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Hybrid Solar PV & Wind Generation System for EE 452 Lab

Contents

1 Introduction

1.1 Project statement

Expand the current solar and wind generation lab to be more user friendly and educational by updating the apparatus to better communicate some characteristics and functions of a stand-alone Photovoltaic (PV) system. Focal point of this project is for future EE 452 lab students further their understanding with stand-alone system through a unique lab experience. The concepts applied in the lab and learned in class can be related both for standalone applications as well as grid connected technology. The main difference is converting the final result into 60 Hz three phase to connect to the grid and also that batteries are not necessarily required when connecting to the grid but can still be used.

1.2 Purpose

Recent technological advances have made solar and wind generation more economical and thus more common throughout the world. The increased demand of renewable energy produces a great demand Electrical Engineers educated about the process, characteristics and challenges of renewable energy. Iowa State currently offers EE 452 Mechanical Drives and machines. This course discusses electromagnetic conversion, which is a key concept in renewable power systems.

Currently the class uses the Biorenewables Lab, and there is an educational station for student to collect data from solar panels. This station is currently disorganized and limits what the students can test and measure. Our project would rebuild the station and software at the station to give the students a better and safer learning environment. We will generate more lab manuals so students will have more time with the equipment. We would like to also like to expand that system either via more panels, more batteries or better panel location. This way the closed system will be more powerful and last longer. Giving every student, now and years in the future, an equal chance to collect good and meaningful data.

1.3 Goals

1. Create a more compact, updated, and user friendly workstation for students to conduct lab exercises.
2. Create lab material for future EE 452 labs.
3. Generate ways to optimize small educational stand-alone systems to be mobile and present knowledge in fun new ways.
4. Study and model theoretical daily power use and generation of a solar system

2 Deliverables

<u>Workstation</u>: Remodeled workstation that is adjustable for future implementation and easy to be transported. Pictures of the new workstation along with the blueprint of the wiring setup of the equipment in the updated workstation.

<u>Lab Manuals</u>: Lab instructions and analysis of the experiments. Instructions need to cover; purpose, theory, data, analysis and conclusion. Analysis will provide data measured when performing the task under that certain weather condition as a guideline. There will be operational manuals and safety guidelines for the equipment used to conduct the lab. Software and code developed to gather/display data in the apparatus. Video representation of operating the laboratory equipment.

<u>Additional Panels</u>: Provide cost analysis and scope for adding more panels to the current system. A project plan for installation will be needed as well as site location. The cost analysis of two new fully integrated solar panels to replace the current ones.

3 Design

Initially, this project was to include wind generation as well. After discussing with professor Ajjarapu at the end of the previous semester, we all agreed to only focus on the solar portion only. This would allow us more time on the topic and get at least one system working before we graduate. Wind generation will be done by another Senior Design team in the future.

First and foremost, we could not begin implementing any of our main tasks until we had a complete working model of an isolated solar power system. This was done via simulations in Simulink. This modeling was important not only for our understanding to the system, but we also used these models in our labs to help other students understand as well.

Next we could begin designing the workstation for the students. We began by listed all of the key concepts that Professor Ajjarapu wanted to teach. The current setup was messy, dangerous, and boring. We wanted to create a space that was safe, and provided some fun. We had the idea of moving the current system off of the large cart and moving it to a shelf. This allows more space in the Lab when this lab is not being conducted. The setup would have a front panel, displaying all the information the students would need. As well as, all required ports for various loads so they can be connected safely.

When we could squeeze in time, we worked on a cost analysis for upgrading the major components of the system. Essentially, we wanted to know what it would cost to double the power of the system. This involves looking at compatible panels, new MPPT and inverter. Moving the panels to a more ideal location, like the roof, was a part of the design. However, due to time constraints and other priorities, this was not completed.

3.1 System specifications

Detail any specifications given and/or assumed about the project.

- Lab manual should be concise, organized and able to be completed in a 3 hour time frame.
- Lab topics should include, but are not limited to, Fundamentals of MPPT, Power measurement, PV cells, Buck/Boost Converters, Irradiance and temperature dependences.
- The Workstation should be neat, organized, intuitive, safe and dependable.
- All simulations should be organized and intuitive.

3.1.1 Non-functional

Understanding of modeling a solar cell along with I-V, P-V curves plotted from the model. Proficient knowledge of maximum power point tracking its relationship to P-V, I-V curves and different algorithms used to attain max power from a solar panel. The physics of a charging/discharging battery and the advantage of using a rectifier, inverter and chopper in a standalone power generation system.

3.1.2 Functional

Modeling solar panel and DC/DC converter in Simulink with visually representation of their respective characteristics. Also modeling MPPT algorithm in conjunction with the converter and solar panel. Integration of a battery bank and load into a solar PV system while maintaining power quality from the power supply. Ability to change loads through various supply standards such as DC, Single Phase and Three Phase voltages. Displays showing Input and output voltages and current; along with the ability to measure the power contributions of each source.

