Developing Bi-directional Charging Functions for Electric Vehicles

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***Abstract*—Electric Vehicles (EV) are increasingly adopted by consumers in the U.S. and around the world. However, the EV draw lots of power from supply feeders for charging, leading to increased power losses in the power lines and depressed feeder voltages. The EV charging also interferes with normal operation of other motor-based equipment such as residential appliances. This study seeks a solution to mitigate the EV adverse impacts while improving its value for the owners. Specifically, the study investigates a technique to enable bi-directional charging (i.e. both charge and discharge) functions for the vehicles using AC-DC-AC converters. These functions can create additional benefits for the EV owners. They can make use of the EV battery power for running other appliances when desired, such as for camping trips. The bi-directional functions are also useful for the grid as the EV can inject their battery power to support the grid under emergency conditions.**

I. Introduction

The growing number of electric vehicles (EV) in production directly correlates to an increase in applications utilizing its capabilities. According to vehicle travel trend, the average personal electric vehicle travels on the road is less than 10 percent of the day. EVs can bring benefits to home energy management, especially to feed priority loads during power outages and other emergencies. From the point of view of the power grid, EVs can bring benefits to ancillary services and compensation for the renewable energy sources intermittency. Energy is stored in electric vehicles during the night-when the price is low, and is withdrawn during peak-time, when the price is high. Electric vehicles act like pumped-storage units and allow vehicle owners to gain revenue from the difference of prices and compensate part of the initial investment.

The growth in electric vehicles is mirrored in the amount of research that this growth is generating. In the article Bidirectional battery charger for electric vehicle, Kang Miao[1] begin by describing four ancillary functions electric vehicles can provide to the grid. Peak power is hard for an electric vehicle to discharge due to storage limitations, however this obstacle can be overcome if the vehicles aggregated or if there were refueling. Electric vehicles can have the option of providing these ancillary services during peak periods while consuming power during off-peak periods. Since spinning reserves are paid by the time they are available the arrangements can be favorable for electric vehicles. While connected to the grid there are considered spinning, yet incur short periods of generating power. Electric vehicles can be great for renewable energy storage and backup. Since a fair amount of renewable energy is generated during the daytime and remains unused, electric vehicles have the ability to act as capacitors and store it, which can be later used during off-peak hours.

Similarly, the article Accurate electrical battery model capable of predicting run-time and I-V performance Min and Rincon-Mora[2], propose and implement an accurate, intuitive, and comprehensive electrical battery model. The authors discuss the complexity of electric batteries and design a model that can be utilized in calculations and designs involving batteries. This model accounts for all dynamic characteristics of the battery, from nonlinear open-circuit voltage, current, temperature, cycle number, and storage time-dependent capacity to transient response.

A more developed example of this type of work can be seen in Bidirectional battery charger with Grid-to-Vehicle, Vehicle-to-Grid and Vehicle-to-Home technologies. In this publication Pinto[3] discusses a design, control algorithms, and hardware topology for a portable bidirectional battery charger, to be implemented in Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Home (V2H) situations. IGBT transistors are used to implement a full bridge rectifier. The rectifier circuit is connected to a reversible DC-DC converter circuit that utilizes two additional IGBTs in conjunction with an inductor and capacitor, to create a buck or boost effect for charging and discharging respectively.

In order to accomplish maximum amplitude of the individual current harmonics a single-phase Phase-locked Loop (PLL) is first implemented. Two sine waves with unitary amplitudes, shifted by 90 degrees are used to synchronize with the power grid. During the G2V operation mode, the full-bridge AC-DC bidirectional converter operates as active rectifier with sinusoidal current and unitary power factor. The buck portion of the DC-DC link is also active in order to supply the battery with the lower needed voltage.

During V2H and V2G operation modes the rectifier circuit is inactive and the boost circuit becomes active in order to get the DC link voltage to the rated amount. Voltage levels decrease during discharge mode, in order to keep the active power constant, current is proportionately increased. This is done by a PI controller that self-adjust its duty cycle for a PWM modulator. After design was completed the authors ran simulation test to calibrate the circuit using various values of passive components. The results validated the hardware topology and controls algorithms. Once calibrated a scale proto-type was created and tested.

