

Design and Implementation of a Small Scale Standalone Hybrid Solar PV and Wind Energy System

FINAL DOCUMENTATION

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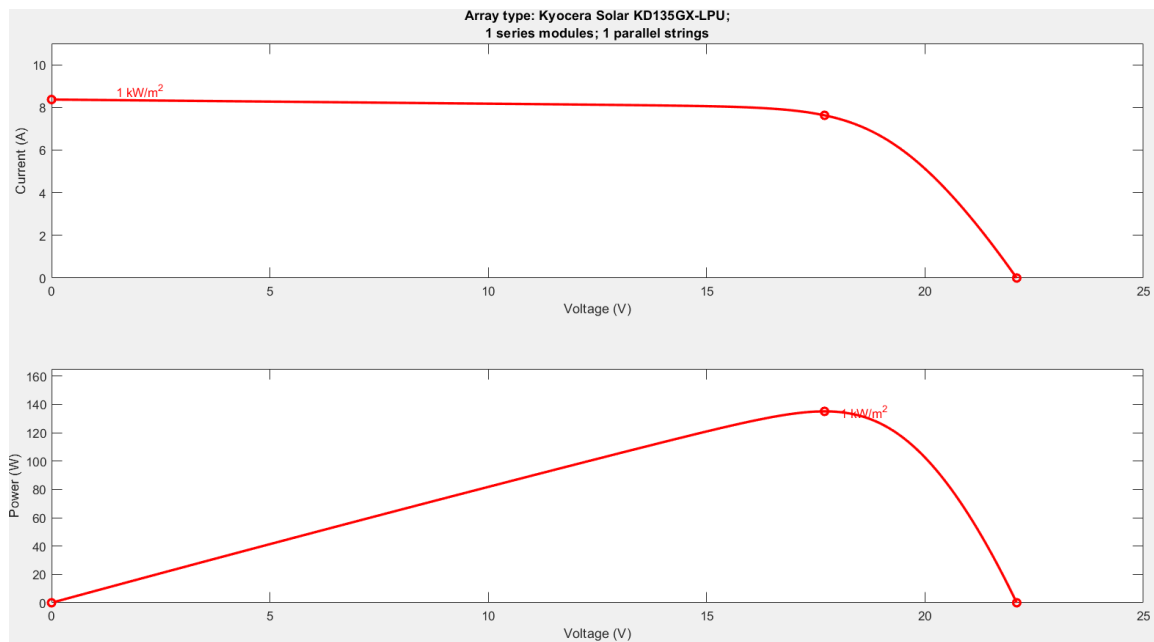
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o Background Information/Definitions

Our project revolves around the Electrical Machines and Power Electronic Drives class at Iowa State, also called EE 452. We were tasked with improving

Photovoltaic Cells (PV or PV array), more commonly known as solar panels, are non-linear devices. This means that for different loads, and the effective resistance associated with that particular load, the output will be a combination of current and voltage. If plotted, these point will form a curve, not a line. An example of this curve is shown below.



The top graph is the I-V curve, and the bottom graph is the P-V curve. As you can see from the bottom graph, the maximum power point (MPP) is found at about 18 V, which corresponds to about 8 A. In the real world, the load is varying all the time, along with the amount of sunlight and temperature at the panel, both of which affect its output.

Therefore, there is a need for a device that always draws the maximum power from the solar panel, regardless of what the conditions are surrounding it. This is called Maximum Power Point Tracking, or MPPT. One of the main drivers for the lab, and our project, is to give the students the ability to plot this curve using hardware found in the lab.

1 Introduction

1.1 ACKNOWLEDGEMENT

We must acknowledge the previous senior design team who worked on the same lab before us. They left us their final deliverables fully outlining the initial design of the lab. Professor Ajarapu has also helped us a great deal by providing us with equipment and funding for the lab design. Pranav Sharma, an assistant to Professor Ajarapu, has helped us by providing technical guidance and suggestions regarding the technologies involved in the lab.

1.2 PROBLEM STATEMENT

The problem that needs to be solved by our group revolves around the EE 452 Solar Power Lab. The lab currently in place is of insufficient quality to properly demonstrate the qualities of solar panels and the MPPT software that is used in conjunction with the panels.

Our solution is multi-faceted to address several issues in the lab. Primarily, the current DC load is too small to test the solar panel, and MPPT, characteristics. Solar panels are non-linear devices that output different amounts of power as the load resistance varies. Currently there is no way for us to measure the Maximum Power Point with relative ease. A system to resistor boxes were used in parallel and series connection to get us close to the maximum power. Therefore, a resistor bank is needed to create a large variety of resistor values so that students can easier find the maximum power point corresponding to a resistance value.

The other major issue with the lab has to do with safety and stability. The current setup has many instances of exposed leads that can have up to 300 Watts going through them at a given time. The workstation was also grounded to the metal rack it rested on, rather than having a proper ground node. Many of the components had live bolts and when turned on, these bolts had arcing around them. Many wires connecting components would produce shorts, resulting in inaccurate data.

Other stability issues include uninsulated wire in the courtyard, and a large group of wires that may harm the Arduino hardware over time. Our solution to both issues is to design a protective circuit that will isolate all dangerous terminals and protect the hardware from longtime damage. This includes redesigning the workstation that the pervious circuit was enclosed upon and creating an enclosure that protects the circuitry from outside interferences.

1.3 PURPOSE

There have been recent technological advances made to solar and wind generation systems that are more economical and environmentally friendly. Currently other countries around the world have been creating wind generation and solar generation farms, thus there has been an increase in demand of renewable energy sources around the globe.

Because of these demands, Electrical Engineers need to be educated on the process, usage, characteristic and challenges that comes with developing and implementing renewable energy sources. Currently, at Iowa State, the course EE 452, Mechanical Drives and Machines, discuss electromagnetic conversion, and is a key concept in renewable energy power systems.

Currently the lab for this class is in room 1011 in Coover Hall, and a workstation is in place for students to collect data from two solar panels placed outside of lab in the Coover courtyard. The purpose of the lab itself is to let students experiment with solar panels and demonstrate their characteristics with hardware. Consequently, the overall purpose of this year's group is to implement a solution that is not only sufficient to fulfil the requirements of the lab, but to make the lab user friendly and safe for the students.

1.4 GOALS

1. Redesign the workstation, this included removing the current rack that the circuitry was on and bringing in a workbench that would allow easier future expansion. Bench can be redesigned by adding extra cabinets and surfaces if needed for future expansion.
2. Rewiring the circuitry, currently the circuit needs to be rewired due to shorts and other hazardous conditions.
3. Fully implementing a schematic of the overall circuitry so that future students understand how each component works and how each component is connecting to one another.
4. Resistor bank needs to be created so that students can plot the maximum power point with more accuracy. The previous train load was unable to provide data to graph the maximum power point. With the new resistor box, students will be able to have a range of resistance values from .5 ohms to 500 ohms.
5. Revising the lab manuals to include the resistor box and other experiments. Making sure that every experiment is very organized and have clear and concise instructions, so students can maximize their time learning about the lab without any unclear instructions.

