Main Controller of DC Microgrid

Jonathan Graziosi

ECE 499: Capstone Design Project

Advisor: Professor Luke Dosiek

March 21, 2019

REPORT SUMMARY

A microgrid is a small network of electricity users with a local source of supply that is usually attached to a centralized national grid but can function independently. Microgrids can be supplied with different types of power generation like natural gas or renewable power generation. A shift towards using renewable power generation leads to cleaner emissions into the earth's atmosphere. This project aims to successfully integrate a power generation of solar and wind power into a microgrid. The system should be able to provide 10 volts to a load using solar and wind generation. The controller should receive a percent power variable which can either curtail or amplify the input power generation. The controller should also be able to stabilize the voltage within ten seconds and react to any changing voltages. The controller will monitor the incoming power, regulate the power, and provide power to the load. The controller will regulate the power by controlling the voltage at the input of the load. The controller uses buck converters, current and voltage sensors, as well as a closed loop feedback proportional integral (PI) controller. The PI controller has an input of the desired power and a current feedback signal at the load. The PI controller has an output of a pulse width modulation (PWM) signal which will be filtered to produce an analog signal. The analog signal controls the buck converters to allow more or less voltage into the load.

As a result of this design, the controller was able to receive power generation from an optimized solar panel as well as an optimized wind turbine. The controller received this power generation, ran it through its control structure, and was able to keep a steady voltage of 10 volts at the load. It was also able to stabilize the voltage at 10 volts within ten seconds. The controller also was able to maintain the desired percent power. The system altogether was able to power a load and acted as a larger scale microgrid.

Graziosi: Main Controller of DC Microgrid

TABLE OF CONTENTS

TABLE OF FIGURES

INTRODUCTION

As sustainable energy increases in admiration due to its cleaner emissions and accessibility, there is an opportunity to efficiently integrate it into homes and small communities. Microgrids are a great new up and coming segment in the energy industry. It represents a shift from larger more in-depth power systems to a more localized and easier to shape power distribution. These microgrids are especially great inside larger cities and areas that are remote and far away from the power grid. Microgrids can also serve as a backup plan in major disasters to support critical services. The control to move away from the larger grid makes microgrids resilient and flexible. Microgrids provide efficient, low-cost, clean energy, to improve the operation and stability of the electric grid.

Typical microgrids are ran using alternating current which provides power to AC and DC loads. Through that process AC to DC converters must be used, which causes excess energy consumption in the system. A DC system will be able to offer higher efficiency and reliability with a low system cost. This research really fascinated me and motivated me to create a project that would successfully integrate sustainable energy into a working microgrid. Although a large-scale operation will not be feasible, the design will still be geared towards a functional microgrid at a small-scale level.

This project will aim to successfully integrate a power generation of wind and solar into a microgrid which could produce around 10 volts DC to power a small load. The power generation will feed into power converters connected to a voltage bus controlled by a micro controller. The bus line will be connected to different loads allowing them to be powered. This project can also be scaled to include an emergency grid tie, which could be connected as an input source allowing the microgrid to always be able to power the load and help the microgrid reach optimal stability.

It can also be scaled to store unused energy in a battery storage unit. Every process and stage will be monitored making for the most optimal power flow. Ideally, this should be affordable, reliable and easy to use.

This paper aims to layout a capstone project that includes a background with societal and historical context, design requirements, design alternatives, a preliminary design, a final design, testing results, a project schedule, a project cost analysis, a user's manual, and a discussion on future work to create a working microgrid.

BACKGROUND

Direct current (DC) power generation is a very old idea that started with Thomas Edison and lasted for several years only until the great technological battle he had against George Westinghouse and Nikola Tesla. This battle is often called the "War of Currents", which plotted Edison's idea that the world should run off DC electricity against Westinghouse's and Tesla's idea that the world should produce and distribute alternating current (AC). "The main benefit of an AC system is that it is able to shift voltages from one level to another, allowing power to be carried long distances at high voltages, which would minimize transmission losses" [1]. DC systems require generation sites in every neighborhood because the low voltage wires needed for a DC system couldn't carry voltage at a constant level across large distances.

In recent years, there has been a vast shift into producing sustainable energy, but often large-scale generation sites are needed to produce enough energy. These generation sites are also often very far away from any neighborhoods which demands a long transmission and distribution of electricity to consumers. Although transmitting energy for long distances is not difficult, it wastes a lot of energy. "In the United States transmission and distribution losses amount to about 7 percent" [1]. Consequently, using Edison's argument of local power generation and distribution as a DC microgrid might be very beneficial.

Local power generation will also be advantageous to the US because of their increasing number of power outages. According to the US Department of Energy (DOE), the US suffers more power outages than any other nation in the developed world. Recently, Hurricane Maria swept pasted Puerto Rico causing power grids to be destroyed. These power grids have been a real problem to fix and have been expensive to become fully operational. In cases like these and the evident nature of needing more power for the ever-growing population, there is an opportunity for improving the power grid. By adding small interconnected power transmission and distribution sites the grid will become modular and very protected.

DC microgrids are not new, but different components added in conjunction with the localized grid offers new and exciting breakthrough ideas. The first and probably the biggest addition to DC microgrids, is the use of sustainable energy as a power generation medium. In the United States, fossil fuels are the largest sources of energy for electricity generation. Inside the umbrella for fossil fuels, coal-fired power plants are the second largest energy source for US electricity generation. Coal offers cheap and reliable forms of generation using steam turbines, but there is often lots of pollution that come from burning coal. According to the American Lung Association and the Clean Air Task Force (CATF), 13,000 people die each year from coal pollution. One might think natural gas is a cleaner way to produce energy, but in fact, when extracting and transporting, it can leak methane through pipelines, which is thirty-four times stronger than $CO2$. These two problems alone should already be a cause to shift away from these types of energy generation to the use of sustainable energy generation like wind and solar energy generation.

In 2012, Krushal Shah, a student member of IEEE, published a paper titled “Smart Efficient Solar DC Micro-grid” [2]. In his paper he discussed “A smart DC micro-grid suitable for efficient utilization of energy available from Distributed Renewable Energy Generators” [2]. Shah used a 40 W solar PV array to power typical residential DC-compatible loads. He described the benefits of using solar panels and laid out a DC power distribution system. Through testing he was able to get maximum simulation and measured efficiencies to reach 90% and 88%, respectively at load current of 50 mA. This is just one whole system that provides great results.

Shah's system does a great job in producing energy, but in addition to having just basic solar panels, there can be an increase in efficiency if the solar panels could track the sun to produce the most power. Lipika Nanda along with her colleagues, created a smart solar tracking system for optimal power generation. Nanda introduces a system that uses light dependent resistors for sunlight detection. "The circuit of the solar tracker system is divided into three sections. There is the input stage that is composed of sensors, a program in embedded software in the microcontroller and lastly the driving circuit that has the motor" [3]. Through the use of this circuit, the solar panel will rotate to get the maximum amount of sun irradiance with the help of the motor. This solar tracking system will increase the power output.

More importantly is how efficient the solar panels are. In the previous few years, advancements in nanotechnology have led the way in more efficient solar panels. Nanostructures are typically around a hundred nanometers in size. Materials at this low of a size scale can often have different properties than the bulk materials. Especially in solar cells, nanostructures can be tuned to allow more light to be absorbed into the cell. Nanoparticles and nanostructures have been shown to enhance the absorption of light, increase the conversion of light to electricity, and provide better thermal storage and transport [4]. The best researched solar cell has an efficiency of 46 percent which uses a multijunction technology [5]. The multijunction structure uses nanotechnology to allow transport of electrons through its cell and be able to take in different parts of the visible spectrum. Some of the most common nanomaterials used in solar panels are, silicon, titanium, graphene and cadmium. Nanotechnology can really help solar panel efficiencies.

Along with adding solar panels, the addition of wind turbines will increase power production. Wind turbines in conjunction with an optimal pitch control can alter the power curve of a wind turbine allowing it to produce more power. Shafiqur Rehman, a researcher at the Center for Engineering Research at King Fahd University of Petroleum and Minerals, reviewed how one can optimally control a wind turbine so it can produce the most power. Wind turbines "produce maximum power if the rotors are driven at the optimum rotational speed for a particular wind speed" [6]. Rehman found through his research that "Two-objective, three-objective, and four-objective optimizations for the 1.5 MW wind turbine blade designs revealed that the proposed algorithm exhibits improved distribution, convergence, and converging efficiency compared to the conventional evolution algorithms" [6].

