Solar Powered Three-Phase Motor

Submitted To

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EXECUTIVE SUMMARY

This paper describes the work of our team on Dr. Baldick's "Solar Powered Three Phase Motor" Honors project. The goal of our project was to develop a system capable of receiving DC power from a solar panel and producing a three-phase AC output. Additional criteria for our project includes independent operation from an electric grid and the ability to drive a variable frequency motor under various solar levels without stalling. As the project is off-grid, the system also has to instantaneously use any power produced by the solar panels since there is no option for energy storage. Real world applications of our project include running air conditioning units or driving water pumps in rural areas where grid access is not available or cheap.

Our project was a continuation of four previous Senior Design teams' work. Therefore, our first task was to evaluate their work and confirm if any working subsystems could be salvaged or improved. By beginning work in the first semester, the team came to an early conclusion that while the motor and solar panels would be usable, the circuitry and code was not in working condition. Thus began the planning and implementation phase of our design.

Our design includes a DC-DC boost converter that boosts the solar voltage received to an appropriate level for the AC motor (nominal operating point of 230 V (AC)). Then, a three-phase inverter transforms this DC power into a three-phase AC waveform. This is then fed to the motor which acts as a water pump. To control the power electronics, our microcontroller adjusts the boost ratio of the DC-DC converter and the frequency of the three-phase inverter. By controlling the voltage and frequency outputs, we were able to implement open loop V/*f* control for our motor.

Upon confirming our design goals, the team began implementation of our system by first dividing the project into multiple subsystems. Each team member was assigned to a subsystem they would be responsible for. The idea was to work on each subsystem in parallel, and then test them independently before interfacing them with one another. Because the solar panels and motor came from previous teams, we developed a boost converter, bought a three-phase inverter, and developed the software control algorithms. Once this was complete, the team began assembling a test bench and a prototype for demonstration. Descriptions of each subsystem are located in section 4.0 while testing for each subsystem is detailed in section 5.0.

Additionally, this report relays our team's evaluation on the time, cost, safety, and ethical constraints of our project. Because this project required so many working subsystems, the team began work on the technical part of the project in the first semester of Senior Design. All expenditures were kept low to allow the project to eventually be released as an open source solution to off-grid power. However, we did find it necessary to purchase expensive components with specific values and ratings in order to fulfill the design requirements set by Dr. Baldick. Finally, our report is tied together with our team's recommendations for other teams that would try to pursue this project. Specifically, we cover some of the challenges our team faced and how we overcame them, as well as documentation explaining our shortcomings.

1.0 INTRODUCTION

For rural and underserved communities, in addition to other scenarios where access to grid power is limited, there exists a need for self-sufficient systems to deliver energy for a variety of applications. As the scientific community continues to develop renewable technology, the price of solar cells has begun to decline. This has made solar energy an increasingly attractive source of power, especially for small operations. The form of this energy, at the time of generation, is direct current (DC). In contrast, many household appliances and motors use alternating current (AC) for both historical and practical reasons. Engineering a system capable of powering a device constrains consumers to purchasing a fully customized system for their specific application. This, in turn, eliminates the benefits which can be obtained from high-volume products in terms of lower system cost. The design solution presented within this document aims to reduce the cost seen by the end user by introducing a degree of modularity into solar installations. Our proposed design is for a system which extracts power from an arbitrary set of solar panels and delivers it to an arbitrary three-phase load. By allowing for a particular set of components within the system to be determined at the time of purchase, we intend to make this system suit a broad class of applications. A key goal for the system is that it should be relatively inexpensive with respect to the solar cells and devices which a typical deployment might use.

As the first semester of the project progressed, our team defined and evaluated the requirements for each of the subsystems to properly function. The set of solar panels used in our final design application were constructed by a team working on this project prior to our own involvement. By recording measurements from the solar panels, we could characterize their behavior. This knowledge, in concert with our understanding of the motor operation, allowed us to properly choose the flexible components needed for our power delivery system. Once the submodule characteristics were specified, we began work on their design. For hardware submodules, we attempted to optimize the debugging process by simulating their performance using circuit analysis software. The software submodules were tested using an integrated development environment (IDE), and an oscilloscope to ensure the signal ports behaved as expected. At the beginning of the second semester we reflected upon the progress up to that point and used this insight as an opportunity to gauge how to proceed with our design. We adjusted the focus of our efforts away from the details of complex submodules, and towards the actions required to construct a functional design. This new direction ultimately led us to buy some of the subcomponents crucial for testing and adjusting the rest of the system.

The modular design of our system allowed for our team to test and debug most of the subsystems simultaneously. Testing the submodules independently allowed for our team to verify their own functionalities. Verification was particularly critical to our design since the power flowing through the system was relatively high, and poor performance from one submodule had the potential to damage the others. The metrics used to define performance was dependent upon the intended submodule function, but we consistently ensured that the voltage and current capabilities were sufficiently above the requirement. Wherever possible, our team then proceeded to test submodules together as subsystems. Such a method for debugging at an increasingly high level enabled us to narrow down the sources of error before adding complexity to the subsystem under test. Towards the end of the second semester of the project, the full system was tested outdoors with the solar panels. By partially shading the solar panels, we could verify whether the motor responded as expected with respect to the level of incident insolation.

The primary factors which guided our decision throughout the project were the time to completion, cost of the system, and the safety guaranteed by the final implementation. The most constraining factor within the context of our design framework was the limited amount of time which we had to both design and fully integrate the system. As a power system, the expectation is that it should be safe for the users. In addition to this, testing had to be carried out cautiously to prevent injury within our own team. The parallel development of our system and early testing was, therefore, crucial for meeting the requirements set by ourselves and Dr. Baldick. Another constraint was the capital investment which went into the system. As with any engineering problem, we face a trade-off between performance and cost. Our decisions within this area were based on the application of our project. Since the power supplied from the panels was to be used instantaneously and the cost of the system had to be affordable to the end user, several of our choices leaned towards capital savings. This was not the case, however, when the cost was weighed against the safety system components. To ensure that an end user, one who may not be familiar with power electronics, would be able to safely operate the system, we selected components which had the capacity to operate well beyond the expected conditions.

