# Design and Implementation of a Small-scale, Standalone Hybrid Solar PV and Wind Energy System

DESIGN DOCUMENT

Team 19
Advisor/Client: Professor Ajjarapu
Team Members/Roles:
Chris Goodrich – Research Engineer
Damon Stubbs – Research Engineer
Drew Wassenaar – Team Leader
Kenny Nguyen – Testing Engineer
Taylor Mullen – Testing Engineer
Team Email: sddec18-19@iastate.edu
Team Website: http://sddec18-19.sd.ece.iastate.edu/
Revised: 3/2/2018

# Table of Contents

# 1 Introduction

## 1.1 Acknowledgement

Professor Venakataramana Ajjarapu has overseen and given assistance to this group, primarily in the form technical advice and equipment. He has given us the necessary resources to learn what background material we will need regarding the solar panel power generation process. He has also provided us access to the EE 452 lab and all its equipment pertaining to our project.

## 1.2 Problem and Project Statement

The objective of this project is to improve upon and design a new element for the EE452 lab regarding solar panel power generation. The goal of this lab is to allow students to gain hands on experience working with the Photovoltaic (PV) array and how it is used to generate maximum power under changing weather conditions. Our solution is to maintain the general framework of the lab, while implementing a new, more realistic load. This load will simulate a small-scale house and demonstrate to the users how solar power can be used to power a home, as well as what might be some common issues encountered when trying to implement a solar panel on a house.

## 1.3 Operational Environment

While the PV arrays remain outside to generate sufficient solar power, our small-scale house load will remain inside the lab room. It will be exposed to dusty conditions, but will not be exposed to any extreme weather. It will always operate under near room temperature, and will not be subjected to any precipitation of any sort.

## 1.4 Intended Users and Uses

Our project is focused around improving and developing on the labs for EE 452. Or design will be used by students who are trying to learn a basic understanding of solar generations and its capabilities. The uses of our design will be to help the students see a load model that could be compared to a real-life home. It will show the different elements of loads that would be seen on a grid: capacitive, inductive, and resistive. It also allows for the students to model the power requirements of what would need to be supplied by the solar panel and the battery that are in the system.

## 1.5 Assumptions and Limitations

Assumptions:

This is something that will be used only as model. It will function at a steady voltage supply and will be regulated for the safety of the circuitry. This is intended to be used for only one user/group at a time, but this can be modified if need be. This load will be stationary and is not made for frequent movement.

Limitations:

This must work off of the already provided PV generation. It must be able to fit in the establish space for different load models in the EE 452 lab. There must be accessible circuit components that are able to be replace as needed. The cost has not been defined at this point.

### 1.6 Expected End Product and Deliverables

The end product is to provide a model home that represents capacitive, inductive and resistive load. It will have protected circuitry that can be accesses when components fail. It will be a model at represents a home and the independent loads it intends to represents. For example, it will look like a house and there could be scaled lights as resistors, electric motors for inductors, and batteries as capacitors. It will have defined I/O that will be compatible with the generation system available. It will also have modeling and test results showing how this load works in the defined system. It will be applied into the existing PV labs and show how it is possible to power a home with this type of generation. This will come with instructions, that will be used in lab documents, on how to connect this load to the generation and potential checks if there are problems. The final product must be completed, tested, documented, and put in place by the end of the 2018 spring semester.

## 2. Specifications and Analysis

### 2.1 Proposed Design

The proposed design consists of multiple components, each playing a key role in the objective. A PV array will be connected to an MPPT. This MPPT will allow for the PV array to generate maximum power at all times. It does this iteratively by constantly changing the load seen by the PV array to get maximum power output. A buck/boost converter will be used in the circuit in order to change the voltage to whatever the load needs. It will power our one of three loads as well as a battery for charging. The battery will be used to power the loads during times when the PV array is not capable of doing it on its own.

This has been tested in Simulink, and the increase in efficiency and consistency that this design provides is significant. Updates to our design will be done first by simulation in Simulink. Then, our change can be slowly implemented into our physical system.

### 2.2 Design Analysis

Various components of our design as well as interactions between them has been thoroughly investigated using Simulink. The simulation of our entire system has not been successful, as parameters need to be changed, and components need to be implemented. However, results still showed a great increase in efficiency and consistency of our proposed design over the simpler design. The MPPT is responsible for greater power efficiency, which leads to fewer power losses. Also, the battery allows for 24 hour consistency, approximately 3 times as often as a simple system. Weaknesses are few and relate only to the complexity of the circuit. More components and variables mean that one thing going wrong will ruin the entire system. It also means that the system will be reasonably more difficult to debug and fix.

