Cyber Smart Home Integrated Environment for Learning and Defense (S.H.I.E.L.D)

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***ABSTRACT* — Cyber S.H.I.E.L.D analyzes power system cyber security issues and presents opportunities for education on renewable energy integration at the grid edge. This project creates a smart home model that makes use of an energy management system (EMS) to select appropriate sources and loads. A touch screen will be used to allow the selection of test cases for the project. It will provide an educational experience for students interested in learning about the evolution of power systems and the function of a smart home. To test the security of the smart home, measurements will be collected from the model and will be sent to the OPAL-RT. The OPAL-RT simulator works to model the grid in real time. This will allow the staging of attacks on the model to observe their implications. Overall, this project is crucial to demonstrate new developments to our power systems and how one can work to detect and prevent cyber-attacks at the level of the smart home. This project is an excellent way to provide an educational overview of renewable energy integration at the grid edge and investigate security and reliability of the grid.**

***INDEX TERMS* — Smart Home, Energy Management System, Power System Cybersecurity, Hybrid Solar System**

I. Introduction

From its development back in the early 1880s, the U.S. electric grid has been constantly growing and evolving. Now, more than ever, the grid is seeing changes that may have never been imagined. Many of these changes are inspired by the expansion of the electric power system to meet growing demands for energy. Other changes to the grid are motivated by the hope of achieving a net-zero future. In any case, the U.S. electric grid is being modernized to develop a smarter grid that allows for larger amounts of electricity generation and more efficient and reliable transmission and distribution. Two of the main forces driving this modernization include the expansion of renewables and a shift towards a connected and decentralized grid. The goal is to create an evolved grid that is flexible to integrate distributed energy resources (DER), accommodate the two-way flow of electricity and information for better power management, and provide protection against physical and cyber risks.

Unfortunately, with the changes towards grid modernization comes an increasing risk for cyber-attacks. These attacks can disrupt the grid, damage costly equipment, and even threaten human life and safety. There are many methods of employing a cyber-attack. For example, there are a growing amount of smart microgrids in the U.S. today. These microgrids are small-scale power supply networks that enable local power generation for local loads. They can be created by installing grid-edge technologies such as solar panels, energy storage systems, smart inverters, smart appliances, and electric vehicles charging stations. The increased interconnectedness between critical operational technology and these grid edge devices leads to a higher complexity and risk for cyber-attacks unless proper security is built in. A hacker can employ a multitude of attacks to violate the confidentiality, integrity, or availability of the network. They can also exploit vulnerabilities of the network to gain access to private information of consumers or illegal access to nodes.

Due to this, it is crucial for engineers to develop a method to effectively detect cyber-attacks for the U.S. to continue modernizing its grid. Once these algorithms are developed, they must be tested to ensure that they are able to function in real time scenarios. While one cannot test these algorithms on the physical grid itself, engineers are able to use real time simulators such as the OPAL-RT to model the grid. These simulators allow cyber-attack detection and prevention algorithms to be effectively tested. Furthermore, through simulations such as the OPAL-RT, students can learn more about how the grid functions and the necessity of security in our power systems as they continue to be modernized. This project is a physical testbench of a cyber-attack detection algorithm as well as an educational outlet for showing the complexity and evolution of electric power systems.

II. System Components

The model smart home is made up of multiple hardware components that work in harmony with the software. This section details an introduction to each of the components in the project and their role.

A. PV Panel

One of the energy sources for our smart home model is a PV panel. The PV panel works by using photovoltaic cells to convert the energy received from the sunlight into electricity. We decided that we would need to go with a monocrystalline solar panel to meet the requirements of our project. The PV panel that was chosen for our project was the Renogy 100W 12V Monocrystalline Solar Panel [1]. This panel was shown to be high in power generation and compact in size. In fact, it was 8-10% smaller compared with other 100W solar panels.

B. Battery

Selecting the appropriate battery for the model smart home was an important task as we needed it to be affordable and capable of supplying both the DC and AC load. Upon reviewing the comparison between the different types of batteries, we were able to select sealed batteries and gel batteries to consider for our project. The battery that we used for the project was the Renogy Deep Cycle AGM Battery 12 Volt 100Ah [2]. This battery met all the specifications we were looking for and was listed at a reasonable price.

