Design and Simulation of V2G Bidirectional Inverter and DC-DC Converter

by

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Winter/Spring 2011
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Acknowledgements

We would like to thank the following people for making this senior project possible:

Professor Dolan for being our advisor and guiding us throughout this entire senior project.

The professors from the California Polytechnic State University, San Luis Obispo Electrical Engineering Department, especially Dr. Taufik, Dr. Shaban, and Dr. Nafisi for support.

Rithy-Newton Mao Chhean for the inspiration to do this senior project.

Lastly, our parents who challenged us to strive for our goals, as well as supporting us throughout our college career. Without them we would not be the person who we are today.

Thank You.

- Allan Agatep & Mason Ung
Abstract

As plug-in hybrid electric vehicles (PHEV) become more popular, the utility companies are forced to feed the grid more electricity. However, these PHEVs are capable of providing power to the grid when they are parked serving as ancillary systems for grid regulation (V2G). Using a system based on photovoltaic (PV) technology, a design for a bidirectional inverter with LCL filter, and a bidirectional dc-dc with a constant current controller, was constructed using LTspice. Various papers were researched and analyzed to determine applicable designs for components. Simulations show the designs are capable of bidirectional power transfer. ETAP simulations show that delivering power to the grid provides additional unnecessary reactive power. Additional design topologies are recommended for future work.

Keywords: Bidirectional, Inverter, DC-DC, PHEV, PEV, Vehicle-to-Grid, V2G
I. Introduction

Motivation

As the power system develops more renewable generation, the need for electrical storage is likely to increase. Today’s predominant renewable power generation fluctuates with the input (for example, sunlight or wind). At today’s levels, fluctuating renewable generation is adjusted via existing mechanisms (for example, by adjusting today’s fossil fuel generators up and down to compensate). At higher levels of renewable generation, storage, transmission, and controllable loads all become useful resources to smooth fluctuating power. [1]

Plug-in hybrid electric vehicles (PHEVs) with vehicle-to-grid technology V2G potentially have the capability to fulfill the energy storage needs of the electric grid by supplying ancillary services such as voltage regulation, and peak shaving.

For a typical location, the energy demand is at its highest around the hours from 5pm to 7 pm as shown in figure 1.

![Figure 1: Estimate Grid Demand Profile](image-url)
During these hours, power plants must ramp up generation in order to keep up with demand. Energy is expensive for the power utility to produce during these hours because the increased generation may come from high cost processes. In contrast, energy demand drops well below the baseline power generation during the late night and early morning hours. Energy during these hours is less expensive to generate for the power utility and also cheap for consumers to purchase.[2]

As electric vehicles become more popular, the utility companies are forced to feed the grid more electricity. Grid integration of plug-in hybrids could also provide storage for vehicle-to-grid (V2G), as cars are parked 95% of the time; reducing peak demand by 5000MW could be worth greater than $600 per car.[3]
II. Background

Scope of the Design

This senior project focuses on designing and verifying the operation of a V2G charging/discharging system. The V2G is based on the photovoltaic (PV) grid-tied technology with power electronics playing an important role both power transfer as well as grid regulation. The block diagram for the complete grid-tied system is shown in figure 2. The purpose of the design is to demonstrate that a bi-directional system can be achieved using minimal components.

![Figure 2: V2G Bidirectional System Block Diagram](image)

Although the entire V2G system is presented, due to given time restraints, the main focus of this experiment focused on the design of the bi-directional DC-DC converter and inverter power stages, as well as the inverter output filter. The two power stages are required to operate in both charging and discharging modes using the same hardware. These systems were designed and verified using SPICE simulation. The two designs along with control circuitry will be used in later development for a complete V2G system.

Furthermore, an analysis on the effects of V2G will be conducted. A modified ETAP grid model will be used to demonstrate these effects.
To understand the V2G concept and the topics presented in this project, the following backgrounds are researched and presented.

**The Grid**

The grid is an interconnected web of production and consumption centers and its basic function is to move power from where it is generated to where it is utilized. This “power system” must balance generation and load, or supply and demand while the energy flow is in the form of real and reactive power. The system frequency must be kept at, or very near to, its nominal frequency – 60Hz in the United States, or 50Hz in many other countries. Any deviation from this requires action by the system operator. If the frequency is too high, that means there is too much power being generated in relation to load. Therefore, the load must be increased or the generation must be reduced to keep the system in balance. If the frequency is too low, then there is too much load in the system and the generation must be increased or the load reduced.

V2G power will serve as an ancillary service in the electric power system. Ancillary services are necessary for maintaining grid reliability, balancing the supply and demand, and supporting the transmission of electric power from seller to purchaser.

**Battery**

In nearly all applications involving battery storage, a charge controller is necessary and at the same time must be able to discontinue power flow when the battery is fully charged or has reached a prescribed state. The controller should also be adjustable to ensure optimal battery system performance under various charging, discharging, and temperature conditions.
Figure 3 shows a three-stage Battery control algorithm. Initially the charge controller acts as a current source. If the charging mechanism is the grid, then full current will be used for charging. This is the *bulk charge* stage. When the charging voltage reaches a preset level, the *bulk voltage*, the charging mode is switched to *constant voltage mode* or *absorption charge* stage. After the absorption mode is continued to a preprogrammed time, the charging voltage is decreased to the *float voltage*. This float voltage is maintained by the charge controller and must be set to a level that will not damage the battery. During the discharge cycle, the charge controller, ideally, should stop the discharging of the batteries at exactly at the prescribed set point. [5]

The vehicle modeled is the Chevrolet Volt that comes with a Lithium-ion battery. This battery is preferred over other batteries most other car use today which is the nickel metal hydride battery. The lithium-ion battery, built by General Motors, will be the preferred battery used in the Chevrolet Volt because of its performance and sizing package. The lithium-ion battery provides about two to three times the power of the nickel metal hydride battery in a smaller package.