Wind and solar used separately can efficiently provide power to a small load but when they are used in conjunction and flawlessly optimized, they can produce a great amount of power which could in turn provide energy to an entire community. Wind and solar are also not the only things one can add when creating an effective microgrid. Another effective way to optimally transfer power from the solar and wind generation sites is through the use of a maximum power point tracking (MPPT) system. There are a lot of MPPT techniques, but the most promising is the modified Peturb and Observe method (P&Ob). In Matteo Berrera's research in "Experimental Test of Seven Widely-Adopted MPPT algorithms" he concluded that "the best MPPT technique is the modified P&O (P&Ob). The logic turned out to be effective in both the situations here considered, providing always the highest efficiency" [7].

In addition to an effective DC-DC converter from the generation sites, a microcontroller-based feedback system, which is connected to the load and the generation sites, can provide the generation sites with knowledge that will determine if they should produce more or less power based on the load requirements. This feedback system should include a transfer function that considers the optimal power flow from the generation sites into the microgrid. The feedback system should work in a way that it powers the load and if there is any excess power, it should be stored in a battery which the microgrid can pull from if generation is slow. The system should also include a connection to the main A/C grid which will provide the microgrid power if all generation sites and the battery are not capable of powering the load.

When connecting to the main grid, there could be some legal considerations to think about. One of the biggest issues comes when the small microgrid produces too much power and the storage system cannot handle any more power. In the real distribution grid, people with solar panels can get paid for producing energy for the grid, but this rarely happens and can sometimes cost the utility provider a fortune. For a small undergraduate capstone project, the system will not be able to input into the main grid because of the economics with the utility company and it can cause a disturbance if the frequency is incorrect.

DESIGN REQUIREMENTS

The first main design requirement is to produce clean and sustainable energy. This part of the project will be focused on by Peter Richmond and Thomas Byrne. To give a brief idea of their requirements, Peter's project will focus on optimally tracking the sun to produce the most power for each day. The goal of his project is to create a system that tracks the sun and allows a solar panel to tilt based on that peak sunlight, so it can produce the most power which in turn will be fed into the microgrid. His project should be able to produce 10 volts DC or more. His project also includes a battery in case excess power is produced. Thomas' project is very similar, but instead of focusing on solar he will be focusing on a wind turbine. The goal of his project is to create a pitch controller for a wind turbine, which will optimally find the best pitch angle according to the wind, to produce the most power output. His project should be able to produce 10 volts DC or more to be fed into the microgrid.

The next most important part of the microgrid should be the DC-DC converters which will be attached to each generation site allowing only the specific set voltage into the main bus. These converters should be fast and reliable because if excess or a lack of voltage gets put into the DC bus, it can cause the system to go unstable. The converter should be able to take in a large amount of voltage and step it down to the specific set voltage. Attached to the generation sites should be a buck converter. A buck converter is a DC to DC power converter which steps down voltage from its input to its output. A buck converter will take in voltages from the generation sites and step the voltages down using a switch, a diode, an inductor and a capacitor. Buck converters are around 90% efficient which will make them very useful for converting the input voltages into the load voltage bus.

A simple DC buck converter is shown in figure 1. The concept for a buck converter in continuous mode, (current never falls below zero) has the voltage across the inductor as $V_L = V_i - V_o$ when the switch in figure 1 is closed. When the switch is opened the diode is forward biased and the voltage across the inductor is $V_L = -V_o$. The energy stored in the inductor is $E = \frac{1}{2}LI_L^2$ therefore, energy stored in L increases during on-time as I_L increases and then decreases during the off-state. L is used to transfer energy from the input to the output of the converter [8]. The buck converter should only allow 10 volts into the load voltage bus.

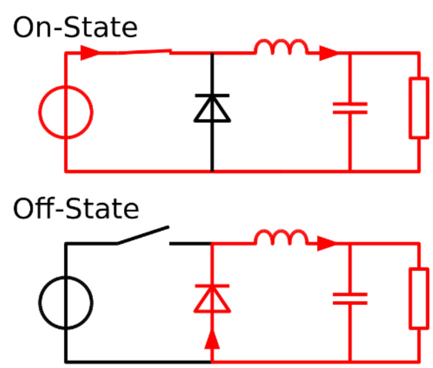

Figure 1: Circuit diagram for a simple buck converter.

If the converter allows 10 volts into the bus and the load is already powered, the energy must not be wasted. In this case, a battery should be included in the system to store any extra power created. This battery should also allow energy to be pulled from it in case the generation sites cannot produce enough energy to power the load. For this case a bidirectional power converter should be connected to the battery so that it can store energy but also pull energy when needed. In addition to a bidirectional power converter, there should be a control strategy connected to the battery to abide to the optimal power flow of the microgrid. This control system should allow the battery to output power when necessary. A simplified control system is shown in figure 2 which is from [9].

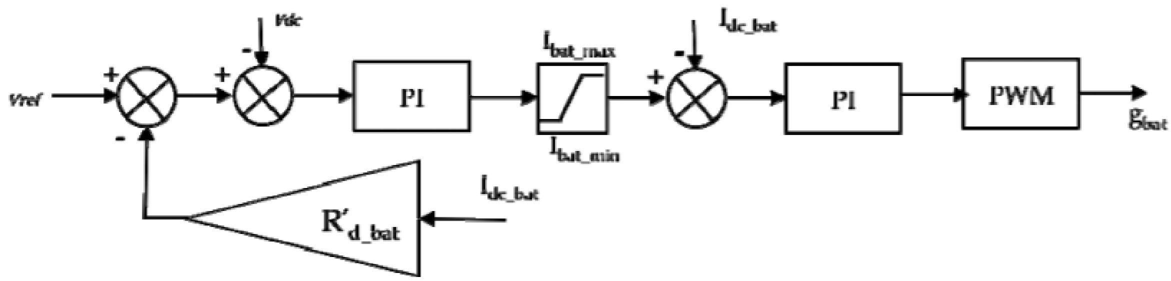

Figure 2: Control diagram of battery converter.

The battery control system should also be different from the main control system which will be connected to the load, generation sites and the battery. The main control system will use basic logic statements as well as a transfer function to determine the optimal power flow and make sure the load is always power regardless if the renewable generation sites cannot produce enough power. On the other hand, the controller must not waste energy if the load is already powered. The basic logic of the controller should draw power from the renewable generation sites first, battery second, and lastly the main AC grid to power the load. If the load is already powered the controller should store any unused power in the battery. If the battery is completely charged and the load is powered the controller should be able to communicate to the renewable generation sites and tell them to slow down production or at last, discharge the power. Lastly, the controller should not allow any extra power into the load. This could cause harm to any load connected to the bus.

DESIGN ALTERNATIVES

The first major design alternative includes not adding a connection to the main AC grid as a power source in addition to the two renewable generation sources. Having a grid connection will take away from the islanded feel of the microgrid. Being completely away from the AC grid provides a great research opportunity because in some countries there is no main power grid and the best-case scenario is a microgrid.

On the other hand, the grid connection could help the microgrid in two ways. First, it could provide power to the load just in case any of the two renewable generation sources cannot. Secondly, the AC grid can provide stability to the microgrid if the load experiences rapid changes of on and off states. "It has been found that if a transient occurs in a DC grid system, the transient overvoltage not only reaches 194% of the operating voltage, but also stabilized at new voltage level of 111%" [10]. The transient could be very bad for the microgrid so a connection to the main AC grid could help stabilize transients. It has been found that the advantages of a grid connection out-weigh the disadvantages, so the designed microgrid will be connected to the main power grid.

Another design alternative that may be implemented is on the load side. On the load side, different loads can be used. The simplest load that could be used would be a resistor. Although this may be a starting point, it does not prove a point that the system works. Through simulation and testing, it will be determined what is the best load to use. If everything works well, the load will draw as much power as the system can provide. Another advanced alternative will be to add a varying load that changes over time. This will cause the main control system to have to work a bit harder to make sure the load is always powered.

The next design alternative is where to place the battery. A microgrid is a very broad term and different microgrids have different properties to them. One can see that a working microgrid can be in the form a submarine that is under water for years. The submarines are technically powered by a microgrid. A microgrid needs to have a source and a sink and then it can be considered a microgrid. In another case, one can look at the power grid. All its sources are very far away from its sinks. The system must use a design that will closely resemble a real-world application.