In the case of V2G specifically, Gallardo-Lozano[4] shows that for the V2G operation to work properly, a Balanced Sinusoidal Source Current control strategy is proposed so that the charger demands or injects into the grid a perfect sinusoidal and balanced source current in phase with the positive sequence fundamental component of the phase-to-neutral grid voltage.

Regarding V2H, Tuttle[5] shows how Vehicle-to-Home capabilities can provide ancillary services in times of blackouts and grid distribution faults. Rooftop photovoltaic generation is required to shut down if the grids power is lost, to ensure the system does not back feed to the grid creating safety problems. However, a V2H system is able to maintain functionality to a islanded load. Data was taken from an ongoing smart grid demonstration study (Pecan Street Inc.) to estimate the instantaneous load that can be put on a PEV system. The overall Pecan Street study utilizes a test bed of 250 modern, green-built homes constructed after 2007, and 160 homes ranging from 10-92 years in age. The homes are instrumented with various forms of energy metering equipment, which tracks electricity, natural gas, and water use. Of the homes in the study, 185 have rooftop PV panels. The power production from rooftop PV is metered separately from electric demand. The study then utilized the PV production and electric demands from data collected over a year as inputs for the system and vehicle model testing.

The system consisted of a PV-PEV-PHEV combo system. The BEVs tested were 19.2 kWh and 32kWh. These values were taking from the rated values of the Nissan leaf and entry-level Tesla respectfully. First energy was consumed from the PV portion, and if load demands we less than the output of the PVs the BEV was charged to its maximum capacity. Once the PV exhausted its reserves the PEV was utilized, until finally the PHEV reserves were tapped. While the PHEV was in use the excess energy was used to charge the BEV which allowed the authors to calculate and map the state of charge vs. gasoline relationship.

During off-peak months, the PV output compliments the PHEV generator to substantially extend backup durations from a few days to nearly 25 days.

II. Methodology

Since the most widely used batteries for electric vehicles are lithium-ion (Li-Ion) and nickel-metal hydride (Ni-MH), I will begin by researching the recharge specifications and limitations for the two batteries. This will allow me to obtain rated performance and load drawing specifications, to optimize a design for both. With the necessary data, I will design electronic replica of circuit using circuit design software such as MultiSim. This allows me to get a global perspective of the design so that I may improve data flow paths and create a more compact design. After the electronic design is completed I will begin running test with software. To check that my control system is running efficiently, I will use toolboxes in Matlab (Stateflow and Control System) to run simulations. Once the design is proficient, I will Integrate the car battery charge-discharge and control system with power loads and perform simulation and analysis of the integrated system. The analysis aims to evaluate the effectiveness of the system in managing the interaction of the EV with the household appliances and the power grid. This will allow me to visually see how the components are working within the design and monitor both input and output current and voltages. With this data I am able to see phase differences between the voltage and current, and have the ability to correct it to reduce reactive power, maximizing power transmission.

III. Development of Bi-directional Charging Function: Modeling and Function Specifications

A. Battery Modeling

From the perspective of power grid, an EV is viewed as a load during charging and as a source during discharging. An appropriate battery model is necessary to accurately represent the characteristics of an EV battery. Likewise, a state of charge (SOC) must be implemented in the controls to select between the two scenarios. The electric circuit-based model is best due to its capability to represent the electric characteristics of a battery. The controlled voltage source is described by an equation developed by Shepherd[1]. This equation describes the electrochemical behavior of a battery in terms of SOC, terminal voltage, open circuit voltage, internal resistance and discharge current.

