Vehicle-to-Grid as an Energy Storage System

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***Abstract*—With the increased use of electric vehicles (EVs), peak loads on the electric grid have soared higher than ever before due to the massive amounts of energy transferred through charging these vehicles. As the load on the grid increases past the support of renewable energy sources, other methods are required to produce the extra energy needed, typically harmful to the environment. A new technology called vehicle-to-grid (V2G) seeks to solve this problem by allowing the transfer of energy from the EV back to the grid to support the grid during these peak load times. This project focuses on a scaled down test system as a proof of concept for V2G technology. This test system will be developed by designing a bi-directional battery charge controller, battery monitor, control system, and user interface to allow the user to control and track energy transfer between the EV battery and DC Grid.**

Keywords—Vehicle-to-Grid, Electric Vehicle, Energy Storage System, V2G

I. Introduction

This project will explore the idea of implementing electric vehicles (EV) as energy storage devices (ESS) for the grid, through Vehicle-to-Grid (V2G) technology. As the grid reaches peak load, electric vehicle batteries can be used as power banks to support renewable energy sources while they cannot provide enough electricity.

This project stemmed from the issue of peak load on the grid. During these hours, more energy is being drawn from the grid than renewable energy sources can produce, causing power generation to be amped up in more expensive and less environmentally friendly ways. One solution proposed for this problem is the investigation of energy storage systems as an alternative support method for renewable energy sources. These systems can be used essentially as a power bank that holds charge until the grid is required to provide more. During peak load hours, the grid would then draw energy from the energy storage systems, providing the extra electricity needed without generation through other means.

One method of ESS, V2G, has been emerging in popularity due to the dramatic increase in electric vehicles in everyday life. Electric vehicles themselves are actually a huge cause of unstable load for energy grids in traditional grid-to-vehicle (G2V) mode, where energy is transferred from the grid to the EV by charging. However, the introduction of V2G may be a solution that could solve both problems.

For the scope of this project, the implementation of V2G will be investigated through the design and development of a V2G system between EVs and a DC grid. The project constraints are limited to the V2G system between the EV and the DC grid, focusing on controlling the energy conversion and transfer based on the user's desire and schedule to ensure the feasibility of V2G. This project will not investigate the statistics and algorithms of peak load hours or convert the energy to or from an AC grid.

II. Vehicle-to-Grid

A. The Concept of Energy Storage Systems

In many electrical systems, energy storage is crucial to the functionality of a system. Excess energy needs a place to go in order not to be wasted. In electrical systems, there are many solutions to the energy storage issue. Energy storage units such as battery, thermochemical, thermal, pumped energy storage, compressed air, hydrogen, chemical, magnetic energy storage, and a few others can be found [1]. In terms of energy within the electrical grid, there are few options available.

The electrical grid provides power to different loads such as residential homes, commercial buildings, etc. Under conditions where the electrical grid has an excess amount of power available, there needs to be a place for the excess power to be stored. The answer to this may lie in an increasingly popular load that is being placed upon the electrical grid, EVs.

B. Application of V2G as an Energy Storage System

Since EVs have become more prevalent, a system called V2G has become an increasingly popular idea to support the power grid. The idea is that an EV on charge can store excess energy within the grid and supply energy when the grid needs it during peak load conditions [2]. Currently, batteries, namely

Lithium-ion (Li-ion) batteries, dominate EV energy storage applications [3].

Besides having a place to store the excess energy, energy management is an important aspect of V2G. Energy management describes the methods used to optimize power flow between the power grid and EV energy storage units during charge and discharge cycles. For example, one alternative would be a switching bi-directional buck boost converter to regulate power between the energy storage unit and grid [4]. Other than hardware, energy management also includes complex control algorithms. These algorithms coordinate charging based on time and grid power demands [5].

Finally, monitoring energy within the V2G system is important. One method chooses the optimal time to manage power distribution by collecting the state of charge information from the EV battery wirelessly [6]. With this information, the control algorithm can determine how to manage the power in the system based on the state of charge [6].

C. *Design Approach*

The V2G system interfaces the electric vehicle with the DC grid as shown in Fig. 1. The user will be able to turn on the system to the traditional G2V mode (charge only), or V2G mode through the User Interface (UI), which then notifies the control system, which is a programmed microcontroller that determines how and which way the power should flow at any given time based on the information from the user input, the battery state-of charge (SOC) monitor, and the current sensors. The charge controller then controls the charging and discharging cycles bi-directionally between the EV battery and the DC Grid, given instructions from the control system. When the grid reaches peak load the current sensors will notify the control system, and the DC grid will be able to draw power from the EV battery treating it as an ESS.

