Bi-directional single-phase voltage source converter for smart grid applications

Submitted in partial fulfillment of the requirements for the course

ELEC-4000: Capstone Design Project

Department of Electrical and Computer Engineering
University of Windsor

August 4th, 2021

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Team 18

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"No action by any design team member contravened the provisions of the Code of Ethics and we hereby reaffirm that the work presented in this report is solely the effort of the team members and that any work of others that was used during the execution of the design project or is included in the report has been suitably acknowledged through the standard practice of citing references and stating appropriate acknowledgments". The presence of the author's signatures on the signature page means that they are affirming this statement.

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Abstract

With the further development in technology, energy demands are increasing and current infrastructure in place needs to be upgraded to meet those demands. To meet those demands, various smart grid applications will need to be implemented to ensure reliability and efficiency of the power grid. With these smart grid applications in place, energy demands needed for the future can be met.

This project's goal is to explore a voltage source converter and determine whether the design can be implemented with various smart grid applications such as solar panels and used effectively. The project will test the converter's operational modes and see if it can be used in smart grid applications. Developing control algorithms to test the converter's operation will be required. However, due constraints from the pandemic, access to equipment will not be as easy, and time will be limited to achieve the results the team is looking for. But the team plans to work efficiently to achieve some of the results.

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Introduction

Technology is evolving rapidly in this day and age, with new discoveries being made on a daily basis. Smart grid applications are increasing in demand, as more houses are being retrofitted or built with smart appliances such as solar grids, electric vehicle chargers, and more. Unfortunately, the current grid system is dated and only provides a one-way communication between the consumer and the provider. With a smart grid, a two-way communication is implemented allowing the provider to know right away if there is a power outage or to be able to provide a more efficient, thus cleaner transmission of electricity.

With the rise in alternatives for energy to power our communities such as wind and solar energy, a voltage source inverter that allows the conversion from DC voltage to AC voltage to be used with smart grid applications is what our project will focus on. With this technology, voltage source inverters can be implemented with photovoltaic inverters, which can be found with solar panel installations. The inverter will allow the DC energy from the solar panels to be converted to an AC voltage to be used with powering our appliances, and any excess energy could be fed back to the grid.

Our project is what will help in further developing this application for smart grids and alternative energy applications, and allow it to be also used with uninterrupted power supplies, grid storage, and active rectifiers as well. For our team, we plan to design and implement a bi-directional single-phase voltage source converter that can be used with the above applications. To achieve this implementation, we planned on using a Texas Instruments Voltage Source Inverter (TIDM-HV-1PH-DCAC) kit. The kit features two modes of operation of the Bi-directional voltage source converter, the first mode is suitable for uninterrupted power supplies, while the second mode is used with photovoltaic inverters. However, due to the COVID-19 pandemic and time restraints, we were unable to acquire the kit and implement it within our project. To achieve some results, we were able to create a reference design in MATLAB/Simulink that implements a single-phase inverter (DC/AC) control using a C2000™ microcontroller.

Muhab

Benchmarking

Most of the current inverter designs utilize the usage of a PI (Proportional Integral) controller in their Current Sensing Module. The PI controller is an easier and simpler implementation and is natively supported by MATLAB SIMULINK. They provide excellent performance, notably a minimal steady-state error, thanks to the (almost) infinite DC gain provided by the integral control action. However, in AC applications, PI controllers inevitably present a delayed tracking response, because finite gains cannot prevent steady-state error.

PR controllers have gained popularity in the power electronics industry due to their performance and relative simplicity to implement. Also, the PR controller can be relatively easily tuned using the controller gains as well as ωc

The figure below shows tuning of the PR controller with variable K_r, (K_p=15).

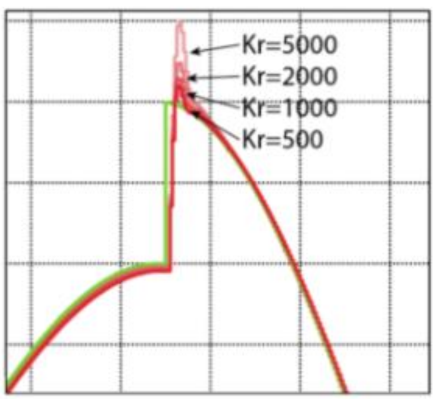

Figure 1: Tuning effect of a PR controller

<u>PI controllers</u> are equipped to resolve this shortcoming by implementing control within a synchronous reference frame. This allows the PI controller to shift the infinite DC gain to the required frequency.

<u>PR controllers</u> operate in the SRF, so it doesn’t require any coordinate transformations. This allows a very high gain at the desired AC frequency,

PR controllers achieve the same tracking and perturbation rejection capabilities as dq-control.

Arsh

Design Criteria

For this project, the design of the inverter should have two modes of operation: a closed loop single phase mode using an LC filter at the output and a resistor to simulate the load. The other mode of operation is a grid-connected mode using an LCL filter at the output and a voltage source to simulate the grid. The single phase mode is suitable for uninterrupted power supplies, while the grid-connected mode is more suitable for photovoltaic applications such as solar panels. These modes of operation should be simulated within Simulink and MATLAB and later developed further using the Texas Instruments inverter kit. The design should be able to handle changing of the load value.

Karnvir

Constraints

With the Texas Instruments inverter kit, there are some constraints present with the controller itself. According to the controller's manual, the controller should not be used outside of a controlled lab environment and should not be used for consumer purposes as this is not a finished product. The controller has only been tested to run at ambient room temperature and not other temperatures. One may find some components on the board can reach high temperatures that could cause injuries if contact is made. Ample space should be available with this controller as the high temperatures may have a negative effect on other components connected. Since the board can operate at high-voltages and currents, failing to follow these steps, one could subject themselves to injuries and or damages to their working environment.

When designing the grid-connected mode, the design was initially tested at perfect conditions, however a constraint was realized when the design did not account for the variable sunlight and radiation levels. To attempt to simulate more realistic conditions, a repeated sequence generator was added into the design, to mimic variable sunlight (such as cloudy conditions, changing of the seasons, etc.).

Karnvir

Deliverables

The requirements specified in the Design Criteria was met for the most part. However, what the team was unable to meet was implementing the design and complete further testing using the Texas Instruments inverter kit. In the Simulink and MATLAB design of this project, both designs were achieved, including adding LC filter in the closed loop single phase mode design, and the LCL filter in the grid-connected mode design. In addition, the team was able to implement a Proportional-Resonant (PR) controller within both designs. The purpose of the PR controller is to introduce an infinite gain at the fundamental frequency, thus reducing the steady-state error to zero. Also, in the grid-connected mode design, the team was able to implement a Maximum Power-point Tracker (MPPT) and a photovoltaic (PV) array.

Karnvir

Design Methodology

Initially, the design began with a basic inverter that was able to convert AC to DC. With this design, four Insulated-gate bipolar transistor (IGBT) modules are connected to an LC filter.

