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Automatic Residential Load Offsetting via Battery Energy Storage System

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Abstract

Electric power delivery is based on a real-time supply and demand process. Residential consumers using electrical grid, off-grid, and photovoltaic solar collection systems can benefit from secondary energy storage. Storing primary grid supplied electrical power or integrating a battery energy storage system (BESS) gives a homeowner the ability to manipulate household electrical load timing that best suits their daily and seasonal needs. Current trends indicate that electrical utility companies will primarily set time-of-use (TOU) billing schedules in most US markets. Under these plans electric rates shift daily and seasonally depending on the demand of the electrical utility grid. The goal of this project is to develop a convenient system that allows homeowners to optimize their electrical usage through an automated controller and BESS. Homeowners on the electrical grid can effectively reduce their monthly bill by shifting when they use electricity throughout the day. An energy controller dramatically simplifies the process by automatically making load shifts, to and from the BESS. Mechatronics engineering fundamentals will be utilized to build a successful product. Mechanical engineering components include relay switches, motors, 3D-printed parts, and automated functionality. Computer engineering and controls are also central to the design with the use of a coded Programmable Logic Controller (PLC).

Keywords: Energy Storage, Optimal Load Shifting, Smart Grid

1. Introduction

The demand and investment in "behind the meter," residential applications of battery energy storage system (BESS) equipment and related technologies are growing rapidly, with expectations of behind the meter storage accounting for 45% of the overall energy storage market by 2019[1]. Applications in the US have drastically increased from 0.2 to 14.1 megawatts between the third quarter of 2013 and the third quarter of 2016[2]. Primary contributing factors are the administration of time-of-use (TOU) billing schedules by companies such as *Duke Energy*[3] and Critical Peak Pricing billing plans by companies such as *Sempra Energy*[4]. Demand and growth in this area are projected to double every 2-3 years[2]. The highest level of investment in the United States for the third and fourth quarter of 2016 was in the residential sector[2]. Relatively new automated energy storage devices like the *Tesla* Powerwall experienced increased exposure in recent years. The Powerwall priced at $3500 uninstalled, requires additional purchase of an inverter and the incorporation of a 10 kWh battery in its design[5]. Meanwhile, the end-product of this research will be a standalone controller with similar functionality, available at a substantially lower price.

On the institutional level, current research targets determining the most efficient use of available energy sources and storage technologies, while rapidly developing the next generation of energy schemes. For example, the incorporation of available and alternative energy sources and energy storage through grid-connected photovoltaic (PV) systems with BESSs provides the greatest benefits to cost savings for the consumer and energy efficiency on the grid level[6]. This example utilizes a solar array and back-up battery, with a grid-tie inverter to convert energy from either power source, to AC power, synchronizes with the grid[7]. BESSs allow for more practical use of power from the grid and alternative energy sources, which is leading to an increase in use of BESSs on the residential and commercial levels[8]. These devices assist in the manual control of energy usage which may result in economic benefits for the consumer and increased electric grid stability as residential usage increases. However, an automated system maximizes these benefits by leveraging changing energy prices in billing schedules to optimize energy usage[9]. This project aims to utilize optimal defined strategies, developed in academia, to determine the best combination of existing energy, renewable energy, and low-to-zero carbon emitting energy sources. Given the seemingly infinite amount of unknown variables (e.g. local/seasonal intensity and exposure to sunlight, residential locale, national grid power system, etc.) current mathematical models such as so outlined by Hu, Entriken, and Ye in “A Mathematical Formulation for Optimal Load Shifting of Electricity Demand” lend quantitative suggestion yet lack concrete established data sets[10].

Our research forecasts that the combination of a grid-tied PV array system with a BESS offers the residential homeowner an efficient, cost-saving solution for utilizing stored energy (produced on-site or extracted from the grid when cost is lowest), while exhibiting opportunities for high investment returns to the emerging renewable energy market. The end-product of this project, an automated controller, should allow any grid-tied BESS homeowner further versatility and potential to reduce monthly power bills and energy usage.