C. Charge Controller

The charge controller is an important component of our project. It does this by managing the flow of electricity between the solar panel and the battery. Charge controllers have five main functions: regulating charging voltage, preventing overcharging, temperature compensation, load control, and preventing reverse current flow. Without a charge controller, we could not connect the solar panel to the battery safely. We selected the Renogy Wanderer PWM 10A Solar Charge Controller [3] as it came with our panel and met the requirements of the project.

D. Inverter

In our project, the inverter is used to convert the DC power from the PV panel and battery to AC power for the AC loads. To select an inverter appropriate for our project, we completed research to find inverters that were compatible with the solar panel and battery that we selected. To determine what capacity of inverter we needed, we calculated our power needs. We needed an inverter with a capacity that was at least 20% higher than the largest power output. The largest power output of our solar panel was 100W. So, we decided that we would get an inverter with higher than 120W capabilities. Upon further research, we found that at least a 12V DC to 220V AC 200W inverter is appropriate for appliances using a 100W panel. From our research, we found that 700W pure sine wave inverters were more common. Due to this, we chose the Renogy 700W 12V Pure Sine Wave Inverter [4] for our project as it was cost effective and met all of our project requirements.

E. Relay

The relay module in our model was a crucial component as it would be used to select the energy sources and the loads that were on according to the user's manual selections or the energy management system. The relay would need to be connected to our microcontroller to ensure that it could turn on and off. For DC applications, we chose to use a Solid-State Relay: SSR-25DD (25A DC to DC Input 3-32V DC to Output 12-220V DC 25A) [5]. For AC applications, we chose to use the 40A DC to AC Solid-State Relay with Input 3-32 VDC & Output 24-380 VAC [6]. We chose these relays as they functioned the best with the requirements of the project. Their ports were large enough for the solar panel and battery wiring. This allowed for safe installation of the relays.

F. Touchscreen

The touchscreen in our project was used to display the user interface and allow for user interaction. The team chose to have a touchscreen that was large enough to see the 3D model of the smart home in detail. The display on the touchscreen supported multi-touch with at least two touch points. After comparing the different types of touch screens, we decided to go with the capacitive touch screen as it would meet the requirements of our project more sufficiently. The touchscreen that the team chose was the Phillips 55BDL4051T [7] as it was able to meet all the requirements we were looking for at a lower cost. This touch screen was available in the UCF Siemens Digital Grid Lab and was able to be integrated with our project.

G. OPAL-RT Simulator

OPAL-RT TECHNOLOGIES is a leader in the development of PC/FPGA based simulators that run in real time, hardware-in-the-loop testing equipment, and rapid control prototyping systems [8]. Due to OPAL-RT's popularity in the industry in simulating power systems in real-time, we decided to investigate OPAL-RT technology for the requirements of the project. The OP5600 digital simulator was chosen due to its availability in the UCF Siemens Digital Grid Lab in the L3 Harris Corporation Engineering Center. Our sponsor, Dr. Wei Sun, is the director of the lab and allowed us to have access to the OP5600 real-time digital simulator.

The complete project tied together all these components to create a completed smart home testbench. The project involves a physical model of a home made up of cedar wood. The front of the model is opened so that the user can see inside to monitor the function of the DC and AC loads. Mounted on the roof of the model is the PV panel. The PV panel and battery are both connected to a charge controller.

The DC load port on the charge controller pulls from the battery. In addition to this, the battery is connected to a DC/AC inverter. The DC/AC inverter is connected to an AC load. In a scenario where there is not enough sunlight or battery charge, there is a wall outlet connection to represent a "grid tied" system. At the battery, PV panel, and outlet connection there will be meters to collect voltage, current, and power. The model will be able to intelligently select what source and load is appropriate for the conditions at the time using a programmed energy management system. To allow the selection of the source and load, relays will be utilized. A touch screen will be used to show all the measurements and allow for selection of the source and load by the user. Measurements will be sent to the OPAL-RT simulator to be used in the RT-Lab model for testing of the UCF Digital Grid Lab's cyber-attack detection algorithm.