1.5 DELIVERABLES

Workstation: The workstation will be placed on a bench that is only used for the lab. This will include our enclosure for the circuitry. This includes all the LCD screens, that are used to tell the students the irradiance, voltage, current and current temperature outside from the solar panels. This enclosure is a redesign of the previous workstation and will allow for future expansion.

Schematic of Circuitry: A schematic will be created showing all components and wiring that leads to each component. This is to ensure that there is no confusion in future students learning to improve and expand upon the system. This will also allow future

students to clearly and intuitively understand how the system functions, and how each component relates to each another.

Lab Manuals: Revised lab manual of experiments will include step-by-step instructions of how to use components of the workstation, the purpose of the lab, and the underlying theories learned in class that allow students to place their knowledge in an experimental environment. It will be noted that experiments will vary due to the exposure of sunlight during the experiment. Due to labs being at different times during the day, exposure of sunlight will be dependent on the current weather conditions and times of the day. Therefore, it needs to be noted that students will have varying results due to these unpredictable conditions. There will also be operating system guidelines included with the lab so that students understand how each component works, and to avoid hurting the equipment or themselves.

Resistor Box: Resistor box will contain 8 resistors: 1, 2, 5, 16, 25, 100, 150 and 200 ohm. Each resistor will be labeled for students to understand which resistor is at what value. This ensures that students have enough varying resistance values to fully graph the maximum power point curve and find the resistance value associated with the maximum power point for the current weather conditions. The resistor box will also help reduce the amount of wires needed to get certain resistor values and allows for more intuitive understanding of what resistors are being connected in series or in parallel.

2 Design

Although, the idea of this project is design and implement hybrid solar and wind standalone energy system, professor Ajjarapu stated that he wanted the focus to mainly be on the solar energy system aspect of the design. However, wind energy design remains a possibility for future teams. The focus is now solely on the implementation of solar energy and cleaning up the circuitry, implementing a new workspace, and developing a resistor box that allows students to graph the maximum power point curve accurately through experimentation.

Firstly, the focus is on cleaning up the workspace by removing the current rack that has many resistor boxes and other components on it that are not related to our experiment. A workbench has been installed solely for the usage of this experiment. This workbench will allow future students to make modifications to it that allows for future expansions in a neat and organized way. The workbench allows for students to know that every component needed for the lab is in a secure location.

Secondly, an enclosure was created for the overall circuitry of the lab. Previous circuitry was in place in a plywood box that was grounded to the metal storage rack which held it. The previous workstation was messy, unorganized, dangerous, and lacked a schematic labeling all components in it. A metal enclosure is now replacing the plywood box and has

been modified to fit all components of the previous enclosure and organized neatly. A schematic was created as well, because there was no previous schematic of the overall system in the previous group that lead us to learn about the components and understand how everything function ourselves. This lead to weeks of learning how the circuitry worked, therefore to maximize time and minimize confusion of the overall circuitry, a schematic will be created to allow future students to fully understand how each component works with one another and the overall layout of the wiring and how they connect to each component.

Lastly, the resistor bank was being designed so that students can fully graph the maximum power point curve with relative ease. The load previously used for this section was a DC train. The students were able to add more weight to the train to increase the load, and thus plot the graph of I-V characteristics. However, the train was far too small to qualify for this lab. It could only handle 15 W of power while the solar panels can output 270 W. This meant that, in practice, it couldn't be connected directly to the solar panels, and would not come close to verifying the characteristics of the PV array. Therefore, by creating a resistor box with varying resistances that can withstand 300 W of load, students will be able to manually create their own resistance values and test them. The idea is to reiterate previous knowledge of connecting resistors in parallel and series and apply it to this experiment, so that students have a more interactive experience with the lab and applying previous knowledge.

2.1 SYSTEM SPECIFICATIONS

1. Workstation needs to be clean, organized, safe, dependable, and overall allows for future expansions.
2. Lab manual needs to be concise, intuitive, organized, and follow information learned from course lectures. Lab needs to be able to be completed in the 3-hour time frame. Students need to fully understand underlying safety hazards. Topics of the lab are to pertain to solar power energy systems, theory of maximum power point tracking, PV cells, buck/boost converters, and how the effects of solar irradiance and temperature from the solar panel.
3. Resistor box needs to be fully labeled with corresponding resistor values and be secured in a location with ease of access in the workstation.
4. All simulations in Simulink should be organized and reflect the overall workstation.

2.2 FUNCTIONAL REQUIREMENTS

The functional requirements of this lab include being able to model all the components used in the lab in Simulink. Using those models, we are going to need to be able to test the system in a safe environment. This is to protect the students and the equipment. The lab needs a load which can fully model the functionality of the solar panels and MPPT. To make these measurements, we also need to provide an interactive interface that allows the

students to see what is happening within the system, while using different loads. This includes providing displays that show voltage, current, and power at different points in the system. Our areas of focus are solar input, battery input, MPPT input, MPPT output, DC output, and AC output. An implementation of a resistor box will be created so that students can plot the MPPT curve with better accuracy.

2.3 OVERALL COST ANALYSIS

The overall cost of the implementation of the workstation and the resistor box is:

1-ohm Resistor: \$21.83

2-ohm Resistor: \$24.32

5-ohm Resistor: \$24.32

16-ohm Resistor: \$21.83

25-ohm Resistor: \$42.10

100 ohm Resistor: \$25.10

150-ohm Resistor: \$35.59

200-ohm Resistor: \$25.29

Circuit Breaker: \$19.19 and \$20.19 x 2

Arduino Uno Rev3: \$22.00 x 2

Banana Pins: \$.65 x 24

Fan: \$5.87 x 3

Digital Multimeter: \$19.99

Terminal Blocks: \$5.60 x 4

Resistor Clips: \$.63 x 8, \$1.36 x 6, and \$9.10 x 2

Resistor Enclosure: \$38.96

Circuitry Enclosure: \$53.70

Buck Boost: \$44.99

Overall Cost: \$568.6

For future expansion of the current system, the cost of additional solar panels and batteries are as follows:

Solar Panels: \$350.00 x 2

Batteries \$45.98 x 2

Overall cost of additional parts: \$791.96

Note: With future expansion of the system, consideration of current hardware and limitations needs to be in place. If current system has an MPPT that can sustain 600 watts, additional solar panels will increase the power that the MPPT can handle, thus another MPPT must be purchased to compensate for the increase in power.

