Power Systems Knowledge Hub

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***Abstract* — The addition of renewable energy sources to the power grid is rapidly increasing. Although this is great for the environment, the grid is becoming increasingly complex to maintain, leading to a need for more engineers that focus on this discipline. Over the past two decades, there has been a decline in the number of students graduating with degrees that specialize in power systems. This project aims to target both issues. It emphasizes the importance of increasing situational awareness in the distribution grid as well as promote interest in power system related engineering education.**

***Index Terms* — Motor drives, power system simulation, printed circuits, solar panels, graphical user interfaces, wireless communication.**

I. Introduction

With increased renewable integration, the grid-of-the-future is becoming increasingly complex to manage. Because of this, better ways to monitor and manage the complexity of the grid are required. On January 11th, 2019, a unit in TECO Energy Inc., or Tampa Electric Company, was vibrating, and it led to frequency oscillations in the entire eastern interconnect as shown in Fig. 1. [1] These oscillations lasted for approximately 15 minutes. The event was solved after an operator at TECO noticed the unit's vibrations and decided to manually remove it from operation. Florida Power and Light (FPL) knew that there were frequency oscillations, but they did not have enough information to detect the source of the event or its location.

Independent System Operator New England (ISO-NE) knew within seconds that the location of the source of the frequency oscillations was outside their regions and that it was coming from the South. This is because they had WAMS, or Wide Area Management System. With the use of Phasor Measurement Units (PMUs), WAMS increases situational awareness and allows for faster diagnosis of system events. If FPL had WAMS during this event, they would have detected the location of the source of the event within seconds. FPL is currently implementing WAMS into their energy management system at the transmission level and is now investigating the possibility of implementing it to their distribution system.

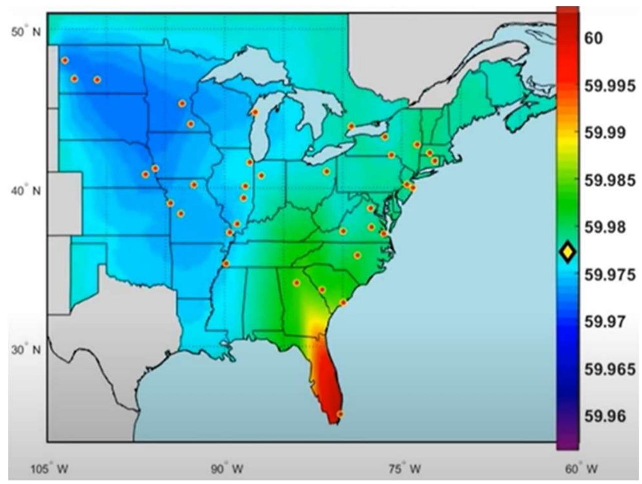

Fig. 1. Frequency Oscillations on January 11th, 2019

To maintain an increasingly complex grid, more engineers that focus on this discipline will be needed. Over the past two decades, there has been a decline in the number of students graduating with degrees that specialize in power systems. To attract more engineers to this field, more interactive learning methods about power systems are necessary. This project aims to target both issues. It emphasizes the importance of increasing situational awareness in the distribution grid as well as promote interest in power system related engineering education.

Over the past two decades, the need for engineers who specialize in power systems has increased while the number of graduating engineers with specialized degrees in this area has decreased. This imbalance has affected the industry's ability to recruit engineers needed to maintain our power systems [2]. In addition, it limits the innovation that could be possible with a large pool of fresh graduates from which employers could choose.

A. Project Description

This project consists of an interactive touch table where users can learn about the power grid by interacting with a solar panel and with a real-time simulated distribution system. Solar panels are very popular types of renewable energy sources and including one in this project assists in promoting interest in power systems. The users will be able to see how the angle change of a solar panel affects its power output and understand that such variability can lead to disturbances in the power system. Fig. 2 shows the high-level view of the project. This project is funded by FPL.

