with other loops and have hence used mathematical models based on capacitor power balance to design the DC bus voltage controller. Part of this research will also look at the dynamic response for each of the control loops in detail. The current loop and the DC bus voltage loop operate independently to each other. The controllers are designed independent to each other so that the voltage controller can provide the reference signal that is required by the current controller. The independent design of the control loops enable the current loop to operate faster than the outer voltage loop which optimizes the performance of the inverter. During the designing of the voltage loop, it will be assumed that the current loop is a pure gain, whereas during the designing of the current loop, it will be assumed that the reference current has no influence on the controlled current in any way. For the purpose of this research project, the voltage control loop and the current control loop will be designed separate to each other as that is the industrial standard.

Another aspect of this project is the maximum power tracker. The maximum power tracker is an extremum seeking loop and hence does not require reference inputs like other loops.

Varjasi (Varjasi, Balogh & Halasz 2006), Gonzalez (Gonzalez et al. 2006) and many other researchers have considered the use of single stage conversion systems. This system will also be used for the purpose of this project. In the single stage conversion system, the voltage reference for the voltage control loop is provided by the maximum power tracker. Once set, the voltage reference is not immediately influenced by the other control loops. During operation, the maximum power tracker sets the reference voltage to a new value and then it waits for the voltage controller to change the DC bus voltage to the new value before it runs again. Hence, the assumption is made that the voltage control loop does not have any influence on the reference voltage.

During the course of this research, it was found that very little work had been published in peer reviewed journals with regards to the controlling of the DC offset current at the output of a grid-connected PV system. It was also found that very little work again was done in relation to the DC offset control loop and its interactions between the other control loops in the system. As part of this project, an independent DC offset control loop will be used under the assumption that the loop does not have any operational effects on the other loops in the system and vice versa.

2.3 Output Current Harmonic Distortion

Another major component of power quality is harmonic content. This falls into two main categories, low frequency harmonics and high frequency or RFI. With the inverter system, low frequency harmonics are caused by injecting current which has distortion and this is typically in the 3rd, 5th, or 7th harmonic realms. This causes disturbance to the grid since that most power system devices are designed for 50 Hz. Therefore frequencies in the 150, 350 and 750 range causes significant increases in losses such as eddy current losses in physical hardware. High frequency harmonics such as the ripple frequency causes disturbances in the megahertz region, typically from a few kilohertz to megahertz region which can cause issues with Wi-Fi and other communication systems.

Due to the inverter continuously switching, it may cause the stray capacitances to charge and discharge very quickly. This may cause the frequency spectra of the stray capacitance to operate in the megahertz region and can potentially be a major source of electromagnetic interference (EMI). During the course of this research project, the effects of low frequency harmonics, ripple frequency harmonics and electromagnetic inference will be considered. The inverter which is being designed and implemented as part of this research project has to comply with the AS4777.2 (Austrailian Standards Commission 2005) standards, as this the standard for all the inverters that are being used in Australia. As per the standard (Austrailian Standards Commission 2005), all inverters are only allowed to have a maximum harmonic distortion of less than 5% for harmonics up to the 50th in the injected current for a grid connected PV system. Researchers such as Kirawanich (Kirawanich & O'Connell 2000), Vasanasong (Vasanasong & Spooner 2000), Calais (Calais et al. 2002) and Spooner (Spooner 2001) have looked into the effects of harmonic injection in AC networks caused by the use of devices such as the inverter. All the measurements that were made by the researchers were based on commercially available grid connected inverters, the results of which indicated that the levels of low frequency harmonics were small. When these low frequency harmonics were compared against the requirements of the Australian Standard AS4777.2 (Austrailian Standards Commission 2005), it was found that the harmonics from those commercial inverters were still significant and were only barely meeting the requirements of the Australian Standard AS4777.2. It is because of these findings, the need for careful inspection of low frequency harmonics in grid connected inverters has arisen, with a common aim of either alleviating low frequency harmonics from the grid or to at least minimize the effects of the low frequency harmonics on the grid.

The research that has been done so far with regards to harmonics has mainly been focused around voltage controlled systems. Some of the possible causes of harmonic distortion in voltage controlled converters that were identified by Olivia (Olivia et al. 2005) are:

- Filter nonlinearities

- Dead-times
- Device voltage drops
- DC link voltage harmonics

A further explanation was provided by Mohan (Mohan, Undeland & Robbins 2005) on the relationship of dead-times and voltage harmonics. This explanation entails that the use of dead-times causes distortion to superimpose itself onto the voltage signal at the zero crossings. A simple mathematical model was derived by Kotsopoulos (Kotsopoulos, Heskes & Jansen 2002) to quantify the harmonic distortion levels at the zero crossings. Oliveira (Oliveira et al. 2003) suggests a technique that can be used with voltage controlled inverters to minimize the harmonic distortion at the zero crossing due to dead times. For current controlled inverters on the other hand, it was thought if the current reference signal was harmonic free, the current coming out of the inverter would also be free of low frequency harmonics. However, this was not the case, as Bowtell (Bowtell & Ahfock 2007) reported significant amounts of low frequency harmonics at the output of current controlled inverters. During this research, it was found that very vague information had been published in literature with regards to low frequency harmonic distortions in current controlled inverters. The few possible causes of low frequency harmonic distortion in current controlled inverters are identified as:

- Distortion in the current reference signal as mentioned by Sakthivel (Sakthivel, Das & Kini 2003)
- Distortion in the control signal generated by the voltage control circuit as reported by Sharma (Sharma & Ahfock 1992)
- Switching Delays as published by Sharma (Sharma & Ahfock 2004) (Sharma & Ball 2009)
- Dead-time as identified by (Olivia et al. 2005)

When dealing with unipolar switched inverters, there may be distortions near the negative going zero-crossing. This distortion is the result of the AC supply voltage not being capable of bringing down the current so that it followed the reference current fast enough. Salmon (Salmon 1992) reported seeing a similar type of distortion at the input current of switch mode rectifiers but at the positive going zero-crossing instead of the negative going zero-crossing. Bipolar switched current controlled inverters seem to have a significantly lower zero crossing distortion which is validated by the Simulink modelling and the Experimental results. Authors such as Lindgren (Lindgren 2002), Ordonez (Ordonez, Quaicoe & Iqbal 2008) and Li (Li & Chung 2008) have suggested the use of a mixed mode inverter. The operation of the mixed mode inverter as proposed by the authors' states that the unipolar switching should be used for most of the inverter's cycle so as to reduce the switching loss and to use the bipolar switching near the zero-crossing to minimize the distortion around the zero-crossing area of the inverter.

A very small fraction of this research project will look at the possible causes of low frequency harmonics and zero crossing distortions in current controlled inverters. An investigation of these causes will highlight any short falls that maybe present. Understanding these shortfalls will provide data to further improve the device if needed and this will also reduce the distortion of the AC signal being fed back into the grid.

Ripple frequency harmonics can easily be filtered out from the inverter using relatively small and low cost hardware. This however is not possible with regards to low frequency harmonics at the present time. Ripple frequency harmonics can easily be filtered using passive electrical components or a combination of passive components. Some of these passive components and combinations that could be used in filtering the ripple harmonics are:

- Inductors (L)
- A combination of inductor and capacitor (LC)
- A inductor, capacitor, inductor filter (LCL filter)

For the purpose of this research project, a LCL filter will be used as it provides an assurance that resonance will not occur. A set of filter design guidelines is given by Bojrup (Bojrup 1999). Even though the Australian Standards AS4777.2 (Austrailian Standards Commission 2005) does not provide explicit guidelines with regards to allowable ripple harmonic content, limits for current up to the 40th order are provided in IEC 61000-3-2 (International Electrotechnical Commission 1998). This also classes the inverter as a 'class A' device. Ripple frequency injection needs to be limited in order to prevent interference with systems that may be using the power lines for communication purposes. Further guidelines with regards to voltage flicker and harmonics are found in IEEE 519-1992 (Institute of Electrical and Electronics Engineers 1992) and in IEC 61000-3-3 (International Electrotechnical Commission 1994). In general, the ripple current of various ranges from typical inverters turn to overlap onto the frequency band which is often used by systems that use power lines for communication purposes. Bojrup (Bojrup 1999), Ordonez (Ordonez, Quaicoe & Iqbal 2008) and Li (Li & Chung 2008) did not give proper consideration with regards to low frequency harmonics and ripple filter transients at the point of transition between unipolar and bipolar operations of the inverter.

During the design process, careful consideration has to be given to the layout in order for the design to meet the necessary EMC requirements stated in the Australian Standards AS4777.2 (Austrailian Standards Commission 2005). It is a known fact that different circuit designs and configurations have different levels of EMI emissions. The EMI emission from the design and configurations is due to the stray capacitive currents that results from the very quick switching of the inverter. A brief theoretical explanation is given by Gonzalez (Gonzalez et al. 2006)with regards to charging and the discharging of stray capacitances between the source of the inverter (solar panel) and ground, however no experimental results were provided. A simulation based approach was used by Jiang (Jiang & Brown 2002) to report the EMC of inverters with different configurations. However, the configurations that were taken into account by Jiang are not being used for the purpose of this project. According to Gonzalez (Gonzalez et al. 2006) if the ripple filter was made up of two identical inductors, with one connected to the input of the inverter and the neutral, while the other is connected to the active terminal, the EMC performance of the bipolar operations is greatly improved in comparison to the unipolar operation EMC.

2.4 Smart Energy Meter:

Smart Energy Meters have started to play a very important role in modern energy distribution networks. Since the focus towards the generation and the usage of renewable energy has increased over the recent years, it has become essential for electricity suppliers and distributors to continuously monitor the service quality and often have to report the performance to governing authorities as mentioned by Capua (Capua et al. 2014). In order to acquire various information with regards to the service quality with minimal error, smart energy meters have to be used. Capua (Capua et al. 2014) breaks down the definition of service quality into three parts as defined below:

- Reliability of supply
- Voltage quality
- Information availability

According to Corbett (Corbett 2013), smart energy meters were designed to increase energy efficiency and to provide data to utility providers in real time. In this research project, data has to be provided in real time for the purpose of power factor correction. However, literature has not been provided for the proposed method of extracting the required information from the smart energy meter. Another major aspect is providing efficient energy using the method that is proposed in this project. According to Capodieci (Capodieci et al. 2011) people who produce and consume energy are called prosumers. Capodieci (Capodieci et al. 2011) also goes further into saying that these prosumers form a small part of the smart grid. A very comprehensive outlook into the design and the functioning of the smart energy meter is provided in Ali's (Ali, Maroof & Hanif 2010) paper. An outstanding feature of the smart energy meter is that it has three ways of communicating information to remote control or monitor rooms. Two of these can be used simultaneously at any one time. These three ways of communication as highlighted by Ali (Ali, Maroof & Hanif 2010) are:

1. Localized digital display on which real time data is presented
2. Power Line Carrier Communication (PLCC) where the data is transmitted in real time to control/monitor rooms
3. Global System of Mobile (GSM) where the mobile networks are used to transmit the data in real time to control/monitor rooms.

PLCC is deemed as the most preferable medium of transmitting data from the smart energy meter in real time to remote control/monitor rooms. This is due to the fact that PLCC uses the same power transmission cables as its communication channel which in turn makes it immune to the effects of the surrounding environment. As per Ali's (Ali, Maroof & Hanif 2010) paper, the information signal which is usually several kilo hertz from the smart energy meters is superimposed onto the power line which is usually operating on the 50 – 60 Hz range. This then eliminates the need for a separate channel which in turn eliminates the need for a separate transmission protocol.

With the advancement in mobile technology, it has also been made possible to use the mobile networks to transmit data from smart energy meters, however this is a bit expensive when compared to the PLCC method but is the second best option of transmitting the data in terms of cost and also in terms of accuracy as pointed out by Ali (Ali, Maroof & Hanif 2010). When using this method, the data is sent in the form of text messages using the short messaging service (SMS) protocol of GSM networks. Even though it is said that the data is transmitted in real time when using this method, this is not entirely true, due to the fact that there is always a delay associated with the use of text messaging. The data transmission is also subject to the network congestion as at times the messages are delayed by several minutes if the GSM networks are overly congested as explained in Verma’s paper (Verma, Sharma & Mishra 2012).

The use of these smart energy meters provides energy distributors more control over their network and also helps automate the switching process for when new users want to use their services. The smart energy meters contain a high voltage and high current relay inside them which allows the utility operators to switch on or off an energy service remotely. This eliminates the need for physical interaction when new services are to be connected to the network and hence reduces the cost and it also allows the utility operators to be more efficient as the service can be switched on instantly as described by Ali (Ali, Maroof & Hanif 2010).

Another very unique feature of the smart energy meter is its unique Anti-power theft system that it has incorporated in its design. This feature works on the basis that the digital meter inside the smart energy meter continuously monitors the amount of power used by a customer and it also has a feedback monitor which compares the amount of power used previously and the most recent consumption, alerting the utility providers of any discrepancies that is sensed as mentioned by Ali (Ali, Maroof & Hanif 2010). This feature allows the utility providers to investigate the possible theft of energy from their networks which in turn reduces their losses.

The functionality of the smart energy meter in the event of a power failure is also questioned by Ali (Ali, Maroof & Hanif 2010) and has been reported that the smart energy meters have a backup battery system installed in order to deal with a situation as such. Ali (Ali, Maroof & Hanif 2010) also further goes into the details of stating that the smart energy meters contain an EEPROM chip on which processed data is stored in the event of a communication failure between the smart energy meter and the utility control/monitor room. The data is also stored on the EEPROM chip when the smart energy meter is operating in its power failure mode and using its backup battery system to support itself.

Benzi (Benzi et al. 2011) has proposed that smart energy meters be interfaced using a zigabee module which will allow it to transmit data to a localized computer which is monitoring the information from other digital meters also connected using the zigabee communication protocol for one household. Benzi (Benzi et al. 2011) has called the proposed plan “the smart house”. Benzi’s paper goes further to say that in the smart house system, the utility providers and other service providers will be able to collect data from the localized computer and this will in turn make the information more readily available to everyone.

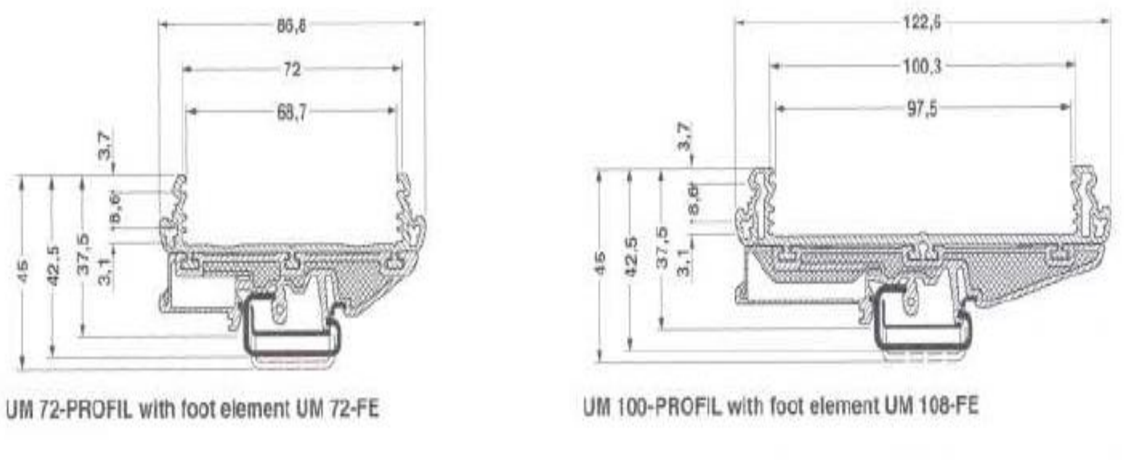
However, for the purpose of this project, the zigabee protocol cannot be used as per the discussion with the manufacturer of the particular smart energy meter being used in this project. According to EDMI PTY LTD, the manufacturer of the EDMI MK7C ATLAS smart energy meter that is being used in this research project, information from registers inside the smart energy meter cannot be transmitted using the zigabee protocol due to limitations of the hardware.

The proposed method of extracting the power factor information from the EDMI MK7C ATLAS smart energy meter is using a Modbus translator which is available as an additional component to the smart energy meter by the manufacturer. Using the Modbus translator and the Modbus function on the PLC, the required information is extracted from the smart energy meter for the processing and the comparison that is required. All the risks and flaws as identified by Ali (Ali, Maroof & Hanif 2010), Capodieci (Capodieci et al. 2011) and Capua (Capua et al. 2014) have been mitigated during the implementation using the methods that were proposed by them.

2.5 PCB Design:

A very important aspect of this project is the PCB design of the STACOM inverter. As per the requirements of the project, the PCB’s were to be designed so that they were immune to noise. The track widths on the PCB’s also had to be wide, in order to allow currents to pass through without distortion. Wide tracks on the PCB also allowed for the operation of the device under high dv/dt conditions. The PCB’s were designed so that they could sit in either a UM72 profile or a UM100 profile. This requirement effectively restricted the size of the printed circuit board that was to be used and therefore the design was done accordingly to accommodate the restrictions. Literature with regards to the UM72 Profile and UM100 profile is non-existent and therefore manufacturers’ catalogues were used as guides for this process. According to the catalogue obtained by Steven Engineering (Steven Engineering 2014), the profile lengths and widths for the UM72 and the UM100 profiles are fixed as follows:

1. UM72 Profile sizes:
    - 72mm x 100mm
    - 72mm x 200mm
2. UM100 Profile Sizes:
    - 100mm x 72mm
    - 100mm x 100mm
    - 100mm x 120mm
    - 100mm x 200mm



UM 72-PROFIL with foot element UM 72-FE

UM 100-PROFIL with foot element UM 108-FE

Figure 2. 1: - Physical Details for the UM72 and UM100 PCB Profiles (Source: Steven Engineering (Steven Engineering 2014)

The sample schematic layout for the UM72 and UM100 profiles are shown in the above picture. It is essential that all three PCB boards that are required for the STATCOM inverter to function properly sit in the UM100 profile as it is more flexible with regards to length and because the UM72 profile was not available for use for this project.

Figure 2. 2: Actual Pictures of UM72 and UM100 PCB Profiles (Source: Steven Engineering (Steven Engineering 2014)).

The above pictures show how the UM72 profile and the UM100 profiles actually look like. The benefit of using the profiles are that if needed in the future, additional PCB boards can be used and the profiles could be stacked on top of each other due to its design.

According to Leonard (Leonard 2013), understanding the anatomy of a PCB forms the basis of designing the perfect PCB board with a proper layout. Leonard also goes further into saying that the material which is used for the PCB also plays a major part on how the actual PCB will function when in operation. Coonrod, (Coonrod 2012) in his documentation gives a detailed outlook of the materials available on the market for the manufacture of PCB's which are used with high frequency applications. Since this project is going to be exposed to relatively high frequency due to the very quick switching between the bipolar and unipolar operations, the high performance FR4 substrate was chosen for the material for the boards as this was also the cheapest option available.

Using Leonard's (Leonard 2013) document as a guide, the PCB was designed as such that the circuits which were switching very quickly at relatively high frequencies were on the opposite ends of the PCB board to minimize any risk of electromagnetic interference. Leonard (Leonard 2013) also goes further into saying that large circuits should be split up into small portions as it makes it easier to debug if there is a problem with the circuit. This advice was also used and the circuit was split into three PCBs which interconnected to each other to form the full STATCOM inverter. In the paper, Leonard (Leonard 2013) also mentions that the tracks which are used to route all the signal paths on the PCB should be relatively thick in order to minimize electromagnetic interference and hence the tracks on the PCBs that were designed were 1.1mm in width.

Chapter: 3

METHODOLOGY

3.1 Overview

This chapter is based on the methodology that was employed to design, simulate and implement the four quadrant STATCOM inverter with a VAR controller which enabled power factor correction capabilities for in localized use and also when connected with the grid. The design of the PCB for the STATCOM was done using CAD software. The design was also simulated using SIMULINK so that theoretical waveforms were available for the purpose of comparing the actual waveforms from the STATCOM with. The chapter will also further explain the analysis that was used for the establishment of the design criteria, the design constraints that were used and the process used for the implementation of the designs. The first step involved meeting with Dr. Bowtell the original designer of the STATCOM inverter schematics that were modified for this project and discussed with him the original short falls of the first design. This meeting also set the boundaries and gave a clear definition of as to what was expected in this project and also set the limitations for the project. The discussions in this meeting led to the collection of information which were used in the redesign process.

The initial design of the STATCOM inverter that was made by Dr. Bowtell was of a current controlled mixed mode inverter which had both unipolar and bipolar operations, the advantages of which is detailed in Chapter 2 above. The initial design of the STATCOM inverter had various flaws which had to be rectified in order for it to operate more efficiently. During the discussion with Dr. Bowtell, some passive elements of the design were identified which were to be replaced by sensors and other active components. The new design of the STATCOM inverter was to include a VAR controller which would enable power factor correction for a localized household and will also have capabilities of correcting power factor in the power networks if allowed by the network operator. This then became the aim of the design process.

Some of the design constraints that were identified included the size restriction of the PCB boards and the compliance with the Australian Standards. The Australian Standards had to be referred to continuously to ensure that the design was within the limitations of the Australian Standards. The Australian Standards also contained the limitations of the amount of harmonics that could be injected into the grid as a result of the power injection from the STATCOM inverter into the grid.

3.2 Theory of the Design Process

The definition of research according to Bock (Bock 2001) is the acquisition of new knowledge and the development of new processes using the acquired knowledge to create new inventions or to optimize current processes for the betterment of people. The development process will be used as part of this research project as the knowledge acquired from the literature reviews will be applied to optimize a current system and will also give rise to a new invention. The four parts of the scientific process as defined by Bock (Bock 2001) are:

- Analysis
- Hypothesis
- Synthesis
- Validation

The four parts as stated above will be used as part of this Research project.

3.2.1 Analysis of the Design Process

The analysis of the problem identifies the current flaws in the design and sets the objectives that are to be achieved at the conclusion of the research project. The objectives of this research project was explained in great detail in Chapter 1 so that the readers could understand what was tried to be achieved in this project. However, the objective in a nutshell is to redesign a four quadrant STATCOM inverter to remove some passive components in order to make the inverter more accurate and to implement a VAR controller to help correct the power factor in localized loads and also in the Grid if permitted by legislations and the network operator.

3.2.2 Hypothesis of the Design Problem

The hypothesis usually defines the specific solutions, sets goals, defines the factors affecting the performance and it also postulates the performance matrix of the research project. The hypothesis of this research project is that the redesign of the schematics is going to yield a more efficient STATCOM inverter which is also going to have power factor correction capabilities through the use of a VAR controller. The overall result would be an optimized STATCOM inverter with more functions then a standard inverter.

The VAR controller is going to be implemented the PLC as a logic algorithm for this project.

3.2.3 Synthesis of the Design Problem

Design problem synthesis includes designing the solution, implementing the solution, conducting experiments on the solutions that were implementing and collating and analyzing the results that were obtained. Since this research project involves a redesign component and also an implementation component, the redesigned STATCOM inverter will first be implemented and tested before the VAR controller is implemented with the device. This will ensure that the device functions the way it should. The redesigned inverter was simulated in SIMULINK before it was actually implemented in hardware. The simulations provided a theoretical comparison for the inverter and it also provided a certainty that when implemented the device is going to behave in a manner similar to what the simulations had shown.

3.2.4 Validation of the Design

Design validation involves computing the performance, drawing conclusions and preparing the required documentation. It also involves soliciting peer review from experts in the field. Once simulated, the STATCOM inverter was implemented onto PCB's which was then lab tested. Only some of the performance indicators were looked at during the lab testing stage due to others being outside the scope of this research project and also due to time restrictions. Some examples of other performance indicators are:

- Electromagnetic Compatibility (EMC) of the design
- Electromagnetic Interference (EMI) in the design
- Total Harmonic Distortion (THD) between the grid and the inverter
- Communication between the inverter and the Grid operator

The following flowchart shows the methodology and the outcomes at various stages:

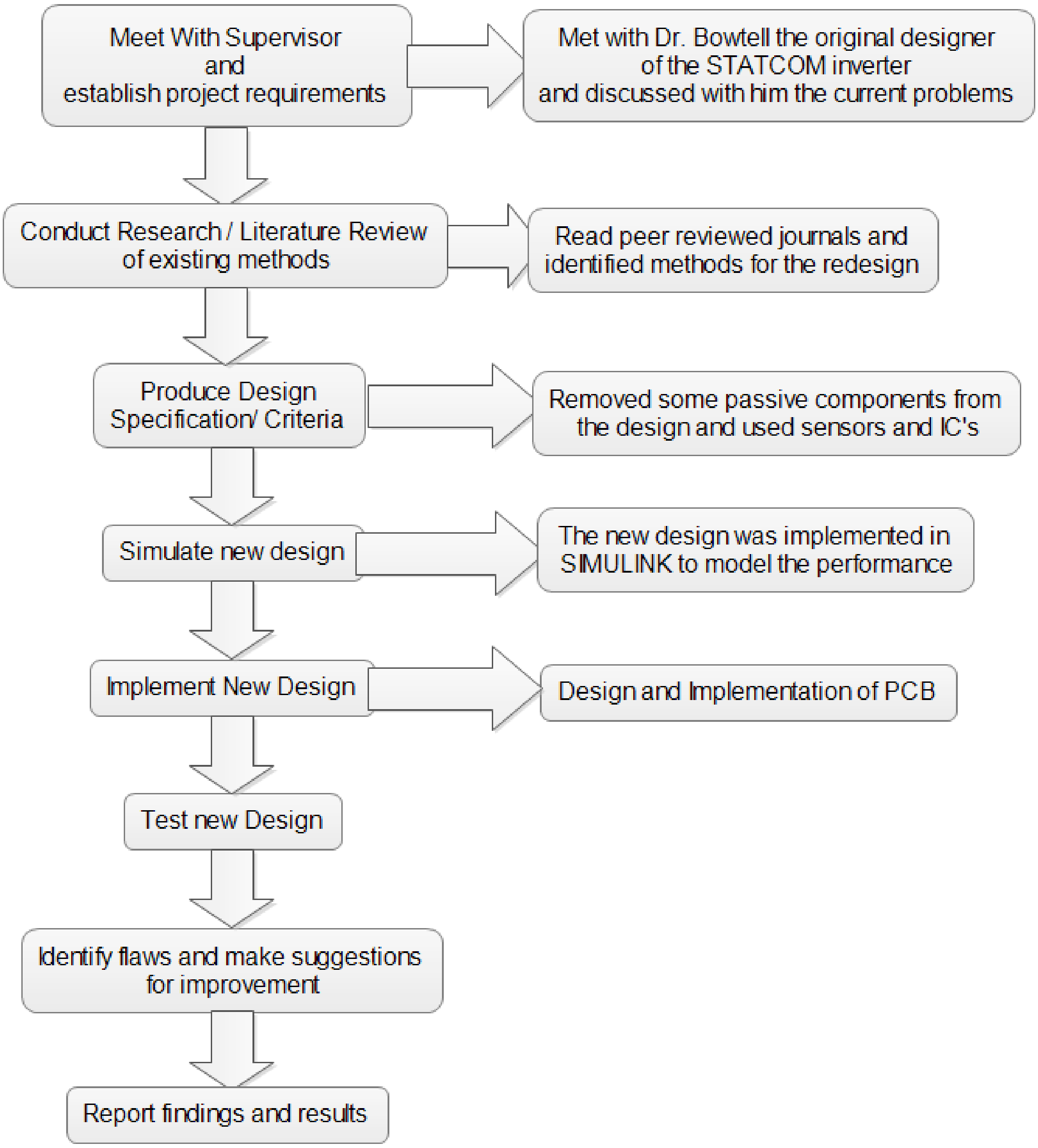


Figure 3. 1: Flowchart of the methodology that was employed

3.3 Needs Identification

The requirements of this project included the redesign of the STATCOM inverter where some passive components are to be replaced using sensors (transducers) and active components (IC’s). The redesigned STATCOM inverter should include a VAR controller which will enable the inverter to use the reactive power to correct power factor for localized loads. The inverter should also be capable of correcting the power factor in the grid (subject to legislative review). The design then has to be implemented on PCB’s conforming to the UM100 profile.