While we completed many of the primary goals of the project, there are several areas upon which teams similar to our own as well as future senior design teams could improve upon this system. These recommendations include both general insights we have gained from our own experience with the project as well as specific points to improve upon within our system. Using the information presented in within this paper, as well the recommendations we present, it is our hope that this project will eventually find its way to serving the needs of individuals who need such a system.

2.0 DESIGN PROBLEM

The problem our team had aimed to address is the lack of power in areas without access to a power grid. Within rural and underserved communities, as well as disaster relief deployments, access to a power grid is often too costly or impractical. However, in the modern world, basic needs such as plumbing, lighting and air conditioning require electric power. Small scale power generation schemes are a potential solution to this discrepancy, and, in the interest of self-sufficiency, the collection of solar energy is an attractive alternative to thermal sources. While solar power generation exists today, these systems present a unique set of challenges when implemented on a small scale. A high initial fixed cost, associated with the reconfiguration required for a particular deployment, serves as a major deterrent to the installation of such systems. This is partly due to the absence of infrastructure in existence for off grid power sources, which supply power in the form of direct current. In general, this must be converted into alternating current before it can be consumed by the end user.

The cost constraints and practical requirements of small scale deployments has led to an interest in configurations which reduce the cost of making drastic changes to the system in order to meet the needs of individual consumers. Such a design would have to accept DC power and convert it to three-phase AC power. Therefore, the objective of our senior design project was to implement a system which draws power from an arbitrary set of solar panels and delivers it as efficiently as possible to a three-phase load.

3.0 DESIGN SOLUTION

The goal of our project is to implement a system that converts DC power from a solar panel to drive a variable-frequency three-phase load, such as a motor, with AC power. The system implementation is unique in that there will be no energy storage or connection to a grid. Therefore, all the power needed for the motor must be provided instantaneously by the solar panels. The team has integrated five subsystems required for this project: an array of four solar panels, a DC-DC boost converter, a three-phase inverter, a microcontroller, and an AC three-phase motor.

An array of four solar panels in series produces DC power when exposed to sunlight. At the output of the system, this power is transformed into mechanical energy by a motor. The DC voltage that the solar panel supplies is not at the appropriate level to feed to the motor, so a boost converter is essential to step up the voltage to a level that can operate the motor. A three-phase inverter converts the DC power to the AC power required by the motor. Both the DC-DC converter and the three-phase inverter are controlled by a microcontroller to ensure that the behavior of these systems is within the constraints of the motor and allows for control of the VFD (variable frequency drive). Below is a block diagram that shows the integration of the complete system and the electrical connections required.

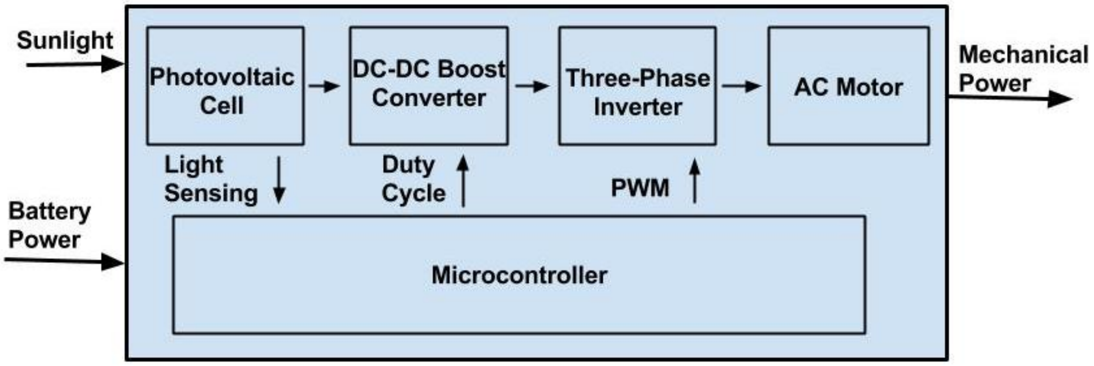

Figure 1. High-Level Hardware Block Diagram

The microcontroller functionality can be broken down into distinct software elements. For control of the DC-DC converter, a square wave with a specific duty cycle will control a metaloxide semiconductor field-effect transistor (MOSFET) that acts as a voltage control switch to vary the output voltage. A pulse width modulation (PWM) square wave is required for the three-phase inverter to convert DC voltage into an AC output. The microcontroller varies the frequency and voltage of the motor based on the incident sunlight of the PV panels measured with a photoresistor that is attached to the solar panels. Below is the depiction of our microcontroller and its subsystems.

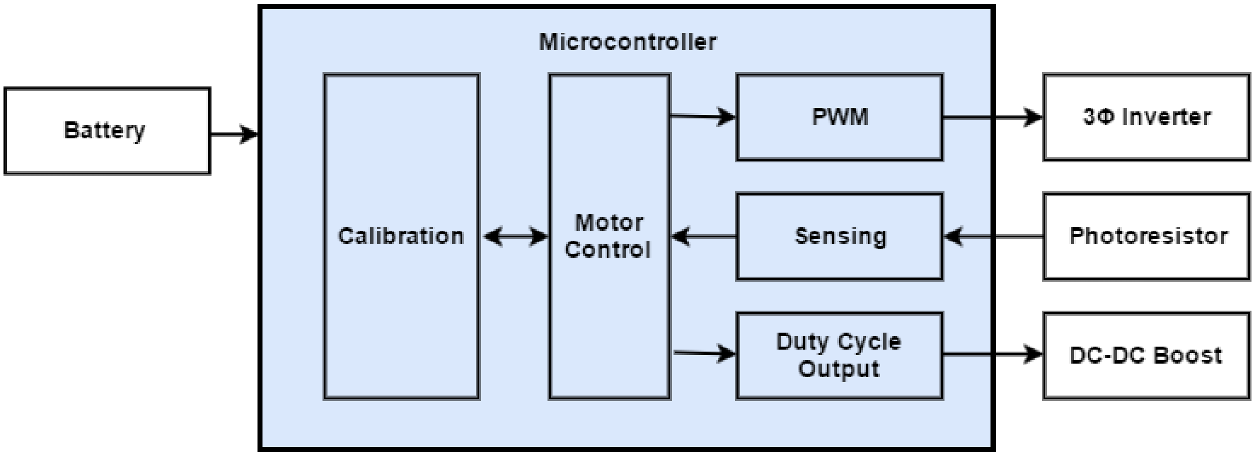

Figure 2. Software Block Diagram for Microcontroller Function

4.0 DESIGN IMPLEMENTATION

The sections below describe how we chose each subsystem in our design on a fundamental level, including the required inputs, outputs, and control specifications.