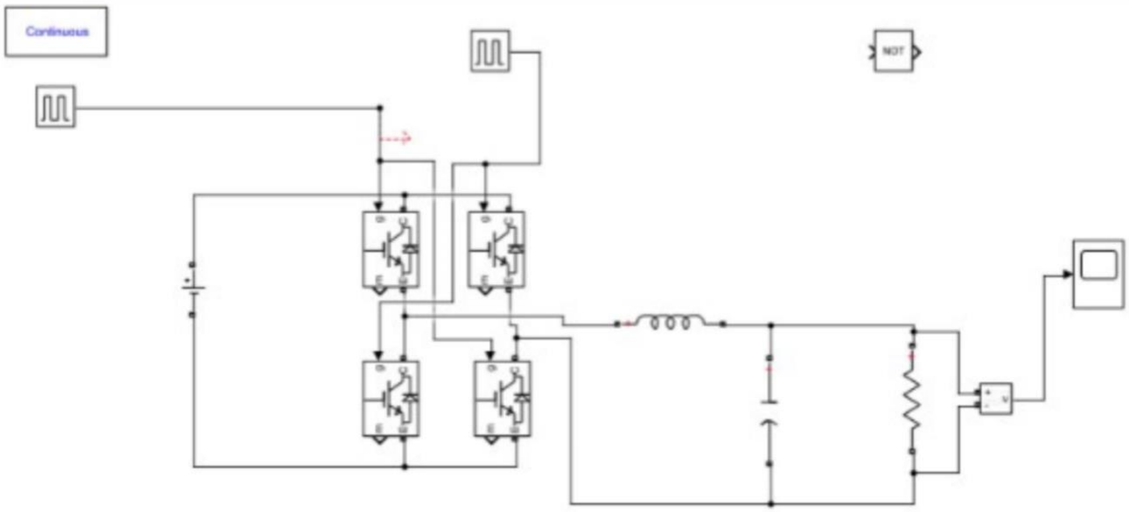

Figure 2: Initial Design of the Inverter

The four IGBT modules' purpose is to vary the voltage and mimic the highs and lows of an AC voltage. The LC filter connected, takes the square waves from those modules and smoothens them out to appear like an AC voltage. The results are shown below.

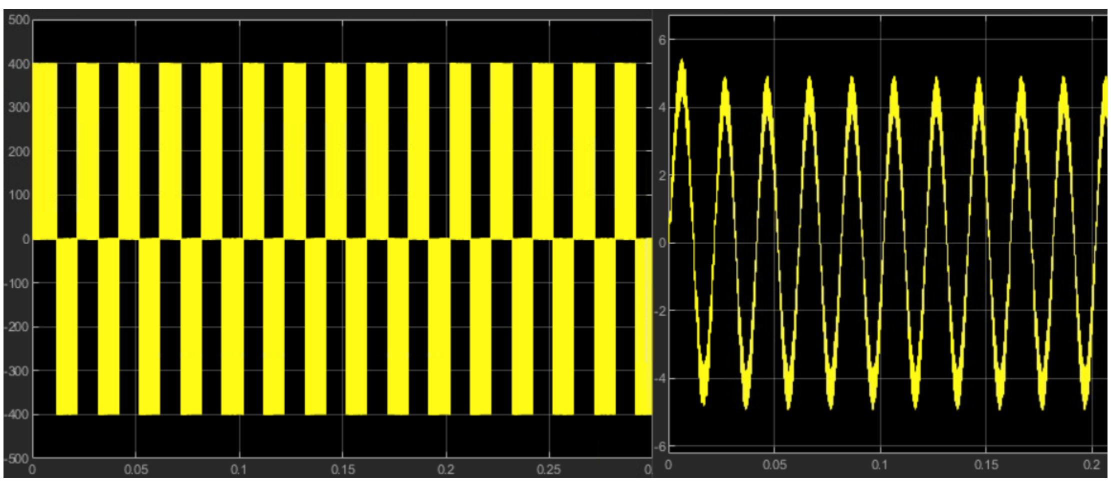

Figure 3: Results from Initial Design (Unfiltered vs. Filtered)

However, this initial design was not able to handle variable loads, so the design had to be changed to accommodate for this constraint. If this issue was not resolved, when the load is modified, the voltage would spike very high or drop very low, which would not meet the design expectations.

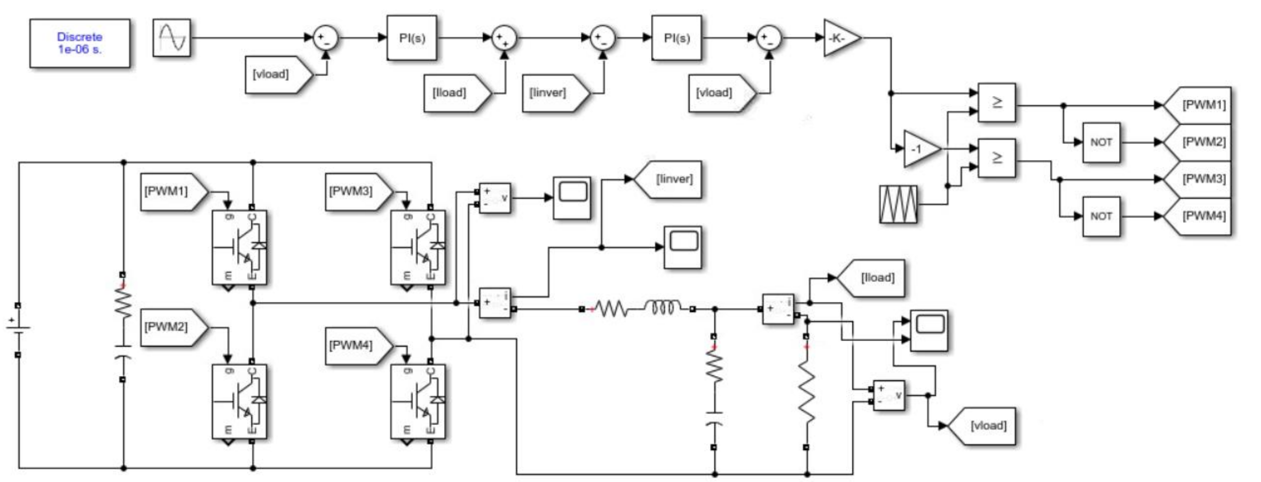

Figure 4: Closed Loop Design with PI Controller

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_p \frac{de}{dt}$$

$u(t)$ = PID control variable

K_p = proportional gain

$e(t)$ = error value

K_i = integral gain

de = change in error value

dt = change in time

Figure 5: Equations used with PI Controller

With the next version of the design, a Pulse Width Modulation (PWM) was implemented. A PWM works by reducing the average power of an electrical signal by splitting it up into discrete parts. Through this addition of a PWM, the input current for each IGBT module can be modified. The modified input currents allow the reference voltage and output voltage to be equal. The drawback with this design was the implementation of a Proportional-Integral (PI) controller built in as a module within Simulink and MATLAB, which also includes a steady state error that could not be measured within this design.

With the final design, instead of determining a solution to measuring the steady-state error, the team decided to swap to a PR controller, which eliminated the steady-state error entirely.

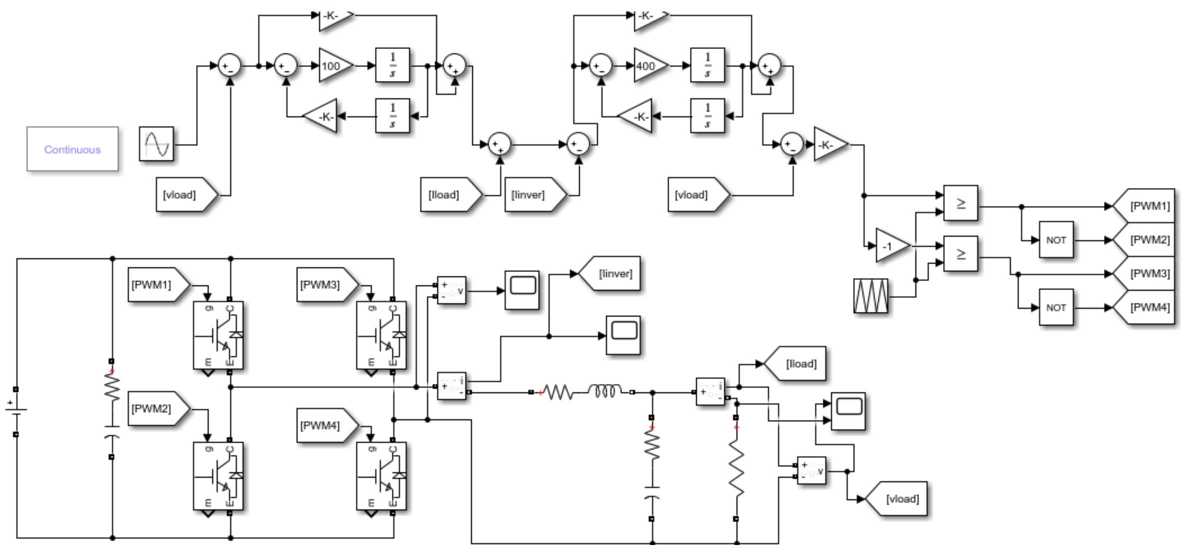

Figure 6: Closed Loop Inverter with PR Controller

In the initial design for the grid-connected mode design, the difference between this and the closed-loop single phase design, was that this design did not have an output load and instead of an LC filter, a LCL filter was implemented instead. Within this design shown below, it still included the PI controller and introduced the steady-state error.