3.4 Design Limitations

The design limitations for this project were identified as:

- STATCOM equipment housing design is not part of this project
- An existing S7200 version PLC was used for the purpose of bus voltage control
- Power quality data i.e. power factor etc. is to be gathered by the EDMI energy meter.

3.5 Design Constraints

The following design constraints were identified for the design of the four quadrant STATCOM inverter and the VAR controller:

- The PCB's should fit a UM100 profile which restricts the size of the PCB's to:
  1. 100mm x 72mm (double layer)
  2. 100mm x 72mm (single layer)
  3. 100mm x 120mm (double layer)
- The PCB's design should no more than two layers.
- The PCB's design should minimize electromagnetic interference and switching noise, hence the track widths were increased from 0.1mm (standard track size) to 1.1mm which was the physical clearance limitation.
- The pads for the components on the PCB's were also made relatively thick. The pad sizes were increased from 1mm (standard pad diameter) to 1.5mm (This was again the maximum pad diameter before the pins on the IC's short circuited themselves).
- The PCB's should interconnect between all the boards and other components such as gate drives and PLC relatively easily.
- The STATCOM Inverter PCB's should be insulated to handle 1000V minimum insulation requirements.

According to Bock (Bock 2001), having a list of performance criteria is a good place to start any research work, therefore the performance criteria of this project is very heavily dependent on the project specification that was agreed upon between Dr. Bowtell and myself and is attached in Appendix B-1 of this dissertation.

3.6 Derivation of Design Criteria

The design criteria were developed in accordance to the project specifications listed and agreed upon at the start of the project. An important aspect in the continued development of the design criteria was the recent technological developments identified in the Literature review.

3.6.1 Improved Data Acquisition

The increased accuracy in the data which is being obtained from the STATCOM inverter is essential for it to function efficiently. The STATCOM inverter relies on the voltage and the current information that it is supposed to obtain from the grid and also from the PV and battery bank side which is computed in the PLC. The VAR controller also needs to obtain accurate data in real time for the purpose of power factor correction. To increase the accuracy of the data being obtained by the PLC of the STATCOM, some passive and active components of the STATCOM inverter were changed from the original design. The new design of the STATCOM inverter included the use of modern hall-effect voltage and current transducers and also the use of a Smart Energy Meter for the purpose of more accurate data which was acquired by the PLC being used.

3.6.2 Power Factor Correction

The power factor is essentially the cosine of the angle between the voltage and current phase that determines by how much the current is either leading or lagging the voltage. Power factor requirements in Australia are between 0.75 and 0.9 lag, with Queensland having a minimum power factor requirement of 0.85 lag. Typically as the energy demand increases at peak periods, the system power factor tends to fall due to high demand (NORMAN DISNEY & YOUNG 2002). Power factor is very critical when it comes to the operation of machines that require high current usage to start, for example, the power factor for an induction motor to start is around 0.8 lag and if the power factor available is below 0.7 lag, the induction motor will not start (NORMAN DISNEY & YOUNG 2002). The proposed design of the STATCOM inverter has the capabilities of correcting the power factor using the reactive power. The VAR controller which is being implemented in the algorithm of the PLC will read the power factor from the smart energy meter and will tell the STATCOM inverter to start pushing current in order to correct the power factor if the power factor from the smart energy meter is below a certain threshold. The power factor correction which is being done using this method is on localized loads. This method can also be used to improve the power factor in the grid but this is subject to legislative review and agreement between the utilities and the consumers.

3.6.3 Standardized PCB’s housing

A very important aspect of this research project was to make the design of the PCB’s as such that it will conform to a standard housing. The choice of housing for this project was chosen to be the UM100 PCB profile. The UM100 PCB profile was chosen as the standard equipment housing for this project because the size of the current controller for the inverter could only be reduced to 100mm x 120mm, which would have only fit the profile that can accommodate a PCB width of 100mm and in this case the UM100 PCB profile was large enough to accommodate it. The other two PCB’s that were part of the inverter were designed to the UM72 PCB profile specification and since their length was 100mm, they easily fit the UM100 PCB profile. Since all three PCB’s were designed as such that they could fit onto the UM100 PCB profile, it was decided that the UM100 PCB profile will be used for the housing since it reduced the need for the use of two different profile sizes and would allow the three PCB’s to be stacked on top of each other if the need arose, therefore standardizing the PCB housing for this project.

3.6.4 Increased Safety

The original implementation of the original design for the four quadrant STATCOM inverter was done on breadboards. Since breadboards have the tendency where wires and components can become loose and come out, it was dimmed unsafe due to operation with high voltages. Since the original design also used some passive components that would easily heat up, this again raised a safety concern. The new design of the STATCOM inverter replaced some of the passive components that would have heated up with active components. During the implementation, the STATCOM inverter was implemented on PCBs and the material that was chosen for the PCB (high performance FR4 substrate) did not have a high electrical conductivity on its surface (Coonrod 2012). This increased the safety as the PCB only had electrical conductivity where there were tracks. Since PCBs were used, the danger of components and wires coming loose and coming out did not exist as the components were soldered onto the PCB and the use of the PCB significantly reduced the use of wires to connect the IC’s. For the wires that were going in or coming out of the PCB’s, MOLEX connectors were used. The use of MOLEX connectors again reduced the risk of wires becoming loose and coming out. It also provided insulation as the wires had to be connected to pins and the pins would be inside the MOLEX connector.

Taking all this into consideration, the new design and implementation is much safer and user friendly then the old one.

3.6.5 Ease and Cost of Manufacture

Since this project has some commercial value in the future, the ease of manufacture and also the cost of manufacture has to be taken into account. Due to this redesign being only a prototype, it is understandable that the cost associated with it will be significantly higher than that when it is being manufactured on a large commercial scale. The components and IC's that were used for the implementation are relatively cheap and are readily available on the market. Due to the IC's being readily available, the cost of maintenance in the event that an IC malfunctions is significantly low. Currently the process of manufacture is manual but in commercial production it may be automated therefore removing most of the labor cost associated with it and hence reducing the cost.

3.6.6 Easy to fault find and repair

Fault finding is a very important aspect when trying to repair a circuit. The way a PCB is structured and the number of layers it has on it impedes on the fault finding process. To make the fault finding and repair process easier, all the PCBs had their component footprints and their values printed on the top layer of it. Fault finding and repair was taken into consideration during the designing of the PCB's and hence all the boards were restricted to a maximum of two layers. With only two layers, it was easy to trace exactly where each of the tracks originated and where they ended.

3.7 Design Options

After looking at the project specification that was agreed upon, and thoroughly reviewing the literature, the following PCB designs were considered:

- A = 1 x multilayered PCB housing the complete inverter measuring 72mm x 100mm
- B = 1 x double layer PCB housing the complete inverter measuring 100mm x 200mm
- C = 2 x double layer PCB board housing the complete inverter measuring 100mm x 120mm each
- D = 1 x double layer PCB housing the current controller measuring 100mm x 120mm, 1 x double layer PCB housing the auxiliary

power supplies and power tracking circuits measuring 72mm x 100mm and 1 x single layer PCB housing high voltage sensors and transducers.

These four designs will be ranked against the design criteria that were derived above.

3.8 Ranking of Design Criteria

The ranking values for the design criteria was determined by the amount of impact each of the design criteria had on each of the design options. For the purpose of this project, a number scoring system was decided. The scoring system will work as follows:

- 10 points = high impact on design criteria
- 5 points = medium impact on design criteria
- 1 point = low impact on design criteria

Once all the design options are scored according to the design criteria, the scores are tallied and converted into a percentage. The design which has the highest percentage score, is dimmed the best option and is used in the implementation phase. The design options of A to D is carried forward from the previous section.

Table 3. 1: Design Ranking Table for STATCOM PCB design

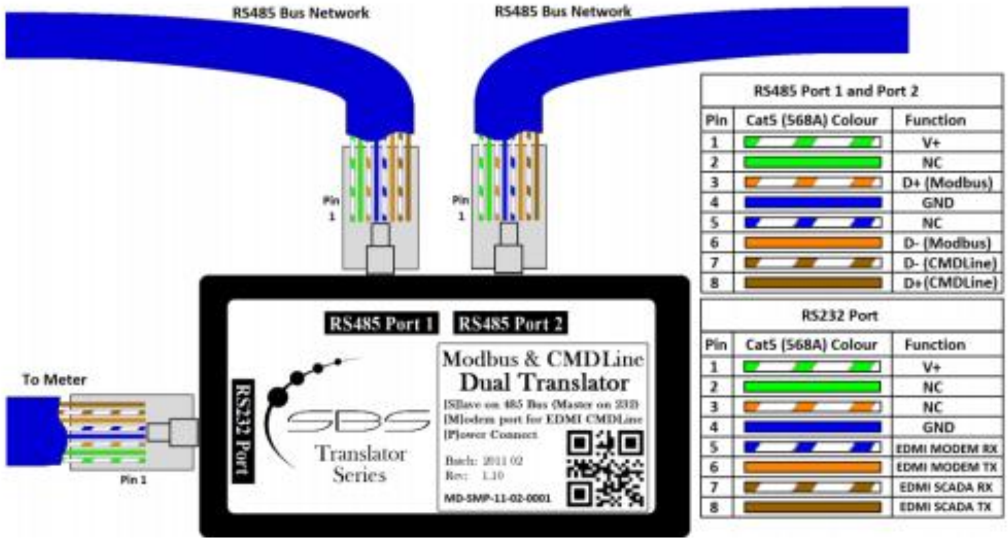
Design Criteria	Design Options for PCB's							
	A		B		C		D	
	Impact	Score	Impact	Score	Impact	Score	Impact	Score
Increased Accuracy	Medium	5	Medium	6	High	8	High	10
Power Factor Correction	High	10	High	10	High	10	High	10
Standardized PCB's housing	High	10	High	10	High	10	High	10
Increased Safety	Low	1	Low	2	Medium	6	High	10

Ease and Cost of Manufacture	Low	1	Low	1	Medium	6	Medium	6.5
Easy to fault find and repair	Low	2	Low	2	Medium	7	High	10
Total Score	29/60		31/60		47/60		56.5/60	
Percentage Score	48.33%		51.66%		78.33%		94.16%	

From the above ranking table, it can be seen that option D which is described as having three different PCB’s for the various parts of the STATCOM inverter has the highest scoring percentage of 94.16%. Since option D satisfies all the design criteria with quite high scores and it has the highest scoring percentage, this will be used for the purpose of this project.

3.9 Proposed Method for VAR controller

The proposed method for the VAR controller requires a power quality algorithm. For the implementation of this VAR controller uses a Siemens S7 - 200 PLC which will be used with the Totally Integrated Automation Portal (TIA) version 13 software for the development of the PLC algorithm. In conjunction with this, the Smart Energy Meter (EDMI MK7C Atlas) being used for this research project had to be configured so, that the power factor register required for this process was made available. Due to safety concerns and to prevent energy theft, EDMI has implemented various anti-tampering mechanisms throughout the device. Some of these anti-tampering mechanisms also prevent the access of data from the device without proper authorization. For this part of this part of the project, there was continuous communication with EDMI, the manufacturer of the Smart Energy Meter and also Smart Building Services (SBS), the designer of the SBS Modbus translator (Smart Building Services 2012) which is required to enable the EDMI Smart Energy Meter to communicate with other devices through the use of the serial (RS 232) port located inside the inner cover of the device. Shown in the diagram below is the diagram of the SBS Translator with the color coding for the wires and their functions with respect to the RS232 and RS485 ports.



RS485 Port 1 and Port 2

Pin	Cat5 (568A) Colour	Function
1	🟩⬜	V+
2	🟩	NC
3	🟧⬜	D+ (Modbus)
4	🟦	GND
5	🟦⬜	NC
6	🟧	D- (Modbus)
7	🟫⬜	D- (CMDLine)
8	🟫	D+(CMDLine)

RS232 Port

Pin	Cat5 (568A) Colour	Function
1	🟩⬜	V+
2	🟩	NC
3	🟧⬜	NC
4	🟦	GND
5	🟦⬜	EDMI MODEM RX
6	🟧	EDMI MODEM TX
7	🟫⬜	EDMI SCADA RX
8	🟫	EDMI SCADA TX

Figure 3. 2: EDMI Modbus Translator designed by Smart Building Services (source: - Smart Building Services, 2012)

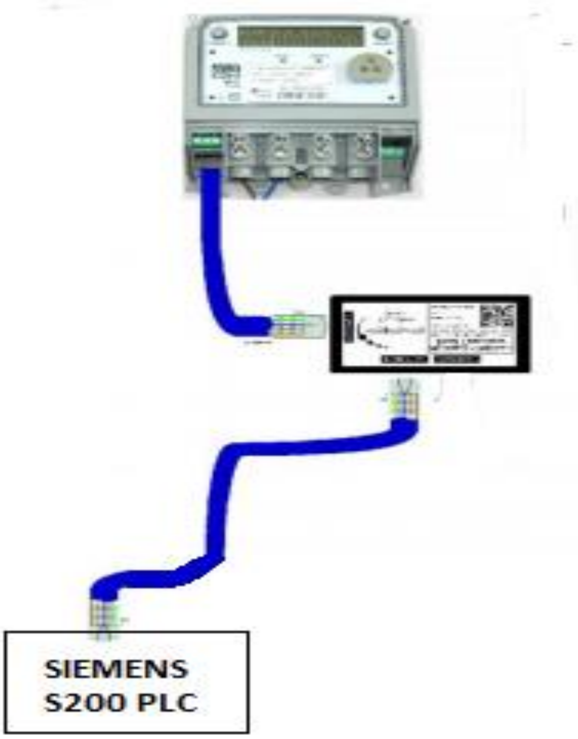
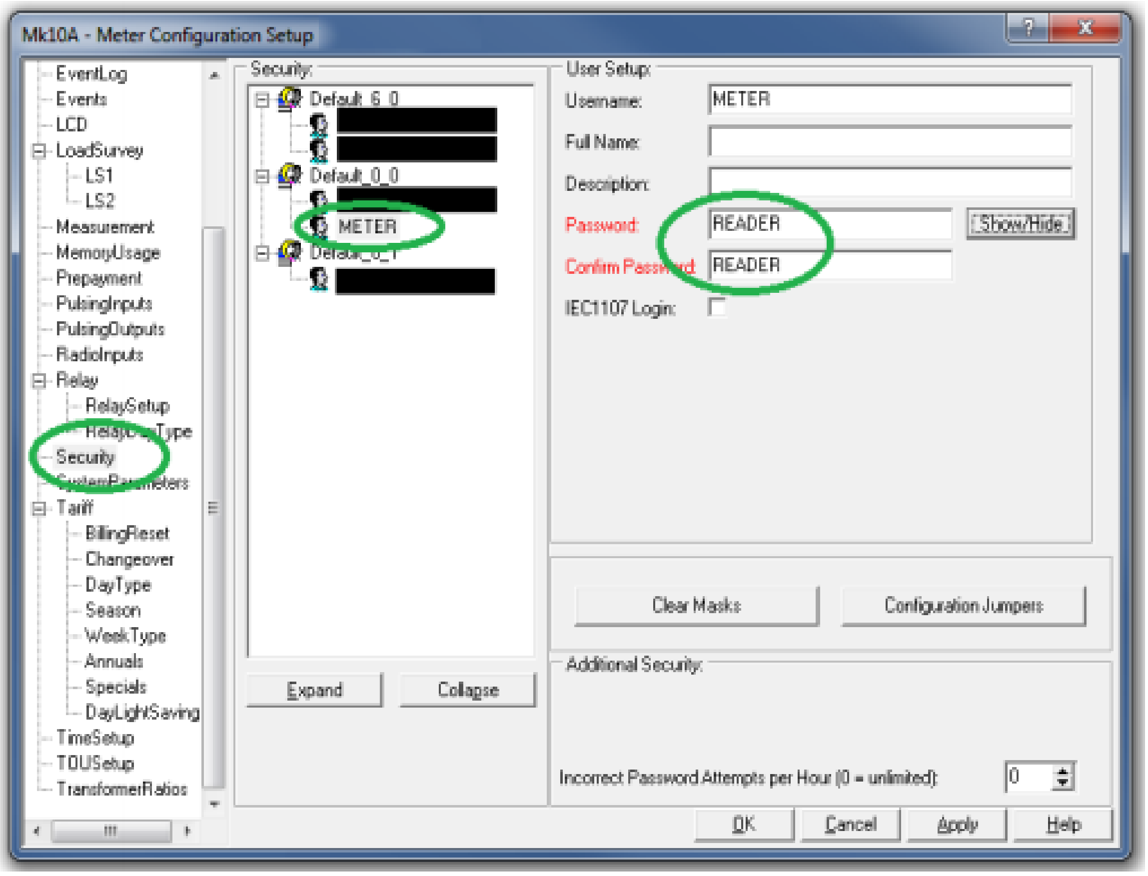


Figure 3. 3: EDMI Smart Meter connection to PLC

The above diagram shows the connection setup of the smart energy meter with the PLC. The RS232 port inside the smart energy meter was configured to a RJ45 socket by the manufacturer instead of the standard DB9 sockets which are usually used. Therefore, a standard CAT5 network patch cable is used to connect to the RS232 port of the smart energy meter. The other end of this CAT5 Network cable is connected to the SBS Modbus translator module. A second CAT5 Network cable is then attached from the DuoBus port of the SBS Modbus translator module and has to be attached to the PLC for the Modbus protocol to be initiated. Before the Modbus protocol could be initiated on the PLC, the

RS232 port has to be enabled for communication on the Smart Energy Meter. This has to be done using the software for the smart energy meter that was provided when the Smart Energy Meters were purchased. The standard means of communication for the Smart Energy Meters are the optical ports on the front of them. This optical port has to be used in order to get inside the meter settings and allow communication via the RS232 port. In order to turn on the RS232 port, it was necessary to log into the smart energy meter. The screenshot of how to logon to smart energy meter by adjusting the security settings is shown below and was provided by EDMI PTY Ltd.



Username: METER

Full Name:

Description:

Password: READER

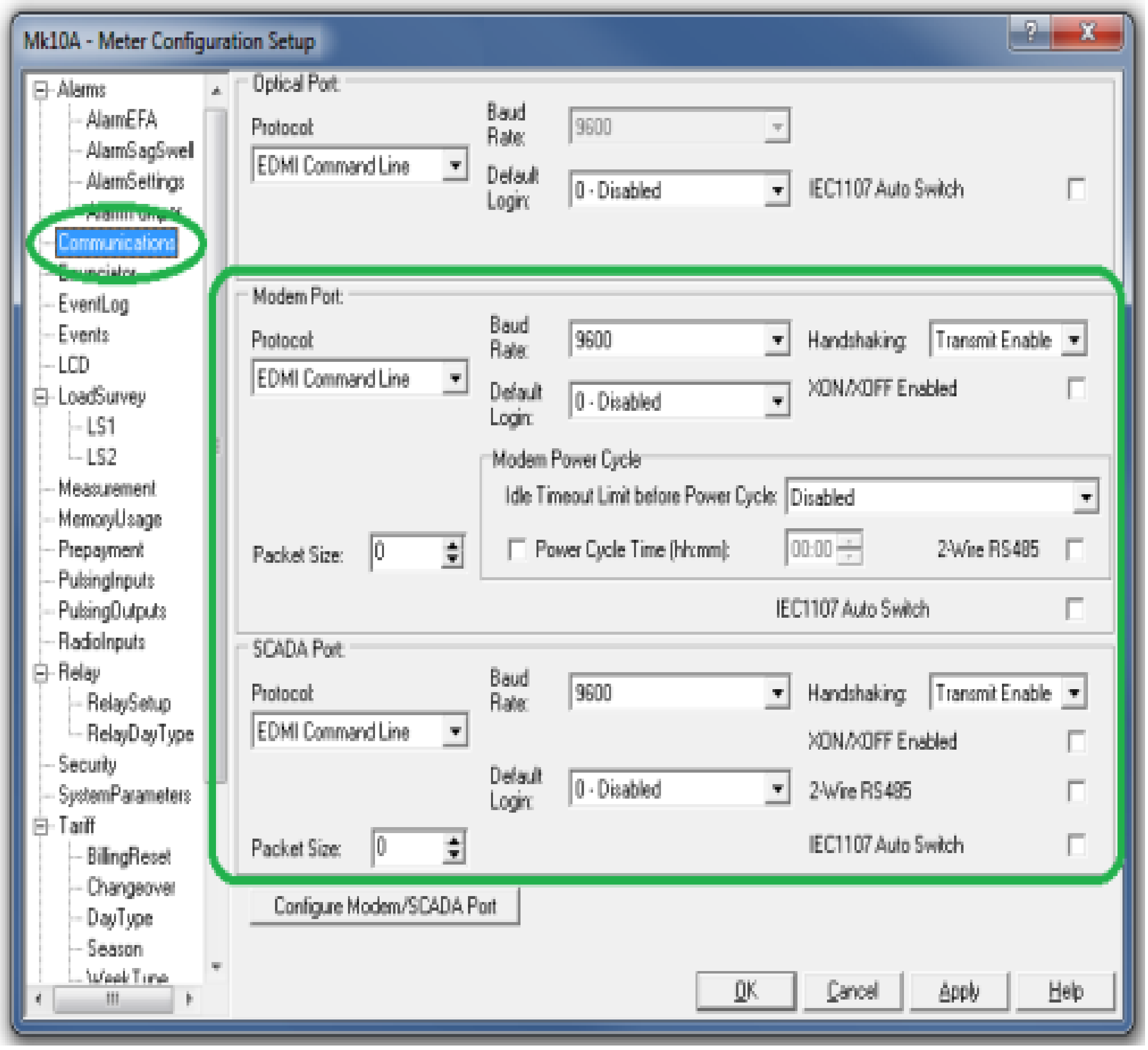
Confirm Password: READER

IEC1107 Login: ☐

Incorrect Password Attempts per Hour (0 = unlimited): 0

Figure 3. 4: Screenshot of EDMI Meter login (Courtesy of EDMI Ltd)

Once logged into the smart energy meter, the meter configuration was accessed and in particular the communications configurations. In the communications configuration, the meter was setup according to the configuration that was provided by EDMI PTY Ltd. The configuration details is as per the screenshot shown in the figure below, courtesy of EDMI PTY Ltd. The RS232 port was enabled once these configurations had been implemented in the smart energy meter.



Optical Port
Protocol: EDMI Command Line
Baud Rate: 9600
Default Login: 0 - Disabled
IEC1107 Auto Switch ☐

Modem Port
Protocol: EDMI Command Line
Baud Rate: 9600
Handshaking: Transmit Enable
Default Login: 0 - Disabled
XON/XOFF Enabled ☐
Modem Power Cycle
Idle Timeout Limit before Power Cycle: Disabled
☐ Power Cycle Time (hh:mm): 00:00
2-Wire RS485 ☐
Packet Size: 0
IEC1107 Auto Switch ☐

SCADA Port
Protocol: EDMI Command Line
Baud Rate: 9600
Handshaking: Transmit Enable
XON/XOFF Enabled ☐
Default Login: 0 - Disabled
2-Wire RS485 ☐
Packet Size: 0
IEC1107 Auto Switch ☐

Figure 3. 5: EDMI Smart Energy Meter configuration for RS232 port (courtesy of EDMI PTY Ltd)

Once all the parameters were setup correctly, and the communication port was enabled, the VAR controller algorithm was implemented. Further details about the VAR controller is discussed in the results section.

3.10 Final Design Specification

The initial specification for the STATCOM inverter and the VAR controller were highly dependent on the design criteria scores and the project specification that was agreed upon. The design materials of the previous STATCOM inverter and the new STATCOM inverter that was implemented are listed in the table given below:

Table 3. 2: Implementation Material Comparison

Design Specifications and Physical factors	Old STATCOM Inverter	New STATCOM Inverter
Material Type	• Standard Breadboard • Vera Board	• High Performance FR4 Substrate printed circuit boards
Connector types	• 2 pin pluggable block socket • 3 pin pluggable block socket	• 2 pin MOLEX connector • 3 pin MOLEX connector • 4 pin MOLEX connector • 10 pin MOLEX connector
Potentiometer	• 25 turn PCB mount with top adjuster • 25 turn PCB mount with side adjuster	• 25 turn PCB mount with top adjuster
Capacitors	• Ceramic • Film	• Ceramic • Film • Electrolytic
Resistors	• Film • Ceramic	• Film
IC mounting	• Direct mounting • IC sockets	• IC sockets
IC connection type	• DIP connections (through hole)	• DIP connections

The following table lists the actual specifications for the PCB boards that were designed and implemented for the STATCOM inverter:

Table 3. 3: STATCOM PCB Specifications

Specification	Board 1	Board 2	Board 3
Material	High Performance FR4 substrate	High Performance FR4 substrate	High Performance FR4 substrate
Size	100mm x 120mm	72mm x 100mm	72mm x 100mm
Number of Layers	2	2	1
Track Width	1.1 mm	1.1 mm	1.1mm
Pad size	1.1mm	1.1 mm	1.1 mm
Minimum track clearance	0.5 mm	0.5 mm	0.5 mm
IC type	• 14 pin DIP IC’s • 16 pin DIP IC’s	• 8 pin DIP IC’s • 14 pin DIP IC’s	• 5 pin DIP PCB voltage transducer • 9 pin DIP PCB current transducer
Connector types	• 10 pin MOLEX • 4 pin MOLEX	• 10 pin MOLEX • 3 pin MOLEX • 2 pin MOLEX	• 2 pin MOLEX • 3 pin MOLEX
Component connection type	Through hole	Through hole	Through hole
Profile Standard	• UM100	• UM72 • UM100	• UM72 • UM100

Please note that although PCB’s 2 and 3 were designed as such that they will both conform to the UM100 and the UM72 profile standards. Since the current controller on PCB 1 was too big to fit onto the UM72 profile standard, the UM100 profile standard and the UM100 PCB profile has been utilized for the purpose of this project.