4.1 Solar Panels

In the interest of operating independently of a power grid, we use solar panels to generate a DC voltage and current to power the system. The panels we implemented were constructed by a previous team and were what we integrated into our final prototype. The four solar panels take solar energy and output a total of 89V (DC) at open circuit and 3.5A (DC) at short circuit. We built mounts for each panel that angled them at 30 degrees, the optimal angle for maximum solar potential (insolation) based on Austin’s latitude.

4.2 DC-DC Converter

The DC-DC converter is intended to either buck (decrease) or boost (increase) the input voltage as the available solar power varies. The output voltage is linearly proportional to the duty cycle observed in the periodic signal, provided by the microcontroller, at the gate of the MOSFETs. The LM5022MM/NOPB is a low side non-isolated single-ended primary-inductor converter regulator that has ten pins for feedback control, deadtime control, current amplification, and current sensing [1]. This chip thus served as a gate driver for our MOSFET. Combined with the microcontroller, we were able to control the duty cycle of the MOSFET and thus the boost ratio. This module is capable of handling an input voltages between 6 and 95V DC.

We first intended to use a single-ended primary-inductor converter (SEPIC), which would be able to increase and decrease the DC voltage relative to the solar panel output. The SEPIC can increase or decrease the voltage depending on the duty cycle sent to its MOSFET. However, it has more components than other converters, making it much more complex to build and debug. In addition, the three-phase inverter (see Section 4.3) can step down the voltage, and a DC-DC converter able to simply step up the voltage would be enough. Therefore, we chose the boost converter.

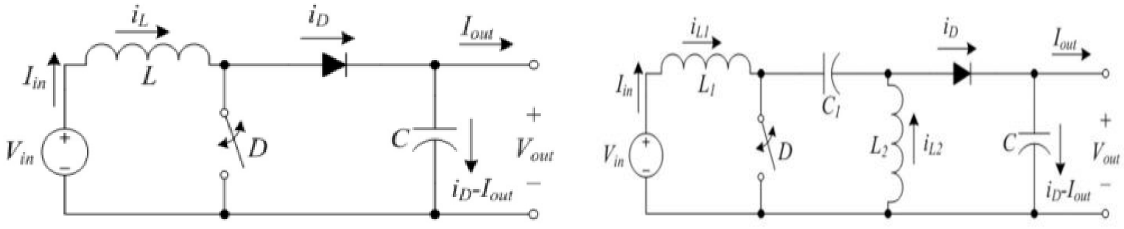

Figure 3: Circuitry Comparison between Boost Converter (left) and SEPIC (right) [2][3]

An obstacle that we had to address in this subsystem was grounding. The MOSFET switching requires a certain level of voltage between its gate and source. This voltage in our circuit is the difference between power ground, and the gate signal provided by our gate driver. However, if the gate signal was referenced to a ground with a different voltage than the power ground, the MOSFET could be turned on or off indefinitely. Because of this, we tied both power and gate driver grounds together.

4.3 Three-Phase Inverter

The three-phase inverter serves the function of transforming a dc input source to a sinusoidal ac power to the motor. We needed to be able to modify the frequency of the inverter output as determined by the microcontroller. The inverting system consists of a PWM source, high power transistors (either MOSFETs or insulated gate bipolar transistors - IGBTs), an integrated circuit driver to modulate the gates of the transistors, and passive components (e.g. resistors, capacitors, and inductors). In our application, a microcontroller outputs the PWM signal to the driver integrated circuit (IC). The driver generates pairs of outputs linearly proportional to the received PWM signal from the microcontroller, which switch the MOSFETs. Generated at the output is the original PWM curve, but boosted to the voltage delivered by the DC-DC converter. Additionally, the three-phase inverter can buck (reduce) the voltage delivered to the system by adjustments in the PWM algorithm.

In the interest of time and due to complications in our own design for a three-phase inverter, we instead decided to buy a fully integrated three-phase inverter PCB that included all parts already soldered on, excluding one capacitor. The inputs to this PCB include the PWM signals from the microcontroller, the operating voltage from the DC-DC boost converter, and 15V DC for powering the driver. The circuit then outputs the three phases of the PWM at the boosted voltage, which are smoothed by the motor’s inductance into sine waves that allow the motor to run.

4.4 Sensing

Sensing of power involves taking measurements at various locations of our circuit. There are four types of power sensing: DC voltage, DC current, AC voltage, and AC current. These values allow us to calculate the input power from our solar panel as well as the output power to our motor. Initially, we planned to implement these types of sensing, but we were not successful due to low resolution of the sensors that we used. When we tried to integrate the sensing into our system, we could not sense current changes that were small enough to be effective in our system.

Because we were unable to implement the current sensing for the prototype, we instead used a photoresistor to estimate the intensity of sunlight incident on the solar panels. This did not allow us to measure the input and output power, and as such did not allow accurate power consumption measurements. It did, however, allow us to control the motor frequency and voltage based on the incident sunlight.