If the system would to use the submarine idea, the real-world application for the system would be a house that has a solar panel on its roof and a wind turbine in its backyard which will feed power directly to the home and store any unused power only for the home. If the system would to use the main power gird idea, the real-world application for the system would be having a solar farm and a wind farm very far away from my load. In this case, the system will have to include line-losses from generation sites to the load, an economical hierarchy that determines when each generation site should turn on or off, and lastly a battery at the generation sites rather than inside a home. Both cases will resemble real world applications and therefore the system must choose which application to use. The preliminary design will use the submarine idea and then eventually turn into the grid design.

The last design alternative that may be added, is going to determine if the microgrid needs a control system that connects to the load or a control system that just changes the buck converters output to allow only a specific amount of voltage or power into the load. In addition to that, the microgrid needs to decide whether to control the voltage or the power into the bus. If the microgrid just controls the voltage, the current can become unstable but if the microgrid controls the power, the system can control both the voltage and current. As well as controlling the voltage and current, by controlling the power, the system can determine which generation site can provide the most power to the load. This could be done by controlling the voltage and then having a desired percent power variable for each generation site. This will be determined when the system is built.

PRELIMINARY DESIGN

Through extensive research, a top-level design was created that can be broken down into four distinctive levels. The top-level design is shown in a block diagram form in figure 3. This block diagram showcases generation sites, power converters, a battery storage system, a microcontroller, and lastly a load.

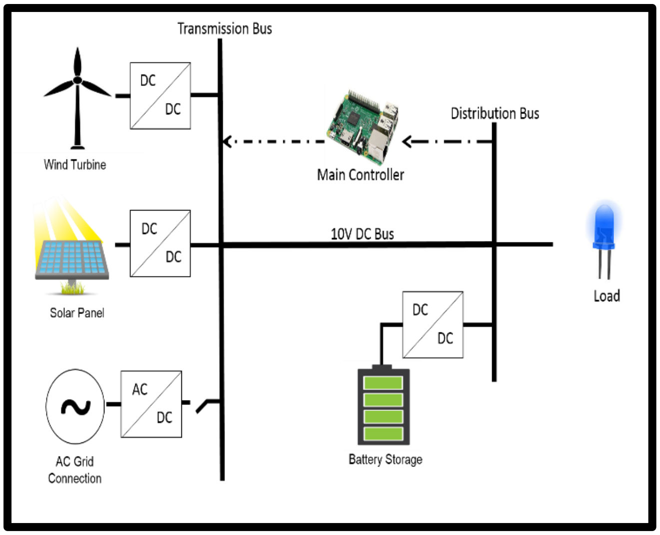

Figure 3: Top-level block diagram of DC Microgrid

The two renewable generations will not be included in this design because they are being worked on by Thomas and Peter. Thomas is working on optimizing a wind turbine [11] while Peter is working on optimizing a solar panel [12]. Both of their projects will feed directly into the microgrid which then then the system will have to direct the power to the right place. The microgrid will begin with the acceptance, conversion, and distribution of each of their power generation sites. This will be done using a DC to DC converter. The DC to DC converter will be a buck converter. The buck converter will allow any voltage generated into it, but it will only output the desired voltage. In my case, the desired voltage will be 10 volts. The buck converters will control the input voltage and lower it to the desired load voltage.

For this design, a desired power percentage for each generation source needs to be added to control how much power each generation source provides to the load. In a general state, each generation site should be able to produce half of the necessary energy to power a load. These power percentages could be tuned to allow one source to provide most of the power to the load. In conjunction with the buck converter, there needs to be a control signal that is fed back from the load, telling the converter to allow more voltage or not. This will be done using a PI controller.

The PI controller will have an input of 10 volts multiplied by a desired power percentage minus the voltage coming from the load. The PI controller will have a proportional gain of 0 and an integral gain of 10, which were tuned using MATLAB's tune function on the PI controller. These gains may need furthering tuning. This was used because voltage and power had to be converted into a duty cycle that will then be fed into a PWM generator, which in turn will control the voltage the converter has to regulate.

A simplified block diagram of the converter along with the attached controller is shown in Simulink in figure 4, was created by Luke Dosiek and modified by Jonathan Graziosi. The two DC supplies with a 0.1 Ohm resistance simulate the wind turbine and the solar panel. The 36 volt supply is the solar output while the 24 volt supply is the wind turbine. Those two power supplies will both be connected to separate buck converters which has a diode on-state resistance of 1e-3 Ω, diode snubber resistance of 1e6 Ω, an infinite snubber capacitance, a diode forward voltage of 1e-3 volts and an infinite current source snubber resistance. This block diagram will help simulate different resistance values to use for the final design.

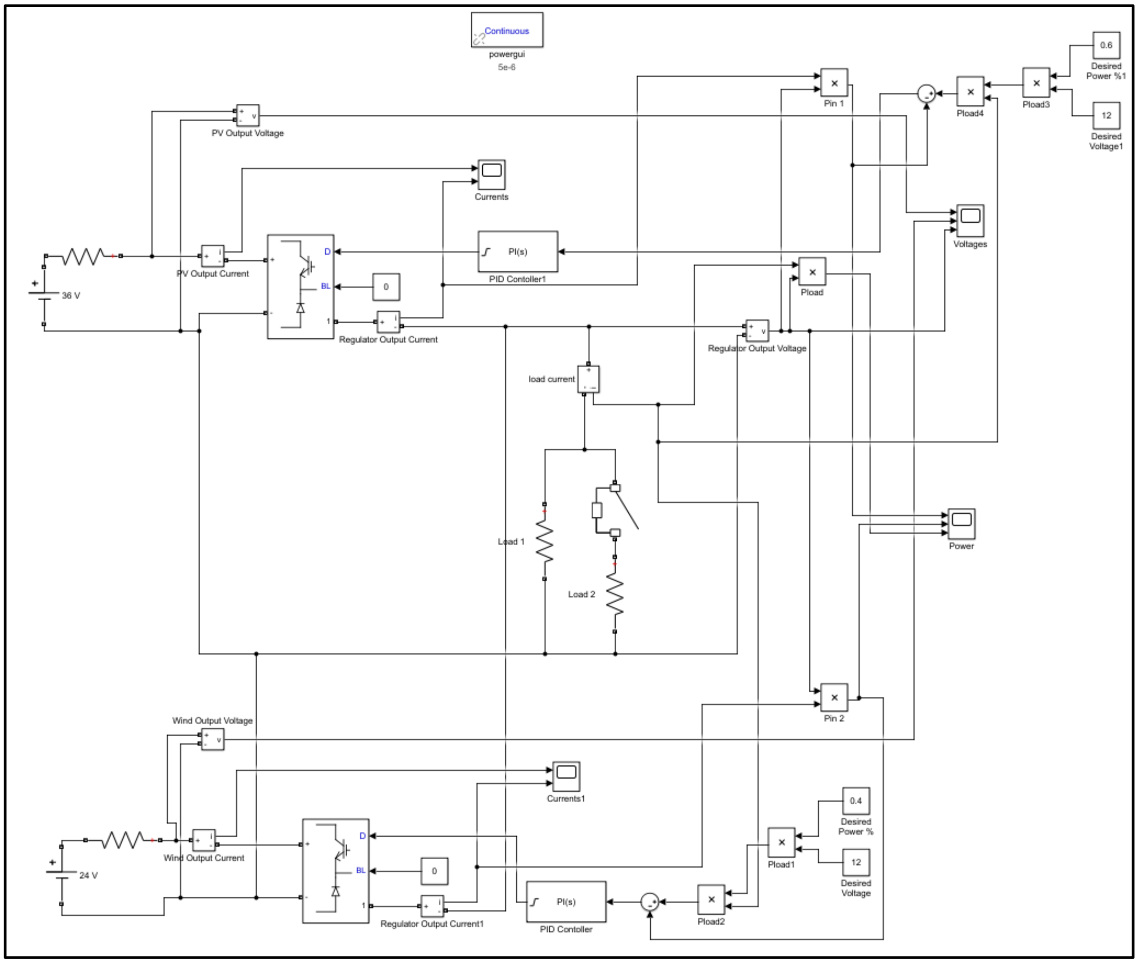

Figure 4: Simulink block diagram of designed microgrid

The next aspect of the project will be the battery storage system. This part has not been fully scoped out. As for a preliminary design, a lead acid battery will be used to collect any unused energy from the generation sites. Lead acid batteries are often cheap and very reliable. Attached to the battery will be a bidirectional power converter. This power converter will be very similar to the buck converter shown in figure 4 but it will use two different power flow directions. The reason for this is because the battery must store energy but also provide energy to the load in case the generation sites cannot.