# 3 Testing and Implementation

Tests will be needed to approximate mostly one variable, power, over time. While looking at certain voltages or currents will help understand a problem, if the power output is consistent and efficient, nothing else is really necessary. Simulink will be used to simulate this on the software side.

## 3.1 Interface Specifications

Simulink will be the main program used to model our project on the software side to see if a hardware result is feasible.

## 3.2 Hardware and software

The hardware that is being used is the current setup that includes different loads such as DC Train, single phase light bulb setup, 3-phase motor, with heavy emphases on the model home load. The loads will allow students to understand how power flow works in a small model home with different loads that represent appliances in the home. Students can then motor the amount of power flow going through the system and where there are losses in the system. They can observe the amount of solar power being produced by the solar panels and how it can be used in real life application of powering appliances in homes.

The Software that is being used is Simulink and MATLAB. Simulink is a function in MATLAB that allows the user to be able to simulate, model and analyze systems in a safe environment. Simulink will allow us to simulate the amount of voltage and current across each component of our home, be able to see the power consumption when each load is turned on and the amount of solar energy needed to power the home. Main part is Simulink will allow us to test certain loads within small home without the harming the current sent up and allow us to test it in a safe environment before building the final model.

## 3.3 Functional Testing

In Simulink, the system will be tested by simulating a full day cycle of the power the home uses. For example, the home will have appliance such as scaled lights, acting as resistors, batteries, acting as capacitors, and motors, acting as inductors, the Simulink design will include measurements of voltage and current going through each of these components. An excel file will be able to be extracted that gives the following details of each component, the irradiance and temperature at certain times during the day with the respective component values of voltage and current going through each at certain time periods. With these will be able to measure the amount of power flow through the system and how much power is loss going through each appliance, and effects of the battery when each load is turn on. The idea is that the solar panel will produce enough energy to be stored in the battery so the home can run during the nighttime.

## 3.4 Non-Functional Testing

In addition to testing the following components under normal load, we will need to test the components under small amounts of energy produced from the solar panel. Since there is only one set up for the lab, and the amount of energy being produced by the solar panel depends on the day and the amount of sunlight that is hitting it during the day, the amount of energy being stored could be less than optimal. So, the determination of the smallest amount of energy to be able to run this lab needs to be taken into account. Since there are also multiple lab sections, we need to take into account that the minimum power being stored to run the lab multiple times during the day. When the design is setup and it is determined that the lab cannot be run more than twice during a given day, then revisions will be made to the loads in order to be usable during multiple labs. If the system can be run twice during the day at minimum amount of energy, then the system is feasible and able to be implemented.

### 3.5 Process

Simulink will be the first test all of our designs go through. It is the first step because we need to ensure that the model works in the ideal case before we continue to prototype our design. Simulink has very well-defined models for most of the components we will use in our design, and for those that are not predefined, we will design our own models for use in Simulink.

To test our prototype small-scale house, we will first use a standard AC source, without the solar panel to minimize variables. The next step will be to test the model home with a DC source connected to an inverter to produce the AC signal necessary for the load. Lastly, we will test the entire system together.

### 3.6 Results

We do not yet have results from our testing.

## 4 Closing Material

### 4.1 Conclusion

For this project, we have done the necessary amount of research of PV cells and MPPT's to move forward with our project of the model house and testing of the current state of the EE352 Lab. From the testing of the lab, we will work to improve the lab with understanding the work done to finish the lab and by including the element of the model house into the lab steps. Having done these will give students a better comprehension of the lab as well as an extra element to give students a better understanding of the model house load on a PV system.

### 4.2 References

We currently do not have any references.

### 4.3 Appendices

E E 452. Electric Machines and Power Electronic Drives Iowa State University

**Iowa State University**

**Electrical and Computer Engineering**

**E E 452. Electric Machines and Power Electronic Drives**

# Laboratory #12

# Study of Conservation of Energy and PV Power Generation

## Introduction

The purpose of this lab is to become more familiar with Photovoltaic (PV) power generation, conversion and storage. This Lab is broken up into two parts; Simulation and Hardware. Each section has three corresponding experiments. The simulation section uses pre generated Simulink files to discover how the effects of Irradiance and temperature affect power. After understanding how these variables affect power, Max Power Point Tracking MPPT can be implemented. The hardware section provides hands on experiments with actual PV equipment. Students will observe and measure the effects of varying loads (via light bulbs) and varying sources (with and without batteries).