III. System Concept

To understand the complete system, the block diagram below shows the smart home model structural illustration.

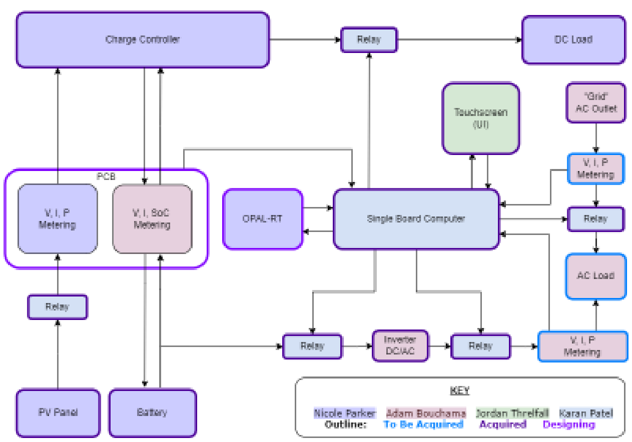

Figure 1: Complete System Block Diagram

To more accurately test the algorithm, the model smart home must function using a hybrid solar system. A solar panel will be used to provide energy to the loads within the model smart home. There will be a battery used for energy storage. This battery can be used in the case where the solar panel is not generating enough energy. In the model, multiple loads will demonstrate that the system is functioning correctly. Data collected from meters on the model will be sent to the OPAL-RT simulation in the Digital Grid Lab. This data will be used to employ multiple forms of cyber-attacks. If an attack is detected, then appropriate measures should be taken for the event to be isolated. For example, the power supplying the loads could be disconnected to ensure the safety of the home.

The model smart home will have a functioning energy management system (EMS) to appropriately distribute and store energy. The EMS must be able to account for instances in which there is not enough power being generated by the solar panels and efficiently switch to an alternative power source, such as a DC battery or AC power source. If there is more power being generated than absorbed by the loads, then the EMS must allow the charging of the DC battery. A digital touch screen will be utilized to encourage interaction with the project. Users will be able to select areas of the model to see the voltage, current, and power absorption or supply.

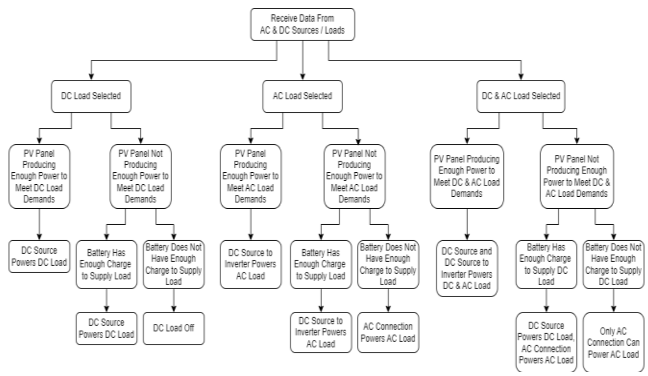

Figure 2: Energy Management System

Furthermore, the illustration for the user interface can be seen in the figure below. This figure shows off the model home we integrated in our UI application.

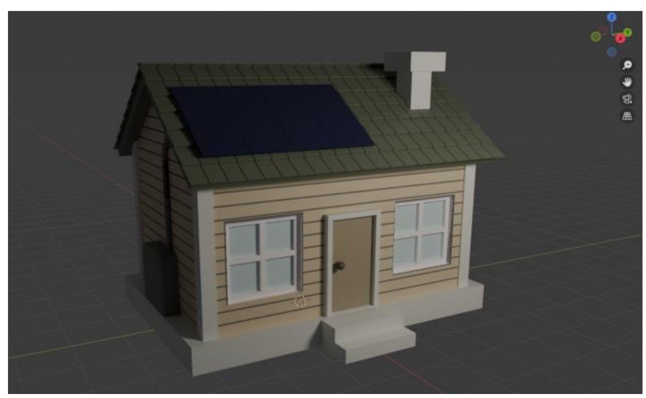

Figure 3: User Interface Smart Home Illustration

Within the application, we wanted to be able to display a notification of when a cyber-attack was launched. We then wanted to prompt the user to ask if they wanted to test the cyber-attack detection algorithm. After they deploy the algorithm, we see if it was successful in the detection of the attack. If it is successful, the attack detection will display a "1" as the output. If there was no attack detected, then the algorithm will display a "0".