2.4 STANDARDS

There were a variety of standards that were applied to this project. Since solar energy is relatively a new concept and is making remarkable improvements to renewable energy sources in the industry, standards are still being refined and developed. IEEE standards still apply to this project. IEEE Recommended Practice for Testing Insulation Resistance of Electricity is outlining the process of what it means for testing the insulation resistance of polarized machine windings. It goes into definitions, reasoning for importance, testing conditions and procedures and expected outcome of different systems. IEEE Guide for Insulation maintenance of Electric Machines is an overview of the standard procedure that goes into testing and maintaining different electric machines. It is focused around how you can prevent problems or how to fix problems when they arise. IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems is focused on providing a structure for determining the battery capacity needed to have an independent PV system. It also covers a lot of definitions, and information on what it will take to have a PV as your only power source and batteries as your storage. IEEE Guide for Selecting, Charging, Testing, and Evaluating Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV Systems), mainly discusses that lead acid battery charging requirements in relation to operational parameters of the PV system and battery performance. It also provides a guideline to best test the battery and selection of battery. It also gives very thorough hazards that can occur with handling batteries and how to prevent these problems, and how to deal with situations when a problem does occur. Although many of these standards will not be used outside of college, it is educational that students learn about standards and follow them. Since the project is based on solar power energy, if the project were to expand to a grid like system, then the standards of importing solar energy to the grid by the City of Ames will apply. Safety of the students come first, due to the potential usage of high voltage and current, it is our responsibility to ensure that the safety of the student is been made aware of.

2.5 DESIGN ANALYSIS

The workstation redesign was necessary. Due to the previous workstation being on a metal rack that was being used for storage of other components, a new workstation was needed to be solely used for the 452 Lab. As a result, this allow us to move the circuitry to

a more secure enclosure. The previous enclosure the circuitry was placed on was plywood. The enclosure itself wasn't fully enclosed, students could reach into the circuitry during the lab, and due to the circuitry having live bolts and live wires, it was clearly unsafe for students to have that ease of access. As a safety hazard, the concern of the student's safety must come first, therefore the implementation of a new workstation and enclosure for the circuitry was created. With the circuitry being enclosed in a metal box and grounded to a grounding rail connected to the building, the circuitry now is safe for students to experiment on.

The resistor box was implemented, due to the insufficiency of the DC train load previously employed. We chose to design a resistor box because it is extremely functional and versatile. It can be used with both AC and DC power; it can be easily changed from a low resistance of 0.5Ω to 500Ω ; and it can dissipate all the power produced by the solar panels. By creating a resistor box, the students will be able to have a large variety of resistances that they can create by connecting each resistor in parallel, series or a combination of both. This will allow the students to plot the maximum power point curve, and clearly see how different resistances affect the maximum power point.

Overall, these two designs were needed to help organize the lab workstation, provide a workstation that allows for modification and future expansion, for students to have a better understanding of how resistance affects the maximum power point, and to ensure that safety of the students is ensured.

2.6 SAFETY CONSIDERATIONS

Safety considerations are a large part of our project. A standalone solar PV and battery system naturally has potential risks as there can be up to 300 Watts of power flowing through the devices and into the load. With up to 8 Amperes of current, touching an open terminal can seriously harm the individual, and it could possibly be fatal. Because last year's group failed to make their design secure and safe, a lot of emphasis was put on covering any open terminals and making sure the students do not have access to dangerously large amounts of electrical power.

3 Testing and Development

3.1 INTERFACE/HARDWARE

EE 452 Students will have an organized workstation that allows them to measure different variables of the system safely. These measurable variables include voltages, currents, Irradiance and temperature from the solar panels. In addition, there are loads different loads that can be measured as well. These include the resistor box and the 3-phase motor. The resistor box load will help students be able to graph the maximum power point curve and see the effects of how resistance changes the point on the curve. This will help

emphasize prior knowledge of creating parallel and series resistors to achieve desired resistance. The 3-phase motor will help students understand how power flows through a system and where losses will occur. This allows students to understand the effects of weather conditions on the power the solar panels can use and the power that can be used to power these loads.

3.2 SIMULATION OF WORKSTATION

MATLAB was used to simulate the work station by using Simulink. The Simulink model has every component in the workstation and allows students to be able to test data in a safe environment before going to workstation and experimentally test their results from simulation. Simulink allowed the modeling and analyzing of circuit characteristics such as voltage and current across each component. The effects of each component can be identified in a safe environment. The simulation allows students to learn about modeling the solar cell, maximum power point tracking, and loads and understand how the setup works. Simulation is a huge part of the overall lab, and by enabling students to learn how to use the workstation in a safe environment helps minimize the amount of unwanted problems and results and helps maximize the end results that students will be able to achieve the correct experimental results both in simulation and experimentally.

3.3 PROCESS

Overall, the workstation needed to be revamped for easy usage by the students. The circuitry needed to be placed in a standalone containment, so no students can tamper with the components without having to remove a panel. All values simulated from the lab in Simulink need to be able to be simulated experimentally within the lab station, with values no more than 10 % error.

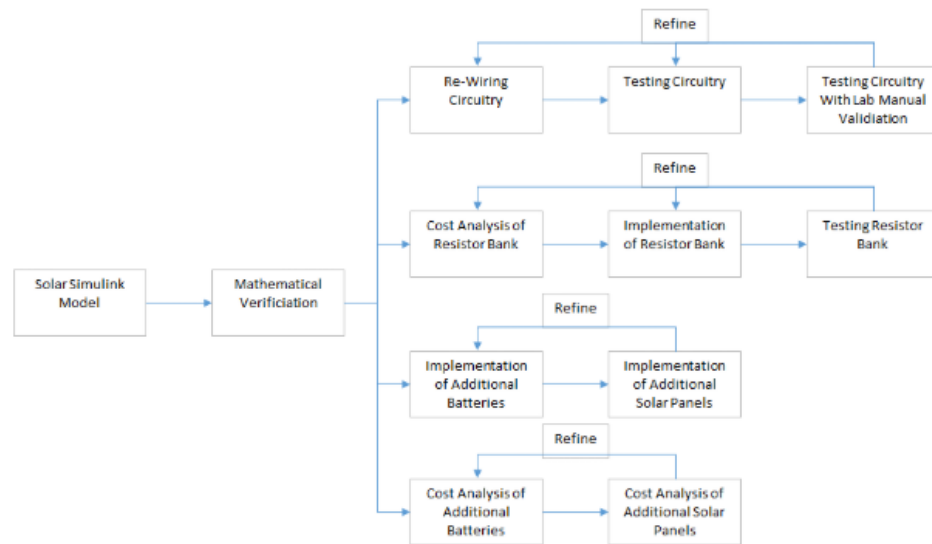
Validation of the workstation working fully will be from simulating the workstation using Simulink with real life values obtained from the station. These values were compared to the simulated values to verify that the overall workstation values produced are the same as the values projected by the simulation. These experiments were run throughout the day to get different values for solar contact with the solar panels. This allowed us to validate that the experimented results match the simulated results. Since labs are going to be throughout the day with different varying amounts of sunlight hitting the solar panel, experiments with varying weather, and sunlight contact will help determine if the workstation is running correctly. The workstation will be easily accessible so that future students can make improvements upon the system.