3.11 Implementation

The first step in the implementation included updating the system schematic with the modifications that were made with regards to the removal of the passive components and the implementation of active components in its place. The schematic was drawn using Altium Designer Summer 09 version software and a copy of the schematic can be found in Appendix A.1 at the end of this thesis. Once the schematics were drawn, an initial prototyping on breadboards were done for the summer circuits and tested. This was done to verify that the summer circuit was performing as it was expected to. Once all the new active components that were replacing the passive components were tested on the breadboard and the results verified with the passive components, the schematic was then converted into a PCB design. Since the version of Altium Designer that was available did not contain all the libraries and the purchasing of the libraries would have been too expensive, an alternative PCB design software was used. The PCB design software that was used for this project was the freeware version of DIP Trace. The freeware version of DIP trace had all the necessary library files for the development of the printed circuit board designs for this project. Screenshots of the PCB designs are shown in section 4.3 of this thesis. Once the designs were completed, the PCB design files were converted into Gerber files so that the manufacturers could make the PCB's. Upon completion of the conversion of the files, quotations were taken from local and international companies for the manufacture of these PCB's. During the quotation process, it was found that local manufacture would have been too expensive for this project and hence international manufacturers were used. Boards 2 and 3 were manufactured in the United States and cost $30 dollars each to manufacture while Board 1 was manufactured in China for $40. The manufactures also provided a compliance certificate for the bare board testing that they had done. The compliance certificates can be found in Appendix C.

While the PCB's were being manufactured overseas, the development of the SIMULINK models of the various switching types that are used in this STATCOM inverter were made. A SIMULINK model of the bipolar switching, unipolar switching and the multimodal switching were developed. The SIMULINK models provided a set of Theoretical results for comparison with when the STATCOM inverter was implemented in hardware.

By the time the SIMULINK models were completed, the first set of PCB's had arrived and the manufacturing process began. By the time the first PCB board was ready, the other two PCB's had arrived and were also manufactured. Once all three PCB's had been manufactured, the PCB’s were then interfaced to a Siemens S7 – 200 PLC and the testing process was commenced. The testing process is described in detail in the following section. Upon the completion of the testing process and when the results that were obtained were dimmed satisfactory, an EDMI MK7C atlas smart energy meter was obtained and was interfaced to a PLC. Once the Energy Meter was successfully interfaced to the PLC, the power factor register from the smart energy meter was read via the MODBUS command. This power factor was then compared in the PLC. The PLC would have then triggered the Q control loop in order to enable the STATCOM inverter to push current into the grid to correct the power factor. In order to check if the power factor section is working, the STATCOM inverter first has to be commissioned and unfortunately due to time constraints the commissioning of the STATCOM inverter has been pushed onto a later date.

3.12 Testing Procedures

The following test procedures were used to obtain the results that are discussed in the following section of this report:

1. The laboratory power supply was configured to create a positive nine volts and negative nine volts with a floating ground. This was done to ensure that there were no ground loops in the setup and that everything had a single common ground connection.
2. Once the power supply was configured, the STATCOM inverter was connected to the power supply so that all the active components started working. After the STATCOM inverter was connected to the power supply, it was interfaced with a Siemens S7-200 PLC. The overall setup of the equipment is shown in the photo below.

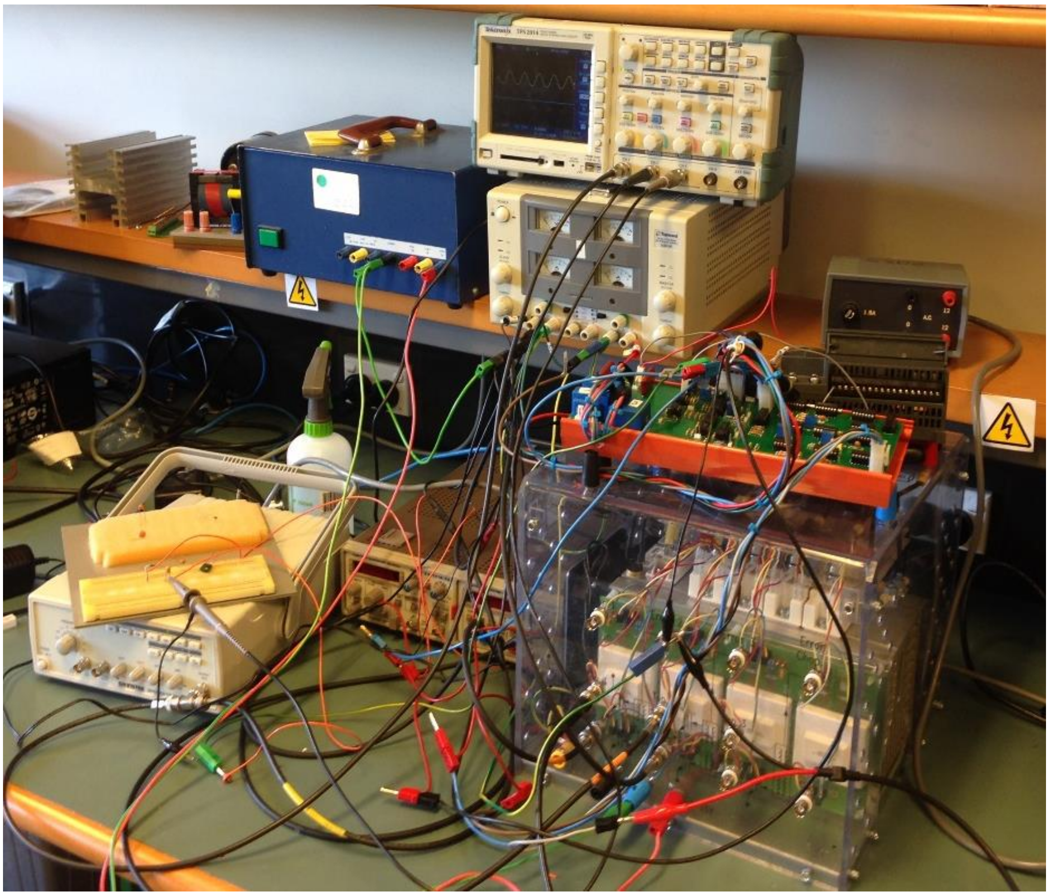


Figure 3. 6: Photo of overall setup

Once the STATCOM inverter was connected to both the power supply and the PLC, a function generator which was producing a 50Hz sine wave was used as the reference current for the STATCOM inverter and a phase shifted 50Hz sine wave was used to as the input current for the STATCOM inverter. The results obtained are discussed in the following chapter.

3. Once the STATCOM inverter was tested and the results obtained were deemed satisfactory, the STATCOM inverter was interfaced with a SEMI TEACH DEVICE. This contained a heat sink, two large capacitors and isolated gate drives that would be used for the high voltage switching. Due to time constraints and the fact that the STATCOM inverter would have been required to be connected to the grid, this part of the testing was not done. This part of the testing has been left to the commissioning phase, where experienced University of Southern Queensland technicians who specialize in high voltage power would be available in order to supervise the high voltage testing.
4. After the STATCOM inverter testing was done, the focus then turned to the implementation of the VAR controller. Although there was limited hardware involved in the VAR controller side of things, the challenge was implementing

the algorithm and getting the PLC to extract the register from the smart energy meter.

5. The first step of the VAR controller implementation involved the configuration of the hardware. The EDMI smart energy meter had to be connected to the SBS MODBUS translator in order to extract the power factor register from it. The MODBUS translator was then connected to a network switch which in turn was connected to a computer and a PLC.
6. Once all the hardware associated with the VAR controller was connected, the settings on the smart energy meter had to be changed in order to initialize the RS232 port on which the SBS MODBUS translator was attached to. After the communication was established, a PLC algorithm was developed where by the power factor register was extracted from the smart energy meter and was compared in the PLC. The PLC would then send a signal to the STATCOM inverter to push current into the localized load or grid until a unity power factor is achieved.

Chapter: 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter looks at the results of research carried out in the project and compares theoretical results from SIMULINK models for various switching topologies, which are unipolar, bipolar and multimodal. It also discusses aspects of the PCB design and delivered product.

4.2 Simulation Discussion

For the purpose of acquiring theoretical results, SIMULINK models were made. The SIMULINK models were made for:

1. Bipolar Switching
2. Unipolar Switching
3. Multimodal Switching

A standard version of MATLAB was used for the creation of this SIMULINK models and therefore all the blocks are just basic mathematical functions. These functions work together simultaneously to produce the waveforms that are expected from the actual STATCOM inverter once it is implemented. These theoretical results form the basis of the results which are expected from the STATCOM inverter. A virtual scope that is available with SIMULINK was used to view the waveforms from the SIMULINK models.

Whilst only the standard version of MATLAB and SIMULINK was used for this project, there are toolboxes available which would give the theoretical comparisons quite easily. The toolbox in particular that contains the GTO-Based STATCOM inverter in SIMULINK is called Sim-Power-Systems (MathWorks Pty Ltd 2014). According to the MathWorks (MathWorks Pty Ltd 2014) website, the GTO-Based STATCOM is available under the power electronics based models. The Sim-Power-Systems toolbox was not used for the purpose of this project due to the cost of purchase associated with it, since the toolbox is a relatively expensive add on and is only compatible with newer versions of MATLAB. The SIMULINK models that were made are discussed below:

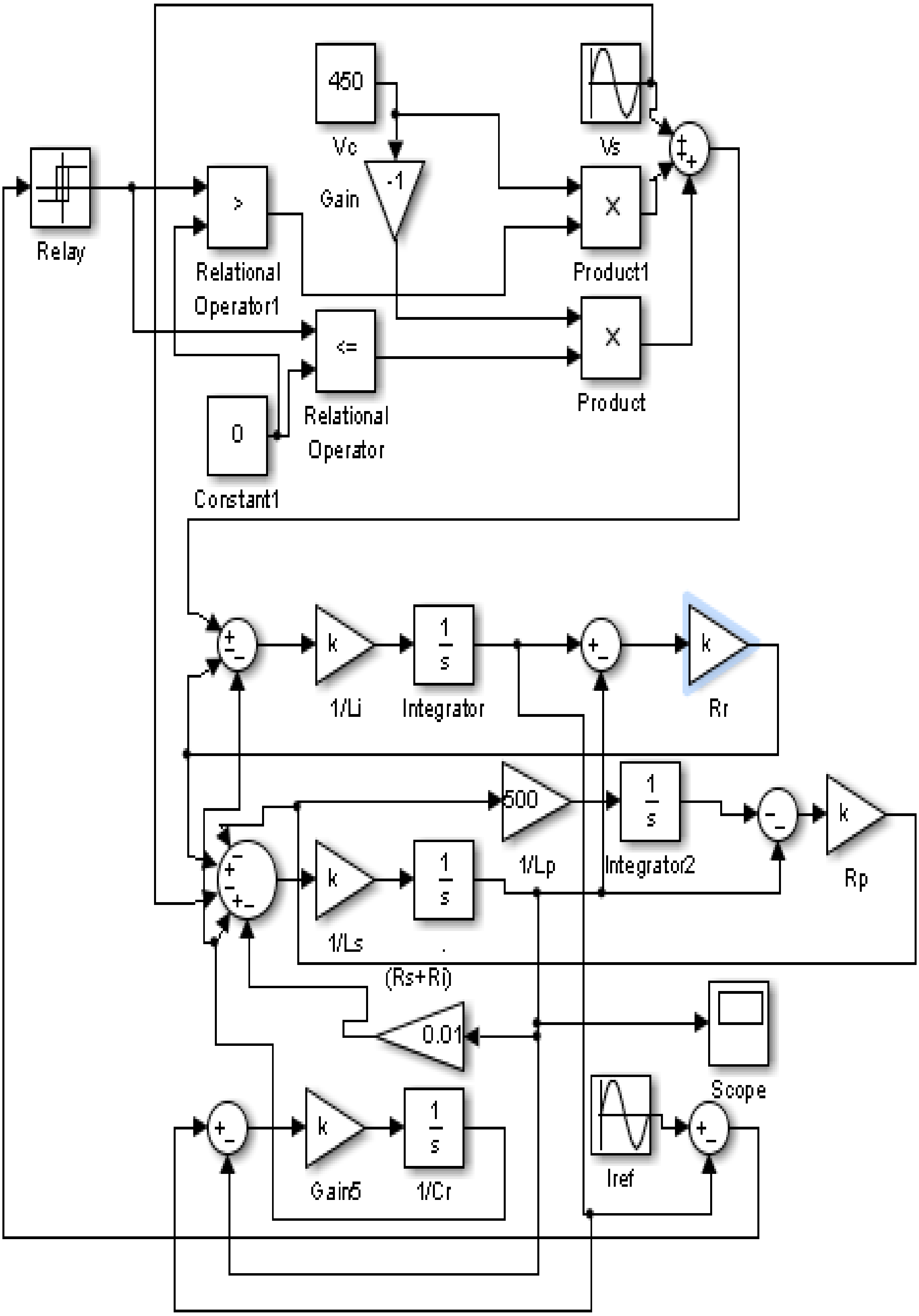


Figure 4. 1: Bipolar Switching with Ripple Filter Simulink Model

The SIMULINK model which is shown above is created to model the bipolar switching strategy. In order to achieve the bipolar switching model, a combination of simple mathematical functions which are built into SIMULINK were used. The model also contains a LCL ripple filter, so that the theoretical waveforms which are simulated can produce the results which would be expected with the actual STATCOM inverter. A sample of the SIMULINK output for the bipolar switching is attached below

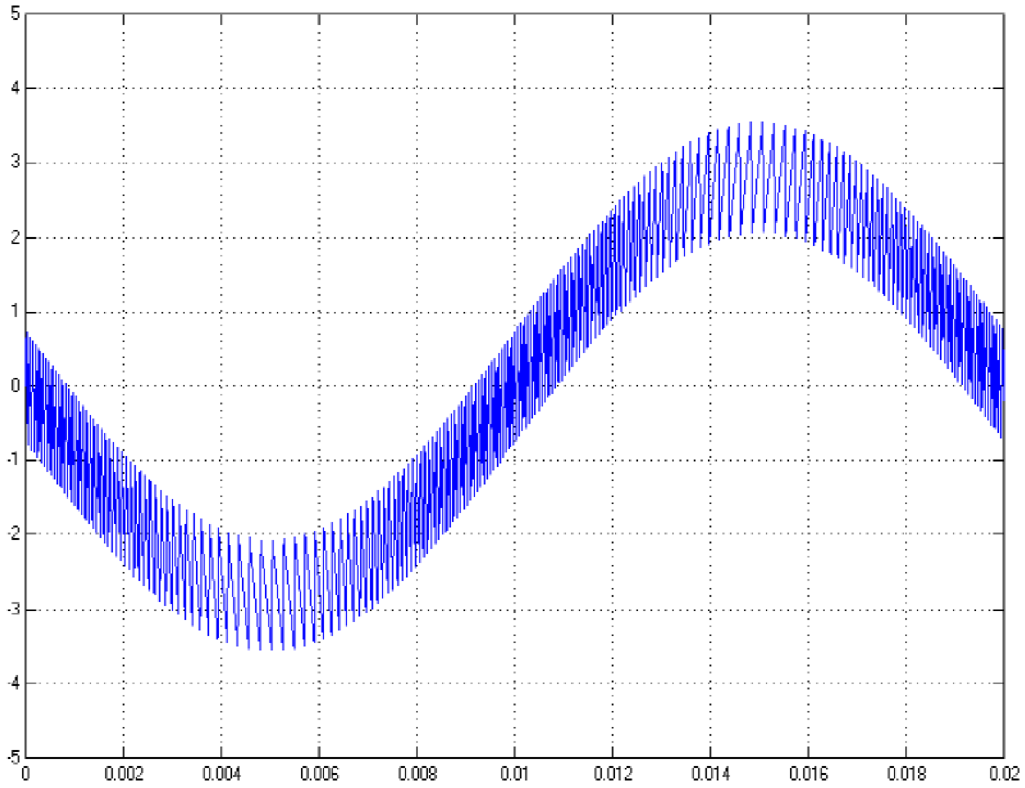


Figure 4. 2: Simulink model results of the Bipolar switching output

Although the above waveform sample is only from the SIMULINK model, the distortions and the ill effects of the bipolar switching method are quite obvious. From the bipolar switching waveform shown above, it can be seen that it has a lower frequency at the peak (top) and at the trough (bottom) of the waveform. A lot of total harmonic distortion would be caused by this switching strategy because of its relatively fast switching. Since the waveform given above is a SIMULINK model, it is entirely based on mathematical models, the actual waveform from the STATCOM inverter is expected to be a bit worse due to real world losses.

The SIMULINK model given below is of a unipolar switching strategy. This model has again been made with a combination of basic mathematical functions from SIMULINK and the virtual scope in SIMULINK was used to observe the waveform at the output.

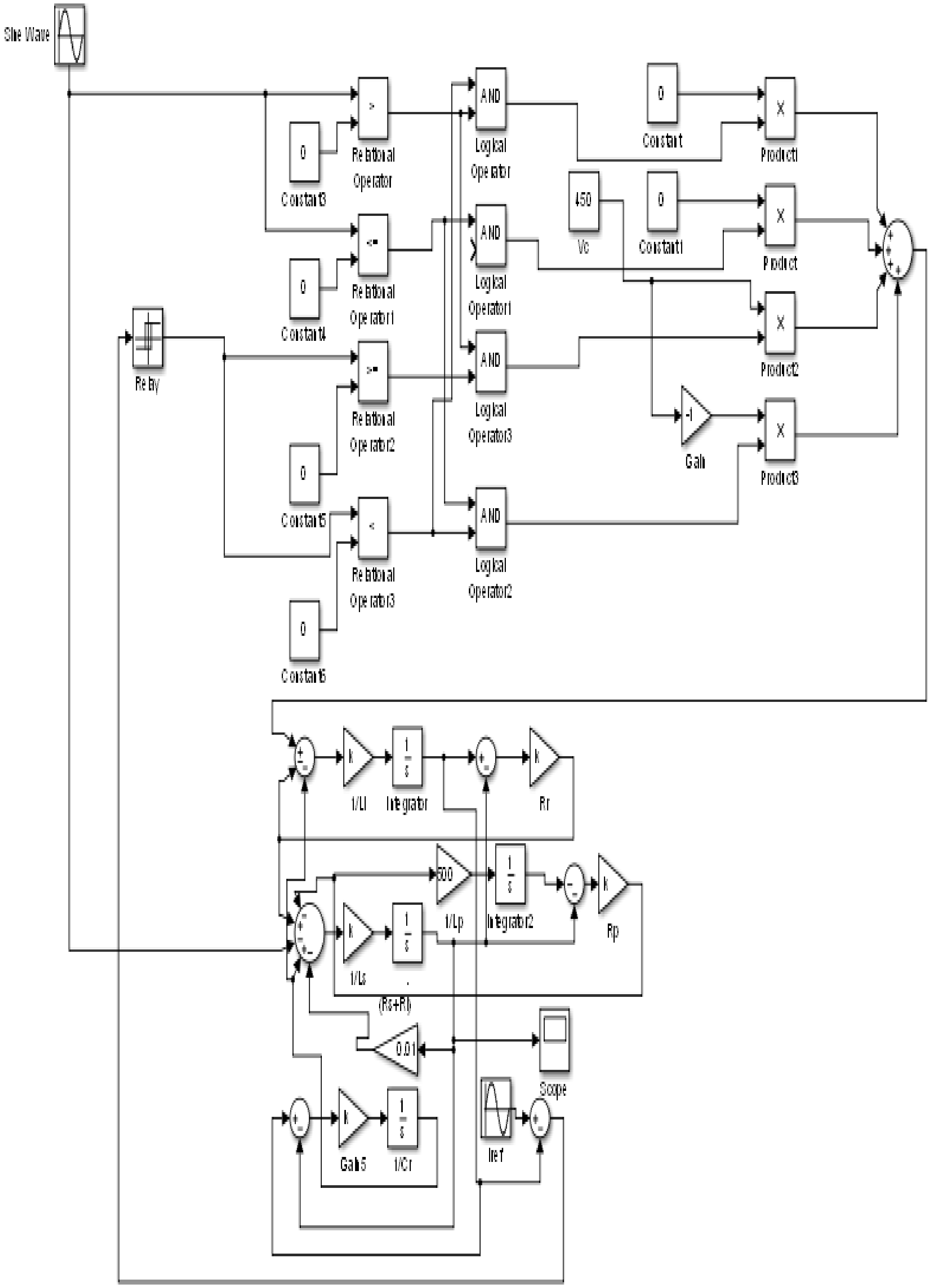


Figure 4. 3: Unipolar Switching with Ripple Filter Simulink Model

The theoretical waveform for the unipolar switching is shown in the picture below. From the theoretical results that has been obtained from the SIMULINK model, it is evident that the unipolar switching produces a much cleaner waveform in comparison to the bipolar switching. On the other hand it is also evident that the unipolar switching is unstable around the zero crossing area and therefore there is a huge amount of distortion around the zero crossing area. This distortion around the zero crossing will cause ringing in the LCL filter.

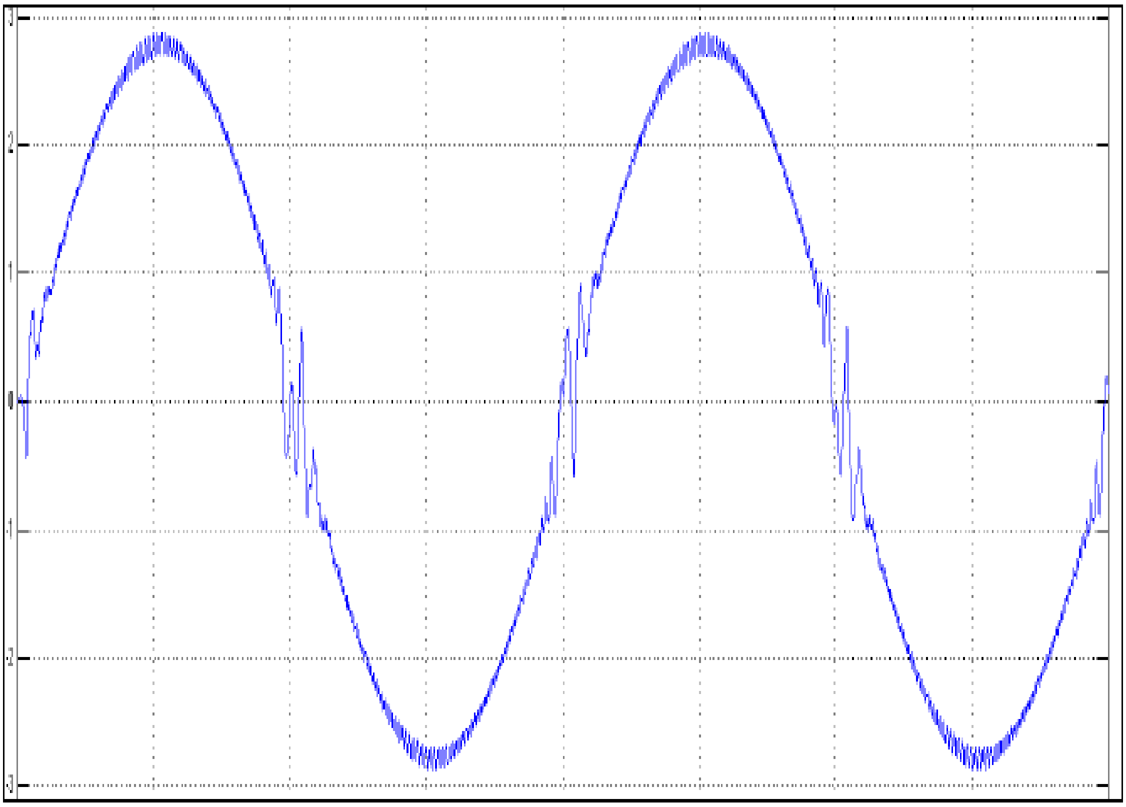


Figure 4. 4: Simulink Results for the Unipolar Switching Operations

With the results of both the theoretical bipolar switching and theoretical unipolar switching analyzed, it was seen that both the switching types had their own advantages and disadvantages. It was therefore decided that a multimodal switching strategy be modelled. Therefore a multimodal switching SIMULINK model was made by combining both the unipolar switching and the bipolar switching models. System delays were also introduced and virtual scopes were placed at multiple places along the model to find out the waveform models being output by the SIMULINK model. However, only the sine wave which will be injected into the grid is looked at in this section and is attached below:

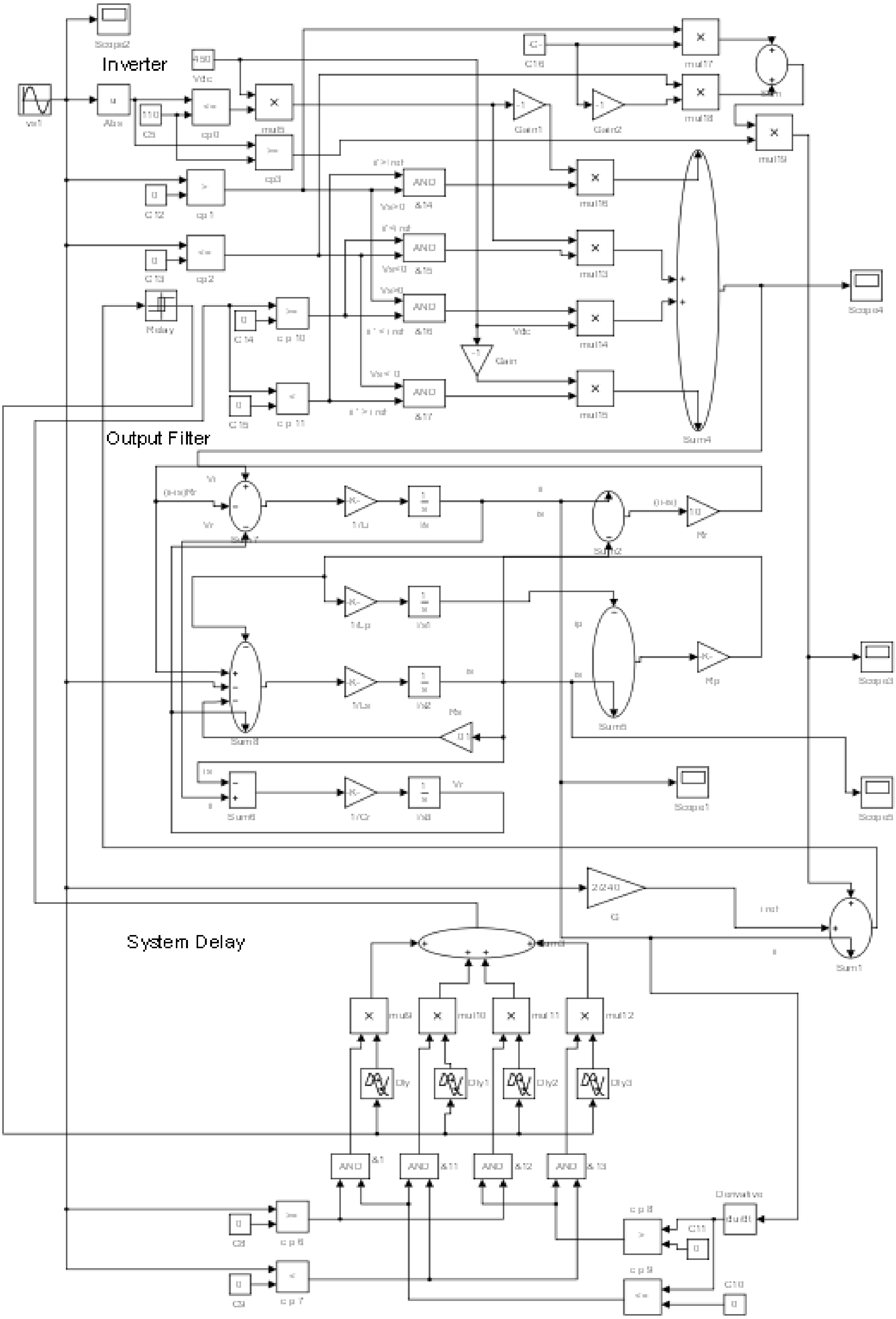


Figure 4. 5: Multimodal Inverter with Delay Simulink Model

From the waveform that is shown below, it can be said that multimodal switching would be the ideal switching type to be used, as it is much cleaner than the other two switching types. The multimodal switching type works on the basis that unipolar switching will be used for most part of it and the bipolar switching will be used around the zero crossing area where the unipolar switching is distorted, and hence yielding a much cleaner sine wave which will be injected into the grid.