IV. Hardware Design

The block diagram presented previously shows the inputs and outputs of each block, both internal and external. This aids the team in getting an idea of what components will be connected to each other and how the system will function. Beyond this, it is vital to create block diagrams for subsystems within the overall system.

A. Raspberry Pi Integration with Relays

The first subsystem that will be discussed involves the system of relays controlled by the Raspberry Pi. The relays work to control the sources and loads that are connected to the system. Each relay will be toggled using one of the GPIO pins on the Raspberry Pi. Our EMS algorithm will automatically toggle each relay based on the metering information sent to it. These GPIO pins will be manually wired to the relays. To confirm the right relays are configured to the Raspberry Pi, it will be important for us to give appropriate labels for the pins controlling the relays. This labeling will be done during programming, simplifying the development process.

Our relays will operate across a wide voltage range, from the battery's 12V up to mains voltages of 120V. It is crucial that our relays can withstand these voltage levels to ensure reliable performance. Fortunately, our relays are rated for up to 250VAC and 30VDC, making them well-suited to handle the required voltage range with a significant margin of safety. We are not utilizing all the relays on our eight-channel relay module. This approach provides the potential for future expansion of our project and offers redundancy in case of relay failure.

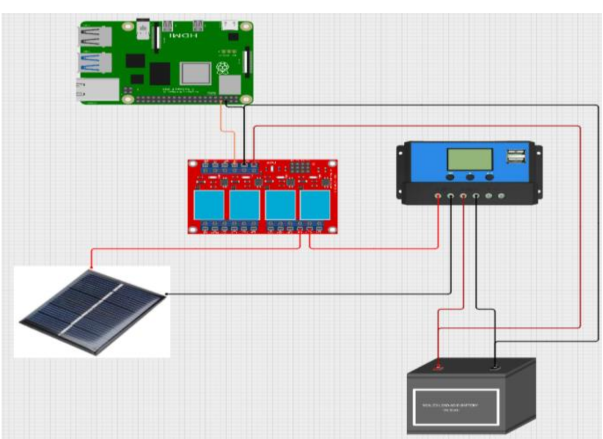

Figure 4: Example Connection of Relays to Solar Panel

B. Raspberry Pi Integration with Metering Devices

The second subsystem that will be discussed involves the system of metering devices communicating with the Raspberry Pi. In this project, the metering devices serve an important role. They must collect the current, voltage, and power measurements from all the sources. This enables the user to see the measurements on the touch screen and allows the OPAL-RT simulator to receive measurements from the testbench. The DC metering devices for our project were created by the electrical engineers on the team. Two PCBs were designed: one for metering the solar panel and one for metering the battery. For both metering PCBs, a consistent subsystem was followed. The PCBs included a buck converter, a current sensor, voltage sensor, analog-to-digital converter, USB and USB-UART connector, and the ESP32. Figure 5 shows the subsections of the PCB design. These are the key components of the metering PCB.

There were a few important things to note with the DC metering PCB. Firstly, the current sensor's input voltage was 5V while the ESP32's input voltage was 3.3V. Secondly, the design needed to integrate a USB to program the ESP32. Thirdly, the ESP32 is able to perform analog-to-digital conversions on certain GPIO pins, but it is more accurate to have an external analog-to-digital converter that feeds into the ESP32. With these things in mind, we began to design the DC metering PCBs. All the measurements collected by the ESP32 would be sent over UART to the Raspberry Pi.