Several advantages to the lithium-ion battery are its high efficiency, superior specific energy and power, long life, lower initial material cost and fewer replacements, high cell voltage which leads to fewer cells, higher energy-to-weight ratio, suffers little or no memory (lazy battery) effect which can occur when batteries lose their maximum energy capacity, and recharging the vehicle will take
about eight hours using a 120V and less than three hours on 240V.

**Inverter (DC-AC)**

An inverter is necessary for any PV system involving a conversion between AC and DC power. Depending on the load requirements and application it is used for, the inverter selection, as with any other systems, must be chosen carefully. For this project, a pulse-width-modulated inverter (PWM), is discussed.

PWM inverters are suitable for PV applications since it is desired to have a sinusoidal waveform with a predictable amplitude and frequency. A PWM waveform can produce different waveforms by controlling the duty of successive pulses. The amplitude is controlled by controlling the overall duty cycle, while the frequency can be adjusted by controlling the repetition time for the pulse sequence.

The H-Bridge topology was used in the simulation when converter between AC to DC and DC to AC. The H-Bridge topology was chosen rather than the NPC (Neutral Point Clamped) because it is widely used and is simple to understand. Phase 1 of this project is consists of simplicity and basic topology. [5]

In addition, there are several disadvantages to the NPC topology where it is more complex which makes it more sensitive to noise. Rather than one positive DC voltage source like the H-Bridge topology, the NPC requires a positive and a negative DC voltage source. Therefore, simulating and converting from AC to DC will be much more difficult. Furthermore, additional disadvantages include complicated pulse width modulation and control, and a complex bus-bar structure. [6]
LCL Filter

The importance of the filter is to filter out the sinusoidal currents delivered to the grid. Without the filter, non-sinusoidal currents, including higher-order harmonics are transferred to the grid which may cause non-sinusoidal voltage drop across the line impedance and increase the voltage distortion supplied to the load. [7]

The LCL low-pass filter is used rather than L or LC filter because of the advantages it supplies to the user. A third-order LCL filter is connected the between the inverter and the grid so it may handle high switching frequency switches such as the IGBT and reduce the switching frequency ripple. [7] It is consists of smaller inductance values in comparison to the L type filter, thus it is used in high-powered, low frequency current controlled grid-connected converters. With the small component values, the filter provides higher harmonic performances and good attenuation is achieved at a reasonable filter cost. [7]

Bidirectional Power Flow

For many power electronics applications, especially PV systems, the basic requirement for efficient control is that the circuit should be capable of handling bidirectional power flow [8], i.e., energy transfer should be possible from the grid to battery during charging mode and battery to grid in discharging mode. A bidirectional charger will need to function smoothly in both directions. While in discharge mode, the charger should return current in a similar sinusoidal form that complies with regulations. [8]
Following the bidirectional block diagram in figure 2, an AC waveform is passed through the filter to remove unwanted harmonics. The AC waveform is then rectified into DC waveform as it passes through the bidirectional inverter. The bidirectional DC-DC converter then steps up the voltage to that of the battery to ensure a proper charging voltage.

In discharge mode, the charging mode is reversed. The bidirectional DC-DC converter steps down the voltage to that of the rectified grid. The DC waveform is then passed through the inverter back into a unipolar modulated signal and out through the filter producing an AC waveform acceptable to the grid. [9]
III. Requirements

Simulate and design a simple V2G bidirectional inverter, and a DC-DC converter. Research other topologies used in DC-DC and DC-AC.
IV. Design

This System can be broken down into multiple sub-systems

1. Bidirectional DC-DC Converter
2. Bidirectional Inverter
3. LCL Filter
4. Model of a Li-Ion Battery

The intent of the design was to provide a proof of concept for the system to allow later development in capacity and complexity.

Bidirectional DC- DC converter

The bidirectional DC-DC converter key performances are as follows

1. Single converter
2. Simplicity using minimal storage elements
3. Allowing bi-directional current flows or charging and discharging modes
4. Control battery charging and discharging current

Common non-isolated topologies are shown in figure 4. They can be categorized into basic topologies such as Half-bridge converter, Cúk converter, SEPIC/Luo converter and derived topologies such as cascaded half-bridge converter and interleaved half-bridge converter. One widely used topology is half-bridge converter which operates either in buck or in boost mode. Cúk and SEPIC/Luo can convert power bidirectionally by using two active switches. The cascaded and interleaved half bridge can be considered as derived topologies from the basic half bridge, and their performance can be evaluated based on the performance of half bridge converter.\[\text{10}\]

In some dc-dc converter applications isolation may be needed when 1) either LV and HV side cannot be grounded together and 2) the HV: LV voltage ratio is high enough that the device is not suitable to handle high voltage and high current simultaneously. Isolation is provided by a
transformer. However, this addition implies added losses and costs.\textsuperscript{[11]} In this design application, the voltage ratio (365:170) does not require any additional isolation.