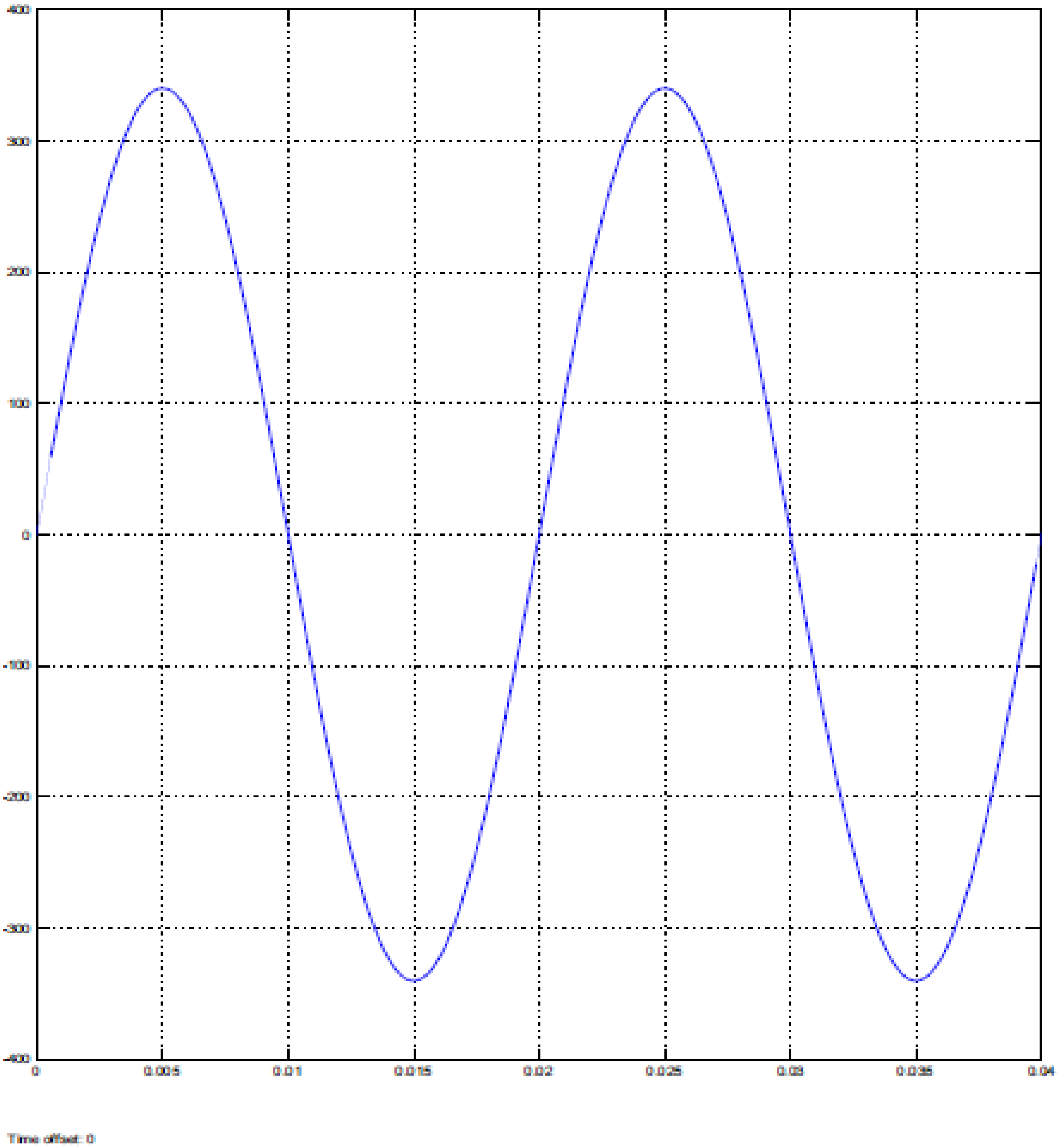


Figure 4. 6: Multimodal STATCOM Inverter Waveform

With the theoretical results now available for comparison, the waveforms from the actual STATCOM inverter will be discussed in the later part of this thesis.

4.3 PCB Design and Implementation

A very important aspect of this project has always been the design and implementation of the STATCOM inverter on PCB's. Although all the circuits could have been designed on a single PCB, it was decided to use multiple PCB's in order to make debugging easier. All the PCB's had to be strategically designed so that the circuits would not interfere with each other and probing the circuit was made much easier. All the PCB's that were designed and implemented are discussed in detail in this section.

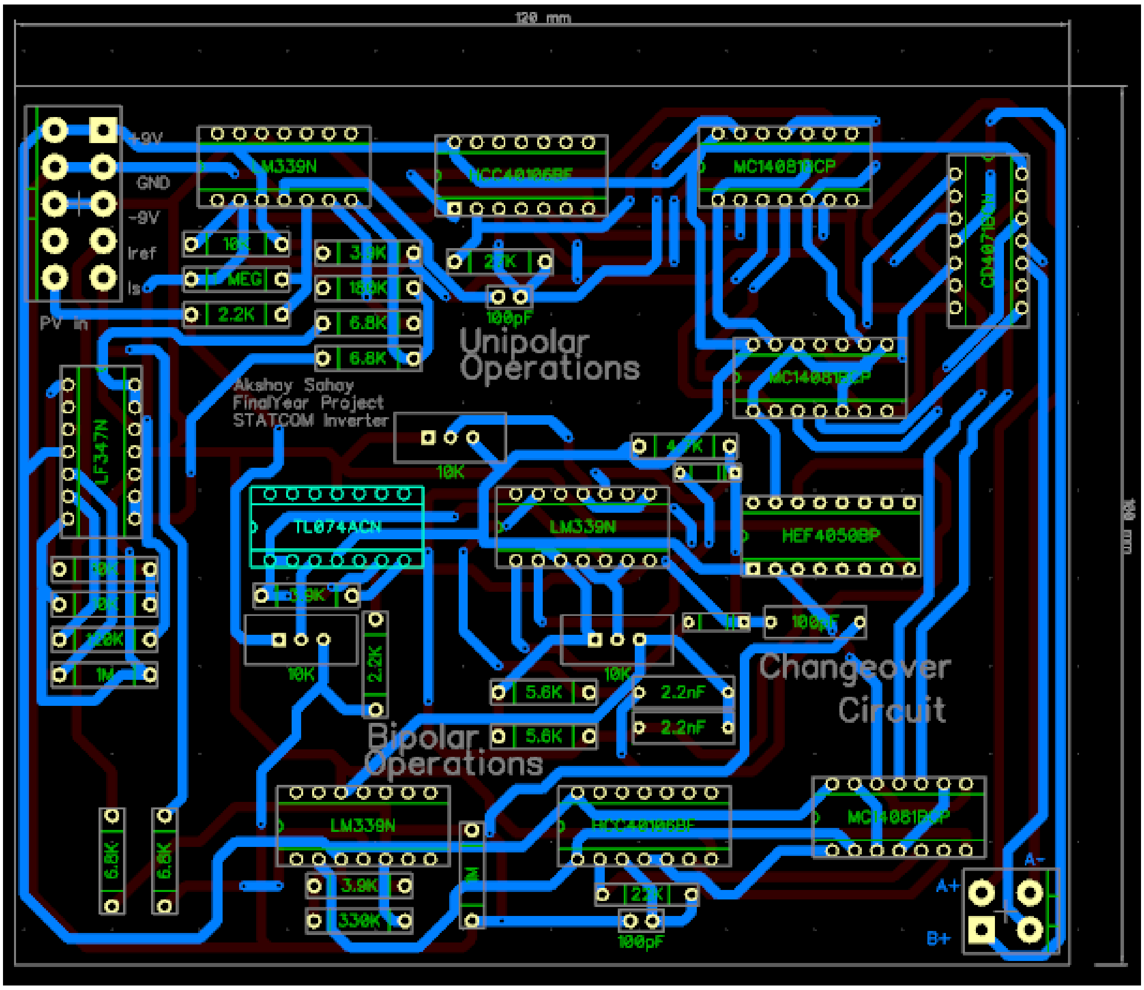


Figure 4. 7: PCB 1 DIP Trace Circuit design

The above picture is of the PCB design for the first PCB which was bigger in size than the other two PCB's, but was designed to sit on a UM100 profile. The dimension of PCB 1 was 100mm x 120mm as seen in the above picture. The PCB was designed to have one input and one output. The input of the PCB was the ten pin MOLEX connector on the top edge and the output of the PCB was a four pin MOLEX connector at the bottom edge. The unipolar switching circuits were at the very top of the PCB and the bipolar switching circuits were on the opposite end (at the very bottom) with the changeover circuit in the middle of the board. This strategy was adopted to minimize signal distortion and interference of the two switching types with each other.

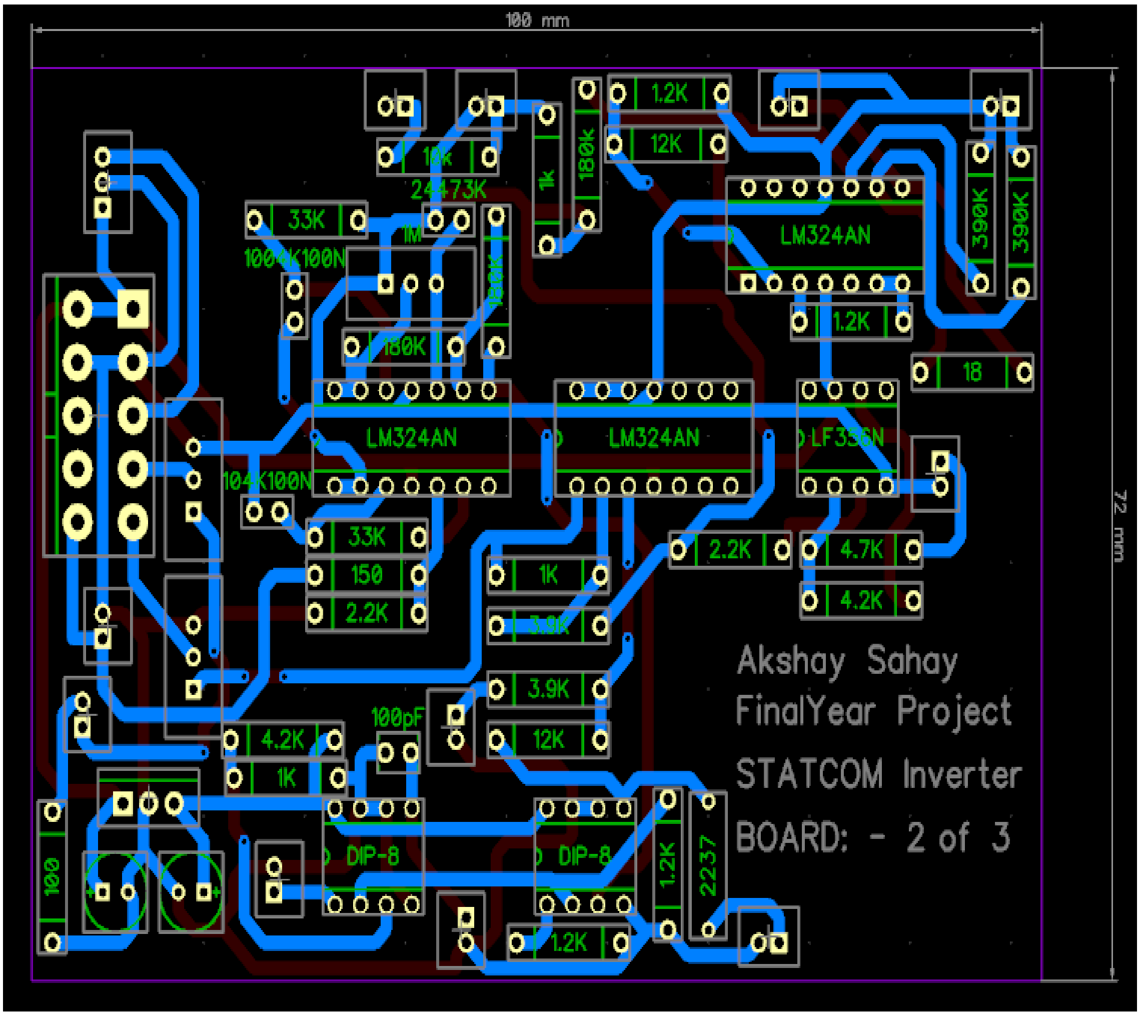


Figure 4. 8: PCB 2 DIP Trace Circuit design

The above picture shows the design of PCB 2. PCB 2 was probably the most important PCB in the design as it was responsible for providing the electricity and the signals to the other two PCB's. There were multiple inputs and outputs for PCB 2. The ten pin MOLEX connector on the left hand side of the PCB was used to transfer the signals across to PCB 1 (the current controller). The other two pin and three pin MOLEX connectors were used as either inputs to the board itself or as an output from the board and into the PLC. Although PCB 2 was initially designed for a UM72 profile with dimension size of 72mm x 100mm, it also fit the UM100 profile with ease and therefore the UM100 profile was determined as the standard housing for this project.

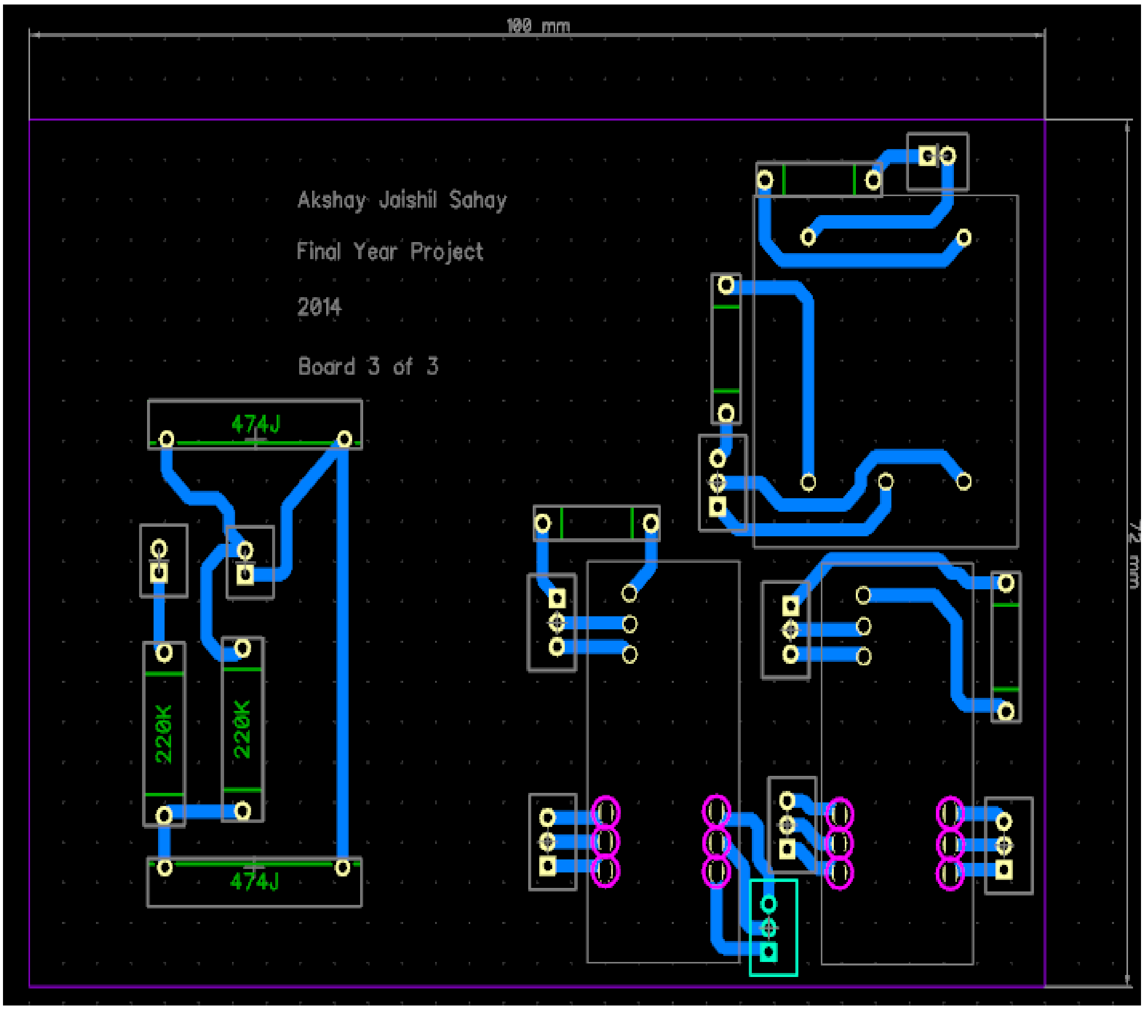


Figure 4. 9: PCB 3 DIP Trace Circuit design

The above picture is of the design of PCB 3. Since PCB 3 had most of the high voltage connections on it, it was decided to have some free space on it for the purpose of safe probing. PCB 3 mainly housed the two current transducers, a voltage transducer and the DC offset circuit. The dimensions of PCB 3 was 72mm x 100mm.

The following pictures are of the actual PCB's that were printed and manufactured for this project. The pictures are of the individual PCB's that were manufactured and the solder work that was done on the other side of the PCB is also shown in the pictures below:

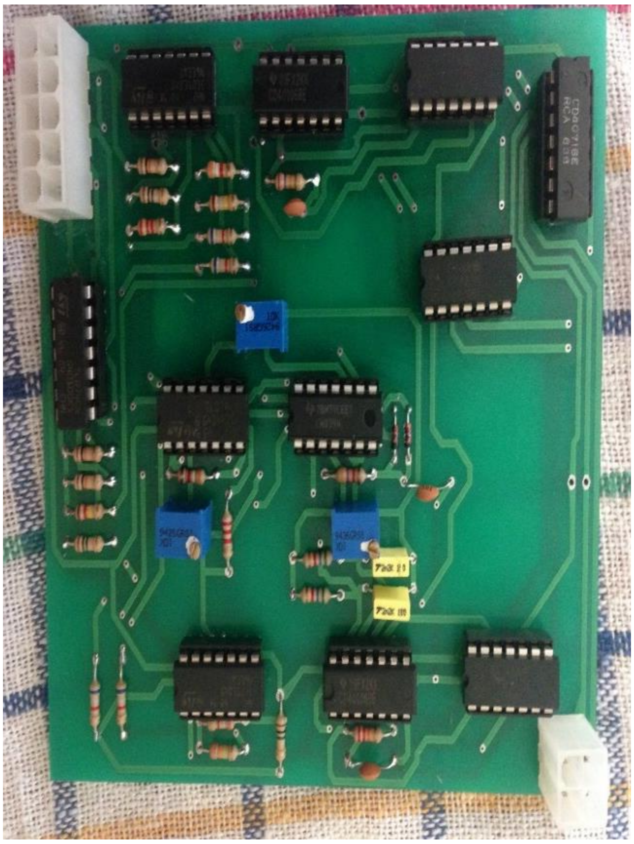


Figure 4. 10: Photo of Board one assembled

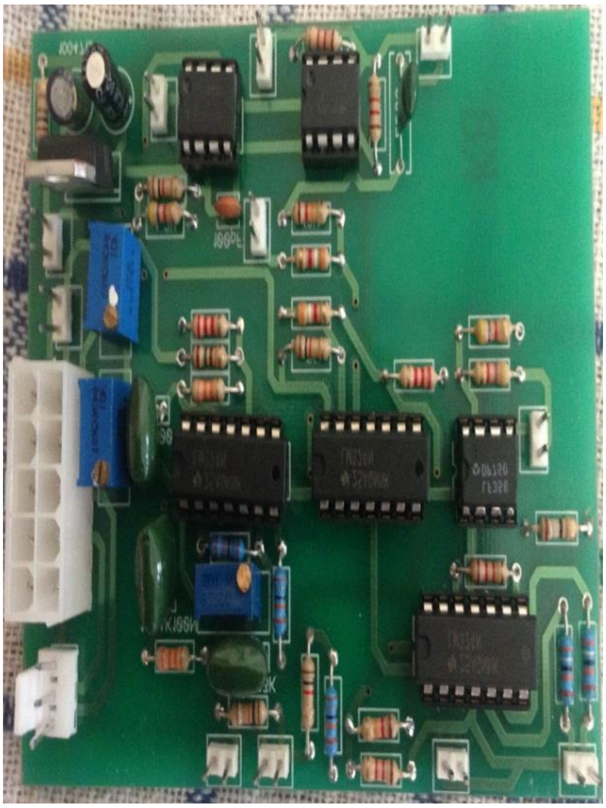


Figure 4. 11: Photo of Board two assembled

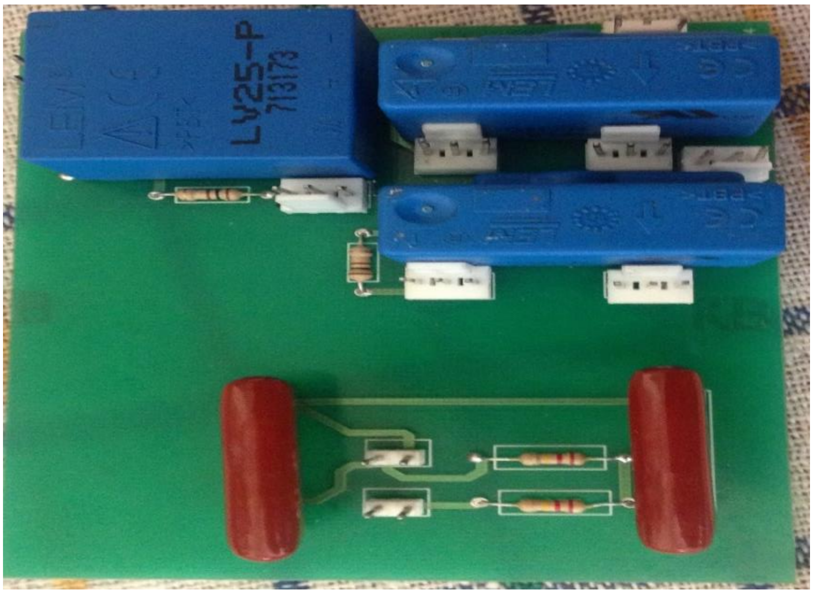


Figure 4. 12: Photo of Board three assembled (left), Solder work for board three (right)

The above pictures show the work done on each the individual PCB’s. Once the PCB’s were manufactured, they were sprayed with a PCB cleaner which took out any dirt which might have been on the PCB board and coated the PCB’s with a thin film layer which sealed off any dead spots on the PCB’s. The final assembly of the PCB sitting on the UM100 profile is shown in the picture below:

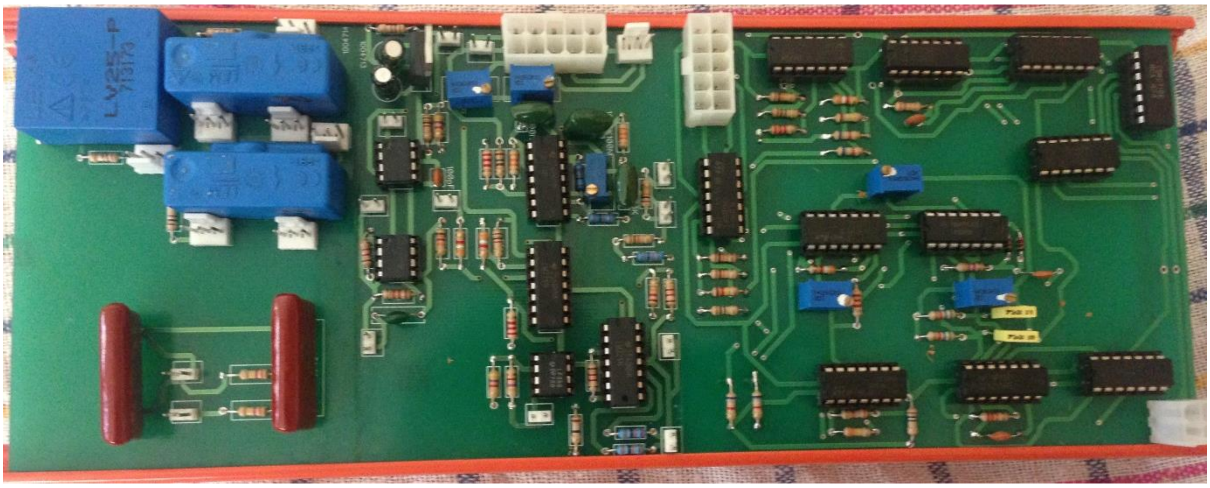


Figure 4. 13: Photo of Complete STATCOM inverter (fully assembled) on UM100 PCB profile

4.4 STATCOM Inverter operations

The overall operations of the STATCOM inverter is shown in the block diagram below which was adapted from Dr. Bowtell’s PHD thesis (Bowtell 2010).