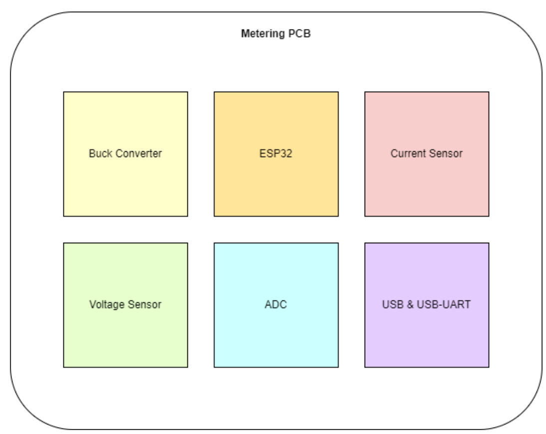

Figure 5: DC Metering PCB Subsections

For the AC load metering, the team decided to utilize current transformers to send the information back to the Raspberry Pi. The AC load metering was set to take place right after the inverter and right after the AC source connection (wall outlet). The current sensors could collect current and voltage measurements. On our program, we were able to calculate power from these measurements.

The key aspects of system architecture in hardware design include the subsystems and any components utilized in the design. This includes all physical components such as circuits, MCUs, sensors, and any communication interfaces. Between these components there should be interconnection with signal paths that carry data and control signals and power distribution paths. Data flow is shown on the system architecture to display the movement of data through the system. This includes inputs and outputs. From here, communication protocols are labeled. The standards and protocols that allow for data exchange within the system are clearly visible.

The diagram detailing the system architecture for the Cyber S.H.I.E.L.D. can be seen in Figure 6. This diagram shows all inputs and outputs for the components as well as communication of data throughout the system.

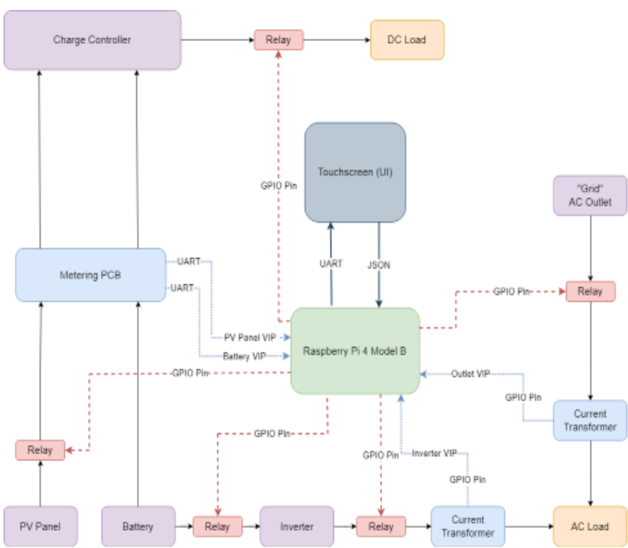

Figure 6: Hardware System Architecture

As shown in the system architecture flowchart, the relays are connected with the Raspberry Pi through the GPIO Pins. This allows for the communication of commands to the relays to turn on or off. Furthermore, the DC metering PCBs can communicate using UART to the Raspberry Pi. Data such as the PV panel and battery's voltage, current, and power measurements are communicated. All data is stored within the PCB's ESP32 chip and is communicated to the Raspberry Pi. In addition to this, the current transformers can complete metering of the AC sources. This includes power, voltage, and current measurements for the inverter and the AC outlet. Again, this communication takes place through GPIO Pin connection. Lastly, the user interface on the touch screen was able to communicate with the Raspberry Pi 4 to send and receive data and commands. These actions would take place using UART and JSON.

V. Printed Circuit Board Design

The PCB schematic serves as the blueprint of our design. It provides a detailed diagram of the electronic components and their connections throughout the system. Schematic diagrams helped with the physical placements of components on the board, allowing us to know which components should be placed with each subsystem. PCB layout plays a crucial role in determining the operation and electrical performance of the design. Therefore, adhering to industry-recommended standards such as IPC-2221 is essential. It is highly advantageous to use a PCB software package that supports both schematic and layout design. KiCad was chosen for this project as it is a free and open-source tool, making it accessible to a wide range of users. Being open source means that the software is continuously improved by a community of developers, ensuring it stays up-to-date with the latest advancements and user needs.