2. Controller Design

This control unit is a self-contained device composed of hardware, programmed control algorithm, and a graphical user interface. The unit provides a means of efficiently integrating grid-tied power and on-sight battery-stored energy. Primary components include input interfaces for connecting the control unit to “behind the meter” electrical grid and to battery storage, an output interface that delivers power to the home, internal switching and blending components, programmable logic unit, safety fusing, and the means to support user-interface connectivity. Required elements include a residential scenario, low power scale model home, reactive and resistive load components, battery bank, controller (*Arduino* Mega or similar microprocessor), WIFI shield, *Bluetooth* shield, ethernet shield or USB, controller protective casing, programmable logic controller (PLC) programming in C-language, intercompatibility with user end scenarios, optimal user experience, a custom App presenting data and tracking power usage, and compliance with *UL* and *NEMA* safety standards.

As an overview, the final product will accept electrical inputs from a battery power source as well as grid power. The controller will determine how much power will be provided from each source (Figure 1). A scaled home which simulates a home’s power usage and costs for a set timeframe, using both resistive and reactive loading, will be used as a test bench. Based on an average residential home power demand from Duke Energy of 6000 Watts, a scaled down power of 650 Watts was determined for the model home[3]. The controller will be programmed in C-language and will exhibit safe, predictable operability. Team-built and off-the-shelf interconnected hardware, PLC programming, custom algorithms, and user input will be utilized. The user interface will allow for differing scenario options and provide visual power consumption data. If successful this project will educate consumers in basic electrical production and storage options. Ultimately, the controller will automatically decide between battery and grid power sources, which will lead to the consumer’s energy and/or cost savings for the consumer.

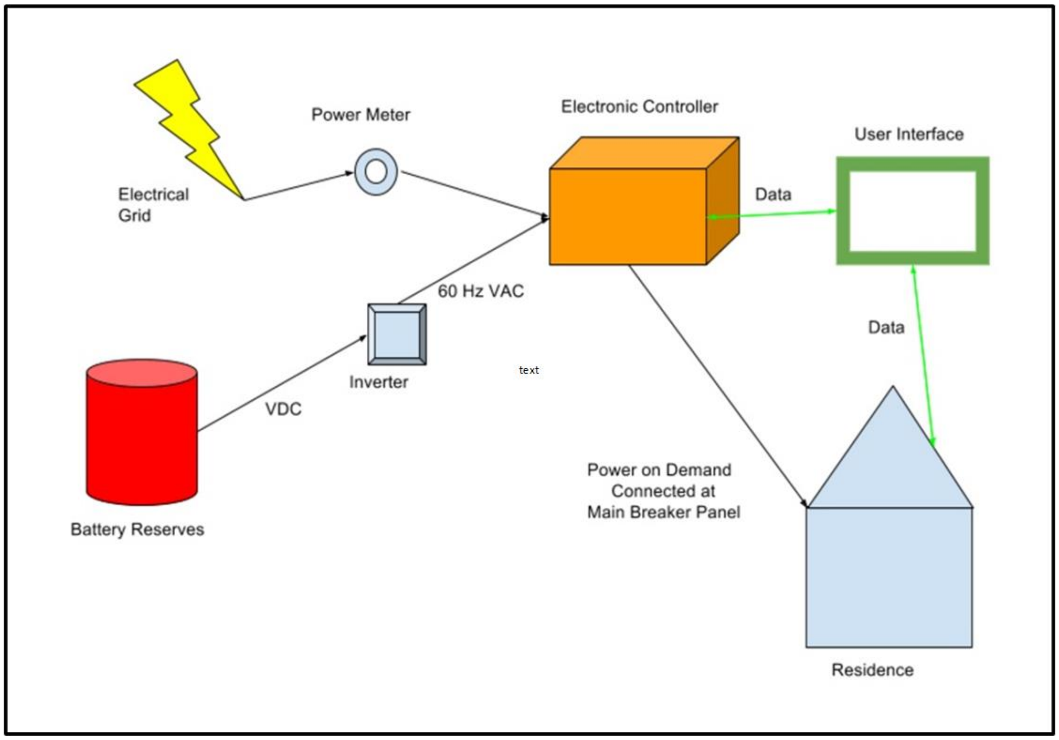

Figure 1. Electricity supply regulated by controller; flows from either the power distribution grid or a backup energy storage system delivered to residential home.

This design was created with several defining constraints. Each home is expected to have some sort of energy storage device to be paired with this controller (eg. BESS or other energy storage system, 48V or 24V capacity). The home's grid supplied electricity possesses a 120 Volt, 60 Hertz sinusoidal signal. There are no uninsulated accessible or visible wiring/connections. All components meet local, state, and federal safety standards. The controller is enclosed in a protective casing. The product possesses a simple and professional aesthetic. The product is economically optimized.