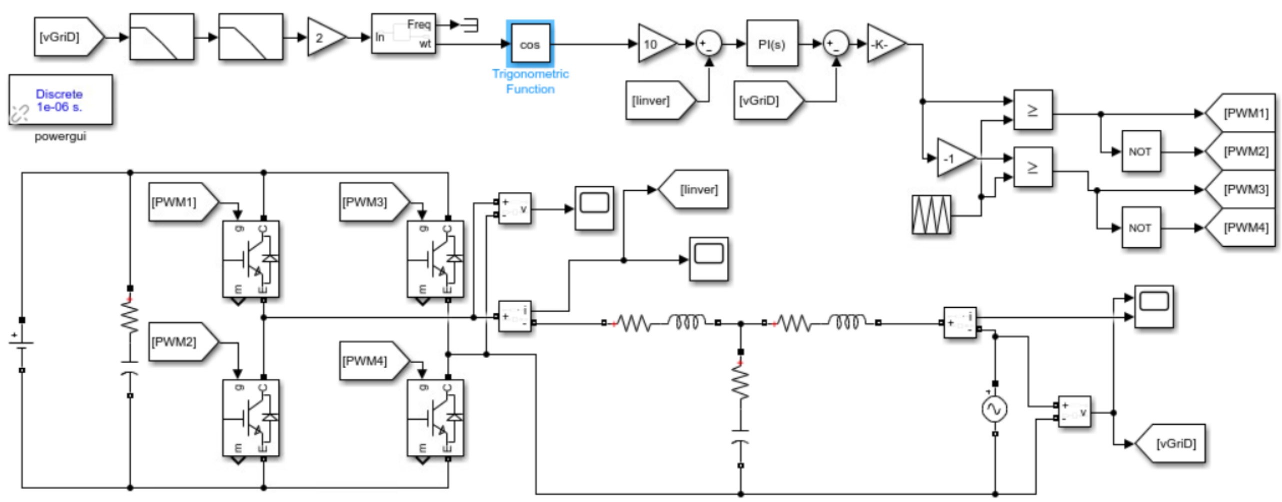

Figure 7: Initial Grid-Connected Design

In the final design, the PR controller was manually implemented to eliminate the steady-state error. In addition, the PV array was added to mimic a solar panel in the simulation. At the bottom of the design, a phase-locked loop was also implemented. The repeated sequence generator is connected to the PV array to allow the simulation to mimic variable weather conditions that could affect the PV array. The repeated sequence generator's purpose is to vary the radiation levels that the PV array receives.

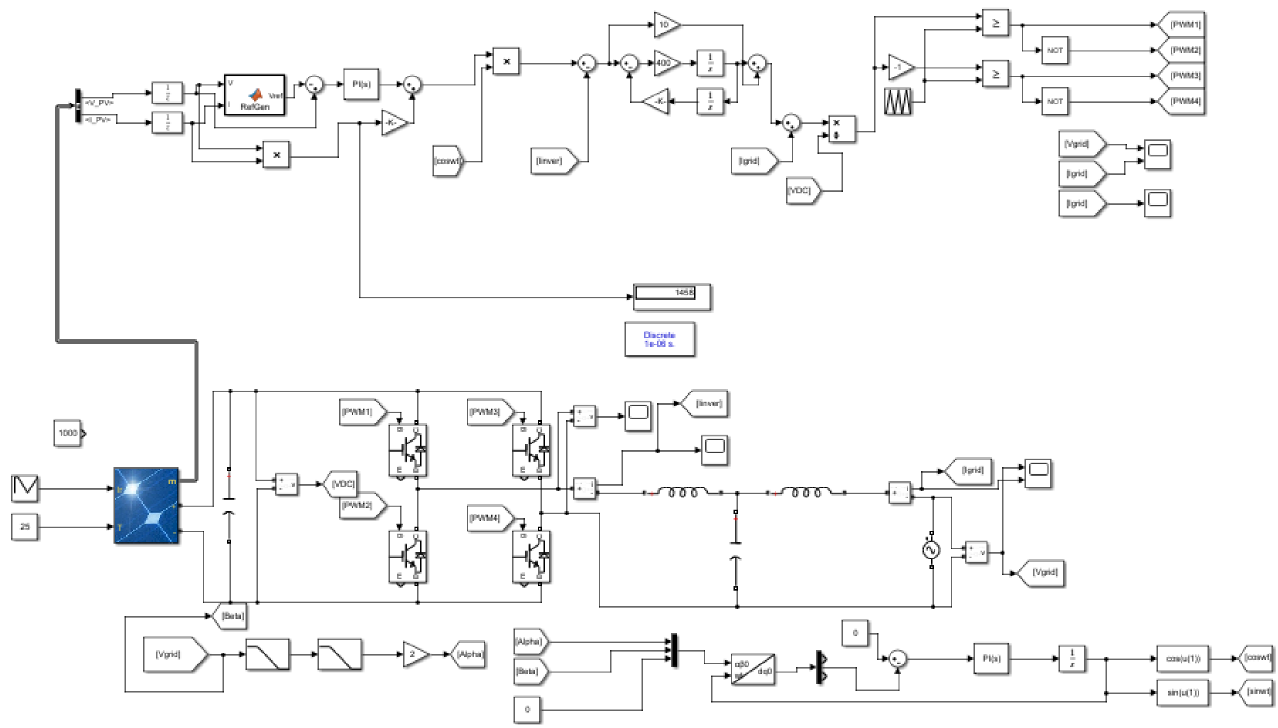

Figure 7: Grid-Connected Design with PR Controller, MPPT Module, and PV Array

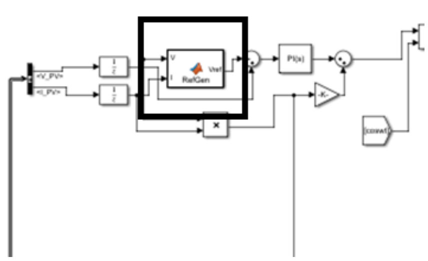

Figure 8: MPPT Module

An MPPT Module was specifically coded for the grid connected mode. An MPPT's is job to take DC voltage from the solar panel, and convert it into a high-frequency AC voltage and then once again convert it back to a DC voltage. The reason behind this is to match the voltage specifications of the circuit. The code was obtained and coded through the help of various royalty free available online resources.