The following process was used for testing the model and is explained in more detail below. For testing the model, the group will mathematically prove that the overall model was accurate. Equations were used for the PV system, conservation of energy, and more. Once the mathematical verification is finished, simulation of each component will be the next step.

Simulation of the battery, solar panel, MPPT, and dc output will be used in simulation in Simulink and compared to values experimentally conducted. Simulation will allow us to

see if the mathematical calculation is accurate and acceptable to our client. This ensures that there are two different tests that can validate our model. A lab manual was provided to us from pervious group, an updated manual (see Appendix 7.1) was developed by us and thus will be used to run through the experiment. Recorded values from different time periods with different amount of irradiance and temperature will be used to compare to simulated values to validate that the model works properly.

Below in figure 1 of the process we will be using for this project. This helps ensures that we deliver a product that meets or exceeds the requirements of our client. The improvement of the overall workstation and to help students effectively learn about solar power and different concepts learn through the EE 452 class.



(Figure 1: Block diagram for our design process)

4 Results

The desired outcome for the project is having a working lab station that is intuitive for students to learn about concepts about MPPT, and the P-V, I-V characteristics of solar panels. The workstation was cleaned up, an LCD display was mounted that displays the DC output voltage coming from the solar panel before it is converted into the MPPT. The buck chopper that is currently controlling the DC voltage is available to attach to the main circuit via wires with pins to manage the amount of wires needed for the lab. Currently, the display measures the load and solar energy coming from the solar panels. The circuit was rewired entirely to ensure all elements are safe, stable, and mounted with room for expansion with a future group. This will allow future groups to make changes to the circuitry without having to fumble around figuring out where the wire is inputted and to what device is it outputting to.

5 Related Literature

There are other standalone PV systems for sale on the market but designing and implementing one from scratch is far more cost effective. This has already been done for us by groups in the past, who included many useful things in their design, yet fell short in several key areas. Because of their work, there are several things that we do not have to worry about. Some examples of these include the wiring between solar panels, battery, and MPPT, the irradiance and temperature display, the AC load display, and connecting the DC-AC inverter. However, they failed to make the system safe and reliable, to implement a DC load capable of showing the MPPT's usefulness, and to display accurate voltage and current readings from the solar panels and to the DC load. Nonetheless we are building upon their work and are grateful for the effort they put in before us. Their team website is cited in the References section.

We also have benefited from several research documents regarding the function of solar panels, the MPPT, and their respective Simulink models. To properly design an addition to this lab, we first needed a solid understanding of the science and software behind each component involved in the lab. These reference documents are the main way we gained an understanding of the solar IV characteristics, and the MPPT's tracking algorithm. Each document is cited in the References section.

6 Conclusion

The project plan was to redesign the workstation that is simple, organized, and safe. The goals were to create a workstation that was simple, organized, and safe, the workstation also needed to be able to be expanded upon for future design groups. A schematic of the overall layout of each component in the circuitry needed to be implemented so that future design groups have a better understanding of the system. Another goal was to create an enclosure that was organized and safe for students. This was so that students cannot tamper with the circuitry and creates a more organized workstation. Another goal was to create a resistor box that allows students to better to plot the maximum power point curve and allows students to have a larger range of resistances to use. Our project was successful in the completion of above goals and should allow future design groups to intuitively understand the system.

7 Appendices

7.1 LAB MANUAL

Experiment 1: Basics of PV - Simulation

The objective of this first experiment is to simulate the basic characteristics of photovoltaic (PV) cells. We will test the effects of temperature, irradiance, and load resistance on the solar panels, and the resultant change in the I-V characteristics. All tests for this experiment will use the provided Simulink model called “Resistive Load Only.”

1. Changing temperature
 - a. Set the resistor to 10Ω , and irradiance to 1000 W/m^2
 - b. Run the simulation several times with varying input temperature (into the PV Array).
 - i. Hint: use a range between $0 - 40 \text{ }^\circ\text{C}$
 - c. Record the Voltage, Current, and Power output, and take note of any trends.
2. Changing irradiance
 - a. Set the resistor to 10Ω , and temperature to $25 \text{ }^\circ\text{C}$
 - b. Run the simulation several times with varying input irradiance (into the PV Array).
 - i. Hint: use a range between $100 - 1000 \text{ W/m}^2$
 - c. Record the Voltage, Current, and Power output, and take note of any trends.
3. Changing resistance
 - a. Set the irradiance to 1000 W/m^2 and temperature to $25 \text{ }^\circ\text{C}$
 - b. Run the simulation several times with varying resistance
 - i. Start with these values: 1, 2, 3, 4, 5, 7.5, 10, 15, 20, 50, 100, 200
 - c. Record the Voltage, Current, and Power output
 - d. Plot both Voltage vs. Current and Voltage vs. Power (Voltage on x-axis)
 - i. Use plots to estimate the resistance value that draws the maximum power

- e. Based on your value from the last part, run the simulation a couple more times and try to get close to the maximum power point
4. Effect of irradiance and temperature on the maximum power point
 - a. Follow the steps of part 3, with varying irradiance and temperature, to fill out the tables below.
 - b. For each step you do not need to plot as many points as part 3 – 5 to 7 for each should suffice.
 - c. You **do not** have to turn in each plot made. Simply estimate the resistance at the maximum power point and fill in the table.

Irradiance (W/m ²)	Temperature (°C)	Resistance for MPP (Ω)		Irradiance (W/m ²)	Temperature (°C)	Resistance for MPP (Ω)
200	25			1000	0	
400	25			1000	10	
600	25			1000	20	
800	25			1000	30	
1000	25			1000	40	

DELIVERABLE 1: Document your observations about the effects of both changing temperature and irradiance. What patterns did you notice?

DELIVERABLE 2: Include both plots created in your report. What happened when you changed the load resistance? What resistance value did you find that drew the most power from the solar panels?