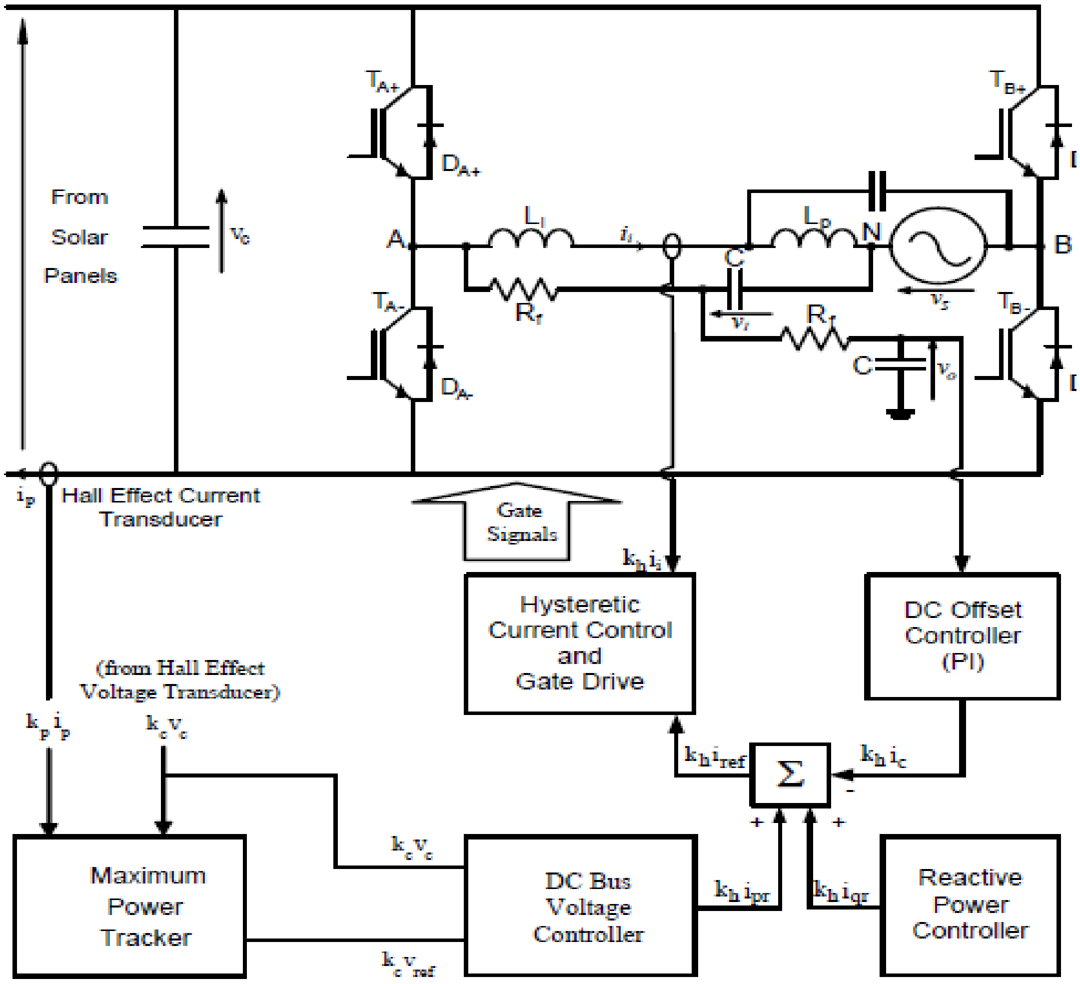


Figure 4. 14: Block diagram of STATCOM inverter operations (Source: - Bowtell PHD Thesis (Bowtell 2010))

The above diagram shows the overall operations of the four quadrant STATCOM inverter. The diagram is a block representation of the individual circuits and the PLC algorithms that are required at the different stages of operations for the STATCOM inverter.

The photo given below identifies all the different components that form the overall STATCOM inverter. PCB 3 is mainly connected to the high voltage side of the inverter and it is for that reason all the components used on it have an average voltage rating of 400V AC. As an added precaution, all the connections coming in and out of the PCB's were through MOLEX connectors which insulate all the wires. All the testing that was done with regards to this STATCOM inverter was done at relatively low voltages as an added precautionary measure in consideration of other users of the research project lab.

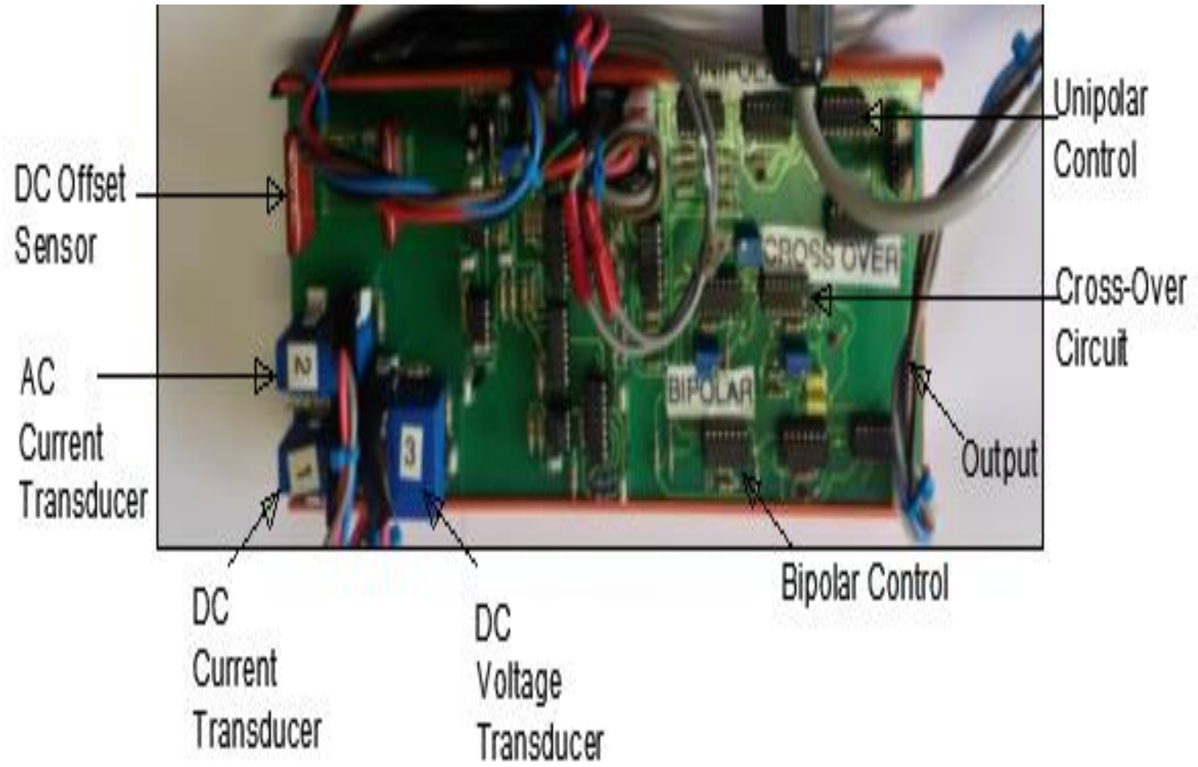


Figure 4. 15: Photo with identification of components

The STATCOM inverter has to then be connected to the SEMI TEACH DEVICE box that was setup by the University’s power technicians. The SEMI TEACH DEVICE box contained a large heat sink, gate drives and capacitors. In order to connect the four output signals of the STATCOM inverter to the SEMI TEACH DEVICE box, BNC cables which got divided into positive and negative banana leads were used. The negative leads of the BNC cable were connected to the floating ground of the power supply in order to prevent a ground loop or to have any interference from any of the other sources. The overall setup of the STATCOM inverter is shown in the following picture. The results that were obtained for the different switching styles were obtained using partially this setup. The breadboard which is part of the overall picture below contains a small RC load which was connected to the output of the function generator in order to get the STATCOM inverter to switch.

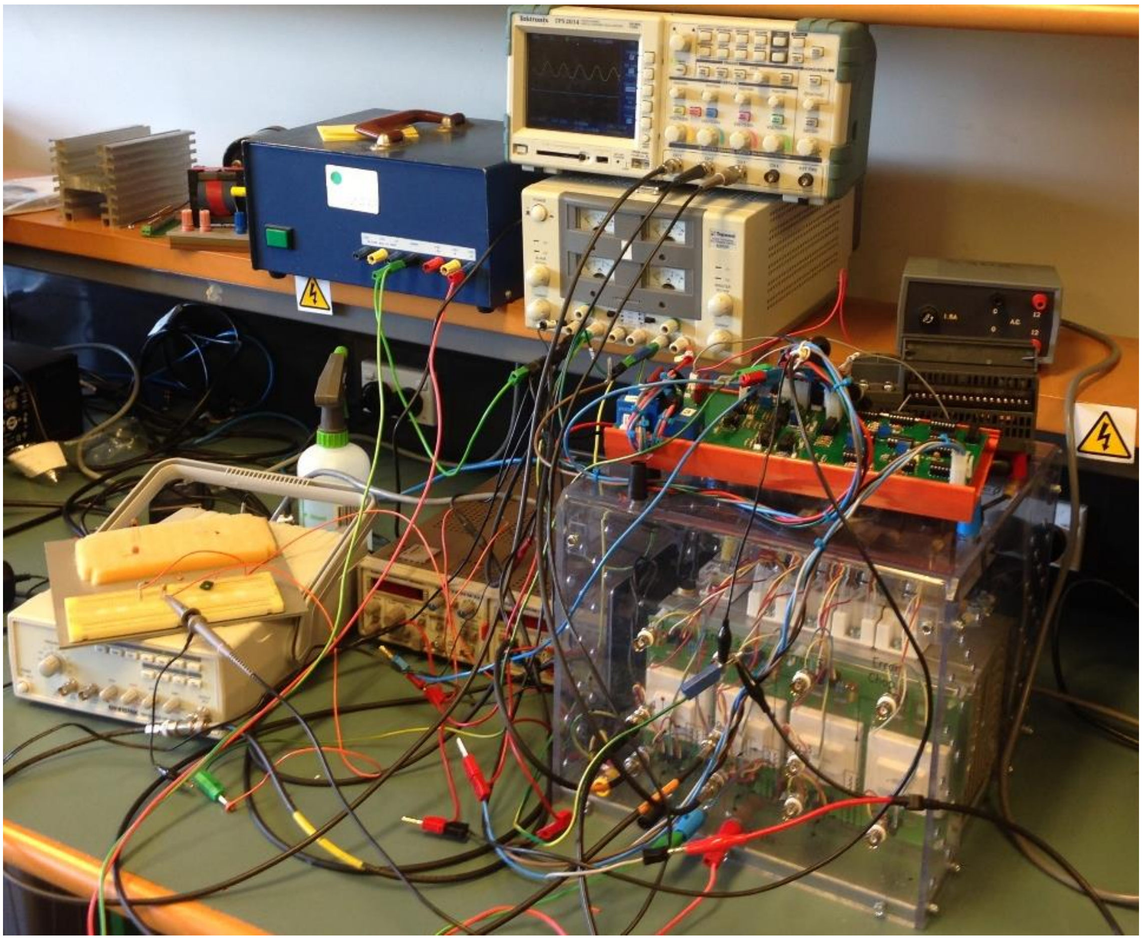


Figure 4. 16: Overall STATCOM inverter setup

The following waveforms were obtained at the different points of the STATCOM inverter:

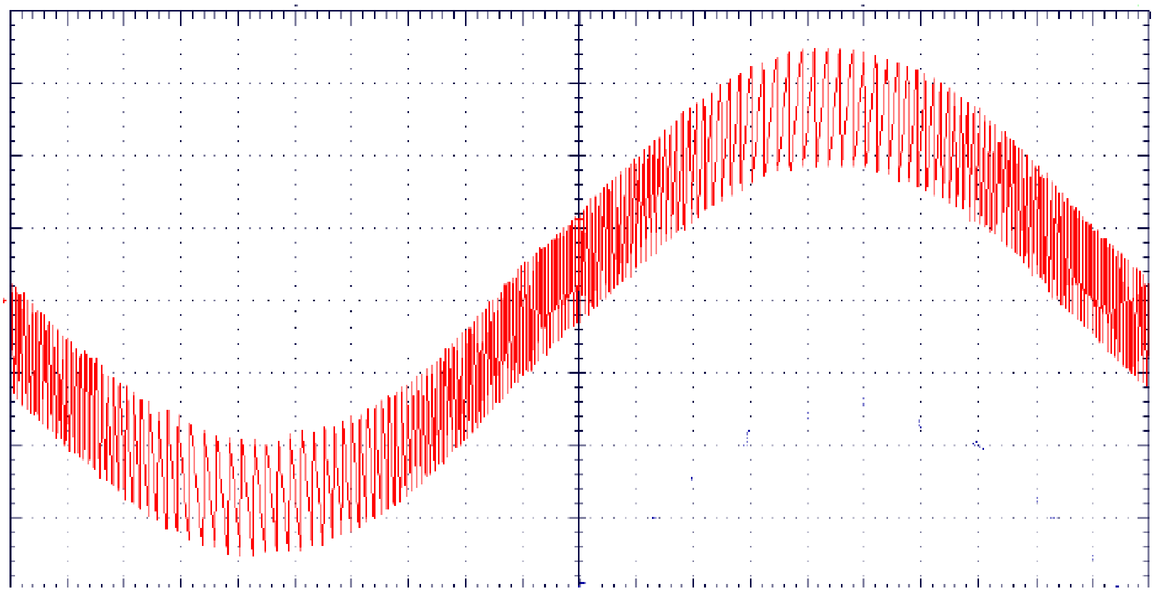


Figure 4. 17: Experimental Bipolar Switching Waveform

In the above picture, the experimental bipolar switching waveform is shown. This waveform was obtained by probing at the output of the bipolar circuit which is located at the bottom end of the current switching waveform. When the experimental waveform is compared against the theoretical waveform that was shown in the earlier part of this thesis, it can be seen they are very similar to each. The experimental waveform has a little bit more distortion in comparison to the theoretical waveform but that was to be expected due to imperfections and losses with regards to the IC's being used. In the experimental waveform, the low frequency at the trough (bottom) and at the peak (top) is more evident in comparison to the theoretical waveform that was shown earlier. And as per the literature review there will be a higher loss during this switching mode.

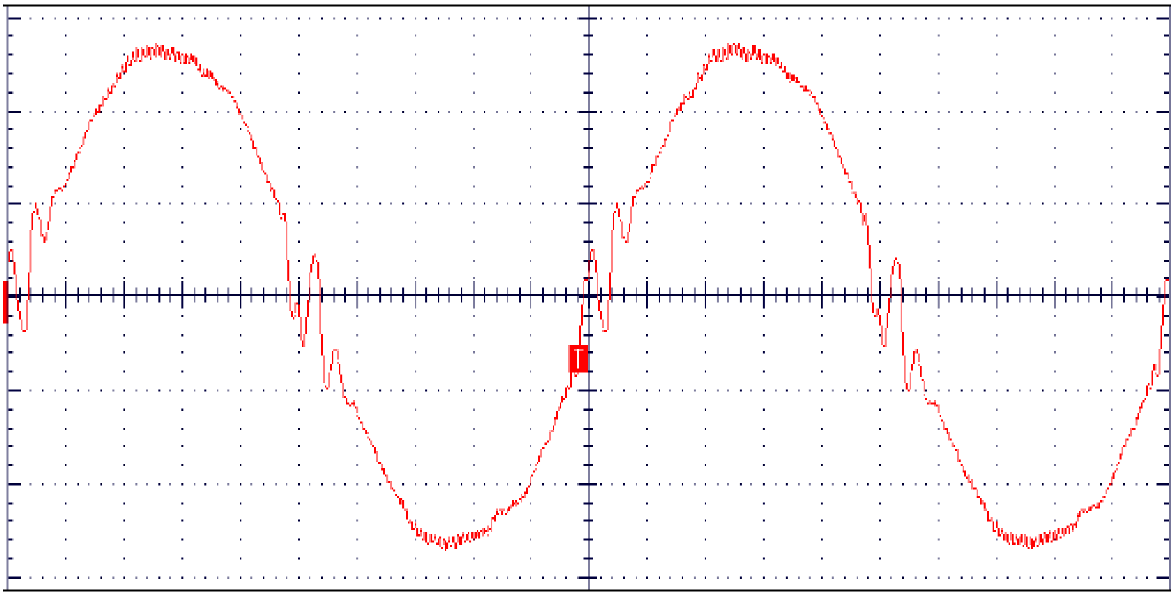


Figure 4. 18: Experimental unipolar switching waveform

The waveform shown above shows the experimental output at the unipolar switching circuit. When this experimental unipolar waveform is compared against the theoretical unipolar switching waveform which was discussed earlier on in this dissertation, it can be seen that there is a lot more distortion in the experimental waveform in comparison to the theoretical waveform, this was again expected due to imperfections and losses in the IC's that were being used for this project. The distortion of the unipolar switching around the zero crossing is also more evident in the experimental results in comparison to the theoretical results that were discussed. The experimental results indicate that the unipolar waveform was not as clean as it was indicated in the theoretical results. However, this unipolar switching will be combined with the bipolar switching to obtain the multimodal switching results. Due to the distortion around the zero crossing area, there was some ringing in the LCL filter, however this was not considered for the purpose of this project.

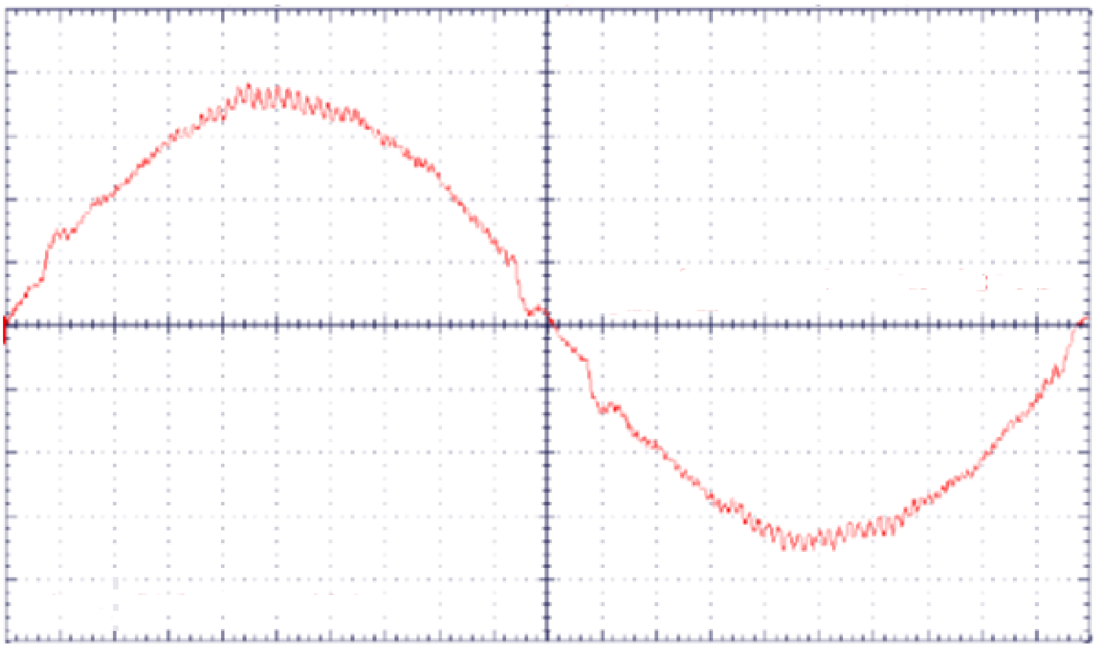


Figure 4. 19: Experimental results for multimodal switching

The above picture shows the experimental waveform for the multimodal output of the STATCOM inverter. When this waveform is compared against the theoretical waveform from the earlier section, it can be seen that there is a lot more distortion in the experimental results in comparison to the theoretical results. The theoretical waveform that is shown in the earlier section is almost a pure sine wave with little to no distortion evident on it, whereas this experimental waveform shows a lot of distortion. The distortion which is present in this waveform is mainly around the zero crossing area of the waveform. Although the distortion around the zero crossing is not as bad as the distortion which is shown with the unipolar switching, there is still a significant amount of distortion present. The multimodal switching of the inverter is achieved by combining the unipolar switching and the bipolar switching. The STATCOM inverter mainly uses unipolar switching except around the zero crossing, where it switches to bipolar switching so that it smoothers out the distortion that was present around the zero crossing for the unipolar switching. The small distortions which are present at the zero crossing for the experimental multimodal waveform is from the changeover circuit. The distortion is caused when the unipolar is switching to bipolar for the zero crossing and vice versa. However, a much cleaner waveform is injected into the grid which has significantly lower ill effects with regards to harming the electrical network infrastructure, as was discussed in the literature review.

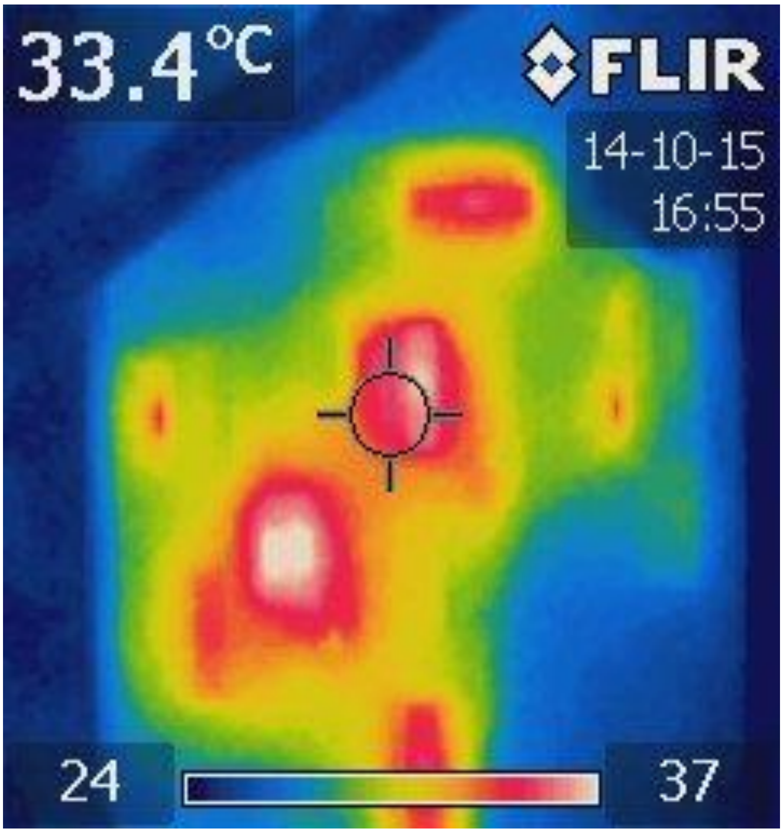


Figure 4. 20: Thermal Test Results for the STATCOM inverter

The above picture shows the thermal stability of the four quadrant STATCOM inverter. To obtain the thermal results, a FLIR thermal imaging IR camera was used. The ambient temperature of the lab on the day this thermal testing was done was twenty-five degrees Celsius as the air conditioning was kept off for the purpose of this thermal testing. The above picture shows that the hotspots on the circuit boards. The hotspots are mainly concentrated around the areas where there are active chips. This thermal testing also confirms that there are no short circuits present on the PCB's, as the short circuits would have caused excessive heating on the PCB's which would have in turn would have led to a potential fire risk.

4.5 VAR Controller

The VAR controller which is being implemented as part of this project is mostly algorithm based. There is very minimalist hardware setup for this part of the project. The hardware which is required is an EDMI MK7C Atlas smart energy meter, an SBS MODBUS translator, a Siemens S7 – 200 PLC or Siemens S7 – 1200 PLC, a network switch, a serial to Ethernet translator and a computer with the EDMI software. For this part of the project, a Siemens S7 – 1200 PLC was used because the algorithms that was written for the

Siemens S7 – 200 PLC has to be migrated to the Siemens S7 – 1200 PLC at a later date since the Siemens S7 – 1200 PLC is the current industry standard for the PLC's. The hardware for this part of the project was configured according to the picture shown below:

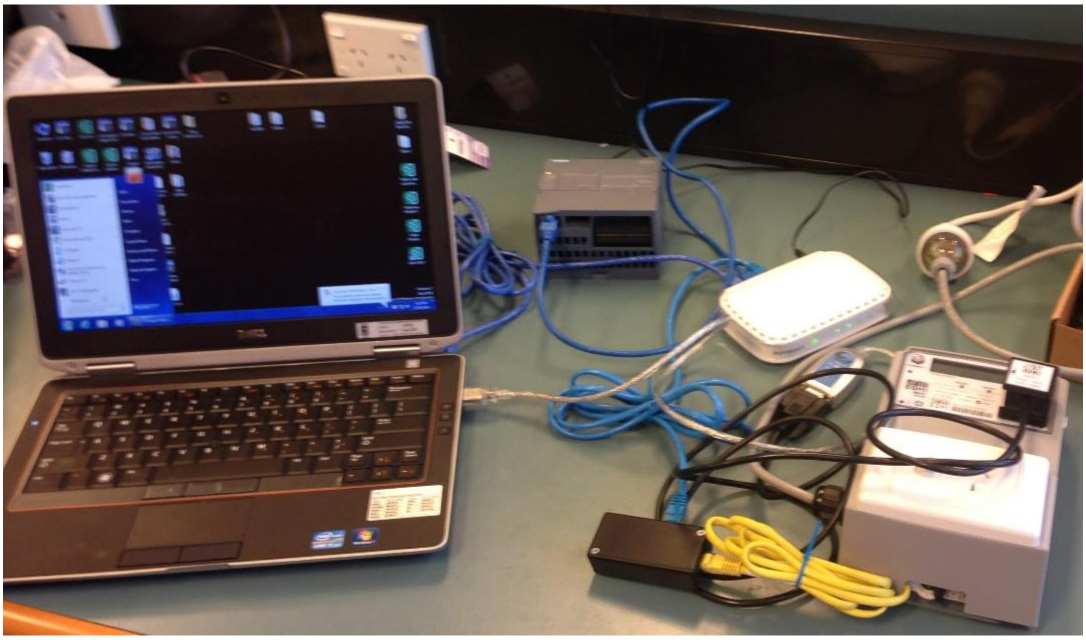


Figure 4. 21: VAR controller hardware setup

Once the hardware was setup, the procedure that was outlined in the methodology was used to initialize the RS232 port to enable communication with the EDMI smart energy meter with a PLC.