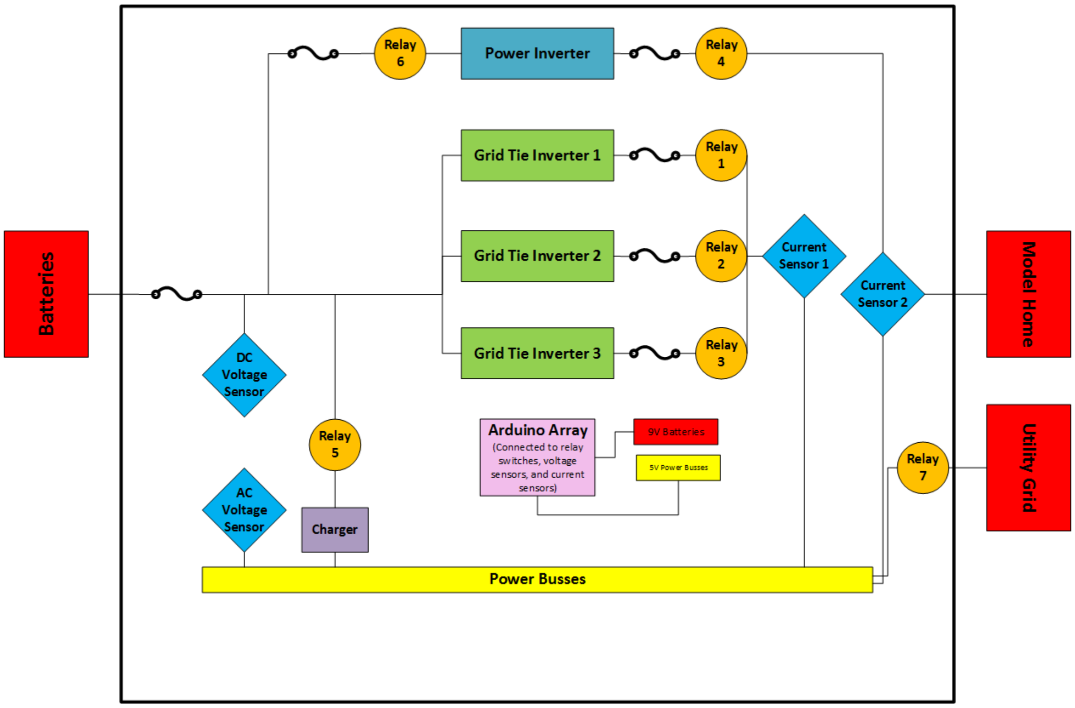

Figure 2. Proposed controller design includes: Grid Tie Inverters 1-3: *iMeshbean* 250 watt grid tie power inverters converts 10.8-30 VDC battery power to 120 VAC power synchronized with utility power.

Power Inverter: *Bestek* 300 watt pure sine wave power inverter, converts 12 VDC battery power to 120 VAC power unsynchronized with utility power. *Arduino* Array: One *Arduino* Mega and two *Arduino* Unos, *Arduino* Mega controls hardware by incorporating graphical user interface from one *Arduino* Uno and real-time-clock information from another *Arduino* Uno. Relays 1-5: 5 VDC input voltage, 10A and 120 VAC rated, normally open relay switches. Creates a connection between two components upon receival of pin signal from the *Arduino* Mega. Relays 6-7: 5 VDC input voltage, 30 A, 120 VAC and 30 VDC rated, normally open relay switches, creates a connection between two components upon receival of pin signal from the *Arduino* Mega. Current Sensor 1 and 2: ACS 712 30A rated current sensors, measures current between grid tie inverters and power busses and between the model home and power busses. DC Voltage Sensor: 24 VDC rated voltage sensor, measures voltage across batteries. AC Voltage Sensor: 120 VAC to 12 VDC voltage transformer connected to a 24 VDC rated voltage sensor, measures voltage across power busses. Power Busses: The central location for power connections within the controller. Charger: 120 VAC to 12 VDC battery charger .Batteries: Two 12 VDC, 135 Ahr batteries that store and release excess power. Model Home: scaled model of typical home owner power demands. Utility Grid: Power available from electrical grid.