Project development was split into four steps: understanding theory, study of design methods, part search and design, and testing. The development process was further split into 4 main design sections, with members splitting into separate groups and working on the charge controller, SOC monitor, control system, and user interface concurrently. This ensured maximum design experience for all members of the group as each member experienced the entire design process for an entire section.

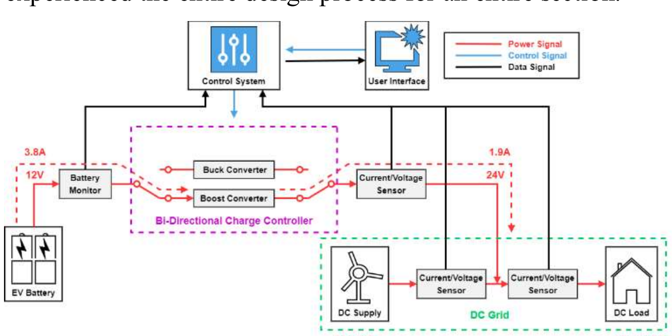


Fig. 1. Block diagram of the system detailing the directions of power flow

D. *Additional and Safety Considerations*

Globally, this project is meant to benefit EV owners as it involves maintaining stable energy transfer to and from the battery in the V2G system to solve the issue of an overloaded grid. Since EV users are not as abundant as gas car users, this design offers a chance to show that EVs can be more than just a means of transportation but can be utilized as an ESS as well as a bi-directional charger to support the grid when at peak load. With more people gradually converting to owning an electric or hybrid vehicle, the emissions of pollutants from gas will be significantly reduced. This system would generally benefit larger cities since the possibility of them incorporating this design is highly likely with there being more electric vehicle users compared to smaller cities.

A concern with V2G is that allowing a utility to draw on the energy storage from stationary vehicles would increase the stress on the batteries. This causes a question of who would cover the cost of battery replacements in this scenario. With that being said, the performance of the battery is not harmed, it is enhanced. This in turn will reduce fuel consumption and costs thus reducing emissions.

For the project the handling of these items will be present; low voltage electricity, solders, and Li-ion batteries. PPE like insulated tools and gloves, eye wear, venting for solder, and safely monitoring the Li-ion battery were used during the making of the V2G system. Putting safety first was primitive to prevent any damage or harm to one and the equipment used. The team worked on the project with no less than two people at a time. This buddy system allowed a safety net in case an accident occurred for one individual while the other was able to get aid or call for help.

III. Methods and Procedures

A. *Bi-directional Charge Controller*

The bi-directional charge controller was designed to control the direction of power flow within the V2G system. The bi-directional charge controller needed to step down a voltage of approximately 24V to a voltage of approximately 12.6V. Also, it needed to step a voltage range of 9V to 12.6V to a voltage of approximately 24V. With these voltage requirements in mind, the bi-directional charge controller was implemented using individual buck and boost converter modules. The converters were toggled based on which direction the power was designated to flow by two relays on the input and output sides of the converter modules. Fig. 1 includes the design of the bi-directional charge controller. The DROK 180078, max output current of 4.5A, was chosen for the buck converter, and the TPS55340, max output current of 1.9A, was chosen for the boost converter. The DROK 180078 is equipped with a constant current function to control the maximum current allowed to flow into the battery. This helps maintain a healthy charge cycle for the battery. The current limit was set to 2.6A, the specified fast charging current listed by the battery. The relays chosen were the HiLetgo 5V One Channel Relay Modules with a 10A current rating. Diodes were added to the outputs of the converter modules to prevent reverse currents.

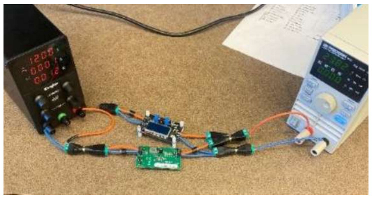


Fig. 2. Test Setup for Bi-Directional Charge Controller Efficiency Test. Top module is DROK 180078 Buck Converter and bottom module is TPS55340 Boost Converter.

An efficiency test was done on the components of the bi-directional charge controller disregarding the relays. Fig. 2 shows the test setup. The individual buck and boost converters were connected to the power supply on the input and the DC programmable load bank on the output. The load bank was adjusted to pull an increasing current through the converter that was connected to the power supply. The input and output power of the converters were recorded along with their efficiencies at various output currents.

B. SOC Monitor

For the SOC monitor, the MAX17263 was used to provide accurate charge readings of the 12V Lithium-ion battery to the Control System. The MAX17263 is a battery fuel gauge that monitors multi-cell battery fuel packs. It uses the ModelGauge m5 algorithm that combines the short-term accuracy of coulomb counting with the long term stability of open-circuit voltage (OCV) to provide an accurate battery SOC as a percentage.