Connected to the power converters will be a microcontroller which is also connected to the load. This microcontroller will provide real time data from the load to the power converters and vice versa. The microcontroller is included is, so the system can control what sources provide power to the load. The design will implement basic logic statements that will run through different scenarios to always keep the load powered regardless if the generation sites and battery cannot provide enough power. The basic logic of the controller will draw power from the renewable generation sites first, battery second, and lastly the main AC grid to power the load. If the load is already powered the controller will store any unused power in the battery. If the battery is completely charged and the load is powered the controller will be able to talk to the renewable generation sites and tell them to slow down production or at last discharge the energy.

Altogether, generation sites, power converters, a battery and a load will come together to create a working microgrid.

FINAL DESIGN

The main controller design underwent many changes before coming to a final design that worked efficiently and correctly. The final design is comprised into three parts: the circuitry, which is all the components and how they all work in conjunction, the controller, which includes the closed loop PI feedback controller, and lastly the implementation, which is how the system works all together to provide power to a load.

Circuitry

The circuity used in the final design is divided into three parts that all work in conjunction which each other. The first part is the incoming power generation and acceptance into the controller. Two 12 volt DC power supplies were used to act as the incoming power generation for the system. This was done to make testing easier. These two power supplies could easily be swapped out for the wind turbine and solar panel. The power supplies were connected to the system through the use of banana cables. Each voltage source received their own voltage bus and was fed directly into their own buck converter. The buck converters used in this design were Texas Instrument's LM2596 buck converters. The converters could use two different ways of lowering the incoming voltage. The first was through a potentiometer, which can be manually tuned to lower the voltage to a desired output voltage. This method was never used because the system needed to be able to react to any change in voltage, so the control of the buck converter had to be done automatically. The buck converter's outputs stayed constant if the input voltage was above the desired load voltage. For the buck converter to work automatically, an analog signal must have been inputted into the feedback pin of the buck converter.

The second part is controlling the buck converter automatically. The analog signal that is fed into the buck converter comes from a PWM signal that is generated from the PI controller which will be discussed in the controller section. The PWM signal generated had to be converted into an analog signal to communicate with the buck converter. The PWM signal was converted using a RC filter. The RC filter used a 220 Ω resistor and a 330 µF capacitor. This filter has a cutoff frequency of 2.19 Hz, which was calculated using equation 1. The output of the RC filter must be 1.25 volts to connect to the feedback pin of the buck converter. To make sure the voltage connected to the buck converter was 1.25 volts, an additional resistor was added at the output of the RC filter to lower the voltage to 1.25 volts. The resistor has a value of 910 Ω, which was calculated from the voltage divider inside the buck converter. The circuity used for the analog signal is shown in figure 5. The calculation for the additional resistor is shown in equation 2.

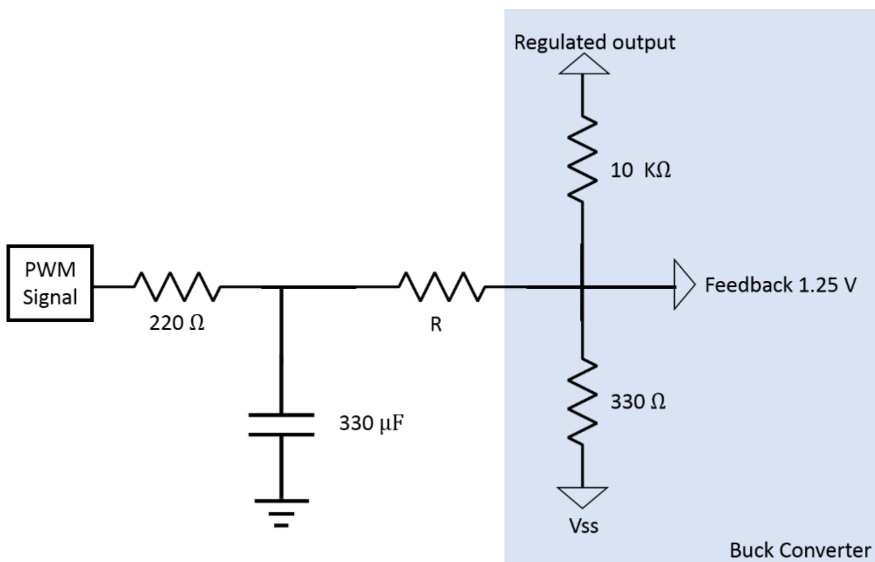

Figure 5: Digital to analog conversion circuitry.

$$1)\ F_c = \frac{1}{2\pi RC}$$

$$2)\ R = \frac{(5V*330\Omega)-1.25V*330\Omega}{1.25V}$$

The output of the buck converter fed directly into the third part of the circuity, the voltage and current sensors. The sensors used were Adafruit ina219 current sensors. The sensors need a voltage of 3.3 volts to operate. This voltage was provided from the 3.3 volt bus on the Arduino. Two sensors were used for the two different buck converters. The buck converters output fed directly into the sensors and then the output of the sensors fed into the next part of the circuitry. The sensors used could measure voltage, current, and power. For the final design, only the voltage and current measurements were used. A more in depth use of these measurements can be found in the control section. Multiple sensors could be connected together to communicate with the Arduino by only using two input pins on the Arduino. Each sensor had to be assigned a unique I2C address. The output of the sensors was connected and fed into the Arduino through a clock (SCL) pin and a data (SDA) pin. More knowledge on using I2C address can be found at [13].

The last part in the circuitry was the load. Connected before the load were two 10 Ω resistors acting like typical transmission line loss in the larger grid. Connected to the input side of these resistors were the two separate voltages from each buck converter. The output of each resistor connected to each other to feed into the load. Before the load, another sensor was added to monitor the load voltage, current and power. The final component in the circuitry was the load. A 12 volt DC LED as well as a 12 volt DC fan was connected to act as typical loads on the system.

Controller

The controller is far more complex than the circuity. Multiple different iterations, described in the design alternatives section, were tested and ultimately one controller design worked correctly and was used. The control block diagram is shown in figure 6.

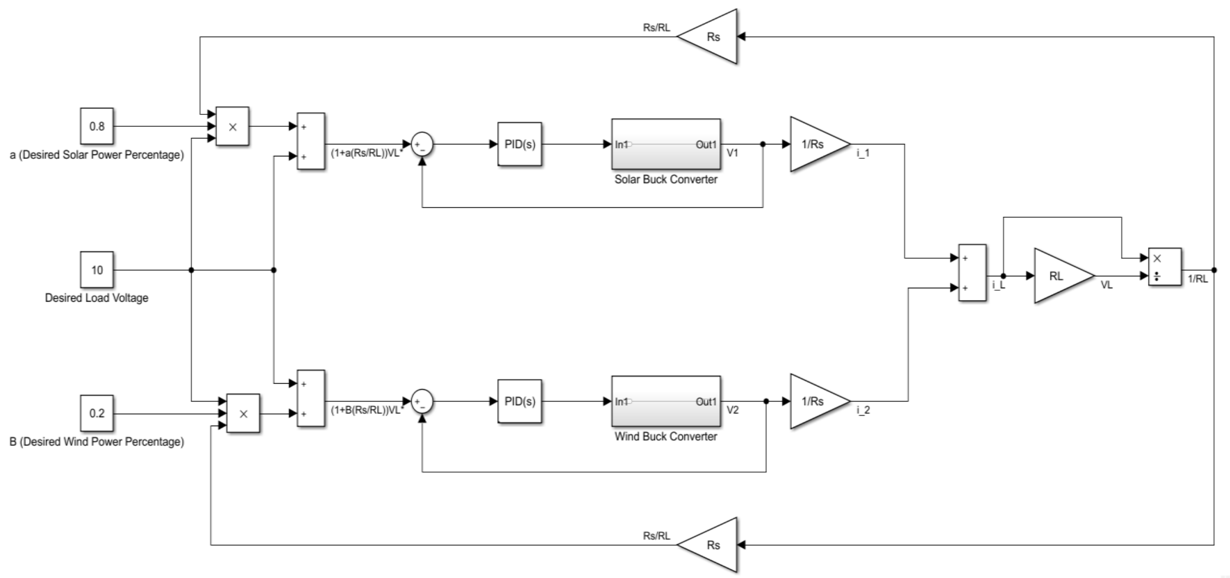

Figure 6: Full feedback control system block diagram.