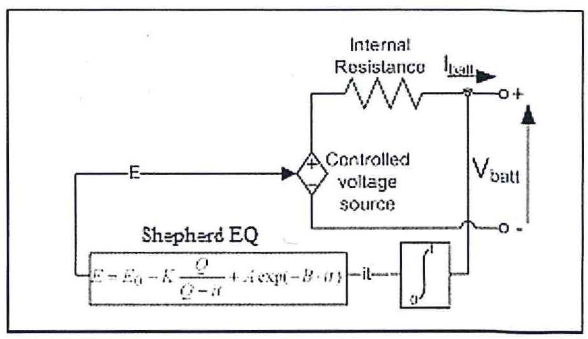

Fig. 1. Electric circuit battery model

The electrical battery model is able to calculate the SOC[2] of a lithium Ion battery by:

$$SOC = 100\left(1 - \frac{it}{Q}\right)$$

Fig. 2. State of charge equation

B. Bidirectional Battery Charger

The key components for an EV bidirectional battery charger are AC/DC converter and DC/DC converter. During EV charging mode, an AC/DC bidirectional converter rectifies the AC power to DC power. Meanwhile, the AC/DC bidirectional converter inverts the DC power of the EV battery to AC power and injects it to power grid during EV discharging mode. On the other hand, the DC/DC converter is responsible for controlling the bidirectional power flow by using direct current control technique. It acts as a buck or boost converter during charging or discharging mode, respectively[3].

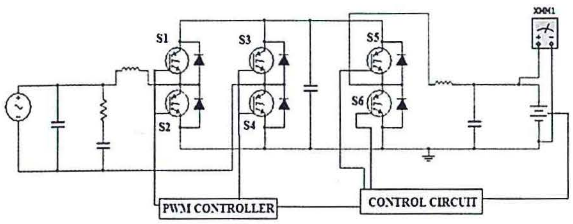

Fig. 3. Circuit design

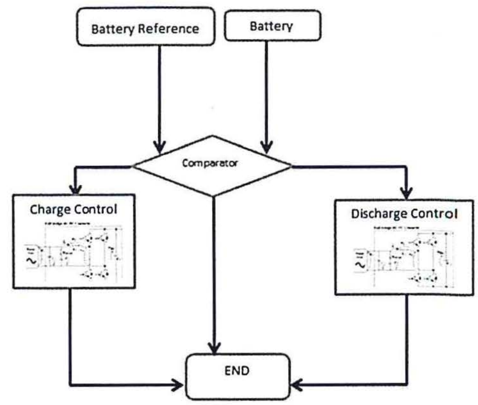

Fig. 4. State diagram

C. Controls

The direction of power flow can be represented by the direction of the current. In this paper, the direct current control technique is used to control the bidirectional power flow for V2G implementation. This control strategy is applied to the DC/DC converter where it acts as a buck converter when IGBT1 is triggered and as a boost converter when IGBT2 is triggered. DC/DC converters controller can be categorized into two control parts, which are the charging control and discharging control. Initially, this controller compares the reference battery current with the measured battery current to decide between the charging and discharging mode. This is an important procedure to decide the next step of the controller. For charging mode, the error between the measured battery current and reference battery current is computed. This error passes through the PI controller for tuning. The output of the PI controller will be used to generate pulses by using sinusoidal pulse width modulation (SPWM) technique. The pulses generated in this stage are used to trigger IGBT1. Throughout the charging process, IGBT2 is turned OFF. For discharging mode, the controller computes the error between the reference battery current and measured battery current. Then, the PI controller will perform the tuning of the calculated error. The output is sent to SPWM to generate the necessary pulses for IGBT2. During the discharging mode, IGBT2 is turned OFF.

D. Vehicle-to-Home (V2H)

Vehicle to home technology is a system that allows owners to utilize EVs as power source for home utilities. It requires the aforementioned bidirectional AC-DC circuit to be implemented. During the V2H operation mode the full-bridge AC-DC bidirectional converter synthesizes a sine-wave voltage with the desired amplitude and frequency to feed the home loads. In order to the full-bridge AC-DC bidirectional converter deliver back to the power grid the energy stored in the traction batteries, the DC link voltage must be slightly greater than the peak value of the power grid voltage. Therefore, the reversible DC-DC converter has to operate as a boost converter, once the traction batteries voltage is smaller than the required to the DC link voltage. The circuit is composed of two power converters that share a DC link. One is to interface the power grid and other is to interface the traction batteries.