Using the MAX17263GEVKIT evaluation module (EVM), the MAX17263 was easily implemented into the system through the EVM's pre-designed voltage divider circuit, measurement LEDs, and I2C connections (to connect to the control system). This allowed the fuel gauge to connect directly to the battery and V2G system without designing the fuel gauge circuit itself. The EVM could also be connected to a PC through the USB connection that allowed for easy testing through the EVM's software. Fig. 3 shows the testing through the software.

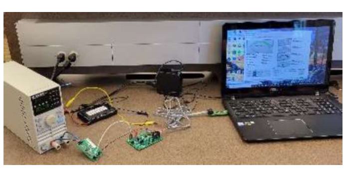


Fig. 3. Testing of the fuel gauge with load bank, battery, and PC software.

C. User Interface

The UI consists of an android app created using the Massachusetts Institute of Technology (MIT) App Inventor software and an Arduino RP2040 Connect microcontroller. Interaction between the user and the V2G system was accomplished through the user's input in the app, which then signals the changes through Bluetooth Low Energy (BLE) to the Arduino, which acts as the main computer of the UI. From the app, the user is able to send requests such as changing the charge mode of the battery to off, G2V, or V2G mode. The user is also able to select a charge time for how long they want to leave the EV with the system. Taking the information sent from the app to the Arduino, the Arduino then relays the relevant changes to the separate RP2040 Connect of the Control System through the Universal Asynchronous Receiver-Transmitter (UART) serial bus. Testing consisted of establishing communication between the app and the Arduino, and between the Arduino and the Control System (Fig. 4).

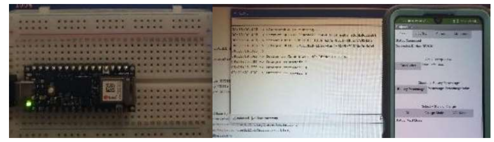


Fig. 4. Testing between the UI's app (right) and Arduino (Left.

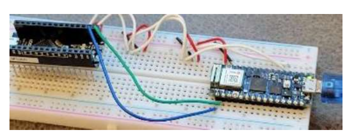
D. Control System

The control system contains the "brains of the V2G systems and was programmed on the Arduino RP2040 Connect microcontroller. The two cores were utilized with core0 updating the measured voltages, currents, and battery SOC, and sending the updated data to the UI, and Core1 checking for input from the UI for which charge mode the V2G system is in and determining the direction of the power flow using the main algorithm to switch the relays in the charge controller. The algorithm determines the power direction by checking for three main factors, assuming the user selected mode is V2G:

1. Is the timer off or above the time needed to charge the EV fully?
2. Is the battery SOC above halfway (for battery health)?
3. Is the DC grid load trying to draw more current than the DC grid supply can provide?

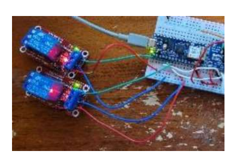
While the user would typically select a time to pick up the vehicle, this project used a timer for a scaled down version of the same purpose, where the user sets a timer and the system switches to charge only before a selected time frame to ensure the EV is fully charged by the end of the timer. The SOC limit was 40% to keep about half charge. The current grid load current limit was set to 2.5A.

Tests were conducted on separate functions: the readings of the ADCs through I2C for voltage and current on the high-voltage side (DC Grid) (Figure 5b), the readings of the battery fuel gauge for voltage, current, and SOC through a separate I2C bus, reading from the UI through UART (Figure 5b), sending to the UI through UART (Figure 5a), and running the algorithm to control the relays (Figure 5c).



a)

b)



c)

Fig. 5. Testing between control system Arduino and components
a) UART between control system and Arduino Nano (for testing)
b) Fuel gauge and ADCs between battery, power supply, and electronic load.
c) Control System algorithm to control charge controller relays.