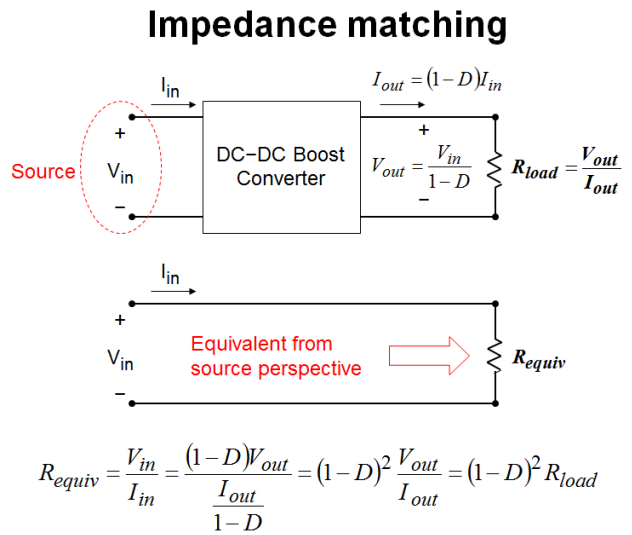
DELIVERABLE 3: Include both tables from part 4. You do not need to include each individual graph created. Describe any trends you noticed as you filled out the tables.

Experiment 2: Solar Panel with MPPT – Simulation

As seen in the first experiment, solar panels are nonlinear devices. The curve obtained in Experiment 1 from varying the load resistance is called the I-V characteristics. As we have already seen, these characteristics vary with changes in temperature and irradiance, each with its corresponding maximum power point. When using solar panels in real life, however, the temperature, irradiance, and load can all be changing – sometimes all at the same time! This makes always drawing the maximum power from a solar panel very difficult, because as the variables around it all change, so does its maximum power point. To remedy this issue, an impedance matching circuit is used to remain at the maximum power point. The device that does this, is called Maximum Power Point Tracking (MPPT). It utilizes a DC conversion circuit, along with a logic circuit to alter the duty ratio continuously. In our case, we will use a Boost Converter. All tests for this experiment will use the provided Simulink model called “MPPT_MANUAL.”

1. Duty Ratio (D)

- a. You should see a similar model to Experiment 1, except there is an additional circuit in the middle
- b. To begin, make sure that the Irradiance is set to 1000 W/m² and temperature to 25 °C
- c. Find the resistance value you found in the previous exercise that drew the most power with these input conditions
 - i. This is your equivalent resistance
- d. Set the load to 50Ω, and using the formals provided above, solve for the duty ratio required to reach the maximum power point.



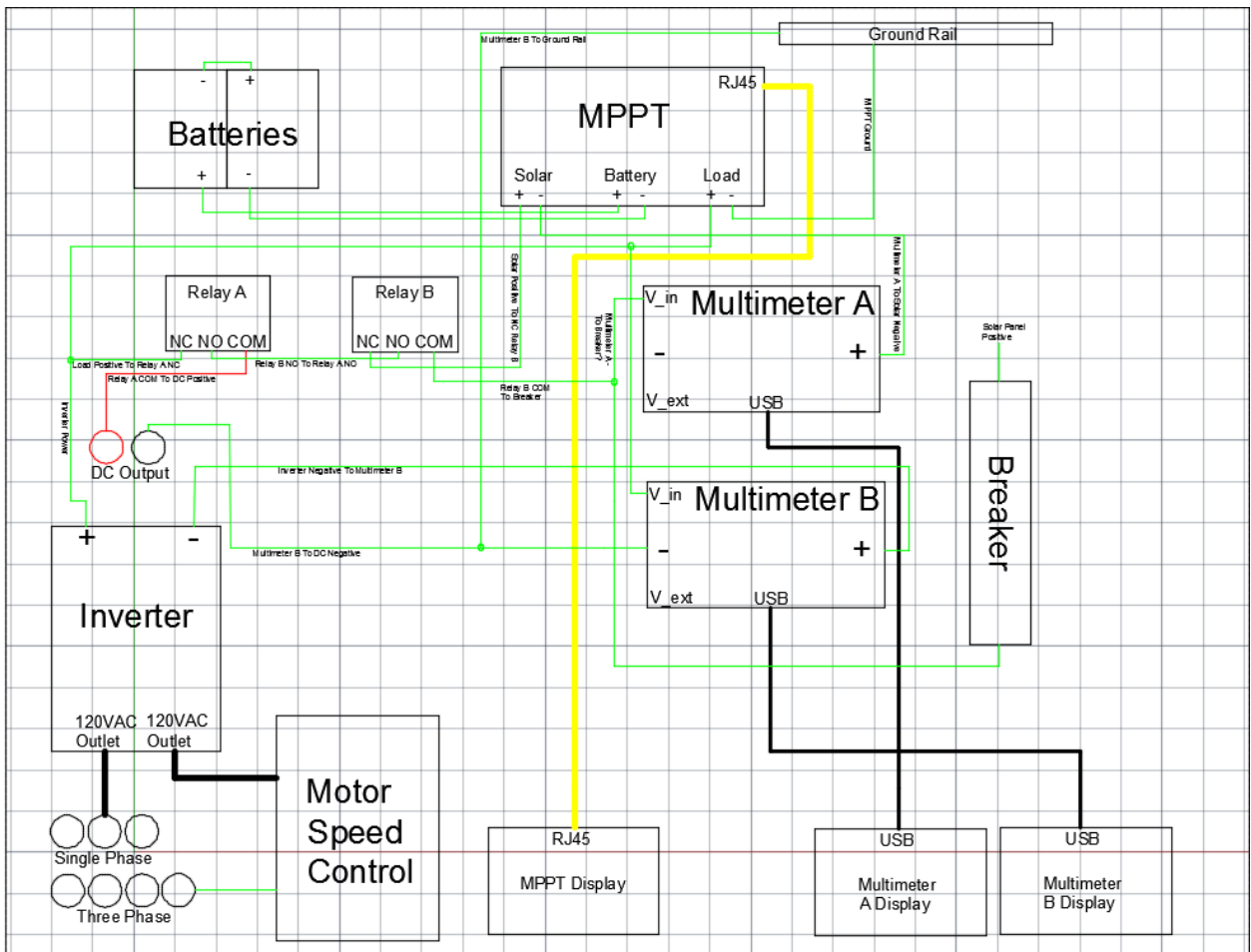
- e. Run the simulation several times, with a varying duty ratio, and record the Voltage, Current, and Power output. You should also calculate the effective resistance using Ohm's Law.
 - i. Be sure to use your value from part d as one of the duty ratios!
 - ii. Note: the input to the switch is $1-D$, not D

DELIVERABLE 4: With the irradiance and temperature unchanged, what is the duty ratio needed to reach maximum power? Hint: you want to keep the equivalent resistance constant

DELIVERABLE 5: Document your observations about the effects of changing the duty ratio of the converter. What patterns did you notice?

HARDWARE BACKGROUND

The general layout of the equipment is as follows: the PV array takes inputs of irradiance and temperature, which feed into the MPPT, which adjusts voltage and current inputs to find the maximum power output of the panels. From there, power is outputted from the MPPT to an inverter and DC output. The inverter converts the DC power into single phase. The single phase has its own output and also enters a VFD that converts the single phase to three phase. When the load requires more power than what solar can currently provide, supplemental power will be taken from the batteries. The relays are used to allow the solar to bypass the MPPT and go directly to the DC Output terminals at the flick of a switch. The Arduino powers the graphical display showing IRR and Temp. Lastly the switch turns the measurement devices on or off.