# Software

## Experiment 1: Temperature, Irradiance and Load

Background:

In this experiment, student will establish an understanding of the major variables that effect performance of a standalone PV system. Specifically students will be able to understand how temperature, Irradiance and load affects PV arrays on a component and full-scale level.

Objectives:

- Observe the effects of temperature, Irradiance and load on a PV panel.
- Understand what MPPT is and why it is important for these systems.

Deliverables:

1. The provided spreadsheet plots and answers to any questions asked in the procedure.

### Part 1: Temperature

1. Open the provided Excel Spreadsheet titled “Simulink Spreadsheet”. All data for this portion of the lab will be entered into this spreadsheet.
2. Open the MATLAB Simulink file named “Resistive Load Only”. You should see a simplified model of only a PV array connected to a resistor as the load.
3. Set the temperature values of each model to 0, 10, 25, 50, and 100. (you can do this one at a time or copy and paste multiple systems)
    a) Verify the load resistance is 144 ohms (i.e. one light bulb).
    b) Verify the irradiance on all the models is a constant 1000 W/m^2.
4. Run the simulation and record the voltage and current from each system

in an excel document in the Temperature sheet.

5. Repeat step 1 & 2 but now set the irradiance values of each model to 0, 10, 25, 50, 100, 250, 500, and 1000.
    a) Verify the load resistance is 144 ohms (i.e. one light bulb).
    b) Verify the temperature on all the models is a constant 25 C
6. Run the simulation and record the voltage and current from each system in an excel document in the Irradiance sheet.
7. Repeat step 1 & 2 but now set the resistance values of each model to 0.1, 1, 3, 5, 10, 20, 40, 60, 80, 100.
    a) Verify the temperature on all the models is a constant 25 C
    b) Verify the irradiance on all the models is a constant 1000 W/m^2.
8. Run the simulation and record the voltage and current from each system in an excel document in the Resistance sheet.

Analysis:

1. What do you notice as Temperature increases/decreases? Does this make sense why or why not? What temperature provides max power?
2. What do you notice as Irradiance increases/decreases? Does this make sense, why or why not? What Irradiance provides max power?
3. What do you notice as Resistance increases/decreases? Does this make sense, why or why not? What resistance provides max power?

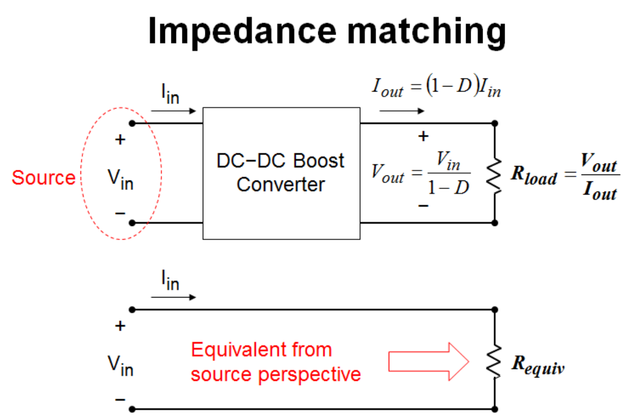
# *Experiment 2: MPPT*

Background:

Solar Arrays are nonlinear devices that will have non-linear relationship between the output current and voltage at a specified load. By adjusting the load we will have more or less power generated at the Solar Array depending on our load. However, in the real world load can vary, which will vary power. To correct this, we use matching networks that make the solar panel see the resistance that creates max power. This process is done automatically by a device called a MPPT device (Maximum Power Point Tracking) by adjusting the voltage/current draw through a virtual load in order to shift to the maximum power in the voltage/current relationship. MPPT is essentially a microcontroller that reads the current power output from the PV Array and sends a data signal to hardware to adjust the virtual load. The actual device that interacts with the power side is a Buck converter. The microcontroller from the MPPT uses its data to send a corresponding PWM signal to the Converter. The Converter then undergoes as switching sequence that breaks up the current from the Solar Array to set a virtual load. If the MPPT microcontroller measures better power from increasing the Duty Cycle of the PWM signal, then it will continue to do so in ever increasing amount of Duty Cycle until measured power output decreases. It will then decrease PWM Duty Cycle in order to increase power output until measured power decreases. This process will reach a steady state. Below is the equation for relating the resistances and duty cycle.