KiCad integrates a comprehensive schematic and PCB layout capabilities and offers valuable features such as a built-in BOM generator, a robust library management system, and seamless integration with external tools for design verification and manufacturing quotes, enhancing the overall design workflow. KiCad supports plugins that extend its functionality. These plugins provide additional capabilities such as enhanced design rule checks, 3D visualization, automated routing, and more. The plugin ecosystem allows users to customize and optimize their design environment to suit specific project requirements.

Our PCB has a few key components to ensure its functionality. The main component being the hall effect current sensors shown in Figure 7.

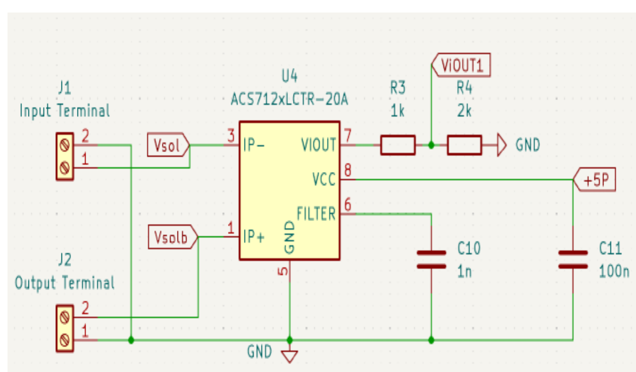

Figure 7: ACS712 Schematic

The hall effect current sensor we are using is called the ACS712. We are using the 20A version of the chip to ensure compatibility within our system. The component is connected in series with a current flow, and outputs a voltage that is proportional to the current flow. With some software conversions this output can be calculated to find the current flow. This chip as well as a simple voltage divider are used in tandem to measure both the current and voltage of our sources.

The next vital component of our PCB is the analog to digital converter (ADC). This component converts an analog voltage to a digital signal that our microcontroller can read and understand. The ADC we chose is a 16-bit ADS1115. We wanted an ADC that had a high resolution to ensure we could take the most accurate measurements. The circuit is shown below in Figure 8.

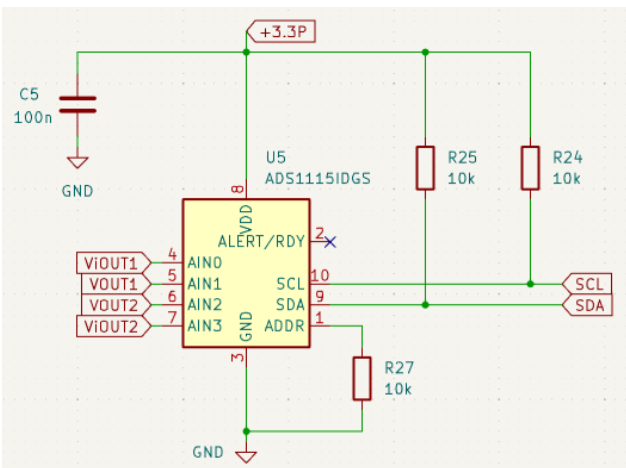

Figure 8: ADS1115 Schematic

All of our inputs are connected to the four input pins of the ADC. These values are converted and sent to our microcontroller using I^{2}C communication. Because we are using I^{2}C communication, the four values cannot be sent simultaneously. This means we have a small delay between each measurement which has to be accounted for in the code. We are currently using a 50-millisecond delay between measurements, which is sufficiently fast for our purposes and does not interfere with the system.

The final critical component in our system is the power switching multiplexer, which plays an essential role in maintaining a stable and reliable power supply. This multiplexer is designed to select between two different power sources, ensuring that the system receives continuous power even if one source becomes unavailable or unstable. By actively monitoring both input sources, the multiplexer can seamlessly switch between them as needed, minimizing downtime and enhancing the system's resilience. This redundancy is particularly valuable in applications where uninterrupted power is crucial, as it allows for a smooth transition without manual intervention. Overall, the power switching multiplexer contributes significantly to the reliability and robustness of our system's design.

We are using the TPS2121 power multiplexer and have configured it according to the datasheet to prioritize Input 1, which is our battery. This setup ensures that the system draws power from the battery as the primary source. If the battery becomes unavailable or its voltage drops below a certain threshold, the TPS2121 will automatically switch to Input 2, which is connected to our solar panel. This automatic transition provides a seamless backup, allowing the solar panel to supply power when the battery is depleted or disconnected. The schematic is shown in Figure 9.