3.1.3 Standards

A variety of standards can be applied to this project. Since Solar power is a relatively new source of power, standards are still being developed. However, IEEE standards that should be applied to the project. There are IEEE standards for the sizing, installation, and maintenance of lead acid batteries. There is also a IEEE standard that involves measuring different parameters for wind turbines. Standards are always important to follow regardless of the application so that it is easier for others to understand. Even if the project never has a use outside of the 452 lab, educating college students it is important to design it as if it will which is why applying all applicable standards is especially important. It is also important that we follow the city of Ames Standards when importing solar energy into the grid. Even though there is no plan for this power to be connected to the grid following the method put forth by the city of Ames should be observed for the possible application at a later date. Ethical issues that may apply will the safety of the students that will be interacting with the equipment in the lab. It is absolutely necessary that the measuring equipment is safe as some of the voltages and the current have potential to be fairly high. it is our responsibility to make sure all the equipment is safe and if it is not the user must be aware of it.

3.2 PROPOSED DESIGN/METHOD

After defining all of the standards and functions of the setup, we began selected hardware. When searching, we kept in mind that these devices needed to have the ability to be flush mounted for the front panel, or small enough to fit comfortably behind the panel. Parts to add included; an Arduino and display, two multimeters with displays, MPPT display and a one phase to three phase Variable Frequency Drive (VFD), an adjustable buck booster, and a pair of switches. We found a model train to act as a variable DC load and knew that we wanted a 4' diameter track. We could then put the one and three phase loads in the center of the circle track. Allowing for better use of space. With the parts selected we came up with a layout design of how the system would look, which was approved by the professor.

3.3 DESIGN ANALYSIS

Fortunately, there was were no major design changes. One change however was changing the buck booster to a buck chopper. Our expectation was during low sunlight hours, the solar panels would produce less voltage. This was true to some degree, but not to the extent we were expecting. Therefore, a buck chopper proved to have more adjustment capabilities. The buck booster did provide us with a safety design change however. Initially we had two ports on the device one input in the other was output. Upon setup one testing day, these were pulled in oppositely and caused the capacitors on the board to burst. Luckily there was a protective box around the booster, so no one was harmed. This resulted in us changing the design so each load only had to plug in one set of wires (rather than the previous two) so this could not happen again.

4 Testing/Development

4.1 Interface/Hardware specifications

Students now have a workstation that enables them to measure elements of the system safely. They are able to measure currents, voltages, Irradiance and temperature. In addition to the measurements, there are also controls for the different loads on the system. These loads include a DC model train, a single phase light bulb setup, and a 3 phase motor. These loads help the students understand how power flows through the system as well as where losses are. They can observe the amount of power coming in from the panels and being used at the load in order to get a more complete picture of how solar power can be used.

4.2 Software

Software used in the project is Simulink, MATLAB, and Arduino. Simulink is a program within MATLAB, which is an environment for modeling, simulating and analyzing multidomain dynamic systems. Simulink allows us to model and analyze circuit characteristics like voltage/current across a component and behavior of AC components in non-ideal circumstances. Also if we need to implement another component we can get an idea of how it will affect or change characteristic of other circuit elements. Students coming to lab will have Simulink models provided by us. Some of these models will be complete, others partially completed for the students to finish. Simulink will play a vital role in quickly learning how different parameters and components affect a solar power system. Some of the specific objectives the students have in lab involve modeling a solar cell, maximum power point tracking, and load to understand how the real setup works. There are nice tools that allow for analyzing where the maximum power point is as well as how a load affects the solar cell's impedance. These are crucial items for today's students to know since alternative energy sources are a presently popular topic. In addition to learning, Simulink can also help in determining any issue the physical circuit may arise in the future.

An Arduino environment was used in our final product to take two data measurements, irradiance and temperature. The Arduino performs an analog to digital conversion on both signals to receive the value and displays the measured data on the display. A significant amount of coding was required to make the display function properly and this can be found in the appendix. The finished product measured the irradiance and temperature, displayed the associated values, and plotted the irradiance. The graphing function is very fun to observe since you can view past data points and see the irradiance change when the sensor is exposed to sun or hidden in the shade.

4.2 PROCESS

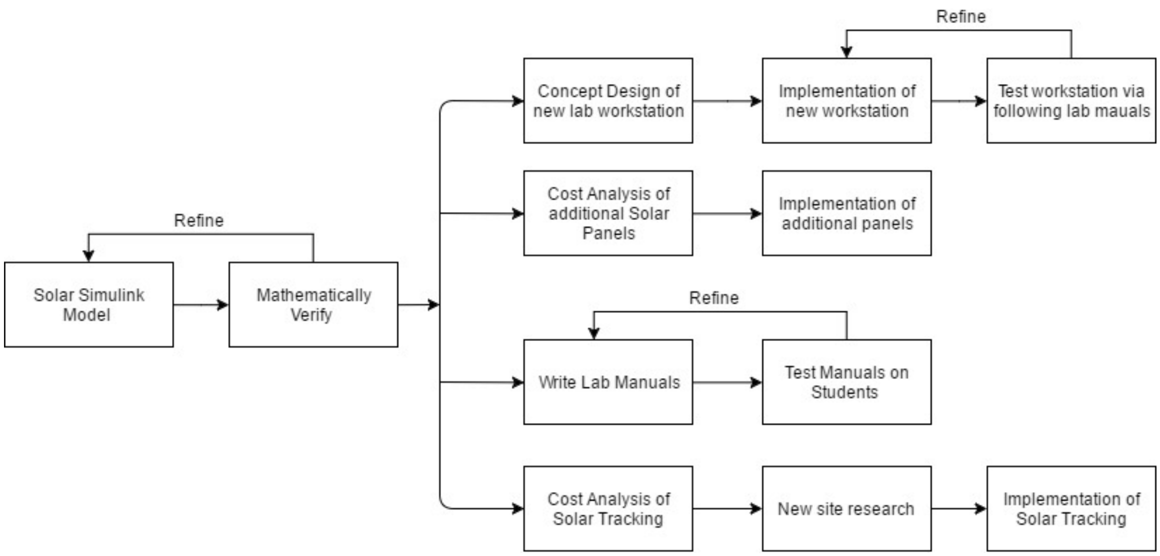
For testing of the model, we mathematically proved that our model was accurate. We used equations for the PV, Booster, conservation of energy, the diode equation and more. The last portion of simulation we completed was is adding a battery to the model. Once we finished the testing and mathematical verification we finished the next stages.