## Part 1 Duty Cycle

1. Open the Simulink model titled "MPPT_Manual". You should see the same setup as before with the resistor and PV array. Only now there is an adjustable matching network between them and an additional input of duty cycle.
2. Find the value of resistance discovered in the previous section that provides maximum power for IRR = 1000 at 25C, this will be your R-equivalent.
3. Calculate the duty required to match a 50Ω load.
4. Verify your calculated duty cycle with the MPPT model provided.




$$R_{equiv} = \frac{V_{in}}{I_{in}} = \frac{(1-D)V_{out}}{\frac{I_{out}}{1-D}} = (1-D)^2 \frac{V_{out}}{I_{out}} = (1-D)^2 R_{load}$$

a. This is done by entering your calculated value into the duty cycle block. Remember to set IRR, Temp, and load values.

## *Part 2 Duty Cycle & Power*

1. *With the same Simulink model open, with constant IRR, Temp and Load, see what happens to the output power as the duty cycle of the MPPT is increased.*
    a. *Set IRR = 1000, Temp = 25C, Load = 50 ohms.*
    b. *Increment duty cycle by [0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9] entering values for the voltage and current on the panel and the output power.*

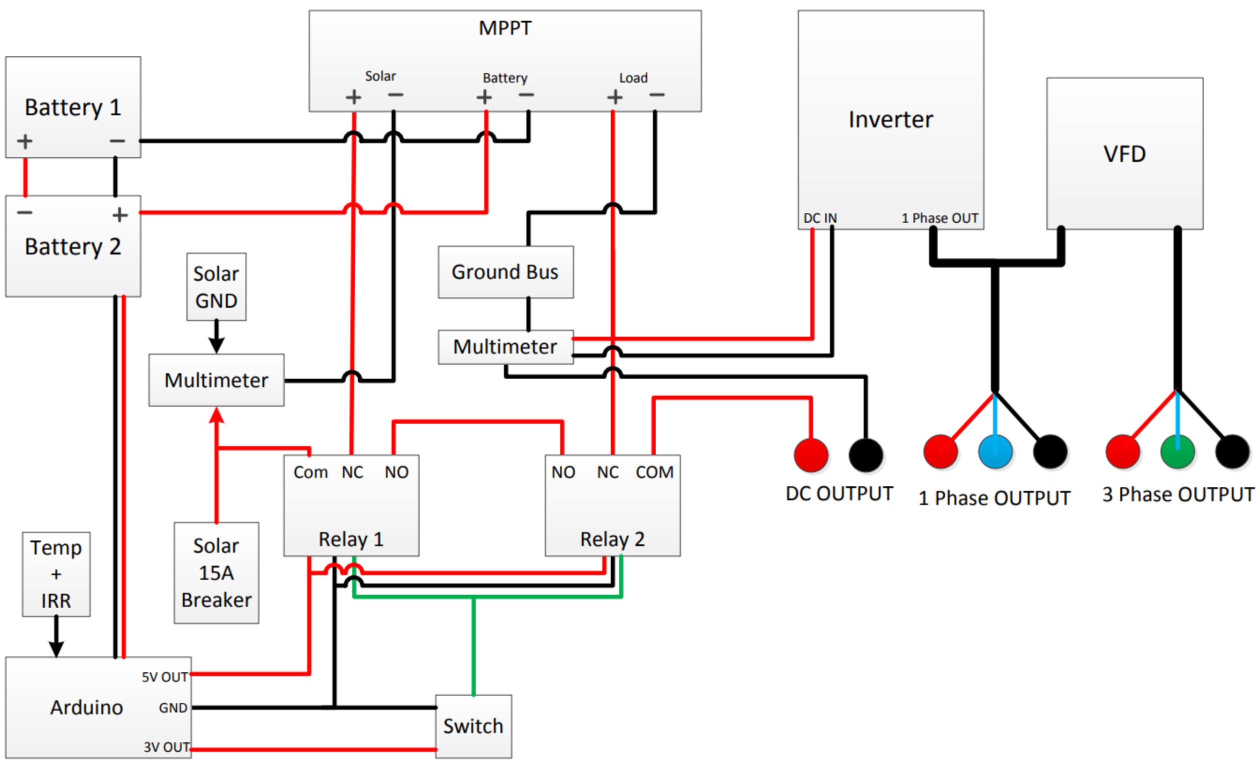
Analysis:

1. State the duty cycle needed to reach max power with; IRR = 1000 at 25°C and a load of 50Ω, 100Ω and 200Ω loads.
2. Describe what you see in the plot of Power vs Duty Cycle. Why is this significant?

# 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.



*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 resistive load consisting of 4 lightbulbs, all of which are 144 ohms.