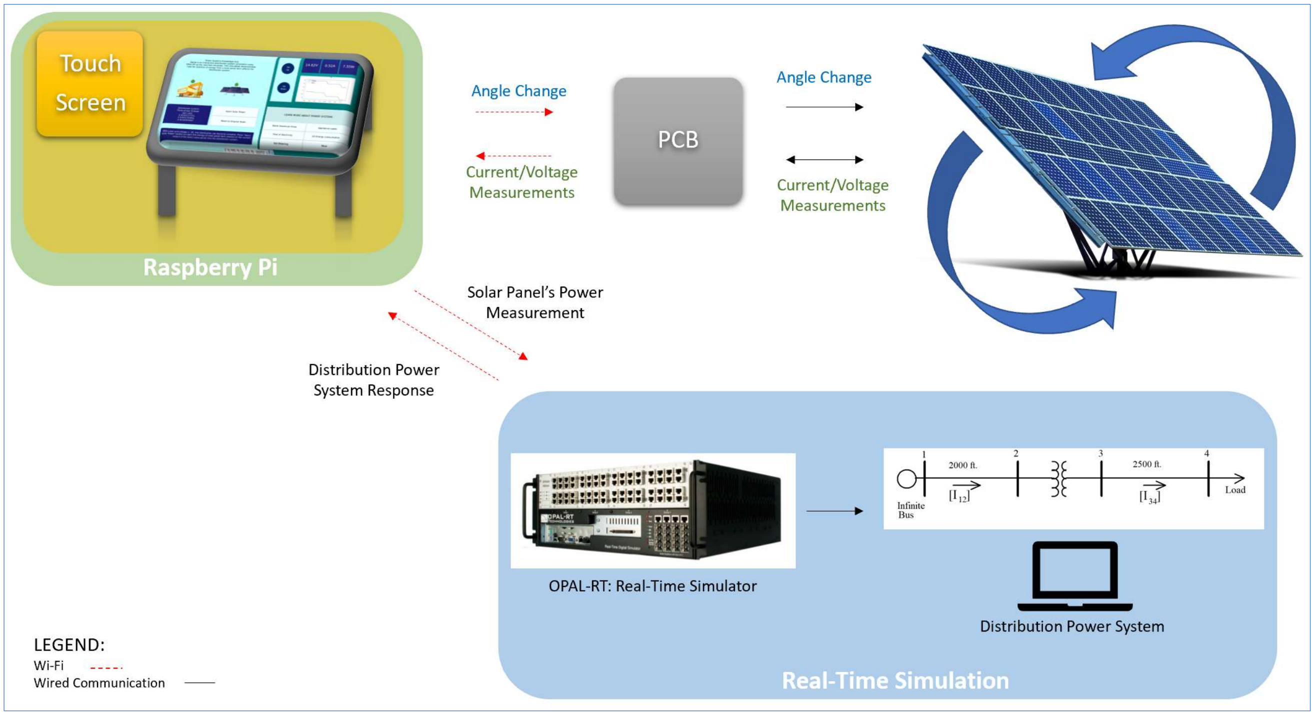

Fig. 2. Project Overview

B. Goals and Objectives

The project has two main objectives. First, to promote interest in power systems related engineering education. Second, to emphasize the importance of increasing situational awareness in the distribution grid. The following goals were set to meet the objectives:

- Basic: Interactive touch table that allows users to change the angle of the solar panel and see how that affects its power output. The table will also display educational material about power systems.
- Advanced: Interactive touch table displays a simulation of a real-time distribution system with the use of OPAL-RT.
- Stretch: User initiates a disturbance in the simulated distribution system and WAMS (Wide Area Management System) algorithm analyzes the data and determines the type of disturbance and its location.

C. Requirements and Specifications

Table I summarizes the main engineering requirements of the project. These specifications were chosen to be demonstrated to the review panel.

TABLE I
ENGINEERING REQUIREMENTS AND SPECIFICATIONS

Parameter	Specifications
1) Wireless functionality	Ability to transfer data wirelessly in UCF's 2.4 GHz network
2) Angle change response time	<12s
3) Printed Circuit Board (PCB) Voltage Input Capacity	0- to 18-V input voltage support for PVs

II. DESIGN ARCHITECTURES

A. System Architecture

Through a graphical user interface (GUI), the user will be able to:

1) Change the angle of a solar panel and see real-time voltage, current, and power readings coming from the panel
2) Inject the power output measurements of the solar panel to a bus in a real-time simulation of a distribution power grid and display the results from the injection to the user

3) Select educational topics on power systems and read corresponding educational material