Once the communications port for the smart energy meter was enabled, a short MODBUS RTU protocol was setup for the PLC whereby the PLC would read register 9105 of the SBS MODBUS translator. The SBS MODBUS translator copies register 9043 of the smart energy meter into itself and releases it to the PLC. All the smart energy meter register information was obtained from MODBUS DUO Quick Start Guide (Smart Building Services 2012). The power factor was successfully read from the smart energy meter into the PLC using this method and the PLC algorithm was set to compare it against a set threshold. For the purpose of this project, the set threshold was set to 1 meaning unity power factor, but if this method is going to be used at a later date for other purposes, then the power factor threshold could be set between 0.65 lag to 0.9 lag depending on the state and the operator requirements as discussed earlier in the literature review. Once the STATCOM inverter is commissioned and a smart energy meter is interfaced between the STATCOM inverter and the grid, this method could be used for the power factor correction as the algorithm can then be further edited telling the STATCOM inverter to start pushing current into the grid in order to achieve unity power factor.

Chapter: 5

RECOMMENDATION AND FURTHER WORK

It is recommended that a legislative review is encouraged with regards to the Australian Standards so that the full potential of this device can be used in order to improve the power quality in the Australian Grids. It is also recommended that this device be commercialized as it has a lot of potential and will encourage the generation of renewable energy which in turn is going to provide some relief with regards to the increasing demand in electrical energy.

Some other aspects of this project which is yet to be investigated and can form the basis of research projects for future research students are:

- The design of a suitable equipment enclosure incorporating EMI immunity
- Investigation of microcontrollers for control of the STATCOM inverter.
- Design of a SCADA network allowing this setup to be part of the grid controls
- Design of a handshake protocol using the PLCC to enable utility providers to use the setup to improve power quality in their grids by using the STATCOM inverters at peak demand times to help distribute the load on their networks.
- The migration of the Siemens S7 - 200 PLC program to the Siemens S7 - 1200 PLC, as the S1200 PLC is the new standard.

Chapter: 6

CONCLUSION

At the end of this project, a four quadrant STATCOM inverter was successfully redesigned in order for it to be used as a grid based STATCOM inverter. The inverter was successful in acquiring power quality information in real time from a standard smart energy meter. The power quality information obtained from the smart energy meter allowed the algorithm to decide whether active power or reactive power needed to be injected into the grid.by the inverter. The inverter was able to further monitor the power quality while it was injecting the active and reactive power into the grid.

6.1 Four Quadrant STATCOM Inverter Redesign

The first stage of the STATCOM inverter redesign involved enhancement of existing design elements including the general improvement to accommodate adjustment in the system, particularly in the case of elimination of low frequency harmonics in the unipolar controls. The multimode configuration was kept but further system components were added to enable full STATCOM operations with VAR control. Enhanced isolation was achieved by replacing the differential amplifier voltage measuring system with a fully isolated Hall Effect voltage transducer. The current transducers were also upgraded to the most recent technology that was available.

6.2 VAR Controller

Another very major aspect of this research project was the design and implementation of a VAR controller. The function of the VAR controller is essentially to use the reactive power of the STATCOM inverter and help improve the power factor for localized loads and also in the Grid. The VAR controller that was designed and implemented as part of this research project was mostly algorithm based. A PLC was used to extract the power factor from a smart energy meter and compare it against a fixed threshold. Since there was no literature available with regards to implementing a VAR controller with the proposed method, only experimental results are available. From the experimental results, it can be confirmed that the power factor from the smart energy meter was successfully extracted and compared. If the comparison saw that the power factor was below the set threshold, it would trigger the reactive power control loop for the STATCOM to start pushing current into the grid in order to correct the power factor. Even though it is possible to do power factor correction in the grid, this cannot be done in Australia at the current time due to legislations and agreements between utility companies. This may be subject to review at a later date by the Australian Government and the Australian Standards Committee.

References

Ahfock, A & Bowtell, L 2006, 'DC Offset Elimination in a Transformerless Single Phase Grid-Connected Photovoltaic System', *Australasian Universities Power Engineering Conference*, AUPEC06, Melbourne.

Ahfock, A & Hewitt, A 2006, 'DC Magnetisation of Transformers', *IEE Proceedings in Electrical Power Applications*, vol 153, no. 4, pp. 601-607.

Ali, SS, Maroof, M & Hanif, S 2010, 'Smart Energy Meters for Energy Conservation & Minimizing Errors', *IEEE Power Electronics, Drives and Energy Systems (PEDES) & 2010 Power India, 2010 Joint International Conference*, pp. 1-7.

Armstrong, M, Atkinson, DJ, Johnson, CM & Abeyaskera, TD 2006, 'Auto-Calibrating DC Link Current Sensing Technique for Transformerless, Grid Connected, H-Bridge Inverter Systems', *IEEE Transactions on Power Electronics*, vol 21, no. 5, pp. 1385-1393.

Austrailian Standards Commission 2005, 'Grid Connection of Energy Systems via Inverters Part 2: Inverter Requirements', *Standards Australia*.

Benzi, F, Anglani, N, Bassi, E & Frosini, L 2011, 'Electricity Smart Meters Interfacing the Households', *IEEE Transactions on Industrial Electronics*, vol 58, no. 10, p. 4487.

Blewitt, WM, Atkinson, DJ, Kelly, J & Lakin, RA 2010, 'Approach to low-cost prevention of DC injection in transformerless grid connected inverters', *IEEE Transactions on Power Electronics*, vol 3, no. 1, pp. 111-119.

Bock, P 2001, *Getting it Right: R & D methods for Science and Engineering*, Academic Press, USA.

Bojrup, M 1999, 'Advanced Control of Active Filters in a Battery Charger Application', *Doctoral Thesis*.

Bowtell, L & Ahfock, A 2007, 'Comparison between Unipolar and Bipolar Single Phase Grid-Connected Inverters for PV Application', *Australian Universities Power Engineering Conference*, p. AUPEC 07.

Bowtell, L & Ahfock, A 2010, 'Direct Current Offset Controller for Transformerless Single-phase Photovoltaic Grid Connected Inverters', *IET Renewable Power Generation*, vol 4, no. 5, pp. 428-437.

Bradley, S & Crabtree, J 2005, 'Effects of DC from Embedded Generation on Residual Current Devices and Single Phase Metering', *Engineers Australia Technology Report*, no. WS4-P11.

Buticchi, G, Franceschini, G, Lorenzani, E, Tassoni, C & Bellini, A 2009, 'A novel current sensing DC offset compensation strategy in transformerless grid connected power converters', *Energy Conversion Congress and Exposition* , pp. 3889-3894.

Calais, M, Myrzik, J, Spooner, T & Agelidis, VG 2002, 'Inverters for Single-Phase Grid Connected Photovoltaic Systems - An Overview', *IEEE Power Electronics Speacilist Conference*, vol 4, pp. 1995-2000.

Capodieci, N, Pagani, GA, Cabri, G & Aiello, M 2011, 'Smart Meter Aware Domestic Energy Trading Agents', *ACM Proceedings of the 2011 workshop on e-energy market challenge*, pp. 1-10.

Capua, CD, Lipari, G, Lugara, M & Morello, R 2014, 'A Smart Energy Meter for power Grids', *IEEE International Instrumentation and Measurement Technology Conference (I2MTC)* , pp. 878-883.

Coonrod, J 2012, *Selecting PCB materials for high-frequency applications*, viewed 4 May 2014, <http://www.edn.com/design/components-and-packaging/4390174/2/Selecting-PCB-materials-for-high-frequency-applications->.

Corbett, J 2013, 'Using information systems to improve energy efficiency: Do smart meters make a difference?', *Information Systems Frontiers*, vol 15, no. 5, pp. 747-760.

Fathi, & Hassan, B 2013, 'Adaptive Energy Consumption Scheduling for Connected Microgrids Under Demand Uncertainty', *IEEE TRANSACTIONS ON POWER DELIVERY*, vol 28, no. 3, pp. 1576-1583.

Gonzalez, R, Lopez, J, Sanchis, P, Gubia, E, Ursua, A & Marroya, L 2006, 'High efficiency Transformerless Single-phase photovoltaic Inverter', *IEEE Transactions on Power Electronics*, pp. 1895-1900.

Haeberlin, H, Ch.Liebi & Ch.Beutler 1997, 'Inverters for Grid-Connected PV Systems: Test Results of New Inverters and Latest Reliability Data of Most Popular Inverters in Switzerland', *14th European Photovoltaic Solar Energy Conference*.

Institute of Electrical and Electronics Engineers 1992, ' Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems', *IEEE 519-1992*.

International Electrotechnical Commission 1994, 'Limitation of voltage fluctuation and flicker in low-voltage supply systems for equipment with rated current < 16A', *IEC 61000-3-3*.

International Electrotechnical Commission 1998, 'Electromagnetic Compatibility (EMC) - Part 3: Limits - Section 2: Limits for Harmonic Current Emissiona (equipment current < 16A per phase)', *IEC 61000-3-2 Document*.

Jiang, Q & Brown, J 2002, 'Simulation of EMS performance of Grid Connected PV inverters', *Australiasian Universties Power Engineering Conference Proceedings*.

Kaur, M, Kakar, S & Mandal, D 2011, 'ELECTROMAGNETIC INTERFERENCE', *Electronics Computer Technology (ICECT)*, vol 4, no. 3, pp. 1-5.

Kirawanich, P & O'Connell, RM 2000, 'Potential Harmonic Impact of a Residential Utility-Interactive Photovoltaic System', *IEEE Power Speacilist Conference*, pp. 983-987.

Kotsopoulos, A, Heskes, P & Jansen, M 2002, 'Zero-Crossing Distortion in Grid Connected PV Inverters', *IEEE Power Specialist Conference*, pp. 1101-1106.

Leonard, M 2013, *How to Design the Perfect PCB*, viewed 4 May 2014, <http://www.michaelhleonard.com/how-to-design-the-perfect-pcb-part2/>.

Li, RT & Chung, HSH 2008, 'Application of hybrid PWM and passive resonant snubber for grid-connected CSI', *Proc of IEEE Power Electronics Specialists Conference*, pp. 837-843.

Li, RTH, Chung, HSH, Wing, HL & Zhou, B 2010, 'Use of Hybrid PWM and Passive Resonant Snubber for a Grid-Connected CSI', *Power Electronics, IEEE Transactions on*, vol 25, no. 2, pp. 298-309.

Lindgren, B 2002, 'Power-generation, Power-electronics and Power-systems issues of Power Converters for Photovoltaic Applications', *Doctoral Thesis*.

Masoud, K & Ledwich, G 1999, 'Grid Connection without Mains Transformers', *Journal of Electrical and Electronic Engineering*, vol 19, no. 1/2, pp. 31-36.

MathWorks Pty Ltd 2014, *GTO-Based STATCOM*, viewed 20 October 2014, <http://www.mathworks.com.au/help/physmod/sps/powersys/ug/gto-based-statcom.html>.

Mohan, N, Undeland, T & Robbins, W 2005, 'Power Electronics: Converters Applications and Design', *Wiley*, pp. 389-391.

NORMAN DISNEY & YOUNG 2002, *Power Factor Correction Evaluation* , C edn, Australian Building Codes Board , Sydney.

Oliveira, A, Jacobina, C, Lima, A & De Silva, E 2003, 'Dead-time Compensation in the Zero Crossing Current Region', *IEEE Power Electronics Specialist Conference*, vol 4, pp. 1937-1943.

Olivia, A, Chiacchiarni, H, Aymonino, A & Mandolesi, P 2005, 'Reduction of Total Harmonic Distortion in Power Inverters', *Latin American Applied Research*, vol 2005, pp. 89-93.

Ordonez, M, Quaicoe, JE & Iqbal, MT 2008, 'Advanced Boundary Control of Inverters Using the Natural Switching Surface: Normalized Geometrical Derivation', *Power Electronics, IEEE Transactions on*, vol 23, no. 6, pp. 2915-2930.

Pepermans, G 2014, 'Valuing Smart Meters', *Energy Economics*, vol 45, pp. 280-294.

Raoufi, M 2004, 'Average Current Mode Control of a Voltage Source Inverteronnected to the Grid Application to different filter Cells', *Journal of Electrical Engineering*, vol 55, no. 3-4, pp. 77-82.

Sakthivel, KN, Das, SK & Kini, KR 2003, 'Importance of quality AC power distribution and understanding of EMC standards IEC 61000-3-2, IEC 61000-3-3 and IEC 61000-3-11', *Electromagnetic Interference and Compatibility*.

Salas, V, Olias, E, Alonso, M & Barrado, A May 2006, 'DC Current Injection into the Network from PV Grid Inverters', *IEEE 4th World Conference on Photovoltaic Energy Conversion*, pp. 2371-2374.

Salas, V, Olias, E, Alonso, M & Chenlo, F 2008, 'Overview of the legislation of DC injection in the network for low voltage small grid connected PV systems in Spain and other countries', *Renwable and Sustainable Reviews*, vol 12, no. 2, pp. 575-583.

Salmon, J 1992, 'Techniques for Minimizing the Input Current Distortion of the Current-Controlled Single-Phase Boost Rectifier', *IEEE Power Specialist Conference* , pp. 368-375.

Sharma, R 2005, 'Removal of DC Offset Current from Transformerless PV Inverters Connected to Utility', *Proceedings of the 40th International Universities Power Engineering Conference*, Cork Institute of Technology, Ireland.

Sharma, R & Ahfock, A 1992, 'Perfromance Analysis of Utility Connected Photovoltaic Generation ', *Australian Unversities Power Engineering Conference*, p. AUPEC 92.

Sharma, R & Ahfock, A 2004, 'Distortion in Single Phase Current Controlled PV inverters for Grid Connection', *Australasian Universities Power Engineering Conference Proceedings*.

Sharma, R & Ball, J 2009, 'Unipolar Switched inverter low frequency harmonics caused by switching delay', *IET Power Electronics*, vol 2, no. 5, pp. 508-516.

Smart Building Services 2012, *Modbus Duo - Quick Start Guide*, SMART BUILDING SERVICES Pty Ltd, Brisbane.

Spooner, ED 2001, 'A New Australian Standard for Small Grid-Connected Renewable Generation System Connected via Inverters', *Australian Universities Power Engineering Conference Proceedings*, pp. 25-30.

Steven Engineering 2014, *UM... Profile PC Board Bases are Available in the Following Fixed Lengths:*, viewed 3 May 2014, <https://stevenengineering.com/pdf/67HOUSING_UM72-100.pdf>.

Suganthi, L & Samuel, A 2012, 'Energy models for demand forecasting—A review', *Renewable and Sustainable Energy Reviews*, vol 16, no. 2, pp. 1223-1240.

US Department of Energy 2014, *How do wind turbines work?*, viewed 19 May 2014, <http://energy.gov/eere/wind/how-do-wind-turbines-work>.

Varjasi, I, Balogh, A & Halasz, S 2006, 'Sensor Less Control of Grid Connected PV Converter', *IEEE Transactions on Power Electronics*, pp. 901-906.

Vasanasong, E & Spooner, ED 2000, 'The effect of Net harmonic Currents produced by numbers of the Sydeney Olympic Village's PV Systems on the Power Quality of Local Electrical network', *IEEE Power Speacilist Conference*, pp. 1001-1006.

Verma, P, Sharma, P & Mishra, SK 2012, 'Dropping of Call Due to Congestion in Mobile Network', *Journal of Computer Applications*, vol 5, no. 1, pp. 26-30.

Wodrich, R 2007, 'Understanding harmonics: Winning the fight against 'electrical pollution', *Plant Engineering*, vol 8, no. 61, pp. 37-42.

Appendix A

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Appendix A.1: Overall Schematic of STATCOM Inverter

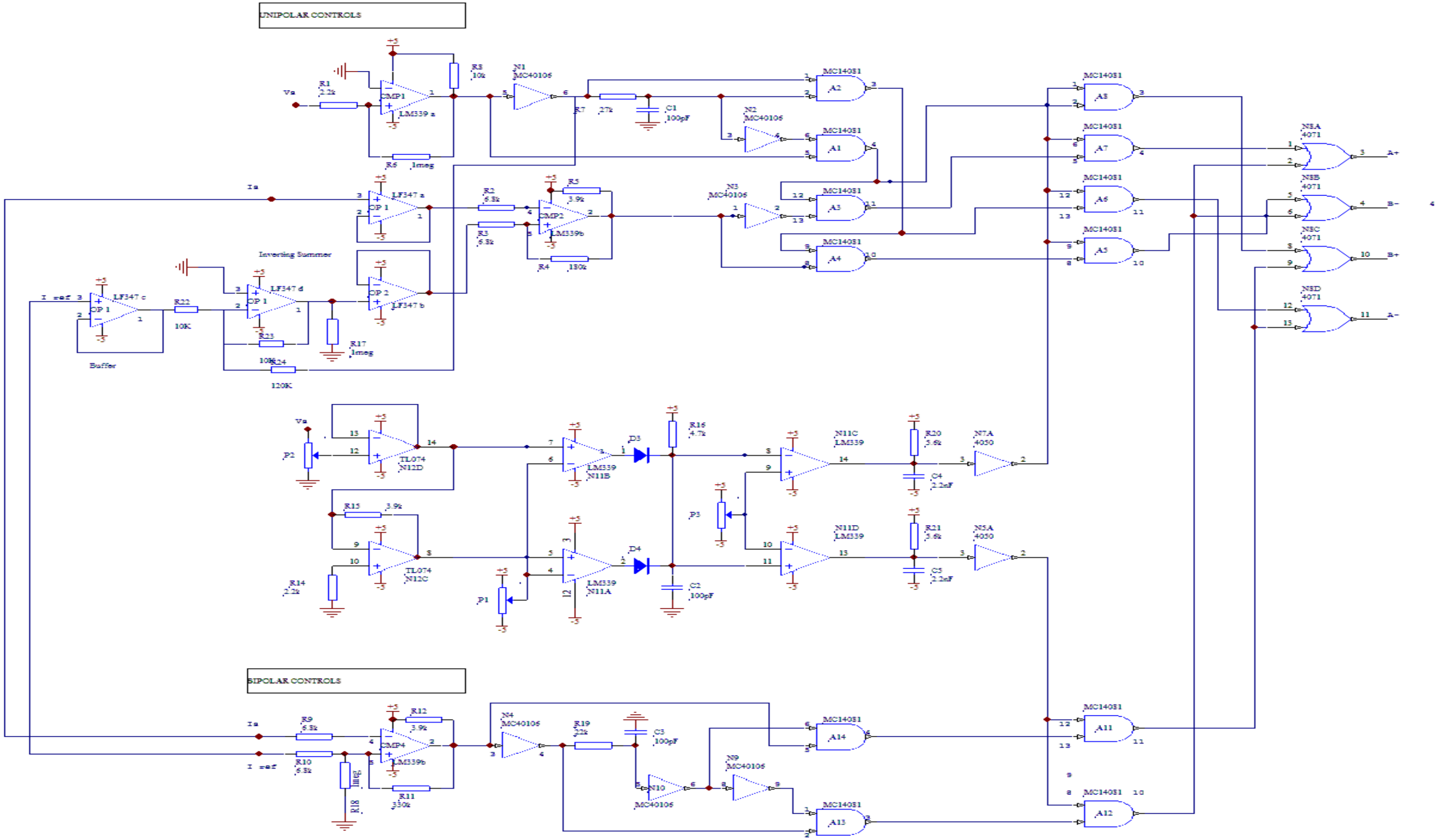

Figure A. 1: STATCOM Schematic

Figure A – 1 is the overall schematic view of the four quadrant STATCOM inverter that was implemented. The schematic shown above was implemented on PCB. The above schematic identifies each individual IC that was used in the implementation of this four quadrant STATCOM inverter and the numbers shown on the amplifiers, comparators and the gates represent the pin number on the IC package on PCB 1. The following few pages of this appendix shows the smaller circuits which combine to form the overall schematic for this project. The role of each of the small circuits is also explained briefly and how they contribute to the functioning of this four quadrant STATCOM inverter.

Appendix A.2: Bipolar Switching Circuit:

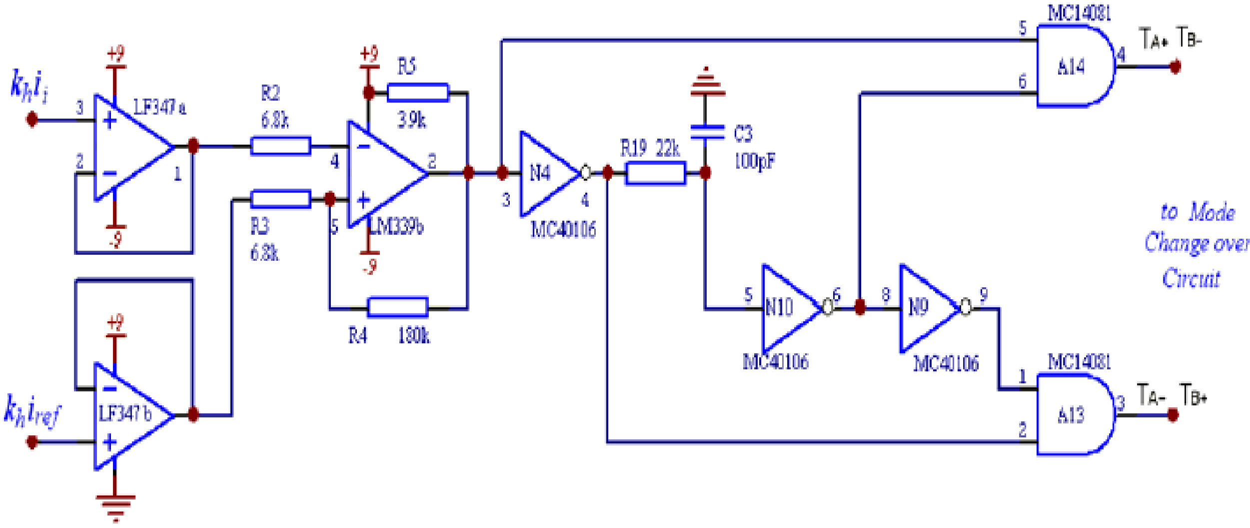

Figure A. 2: Bipolar Switching Circuit Schematic

The above circuit is used for the bipolar switching. The inputs for the above circuit are i_{ref} and i_s. More details about the switching strategy are discussed in the literature review and the theoretical and experimental results of the switching strategy is discussed in the discussion chapter.

Appendix A.3: Unipolar Switching Circuit:

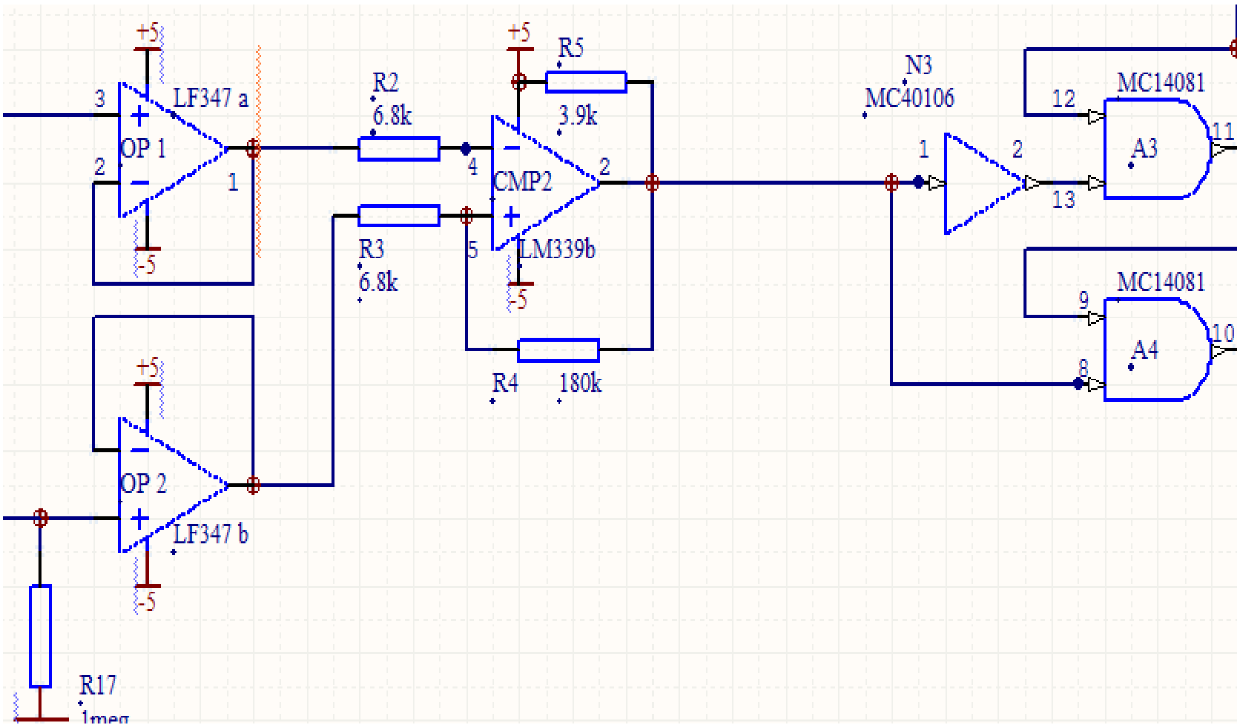

Figure A. 3: Unipolar Switching Schematic

The above circuit is used for the unipolar switching. The inputs for the above circuit are i_{ref} and i_s. More details about the switching strategy are discussed in the literature review and the theoretical and experimental results of the switching strategy is discussed in the discussion chapter.