The proposed controller incorporates three 250 Watt grid tied inverters and one 300 Watt pure sine wave inverter to provide the user with auxiliary power during all potential cases. The primary use case involves optimization of utility power usage for both cost and demand-leveling purposes. A potential user would desire the ability to use all home appliances freely during any time of the day while avoiding purchase of power from the utility company during peak-rate hours. To meet both constraints, a BESS must operate in conjunction with utility power. Grid tie inverters provide this capability, allowing a user to convert DC energy to AC power that may function simultaneously with grid power. The operation of a grid tie inverter is dependent upon the operation of the power grid. This is because the inverter measures the input sine wave of power from the grid to produce 120 VAC synchronized with the phase angle and frequency of the utility grid power. In order to remain in compliance with energy regulations, a grid tie inverter must shut down upon disconnection from the grid to avoid unsafe power feedback during a power outage (Figure 2).

To optimize a user's power cost and utilization, three grid tie inverters are "stacked" (used in conjunction with one another). The tiered stages include: all grid tie inverters are turned off, one is on, two are on, or all are turned on (Figure 2). The model home used demands +/- 700 Watts maximum, meaning the grid tie inverters can provide full power to the model home when all are used. The project team justifies this because of the nature of grid tie inverters; when turned on, a grid tie inverter always produces its maximum power, regardless of power demand. Any power left unused is provided to the utility grid. Because the defined user desires cost efficiency, the grid tie inverters must be used in a manner that minimizes the power lost to the utility grid. Thus, the software only turns on an additional grid tie inverter when the power demand is high enough to be cost effective. Another method explored was the use of pulse width modulation to control the power output of the grid tie inverter. Although this method was potentially effective, preliminary tests suggested it was too unreliable for the time constraints inherent in the project (Figure 2).

Having a source of backup energy is an additional requirement of the controller in the case of a utility power outage. For this constraint, a pure sine wave inverter is used. This auxiliary options maximum power output is 300 Watts, it cannot supply the full power demand of a home; a characteristic similar to off-the-shelf back-up generators. Additionally, limiting the user to about one third of their maximum power demand allows the user to conserve stored battery power in case of an emergency. The batteries are kept charged by a combination of grid tie inverter and utility power during the time when utility power is on and may be used until discharged by the pure sine wave inverter (Figure 2).

The interaction of these inverters with utility power, the model home, and the batteries is controlled by one *Arduino* Mega microcontroller, two *Arduino* Uno microcontrollers, seven relay switches, two voltage sensors, and two ACS712 current sensors. The Arduinos control these components; one *Arduino* Uno acts as a real-time-clock (RTC) emulating a model “day” on the TOU schedule, another *Arduino* Uno serves as the user interface, and the *Arduino* Mega runs the controller algorithm, receiving inputs from and providing outputs to each of the listed components (Figure 2).

The relay switches receive low power inputs to control high power energy paths. Relay switches 1-4 control the release of 120 VAC power from each of the inverters to the home. Relay switch 5 controls the release of 12VDC power from the charger to the batteries. Relay switch 6 controls 12VDC power to the pure sine wave inverter. The pure sine wave inverter does not turn off when disconnected from AC power and therefore must be shut off on the DC power side to prevent additional energy loss. Relay switch 7 controls connection to grid power. This is crucial to prevention of power backfeed into the utility grid in the event of power outage.

The current sensors are utilized to calculate power, assuming a voltage of 120 VAC, and to determine the optimal number of grid tie inverters to use. Current sensor 1 measures current released from the grid tie inverters. Current sensor 2 measure current entering the model home. The difference between the readings of current sensor 1 and current sensor 2 indicates the amount of power lost to the wall. Using these readings, the software minimizes this loss (Figure 2).

Voltage sensors are used to determine use of the battery charger and pure sine wave inverter. The DC voltage sensor is composed and *Arduino* compatible voltage sensor that utilizes resistors to divide input voltage of up to 25 VDC to a 0 to 5 VDC input for *Arduino* reading. It is used to determine when the charger should be turned on. The AC voltage sensor is composed of a 120VAC to 12VDC transformer and another 0 to 25 VDC voltage sensor. It is used to determine when the utility power has failed and the pure sine wave inverter should be turned on (Figure 2).