Main Circuit: All the circuitry shown above, is contained in a metal enclosure that has three outputs – DC, single phase AC, and three phase AC. We will use each of these in the following three experiments.



Solar Panels: Two Kyocera KD135GX-LPU panels with maximum power rating of 135W per panel.

Batteries: Two 12V batteries in series for 24V output.

Inverter: Peak efficiency of the inverter is 85%. Converts DC voltage to 120VAC to power load.

MPPT (maximum power point tracker): A DC to DC converter that optimizes the match between the solar panels and battery of the PV array. Its functionality is to convert higher DC output voltage from solar panels to lower voltage output needed to charge batteries. The maximum power point tracking comes from the MPPT reading the output of the solar panels in order to compare it to the battery voltage. From these readings, it figures out what the optimum power the panels can output to charge the battery.

Load: A resistor box with 8 different resistors (1, 2, 5, 16, 25, 100, 150, and 200 ohm)



Note:

This experiment is extremely weather dependent. The available irradiance will determine how many measurements you will be able to take. If you attempt to increase the load, or isolate PV and battery to power the load, it may pull the inverter under its required power. You will know that this is happening because the inverter will beep before it cuts power to the load. If this happens, power all of the equipment down and decrease the load. Turn the inverter off and back on

again. If this issue persists with only one light bulb powered by both PV and battery, you will not be able to complete this portion of the lab.

Safety:

Refer to the circuit diagram provided for the graphical connections and locations of each switch for the equipment. *For the safety of everyone using the hardware, it is very important that the equipment is hooked up correctly. Verify with the TA that everything is correctly connected before moving on to the next steps. Do not manipulate the circuit while it is powered on.*

Experiment 3: Solar to Resistive Load – Hardware

In the first 2 experiments, you were working only with simulated models of the solar panels and MPPT. In this experiment you will begin working with these devices in the real world. The objective of this experiment is to see how the hardware compares to the ideal simulated models. In the first part you will test the characteristics of our solar panels by connecting them directly to the load.

1. PV directly to load
 - a. Check the displays to record the current temperature and irradiance in the courtyard.
 - i. Have ready the resistance value found for the maximum power point with the current conditions
 - b. Using the resistance box load and the DC output, connect the PV to several different values of resistance, half above and half below the maximum power point
 - i. Note: include the maximum power point as one of your values!
 - ii. Record voltage, current, and power for each different load value

DELIVERABLE 6: Create 2 plots like you did in experiment 1, Voltage vs. Current and Voltage vs. Power. Was the simulated MPP the same as you found with the hardware? What do you think accounts for any discrepancies?

Experiment 4:

1. Buck-Boost Converter
 - a. Connect the DC output to the Buck-Boost Converter, and from the converter to the resistance box. Ensure that the resistance is significantly higher than the maximum power point, and REMAINS UNCHANGED for all duty ratios tested.
 - b. Record voltage, current, and power output from solar panels while varying the duty ratio.
 - c. For each different duty ratio, calculate the equivalent resistance using Ohm's Law and the solar output. Graph Equivalent Resistance vs. Power.
2. Repeat all these steps but use a resistance value that is smaller than the maximum power point.

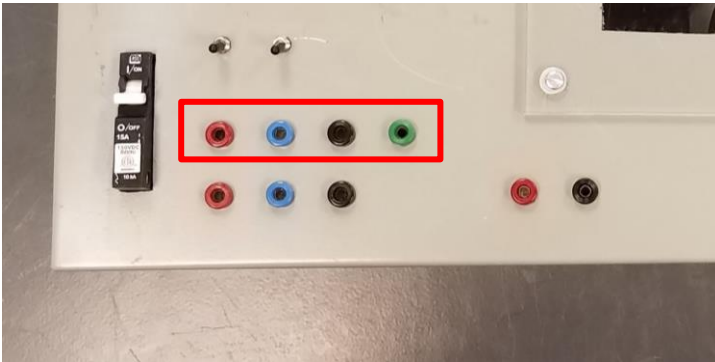
DELIVERABLE 7: Include both plots created in your report. What duty ratio provided the maximum power for each value of resistance tested?

DELIVERABLE 8: How did the power output with the converter compare to when the solar output was connected directly to the resistors? Can you calculate the efficiency of the Buck-Boost Converter?

Experiment 5: 3-Phase Induction Motor

This part of the lab will show that a three phase AC load can be operated using a series of DC to AC and AC to AC conversions. Using the built in modules and other tools, the power and speed will be measured and calculations regarding the efficiency and power output will be made and observed. This lab will use the KBMA Induction motor drive and the ½ HP Marathon induction motor.

1. Setup the motor by plugging in the appropriate pins.



2. Using the Solar in display panel write down the voltage at the solar terminals. Also record the IRR using the appropriate display module. Using these two measurements and the Simulink information that was gathered in part 1, what is the max power available.
 - a. It should be noted that if we just had a PV system without batteries our system would be limited to the amount of power we are getting from the solar panel but since we have batteries and a charge controller the MPPT module will automatically pull power from the batteries to compensate for any power that is not being produced by the solar panels that we need. That leads us to one of the core ideas for this lab. The idea is that we can run multiple different loads from a PV system in conjunction with a battery and charge controller if the load is properly sized. **(We need to be careful to not fully drain the battery).**
 - b. **Measured V:**
 - c. **Measured IRR:**
 - d. **Calculated P_{In} :**
3. Calculate the amount of solar power that should be output at the end of Inverter (Note: The inverter has an efficiency of 85%)

Estimated solar power available based on max power calculation at the output of the Inverter:

4. Turn on both the power supply and the KBMA drive. There will be some power being drawn when the motor drive is on but the motor is not running. Record this power using the load display module.

KBMA Drive Power Loss:

***MAKE SURE THAT THERE IS NOTHING THAT COULD GET CAUGHT IN THE TURNING OF THE MOTOR!!**

***SAFETY IS THE MOST IMPORTANT WHEN OPERATING THE MOTOR!!**

5. In order to control the speed of an Induction motor in general a V/F control is used where V = voltage and F = frequency. The drive outputs a percentage of the rated Hz of the setting that we have it at. The drive is set at 60 HZ this means if I have the main speed Potentiometer set at 10 it will output 10% of the rated nameplate speed and frequency.
 - a. Calculate the speed of the motor at two different points one from 0-50 and one from 51-100

Calculated Speed

0-50:

51-100:

6. With the KBMA drive switched on turn the drive spots of your choice one from 0 – 50 and one measurement from 51-100. For each of these two drive speeds measure the speed of the motor using a tachometer. Also record the power being drawn by the motor using the load display module and the power injected by the solar panel using the Solar In display module.