After we developed the concept of how the workstation would be set up, we presented the design to Prof. Ajjarapu. We then refined the design in accordance to his thoughts and the needs of the class. After an important discussion, everyone agreed on the initial design we implemented the workstation. Once the station was complete, we tested the functionality of the space by carefully working through the lab manuals (individually and in groups) to ensure the station meet the specifications.

Lab manuals were the most important aspect of our project. To make sure the manuals met our specifications, we completed the lab manuals ourselves as well in addition to having other Electrical Engineering students attempt the labs. Lab reports are used as a measure of how well the test subject materials are learned. Changes can be made based off of this data if needed since the labs are flexible.

A cost analysis of the solar tracking and additional panels was performed during the semester to see if any benefit would be yielded by expanding the system. It was discovered that a new solar panel and maximum power point tracking box could be easily added and installed in the future. We left room in the final product to allow a future team to make these additions. We were not able to perform them on our own due to limited time remaining as well as it being outside the project requirements.

Below is a figure of the process we used while working on our project. We took many steps to refine and ensure the delivered product met or exceeded the requirements laid out in the beginning. The resulting setup allows students to effectively learn about solar power and apply different principles learned throughout the engineering program to the EE 452 lab.



A flowchart of the process we used.

6 Results

One of the main focuses of this semester was cleaning up the workstation. In this context the results were successful. Four new display and measurement modules were added. These modules allow for easy measurement of voltage, current, and power at the important parts of the solar panel system such as the load, solar panel, and battery terminals. These measurement points allow us to observe or predict important values at all the parts of the system. The two main display modules that measure the load and solar in panel also allow for a user to record and transfer data if it was desired which is a positive aspect. In terms of cleaning up the workstation a one line diagram was created and the main contents were reduced into a small shelf. There were also ports created that allow users to access the different types of power being generated with ease. The goal of a cleaner and smarter workstation allows students to focus more clearly on learning the important concepts that will be conveyed in the lab. Instead of spending large amounts of effort to understand what, where, and how to perform the lab they can complete the lab and learn from it in a streamlined manner.

In the contexts of creating and implementing the labs the results were mildly successful. Four labs were developed two were new and two were recycled and updated from an older groups work. The two new labs were the DC train lab and the induction motor lab. Implementing the hardware design went smoothly there were some hiccups when deciding whether a boost or buck converter was needed to run the train. Through trial and error it was determined that a buck converter was needed when it was originally thought that a boost converter would be needed. The train lab does not draw as much power as was originally predicted which presents some minor problems when performing the lab. The lab is also limited by the amount of sun power that is available which was an unforeseen problem as well. It still is a good way to convey the ideas of MPPT and standalone PV system. The train also still has the same core behavior that was originally predicted which means the lab still works. The behavior that was expected was that the train would speed up or slow down based on the impedance that was seen from the solar panel. In that sense the results were as we expected. The induction motor implementation also had some hiccups. The lab had to be reworked because the drive did not run the motor that was originally planned. The motor that it did run was 1/2HP which was up from 1/4HP and the voltage was higher than expected. This causes the induction motor to draw more power than had been predicted. The motor that had to be used presents some more safety issues so structures had to be built the remedy this situation. It is also harder to measure the speed and predict the power usage on the motors. This is not cause for much concern as the measurements that are needed can be easily verified due to the robust nature of the measurement systems that were installed. The lab is still capable of being completed and productive. The light bulb and Simulink lab which recycled from the other group work great. These two labs are simple and the Simulink lab has been scrutinized and developed through two different groups so it is robust. The lightbulb lab is simple and the new measurement tools make it incredibly easy and effective to implement.

Overall the results are that the goals that were set were achieved. Each of the lab implementations and labs themselves had their own hiccups which another group may be able to correct or improve on. Other groups should perform the labs that are developed and develop their own results so that they can effectively correct inconsistencies and imperfections that may not be apparent in the first implementation of the labs and the upgraded workstation. The workstation and labs are designed with the idea that they are to be upgraded with more capacity and better equipment. This presents a avenue for other groups to upgrade and fix the current setup.