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 1: Varying Load*

Objectives:

This experiment is meant to give you a quick overview of how to use the PV array hardware. To accomplish this, you will be analyzing power measurements taken from the following nodes: PV array, batteries, and the inverter (load) under different load conditions. The learning objectives for this lab will include understanding and explaining the circuit diagram of the system in order to:

- Analyzing voltage and current measurements to verify conservation of energy.
- Analyzing power loss in the system.
- Analyzing the effects of isolating power sources going to the load.

Deliverables:

For each test case, note the input power to the load (power produced from solar panels and batteries), as well as the output power. Calculate the efficiency of the system (input/output) and note the difference between power consumed and power generated. Calculate the losses seen in the system and verify conservation of energy.

## *Part 1: Light Bulbs with PV and Battery*

1. Plug the light bulb box into the single phase ports
    a. Red on the box goes to red on the panel.
    b. Black on the box goes to black on the panel.
2. Turn the hardware on
    a. Make sure that the inverter is turned on behind the panel.
3. Note the power coming from solar and from the Load. Is there enough solar to power the light bulb on its own?
4. Continue adding more load (lights) to the system. Again, compare how much power is coming from the batteries and how much is coming from solar. Continue until there isn't enough power by either to turn the lights on (loud beep will sound from inverter).

# *Experiment 2: MPPT Duty Cycle*

## Objective:

The tasks performed for this experiment will introduce you components of a PV system that help achieve max power from a solar panel to the load. Just as you did in the Simulink simulations, you will be varying the load and observing the changes in power. In the case, the load is a model train that represents any DC load that would be on a standalone PV system. A buck chopper is provided to allow you to manipulate the voltage and current (and therefore power) being supplied to the load. The purpose of this experiment is to supplement your understanding of different applications for a standalone PV system as well as physically observe the changes in power for a varying DC load.

## Deliverables:

Record the data requested in the lab steps. What are your main take a ways from this experiment?

NOTE: This lab is very dependent on the solar panel individually. If IRR isn't around 250 or greater, than it may be best to skip this portion of the lab. Ask your Lab TA if this experiment should be conducted today. They may provide you insight on how this system works and what the takeaways are.

## Part 1:

1. Find the maximum power of the train & losses of the system.

a. When the buck chopper is turned off, supply 20 Volts and 2 Amps to the train.

b. Hold the train in the rear to prevent the train from moving forward.

c. Press the power button to turn on the train.

d. Observe the power consumed from the train via the buck chopper display and the Solar IN display.

   i. The difference between the two are the losses of the system. What may be the causes of these losses?

## Part 2:

1. Now it is your turn to be the MPPT. Plug the input to the Buck Chopper into the DC supply ports on the panel. Move the selector switch to Solar to DC OUT.
2. Find the amount of current needed to move the train

a. At the very top of the screen you should see two numbers next to the word SET. The left number is Voltage and the right is Current.

b. Press the SET button and you should see the word SET is highlighted in the top left corner of the display. Press the adjustment knob (sliver knob). This will shift the highlighted digit to the right. In this case, the first digit of the voltage. Continuing to press this knob will allow you to cycle what digits of voltage and current you wish to change via turning the knob.

c. Set the voltage to 20V and the current to zero.

d. Turn the output on by pressing the power button in the lower right corner. The power button icon on the display should now turn green.

e. Adjust the hundredths place of the current until the train starts to move. Record this Amperage.

f. Turn off the train via the power button.

3. Find the required voltage needed to move the train.
   a. Set the current to 2 Amps and the Voltage to 0.
   b. Turn on the train.

c. Adjust the one's place of the voltage until the train starts to move. Record this value.
d. turn off the train

## Part 3:

1. Now it is time to have some fun. Adjust the voltage and current leaves of the train until you can reach a maximum power.
   a. Is the power what you expected? Why or why not?
   b. Set the Voltage to the minimum voltage required to move the train. Adjust the current and see what maximum power you can receive.
   c. Set the current to the minimum amperage needed to move the train. Adjust the voltage and see what max power can be achieved.

## Part 4:

1. Repeat Part 3 but now place a load on the train. This can be done by adding more train cars to the rear. However, these trains cars are very light and don't add much load (but is super fun). Placing a weight on the flat bed car and placing it in the front of the train will help. See image below.

# Experiment Three: Induction Motor

Objectives:

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.

- Show that a three phase load can be operated using this setup.
- Make various power and speed calculations.
- Calculate the efficiency of running the motor.

Deliverables:

- All required measurements.
- All required calculations.
- Answer each question.