Appendix A.4: Multimodal Switching Circuit:

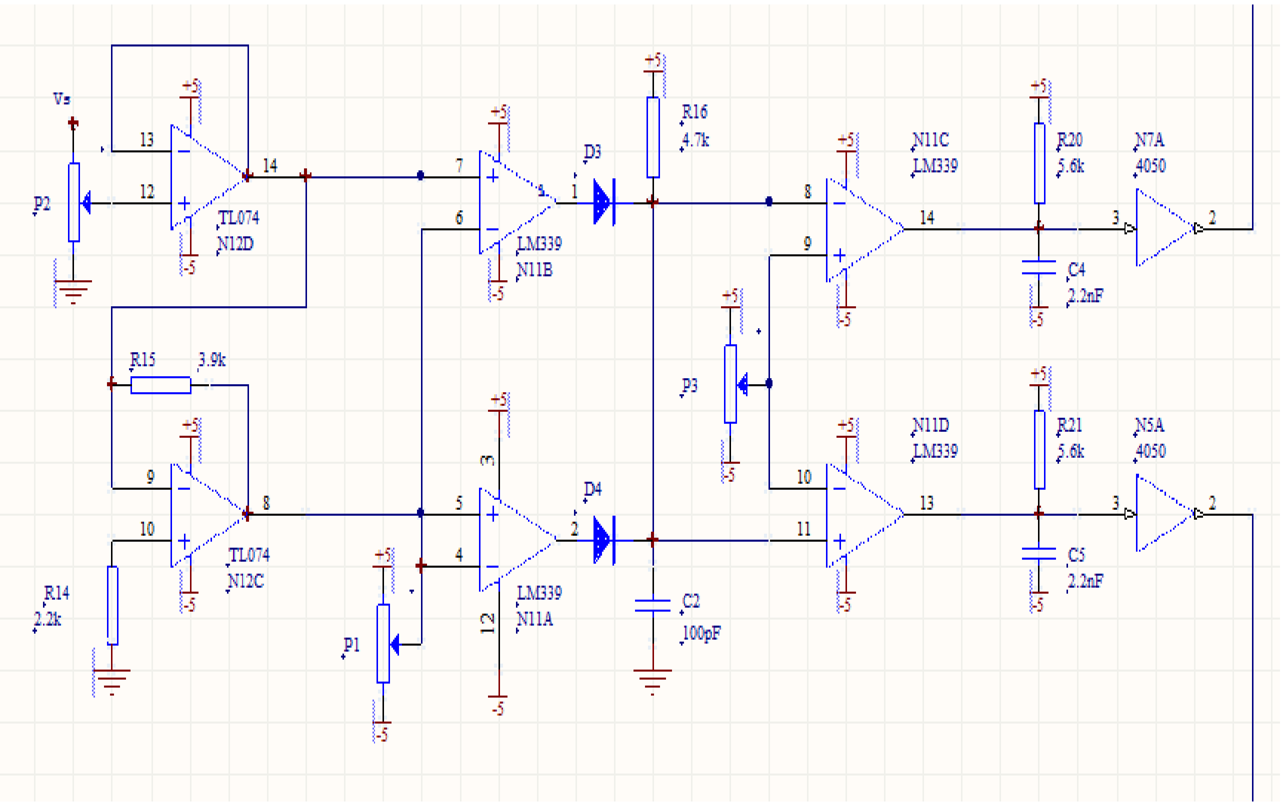

Figure A. 4: Multimodal Switching Schematic

The above circuit diagram is of the multimodal switchover circuit. This circuit takes in both the bipolar switching signals and the unipolar switching signals and combines then together to achieve the multimodal signal. The details of the switching strategy are discussed in the literature review and the results are presented in the discussion section.

Appendix A.5: Mode Change Over Circuit:

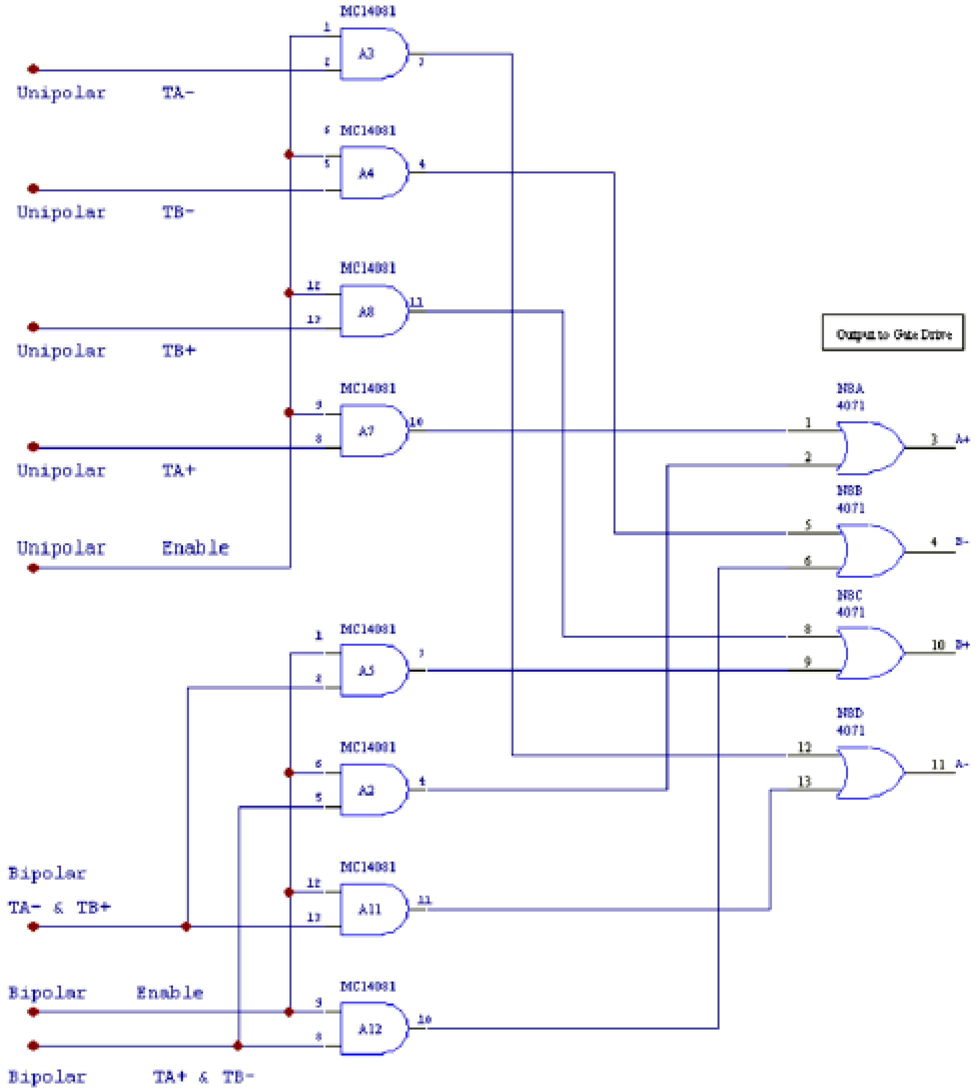

Figure A. 5: Mode Change Over Schematic

The above circuit is used for the output of the STATCOM inverter which goes into the SEMI TEACH DEVICE gate drives. This circuit effectively collects the bipolar signals, unipolar signals and the mode control circuit signals before it is being output into the gate drives.

Appendix A.6: Inverting Summer Circuit:

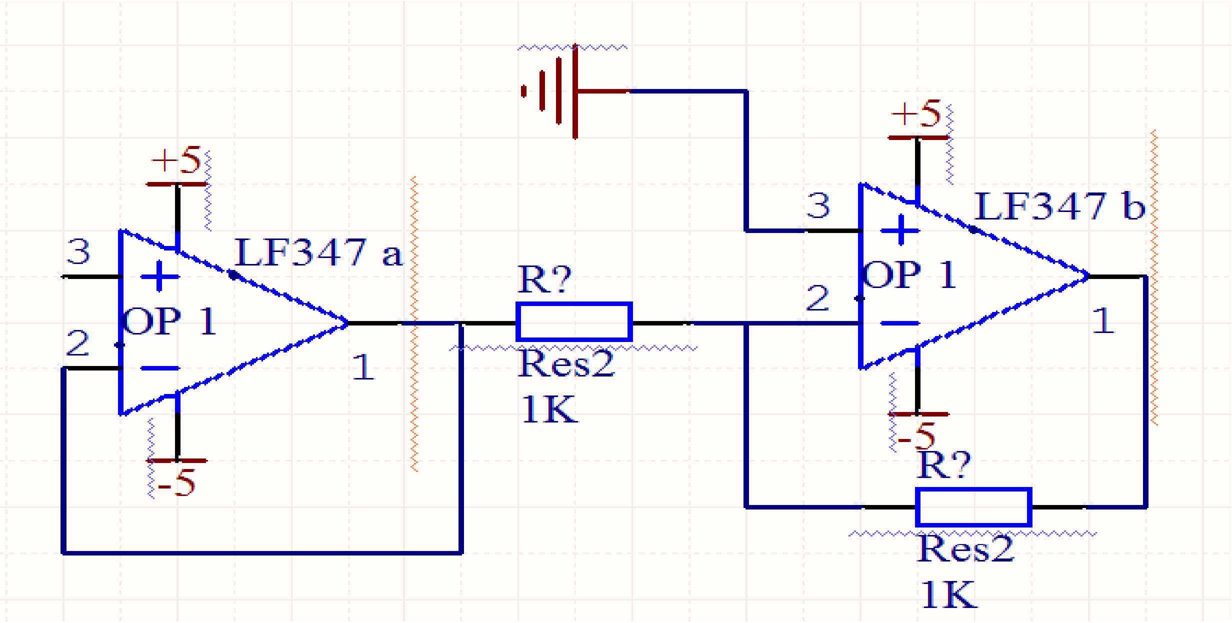

Figure A. 6: Schematic of Inverting Summer Circuit

The figure shown above is of an inverting summer circuit. This circuit was implemented in order to remove two diodes at the input of the unipolar operations. The input is first buffered before the signal goes into the inverting summing amplifier and the output is then sent further into the unipolar operations of the STATCOM inverter.

Appendix A.7: Zero Phase Shift Filter Circuit:

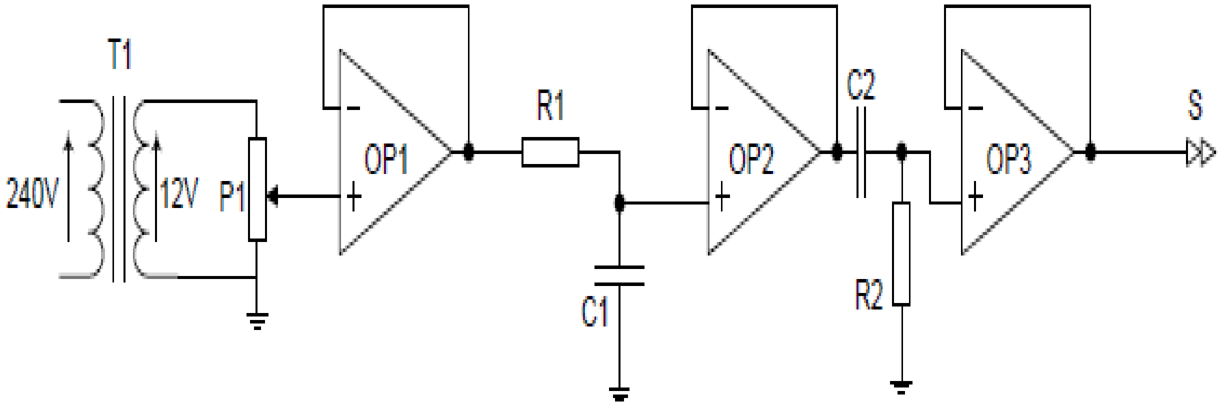

Figure A. 7: Zero Phase Shift Filter Schematic

The figure shown above is a basic zero phase shift filter that was used for this project. This zero phase shift filter was used for detecting the zero crossings of the input signal so that it could be manipulated at the other parts of the STATCOM inverter.

Appendix B

Figure B. 1: Project Specification 77

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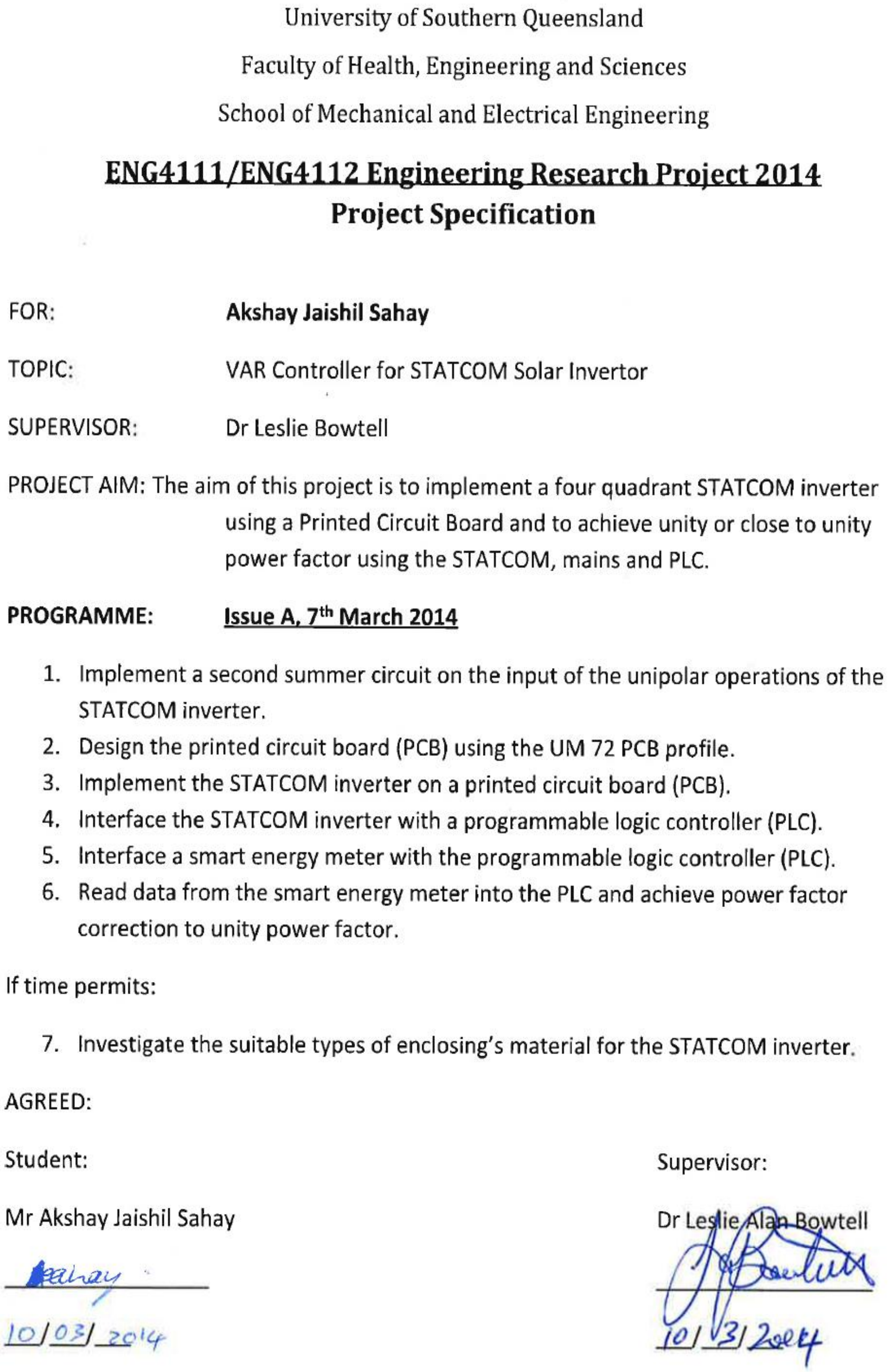
B.1: Project Proposal:

Figure B. 1: Project Specification



University of Southern Queensland
Faculty of Health, Engineering and Sciences
School of Mechanical and Electrical Engineering

ENG4111/ENG4112 Engineering Research Project 2014
Project Specification

FOR: **Akshay Jaishil Sahay**

TOPIC: VAR Controller for STATCOM Solar Invertor

SUPERVISOR: Dr Leslie Bowtell

PROJECT AIM: The aim of this project is to implement a four quadrant STATCOM inverter using a Printed Circuit Board and to achieve unity or close to unity power factor using the STATCOM, mains and PLC.

PROGRAMME: **Issue A, 7th March 2014**

1. Implement a second summer circuit on the input of the unipolar operations of the STATCOM inverter.
2. Design the printed circuit board (PCB) using the UM 72 PCB profile.
3. Implement the STATCOM inverter on a printed circuit board (PCB).
4. Interface the STATCOM inverter with a programmable logic controller (PLC).
5. Interface a smart energy meter with the programmable logic controller (PLC).
6. Read data from the smart energy meter into the PLC and achieve power factor correction to unity power factor.

If time permits:

7. Investigate the suitable types of enclosing's material for the STATCOM inverter.

AGREED:

Student:
Mr Akshay Jaishil Sahay
Sahay
10/03/2014

Supervisor:
Dr Leslie Alan Bowtell
10/3/2014

B.2: Risk Assessment:

Description of hazard:	**People at risk:**	**Number of people at risk:**	**Parts of the body at risk:**	**Risk Level:**	**Part of project associated with this:**	**Short term controls:**	**Long term controls:**	**Completion details:**
Eye strain	Myself	1	Eyes	High	• Redesigning the circuit • Typing of the report • Soldering PCB components	• Use a room with sufficient lighting • Take breaks at regular intervals • Use magnifying glass	• Create an environment with good lighting. • Take regular breaks	**Employer:** USQ **Prepared by:** Akshay J. Sahay **Date:** 29/05/2014 **Signature:**
Soldering Fumes	Myself	1	Respiratory system	High	• PCB Assembly • Wire Assembly	• Use a well-ventilated room and keep windows open	• Use a fume extractor to extract fumes	**Employer:** USQ **Prepared by:** Akshay J. Sahay **Date:**

						during soldering to let out fumes		29/05/2014 **Signature:**
Solder Splatter	Myself	1	Eyes	High	• PCB Assembly • Wire Assembly	• Wear protective goggles while soldering	• Wear protective goggles while soldering	**Employer:** USQ **Prepared by:** Akshay J. Sahay **Date:** 29/05/2014 **Signature:**
Burns	Many	1 to 10	General Body	High	• PCB Assembly • Wire Assembly • STATCOM Testing	• Wear protective gloves and clothing while soldering and testing • During testing be cautious and not shorting any components.	• Wear protective clothing while soldering and testing • During testing be cautious of	**Employer:** USQ **Prepared by:** Akshay J. Sahay **Date:** 29/05/2014 **Signature:**

							not shorting any components	
Trip hazard	Many	1 to 10	General Body	High	- STATCOM testing - Power factor correction	- Use witch hats to identify trip hazard	- Tape down the trip hazard along the floor	**Employer:** USQ **Prepared by:** Akshay J. Sahay **Date:** 29/05/2014 **Signature:**
Electrical Shock	Many	1 to 10	General Body	High	- STATCOM Testing	- Ensure that all the wires are properly insulated. - All terminals are properly insulated.	- Ensure that all the wires are properly insulated. - All terminals are properly insulated.	**Employer:** USQ **Prepared by:** Akshay J. Sahay **Date:** 29/05/2014 **Signature:**

				🟥		• Everything is properly earthed. • High voltage signage to indicate high voltage • Have a secondary person during the testing phase	• Everything is properly earthed. • High voltage signage to indicate high voltage • Have a secondary person during the testing phase	
Electrical Fire	Many	1 to 10	General Body	Low	• STATCOM Testing	• Ensure that all the wires are properly insulated.	• Ensure that all the wires are properly insulated. • All terminals	**Employer:** USQ **Prepared by:** Akshay J. Sahay

				🟨		- All terminals are properly insulated. - Everything is properly earthed. - High voltage signage to indicate high voltage - Have a secondary person during the testing phase	are properly insulated. - Everything is properly earthed. - High voltage signage to indicate high voltage - Have a secondary person during the testing phase	**Date:** 29/05/2014 **Signature:**

Table B. 1: Risk Assessment Table

Scale:

Low	**Moderate**	**High**

B.3: Project Timeline:

Task	Semester 1															
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16
	25/2 - 2/3	4/3 - 9/3	10/3 - 16/3	17/3 - 23/3	24/3 - 30/3	1/4 - 6/4	7/4 - 13/4	14/4 - 20/4	21/4 - 27/4	28/4 - 4/5	5/5 - 11/5	12/5 - 18/5	19/5 - 25/5	26/5 - 1/6	2/6 - 8/6	9/6 - 15/6
Topic Allocation	■															
Project Specification		■														
Literature review		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
PCB Designs		■	■	■	■	■										
PCB Manufacture						■	■	■	■	■						
Project preliminary report - interim							■	■	■	■	■					
Order Components							■	■								
Project preliminary report - final											■	■	■			
Assemble PCB														■	■	■

Table B. 2: Semester 1 Timeline

Task	Semester 2															
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16
	15/7 - 20/7	21/7 - 27/7	28/7 - 3/8	4/8 - 10/8	11/8 - 17/8	18/8 - 24/8	25/8 - 31/8	1/9 - 7/9	8/9 - 14/9	15/9 - 21/9	22/9 - 28/9	29/9 - 5/10	6/10 - 12/10	13/10 - 19/10	20/10 - 26/10	26/10 - 2/11
Test STATCOM	■															
Test Power factor correction		■														
Collate Results			■	■												
Prepare first draft and submit			■	■	■	■	■	■	■	■						
In cooperate supervisor’s feedback into final dissertation										■	■	■	■			
Prepare final dissertation										■	■	■	■	■		
Proof read & submit.														■	■	■

Table B. 3: Semester 2 Timeline

B.4: Resource Planning:

B.4.1: Materials, Equipment and Software:

The following materials and equipment are required for the successful completion of this research project:

Item	Purpose	Acquired
Printed Circuit Boards	To form the circuit	Yes
Resistors	To form parts of the circuit	Yes
Capacitors	To form parts of the circuit	Yes
Diodes	To form parts of the circuit	Yes
IC sockets	To hold the IC's and provide the option of an easy swap if required	Yes
IC's	To create the operational amplifiers required for the STATCOM	Yes
Molex Connectors	To connect wires coming into the printed circuit boards	Yes
Wires	To interconnect the printed circuit boards and all the devices	Yes
Current and Voltage Transducers	To accurately measure the voltage and currents coming into the STATCOM and measure the current going out of the STATCOM	Yes
Potentiometers	To control various signals coming into the STATCOM inverter	Yes
Multimeters	To measure voltages and currents at various stages of the setup	Yes

Energy Meters	To help measure the power factor, and see the power coming in from the main grid	Yes
PLC	To help control the DC offset and also to provide power factor correction using the energy meter	Yes
Transformers	To help control the voltage on the primary side of the circuit	Yes
Oscilloscope	To observe the waveforms coming in and out of the STATCOM and to observe the power factor	Yes
Power Supplies	To power the three printed circuit boards	Yes
Inductor	To help control power factor	Yes
Signage	To indicate and make people aware of high voltage testing	Yes
Software		
DIP Trace and ALTIUM Designer	To design the circuit and to design the printed circuit boards for the assignment.	Yes
Microsoft Office	To type up the final dissertation and to create PowerPoint presentations.	Yes

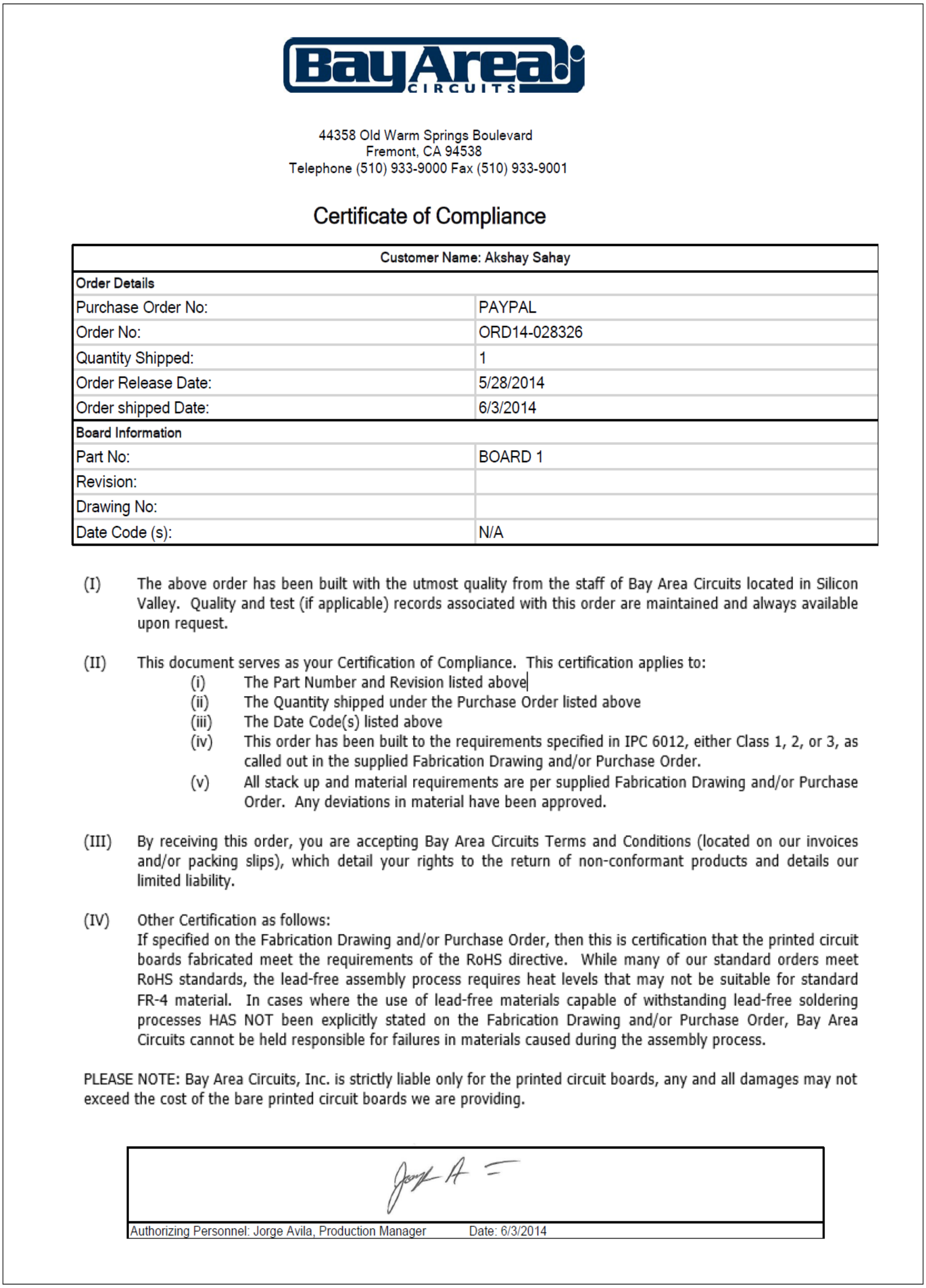
Table B. 4: List of materials, devices and software required

Most of the materials for this project has either been sought at my own expense or has been provided by the University.