Fig. 3 summarizes the system architecture which is composed of five main components. 1) A Raspberry Pi (RBP) was used as the stand-alone MCU to power our graphical user interface (GUI). A touch screen monitor was chosen to provide a more interactive learning experience for the user. 2) The PCB was designed and used to measure the voltage output of the solar panel, send the control signals to change the angle of the solar panel, and communicate wirelessly with the RBP. 3) The PCB sends the control signals to a Stepper Motor Driver, which then 4) makes the stepper motor move. 5) The RBP processes the readings from the PCB and then sends it to OPAL-RT. OPAL-RT is a real-time simulator that was used to simulate a distribution power system.

The power measurements read from the PCB and sent through the RBP is injected to a three-phase bus in the distribution grid. This is done to show the users how the variable output power of the solar panel affects the system. It is important to note that the communication between the RBP, PCB, and OPAL-RT is through Wi-Fi, while the communication between the PCB, Stepper Motor Drive, and the Stepper Motor is wire-based communication.

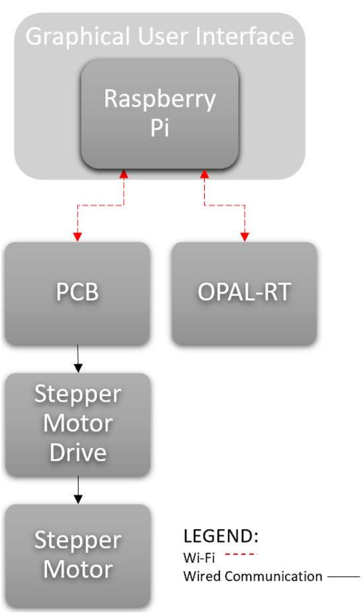

Fig. 3. System Architecture

B. System Communication

OPAL-RT is located at the University of Central Florida (UCF) in Harris Corporation Engineering Center and can only be accessed through UCF's network. Therefore, all components of the system were configured to connect to UCF's network. As shown in Fig. 4, OPAL-RT and the RBP are both connected to UCF's network via ethernet while the PCB is connected to UCF's network via UCF's WPA2 Enterprise Wi-Fi. The components communicate with each other over Transmission Control Protocol (TCP) sockets. The RBP is the server, while the PCB and OPAL-RT are both clients. It is important to note that the RBP communicates with both the PCB and OPAL-RT but there is no direct communication between the PCB and OPAL-RT.

Special script was developed to connect the Wi-Fi module in our PCB to UCF's WPA2 Enterprise. In addition, the root certificate for connecting to WPA2 Enterprise was required. The certificate was provided by UCF's IT department.

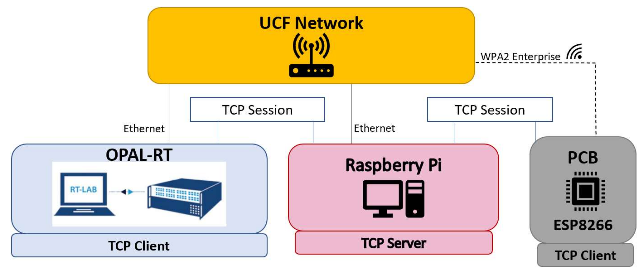

Fig. 4. System Communication

III. DISTRIBUTION SYSTEM DESIGN

A distribution system was designed to allow users to learn about power systems in a more interactive way. Users will be able to inject the power output of the solar panel to the distribution grid. As previously stated, the PCB measures the power output of the solar panel and it sends it through Wi-Fi to the RBP. Through the GUI, the user has the option to inject the power reading to a three-phase bus in the distribution grid. This injection causes the voltage of the bus to change. The change in voltage is then displayed in the GUI in per-unit, which demonstrates the user how the variability of the power output of a solar panel affects the grid and why it is important to have monitoring systems.

A. One-Line Diagram

To run the simulation in real-time, the distribution grid was designed in ePHASORSIM. ePHASORSIM is a Solver block in MATLAB/Simulink. The one-line diagram of the distribution system design is shown in Fig. 5. As shown, the IEEE 4-bus test case was chosen as the distribution grid. Bus 5 and the delta-wye transformer connected to bus 4 were modifications done to the system to inject the power measurements. The power measurements received from the PCB/RBP are scaled up to simulate a solar panel farm which would show a more accurate representation of how variable output power affects the system. As shown in Fig. 5, the load of the system is 5400 kW. This is equivalent to approximately 20 UCF buildings [3]. The solar panel used for the project is rated to output 100 W.