Measured Speed

0-50:

51-100:

Does the measured speed match the calculated speed in Step 12 if not give reasons as to why?

Measured Power

Solar In

0-50:

51-100:

Solar Load

0-50:

51-100:

Subtract the load power from the solar power.

Power Difference

0-50:

51-100:

How much power is the motor pulling from the battery or is the solar panel injecting into the battery?

What is the max speed that the motor can be operated at so that it is only drawing power from the solar panel?

7. As you can probably guess running a motor this way is not very efficient. Calculate the Efficiency of running the motor using this system.

$$Eff \% = \frac{|P_{In} - P_{Loss}|}{P_{In}} * 100$$

Where P_{Loss} is the amount of power lost in the inverter as well as the KBMA drive

Eff %:

7.2 REFERENCES

References include prior senior design groups work, senior design group DEC1706 and DEC1621. These includes all Arduino code, lab manual, and documentations.

Literature files used and will be used in future work include:

- Anca D. Hensen, Poul Sorensen, Lars H. Hansen, Henrik Binner, "Models for a Stand-Alone PV System", *Riso National laboratory*, Roskilde, pp. 1-78, 2000.
- G.Bhucaneswari, R. Annamalai, "Development of a Solar Cell Model In Matlab For PV Based Generation System", *India Conference (INDICON)*, 2011 Annual IEEE, pp. 1-5, 2011.
- "IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems," in *IEEE Std 1562-2007*, pp.i-22, May 12 2008.
- "IEEE Guide for the Selection of Monitoring for Circuit Breakers," in *IEEE Std C37.10.1-2000*, 2001.
- Merrifield, T., Chartouni, N., Korhonen, E., Ukpan, S. and Pachtl, J. (2017). *Senior Design - Renewable Energy Lab Project Team - Iowa State University*. [online] Available at: <http://dec1706.sd.ece.iastate.edu/>
- Mishra, Bibek, and Bibhu Prasanna Kar. "Matlab Based Modeling of Photovoltaic Array Characteristic." Thesis. *National Institute of Technology*, Rourkela, 2012.
- Ting-Chung Yu, Yu-Cheng Lin, "A Study on Maximum Power Point Tracking Algorithms for Photovoltaic Systems", *Lunghwa University of Science and Technology*, pp. 1-10, 2010.
- Tyson DenHerder, "Design and Simulation of Photovoltaic Super System Using Simulink" *California Polytechnic State University*, San Luis Obispo, 2006.

7.3 APPENDICES

Arduino Code:

```
// IMPORTANT: Adafruit_TFTLCD LIBRARY MUST BE SPECIFICALLY // CONFIGURED
FOR EITHER THE TFT SHIELD OR THE BREAKOUT BOARD. // SEE RELEVANT
COMMENTS IN Adafruit_TFTLCD.h FOR SETUP.
```

```
#include <Adafruit_GFX.h> // Core graphics library #include <Adafruit_TFTLCD.h> //
Hardware-specific library #include <Fonts/FreeSerif24pt7b.h> #include
<Fonts/FreeSerif9pt7b.h>
```

```
// The control pins for the LCD can be assigned to any digital or // analog pins...but we'll
use the analog pins as this allows us to // double up the pins with the touch screen (see
the TFT paint example). #define LCD_CS A3 // Chip Select goes to Analog 3 #define
LCD_CD A2 // Command/Data goes to Analog 2 #define LCD_WR A1 // LCD Write goes
to Analog 1 #define LCD_RD A0 // LCD Read goes to Analog 0
```

```
##define LCD_RESET A4 // Can alternately just connect to Arduino's reset pin //A4 is
used for irradiance ADC input
```

```
// When using the BREAKOUT BOARD only, use these 8 data lines to the LCD: // For the
Arduino Uno, Duemilanove, Diecimila, etc.: // D0 connects to digital pin 8 (Notice these
are // D1 connects to digital pin 9 NOT in order!) // D2 connects to digital pin 2 // D3
connects to digital pin 3 // D4 connects to digital pin 4 // D5 connects to digital pin 5 //
D6 connects to digital pin 6 // D7 connects to digital pin 7 // For the Arduino Mega, use
digital pins 22 through 29 // (on the 2-row header at the end of the board).
```

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```
// Assign human-readable names to some common 16-bit color values: #define BLACK
0x0000 #define BLUE 0x001F #define RED 0xF800 #define GREEN 0x07E0 #define
CYAN 0x07FF #define MAGENTA 0xF81F #define YELLOW 0xFFE0 #define WHITE
0xFFFF #define GRAY 0x5AEB #define SCREEN_WIDTH 320 #define SCREEN_HEIGHT
220 #define PLOT_WIDTH 290 #define PLOT_HEIGHT 160 #define PLOT_X_OFFSET 30
#define PLOT_Y_OFFSET 60 #define PLOT_Y_WIDTH 10 #define MAX_IRRADIANCE
1150 #define SCREEN_ROTATION 1 #define TFT_SCREEN_IDENTIFIER 0x9341
```

```
Adafruit_TFTLCD tft(LCD_CS, LCD_CD, LCD_WR, LCD_RD, 0); // If using the shield, all
control and data lines are fixed, and // a simpler declaration can optionally be used: //
Adafruit_TFTLCD tft; uint16_t irradiance[33] = { }; long firstTaskMillis = 0; long
secondTaskMillis = 0; long thirdTaskMillis = 0; long oneSecondTask = 100; long
twoSecondTask = 2000; // interval at which to run (milliseconds) //change this
variable to extend the plot refresh rate. It is at 5 sec now long fiveSecondTask = 5000; float
sensorReading; long averageReading = 0;
```

```
void setup(void) { Serial.begin(9600); Serial.println(F("TFT LCD test"));
Serial.print("TFT size is "); Serial.print(tft.width()); Serial.print("x");
Serial.println(tft.height()); tft.reset(); tft.begin(TFT_SCREEN_IDENTIFIER);
initializeDisplay();
```