The more in-depth control system begins with the knowledge of Kirchhoff's current law (KCL). KCL states, all currents flowing into one node must sum to equal the current flowing out of the node. For the system design, two separate currents are flowing into a node from the wind and solar generation and then adding up together to provide current to the load. A simplified circuit diagram of this is shown in figure 7. This circuit is very important in understanding how the basis of the control system works. The system also requires a desired percent power variable and that variable can be multiplied to these currents to adjust the power of each generation source. The percent power variables are α and β. α represents the desired power percentage of the solar generation and β represents the desired power percentage of the wind generation. α and β must add up to one.

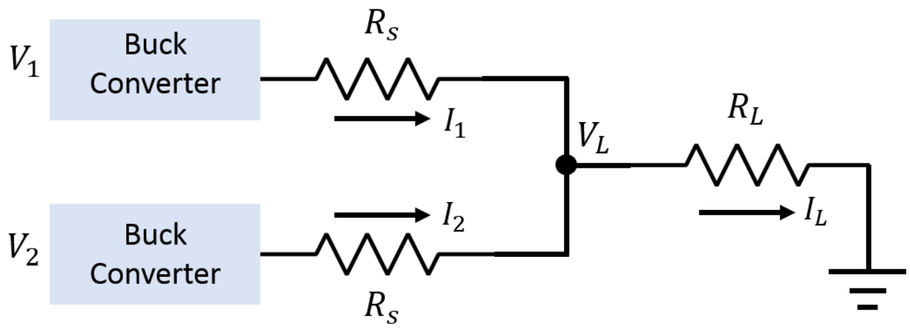

Figure 7: Circuit design after buck converters.

To begin with formula manipulation, the current coming from one source is to be the key observant. Knowing this, the single source current can be found in two ways. The first way is that the load current can be interpreted as the desired power percentage of one source multiplied by the load voltage, shown in equation 3. The load current can then be converted into the load voltage divided by the load resistance from Ohms law, shown in equation 4. The second way is knowing the voltage drop across the line resistor. The current can then be viewed as the load voltage subtracted from the input voltage and then divided by the line resistor, shown in equation 5. By setting these two equations equal to each other, shown in equation 6, the incoming voltage can be found using equation 7.

$$3)\ I_1 = \alpha I_L$$

$$4)\ \alpha I_L = \alpha \frac{V_L}{R_L}$$

$$5)\ I_1 = \frac{V_1 - V_L}{R_s}$$

$$6)\ \frac{V_1 - V_L}{R_s} = \alpha \frac{V_L}{R_L}$$

$$7)\ V_1 = \left(1 + \alpha \frac{R_S}{R_L}\right) V_L$$

Equation 7 is used as the setpoint of the controller. Three out of the five variables in equation 7 are known. α is the desired power percentage, which can be manually varied, R_S is the line resistance, which is 10 Ω, and V_L is the load voltage, which is 10 volts. This leads to having two unknown variables. One of those variables is V_1, which is the variable the system is trying to control. The last variable R_L, is constantly being measured and fed back into this equation. Equation 7 can be replicated and be used to control the second incoming voltage source. The only change to this equation is changing the percent power variable to β.

The next aspect of the controller is setting up the inputs, outputs, and gains of the PI controller. The input of the controller is the voltage incoming from the solar and the wind, which is measured with the sensors. The output is a PWM signal which gets directly fed into a RC filter described in the circuitry section. A higher duty cycle of the PWM signal, results in a lower output voltage of the buck converter. The gains used for the controller were a proportional gain of 0.01 and an integral gain of 1000. The proportional gain determines the ratio of output response to the error signal. The integral gain sums the error over time. A high integral value will sum the errors at a faster rate, resulting in a quicker stable output.

Implementation

The controller was connected to the circuitry by embedding the controller into code on the Arduino. The Arduino connects the circuity and controller together and makes the system work. A PID Arduino library was downloaded to work as the PID controller [14]. This library has all the inner workings of a PID controller and all it asked for was the gains, setpoint, input and output. The input of the PID controller was generated from the sensors and the output was a

PWM signal generated from the Arduino. The Arduino also used a library for the sensors [15]. This library was able to communicate with the sensors and output a value for the current, voltage and power measurements in real time. The full Arduino code is shown in figure 12 (Appendix). With the circuitry connected to the controller, the system was able run.

PERFORMANCE ESTIMATES AND RESULTS

Estimates

Before the design was built, estimates were calculated and written down to determine if the results exceed expectations, or if the design feel short. The first estimate made was how quick the controller could stabilize the output voltage without any overshoot. The estimation written down was that the voltage would stabilize within 5 microseconds even if loads were added or subtracted. This estimation came from the simulation results in Simulink. The voltage in the simulation stabilized at 12 volts in 5 microseconds. This was a very optimistic estimation.

The next estimation made was that the PID controller would use a power measurement as its setpoint. This estimation came from the first preliminary design. This design used a desired voltage multiplied by the measured load current as it's setpoint. This simulation worked flawlessly so this was the first design choice.

The last estimation made was the power efficiency. Before the circuit was built, figure 8 was used to determine how efficient the system would be and how much power would be lost. In this circuit diagram, a line resistance of 10 Ω, a 10 volt load bus, and a 100 Ω load was used. Input voltages were calculated to be 10.2 volts and 10.8 volts. It was calculated that the power efficiency would be 93.63%.

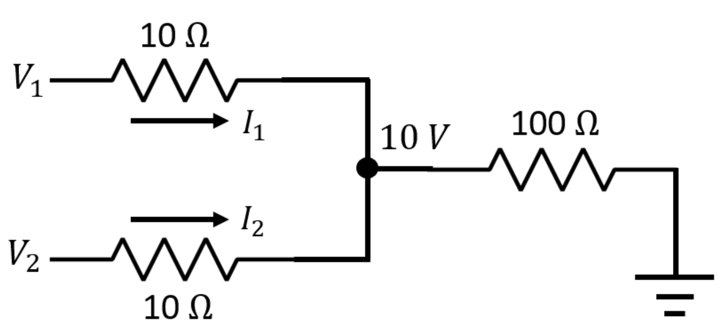

Figure 8: Power efficiency test circuit

Results

The following results were obtained by using two input voltages of 12 volts, a DC 12 volt 1.26 watt fan as the load, a 0.8 desired solar power percentage and a 0.2 desired wind power percentage. The controller scheme used equation 7 as the input. The first result gained was the voltage stabilization. A graph of the load voltage is shown in figure 9. The voltage stabilizes at 10 volts within 5 seconds. This response was not as quick as the simulation, but it was still very fast in real time. One major factor that played a role in not allowing the voltage to stabilize quicker was the current sensors being used. The sensor in conjunction with the built-in PID controller could not sample quick enough. Another voltage result was how the system stabilized at 10 volts with a threshold of 0.05 volts. The output voltage never dipped below 9.95 volts.

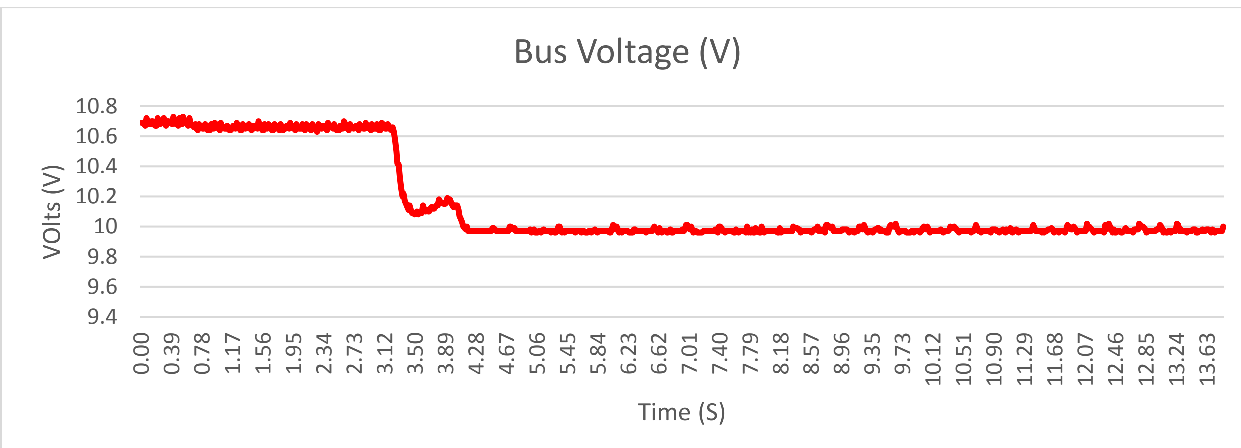

Figure 9: Load bus voltage

The next result viewed was the different powers at the load. The output powers for the solar and wind are shown in figure 10. The desired solar power percentage stabilizes at 80 percent and the desired wind power percentage stabilizes at 20 percent within 10 seconds. The power efficiency of the resulting system was calculated to be 92 percent efficient.