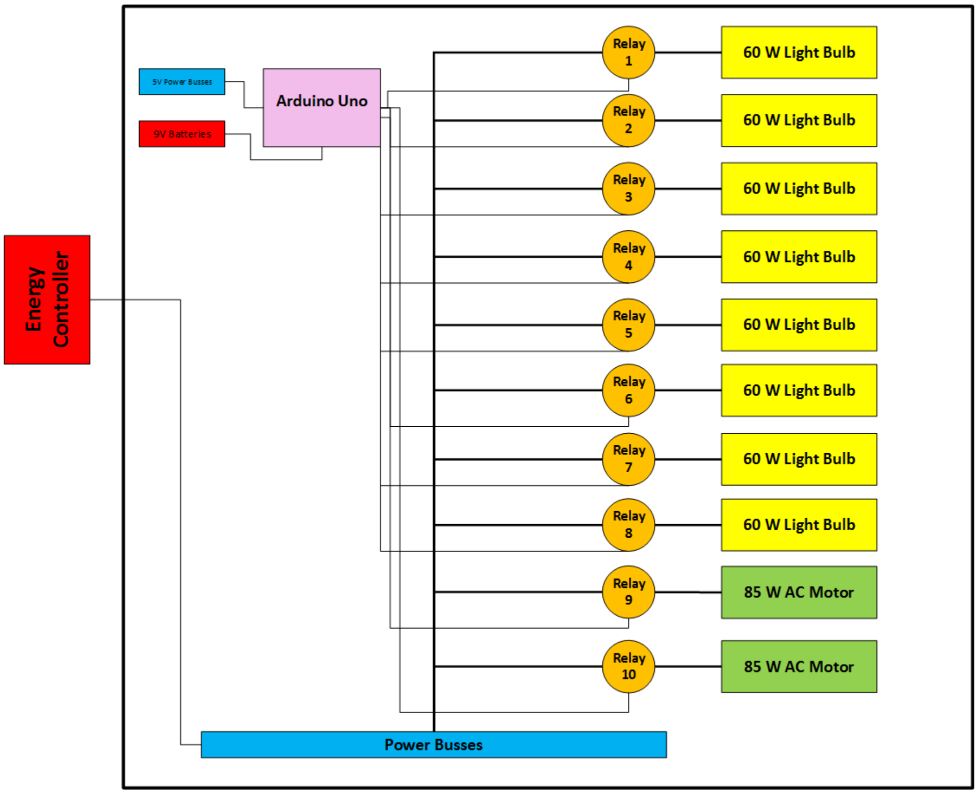

Figure 3. The model home, isolated from the controller, behaves autonomously and serves as test bench for the proposed controller.

The model home emulates a typical power demand of an American home. According to *Duke Energy*, the average power factor of a residential home in their servicing regions is 95%[3]. In an attempt to simulate a real scenario, both resistive and reactive loads are incorporated into the model home design. A value of 480 W maximum power is demanded by the eight light bulbs representing purely resistive loads while 170W maximum power is demanded by the two motors possessing a combination of resistive and reactive power. The average power factor of the model home is about 90% according to the Emon *Arduino* library[12].

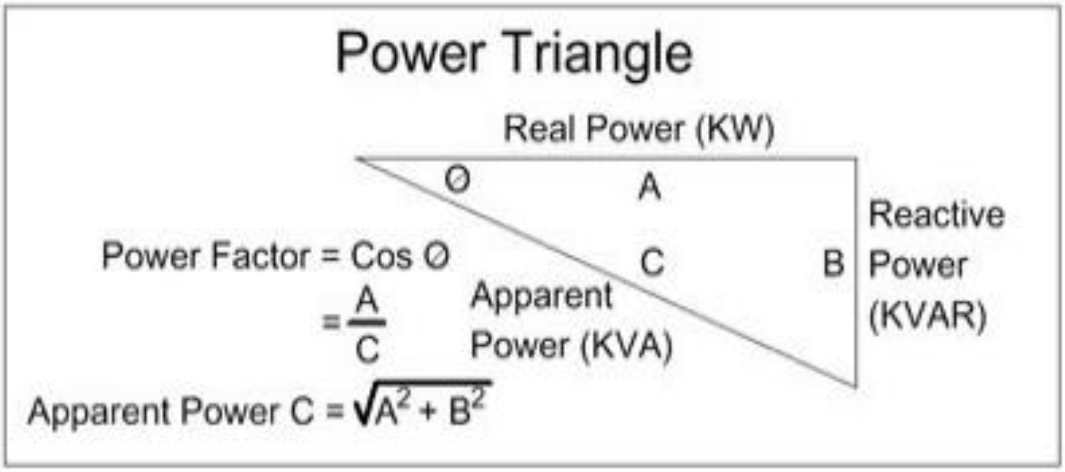

Figure 4. The power triangle, displaying resistive, reactive, and apparent power and the relations between each.