**NOTE: SAFETY IS OF UTMOST IMPORTANCE PLEASE VERIFY EVERYTHING THAT IS DONE WITH A TA AND THAT IT MAKES SENSE.VOLTAGE ON THE EQUIPMENT YOU ARE WORKING WITH IS VERY DANGEROUS!!!**

Est. Time: 20 Minutes

This lab will use the KBMA Induction motor drive and the ½ HP Marathon induction motor.

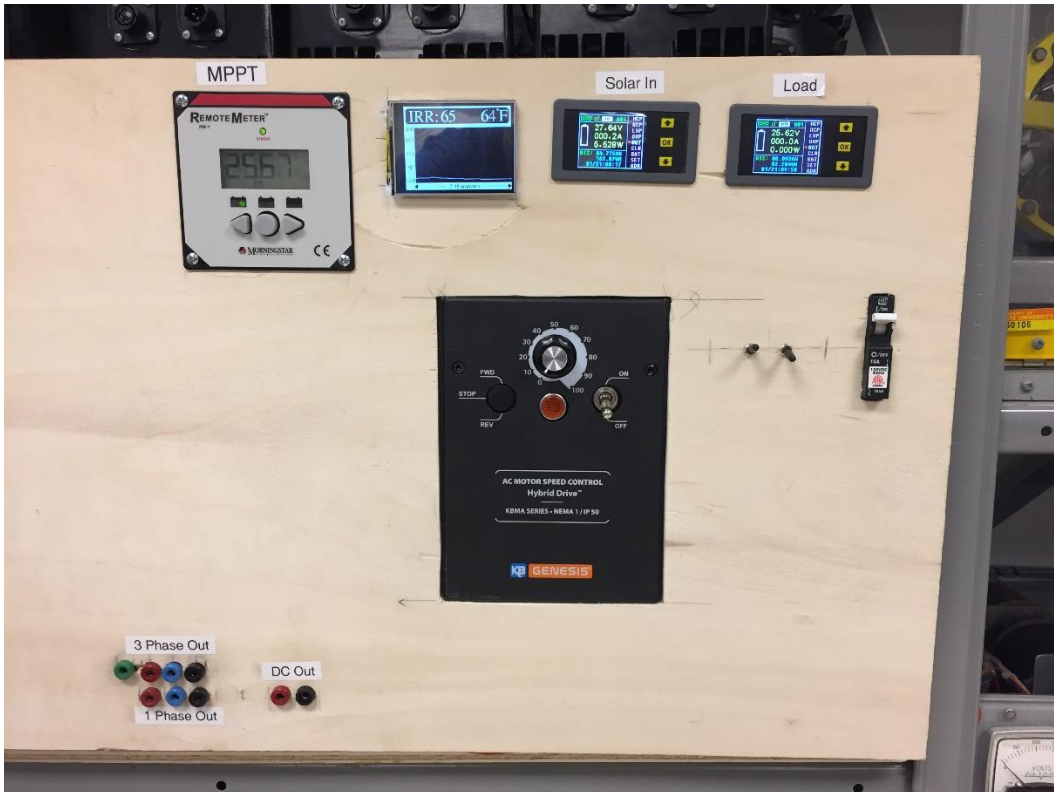