5 Related Literature

5.1 Stand-alone Systems Development

While doing research on these different systems a project that was very similar to ours was a research paper that was presented at the 49th North American Power Symposium Hosted by West Virginia University. “Portable PV energy conversion system Suitable for Educational Purposes; Part 1 : Pollution Reduction Rate and Reactive Power Delivery Estimation”. They use a mobile cart with a PV panel, an inverter, a typical load, two MyDAQs, a computer, and a monitor. They use these tools to observe the output of the solar panel and the inverter. The primary objective of their project is suggested in the title. It is to observe the pollution reduction and also to estimate the reactive power that is generated by the inverter. These two concepts are both applicable when considering connecting a PV system to the grid. One would want to know the reactive power injected into the system as this affects the stability of the power grid as well as the voltage. In a distribution system where the PV system is large versus the load too much reactive power can cause high voltage problems for the utility. For example at Alliant Energy they have high voltage issues in areas with high PV penetration. Pollution has also been a huge topic in both politics and industry and although the current presidential administration is not as adamant about pursuing goals for reducing emissions many companies and States already put a huge amount of resources into reducing emissions. They also are more committed to protecting the environment. This highlights the importance of understanding how solar panels can help us in this manner. These companies and states will not want to see the large amount of resources put into these areas be wasted so it is unlikely that they will slow down their pursuits of this, thus putting more solar onto the grid. The way the paper proposes to measure how the solar panels could help reduce carbon emissions is they simply measure the amount of energy produced by the panels and then compare this to the amount of energy that would be used by an electric car. By making this comparison they can reach the conclusion that if the power produced is used by one of these cars then the amount of carbon produced by a car that produces emissions traveling a similar distance would be saved. I believe that comparison is a little bit of a reach because cars would generate carbon at a different rate than say a coal plant which is what the solar panel would more likely replace. Nonetheless it is a good way to get an Idea the impact the solar panel has. With the mobility as well as the measurement systems that are involved in the project described above It creates a good platform for students to observe and participate in the output of the solar panel.

Differences' from our project f is the lack of an MPPT module. One of the core concepts of our project is to educate students about the importance of Maximum Power Point tracking. This is a tool that manipulates the voltage and current of the Solar panel to make sure that for a given Irradiance we are receiving the most power possible from the panel. Another significant difference is that our system is more designed to demonstrate a standalone system. Also our system uses batteries as well as the MPPT module to manage output. This means that the MPPT module controls whether to use solar output or battery output based on the voltage of the solar panel and the batteries. An additional difference is that we choose a load that is sized to the batteries so that theoretically it should be able to operate all of the time. Our project also has several different loads that can be tested. An induction motor, a DC motor, and also standard light bulbs. This allows us to derive and perform a few different educational experiments. The class is power electronics and motors so using the motors we can combine solar and motors and then the light bulbs allow for an easy way to observe the behavior of an inverter connected to a PV system. An inverter is a useful piece of power electronics that is also highlighted in the class. While the observable outcomes between the two projects are different the goal of educating students about emerging solar technology remains the same. While there are not many direct applications of standalone PV it is a technology that could become more prevalent as good energy storage systems emerge.

An example of a standalone PV project that has not been started yet but is worth keeping an eye on is being debated because of the recent tragedies in Puerto Rico. According to the BBC article *"Elon Musk says he can rebuild Puerto Rico's power grid with solar"* Elon Musk would like to rebuild Puerto Rico's electric grid using solar panels and Tesla's solar storage technology. The article also states that *"The Company (Tesla) says it has powered small islands, such as Ta'u in American Samoa. There, it installed a solar grid which can power the entire island and store enough electricity for three* *days without any sun" This* has broad implications if this project is carried out. This would increase the relevance of our project because it would provide a direct application of the PV system that our project models on a much smaller scale. These kinds of applications again highlight the importance of educating students about PV systems in general which our project attempts to do.

With the emerging of PV systems throughout the power grid in the U.S. system and around the world it is important that Iowa State University educates its students about Solar panels and how they provide power to different loads and the various electronics that are involved with those systems. This is what DEC1706 aims to do with our project. While the concepts and methods that we choose to educate about are different from other ways of doing it. It can be seen that it is a useful and necessary task that can be adapted in the future as the future of this technology evolves because of the flexibility of our system

5.2 Photovoltaic System Developments

DEC1706 project is focused on educating students in the 452 lab about solar panels. There are several big concepts that can be applied in this case. With the emergence of Solar Power in the U.S. and around the world there is a large amount of research being done on PV systems. Some of the research papers that will be explored cover such topics as theory behind solar panels, Maximum Power Point Tracking (MPPT), Standalone PV systems, and Matlab modeling of a PV system.

The first paper reviewed was "Development of a Solar Cell Model in Matlab for PV Based Generation System" which discusses the differences between solar cell models that are available in Matlab and a solar cell model that is proposed in the paper. This paper can be related to our project because it is important to simplify the equipment we use into a model so that we can simulate different loads and other connections. This allows us to better predict when things will or will not work. Another reason is that our final lab that is created for the EE 452 class will also involve the students running some simulations and collecting data in MATLAB. This brings an important factor to understanding the models of solar cells in MATLAB. Building intuition about solar cell characteristic is pristine to depict shortfalls and advantages of different possible solar cell models that could be used in the simulation.