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Simulation Model Development

Closed Loop Mode

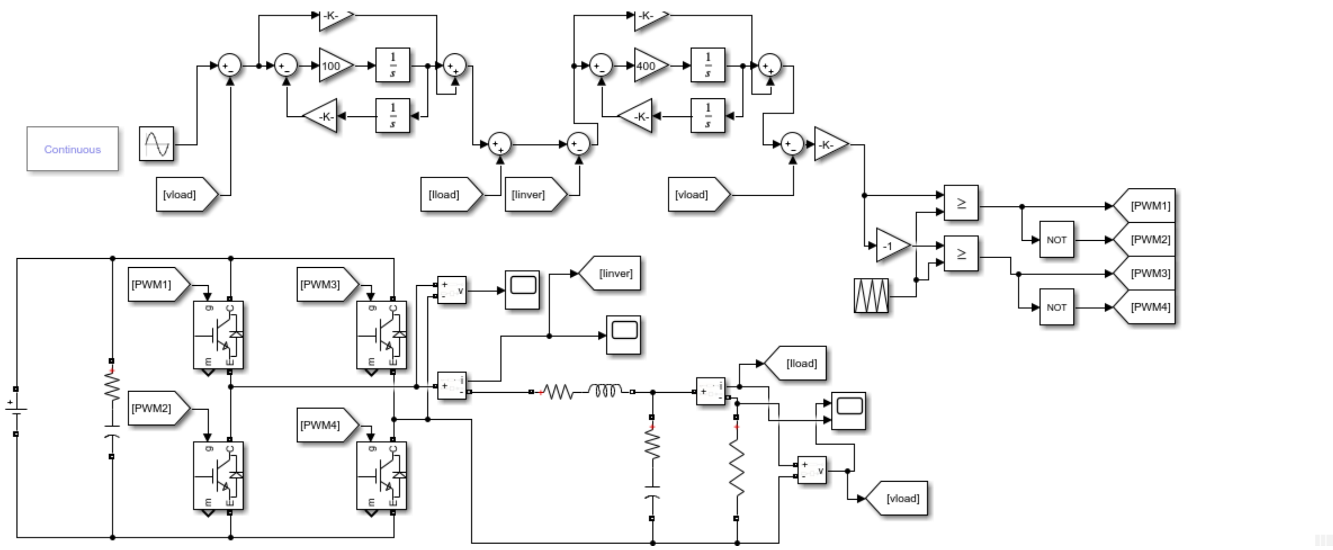


Figure 9: Closed Loop Design with PR Controller

This closed loop design is comprised of two modules: the Control module and the Main inverter module.

Main Inverter

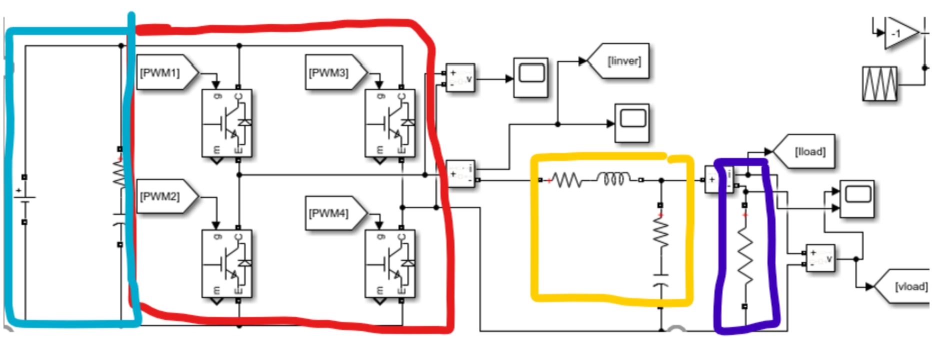


Figure 10: Main Inverter Components

For the main inverter, these are the main components highlighted above. From left to right:

- DC Voltage (380 Volts spec) and Parallel Stabilizing Capacitor
- IGBT modules that perform the main switching function
- LC Filtering Capacitors
- Load

Current Sensing Controller

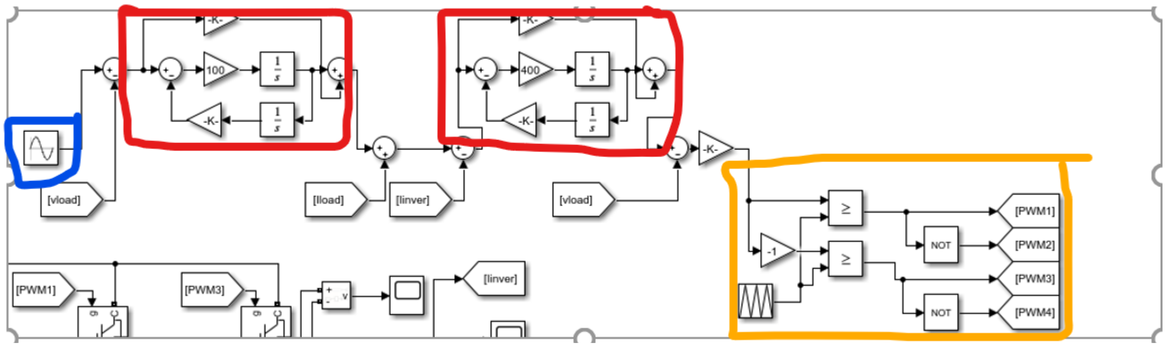


Figure 11: Current Sensing Controller Components

For the current sensing controller, the main components from left to right are as follows:

- The reference voltage (usually set to the region's standard)
- Two PR Controllers, custom designed to match design specification
- PWM module to regular the inverter current and the switching function, controlled by a sawtooth wave generator.

Grid-Connected Mode Design

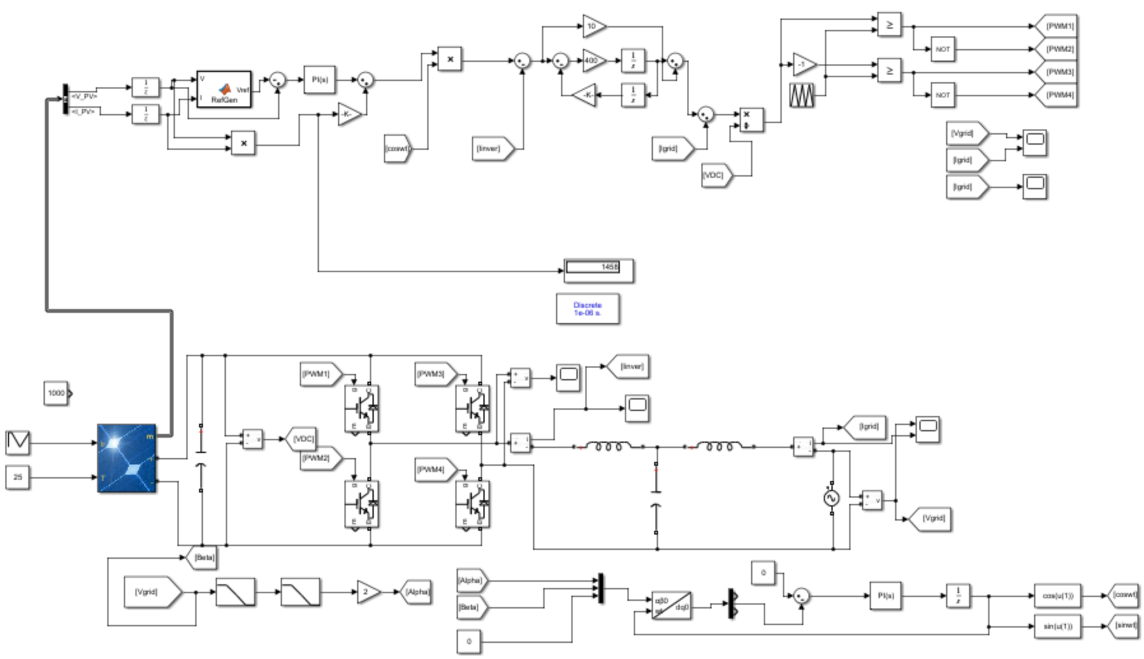


Figure 12: Grid-Connected Mode Design

This design consists of three different sub-modules: Current Sensing Module, Main Inverter, and PLL circuitry.