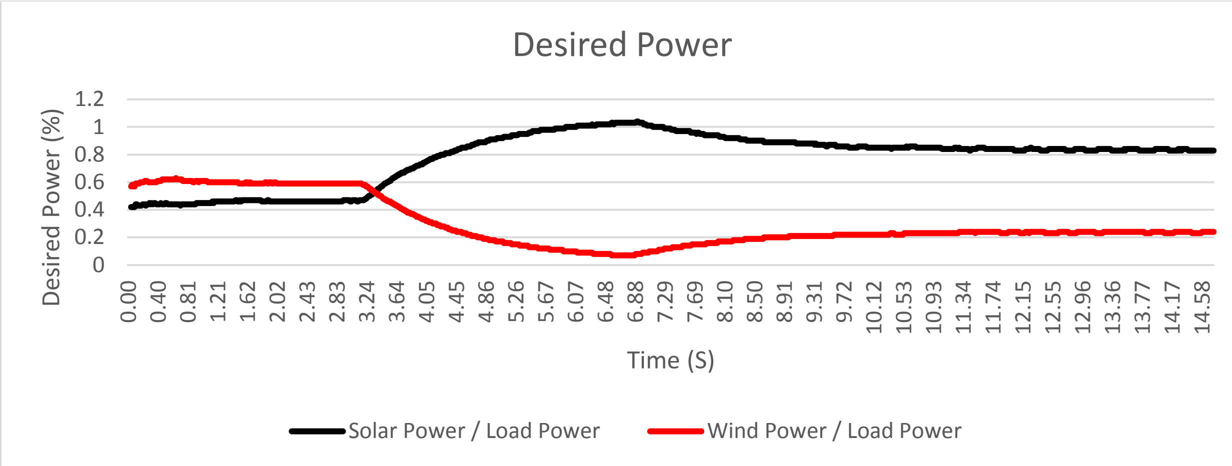

Figure 10: Desired power percentages.

Although this design worked properly, other considerations could have been considered to make the system work more quickly. The first change that could have been made was using more rapid current sensors. When trying to measure currents for the power control scheme, the sensor could not measure as quick as the PID controller was sampling. This caused inaccuracies and made the system never reach its setpoint. The control scheme had to be changed to take this in account. The next change that can easily be implemented is to increase the input voltages. By increasing the voltages, the system was able to get to its desired setpoint and respond faster. The last consideration is, what if the input voltage dropped below the desired load voltage? This caused the load voltage to be as low as the lowest input voltage. To counter this effect, sensors at the generation sources needed to be installed along with a switch to turn the input completely off and allow another generation source to take over the desired power percentage of the turned off source. Another work around to a low input voltage, is adding a buck-boost converter instead of just a buck converter. A buck-boost converter could lower as well as increase incoming voltage if the voltage goes below the desired load voltage.

PRODUCTION SCHEDULE

Spring 2018:

- Background research on microgrids.

Fall 2018:

Week 2

- More in depth microgrid research.

Week 3

- Microcontroller research and software.
    - Arduino Uno was chosen as the best microcontroller to use

Week 4

- Load research (type of loads, power of load, does it need full power, or can it receive half?).
    - 3 different types of loads (basic, load, burst).

Week 5

- AC/DC conversion from generation sites research.
- Group meeting so teammates are on the same page

Week 6

- Battery storage research.

Week 7

- Sensors at load, generation sites, and battery storage research.

Week 8

- Microcontroller code and logic research.

Week 9

- Preliminary Simulink testing and simulations.

Week 10

- Finalized Simulink and implemented different scenarios.

Winter 2019:

Week 1

- Finalized microgrid design.
- Started buck converter design.

Week 2

- Ordered micro-controller and other parts.
- Worked on basic PWM code in Arduino.

Week 3

- Tested PWM Arduino code.
- Started feedback code.
- Created RC filter for PWM.

Week 4

- Applied for SRG
- Wired and connected buck converter to Arduino PWM generation
- Looped through different duty cycles to control buck converter output with steady DC power source.
    - Found duty cycle thresholds for buck converter.

Week 5

- Implemented sensors to measure voltage and current
- Worked on feedback control using voltage.

Week 6

- Added another voltage source.
- Performed intensive, different scenario, tests.
    - Voltage controller did not work with two sources

Week 7

- Changed to a power controller.
    - Power controller did not work properly with a load connected.

Week 8

- Changed to a current controller which used the bus voltage, line resistors and the load resistor.

Week 9

- Added multiple loads

Week 10

- Started working on grid connection.
    - Current controller was not working properly.

The first main improvement to this schedule would be to do less research during the fall term. Although research is great, more simulations and circuit designs could have been made and tested. Having different case scenarios would have been beneficial in case one design did not function properly.

Graziosi: Main Controller of DC Microgrid

COST ANALYSIS

Item	Description	Vendor	Consumable (C) or Reusable (R)	Quantity	Price	Subtotal
Arduino Uno	Microcontroller to be used as main processor.	Arduino	R	1	$22.00	$22.00
Mux Shield	Used to add additional I/O pins to Arduino.	Spark Fun	R	1	$24.95	$24.95
DC Buck Converter	Used to control voltage from generation to load.	Amazon	R	6	$1.83	$10.98
Battery	Used to store excess energy.	Amazon	R	1	$19.99	$19.99
Battery Charge Conditioner	Used to allow bidirectional power flow	Amazon	R	1	$12.99	$12.99
LED Lights	Used as a load	Amazon	R	2	$4.06	$8.12
Fan	Used as a load	Digi-Key	R	1	$4.09	$4.09
Current transducer	Current sensor	Digi-Key	R	5	$1.57	$7.85
Construction Materials	Housing for circuitry	Amazon	C	2	$8.57	$17.14
Switches	Used to turn on and off generation sources	Digi-Key	R	4	$2.24	$8.96
Resistors, Capacitors, Diodes	Basic circuitry	Digi-Key	R	10	$0.25	$2.25
					Shipping	$24.50
					Total	$163.82

Table 1: Cost analysis

Some parts including the mux shield, battery, battery charge conditioner, and switches were not used. These parts will be used in future work so they will not be wasted.

Graziosi: Main Controller of DC Microgrid

USER'S MANUAL

The user's manual is to be broken up into two parts. The circuitry, which includes component connections and the code, which will explain how the code works and how variables should be changed. The final circuit and code are shown in figures 11 and 12 (Appendix).

Circuitry

The first part of the circuit is the voltage input. This can be provided by any type of source, a wind turbine, a solar panel, a power supply or a battery. The only caveat for the voltage input is how high the voltage is. The voltage should not exceed 40 volts, which is the threshold for the buck converters. The voltage for any source should also not go below the desired bus voltage. Having an input voltage lower than the bus voltage will tank the load voltage causing the system to never reach the desired voltage. The voltage sources can be connected via the banana connectors on top of the protoboard.

After the voltage inputs are connected, they should be directly connected to their own buck converter. The buck converters used are Texas Instruments LM2596 DC-DC Adjustable Buck Converter. The buck converter has five main connections. For all connections, solder is necessary. Additional wires were soldered to each connection to allow for ease of use. The IN+ connection is where the positive side of the voltage source gets connected to. The IN- connection is where the negative or ground side of the voltage source gets connected to. The OUT+ connection is the positive output of the buck converter and the OUT- connection is the negative output which should be connected to ground. The final connection is the feedback signal. While looking at the main chip on the buck converter, the circle indentation should be on the left. With this information, the fourth pin from the left is the feedback pin of the buck converter. A resistor that follows equation 2 (910 Ω) should be soldered onto the pin. The opposite side of the resistor will connect to the RC filter.