The next paper is "Performance of Stand-alone Hybrid Wind-Photovoltaic System with Battery Storage" which observe the performance of a PV system combined with a Wind generator. The main point that can be related here is the paper goes in depth on how the battery works and what a proper model for the battery is. This is important as discussed in the previous paragraph it was noted that part of our lab is modeling in Simulink. The standard battery model in Simulink causes the simulation to crash when simulating certain charge controller behaviors. This is cause mostly from perceived instantaneous changes in voltages. In order to better understand those problems it was important to understand the model of a battery in general. It can also understand how are charge controller performs switching between battery power and solar panel. While our system does not have wind power integrated into it our client hopes that his next group will be able to implement wind power into our system as well. The paper also spends a little time discussing

MPPT which is discussed more in depth in the next research paper that is looked at.

The third paper is “Models for a Stand-Alone PV system” which discusses the modeling of a whole standalone PV system in matlab. This paper provides an idea of how to generally model and the idea behind a standalone PV system. It lays out in simple terms each of the parts. In this case a Solar cell, a controller, battery, inverter and AC load. The paper describes the models of each one that it used and provides a very good framework for developing our own Simulink model as well as a good basis for our own standalone system. While the loads may change for our system the overall concept is the same.

The fourth paper is “A Study on Maximum Power Point Tracking Algorithms for Photovoltaic Systems”. One of the most important conceptual aspect of our project is MPPT. This is the primary subject that we will be trying to demonstrate in the Simulink simulation and also with the model train that we will be using. The train will go faster or slower depending on where the user is on the I-V curve. The Maximum power point is located at the knee of the PV system IV curve. The paper specifically discusses the difference between several different methods that are used to perform the maximum power point tracking. One of the methods that is discussed and the one that our Simulink model uses is the Perturbation and Observation method. This method to put it simply checks the voltage and current makes a power calculation and then increments the voltage. It then recalculates the power and compares the two quantities and until the (change in power / change in voltage) equals 0. This is the simplest method and it also yields results that are good enough for our purposes. The two other methods it discusses are the Incremental Conductance Method and the Hill climbing methods. These two methods will more accurately derive the knee of the I-V curve but they are much more complicated and require more measurements to be taken. It should also be noted that our MPPT module does this for us but does not release the method that they use to perform the MPPT operation.

Each of the papers discussed here represent projects and research that is related to our project. They all discuss topics and concepts that our project is using and trying to teach to other students. In order to for our project to be successful we must have an in depth and intimate knowledge of how a standalone system operates and each part in it. Without this it would be impossible to educate students on similar topics.

7 Conclusions

The generated project plan was to continue developing a simple understanding of the concept, model, design, proposal, implementation, and testing. This design method was applied to the three goals which were attempted. Streamlining the system, creating new lab manuals for students, and implementing the solar panels in a new and interactive way. We were able to redesign the entire setup of the lab into a more clean and streamlined fashion. This included removing the dated computer system and instead design an Arduino board that was able to handle the processes and output better data that is controllable. We also were able to implement the panels in different ways allowing for 452 students to experiment with the system and learn how the panels can provide and convert power between 3 phase, 1 phase, and DC systems. Students will also be able to see how motors and loads affect the system and how it can be supplemented through other sources. We have been able to achieve a new layout design, implementation of solar panels and a more user friendly interactive lab for 452 students. Our project was successful in completion of our above goals and should be helpful for future students and users.

8 Appendices

"Elon Musk says he can rebuild Puerto Rico's power grid with solar." *Bbc.com*, Bbc, 6 Oct. 2017, www.bbc.com/news/world-us-canada-41524220

8.1 Arduino Code: Lab Manual

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).
```

```
// 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();
```

```
  //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 A0
      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];
      }
```

```
      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 varible type mismatches
  double divisor = (double)MAX_IRRADIANCE/(SCREEN_HEIGHT-
PLOT_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
```

```
    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("0");
  tft.setCursor(0, 69);
  tft.print("1");
  tft.setCursor(5, 69);
  tft.print("1");
  tft.setCursor(11, 69);
  tft.print("5");
```