Main Inverter

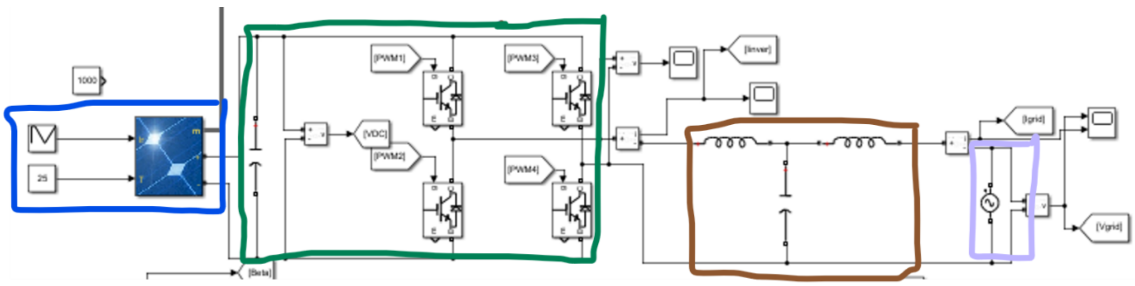


Figure 13: Main Inverter Components of Grid-Connected Design

The main inverter works as follows from left to right:

- PV Array with the a pre-set variable radiant scheme
- IGBT modules for switching function
- LCL filters to smoothen out the waveform
- Grid connection

Current Sensing Module

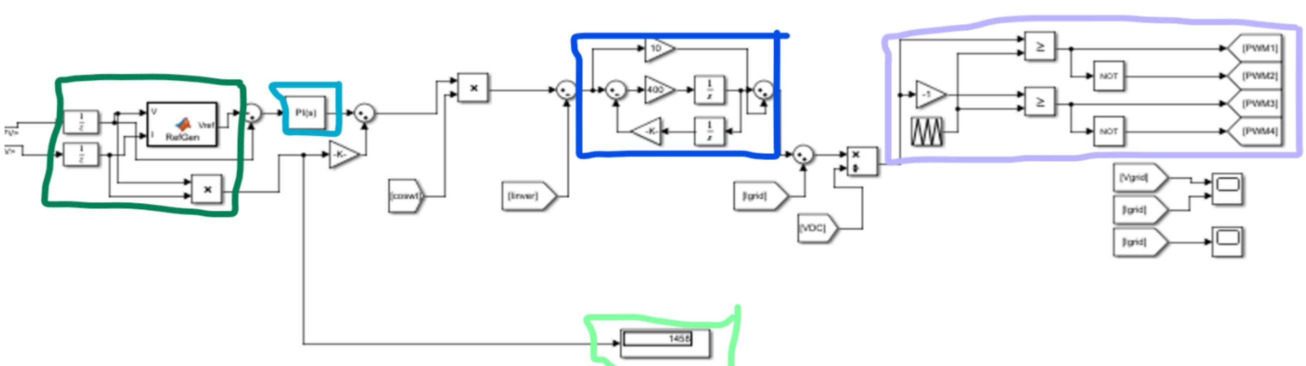


Figure 14: Current Sensing Module Components of Grid-Connected Design

The current sensing module from left to right:

- MPPT, DC to DC Converter to regulate the voltage and match the specifications
- Supplementary PI module to the MPPT

- (Light Green) Scope to measure radiance
- (Blue) PR Controller
- PWM Module to control the IGBT switching functions

PLL Module

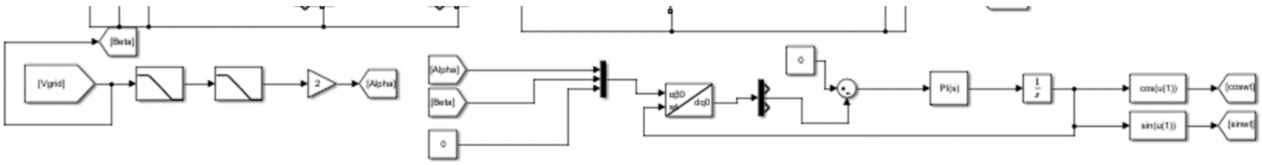


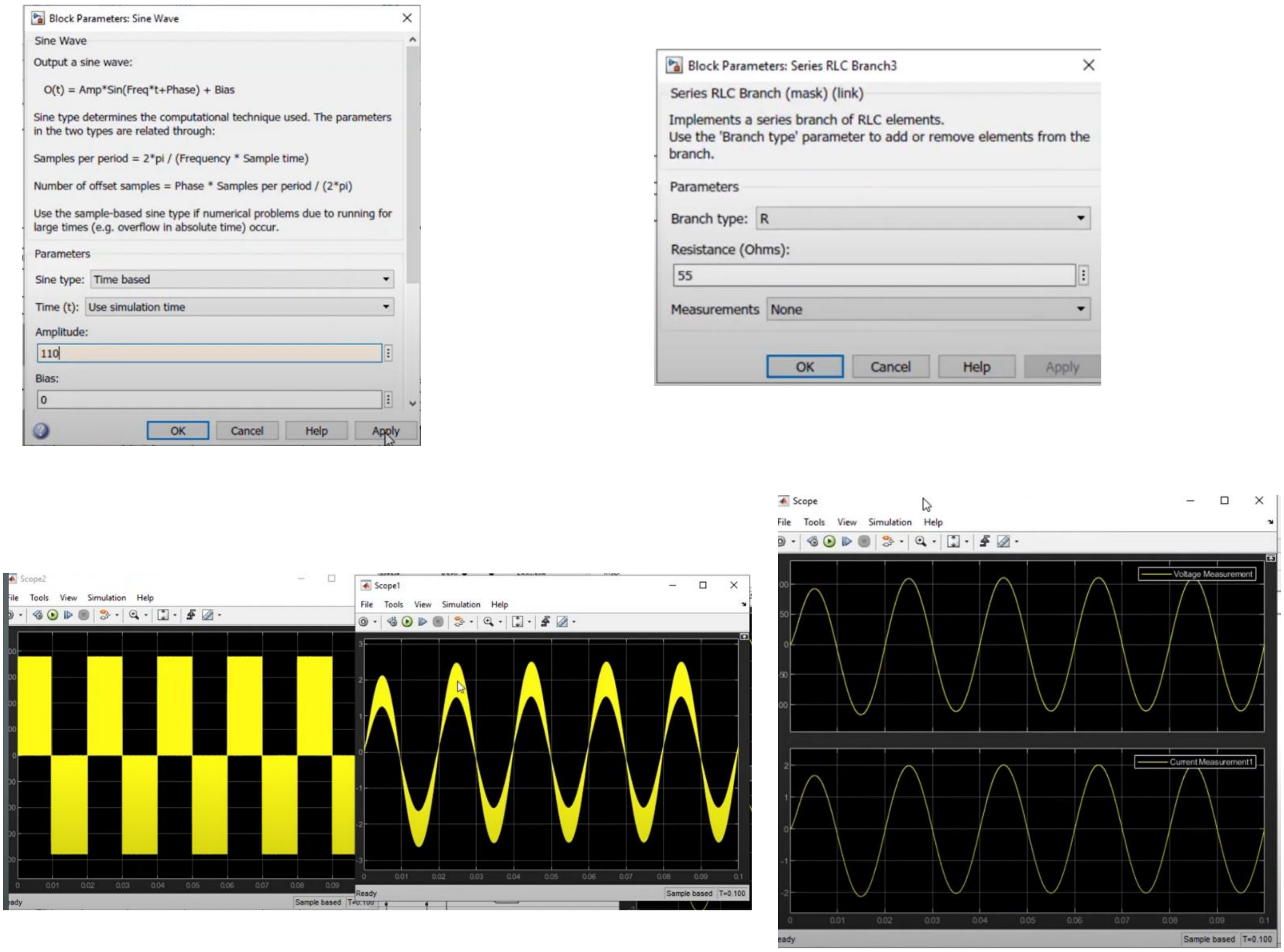
Figure 15: PLL Module of Grid-Connected Design

The PLL module is an additional circuitry required to operate the photovoltaic array.