![Basic Topologies](image)

**Basic Topologies**

- Half-bridge Converter
- Cuk Converter
- SEPIC/Luo Converter

![Derived Topologies](image)

**Derived Topologies**

- Cascaded Half-bridge Converter
- Interleaved Half-bridge Converter

Figure 4: Common non-isolated DC-DC converter topologies\textsuperscript{[11]}

The cascaded half bridge and interleaved half-bridge can be simplified into half-bridge topology. The main disadvantage of the half-bridge converter is its discontinuous output current when operating as a boost converter which can affect the output capacitor size.

The main advantage of using the half-bridge converter is that the topology requires minimal storage elements and two switching devices. This means less space ultimately less cost. The half-bridge is potentially capable of higher efficiencies than the Cuk and SEPIC since it has lower inductor conduction and lower switching and conduction losses on the active components.
The main advantage of the Cúk converter is its reduced ripple output currents as well as its ability to be isolated, making the Cúk converter a good candidate for fuel cell applications. The main drawback of the Cúk converter is its large inductors and that the output capacitor has to be rated at $V_{in} + V_{out}$.

Finally, the main advantage for the combined SEPIC converters is that the transfer capacitor is rated to $V_{in}$. The main drawbacks are the fact that it requires two large inductors, the output current is discontinuous and the output capacitor is large.\cite{10,12}

<table>
<thead>
<tr>
<th>Type of bidirectional Converter</th>
<th>DC conversion on ratio</th>
<th>Control Method</th>
<th># of Switch Devices</th>
<th>Device Stress</th>
<th>Storage Elements (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Bridge (Buck/Boost)</td>
<td>D</td>
<td>PWM</td>
<td>2</td>
<td>Low</td>
<td>3</td>
</tr>
<tr>
<td>Cascaded half-Bridge (Buck-Boost)</td>
<td>D/(1-D)</td>
<td>PWM</td>
<td>4</td>
<td>Low</td>
<td>3</td>
</tr>
<tr>
<td>Cúk</td>
<td>D/(1-D)</td>
<td>PWM</td>
<td>2</td>
<td>Middle</td>
<td>5</td>
</tr>
<tr>
<td>SEPIC</td>
<td>D/(1-D)</td>
<td>PWM</td>
<td>2</td>
<td>Middle</td>
<td>5</td>
</tr>
</tbody>
</table>

D: duty cycle

DC conversion ration Vo/Vi

Table 1: Comparison of various non-isolated DC-DC topologies

The half-bridge derived interleaved half-bridge topology would be the best choice due to higher efficiencies and reduced stresses. However, based on the desire to minimize the cost, weight, volume as well as to have a reliable and simplistic design, a simple half-bridge topology would be designed and tested.

Figure 5 shows the proposed bidirectional dc-dc converter using half-bridge non-isolated topology. The battery pack is placed on the high voltage side, while the low voltage side is connected to the rectified side of the inverter. This topology can be further categorized into buck or boost type, based on the placement of the energy storage unit. This circuit is a “buck-type,” Since the
battery is placed on the high voltage side. Both will be modeled as a source with equivalent series impedance. The two inductors corresponding to the buck and boost $L_1$ and $L_2$ are integrated in one core inductor $L_C$. The inductance current $I_{IL}$ is designed to operate in continuous conduction mode.

Two capacitors, $C_1$ and $C_2$, are used to filter out the ripple currents on both of discharging current to inverter and to charging current to the battery. Using this topology, the previous key performances are satisfied.

![Figure 5: Chosen DC-DC Converter Topology](image)

**Circuit Operation Principle**

The converter operates in two modes and is defined according to the direction of current flow in the inductor. The direction of the current flow from the low voltage to the high voltage sources is called the “boost” or charging mode. In this mode the lower MOSFET $M_2$ is the main switch and the upper MOSFET $M_1$ is the auxiliary switch with $D_1$ acting as the freewheel diode. An equivalent model is shown in figure 6.
Figure 6: Boost-Mode Equivalent Model

Figure 7 shows the flow of current into the battery while the boost switch is open.

Figure 7: Boost mode with boost switch open

When the boost switch turns on, the equivalent model is shown in figure 8.

Figure 8: Boost Mode with Boost Switch Closed
On the other hand, the direction of current flow from the high voltage to the low voltage sources is called “buck” or discharging mode. In this mode the upper MOSFET $M_1$ is the main switch and lower MOSFET $M_2$ is the auxiliary switch with $D_2$ acting as the freewheel diode.

Figure 8 shows the flow of current into the battery while the buck switch is open.

When the buck switch turns on, the equivalent model is shown in figure 9. Current is shown to flow into the grid.
DC-DC Converter Calculations

According to the design parameters, the following calculations were made. Appendix B shows the complete calculations.