```
  tft.setCursor(20, 69);
  tft.print("0");
  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);
}
```

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, Irranidance 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:

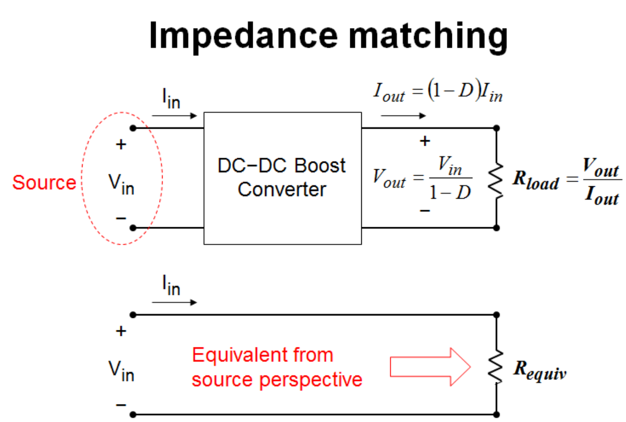
1. What do you notice as Temperature increases/decreases? Does this make sense why or why not? What temperature provides max power?
2. What do you notice as Irradiance increases/decreases? Does this make sense, why or why not? What Irradiance provides max power?
3. What do you notice as Resistance increases/decreases?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



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

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.

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.

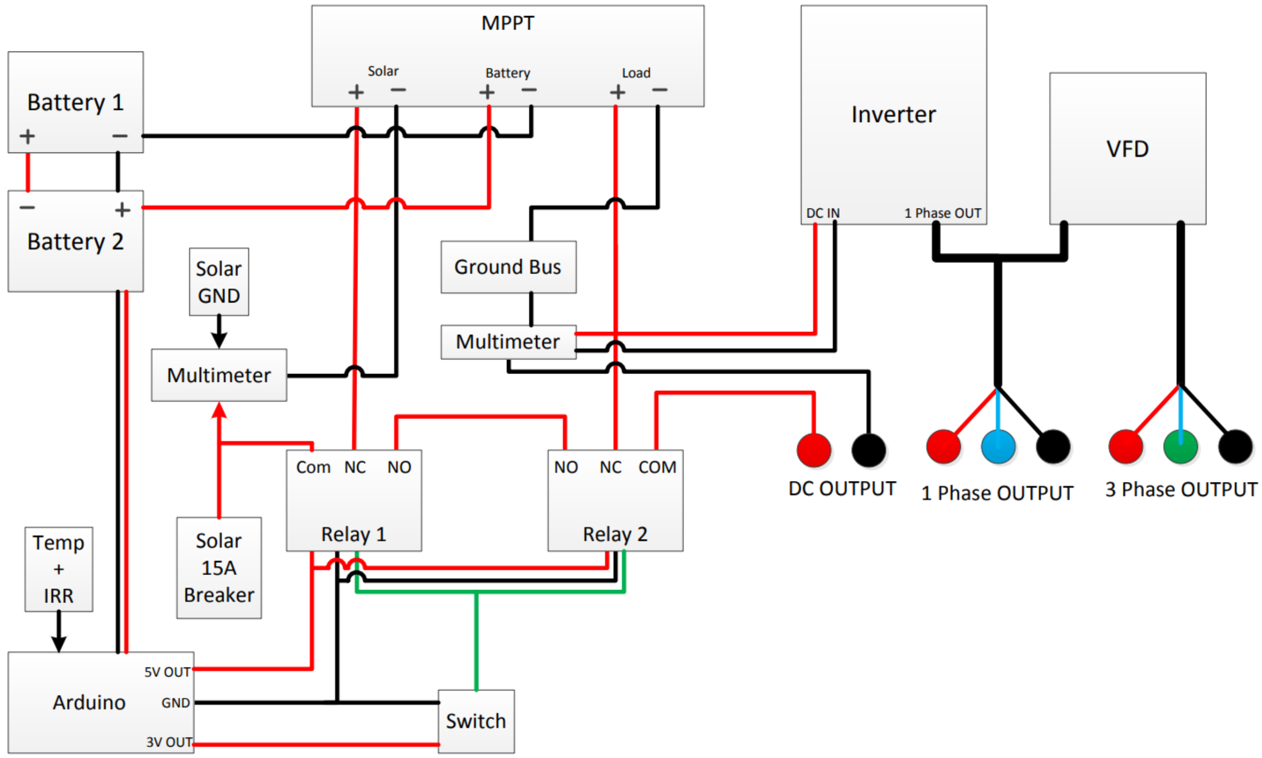
Analysis:

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

b. Press the SEL button and you should see the word SET is highlighted. Press the adjustment 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.