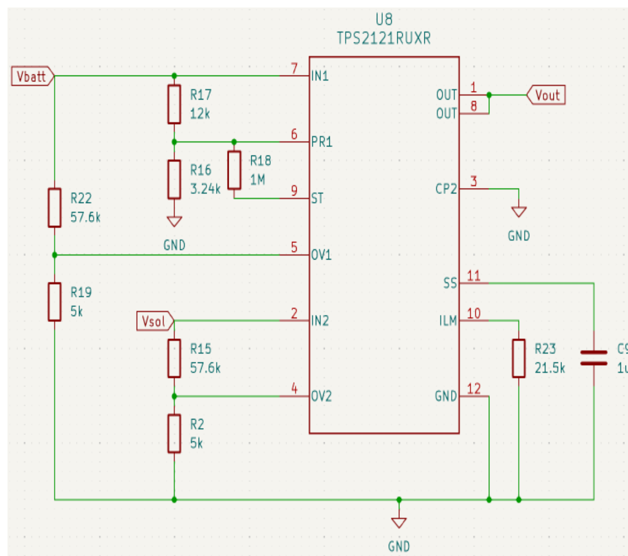

Figure 9: TPS2121 Schematic

As shown in the TPS2121 schematic, we have our two connections to the input. One being the battery connected to Input 1 and the other being the solar panel connected to Input 2. The resistor and capacitor values have been specified by the datasheet.

Due to reliability issues with the original circuit, we have added an alternative way to power the PCB via a USB connection. By simply switching two headers on the board, we can easily transition from the battery and solar panel power supply to USB power. This setup ensures that if we encounter any issues during a demo, we can quickly and seamlessly switch to the USB connection, minimizing downtime and maintaining consistent power to the system.

VI. Software Design

This project involves the creation of two major software components. One is a user application that provides a visual and interactive experience of the project's entirety. The second is the software uploaded to the Raspberry Pi, which controls the various hardware components and provides information back to the user application. These two pieces of software contribute to the success of the project and have their own established goals. The goal of this software are as follows:

1. Create a destination that displays the simulated smart home in real time
2. Allow the user to interact and adjust various parameters in the smart home including time of day, load type, energy source, etc.
3. Serve as an interactive platform that shares information on the simulator, the various components involved and the impact of adjusting the various parameters.

These goals help guide our team to create an interactive and informative application, fully displaying the capabilities and impact of this project. With these goals in mind, we have designed the software such that it achieves the goals presented and creates an interactive application and impactful learning experience.

A. Various Point of Views

We are giving the user the ability to interact with the hardware and adjust it in real time. The user will have options such as choosing AC / DC, Day / Night, Battery Power / Grid Power, etc. When changing these various components, the hardware will receive these commands and update them in real time. If the user chooses to switch to grid power, the hardware system will change its energy source to the "grid" or the outlet connection. Once switched, the hardware will confirm the success in the switch and the software will adjust to reflect this change, providing updated data on the current state of the system.

B. Learning Opportunities

Once a component is selected, the user is shown information on the significance of this component to the smart home and is given an opportunity to learn about the role of this component in the system. The user is also given the option to return to the home state of the house where they may choose to visit another location.

The start of the application displays a 3D model of a home. This 3D model will have various locations in the house that the user may click on to zoom into the specific location. These locations include, but are not limited to the roof with a solar panel, battery behind house, and appliance inside the house, etc.

C. Metering

Another important feature of this house is being able to display the metering information of each component in real-time. The simulated smart home application should be able to display data of the load powering the appliances, the energy source and more. This should reflect the hardware and serve as a visualization of its current state.

D. Configuration

The start of the application displays a 3D model of a home. This 3D model will have various locations in the house that the user may click on to zoom into the specific location. These locations include, but are not limited to the roof with a solar panel, battery behind house, appliance inside the house, etc.