Given:

- The low side or grid voltage
  \[ V_{\text{grid}} = 170V \]

- The high side or battery voltage
  \[ V_{\text{bat}} = 365V \]

- Switching Frequency and Period
  \[ f_{\text{sw}} = 300kHz \quad T_s = \frac{1}{300kHz} = 3.33\mu s \]

- The maximum load current
  \[ I_{\text{omax}} = 16A \]

- The minimum current in ccm at 10% of load current
  \[ I_{\text{ccm}} = 16 \times .10 = 1.6A. \]
The output ripple voltage

\[ \Delta V_o = 1\% \cdot (365) = 3.65V \]

**Boost Calculations:**

**Critical Inductance**

\[ L_c = \frac{D(1 - D)^2 \cdot V_o}{2f_{sw} \cdot I_{ccm}} \]  

(2)

**Output Capacitance**

\[ C_{boost, ou t} = C_2 = \frac{DI}{f \cdot \Delta V_o} \]  

(3)

**Buck Calculations:**

**Critical Inductance**

\[ L_c = \frac{(V_{battery} - V_{grid})}{2I_{ccm} \cdot t_{on}} \]  

(6)

**Output Capacitance**

\[ C_{buck, ou t} = C_1 = \frac{65 \cdot 10^{-6} \cdot s}{ESR} \]  

(9)

**Switch Ratings**

\[ V_{DS1} = V_{DS2} = V_{omax} = 365V \rightarrow \text{Choose } V_{DS} > 400V \]

\[ I_{D1} = I_{D2} = I_{omax} = 0.5342 \cdot 16A = 8.54 \rightarrow \text{Choose } I_D > 10.256A \]

When dealing with such high voltage and current levels a large safety factor >1.2 was considered for the component ratings. Table 3 shows the summary of chosen components along with additional key characteristics.
<table>
<thead>
<tr>
<th>Component</th>
<th>Boost</th>
<th>Buck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor</td>
<td>11.6μF</td>
<td>23.76μH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>3.12μF</td>
<td>201.863μF</td>
</tr>
</tbody>
</table>

Table 2: Summary of Calculated Components

Table 3 shows the actual components chosen for simulation parameters.

<table>
<thead>
<tr>
<th>Component</th>
<th>Current Rating</th>
<th>Voltage Rating</th>
<th>Selected Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMosfet (M1, M2)</td>
<td>35A (Continuous)</td>
<td>600V</td>
<td>FCA35N60 312W, R\textsubscript{ds(on)}=.079Ω</td>
</tr>
<tr>
<td>Diode (D1, D2)</td>
<td>15A</td>
<td>1200V</td>
<td>Infineon IDH15S120 t\textsubscript{c}=&lt;10ns</td>
</tr>
<tr>
<td>Inductor (Lc)</td>
<td>17A</td>
<td>-</td>
<td>Bourns 2300LL-270-RC L= 32µH , DCR=.012Ω</td>
</tr>
<tr>
<td>Capacitor (C1),(C2)</td>
<td>-</td>
<td>450V</td>
<td>CGS451T450R5L Aluminum Electrolytic 400µF</td>
</tr>
</tbody>
</table>

Table 3: Summary of Components for DC-DC

Charging/Discharging Principle

The defined inductor averaged current $I_L$ reference flow direction is the same as the battery charging or boost mode power flow direction this is shown as $I_1<0$ in figure 12. To charge the battery, inductor averaged current $I_L$ should be greater than 0. To discharge the battery, average inductor current $I_L$ should be less than 0. This is shown as $I_2<0$ in figure 12.
Current-Mode Controller for Bidirectional DC-DC converter

Measuring the voltage on the high side bus would require a Li-ion battery model, and a voltage change would represent that power is being transferred. LTspice did not contain any battery model, so the battery was modeled using a voltage source placed on the high side bus. Since the voltage remains constant at 365V, the direction of inductor current would determine the power flow.

Figure 13 shows a single feedback current-mode controller capable of switching between bucking and boost modes.\(^{[13]}\)
One of the primary objectives of this system is to minimize the amount of parts in the design. Conventional bidirectional DC-DC controllers utilize two PWM ICs each controlling either the buck or boost switches. This circuit is designed as a single controller which can be operated regardless of the direction. It consists of one error amplifier, one difference amplifier, three comparators which are fed by positive and negative power supply voltages, and some logic devices including a RS flip-flop.

Current control is applied since the load of the converter is a battery which acts as a voltage source. When the battery voltage needs to be controlled, a voltage control loop which outputs the current reference may be added externally to the controller. If the current reference signal is positive, the converter controller automatically operates in buck mode, and boost mode when negative.

The clock oscillator circuit generates a clock signal for fixed PWM frequency operation. This circuit is connected to the inputs of the AND gates together with the conversion director signal.
by the comparator 3.

Comparators 1 and 2 compare the switch current signal from the differential amp with the output signal of the error amp compensator and output the result. Figure 10 shows the simplified controller block diagram without any AND/OR gates according to buck and boost mode. The clock is connected to set terminal of the flip-flop in buck mode and reset terminal in boost mode because the output of the comparator #3 is in the high state in buck mode and the low state in boost mode. Thus Q1 is the main switch in buck mode and Q2 operates as the main switch in boost mode. The differential and error amp output signals are compared with comparator #1 and #2 and determine the moment to turn off the operating main switching according to buck/boost mode.