1) Vehicle-to-Grid (V2G): Vehicle-to-grid (V2G) technology allows users to plug EVs directly into the grid and act as a power source to stabilize grid operations. The framework of V2G concept involves several important elements, such as energy resources, power utility, system operator, aggregator, bidirectional battery charging facilities, communication facilities, intelligent metering and battery management[4]. A bidirectional V2G charger has the similar benefits as unidirectional V2G charger, as well as can achieve load leveling, peak load shaving, reactive power support, active power regulation and harmonic filtering[2][5]. Furthermore, a bidirectional V2G concept can provide more system flexibility to power utility and offer significant financial benefit's to EV owner.

IV. Simulation and Results

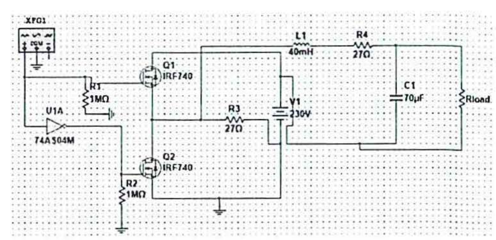

Fig. 5. Inverter

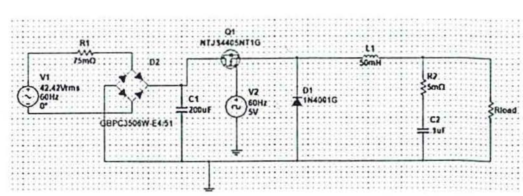

Fig. 6. Converter (Charger)

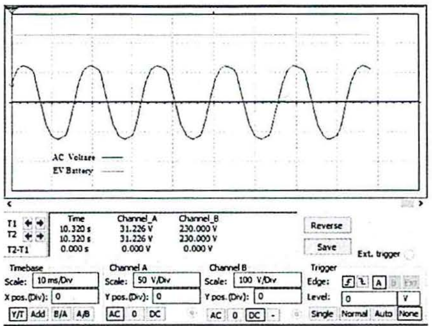

Fig. 7. AC output vs. DC input (Discharge)

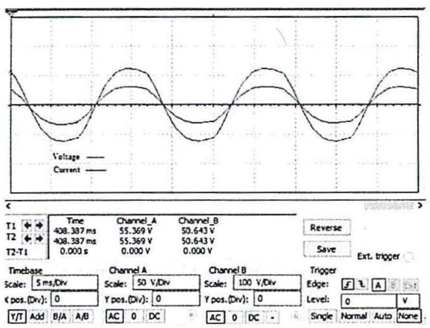

Fig. 8. Voltage vs. Current output (Discharge)

A. *Charge/Discharge*

The following figures (Fig. 5 - Fig. 9) represent a simplified replica of the circuit, and various forms of analysis and efficiency examinations. Fig. 5 shows a simplified circuit of all components which will be on during discharge (inverter). Fig. 6 depicts the the working inverter, with a 230V DC input, and 120V AC out at 60Hz. Fig. 7 depicts the voltage along with current AC sine waves in phase with one another with roughly the same amplitude (Note: a 1 kilo ohm resistor is used as load resistance). Fig. 8 shows a simplified circuit of all components which will be on during charging (converter). Fig. 7 depicts DC voltage and currents with one each roughly the same amplitude (Note: a 1 kilo ohm resistor is used as load resistance).

V. Conclusion

As of now I have completed the design for the bidirectional circuit. With a relative low load resistance and ideal passive components, currents and voltages, during both discharge and charge, has seen a relatively high efficiency rating. Currently working on methods to improve efficiency with a varying load resistance, while maintaining high power flow efficiency.

1) Future Work: After high efficiency is maintained, I plan to introduce varying passive components for a wide range of EV battery voltages before beginning the physical design. At which point I plan to create a program with a user interface which will monitor, initiate, and cease power transmission.

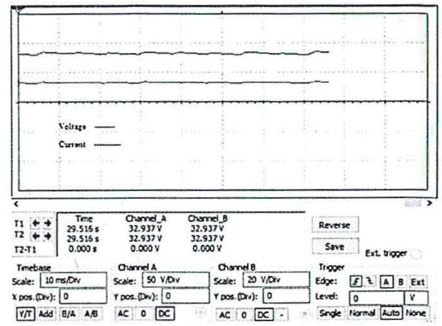

Fig. 9. Voltage vs. Current output (Charger)

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