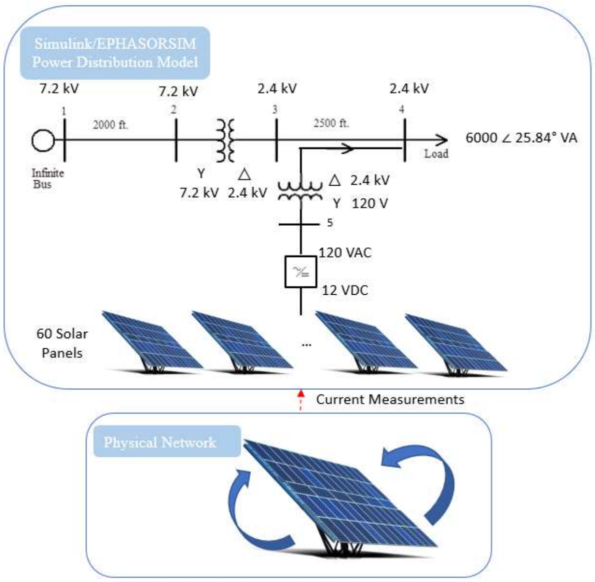

Fig. 5. Distribution System Design

B. Model Verification

To verify the distribution system design, the same model was designed in OpenDSS. OpenDSS is an electric power Distribution System Simulator (DSS). The base case of both models were ran, and the results matched. As shown in Fig. 6, the largest percent error found was 0.126 %. It is important to note that OpenDSS was used only to validate the models, it is not able to run real-time. Therefore, only the base case of both models were validated.

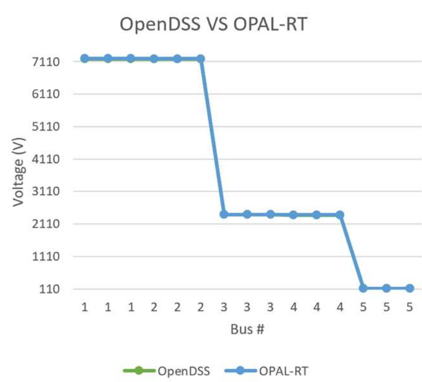

Fig. 6. Model Comparison

C. Real-Time Simulation

OPAL-RT was chosen as the real-time simulator mainly because of its availability at UCF. To run the system real-time, the Simulink/ePHASORSIM model is loaded into OPAL-RT's real-time simulator with the use of RT-Lab. After loading it, the model is then executed for real-time simulation.

The real-time simulation of the power grid offers users the ability to interact with the distribution system model. Users are able to change the values of the solar panel farm which then allow them to see how it affects the grid and understand the importance of monitoring the grid.

IV. Printed Circuit Board

The function of our PCB, shown in Fig. 7, is to enable communication between our solar panel and the interactive touch table. The main components of the design include a 100-pin Texas Instrument (TI) microcontroller unit (MCU), a 22-pin Espressif ESP8266 12-E Wi-Fi processor chip, a TLV342AID TI Operational Amplifier for voltage measurement, a TPS563249 Direct-Current-Direct-Current (DC-DC) TI voltage converter, and a battery mount interface. Integral to the PCB design is the firmware that will be hosted on both the MCU and the Wi-Fi module to ensure communication between all required hardware. An important aspect of the PCB is providing Wi-Fi communication. This enables users to send commands to the field deployed solar panel module and receive results in a specified time interval. The PCB conducts local tasks such as converting analog voltage signals from the solar panel to digital signals and then formatting the data for wireless transmission. In addition, the PCB interfaces with the stepper motor driver which sends control signals to the stepper motor to move the solar panel. The battery mounted to the PCB powers the DC-DC voltage converter which will provide a stable voltage input to drive necessary hardware components.