Appendix C:

Figure C. 1: Compliance certificate Board 2 from Bayarea Circuits 88
Figure C. 2 Compliance Certificate for Board 3 by Bayarea Circuits 89
Figure C. 3: Bare board Test Certificate for Board 1 from Bayarea Circuits 90
Figure C. 4: Test Certificates for Bare Board testing of Board 3 from Bayarea Circuits 91
Figure C. 5: BEC Manufacturing Agreement page 1 92
Figure C. 6: BEC Agreement Page 2 93

Appendix C1: Compliance Certificates:



44358 Old Warm Springs Boulevard
Fremont, CA 94538
Telephone (510) 933-9000 Fax (510) 933-9001

Certificate of Compliance

Customer Name: Akshay Sahay	
Order Details	
Purchase Order No:	PAYPAL
Order No:	ORD14-028326
Quantity Shipped:	1
Order Release Date:	5/28/2014
Order shipped Date:	6/3/2014
Board Information	
Part No:	BOARD 1
Revision:	
Drawing No:	
Date Code (s):	N/A

(I) The above order has been built with the utmost quality from the staff of Bay Area Circuits located in Silicon Valley. Quality and test (if applicable) records associated with this order are maintained and always available upon request.

(II) This document serves as your Certification of Compliance. This certification applies to:

- (i) The Part Number and Revision listed above
- (ii) The Quantity shipped under the Purchase Order listed above
- (iii) The Date Code(s) listed above
- (iv) This order has been built to the requirements specified in IPC 6012, either Class 1, 2, or 3, as called out in the supplied Fabrication Drawing and/or Purchase Order.
- (v) All stack up and material requirements are per supplied Fabrication Drawing and/or Purchase Order. Any deviations in material have been approved.

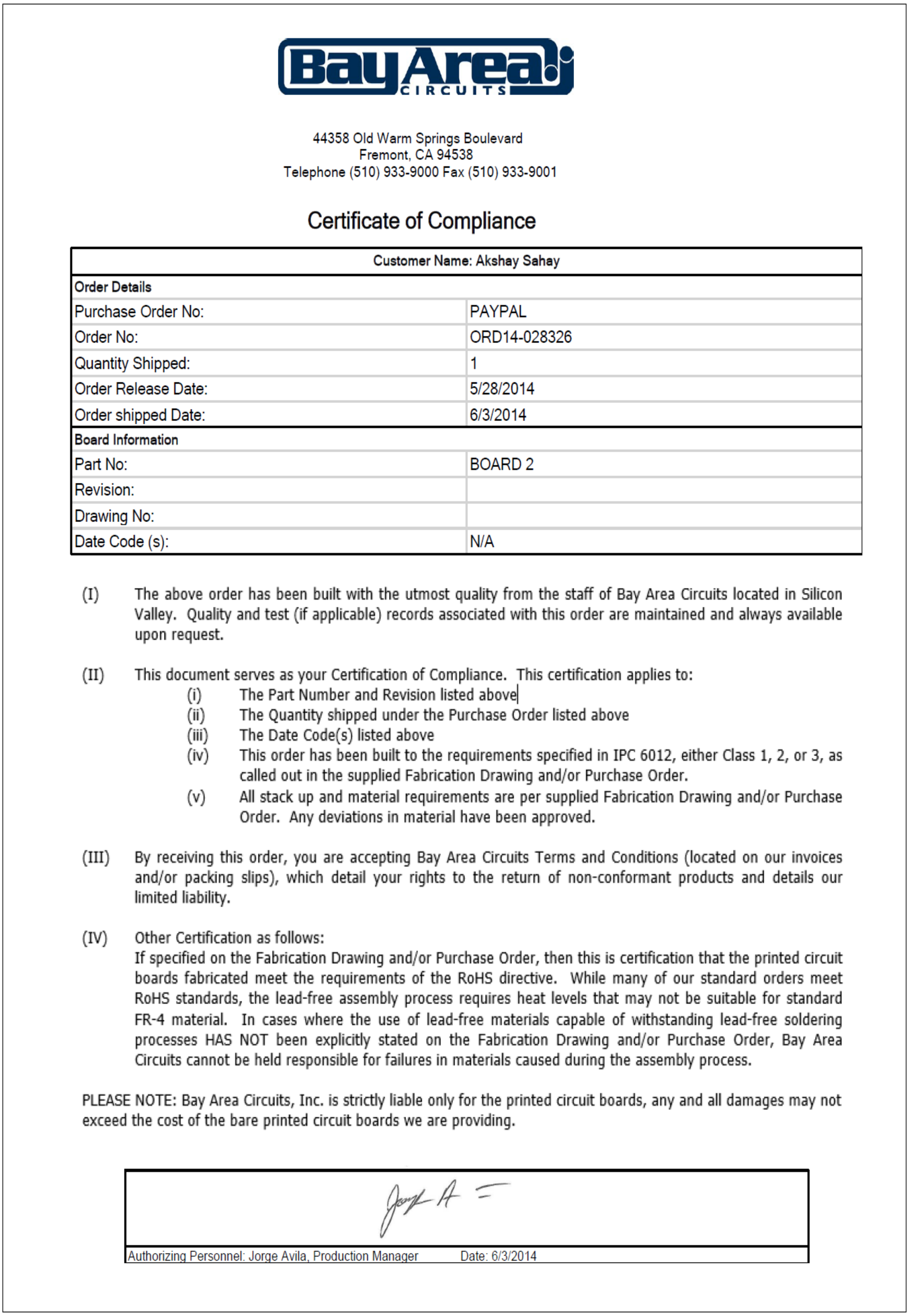
(III) By receiving this order, you are accepting Bay Area Circuits Terms and Conditions (located on our invoices and/or packing slips), which detail your rights to the return of non-conformant products and details our limited liability.

(IV) Other Certification as follows:
If specified on the Fabrication Drawing and/or Purchase Order, then this is certification that the printed circuit boards fabricated meet the requirements of the RoHS directive. While many of our standard orders meet RoHS standards, the lead-free assembly process requires heat levels that may not be suitable for standard FR-4 material. In cases where the use of lead-free materials capable of withstanding lead-free soldering processes HAS NOT been explicitly stated on the Fabrication Drawing and/or Purchase Order, Bay Area Circuits cannot be held responsible for failures in materials caused during the assembly process.

PLEASE NOTE: Bay Area Circuits, Inc. is strictly liable only for the printed circuit boards, any and all damages may not exceed the cost of the bare printed circuit boards we are providing.

Authorizing Personnel: Jorge Avila, Production Manager Date: 6/3/2014

Figure C. 1: Compliance certificate Board 2 from Bayarea Circuits



BayArea CIRCUITS

44358 Old Warm Springs Boulevard
Fremont, CA 94538
Telephone (510) 933-9000 Fax (510) 933-9001

Certificate of Compliance

Customer Name: Akshay Sahay	
Order Details	
Purchase Order No:	PAYPAL
Order No:	ORD14-028326
Quantity Shipped:	1
Order Release Date:	5/28/2014
Order shipped Date:	6/3/2014
Board Information	
Part No:	BOARD 2
Revision:	
Drawing No:	
Date Code (s):	N/A

(I) The above order has been built with the utmost quality from the staff of Bay Area Circuits located in Silicon Valley. Quality and test (if applicable) records associated with this order are maintained and always available upon request.

(II) This document serves as your Certification of Compliance. This certification applies to:
- (i) The Part Number and Revision listed above
- (ii) The Quantity shipped under the Purchase Order listed above
- (iii) The Date Code(s) listed above
- (iv) This order has been built to the requirements specified in IPC 6012, either Class 1, 2, or 3, as called out in the supplied Fabrication Drawing and/or Purchase Order.
- (v) All stack up and material requirements are per supplied Fabrication Drawing and/or Purchase Order. Any deviations in material have been approved.

(III) By receiving this order, you are accepting Bay Area Circuits Terms and Conditions (located on our invoices and/or packing slips), which detail your rights to the return of non-conformant products and details our limited liability.

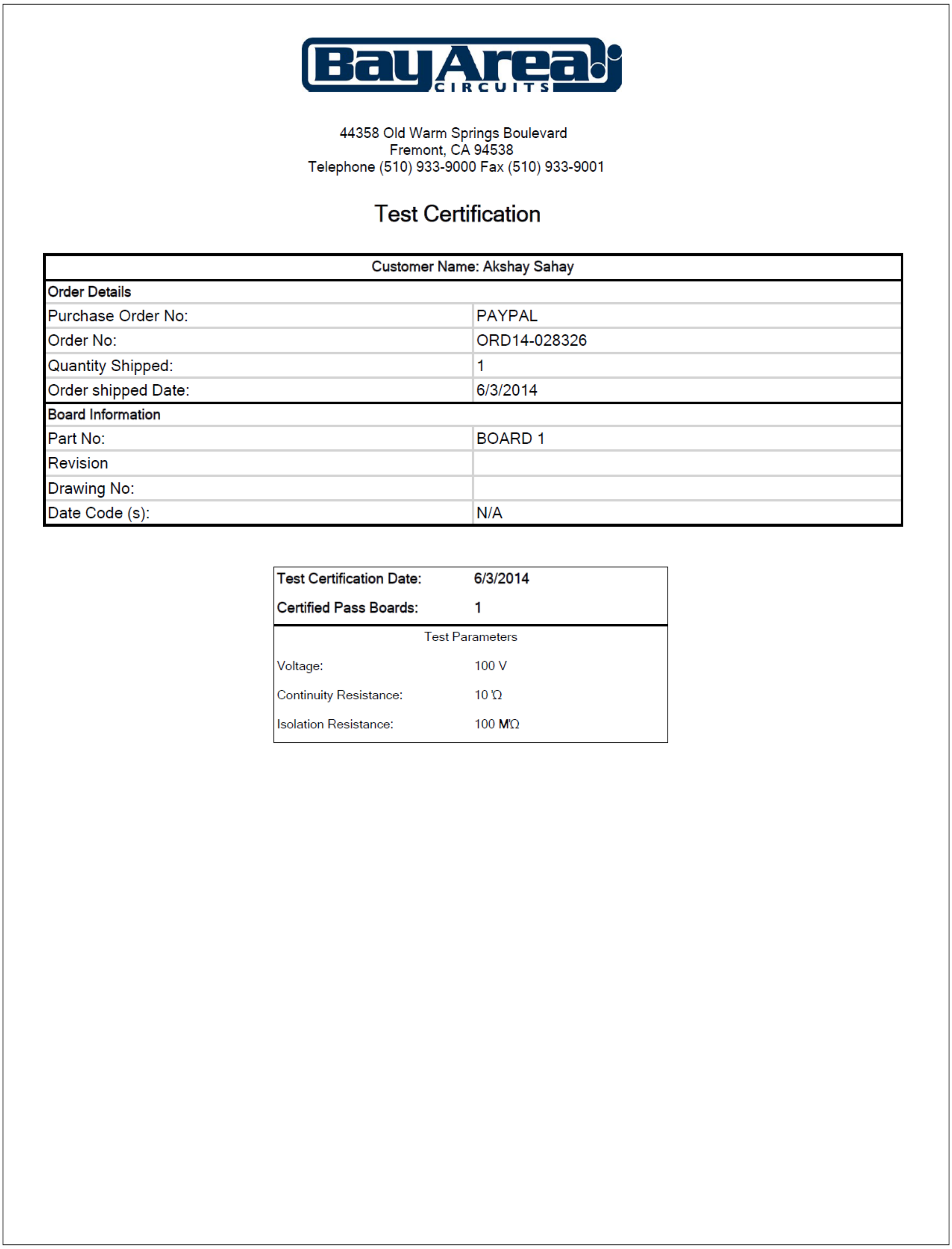
(IV) Other Certification as follows:
If specified on the Fabrication Drawing and/or Purchase Order, then this is certification that the printed circuit boards fabricated meet the requirements of the RoHS directive. While many of our standard orders meet RoHS standards, the lead-free assembly process requires heat levels that may not be suitable for standard FR-4 material. In cases where the use of lead-free materials capable of withstanding lead-free soldering processes HAS NOT been explicitly stated on the Fabrication Drawing and/or Purchase Order, Bay Area Circuits cannot be held responsible for failures in materials caused during the assembly process.

PLEASE NOTE: Bay Area Circuits, Inc. is strictly liable only for the printed circuit boards, any and all damages may not exceed the cost of the bare printed circuit boards we are providing.

Authorizing Personnel: Jorge Avila, Production Manager Date: 6/3/2014

Figure C. 2 Compliance Certificate for Board 3 by Bayarea Circuits

Appendix C2: Test Certificates:



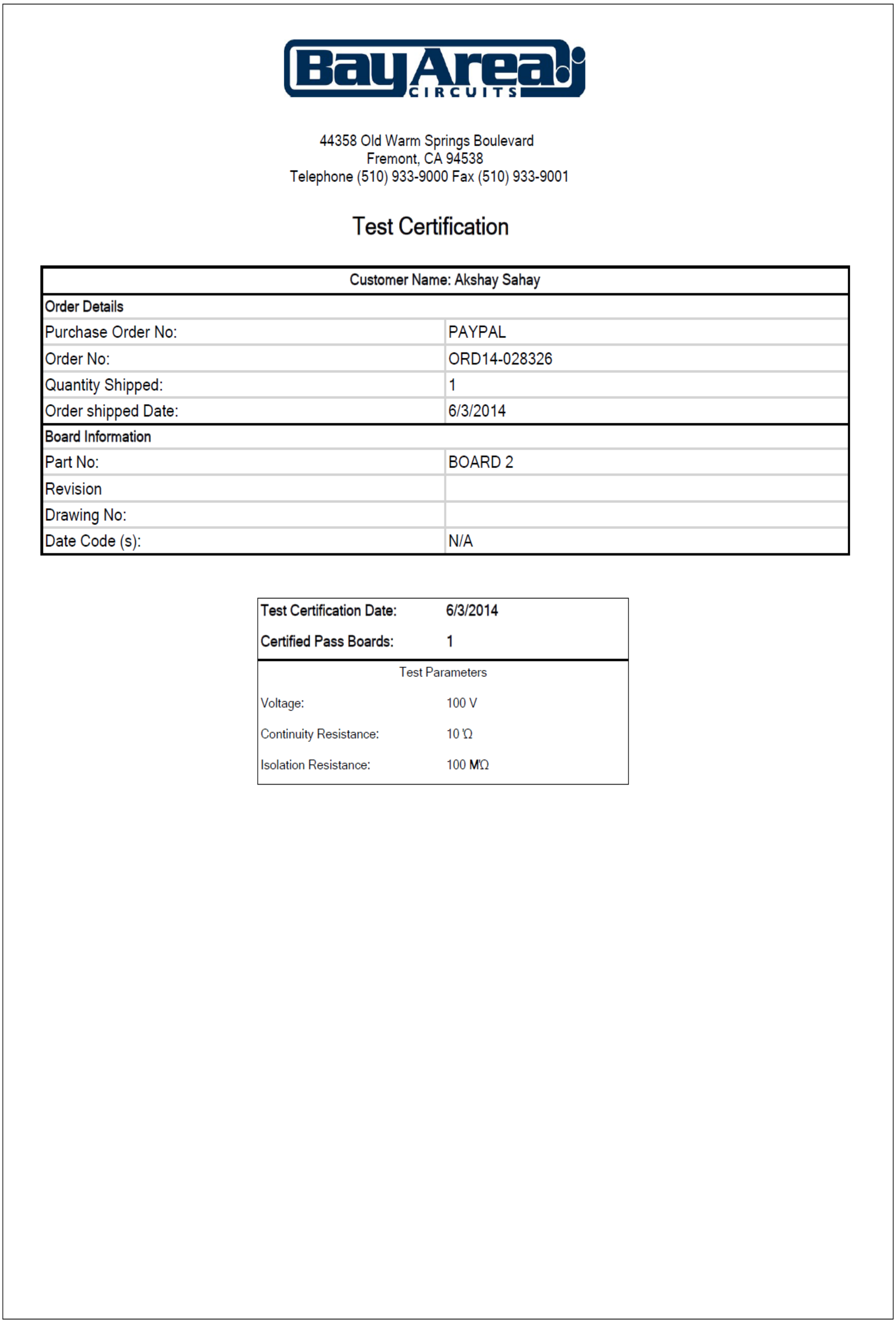
44358 Old Warm Springs Boulevard
Fremont, CA 94538
Telephone (510) 933-9000 Fax (510) 933-9001

Test Certification

Customer Name: Akshay Sahay	
Order Details	
Purchase Order No:	PAYPAL
Order No:	ORD14-028326
Quantity Shipped:	1
Order shipped Date:	6/3/2014
Board Information	
Part No:	BOARD 1
Revision	
Drawing No:	
Date Code (s):	N/A

Test Certification Date:	**6/3/2014**
Certified Pass Boards:	**1**
Test Parameters	
Voltage:	100 V
Continuity Resistance:	10 Ω
Isolation Resistance:	100 MΩ

Figure C. 3: Bare board Test Certificate for Board 1 from Bayarea Circuits



BayArea CIRCUITS

44358 Old Warm Springs Boulevard
Fremont, CA 94538
Telephone (510) 933-9000 Fax (510) 933-9001

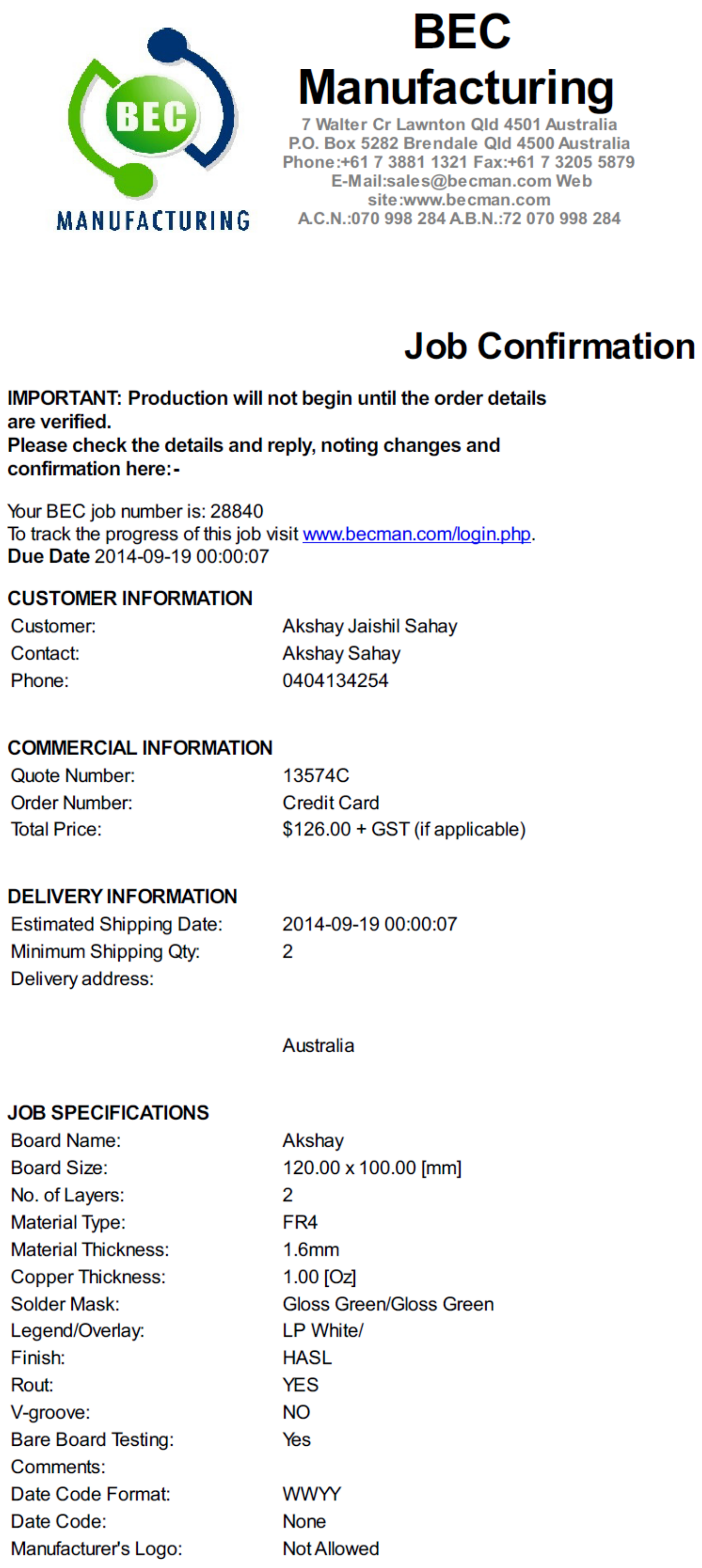
Test Certification

Customer Name: Akshay Sahay	
Order Details	
Purchase Order No:	PAYPAL
Order No:	ORD14-028326
Quantity Shipped:	1
Order shipped Date:	6/3/2014
Board Information	
Part No:	BOARD 2
Revision	
Drawing No:	
Date Code (s):	N/A

Test Certification Date:	**6/3/2014**
Certified Pass Boards:	**1**
Test Parameters	
Voltage:	100 V
Continuity Resistance:	10 Ω
Isolation Resistance:	100 MΩ

Figure C. 4: Test Certificates for Bare Board testing of Board 3 from Bayarea Circuits

Appendix C3: Agreement between BEC Manufacturing and Me:



MANUFACTURING

BEC Manufacturing

7 Walter Cr Lawnton Qld 4501 Australia
P.O. Box 5282 Brendale Qld 4500 Australia
Phone:+61 7 3881 1321 Fax:+61 7 3205 5879
E-Mail:sales@becman.com Web site:www.becman.com
A.C.N.:070 998 284 A.B.N.:72 070 998 284

Job Confirmation

IMPORTANT: Production will not begin until the order details are verified.
Please check the details and reply, noting changes and confirmation here:-

Your BEC job number is: 28840
To track the progress of this job visit www.becman.com/login.php.
Due Date 2014-09-19 00:00:07

CUSTOMER INFORMATION

Customer:	Akshay Jaishil Sahay
Contact:	Akshay Sahay
Phone:	0404134254

COMMERCIAL INFORMATION

Quote Number:	13574C
Order Number:	Credit Card
Total Price:	$126.00 + GST (if applicable)

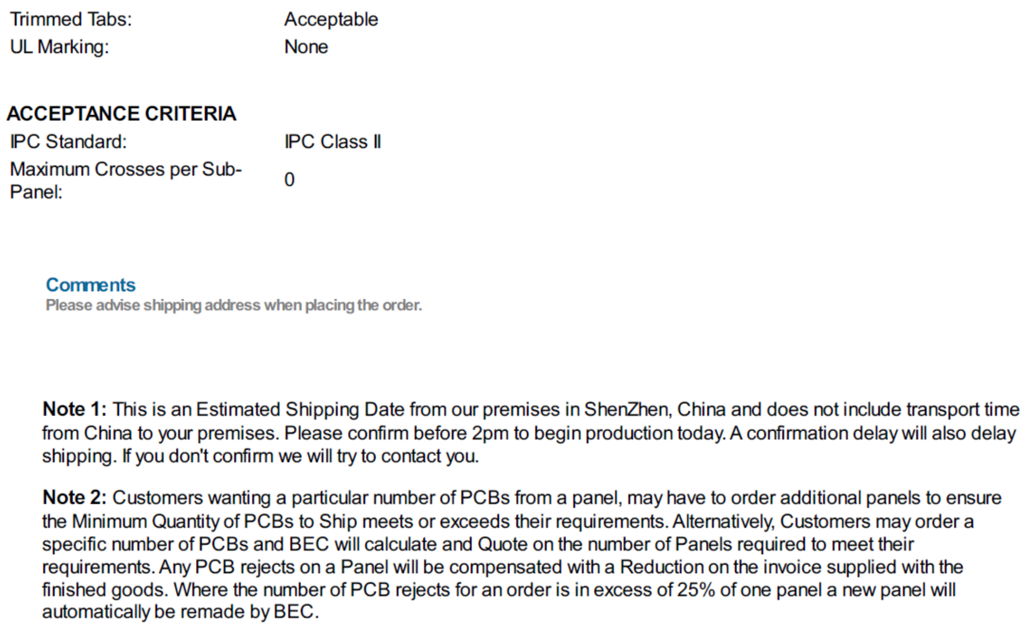
DELIVERY INFORMATION

Estimated Shipping Date:	2014-09-19 00:00:07
Minimum Shipping Qty:	2
Delivery address:	Australia

JOB SPECIFICATIONS

Board Name:	Akshay
Board Size:	120.00 x 100.00 [mm]
No. of Layers:	2
Material Type:	FR4
Material Thickness:	1.6mm
Copper Thickness:	1.00 [Oz]
Solder Mask:	Gloss Green/Gloss Green
Legend/Overlay:	LP White/
Finish:	HASL
Rout:	YES
V-groove:	NO
Bare Board Testing:	Yes
Comments:	
Date Code Format:	WWYY
Date Code:	None
Manufacturer's Logo:	Not Allowed

Figure C. 5: BEC Manufacturing Agreement page 1



Trimmed Tabs:	Acceptable
UL Marking:	None

ACCEPTANCE CRITERIA

IPC Standard:	IPC Class II
Maximum Crosses per Sub-Panel:	0

Comments

Please advise shipping address when placing the order.

Note 1: This is an Estimated Shipping Date from our premises in ShenZhen, China and does not include transport time from China to your premises. Please confirm before 2pm to begin production today. A confirmation delay will also delay shipping. If you don't confirm we will try to contact you.

Note 2: Customers wanting a particular number of PCBs from a panel, may have to order additional panels to ensure the Minimum Quantity of PCBs to Ship meets or exceeds their requirements. Alternatively, Customers may order a specific number of PCBs and BEC will calculate and Quote on the number of Panels required to meet their requirements. Any PCB rejects on a Panel will be compensated with a Reduction on the invoice supplied with the finished goods. Where the number of PCB rejects for an order is in excess of 25% of one panel a new panel will automatically be remade by BEC.

Figure C. 6: BEC Agreement Page 2