Figure 10: Controller Equivalent Operation for (a) Buck Mode (b) Boost Mode

Compensation Calculations

The transfer function for the DC-DC converter is used to determine the amount of compensation needed to make the converter stable.
Choosing which compensation:

\[
\text{Since } \frac{f_{ESR}}{f_{LC}} = 1.25 < 5 \quad \rightarrow \text{choose Type } - II \text{ compensation}
\]

For the type-II network in 15, the complete calculations are shown in appendix b. Table 4 shows the summary of compensation network component values.
<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{so}$</td>
<td>60 kHz</td>
</tr>
<tr>
<td>$R_1$</td>
<td>1 kΩ</td>
</tr>
<tr>
<td>$R_2$</td>
<td>53 kΩ</td>
</tr>
<tr>
<td>$C_1$</td>
<td>139.61 pF</td>
</tr>
<tr>
<td>$C_2$</td>
<td>15.512 pF</td>
</tr>
</tbody>
</table>

Table 4: Summary of Compensation Network Component Values
Bidirectional Inverter

The bidirectional inverter key performances are as follows:

1. Convert 170V$_{dc}$ to a quality 120V$_{rms}$ 60Hz sine-wave output using a filter.
2. Use a Pulse Width Modulator (PWM) scheme operating at 2.5 kHz.
3. Rectify voltage and current when operating in discharge mode.
4. Minimal power loss through filtering and switching elements without sacrificing waveform reproduction.

Converting a DC waveform to AC waveform requires an inverter. Using the summary of inverter performance parameters as shown in table 5, a PWM inverter is chosen based on its versatility as well as high efficiency with minimal distortion.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Square Wave</th>
<th>Modified Sine Wave</th>
<th>Pulse Width Modulated</th>
<th>Sine Wave*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power range (watts)</td>
<td>≤ 1,000,000</td>
<td>≤ 2,500</td>
<td>≤ 20,000</td>
<td>≤ 100,000</td>
</tr>
<tr>
<td>Surge capacity (multiple of rated output power)</td>
<td>≤ 20x</td>
<td>≤ 4x</td>
<td>≤ 2.5x</td>
<td>≤ 4x</td>
</tr>
<tr>
<td>Typical efficiency over output range</td>
<td>70 – 98%</td>
<td>&gt; 90%</td>
<td>&gt; 90%</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Harmonic distortion</td>
<td>≤ 40%</td>
<td>&gt; 5%</td>
<td>≤ 5%</td>
<td>≤ 5%</td>
</tr>
</tbody>
</table>

*Multilevel H-Bridge or similar technology to yield utility grade sine wave output.

To reduce the amount of harmonic content, which ultimately reduces the number output filtering elements, a unipolar PWM is implemented into the design as shown in figure 16. The circuit compares two different types of input voltages, a sine wave and a triangle wave. The sine wave will be known as the control frequency of the inverter where as the triangle wave will be the carrier...
frequency, which will be used to switch the frequency of the inverter. As long as the sine wave is below the triangle wave, the output will be a linear function of the linear modulation and the dc input voltage. The two inputs (sine wave & triangle wave) will be adjusted according to measure the desired output voltage. The more pulses impacted in one area will assist on filtering the signal. By increasing the carrier frequency, there will be very minimal total harmonic distortion (THD) output waveform.

Unipolar topology was used rather than the bipolar switching because it has lower filter losses. The inductor from the filter has core losses that are related to the excitation of the core. The unipolar goes from the positive voltage peak to zero and zero to the negative voltage peak. Whereas bipolar goes the positive voltage peak directly to the negative voltage peak which doubles the excitation of the filter leading to a higher core loss. \(^{[14]}\)

![Figure 16: Three-Level PWM Waveform Configuration](image)
The carrier signal must be greater than the control signal or the system will be over modulated and will be in saturation. The amplitude modulation $m_a$ must be equal to or between 0 - 1.

$$m_a = \frac{V_{\text{control}}}{V_{\text{triangle}}} \quad \text{where} \quad 0 \leq m_a \leq 1$$

The amplitude of the fundamental frequency of the output voltage is shown by the equation below.

$$V_1 = m_a \cdot V_{dc} \cdot \sin(\omega_1 \cdot t)$$

The amplitude of each voltage may be calculated with the equation shown below where $n$ is fundamental harmonic multiple.

$$V_n = \frac{4}{n\pi} \cdot \frac{V_{dc}}{2}$$

As the control signal amplitude increases, the output voltage becomes a square wave known as the Square Wave Voltage switching.  \[^{[14]}\]

Figure 17 shows the proposed bidirectional inverter using H-bridge non-isolated topology. The output from the DC-DC is placed on the H-bridge DC bus while the output $V_{out}$ will be connected to a filter.
Figure 17: Proposed Bidirectional Inverter using H-Bridge Topology

Figure 17 can be represented with figure 18 shown below. The diodes are in parallel (internal diodes) with the switches which converts the voltage from AC to DC, known as a full-bridge rectifier shown later. (The diodes do not play a role when the system is converting the voltage from DC to AC.)

A square wave is generated with the four switches with the H-Bridge topology. Figure 18 below explains the paired switches that will open and close simultaneously.

The orange arrows flow through the positive side of the load when SW1 and SW4 is closed. When SW1 and SW4 open, SW2 and SW3 will close and the yellow arrows flow through the negative side of the load. Both pairs of switches will open and close simultaneously creating a square wave output across the load.
Table 6 summarizes the switching load polarity, where the square wave output will alternate between $+V_{dc}$ and $-V_{dc}$.