4.5 Motor (Water Pump)

Our system works for any three-phase load, but we have chosen to develop the system with a water pump motor. Our motor, a Flair SP-8130 Coolant pump that was passed down to us from a previous design team, is designed to operate at 230V, 0.43A and 60Hz. However, due to the variation in solar power, we intend to adjust the voltage fed to the motor to maximize the mechanical power. To start the motor without consuming a large current, the voltage and the electrical frequency must be ramped up from zero to the desired value in a finite time interval, called a “soft start.” Additionally, if the motor is set to operate at a particular power level, but the power changes due to fluctuations in the sunlight, the motor is at risk of stalling. Stalling occurs when a mechanical load prevents the rotor from turning. If the motor attempts to draw more power than the amount available at it terminals, the motor will stall and heat up. Therefore, we will need to implement a motor control algorithm capable of changing frequency slowly enough prevent the motor from stalling. As can be seen in Equation 1 below, when the water pump is in steady state, the electric torque is equal to the mechanical torque.

$$m_{elec} - m_{mec} = J\frac{dw_{mec}}{dt} \tag{1}$$

Where Melec is the electrical torque applied by the motor, Mmec is the mechanical torque applied by the load, J is the rotational inertia of the whole system, and Wmec is the mechanical speed. In order to increase the mechanical frequency by DWmec over a finite time interval, the electric torque must also increase. The increase in electric torque is inversely proportional to the time interval, and therefore the time interval must be selected such that the power drawn into the motor does not exceed the power the system can deliver.

4.6 Software

The software that controls the system runs on a TI-TM4C123GXL microcontroller, which we chose because we are familiar with it from the embedded systems class. As seen in figure 2, the primary modules are the PWM, duty cycle output, photoresistor sensing, motor control, and calibration. The main logic of the system exists in the motor control algorithm. The value sensed from the photoresistor determines the operating point of the system. The motor control algorithm then uses the other modules to operate the system at the desired operating point.

We chose V/f control for our motor control algorithm because of its simplicity and indifference to motor specifications. The algorithm maintains a ratio between the voltage and frequency of the motor according to the operating point specified by the photoresistor. The calibration data is simply hard-coded to the specifications of our motor. The algorithm controls the rest of the system by outputting the desired frequency in the PWM module and the desired voltage to the boost converter as a duty cycle output. If the boost converter is unable to lower the output voltage enough to reach our desired operating point, the PWM module can also reduce the output voltage from the three-phase inverter by modulating the amplitude of the PWM signal.

5.0 SUBSYSTEM TESTING AND EVALUATION

We began test and evaluation for the system by testing each submodule individually, followed by testing with adjacent submodules. This section details the individual testing for the solar panels, DC-DC boost converter, three-phase inverter, motor, and microcontroller, and finally, the full system.

5.1 Solar Panels

We tested the solar panels for their I-V and P-V relationships, as well as the open circuit voltage and short circuit current. These values were important for designing the voltage and current ratings for rest of the system. To begin, we soldered the by-pass diodes onto the leads of the solar panels and configured the panels to be in-series. The nominal voltage was 88V open circuit, and the nominal current was 3.5A short circuit. Below, figures 4 and 5 show the I-V and P-V curves of 1 panel.

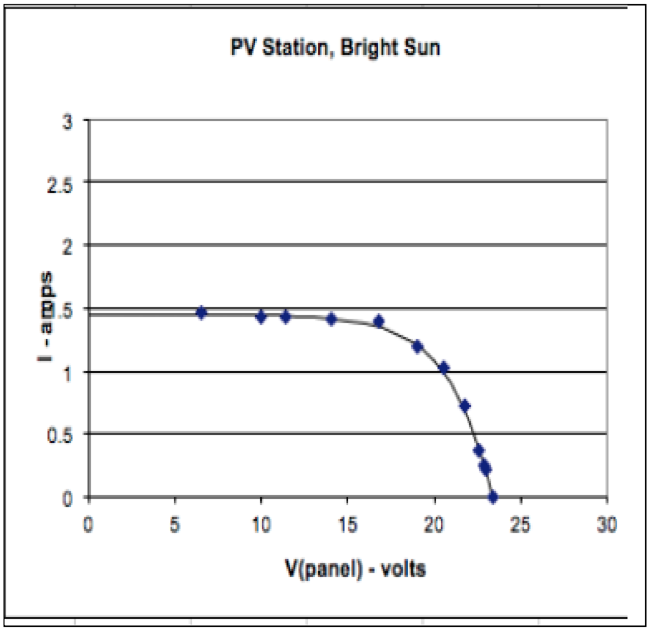

Figure 4. Current to Voltage Curve of One Solar Panel

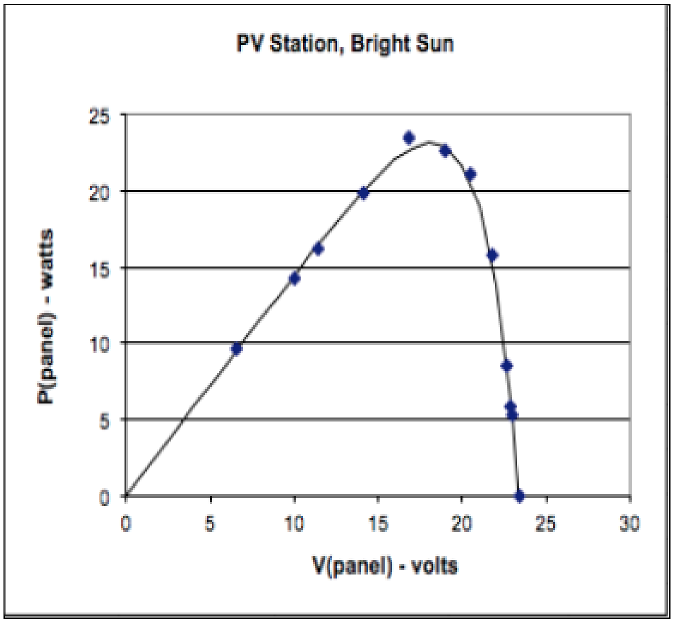

Figure 5. Power to Voltage Curve of One Solar Panel

In comparison to this panel, which had a open circuit voltage of 24V, two of the solar panels showed lower voltage levels around 22V. Because the solar panels are constrained by their weakest link, it would have been optimal to have similar capacity rated panels.