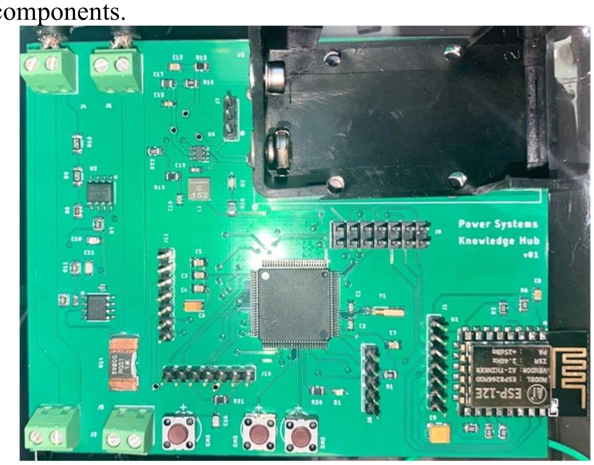

Fig. 7. Finished PCB

A. Parts Description

Component analysis was conducted to select hardware that could meet engineering specifications, keep costs low, and have online communities for support.

The most important component of the PCB is the 100-pin MSP430FR6989 MCU from TI. This MCU was compared against ATmega328P and the ESP32. However, the

MSP430 was selected for a number of reasons. Primary among them is our familiarity with the MSP430. Another factor is its wide input voltage range (1.8 V to 3.6 V), which is particularly helpful since the aim is to power all the chip modules with a common voltage level. This avoids multiple DC-DC implementations and thus reduces cost. Other benefits of the MSP430FR6989 include ultra-low operating currents, 128KB flash memory, and reliable techniques to enable programming. It also has unified memory where program, data, and storage are in one single space. This feature is important as our design collects data before transmitting them wirelessly. Even more benefits of using the MSP430 are its Ultra-Low Power (ULP) modes that are optimized to achieve extended battery life, and it's small 14mm x 14mm footprint. This small footprint was beneficial since the free version of Eagle PCB design tool only allows a maximum of 80mm x 100mm of PCB footprint.

The wireless communication needs were met by implementing the ESP8266 12-E Wi-Fi module. The module met the 802.11/b/g/n standard. It is capable of switching between five power modes. This is a useful feature than can be leveraged to reduce power consumption. The module supports TCP protocols which were used to enable communication between our PCB and the RBP. The preinstalled antenna avoids the need to develop a custom antenna. The module also supports several serial communication technologies to enable data flow between our MCU and the Wi-Fi module. The UART serial interface which supports two wires was selected to transmit and receive data to and from the MCU.

The DC-DC voltage converter employed was designed with WEBENCH from TI. It was designed as a buck converter that could handle an input voltage range from 4.5 V to 17 V. The maximum output voltage was set to 3.3 V. This logic was chosen because the devices that it supplies power to are typically driven by 3.3 V. The DC-DC was also designed to output up to 1000 mA. This is necessary as the connected hardware components need adequate current to function based on their design standards. The actual chip that powers the DC-DC was the TPS563249. This chip provides excellent overcurrent protection as per the datasheet. It also has very high efficiency that is approximately 87% at 3.3 V output while maintaining a very small footprint.

The battery source to power the PCB is a 9 V alkaline non-rechargeable battery. This class of battery delivers adequate power to all PCB components. The power consumption of all the PCB modules including the chips and possible external loads was estimated prior to selecting the battery. From field tests that were conducted, the energy capacity of this selected battery meets all the energy demands of the PCB.

The operational amplifier used to measure voltage from the solar panel was TI's TLV342A dual complementary metal–oxide–semiconductor (CMOS). It provides excellent DC precision that gives accurate readings. It can perform safely between 1.8 V and 5 V. It also features a wide common-mode input voltage range of -0.2 V to (V_+ -0.5 V).

B. PCB Design

The project requires a PCB that can measure the voltage and current output of the solar panel. It should also transmit signals to the stepper motor driver to move the angle of the solar panel. The PCB should also send and receive data from the RBP through the UCF Wi-Fi network. It was designed based on the engineering specifics that were developed at the start of this project.

Some circuit designs were tested and analyzed by using simulation tools like MATLAB Simulink and LTSpice. This allowed for the selection of appropriate capacitor and resistor values for breadboard testing. After successful completion of breadboard tests, the design was then moved into the next phase of development which used EAGLE to build a schematic and design the board layout. Modifications and retesting were constantly done at all design levels until a successful PCB model was developed. Then the PCB design was sent to the manufacturer for production.