The selected driver replaces the switches with MOSFETS. The driver is able to control the high side MOSFET with the addition to the bootstrap capacitor, since the gate voltage is referenced to the source instead of ground. Figure 19 shows the H-Bridge topology with the selected driver.
The input of the driver is the pulse width modulation from the comparator. The gate driver handles current spikes and power losses making the operating conditions for the PWM more suitable. The driver consists of a high and low side, two n-channel MOSFETs and totem pole configuration. Internal logic prevents the high and low side MOSFETS in the half-bridge configuration from turning on at the same time.\cite{15}

![Diagram of an H-Bridge with Drive Controlling the MOSFETS]

Figure 19: H-Bridge with Drive Controlling the MOSFETS

Converting the voltage from AC to DC is the second half of the bidirectional inverter.

Figure 20 represents an ideal bidirectional inverter where each of the diodes is in parallel with the switches. The diodes behave as a full-bridge rectifier, flipping the negative voltage values to positive. The switches remain off due to the direction of the current.
Figure 20: Full-Bridge Rectifier

Figure 20a shows that during the AC signals positive half cycle, the top left and bottom right diodes conduct in series, while the other two diodes are off since they are reversed biased. The load current flows in the same direction. On the other hand, figure 15b shows the top right and bottom right diode conducting in series, while the other two diodes are off since they are reversed biased. The load current flows the same way as before. The voltage across the load will therefore maintain the same polarity.
LCL Filter
The LCL Filter key performances are as follows:

1. Filter the PWM unipolar switches to match the power grid
2. Be able to allow the current to go from the inverter to the grid and vice versa
3. Use appropriate component values that will not cause harmonics or EMI

Power device switching frequencies between 2-15 kHz may cause high-order harmonics that will negatively affect the grid and produce losses. A low-pass passive LCL-filter is used to solve this problem, where it is connected between the inverter and the utility grid. The filter is used to eliminate the PWM carrier and side-band voltage harmonics which may disturb sensitive loads or equipments and increase losses. The LCL-filter is favored because reduces the EMI conductive noise caused by the switching of the MOSFESTs.\[16\]

The converter-side inductance is designed to limit the ripple of the converter-side current shown by the equation below. The ripple is dependent on the number of levels of the PWM voltage. High values of current ripple may lead to saturation problems which may be caused from high inductor values. The inductor on the grid side minimizes the harmonics.\[16\]

The LCL filter is split to two sections; theoretical and calculated values.

Theoretical Values:

*The theoretical component values are based off from the values given from our sources.*\[17\]

\[
\Delta I_{max} = \frac{1}{n} \times \frac{V_{dc}}{L_1 \times f}
\]
The \( n \) is the coefficient that increases the number of levels of the voltage waveform. With the chosen resonance frequency and \( L_1 \), we may find the product of \( L_2 \times C_f \) with the following equations below.

\[
Z_{LC}^2 = [(L_d + L_2)C_f]^{-1}
\]

\[
\omega_{res}^2 = \frac{Z_{LC}^2 (L_1 + L_2 + L_d)}{L_1}
\]

To avoid instability, a resistor is inserted in series with the capacitors to damp out the resonance caused by the filter. The preferred minimal \( R_d \) value is selected to avoid additional power loss. The transfer function is shown below:

\[
G(s) = \frac{i(s)}{v(s)} = \frac{1}{L_s} \frac{(s^2 + \frac{R_d}{L_s} s + Z_{LC}^2)}{(s^2 + \frac{L_2}{L} \frac{R_d}{L} s + \omega_{res}^2)}
\]

![Figure 21: Basic LCL Filter Tied Between Grid and Inverter](image)

Figure 21 represents a basic form of LCL filter attached between the inverter and the grid.

Figure 22 is the H-bridge topology inverter with the LCL filter in the dotted box shown below.
Calculated Values:

The calculated component values of the LCL filter with the minor harmonics is shown below.

\[
V_{dc} = \sqrt{2} \times V_{rms}
\]  

(13)

The equation above (13) is the dc-link voltage, which is also the desired voltage peak to peak value. The hysteresis-band is 10% of the current. (14)

\[
h = 10\% \times I
\]  

(14)

With the known maximum switching frequency, we may also use the two values from above to calculate the total minimal inductance value.

\[
L_{min} = \frac{V_{dc}}{8 \times h \times f_{max}}
\]  

(15)
The $Z_{base}$ equation (16) is used to find the minimal inductor per unit value, where we can find $\alpha$ to determine the total inductor value.

$$Z_{base} = \frac{V}{I}$$

(16)

$L_d = L_1 + L_2 = \text{the total inductance}$

$$L_d = \alpha \cdot L_{min} \quad \text{where} \quad \alpha \leq \frac{0.1 (P.U.)}{L_{min} (P.U.)}$$

(17)

A capacitor is chosen such that the quality factor remains low given (18).

$$Q = \frac{1}{R} \cdot \sqrt{\frac{L_1}{C}}$$

(18)

The inductor ratio $k$ is determined with equation (22)

$$k^2 - (m^2 - 2)m + 1 = 0 \rightarrow \text{solve for } k$$

(22)

where $m$ is

$$m = 2\pi (f_{res}) \sqrt{L_d \cdot C}$$

(21)

Given the equation below (27), the inverter side inductor was determined. Furthermore, the network side inductor was determined using the ratio between the two inductors and the inverter side inductor.

$$L_1 (1 + k) = L_d$$

(23)

The LCL-filters for grid-connected distributed generations are considered in by focusing on the ratio of the two inductances on the two arms of the filter along with the relation of this ratio to the capacitance. 