A potential problem may be the individual construction of the solar cells into an array. The arrays were made 6 years ago by previous teams and since the plastic screen that houses them are adhered to the frame, we cannot inspect them without damaging the containment unit. Since they were not rigorously tested at the time for functionality and hazardous conditions such as spot shading, our solar cells may get hotter than their intended operation point. We recommend that during operation, we don’t allow edge case conditions to occur, such as partial shading of the solar panel, or overheating of the cells. Our demo focuses on proof of concept of the entire system and using the solar panels with optimal functionality is of secondary importance.

During the demo, a gale pushed one of the solar panels and ripped out the leads from a solar cell, breaking it beyond repair. With electrical tape and some wires, we by-passed the broken array element and continued for our system to output 79V (DC). We cannot conclusively say that we wired the electrical leads appropriately as our boost converter soon after started malfunctioning leading to the breaking of the electrolytic capacitor, MOSFET, and diode.

5.2 DC-DC Boost Converter

The DC-DC converter boosts the solar panels output voltage to a level that can be used by the motor. A gate driver circuit is required to drive the MOSFET switching operations. Our goal was to reach a boosting ratio that ranged between 1:1 and 4:1. For the initial testing of the boost converter and the gate driver circuit, the gate driver successfully amplified a pulse width modulated (PWM) signal from 3.3V to 12V. We then attached the driver circuit to feed into the MOSFET gate signal of the boost converter. The boost converter did not produce the boost that we expected. For an input of 23V and duty cycle of 50%, our output voltage was 40V. The expected voltage output of the boost converter was around 45V accounting for the forward voltage drop of the diode and by using the standard formula for a boost converter:

$$V_{out} = V_{in} / (1-D) \tag{2}$$

We also noticed the boosting ratio was saturating at 2.5:1 when going above 50% duty cycle (D > 0.5). To successfully run the motor at its maximum power level we had to overcome this issue and achieve a boosting ratio of 4:1.

After driving the circuit between 10% and 80% duty cycle while probing the drain to source and inductor voltage in the oscilloscope, we realized some improvements needed to be made. The core issue was that the circuit was being driven to discontinuous mode at high voltage conversion ratios. This occurs when the inductor current waveform falls below zero. One thing that wasn’t considered in the initial design was the DC amperage capacity rating for our inductor, which we later increased. Initially, we thought that the inductance value for our input and control was too low, but after an experiment of connecting and combining several inductors in series, we realized that was not why the circuit was going into discontinuous mode. For the given input voltage and the time that the MOSFET remained closed, we found that the magnetic dipoles in the inductor saturated before allowing the inductor to discharge into the circuit for its DC amperage capacity. We decided to use the inductor with the highest current ratio and cast aside the previous design that constrained the inductors in series to the minimum current rating. Furthermore, our output capacitor had to follow the change of replacing our inductor, because the voltage we were boosting now to was 290V (DC) with an input of 80V (DC). Our initial capacitor used only had a 200V (DC) rating which exceeded the output value and would have broken the dielectric in the electrolytic capacitor, incurring in danger to surrounding people. As for the raise in capacitance, since the voltage increased from 180Vdc to 290V (DC), the capacitance needed to be higher to reduce the magnitude in voltage ripple. The results are shown in below in figure 6.

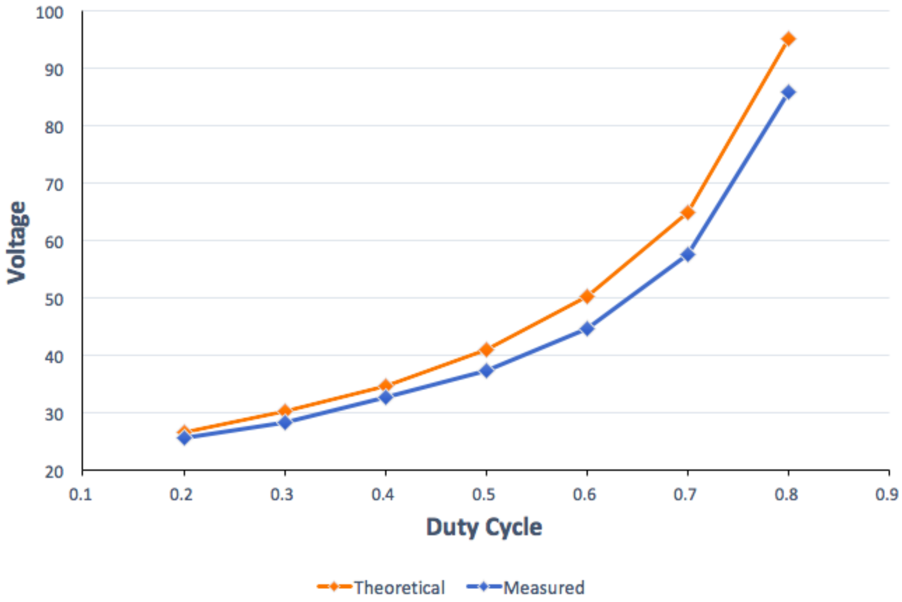

Figure 6. DC-DC Boost Operation Voltage vs. Duty Cycle

5.3 Three-Phase Inverter

Testing for the three-phase inverter first involved the team trying to make designs for our own three-phase inverter to work. After failing to get the original three-phase inverter design to work properly, we purchased an evaluation inverter (the STMicroelectronics STEVAL-IPM10F) that was fully completed and provides the exact functionality we need for all three phases of AC output. To test the board, we first ensured that the microcontroller PWM was functioning correctly for all three phases. We attached a 68uF capacitor at the DC input of the PCB to maintain stability at the maximum output voltage. We then tested the board using all three phases of the PWM from the microcontroller, with an input voltage of 20VDC from a voltage generator in the lab. At first, we had trouble establishing the necessary connections from the microcontroller to the evaluation board, but after careful examination of the data sheet, we successfully generated the output from the three-phase inverter at our frequency of choice. The output was, after low-pass filtering (a reasonable assumption because of the inductance of the motor), three sine waves at the frequency specified by the PWM output of the microcontroller (20Hz and 30Hz). To complete the testing of the three-phase inverter, we connected the three output phases to the motor and ensured that the motor spun, both dry and in water. The motor pumped water through a hose to a height of 2ft at 20 Hz and an input voltage of 70VDC. This ensured the proper functionality of the three-phase inverter when provided with the input DC voltage from the boost converter.