During board layout, the requisite standards were adhered to. Trace angles were kept beyond ninety degrees to provide high signal with a path free of obstruction. Trace width was selected based on the current levels they are expected to transport. This is important because inadequate trace width can result in overheating and board damage. For example, the voltage measurement module trace width was designed to handle up to 7 Amps and 24 V. Bittele Electronics Inc. online trace width calculator was used to estimate correct parameter sizes. The underlined equation applied in their online calculator was published in the IPC-2221 standard section 6.2 and include the following equations where I stand for current, dT is temperature rise above ambient in °C, and A is Area of the trace:

Internal traces: $I = 0.024 \text{ x } dT0.44 \text{ x } A0.725$ (1)

External traces: $I = 0.048 \text{ x } dT0.44 \text{ x } A0.725$ (2)

During the design of the MCU circuit, several references were made to TI documents on design guidelines. These include [4]: "To improve EMI on the LFXT oscillator, observe the following guidelines. • Keep the trace between the device and the crystal as short as possible. • Design a good ground plane around the oscillator pins. • Prevent crosstalk from other clock or data lines into oscillator pins LFXIN and LFXOUT. • Avoid running PCB traces underneath or adjacent to the LFXIN and LFXOUT pins." Likewise, proper connection of unused pins was also followed. The design accounted for using the programming and UART interface of a typical launchpad eZ-FET so that it could be used to flash our MCU.

V. Solar Panel Angle Change Design

For our solar panel to generate fluctuations in energy, a mount design that allowed movement over 80 degrees needed to be created. As shown in Fig. 8, Our design employs an intricate pulley system acting as a linear actuator that pushes and pulls the solar panel by a single point utilizing to achieve our rotational movement over a single axis. The solar panel presents movement in 5 degree intervals to better show the fluctuation of energy depending on its position and time of day.

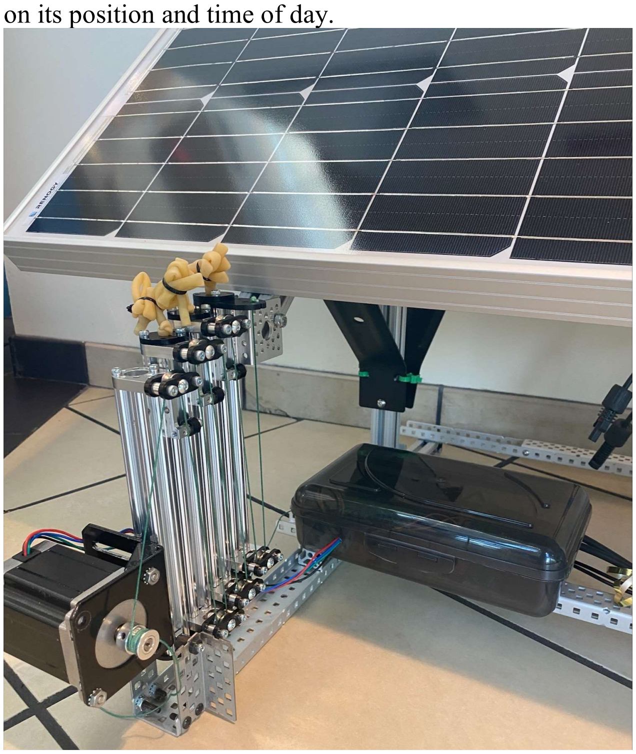

Fig. 8. Solar Panel Angle Change Design

A. Parts Description (Motor/Driver/Pulley System/Mount Design/Solar Panel)

For the solar panel mount design, 80/20 aluminum extrusions were used to form the base taking as inspiration a design similar to that of a drafting table. Two T-shaped stands were made at the end of these and used as the pivot points for our solar panel. Aluminum C-Channels were also used to provide stability and create a sturdier base for better support to manage the solar panels weight.