The RC filter used in this design used a 220 Ω resistor and a 330 μF capacitor. Two filters were used to filter each different voltage source's PWM feedback signal. The input side of the resistor connects to the PWM signal while the output side connects to the positive side of the capacitor as well as the input side of the resistor connected to the feedback pin. The negative side of the capacitor should be connected to ground.

The output of each buck converter connects to its own INA219 current sensor breakout board. The output of the buck converter should connect to the Vin+ pin on the current sensor. The Vin- pin on the current sensor is the output pin and connects to the input of the line resistors. In addition, the current sensor needs power to measure current and voltage. The 3.3V pin from the Arduino provides enough voltage for the sensor to work. The 3.3V pin should be connected to the Vcc pin and ground should be connected to the Gnd pin on the current sensor. The next important connection on the current sensor is the Sda and Scl pins. These pins should feed directly into the SDA and SCL pins on the Arduino. If multiple sensors are needed, these pins can be connected. The only change necessary is having to address each current sensor. Each current sensor can be addressed by soldering a bridge on the A0 or A1 pins. More information on this can be found at [15].

The last circuitry part is connecting the loads. The line resistors' output is passed through a current sensor. The output of the current sensor is the load bus. Here, any type of DC load can be connected. For this system, a 10 volt load voltage was desired, but this can easily be scaled up to provide power to higher powered loads. The input voltages should always be higher than the desired load voltage.

Code

The Arduino code can be separated into two parts, the setup and the loop. The setup portion includes libraries, declares variables, starts the PID controllers and current sensors, and declares the bus voltage as well as the percent power variables for each input source. The libraries included are the PID [14], current sensor [15], wire [16]and filters [17] libraries. If using multiple current sensors, each sensor must be addressed both physically and digitally. The digital hex code can be found at [15]. The current sensors use a digital calibration of 16 V and 400 mA. The PID controllers are set up by declaring an input, output, and setpoint variable. They also need gains, which can control, speed, overshoot, and oscillations at the output. For this design a 0.01 proportional, a 1000 integral, and a 0 derivative gain were used. The PID controller also used a sample time of 1 Hz to allow the controller to sample more quickly.

The loop portion of the code is constantly running once uploaded. The loop portion holds the sensor measurements, the PID set point formula, the output of the PID controller, and any serial prints. The solar and wind load voltages as well as currents are always being measured. The solar and wind voltages are used for the input of the PID controller. The load voltage and current is used to calculate the load resistance. The solar and wind setpoints are calculated by using equation 7. The PID controller outputs to the desired PWM pin declared in the setup. Lastly, if any monitoring or plotting is needed of measurements, this can be done in the loop.

CONCLUSIONS

Some problems the power grids face on a day-to-day basis may be able to be solved with the use of microgrids. Power outages in the United States doubles every five years. Even with new technology, a way to stop power outages is yet to be discovered. Power outages can cause great harm to anyone in need of life support. Another problem is that pollution in the earth's atmosphere from natural gas and coal power plants is increasing at a steady state. Recently there has been a shift into using renewable energy, but it is not enough to stop running natural gas power plants. One way to solve both problems is to set up localized microgrids. Localized microgrids can provide stability to a grid if a major transmission line went down. They also can use renewable energy, which may shut down larger and more polluting power plants.

The main goal of this project was to integrate solar and wind into a microgrid which can then provide power to a load. The designed microgrid was able to provide 10 volts to a load using solar and wind power generation. A percent power variable was used, which could allow both the wind and the solar generation to provide fifty percent of the load power each. This variable can easily be changed to allow one generation source to provide more power than the other source. The main control scheme in this design used a PI controller, which had an input of the desired power and a current feedback signal at the load and an output of a PWM signal to regulate the output voltage at 10 volts. The PWM signal also could only take 256 values which limited the number of outputs of the buck converter. This caused the load voltage to fluctuate between 9.95 and 10.05 volts.

While trying to design a working microgrid, many problems occurred that needed to be fixed before being able to move onto to the next part of the design. The first major issue that arose was properly setting up and tuning the PID controller. Tuning the gains of a PID controller can be complicated, especially without the proper tools and measurements. To properly tune the gains of a PID controller, an output response graph should be used to determine how the system is reacting. Arduino graphing abilities are limited, so it was very difficult to understand how the system was behaving.

The next big issue that arose was when trying to connect more than one generation source. When the second generation source was added, a simple voltage controller was still being used. The voltage controller was not allowing the second source to input any power into the load. The system would only use one source to power the load. This was not correct, so a new controller design had to be implemented. After a new controller design was implemented, the system was still not working properly. This was due to a simple coding error along with the current sensors not being quick enough. A completely new and deeper type of thinking was needed to understand what worked and what did not. This led to the working design outlined.

As discussed in the design requirements, a grid connection as well as a battery storage unit should be implemented into this design. Unfortunately, with only eight months of work, there was not enough time to add these components to the system. These two parts are vital if the system needed to be scaled up. Wind and solar generation may not be available, but the consumer is still going to need power. In this case, a temporary grid connection would benefit the consumer. This can be as simple as switching on a switch to connect to the grid or the grid connection could act as another source with another percent power variable. In both cases, there will be back up power just in case the solar and wind generation sources can not provide enough power.

Secondly, a battery system can help cut down on the amount of times the consumer needs to use the emergency grid connection. This in turns allows the consumer to go completely off the grid. A battery management system can help in two ways, store unused energy as well as provide power if needed. With this in mind, a bi-directional power flow control system needed to be implemented. The battery control system would have to accept power into the system if the load does not need it. It will also have to be able to communicate with the load to see if it needs power, check if it has energy stored, and then be able to provide power to the load. All this combined could take multiple designs and iterations to work properly. With the addition of a grid connection and/or a battery control system, the whole proposed microgrid design might need to be adjusted.

In addition to the grid connection and the battery control system, other future work could enhance the system. The first future addition that could be done to this design is implementing a real time economic pricing system. The economic system added to this microgrid could act as the real power grid. Independent system operators (ISO) constantly receive bids from generation sources. Each generation source must track how much money it will cost to start up production for the day and then send a bid into the ISO. The ISO receives bids from all types of generation sources and must pick the cheapest and the most reliable. The ISO does not receive bids from renewable sources because they are always trying to produce energy and it does not produce as much energy production as natural gas plants nor does it have a high startup cost. This economic system would be added if a high start up cost generation source should be added as an input to the microgrid.

The next future work that can be added to the microgrid is a real time weather tracking device. Although weather tracking is not that accurate, it will be beneficial to get the optimal amount of output power from each generation source. This tracking device could help determine the desired power percentages in the system design. If the tracking device senses a clear sunny day with no wind, the system would then change for the solar panel to output most of the power to the load. If the tracking device can read weather in real time, it can quickly switch the desired power percentages. If it was a clear sunny day and then quickly changed to a rainy windy day, the device could sense this and then change for the wind turbine to output most of the power to the load.

Working on this project was a great opportunity to understand how the larger grid works. Knowing how the power grid works is actually very beneficial for all. Knowing how power is produced, transported, regulated and then distributed can help others transform the power grid to be more efficient and use cleaner form of energy. Many forms of new research are looking into power generation and storage, but not enough research is going into how these forms of generation are getting sent to customers. There is a need for a new grid structure and microgrids can lead the way. If microgrids are never used on a larger scale, they can still be used just as efficiently on a smaller scale. Using a microgrid in a backyard can lead to a shift of off grid housing with a more efficient and cleaner use of energy.

REFERENCES

[1] Singh, Rajendra, and Krishana Shenai. “DC Microgrids and the Virtues of Local Electricity.” IEEE Spectrum: Technology, Engineering, and Science News, IEEE Spectrum, 6 Feb. 2014.

[2] Shah, K, et al. “Smart Efficient Solar DC Micro-Grid.” IEEE Journals & Magazine, Wiley-IEEE Press, 17 Sept. 2012.

[3] Nanda, Lipika, et al. “Smart Solar Tracking System for Optimal Power Generation.” IEEE International Conference, 9 Feb. 2017.

[4] Department of Energy. “Nanotechnology for Solar Energy Collection and Conversion.” NSTC Committee on Technology, Subcommittee on Nanoscale Science. July 2010.

[5] National Renewable Energy Laboratory. “Research Cell Efficiency Records.” Energy.gov, Sept. 2015, www.energy.gov/eere/solar/downloads/research-cell-efficiency-records.