It is unclear why the original designs for the three-phase inverter did not work despite our efforts to debug, and we decided to order the completed board in the interest of time. This was a good decision because we then had a reliable subsystem and were able to work on integrating it into the rest of the system. We broke one three-phase inverter while testing the whole system with the motor and DC-DC boost converter, and had to use the backup PCB. To prevent the same problem from recurring, we ensured the correct connections with the pins on the microcontroller by documenting the pin connections for both the three-phase inverter and the required connections on the microcontroller. We ensured that the PCB was isolated from the motor, water, and other electronic subsystems to avoid short-circuiting any connections. We always purchased an extra three-phase inverter board to keep on-hand to avoid project delays.

5.4 Sensing

We tested the photoresistor used for sensing the level of solar insolation by connecting it to a voltage divider circuit with a potentiometer. With the full system in place, we calibrated the photoresistor by adjusting the potentiometer value until the maximum operating point was achieved under maximum lighting conditions, and shading the sensor resulted in a reduction of the operating point but not stalling.

5.5 Motor (Water Pump)

We aimed to make sure that the three-phase motor received from the manufacturer had no anomaly during its operation, that is, no discrepancies between the rated input voltage to output mechanical power. To test the motor, we need to input a three-phase AC voltage at the motor terminals and immerse the water pump, attached to the motor, into the water. The testing components we used were, apart from the motor, a diode bridge rectifier and an isolation transformer plugged into the wall to convert a single-phase AC waveform into a DC voltage. This is then used by the three-phase inverter to convert it to the three-phase AC voltage needed by the motor. On the other side of the motor, the mechanical system was formed by a hose and two water tanks intended to show the elevation of water from one height to another. The motor-water pump was mounted on top of the first tank, properly isolating the motor side from the water, and the hose came from the motor to the second tank.

A critical factor for this testing was safety, since we were pumping water near electrical conductors and power sources. In the electrical side of the test, the voltage was set below 70 V, in the output of the DBR and the current was not above 0.5 A. These values are the ratings for the DBR and the Motor respectively. On the mechanical side, the water tanks were correctly isolated from the electrical components, setting a safety distance of 5 feet.

Regarding the actual operation of the test, we set the voltage to 90V at the output of the DBR, the frequency to 20 Hz, and we changed the height of the second tank from 0 to 2 feet, to see the change in current and water flow. The results were measured from the output side of the DBR, DC current and voltage. From which we can calculate the power at the water pump side as follows:

$$P_{wp}^{m} = V_{dc} I_{dc} \eta_m \eta_{inv} \qquad (3)\ [4]$$

Efficiency of the motor and the inverter are given by their respective specifications [5][6]. The theoretical power consumed by the water pump is:

$$P_{wp}^{T} = \frac{Q * h * g * \rho}{\eta_{wp}} \qquad (4)\ [4]$$

This is the mechanical power consumed by the water pump. The efficiency, ηwp, of the water-pump is extrapolated from the manufacturer specifications [5]; gravity (g) and water density (ρ) are known constants. Therefore, for the experiment we had control over the water flow (Q) controlling the frequency, and the height, adjusting the second water tank. The results are compared in the following chart:

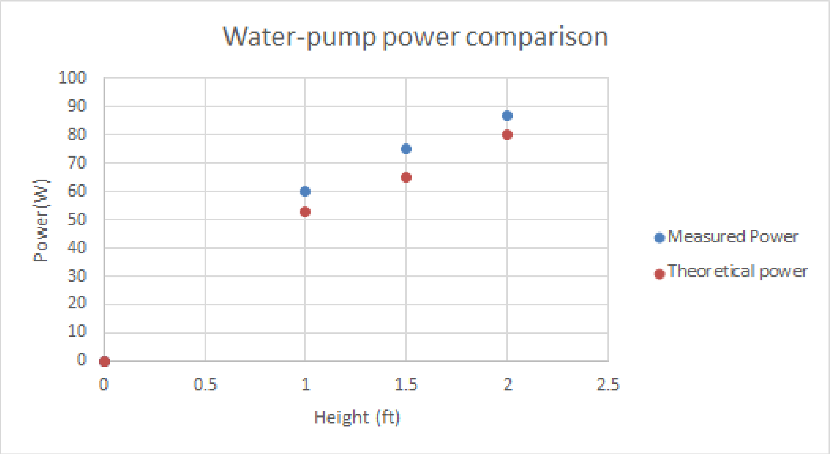

Figure 7. Measured Power and Theoretical Power Consumed by the Water Pump

We can see how there is a 10% error between measured and theoretical power. This is because we are using a fixed efficiency for the motor for the calculations. However, running at a different speed and voltage to what is rated we can expect it not to be this same value. A more accurate calculation could be made through the T-model of the motor [3]. However, the specifications of the motor are not enough to calculate all its parameters.

In conclusion, the motor provided the expected power and is a reliable component that proofed to work during the whole project. A recommendation for future groups would be to avoid letting the motor stay still after stalling because in this condition the motor acts as short circuit drawing a lot of current through its windings. Instead, the motor should be restarted immediately, manually if it was necessary.

5.6 Water housing

The water-housing test simply entailed checking watertight seal between tubes and water tank and no overflowing. For this purpose, we run the motor-water pump to check for any these problems. The result was positive and no further development was needed.