[18]
\[
\frac{L_2}{L_1} = k
\]  

To account for instability, the capacitor's ESR was calculated using the equation shown below (25).

\[
R_d = \frac{1}{2} [(f_{\text{res}} \times C \times \pi)]
\]

**ETAP Simulation:**

The ETAP simulation key performances are as follows:

1. Model a photovoltaic system with a battery, converter, inverter, and line impedance
2. Send a power flow from the battery to the electric vehicle loads

Using ETAP software and a grid model, the electric vehicles were modeled as batteries where it will supply power to a load.

The electric vehicle loads will be represented as an attachment to the power grid where it will take in the power supplied from the vehicles’ batteries. A battery, a DC-DC converter, an inverter, an additional bus bar, and line impedance are used to represent electrical vehicles’ battery that may be plugged into each electric vehicle load.

The batteries, DC-DC converters, and the inverters represent a limited number of electric vehicles that may be attached to the loads. Each EV load limits a number of EVs that be plugged into at once, therefore a model of the worst case scenario situation is simulated.

Due to the limited options on the ETAP program, additional bus bars between the inverter and the impedance line were added so that the power going into and leaving the bus bar may be adjusted.
The grid effects using the ETAP simulation is modeled using five lumped loads of many electric vehicles shown on figure 23 below.

Figure 23: ETAP Grid Simulation with Five EV Loads
For the circled branch in figure 24, the maximum apparent power the EV load’s capacity is 1.92 kVA.

Maximum Apparent Power Load = Number of outlets × Apparent Power
Using equation (27) the apparent power was determined such that the battery is discharging the maximum amount of real power.

\[ \sqrt{P^2 + Q^2} = S \]  \hfill (27)

The equation below represents the power the battery supplies to the electric vehicle load. The additional bus bar is used to adjust the power by changing the angle. \( V_1 \) is the voltage on the bus from the inverter and \( V_2 \) is the voltage from the load. \( X \) is the line impedance given in between the load and the additional bus bar.

\[ P = \frac{V_1 \times V_2}{X} \sin (\delta_1 - \delta_2) \]  \hfill (28)

\[ Q = \frac{V_1^2}{X} \sin (\delta_2) - \frac{V_1 \times V_2}{X} \sin [90 - (\delta_1 - \delta_2)] \]  \hfill (29)

\[ \delta_2 = \tan^{-1} \left( \frac{Y}{X} \right) \]  \hfill (30)

\[ \frac{Y}{X} \rightarrow \text{typical reactance values given on etap} \]

The ideal power supplied from the battery is 19200 W and the reactive power is 0 VAR. Power was calculated to 19.2 kW by picking the desired angles. Changing the power angle resulted in an increase in reactive power. An example of calculating the reactive power with the power as 19.2 kW is shown below. The example below is a step of iteration to make apparent power 19200 kVA.

Example:
\[ P = 19200 = \frac{201 \times 202}{1} \sin(\delta) \Rightarrow \delta = 28.22' \]

\[ Q = \frac{201^2}{1} \sin(87.06') - (201 \times 202) \sin(90' + 28.22') = 4.474 \text{ KVAR} \]

\[ S = \sqrt{19200^2 \times 4474^2} = 19.833 \text{ kVA} \]

According to the calculated values above, and the simulation shown below, it is exceeding the maximum value the EV load can hold.

**Figure 25: Selected EV Overpowered**
**Battery:**
The battery key performances are as follows

1. Model the Chevrolet Volt battery as it charges and discharges

   Since Chevrolet Volt has not released their battery’s datasheet, a model using IBT Power’s lithium ion cell datasheet was constructed instead. The IBT Power’s lithium ion cells are used since they are made of similar chemistry and have the same rated voltage.

   Since the Chevrolet Volt limits the battery state of charge from 25% - 90%, it operates approximately in the linear region. According to figure 26, the 1-120 minute region has a linear change in internal resistance and voltage and can therefore be modeled as a constant voltage and constant current source.

   ![Figure 26: IBT Power’s Lithium Ion Cells Charging Characteristic](image)

   The charging characteristics are similar to the discharging characteristics and can therefore be modeled as a constant voltage and a constant current source as well.
The Chevy Volt has a battery pack with a 365V nominal voltage. It is made of approximately 200 prismatic cells. Given the nominal voltage for the lithium ion cell is 3.7V and the assuming the battery pack is comprised of two strings of 100 cells in parallel, the approximated nominal voltage is 370V.

Assuming that it has a 10% voltage drop, the output voltage of the battery will be 333V. The output power of the battery pack is stated to be 110 kW. If the voltage drop is 37V then the internal resistance can be calculated by $R = \frac{V}{I}$.

\[
P = I \times V \rightarrow I = \frac{P}{V} = \frac{110 \text{ kW}}{37 \text{ V}} = 2.973 \text{ kA}
\]

\[
R = \frac{V}{I} = \frac{37 \text{ V}}{2.973 \text{ kA}} = 0.012 \Omega
\]

The internal resistance of the battery pack is $0.012 \ \Omega$. 