To have a better understanding on how much torque was required to be able to move the solar panel from its extreme points (-40˚ and 40˚), a practical measurement was used. Utilizing a specific point on the solar panel mount as a handle (the same point from where we push and pull our panel) we can determine the amount of torque necessary by applying a force the opposite direction which we could measure. Setting a bag on this point, bottles of water were used as our counteracting force in order to measure the torque required. Utilizing bottles of water and the properties of water itself, we were able to determine the torque required by multiplying the total number of bottes (in this case 6 bottles provided enough weight) times the milliliters per bottle times the density of water. After executing these calculations all that was left was to multiply the result by gravity to find the force we needed (approximately 4.9 N/m). The motor selected is a Nema 23 Stepper Motor which provides 1.9 N/m of torque.

Almost 3 times smaller than the minimum torque required to move the solar panel from its extreme points, a system was needed to redistribute the force. The system chosen was a cascade pulley system. Behind the physics of pulley systems, weight and force are distributed evenly throughout the system. The cascade pulley system designed consists of four stages compacted into a small space in order to provide the correct amount of rotation needed on the solar panel by pushing and pulling the system the same way a linear actuator operates. The design was also Madeira of a cascade lift in order for the system to never block the sunlight on the solar panel. The Nema 23 motor pulls continuously on a string that raises and lowers the stages of the cascade lift every half rotation providing 5˚ of rotation. The pulley system has the same effect as that of a 4:1 gear ratio on a gear box, this means it provides 4 times the amount of torque of the motor by sacrificing 4 times its speed giving us the ideal torque needed to move the solar panel.

VI. Interactive Display

To fulfill our objective of increasing student interest in majors related to the electrical power grid, a highly interactive environment is required to engage the users. This project accomplished this by creating a touch table with an interactive display.

A. Touch Table

Purchasing a pre-made touch table was cost prohibited for this project. Instead, a large touchscreen display was selected, and a table was built to hold the display in a flat position to be used as a touch table.

The touchscreen monitor selected was the Phillips Model 55BDL4051T. This display has a 55 inch vertical measurement with other dimensional measurements of (1271.0 x 741.7 x 91.4) mm or (50.04 x 29.20 x 3.60) inches in imperial measurements. It weighs 18.0kg (39.68lbs). This model has 1920x1080 pixels, and it consumes an average of 76 watts per hour of power. The display has a built-in CPU and memory, but the project requirements exceeded these built-in capabilities, so a stand-alone micro-processing unit was selected to use with the display.

The table shown in Fig. 9 was built out of pressure treated lumber to hold the touchscreen. The table dimensions are (54 x 34) inches with a height of 32 inches including locking casters that assist in moving the touch table. The table frame is open in the back to allow access to all the touchscreen's ports and plugs. The table supports over 500lbs of weight which can easily support students leaning against the edges of the table while using the display.

Fig. 9. Touch Table

B. Stand-Alone MCU

In order to process the distribution simulation data from OPAL-RT, interface with the PCB, run the WAMS algorithm, and provide the graphical user interface (GUI), a stand-alone microcontroller unit was necessary. The main consideration for this unit was based on performance, and the Raspberry Pi 4 Model B was selected for the project.

The Raspberry Pi 4 Model B is the most advanced Raspberry Pi available on the market. It can run on the Raspberry Pi Operating System (previously called Raspbian) which is a Linux Debian based OS. It has a minimum of 2GB of RAM with the option to upgrade up to 8GB which was selected, a high-performance 64-bit quad-core processor, dual-display output via two Micro HDMI ports with up to 4K resolution, Gigabit Ethernet, MicroSD card slot, 2 each USB 2 and 3 ports, and a 40 pin general-purpose I/O header.

The Raspberry Pi was purchased in a starter package by CanaKit that included the 3.5A USB-C power supply with noise filter and a 5-foot cable, a case, 3 aluminum heat sinks, a low noise cooling fan, USB card reader, and a micro HDMI cable. Additionally, a USB type B cord was acquired separately since that is how the touchscreen relays the touch signals back to the Raspberry Pi.

C. Graphical User Interface and Logic

As discussed in the System Communication section, the Raspberry Pi acts as a TCP socket server to communicate with the PCB and OPAL-RT. The data is collected through those sockets for use in the GUI. All code running on the Raspberry Pi was written in Python, and the python framework Tkinter was used to build the GUI. Tkinter is the only framework built-in to Python, and therefore provides a simple method to create user interfaces.