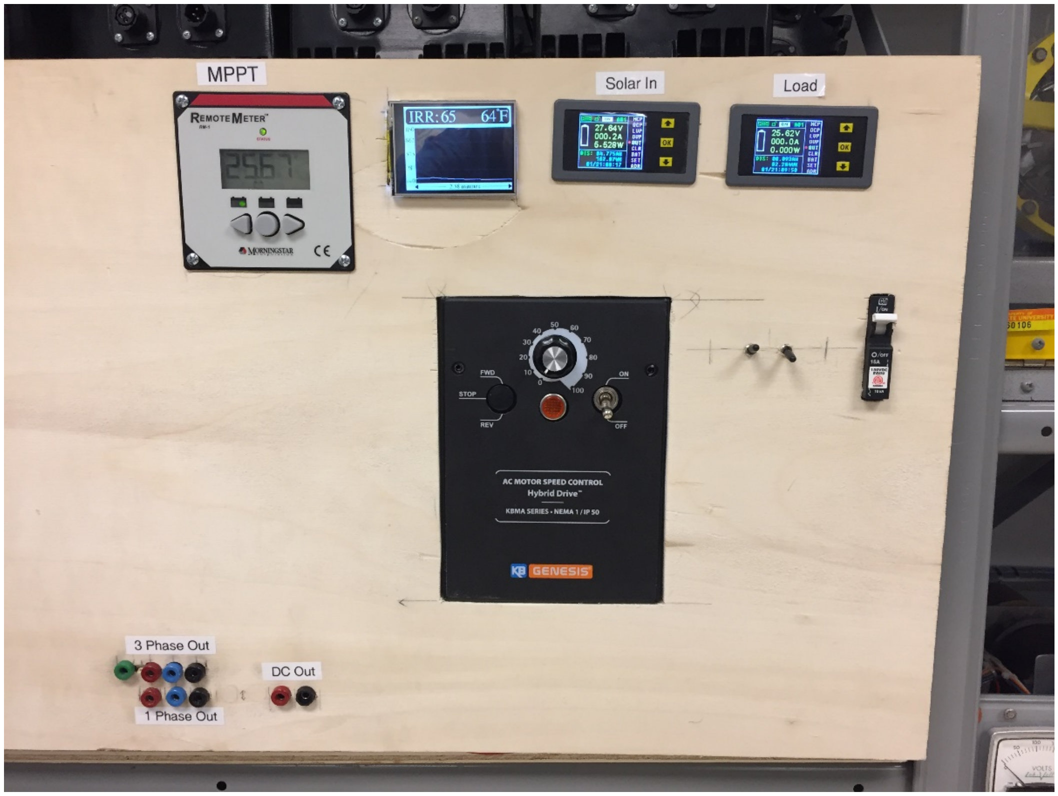


Figure 1: KBMA Variable Frequency Drive

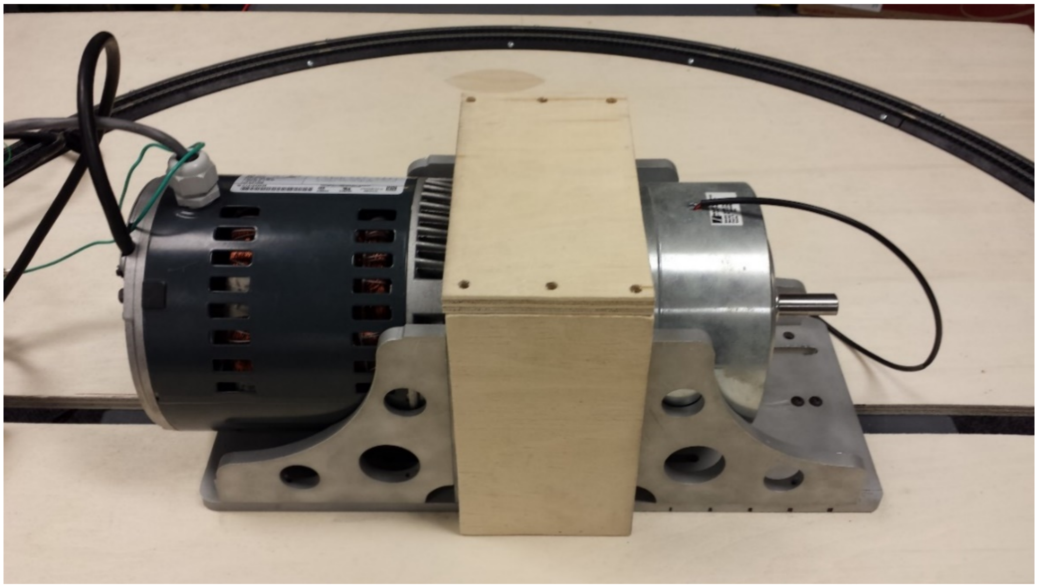


Figure 2: 1/2 HP Induction Motor

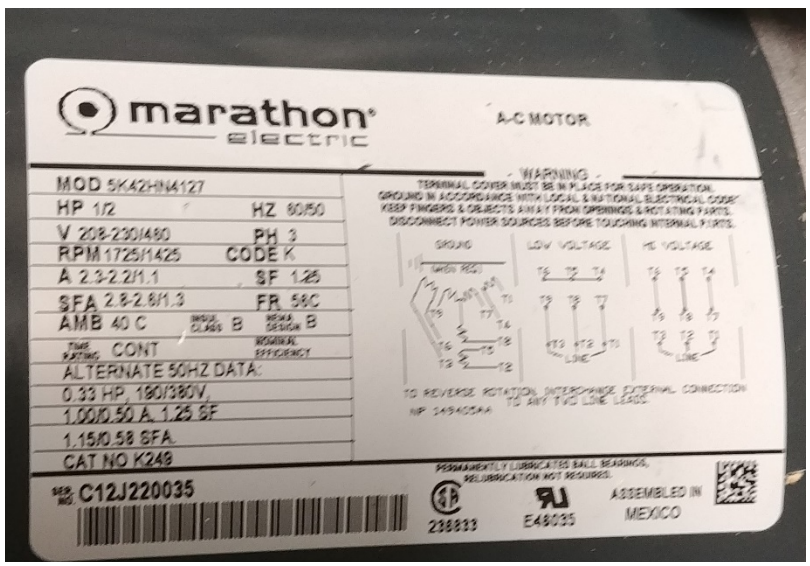


Figure 1: Marathon Induction Motor Nameplate

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).

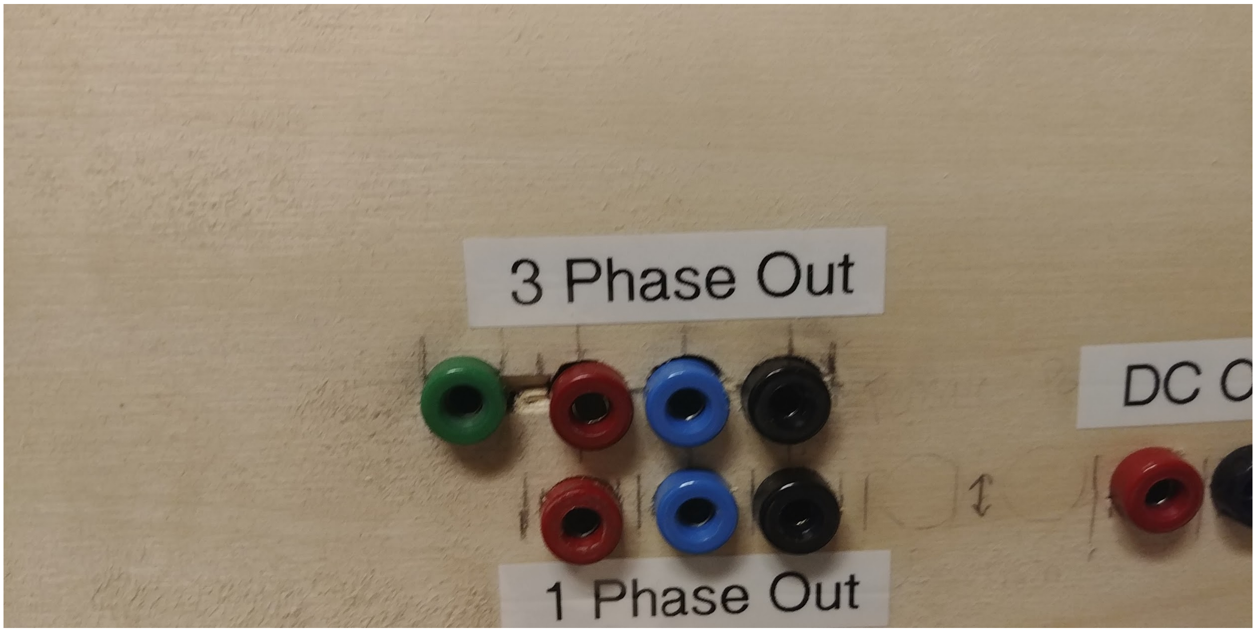


Figure 2: Three Phase Terminals

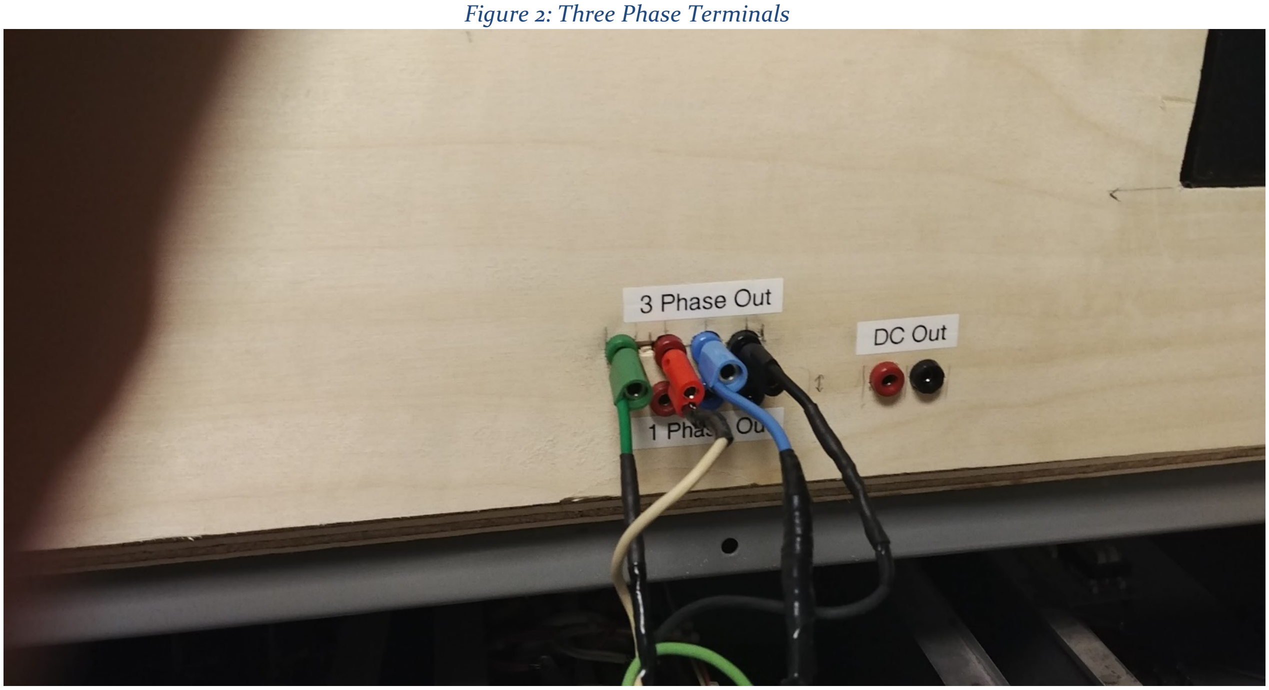


Figure 3: Three Phase Terminals

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.