5.7 Software

The software portion of our project consists primarily of a motor control algorithm that uses PWM, converter duty cycle, and sensing modules to control the operation of the entire system. Each module was tested individually and in conjunction with the full system to verify correctness. The design we settled on has some drawbacks which are addressed in each section with suggestions for viable solutions.

5.7.1 *PWM*

The output characteristics of the PWM module can be tested using an oscilloscope. For the module to be correct, it must output three phases of positive and negative PWM at frequency *f* with at least 500 ns of dead-time at a switching frequency of 10 kHz. In addition, the amplitude modulation should not exceed 0.86 to avoid overmodulation. To test the module, we first confirm that the duty cycle has the proper switching frequency using the frequency measurement. We use the cursors to ensure that the dead-time between the positive and negative duty cycles is at least the minimum required by the three-phase inverter. We attempt to over modulate the output and confirm that the amplitude of the output does not increase. Using the filtering feature, we confirm that each phase is oscillating at the desired frequency *f*. Finally, we probe each combination of two filtered outputs simultaneously to confirm that each phase is offset by 120 degrees from the others. We used an oscilloscope in the lab to verify the above conditions and the PWM module satisfies all of them. It is complete and works as expected.

5.7.2 *Converter Duty Cycle*

The duty cycle output can be tested similarly to the PWM module using an oscilloscope. For it to be correct, the module must simply output a duty cycle *d* at a 30 kHz switching frequency. The software should limit *d* to be between 0.1 and 0.85 according to the safe operating range of the DC-DC converter. To test the module, we measure the frequency and confirm that it is correct for the DC-DC converter. Then, we verify that the duty cycle *d* is indeed output by the module. Finally, we attempt to exceed the safe range of duty cycles and confirm that the software does not allow it. We used an oscilloscope in the lab to verify the above conditions and the duty cycle module satisfies all of them. It is complete and works as expected.

5.7.3 *Motor Control*

The motor control algorithm can be tested using an oscilloscope and voltage source. We vary the input sensing from the photoresistor using the voltage source and observe the output PWM frequency, amplitude, and converter duty cycle on the oscilloscope. The output PWM frequency and converter duty cycle must correspond to the motor operating point given the level of solar insolation detected by the photoresistor. For instance, when the input sensing reads its maximum value, the output PWM frequency must be the nominal frequency of the motor and the converter duty cycle must yield the nominal voltage of the motor after being converted to AC by the three-phase inverter. The other operating points are dictated by the motor power vs. voltage and voltage vs. frequency relationships. If the boost converter is unable to reach a low enough voltage for the appropriate operating point, the output PWM amplitude should decrease to yield the correct voltage at the output of the three-phase inverter. Likewise, if the boost converter is unable to reach a high enough voltage for the appropriate operating point, the output PWM frequency must not increase past the frequency corresponding to the highest voltage attainable. We tested the motor control algorithm in the lab and found that it satisfied all requirements. With the full system connected, the algorithm behaves as expected.

5.8 Full System

After testing each subsystem, we constructed a test bench which we used to mount the modules for ease of setup and use. A diagram depicting the layout of the test bench can be found in figure 8 below.

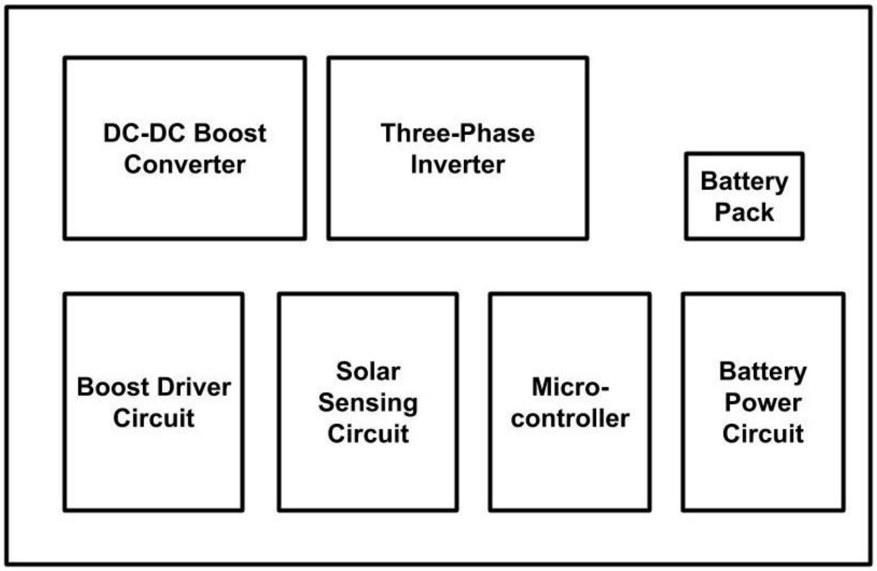

Figure 8. Test Bench Diagram

We tested the full system indoors using the DC power sources in the lab and successfully pumped water to a height of 7 ft. We then took the entire system outside and successfully pumped water to a height of 5 ft. under maximal solar insolation. We partially shaded one of the panels with the photoresistor and observed that the output frequency of the motor decreased, but the motor did not stall. Upon unshading the panel and sensor, the motor resumed operation at full speed. We considered this a successful test of the complete system.

6.0 TIME AND COST CONSIDERATIONS

Time was the most limiting constraint for our project, yet we also had to remain conscious of cost because of the desired accessibility of the design. Time spent ordering and awaiting new parts that were properly rated for our designs halted progress during both the design of the three-phase inverter and the boost converter. As we designed and redesigned portions of the subsystems, we required new parts that were rated for specific voltages based on the power provided by the solar panels, the desired boost level, and the operating point of the motor. We changed the designs for multiple systems and had to wait for new parts, which stalled the progress of the whole project. For example, we could not test the motor without having a functional three-phase inverter. Because our system was based on so many essential subsystems, waiting for any one part pushed back the progress of the entire system.