```
Serial.println(F("Done!")); }
```

```
//Main function where program runs void loop(void) { unsigned long currentMillis =  
millis();
```

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```
//two hundred millisecond task if(currentMillis - thirdTaskMillis > oneSecondTask){  
thirdTaskMillis = currentMillis; //read voltage averageReading = averageReading +  
analogRead(A5); }
```

```
//two second task if(currentMillis - firstTaskMillis > twoSecondTask) { // save the  
last time you blinked the LED firstTaskMillis = currentMillis; //double  
sensorReading = averageReading/5; //averageReading = 0; // Convert the analog  
reading (which goes from 0 - 1023) to a voltage (0 - 5V): //float voltage =  
analogRead(A4) * (5.0 / 1023.0); //shift array values for plot data  
//sensorReading = (voltage * 245); //use Example 3 for conversion
```

```
int sensorValue = analogRead(A4); // Convert the analog reading (which goes from  
0 - 1023) to a voltage (0 - 5V): float voltage = sensorValue * (5.0 / 1023.0); float temp  
= voltage * 245; //use Example 3 for conversion sensorReading=temp;
```

```
float value=averageReading/20; //read from Ao averageReading = 0; float  
volts=(value/1024.0)*5.0; //conversion to volts float something= volts*100.0;  
//conversion to temp Celsius float tempF=something*9/5+32; //conversion to  
temp Fahrenheit displayIRR(temp, tempF); Serial.print("temperature=" );  
Serial.println(tempF); Serial.print("Voltage: "); Serial.println(voltage);  
Serial.print("Irradiance: "); Serial.println(temp);
```

```
}
```

```
//five second task if(currentMillis - secondTaskMillis > fiveSecondTask) {  
secondTaskMillis = currentMillis; for (uint8_t j = 0; j<33; j++){ irradiance[j] =  
irradiance[j+1]; }
```

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```
irradiance[32] = sensorReading; drawPlot(irradiance); }
```

```
}
```

```

//Initialization instructions void initializeDisplay() { tft.fillScreen(WHITE);
tft.setRotation(SCREEN_ROTATION); //Draw black round rectangle for top text
tft.fillRoundRect( 5, 5, 310, 45, 8, BLACK); //Setup text and cursor for title
tft.setCursor(15, 36); tft.setTextColor(WHITE); tft.setTextSize(1);
tft.setFont(&FreeSerif24pt7b); tft.print("IRR:"); tft.setCursor(284, 42); tft.print("F");
//Draw plot background initPlot(); }

```

```

void drawPlot(uint16_t data[]){ //Clear current plot before drawing new values
initPlot(); //divisor value for taking care of variable type mismatches double divisor =
(double)MAX_IRRADIANCE/(SCREEN_HEIGHTPLOT_Y_OFFSET); //draw all new
values for(uint16_t i = PLOT_X_OFFSET; i<=(SCREEN_WIDTH - PLOT_Y_WIDTH);
i=i+PLOT_Y_WIDTH){ //Draw each line. Calculations are done to keep the plot size
relative tft.drawLine(i, SCREEN_HEIGHT-((data[i/PLOT_Y_WIDTH])/divisor),
i+PLOT_Y_WIDTH, SCREEN_HEIGHT-
((data[(i/PLOT_Y_WIDTH)+1])/divisor), WHITE); } }

```

```

void displayIRR(uint16_t i, float temperature){ //Clear the previous IRR value for
printing tft.fillRect(105, 7, 180, 43, BLACK); //Move the cursor to the correct printing
location tft.setFont(&FreeSerif24pt7b); tft.setCursor(110, 42);
tft.setTextColor(WHITE); tft.setTextSize(1); //Print the irradiance value

```

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```

tft.print(i); //temperature = 72; //set cursor to appropriate location
if(temperature>99){ tft.setCursor(212, 42); } else{ tft.setCursor(230, 42); }
//convert digital value to analog temp and print //math goes here
tft.print((int)temperature); //Draw degrees circle here
tft.drawCircle(281,10,3,WHITE); tft.drawCircle(281,10,2,WHITE);

```

```

}

```

```

void initPlot() { //Set font to default tft.setFont(); //Set font color to black
tft.setTextColor(BLACK); //Set font text size to 1 tft.setTextSize(1); //Draw black
rectangle for plot tft.fillRect(PLOT_X_OFFSET,PLOT_Y_OFFSET,SCREEN_WIDTH-
PLOT_X_OFFSET, SCREEN_HEIGHT-PLOT_Y_OFFSET, BLACK); //Draw
middle grid lines tft.drawLine(PLOT_X_OFFSET,(PLOT_HEIGHT/2)+PLOT_Y_OFFSET,
SCREEN_WIDTH, (PLOT_HEIGHT/2)+PLOT_Y_OFFSET, GRAY);
tft.drawLine(PLOT_X_OFFSET,(PLOT_HEIGHT/2)+PLOT_Y_OFFSET+1,
SCREEN_WIDTH, (PLOT_HEIGHT/2)+PLOT_Y_OFFSET+1, GRAY); //The
offset here of -7 determines how high the text is above the lines

```

```
tft.setFont(&FreeSerif9pt7b); tft.setCursor(2, (PLOT_HEIGHT/2)+PLOT_Y_OFFSET);
tft.print(MAX_IRRADIANCE/2);
```

```
//Draw legend text tft.setCursor(2, (PLOT_HEIGHT/4)+PLOT_Y_OFFSET);
tft.print((int)MAX_IRRADIANCE*.75); tft.setCursor(19, 218); tft.print("o");
tft.setCursor(0, 69); tft.print("1"); tft.setCursor(5, 69); tft.print("1"); tft.setCursor(11,
69); tft.print("5");
```

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```
tft.setCursor(20, 69); tft.print("o"); tft.setFont(); tft.setCursor(0,212); tft.print("IRR");
tft.setFont(&FreeSerif9pt7b);
```

```
//Draw top grid lines
tft.drawLine(PLOT_X_OFFSET,(PLOT_HEIGHT/4)+PLOT_Y_OFFSET, SCREEN_WIDTH,
(PLOT_HEIGHT/4)+PLOT_Y_OFFSET, GRAY);
tft.drawLine(PLOT_X_OFFSET,(PLOT_HEIGHT/4)+PLOT_Y_OFFSET+1,
SCREEN_WIDTH, (PLOT_HEIGHT/4)+PLOT_Y_OFFSET+1, GRAY);
```

```
//Draw bottom grid lines
tft.drawLine(PLOT_X_OFFSET,(PLOT_HEIGHT*.75)+PLOT_Y_OFFSET,
SCREEN_WIDTH, (PLOT_HEIGHT*.75)+PLOT_Y_OFFSET, GRAY);
tft.drawLine(PLOT_X_OFFSET,(PLOT_HEIGHT*.75)+PLOT_Y_OFFSET+1,
SCREEN_WIDTH, (PLOT_HEIGHT*.75)+PLOT_Y_OFFSET+1, GRAY); //Draw
legend text tft.setCursor(2, (PLOT_HEIGHT*.75)+PLOT_Y_OFFSET);
tft.print(MAX_IRRADIANCE/4); tft.setCursor(130, 235);
tft.print(((double)(fiveSecondTask/1000)*31)/60); tft.print(" minutes"); tft.drawLine(35,
230, 120, 230, BLACK); tft.drawLine(230, 230, 310, 230, BLACK); tft.fillTriangle(25, 230,
35, 223, 35, 237, BLACK); tft.fillTriangle(320, 230, 310, 223, 310, 237, BLACK);
}
```