E. Cyber-Attack

Lastly, the application will give the users the ability to monitor the smart home system and be notified when a cyber-attack is occurring. Through our partnership with the UCF Siemens Digital Grid lab, we are developing this tool to give them the ability to test their cyber-attack detection algorithm. Our application will visualize when a cyber-attack occurs and allow the user to disconnect their appliances to prevent any damage. This application serves as a way for the user to interact with the hardware and learn about system security.

F. Integration

The final piece to the system is integration. This part mainly involves two major points: networking integration and UI application integration.

The networking part is ensuring that the Raspberry Pi and UI application are integrated and sending the correct messages to each other. To ensure that both systems are aligned, an ICD will be created to ensure that both systems know what messages to send. Once the integration is complete, there will be testing of the systems, ensuring that the messages are being correctly sent between the two.

The UI application integration involves ensuring that each component of the application interacts with its respective components correctly. For example, we want to ensure that when we select the PV panel camera view button, we want the camera to transition over to the correct position and display the specified view. There will be thorough testing of this integration in ensuring that all the systems perform correctly.

Ultimately, the fabrication of the UI application involves preparing each of the components and then ensuring that they integrate correctly with one another. Once we enter the testing phase of this project, we will be able to determine if the components are performing correctly and then adjust them if needed.

In the figure below, we see an application flow chart for turning the application on/off. This shows the process for booting up the application and shutting it down.

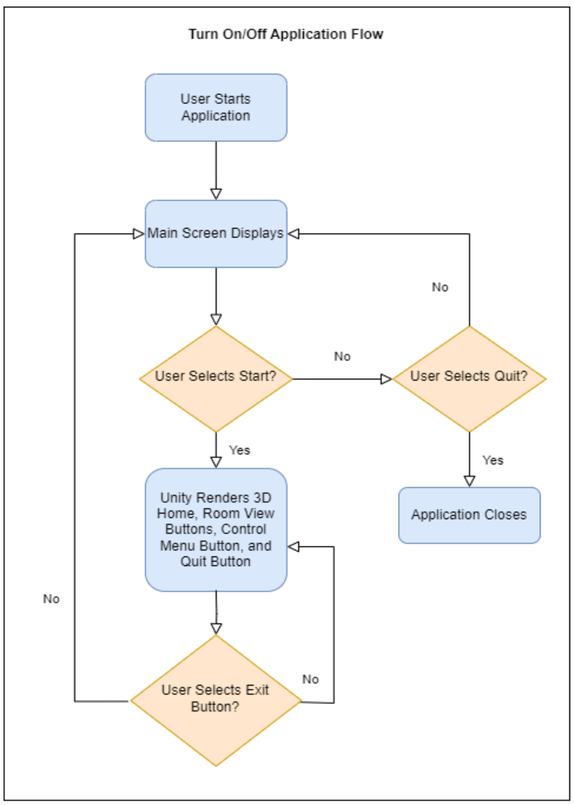

Figure 10: Turn On / Off Application Flowchart

In the application the environment adjusts to this configuration and the hardware model turns on or off sunlight pointed to the solar panel. For the load, the user can choose either an AC or DC load. These options adjust based on the configuration of the other settings, so we will be requesting the settings in order. Lastly, the user can choose their power source. They can either choose to use the PV battery or the grid. This is also related to being able to protect your home from grid cyber-attacks by switching your home source to the battery charged by the solar panel.

VII. Conclusion

Overall, as the U.S. electric grid continues to evolve, there are new challenges arising for the protection of its resilience and reliability. This project successfully completed the development of a model smart home that functioned as a high fidelity testbench for an attack detection and prevention algorithm developed in the UCF Digital Grid Laboratory. The UCF Digital Grid Laboratory is currently working on researching this complexity and how to ensure that our power systems are protected from cyber threats. This project can be integrated with their attack detection algorithms to continue the research.

Acknowledgement

We would like to express our gratitude to our advisor, Professor Sun, for his guidance, feedback, and continuous support. We also want to acknowledge Professor Weeks and Professor Chan for their valuable contributions and excellent suggestions. Your support has been key in enhancing the quality of this project.

Furthermore, we are incredibly grateful to the UCF Digital Grid Lab for their financial support, which has made this project possible. Your generosity is greatly appreciated, and we hope that this project will be useful to your team for many years to come!

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