[6] Rehman, Shafiqur, et al. “Horizontal Axis Wind Turbine Blade Design Methodologies for Efficiency Enhancement—A Review.” Energies, MDPI, vol. 11, no. 3, 27 Feb. 2018.

[7] Berrera, M., et al. “Experimental Test of Seven Widely-Adopted MPPT Algorithms.” 2009 IEEE Bucharest PowerTech, 28 June 2009.

[8] Perez, Filipe, et al. “DC Microgrid Voltage Stability by Dynamic Feedback Linearization.” 2018 IEEE International Conference on Industrial Technology (ICIT), 20 Feb. 2018.

[9] Ma, Thi, et al. “A Control Strategy of DC Building Microgrid Connected to the Neighborhood and AC Power Network.” Buildings, MDPI, vol. 7, no. 4, 20 May 2017.

[10] Kumar, Dinesh, et al. “DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects.” IEEE Access, vol. 5, 1 June 2017, pp. 12230–12256.

[11] Richmond, Peter "Optimization of Solar Power." Union College.

[12] Byrne, Thomas "Design and Efficiency Analysis of a Horizontal Wind Turbine." Union College.

[13] SFUptownMaker. "I2C." SparkFun, learn.sparkfun.com/tutorials/i2c/all.

[14] Beauregard, Brett. "PID Library." Arduino Playground, playground.arduino.cc/Code/PIDLibrary.

[15] Ada, Lady. "Adafruit INA219 Current Sensor Breakout." Adafruit, 26 Oct. 2012, learn.adafruit.com/adafruit-ina219-current-sensor-breakout.

[17] "Wire." Arduino, www.arduino.cc/en/reference/wire.

[18] "Filters." Arduino Playground, playground.arduino.cc/Code/Filters.

APPENDIX

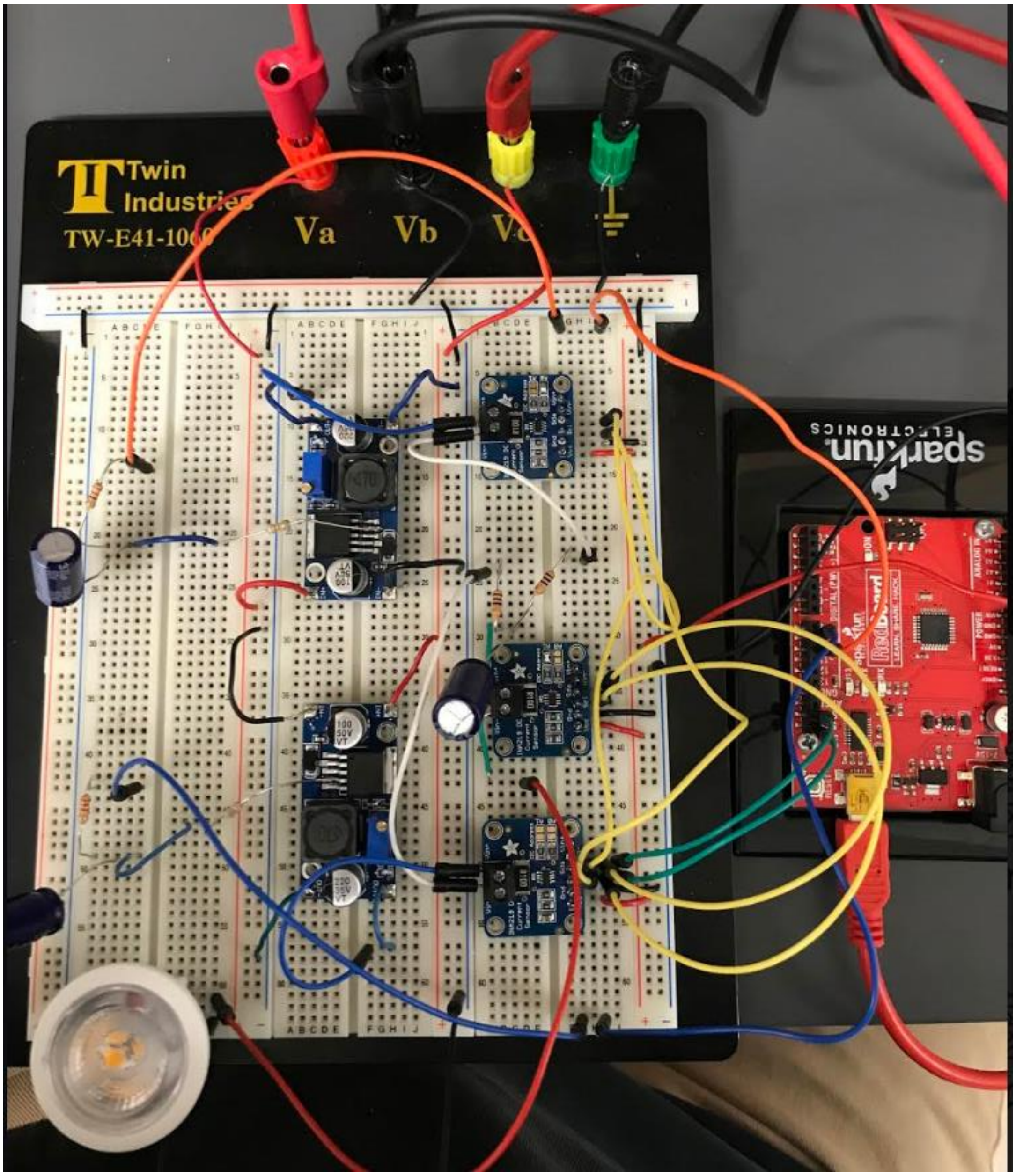

Figure 11: Fully built circuit.

```
#include <PID_v1.h>
#include <Wire.h>
#include <Adafruit_INA219.h>
#include <Filters.h>

Adafruit_INA219 ina219_S;
Adafruit_INA219 ina219_W(0X41);
Adafruit_INA219 ina219_L(0X44);
Adafruit_INA219 ina219_G(0X45);

int PWMSolar = 9;
int PWMWind = 10;
float BusVoltage, SolarDesired, WindDesired;
double SSetpoint, SInput, SOutput, WSetpoint, WInput, WOutput;
const int SampleTime = 1;
float RS = 10;
float RL;
float Freq = .1;
float S_busvoltage, S_power, S_current;
float W_busvoltage, W_power, W_current;
float L_busvoltage, L_power, L_current;

FilterOnePole lowpassFilter( LOWPASS, Freq);
FilterOnePole lowpassFilter1( LOWPASS, Freq);
FilterOnePole lowpassFilter2( LOWPASS, Freq);
PID SmyPID(&SInput, &SOutput, &SSetpoint, .01,1000,0,P_ON_M, REVERSE);
PID WmyPID(&WInput, &WOutput, &WSetpoint, .01,1000,0,P_ON_M, REVERSE);

void setup() {
  Serial.begin(115200);

  ina219_S.begin();
  ina219_S.setCalibration_16V_400mA();
  ina219_W.begin();
  ina219_W.setCalibration_16V_400mA();
  ina219_L.begin();
  ina219_L.setCalibration_16V_400mA();

  BusVoltage = 10;
  SolarDesired = .8;
  WindDesired = .2;

  SmyPID.SetMode(AUTOMATIC);
  SmyPID.SetSampleTime(SampleTime);
  WmyPID.SetMode(AUTOMATIC);
  WmyPID.SetSampleTime(SampleTime);
}

void loop() {

  S_busvoltage = ina219_S.getBusVoltage_V();
  S_current = ina219_S.getCurrent_mA();
  S_power = ina219_S.getPower_mW() ;

  W_busvoltage = ina219_W.getBusVoltage_V();
```

```
W_current = ina219_W.getCurrent_mA();
W_power = ina219_W.getPower_mW() ;


L_busvoltage = ina219_L.getBusVoltage_V();
L_current = lowpassFilter.output();
L_power = ina219_L.getPower_mW();

RL = L_busvoltage / (L_current/1000);

SSetpoint = BusVoltage + (BusVoltage * SolarDesired * RS/RL);
WSetpoint = BusVoltage + (BusVoltage * WindDesired * RS/RL);

SInput = S_busvoltage ;
SmyPID.Compute();
analogWrite(PWMSolar,SOutput);
WInput = W_busvoltage;
WmyPID.Compute();
analogWrite(PWMWind,WOutput);
```

Figure 12: Full code used to create working DC Microgrid.