The GUI provides the user an opportunity to learn more about green energy by interacting with the solar panel in the upper right frame as shown in Figure 10. This panel allows the user to press buttons to tilt the solar panel up or down. Each press of the button sends a message to the PCB, and the code on that side instructs the panel to move 5 degrees per request. The user is able to see the real-time voltage, current, and power readings coming from the solar panel, and they are also able to view the voltage and wattage in a real time plot which is constructed using Matplotlib.

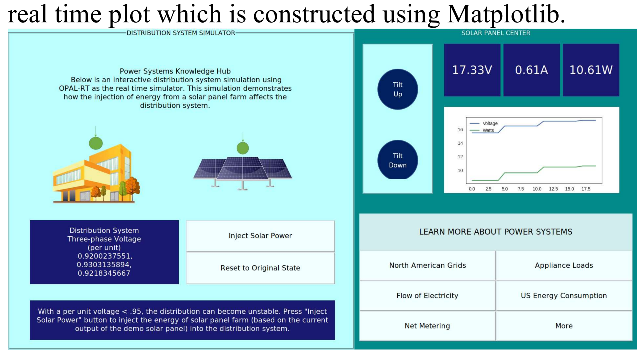

Fig. 10. Graphical User Interface

In the panel on the left half of the GUI display, the user can interact with a distribution system simulation. The user can see the per-unit three-phase voltage data coming from OPAL-RT. Using the button in the panel, the user can then inject the energy from the solar panel into the simulated distribution system and view the effects. This is accomplished by sending the current solar panel voltage reading to the OPAL-RT model when the button is activated, and then OPAL-RT will use a multiplier to convert it to the energy of an entire solar panel farm and inject it into the model. The GUI will reflect how the voltage changes since it is constantly updating the readings from OPAL-RT, and the message box at the bottom will tell the user how the injection affected the system. The user can then press the other button to remove the injection from the simulation and return the state to the baseline of the OPAL-RT model.

In the bottom right panel of the GUI, the user is able to access educational materials about the power grid and electrical engineering. By activating a button for any of the listed topics, a separate window will open and display the educational material for that topic. The "More" button should open a window that contains more topic buttons, and it will be updated in the future as new educational material is created or located.

VI. Conclusion

This project successfully achieved the two primary objectives of promoting interest in power systems related engineering and emphasizing the importance of increasing situational awareness in the distribution grid as it becomes more complex with the increase in green energy. This was done in part by reaching the basic goal of creating an interactive touch table that allows users to control a solar panel, view the real-time changes in voltage, current, and wattage readings based on those changes, and providing educational material to the user.

The objectives were also achieved by reaching the advanced goal of including a real-time distribution simulation in the interactive touch table utilizing OPAL-RT. In this simulation users can inject the green energy of a solar panel farm and see in real-time the effects of that injection on the distribution system. The distribution system designed for this project in OPAL-RT was verified by modeling the same system in OpenDSS. Results from both models matched, thus confirming the accuracy of the design. Due to time limitations, the stretch goal of implementing the WAMS algorithm into the distribution system simulation was not completed, and this is work that should be continued in the future.

Contributing to the success of this project was the PCB creation. Although the PCB design was complex for a Senior Design project, the original schematic and board design was successful and did not have to be modified. The original PCB that was manufactured performed as expected. Since the manufacturer provided five copies of the same board, we opted to solder components onto a second board to provide a backup board if needed, but nothing was changed in the design.

The nature of this project dictated that the PCB would need to connect to a WPA2 Enterprise Wi-Fi network that is widely used commercially since the project needs to reside in at a university, school, or business location. It was difficult to implement this connection as there are no examples of our Wi-Fi module connecting to this type of network available and other Senior Design teams have not been able to successfully connect in the past. However, code was developed for this project that was able to implement this connection, and that was a major success for the project.

Acknowledgement

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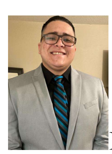
Biography

Ivelisse Rivera will graduate with Summa Cum Laude honors and receive her Bachelor of Science in Electrical Engineering in May 2021.

Christy Wilhite will graduate with National Science Foundation FLIT Path honors and receive her Bachelor of Science in Computer Engineering in May 2021.

Christopher Marks will graduate with his Bachelor of Science in Electrical Engineering in May 2021.



Hector Collazo will graduate with his Bachelor of Science in Computer Engineering in May 2021.