The Emon *Arduino* Library provides *Arduino* code to measure voltage and current. These measurements can then provide power and power factor measurements. Instantaneous power is calculated by multiplying instantaneous current and instantaneous voltage. Real power is calculated by taking the average of the instantaneous power over a given sampling time, to reduce fluctuations. Root Mean Squared (RMS) voltage and current are calculated just as the name implies. First the instantaneous term is squared, the average is taken, and finally the average square root provides the RMS value. Apparent power is calculated by multiplying the RMS voltage by the RMS current. Finally the power factor is determined by dividing the real power by apparent power (Figure 4)[10].

The *Arduino* (Figure 3) controls the relays connected to each light bulb and motor to simulate a typical day of power demand, turning appliances on at various times to prompt a reaction from the controller.


User Info

TOU SCHEDULE
California TOU

DAYLIGHT SAVING TIME
PST - Paci...

BATTERY BANK CAPACITY
24V

BATTERY BANK VOLTAGE
278

Figure 5. User App Graphical Interface - *Blynk* App ‘project’ titled “User Info” includes three drop-down select menus, two power vs. real-time graphs, a voltmeter, and an App notification in case connectivity is offline.

The graphical user interface is an implementation of an *Iphone* or *Android* compatible App that optimizes the homeowner’s experience. *Blynk* software is an App interface created by MIT students to enable *Arduino* users to customize ‘projects’ and populate them with widgets[11]. Several different widgets are available to communicate with the *Arduino*. The *Blynk* ‘project’ displayed (Figure 5) is named “User Info” and can be shared with the homeowner once they download the *Blynk* App. Three options for connectivity include: *Bluetooth*, WIFI, or USB. Once the *Blynk* ‘project’ is online, the user chooses the state or local region applicable in TOU SCHEDULE and DAYLIGHT SAVINGS TIME ‘menu’ widgets to sync real time with the controller. Next, the top graph is Home Power Usage vs. Real Time and the bottom graph is the resident’s Power Usage Minus Effective Load Offset vs. Real Time(Figure 5). The bottom ‘gauge’ widget is representative of the battery bank’s charge. Finally, the user can receive notifications on their phone for two instances: 1) when the ‘project’ goes offline or loses connectivity, and 2) if the battery charge dips to below a healthy threshold. Both notifications are preventative measure to keep the user attune to malfunction (Figure 5).