Experimental Methods

Closed Loop Mode

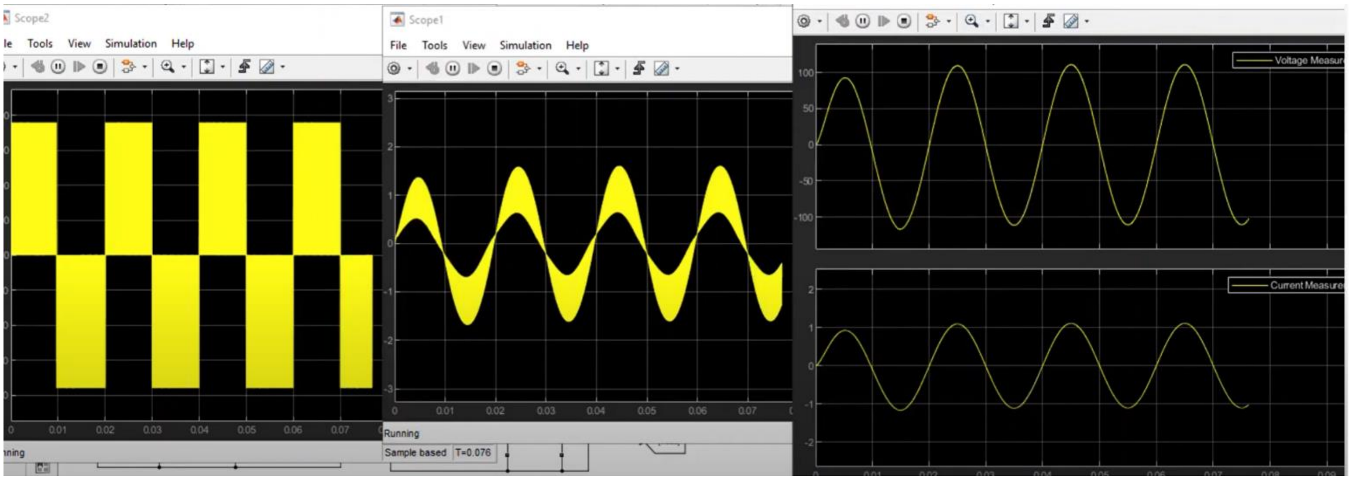
For experimentation, we varied both the reference voltage and the load resistance in order to check the functioning of the inverter. For the initial testing, the following values were implemented as follows: 110 Volts and 55 Ohms.

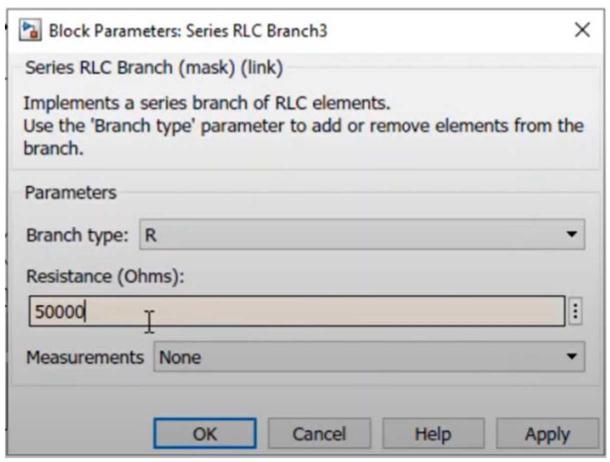


Figures 15-18: Parameters and Results of Closed Loop Design

By observing the figures above, the reference voltage of 110 volts, is equal (110 volts) in the output voltage shown.

Now when the load resistance is increased by a factor of 50, it can be observed that the output voltage still equals the reference voltage (110 volts) as shown below.





Figures 19-20: Increased Parameters and Results of Closed Loop Design

Grid-Connected Mode

Figure 21: Parameters of Repeating Sequence

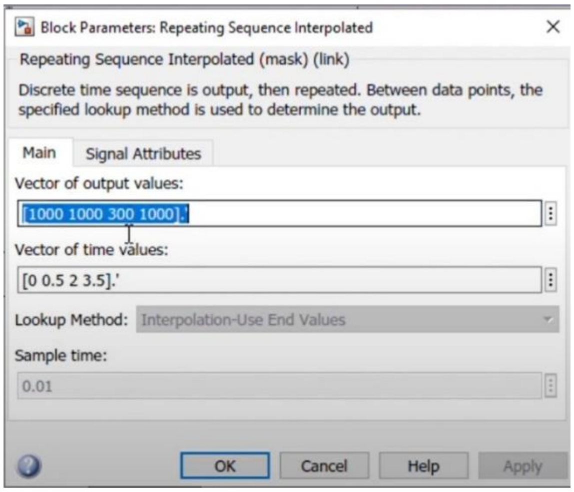
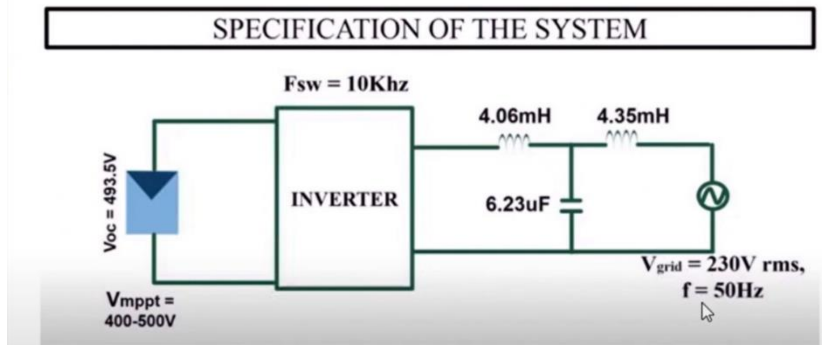


Figure 22: Specification of Grid-Connected System



The radiance varies with the following numbers: 1000, 1000, 300, 1000. If everything were to work as intended, then in the results the current should show variance.