*Figure 1: KBMA Variable Frequency Drive*

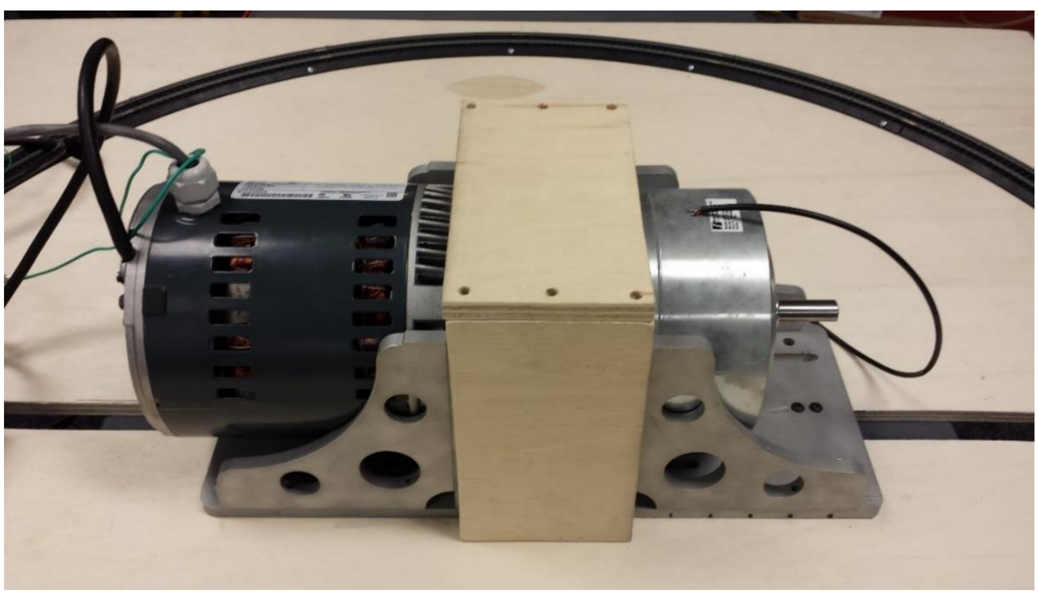


*Figure 2: 1/2 HP Induction Motor*

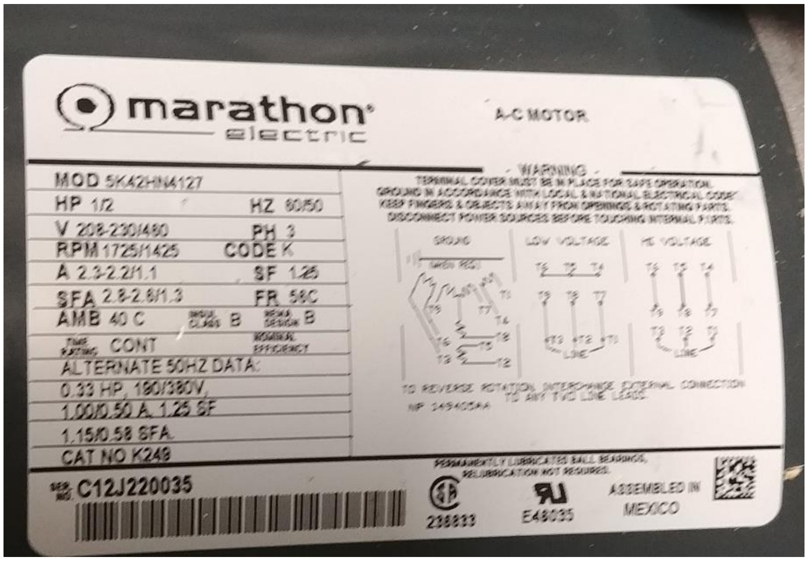



*Figure 1: Marathon Induction Motor Nameplate*

## Part 1: Set Up

Since this is a power electronics lab the first part of this lab will be to observe the primary power electronics used in this part of the lab.