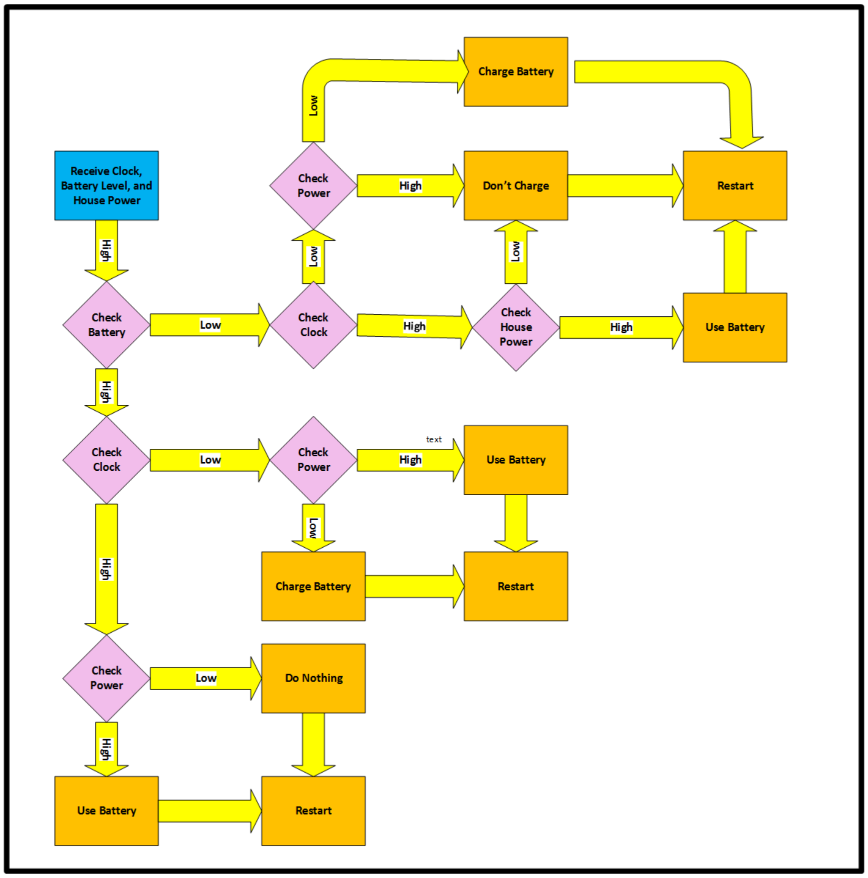

Figure 6. Software logic for master *Arduino*, clock runs uninterrupted on a slave *Arduino*

The microprocessing unit used for the controller includes a master *Arduino* Mega board and two slave *Arduino* boards. The flowchart above (Figure 6) maps the conditional states of the controller and the functional tasks related to that state. The master board maintains primary control and responds to the power demand presented in the model home. One of the two slave boards maintains a real-time-clock (RTC) completely uninterrupted by data flow or processes by the master board, and the alternate slave board is utilized for the *Blynk* App software[11]. *OpenEnergyMonitor's* "EmonLib" is an *Arduino* library of energy and power calculations. This resource proficiently provides all the mathematical calculations needed for this project[12].

The logic of the flowchart is organized to incorporate house power demand, TOU, and battery level (in that order of priority) into ensuring optimal circumstances. For example, if the battery level is low and the TOU tariff is low, the battery may be charged provided the home does not have a high power demand. However, if the battery level is low and the TOU tariff is high, there is no time when charging the battery would prove economically or power demand efficient and therefore the battery is not charged (Figure 6).

4. Discussion

Preliminary results gained throughout project development suggest that by combining home-generation of electrical energy with a BESS, homeowners can reduce their monthly out-of-pocket costs. Additionally, stored energy can be used at calculated optimal times. Based on the project's limiting factors and our expertise, the components utilized in this experimentation maintain adequate efficiency however, less than desirable. Integrating higher efficiency components such as micro inverters could improve adeptness. There also may be ways to further optimize the control algorithms to react more effectively to TOU schedule and energy generation schedules e.g. (for PV and wind generation owners), thereby allowing for more technological advancement in related generation and storage areas. Currently, behind-the-meter, distributed micro-storage systems can perform the desired function of adding significant value in offsetting monthly energy usage billing at the residential level; however, the cost to implement such systems is not viable to the wider sector of homeowners. Since proof-of-concept has been successfully demonstrated with 1) the design, build, and testing of this controller with the model home; and 2) the user interface; a consumer product has great potential to emerge in the upcoming future.

5. Societal and Ethical Impacts

As non-renewable resources deplete, future energy schemes must accommodate for the constantly growing demand on the power grid. Ethically, as global citizens, homeowners who benefit from services provided by the utility company should be conscious of all the stipulations and complexity involved with the current grid system. This algorithm provides the consumer an opportunity to come alongside the utility company to work together in making the most optimal use of energy resources.

6. Conclusion

The final product was successfully finished on time, under the allowed budget of $1500, and according to our target goals. We were mindful of IEEE, NEMA, and UL engineering & safety standards throughout the design, build, and testing processes. The final product successfully utilized three stacked grid tied inverters to offset electrical utility grid usage. During times of peak demand, the controller automated the process of energizing the appropriate number of grid tied inverters to meet the power demand of the model home. The model home worked well as a scaled residential test bench for the controller. The backup inverter also successfully powered the model home during utility power outages. The controller again automated the process by shutting down the grid tied inverters when a power outage was sensed. The backup inverter was then energized as power was demanded from the model home. When grid power returned, the backup inverter was shut down and the grid tied inverters energized again as needed. A battery charging mode was also successfully implemented, to charge the batteries during off-peak hours. The user interface was able to track battery voltage, and power demand from both the utility grid and the grid tied inverters. Given more resources (time, money, expertise, etc.) improvements in controller design could have provided a more sophisticated algorithm to approach unique TOU and other residential schedule needs.

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