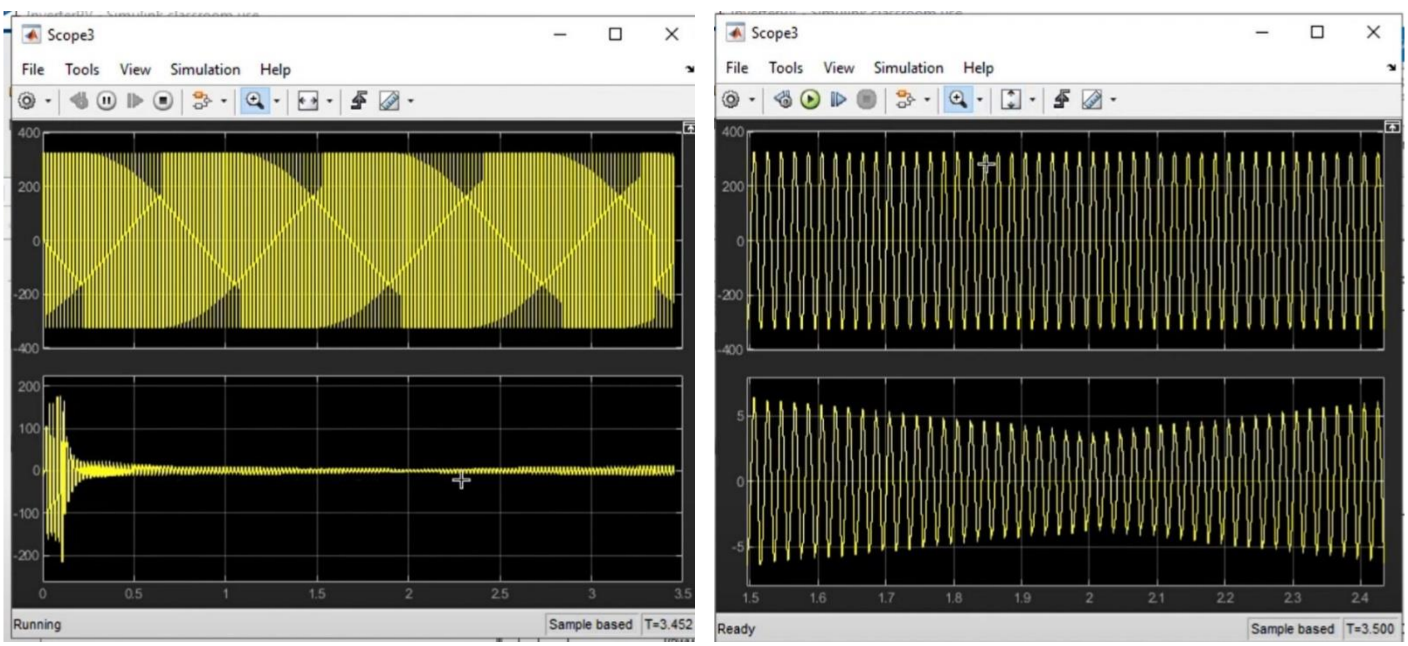


Figure 23: Results of Grid-Connected System

The voltage specification of the grid-connected mode as shown, require the voltage across the grid to be 230V_{rms} (325 V_{pp}). In the results shown above, this specification is met. It can also be observed, the repeated sequence generator works as intended as the grid current is proportional to the radiation absorbed by the panels.

Design Specifications

Closed Loop Mode

- The reference voltage is then modified to match the specifications of the Texas Instruments inverter (110 volts RMS).
- The DC Input was tuned to 380 V as per the specifications
- Output frequency was set to 50 Hz

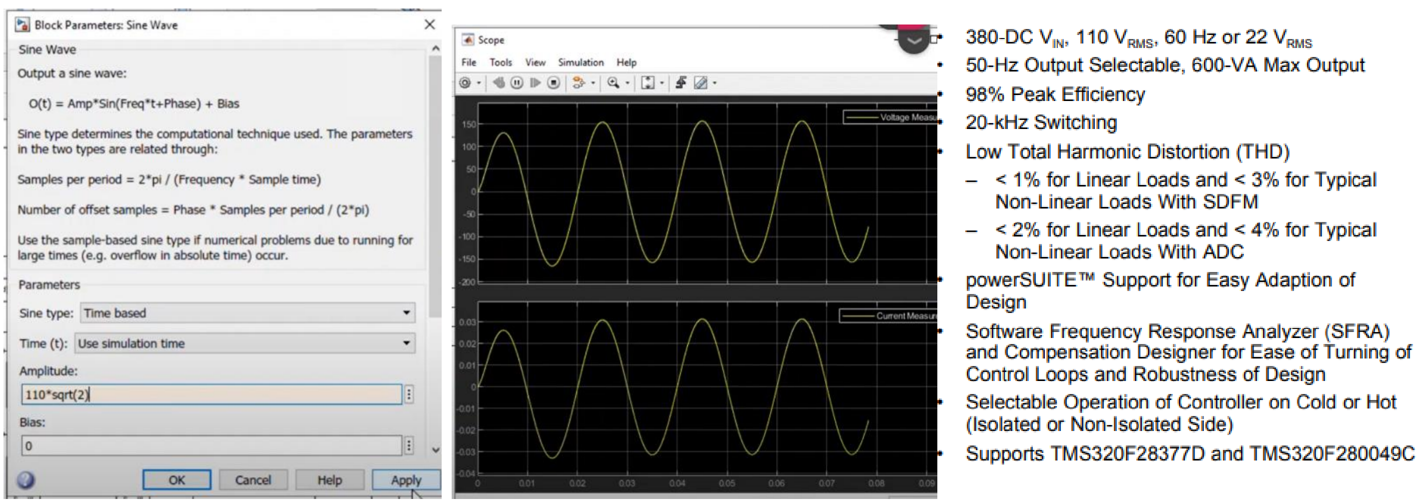


Figure 24: Specifications of Closed Loop System

Therefore, as observed, the output AC Voltage matches the reference voltage as expected. This signifies a perfectly working model of the TI based closed loop inverter

Grid Connected

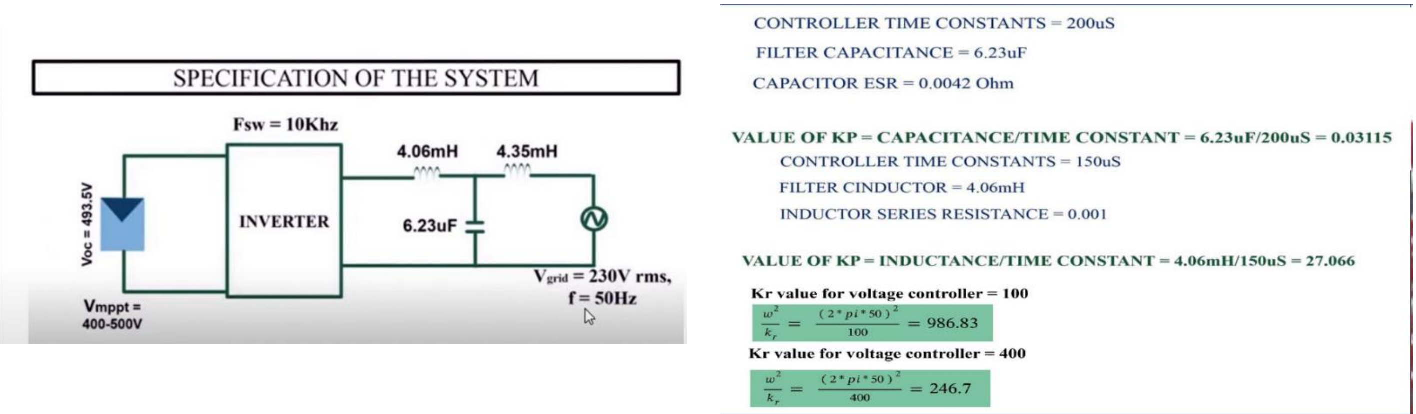


Figure 25: Specifications of Grid-Connected System

For the grid connected variant, calculations were performed to obtain the K_r and K_p values for the capacitor and the inductor. The V_{oc} was set to 493.5V and V_{mppt} was set between 400-500V.

LCL Filter Values

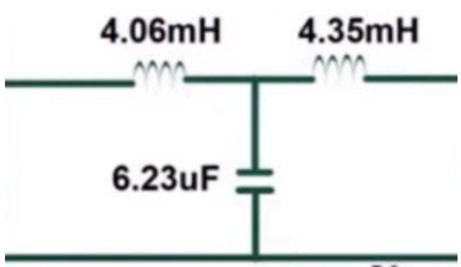
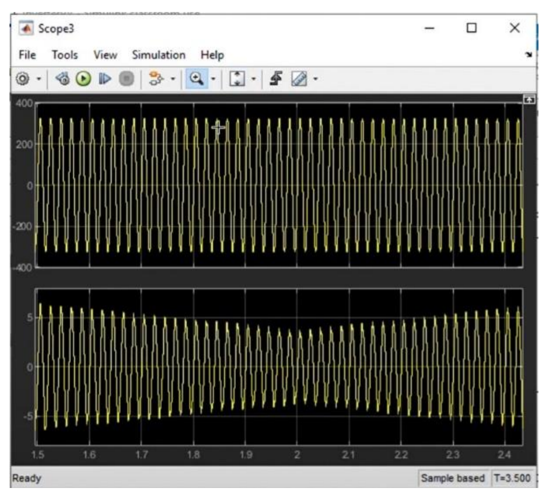


Figure 26: LCL Filter Specifications and Result

L_1 = 4.06mH

L_2 = 4.35mH

C = 6.23µC



As observed, we were able to generate a voltage of $325V_{pp}$ or 230V RMS as per the predicted calculations.