We wanted this project to be accessible and affordable to anyone who has a need for off-grid power, so we ordered parts that simplified the implementation and lowered the cost. This was a challenge because we needed the parts to be rated for high voltage, current, and power levels, which generally cost more. Overall, the total prototype, excluding the motor and the solar panels, cost us about $200. We did, however, consider safety a priority over cost, and bought parts that were more expensive, though still affordable, if they were more appropriately rated for a specific subsystem. For example, we decided to buy a fully functional three-phase inverter with all three phases integrated into one chip, which significantly sped up the process of full integration, and lowered the cost compared to buying the individual components. This allowed us to put more time and effort into designing the boost converter and other subsystems. In general, we prioritized safety over cost concerns, as described in the next section.

7.0 SAFETY AND ETHICAL ASPECTS OF DESIGN

As our project is meant to bring power to off-grid and underserved locations, we wanted the design to be as safe and sustainable as possible. Taking this into account, we chose components with voltage and current ratings that were about twice the expected values. For example, our DC-DC boost converter required a capacitor that needed to handle 330V, and we ordered capacitors rated for 600V. To add to the safety features, we constructed a test bench on which to stabilize each component of the system. Our optimal layout for the test bench setup was one that required the shortest wire lengths and minimized crossing connections. This feature sped up our testing setup and kept our work area organized, decreasing the possibility of misconnections. We also included a cover to keep any water from falling on the electrical components, as well as any people from touching the components.

In addition, we want to emphasize the potential for sustainability with our project, especially that in underserved locations. As the system is off-grid and would, with more development, be completely self-sufficient, it has major implications in the future of power production using solar power. This project could be used to pump water into a water tower, irrigate a field, or provide air conditioning in locations where such luxuries would be unattainable. Our hope is for this project, in the future, to be open-source, affordable, and safe for anyone to construct if desired. Considering this, we documented everything we did so that the next group to work on this project will have the full picture of our progress, as well as how best to proceed from here to implement maximum power point tracking and therefore maximize the efficiency of the system. We worked to make this project safe, easy to use, and self-sufficient for anyone who might need to use three-phase power without a grid.

8.0 RECOMMENDATIONS

There are several points of failure that are expected and inherent to the design we implemented. The following problems with our motor control algorithm, listed in general order of importance, can be fixed to improve system performance. First, rather than using a photoresistor as a first-order approximation for the power available from the solar panels, DC sensing should directly detect the voltage of the solar panels and the current drawn by the system. This would also allow for a Perturb and Observe implementation of MPPT. During our research phase, we examined shunt monitors, isolation amplifiers, and hall effect sensors to measure current. Hall effect sensors combined with a large gain op-amp proved to be the most promising, but the other approaches may work as well. Second, a time constant should be added to prevent the control algorithm from varying the speed of the motor too quickly and possibly causing a stall. Third, a startup procedure should be implemented so that the motor does not need to be started by hand. Such a procedure would involve operating at a fixed startup frequency and slowly increasing voltage so that the motor will start without such a high inrush current, which the solar panels are unable to provide. Fourth, the algorithm should detect stall conditions using sensing and shut down system output to prevent high current from running through the motor. The algorithm should then wait for an amount of time before attempting to restart the system using the startup procedure. Fifth, rather than using a simple quadratic approximation, the algorithm should use a measured power vs. voltage curve for the motor. This will ensure that the motor is operating at the most efficient operating point given the available power. Sixth, the control algorithm should sense the output DC voltage of the boost converter to close the control loop for the converter. Seventh, and finally, with AC power sensing, the algorithm could produce quantitative results for the efficiency of the system.

Additionally, an inductor, capacitor, diode, and MOSFET must be replaced in the boost converter circuit, as these were destroyed during our Open House demo. The entire circuit could also be compacted into a PCB to allow for a more marketable and presentable device. Once current sensing and MPPT are complete, the stretch goals for our project could then be attempted. A user interface could be implemented with the system so that the system can take in solar and motor specs and run the system without the user having to change any of the code. Lastly, DC voltage regulators could be included to provide power to the gate driver circuit, three-phase inverter, and microcontroller directly from the solar panel, eliminating the need for batteries.

To a similar project group that would attempt to do our same project, we have many recommendations for areas in which we struggled or failed. Firstly, we greatly recommend that teams start technical work in the first semester. Upon Dr. Baldick's request, we did so this semester and found that the research and technical understanding work we did first semester allowed us to realize that we would need to build our own implementation of the circuit. We also suggest incorporating some sort of overcurrent protection. In our rush to finish our design, we overlooked the inclusion of fuses to open the circuit in case of high currents. Doing so would have saved us from breaking a three-phase inverter, a microcontroller, and countless MOSFETs. When purchasing components, we recommend purchasing more than the necessary amount, especially MOSFETs, as they are very likely to break from static discharge, melt from high temperatures, or break over time. Lastly, we suggest that teams not shy away from buying existing solutions to subsystems. We spent about two months developing a three-phase inverter before finding a fully implemented PCB that was already on the market and integrated all three phases, providing all the functionality we needed. In summary, most of our recommendations have to do with reducing the risk due to long timelines for development and ordering parts.

9.0 CONCLUSION

To conclude, our team designed an off-grid system capable of delivering solar power to a three-phase load. We successfully designed a self-sufficient system that runs completely off-grid and modulates its operating point based on changes in solar insolation. Using a photoresistor to estimate the changes in incident sunlight, the microcontroller varies the voltage and frequency driving the motor to prevent the motor from stalling due to insufficient input power. In this regard, we were successful in meeting Dr. Baldick's requirements. However, we were forced to make changes to the initial design to guarantee baseline functionality that in the future could be improved. For example, the decision to install the photoresistor instead of the sensing circuitry fell short of our initial plans to implement motor control based on accurate power sensing. However, implementing MPPT based on power sensing both at the output of the solar panels and the input to the motor, to maximize efficiency, would be a reasonable next step. Keeping safety and sustainability a priority, the system we designed could have major implications for off-grid power applications with small improvements such as overcurrent protection and a user interface. Ultimately, we hope that this project will be open sourced to facilitate remote power to under-developed communities and disaster relief efforts.

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