I. Read through the KBMA Set up Document.

II. Plug the drive into the power supply.

III. Plug the motor into the corresponding colored terminals (Figure 4 & 5).

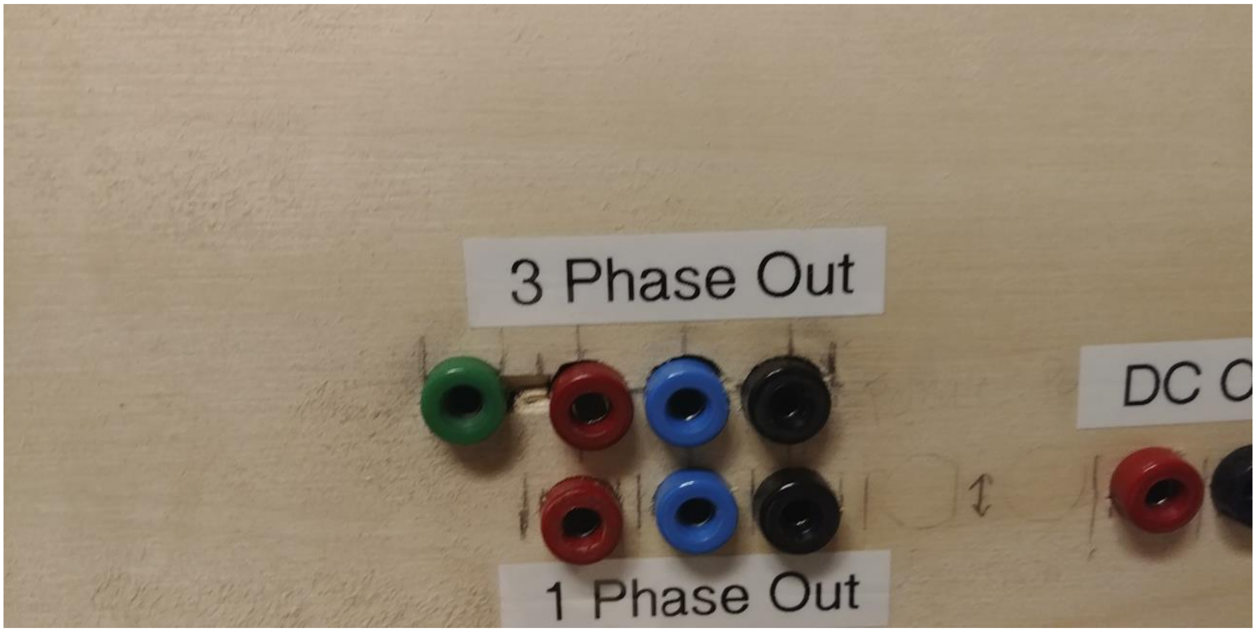



*Figure 2: Three Phase Terminals*

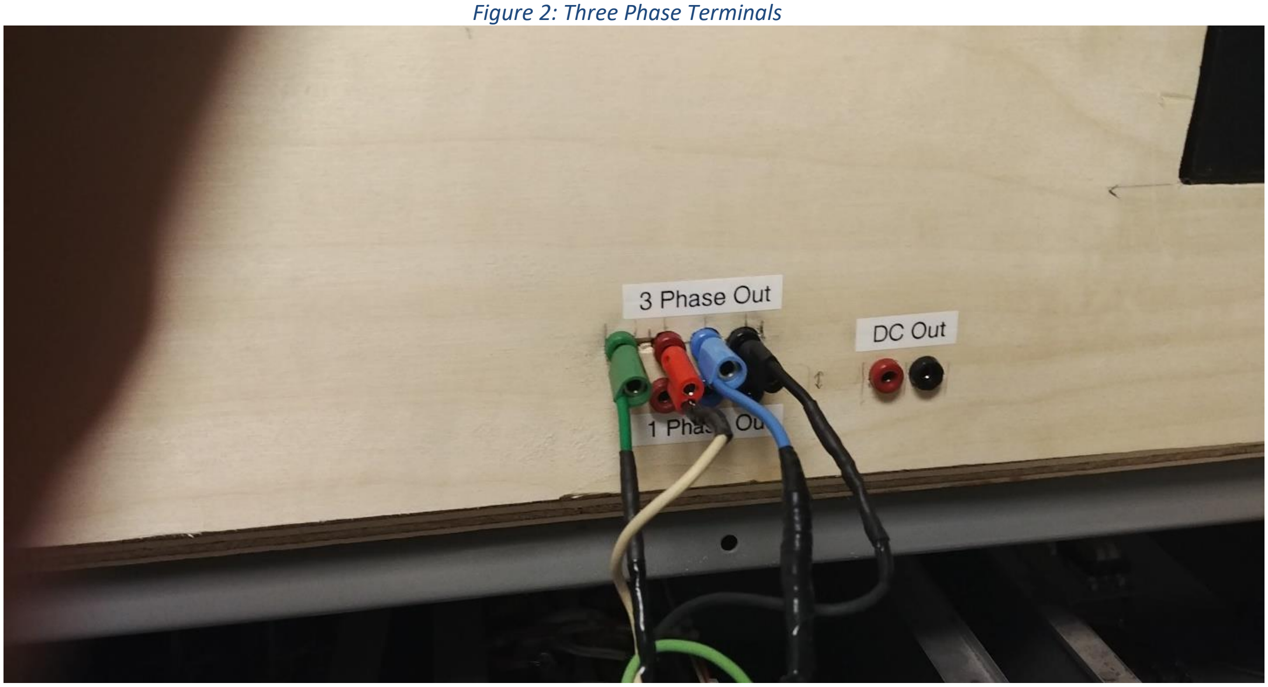


*Figure 3: Three Phase Terminals*

## *Part 2: Measurements*

I. 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.
**Measured V:**
**Measured IRR:**
**Calculated $P_{In}$:**

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.**

II. 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:**

Turn the both the power supply and the KBMA drive on.

III. 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 IIMPORTANT WHEN OPERATING THE MOTOR!!**

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.

IV. 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:**

V. 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?**

VI. 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.

$\boldsymbol{Eff}\ \%$**:**

## Conclusion:

While it is not efficient to operate the motor this way, using better equipment or putting the power supply and drive into one device could improve the efficiency. It should be noted that in a non-experimental system like this efficiency would be of utmost important. None the less we have still demonstrated that we could use this system to run a three phase load.