Karnvir

Evaluation Matrix

Evaluation	Expected Result	Actual Result
Maintain a Constant Voltage	Given 110 volts	Produced 110 volts
Accuracy to the Reference Voltage	Input 110 V_{rms}	Output 110 V_{rms}
Ability of the Grid Current to match the dips in irradiance	Implemented sequence of [1000, 1000, 300, 1000]	Current (observed through the scope) matched the dip in irradiance

Table 1: Evaluation Matrix

Karnvir

Budget

Item	Quantity	Cost Per Unit
TIDM-HV-1PH-DCAC inverter Kit	1	$749.00
Oscilloscope	1	$82.70
DC Power Supply	1	$99.99
Total Cost:		**~$931.69**

Table 2: Initial Budget

Initially the budget found in Table 2 above, was the estimated cost of physically implementing the project by the end of the summer semester, with the assumption that the pandemic restrictions would be lifted for lab access at the university. The budget included the Texas Instruments inverter kit to be used with the design, an oscilloscope to view the voltage and current, and the DC power supply to power the kit. However, due to further pandemic restrictions, the physical implementation could not be completed, therefore the budget given of $600 was untouched.

Muhab

Conclusion

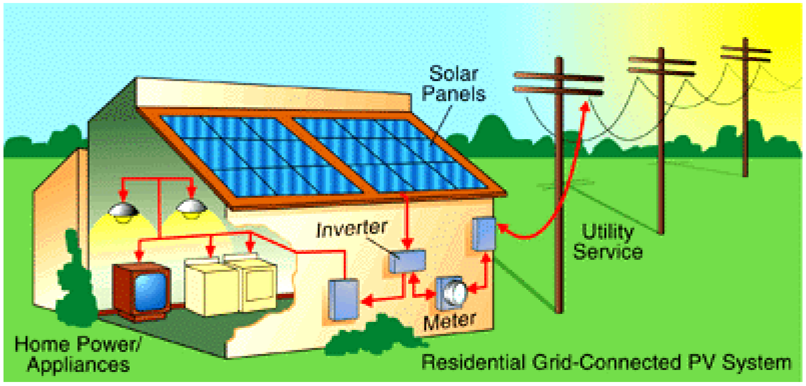


Figure 27: Residential Grid-Connected PV System

We were able to successfully implement a Bi-directional single-phase voltage source inverter using MATLAB SIMULINK.

The two operating modes were:

- Closed Loop Mode
- Grid Connected PV Mode

Closed loop mode essentially means that the inverter runs off grid. It is not connected to the main regional power grid and fully sources its energy from solar radiation. Generated surplus or a shortage are not usually rectifiable due to its independent nature. Pros being the ability to run on an independent voltage and frequency while it cannot source some dependence from the main power line.

Grid Connected inverter is connected to the main electric grid. In the event of a surplus, it can transfer the energy to the local grid and earn credits from the electric agency, whereas in the event of a shortage it can request energy from the grid. Pros being it can never run out of power, while the downside is to have the reference voltage matching the grid.

For the Closed Loop Mode, we referenced the TI C2000 microcontroller manual. The Source voltage was set to 380V, and the reference voltage was set to 110V RMS 50Hz. The initial design utilized an inferior performing Proportional Integral controller but was later modified to utilize a better AC performing Proportional Resonant controller. The design was ruthlessly tested by drastically modifying the Load resistance: Output voltage was found to be constant. An LC filter was fine-tuned by trial and error to achieve desired results.

For the Grid Connected Variant, the initial design implemented a DC voltage source with a Grid connection at the load. The design was upgraded to support a PhotoVoltaic array utilizing a MPPT DC to DC converter and a PLL module. A repeated sequence generator was attached to the Irradiance port of the Solar panel to simulate variable sunlight. The specification required fine tuning the PI controller attached to the MPPT. MPPT code had to be sourced using online research to achieve optimal performance. The Output grid voltage was calculated out to be 230V RMS (325V_{pp}). This was later verified through simulation to be the true value. The grid current amplitude matches the Irradiance experienced by the panel.

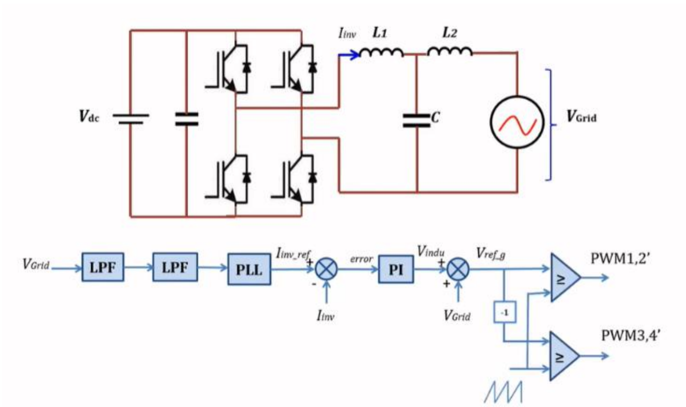


Figure 28: Original Grid-Connected System without PV Array

The main novel innovation came about with the Grid Connected Design. Our original specifications mentioned a barebones grid connection to simulated Solar DC battery inverter, but we decided to reach beyond the requirements and implement a fully-fledged PV panel. This required a ground up redesigning of the Controller and the Sensing equipment.

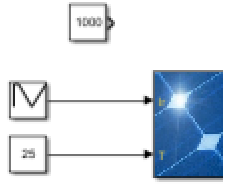
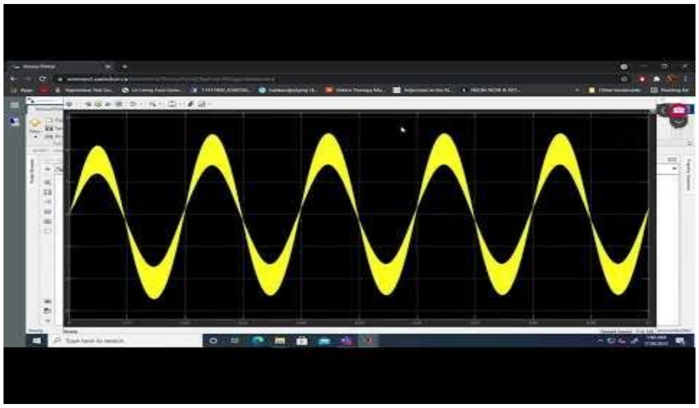


Figure 29:Repeated Sequence connected to PV Array

With the PV equipment in place, we decided to attach a constant 1000 level irradiance to the panel. This wasn't close to the ideal conditions experienced so we decided to attach a decided radiance level array that fluctuates the sunlight received by the panel.



Capstone 2021 Team 18 - Bi-directional single-phase voltage source

Arsh

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Karnvir

Appendices

Project Timeline

Expected	Actual	
March 2021	April 2021	- Reviewing the theory and hardware of single-phase voltage source converters that are typically used with PV inverters and UPSs,
April 2021	End of May 2021	- Simulating basic inverter design
End of May 2021	Beginning of July 2021	- Simulating a functional inverter and Grid-Connected inverter
End of July 2021	End of July/Early August 2021	- Finalize report and presentation

MPPT module implementation in Grid-Connected Design in Simulink (Credit to Tech Simulator on YouTube) :

```
function Vref = RefGen (V, I)

Vrefmax = 363;
Vrefmin = 0;
Vrefinit = 300;
deltaVref = 1;
persistent Vold Pold Vrefold;

dataType = 'double';

if isempty(Vold)
    Vold = 0;
    Pold = 0;
    Vrefold = Vrefinit;
end

P = V*I;
dV = V-Vold;
dP = P-Pold;

if dP ~= 0
    if dP<0
        if dV<0
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold - deltaVref;
        end
    else
        if dV<0
            Vref = Vrefold - deltaVref;
        else
            Vref = Vrefold + deltaVref;
        end
    end
else Vref = Vrefold;
end

if Vref >= Vrefmax | Vref <= Vrefmin
    Vref = Vrefold;
end

Vrefold = Vref;
Vold = V;
Pold = P;
```