E. Final Setup

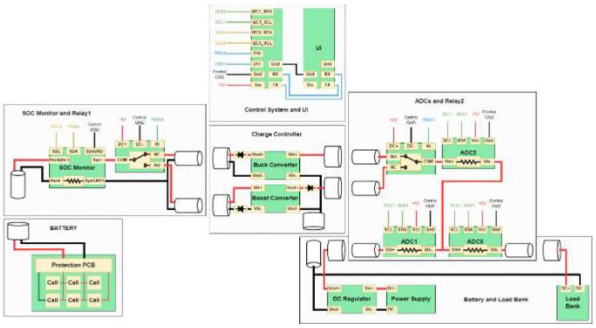


Fig. 6. Connections of the Final V2G Setup

The final setup consisted of the remaining testing apparatus, and the individually designed sections previously mentioned. The testing apparatus consists of the DROK DC Power Supply, DROK DC Buck Converter, B&K 8540 DC Electronic Load, and a 12V Li-ion battery. Using the buck converter as a current limited voltage regulator for the power supply, the power supply was set to 30V, and the regulator reduced the voltage to our DC grid voltage of 24V. By limiting the current with the voltage regulator, a limited renewable energy source was simulated. Lastly, the electronic load simulated the load on the grid, as the current being drawn from it could be adjusted to allow the V2G to react when higher loads were being drawn on the grid. Fig. 6 shows the final setup and their connections. Testing of the final setup consisted of initially switching the relays manually to ensure that power flows in the correct direction when either converter of the charge controller was on. Then implementing the control system with fixed values for two of the factors at a time, with the final one being varied, and lastly with the user interface.

IV. Results

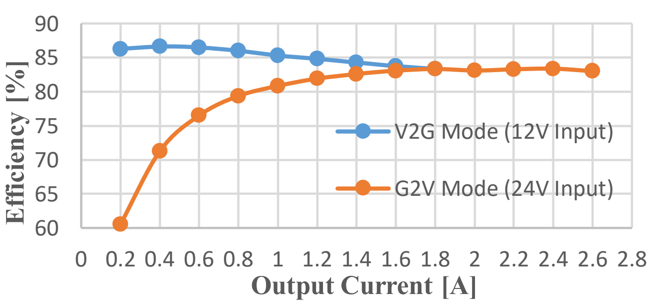


Fig. 7. Efficiency vs. Output Current of the Bi-Directional Charge Controller in V2G and G2V Mode. Power flows through the boost converter from power supply to load bank in V2G. Power flows through the buck converter from power supply to load bank in G2V.

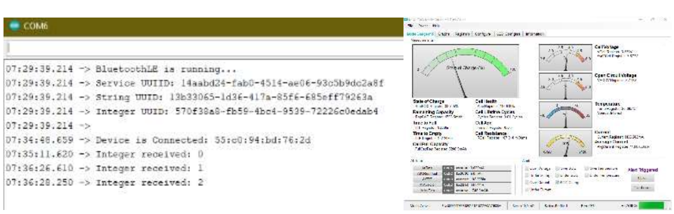


Fig. 8. Serial monitor showing successful BLE ommunication to app (left). SOC Monitor readings through EVM software (right).

Fig. 7 shows the efficiency versus output current of the bi-directional charge controller when it is set to V2G mode, and G2V mode. Fig. 8a shows the serial monitor on successful BLE connection between the Arduino and the app. Fig. 8b shows the readings of the SOC Monitor through the EVM software.

V. Discussion

The components performed as expected. During V2G mode, power flows from the battery to the load bank, indicating power flowing through the boost converter. During G2V mode, power flows from the grid to the battery for charging, indicating power flowing through the buck converter. The SOC monitor instantly picks up the SOC when the battery is initially plugged in and maintains consistency when charging and discharging. Between the UI and the control system, the two Arduinos were able to successfully establish communication by UART connection. Communication between the app and the Arduino has been successful as well with the app being able to send data requests. The control system was also able to read from the ADCs and SOC monitor and controlled the relays when the factor variables were changed. It was also noted that the electronic load prioritizes drawing power from the supply first. The EV battery acts as a secondary source of power to aid in the supply when needed.

VI. Conclusion

With the successful power delivery and control of this project, V2G can be proven to be a possible system to implement. With the goal of proving the concept of V2G, many projects can be created as a continuation of this project to help further the future implementation of V2G. Ideally, next steps would be to bring the scale closer to real EVs and moving towards using the real grid. Steps can be taken in between, such as using an AC grid, increasing power, voltage, and current constraints, and larger batteries.

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Aaron Mattox is a senior studying Electrical Engineering at the University of South Alabama. His primary field of interest is the application of embedded electronics. He is a member of the NSF funded CubeSat project SWARM-EX where he, Joshua Yang, and a graduate student at the University of South Alabama are designing the electrical power system. He is the EE departmental representative for Tau Beta Pi, USA's engineering honor society, member of the IEEE Power Electronics Society, and member of the IEEE Aerospace Electronics Society. Aaron has received President's Scholars List honors six semesters in a row, received the Earl O. Parish and Elizabeth Parish Memorial Scholarship, and received the Chevron Electrical Engineering Scholarship. His future plans consist of joining the Product Engineering Department at Dynetics upon graduation.

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