---

**Figure 27: IBT Power’s Lithium Ion Cells Discharging Characteristic**

The graph shows the discharge characteristic of IBT Power’s lithium ion cells. The cells are designed to maintain a high discharge characteristic even at high discharge rates. The curve indicates good performance at various discharge capacities and voltages, which is crucial for applications requiring reliable power output over wide ranges.
**V2G System**

A basic V2G system was simulated using the basic topology in figure 28. The left was connected to the grid. The grid was modeled as a 120 V$_{AC}$ 60Hz source with some line reactance. The battery was modeled with a 365V source with some internal resistance.

![Full V2G system topology](image)

*Figure 28: Full V2G system topology*

Appendix C shows the actual parameters used for simulation.

**V. Integration and Test Results**

**Bidirectional DC-DC Converter With Controller**

Using the schematic in appendix D, the waveforms in figures 26-29 were produced. Initially the inductors current ramps to 50A. There are some sub harmonic oscillations for the first couple of cycles. The feedback loop corrects the waveform and begins to operate in CCM as shown in figure 29-30.
Figure 29: DC-DC Converter Initial Transient in Buck Mode

Figure 30: DC-DC Converter initial transient in boost mode
Figure 31 shows the boost switch duty cycle (top waveform) and inductor current (bottom waveform) during the transition from boost mode to buck mode. The average inductor current oscillated around -20.19A

![Figure 31: Inductor Current and Boost Switch Duty cycle Transition from Boost to Buck at 2ms](image)

Figure 32 shows the buck switch duty cycle (top waveform) and inductor current (bottom waveform) during the transition from buck mode to boost mode. The average inductor current oscillated around 20.23A

![Figure 32: Inductor Current and Buck Switch Duty Cycle Transition from Buck to Boost at 1ms](image)
Figure 32 shows the full simulation switching from buck to boost mode and back to buck mode. The simulation results show the converter operates as expected. The converter direction can be changed seamlessly according the reference polarity.

![Full simulation of Inductor Current](image-url)

**Figure 33: Full simulation of Inductor Current**
Bidirectional Inverter
Some additional feature

The carrier frequency is set to 2.5 kHz with amplitude from -5V to 5V, whereas the two control frequency is set to 60 Hz with amplitude from -1V to 1V. The carrier and control frequency are inserted into comparators to represent the unipolar switching shown on the figure 34.

The figure 35 represents the voltage across each of the four switches.
The H-Bridge topology sends positive and negative current through load, producing the waveform in figure 36.

![Figure 36: PWM waveform with Unipolar Switching](image)

Figure 37 is an unfiltered H-Bridge rectifier, where the resistor represents the temporary load. The goal of the inverter is to send an AC voltage waveform back onto the power grid, which will be explain and presented later on this report.

![Figure 37: Basic H-Bridge Rectifier](image)
Figure 38 shows the unfiltered simulated unipolar switching graph with 360 ohm load.

A full bridge rectifier converts the AC waveform from the power grid to a DC waveform as shown in figure 39. Each diode is in parallel with a switch, therefore the switches will remain open as the AC waveform is inputted.
LCL Filter

Phase 1 (RLC low-pass filter):

Figure 40: H-Bridge Circuit Used in for Simulation

Figure 40 is the entire H-Bridge circuit, including a zoomed in view of the RLC filter shown below.

Figure 41: RLC Low-Pass Filter

The cutoff frequency was calculated; it should be any value greater than grid frequency of 60 Hz.

$$f_c = \frac{1}{2\pi \sqrt{L \cdot C}} = \frac{1}{2\pi \sqrt{0.1H \cdot 30\mu F}} = 91.8\,Hz$$
Figure 42: Bode Plot of the RLC Low-Pass Filter

The bode plot above represents the cutoff frequency of the RLC filter at 91.8 Hz. The diagram below is the output waveform of the RLC filter with a transient response.

Figure 43: Inverter Output with RLC filter

Phase 2 (LCL low-pass filter):

The LCL filter below represents the inverter leading the grid by adding a time delay on the grid. On a realistic case, the grid may not be delayed, instead, the inverter’s phase shift to either lead
or lag the grid. A zoomed up view of the filter of the grid leading the inverter is shown in the dotted box below. The switch decreases the time of transient response at the beginning of the simulation, and was not used for any other purposes.

**Theoretical Results:**

![LCL Filter Diagram](image)

The bode plots below represent the LCL filter between the inverter and the grid. It verifies that it will filter out the harmonics with the resonance frequency at 3.5 kHz.

![Bode Plots](image)

The red line represents the nodes across the capacitor, the green across the grid’s impedance values, and the blue line represents between the filter and the power grid box.
Figure 46: LCL Filter with the Grid Lagging

Figure 46 shows the LCL filter with the inverter leading and the grid lagging. According to figure 47 and 48, the grid is lagging by 6 mS.

Figure 47: Inverter Voltage across the Capacitor and the Voltage Grid

The blue line is the voltage of the inverter leading the grid, representing the power going back into the grid.
Figure 48: Voltage Across the Capacitor and Current

The red line above represents the voltage of the inverter, the green as the voltage of the grid, and the blue as the current across the grid source.

To charge the battery, it does not matter if the grid is lagging, leading or is in phase with the inverter because the sinusoidal waveform will be rectified and converted to a DC waveform.

Figure 49: LCL Filter with the Grid in Phase with the Inverter

Figure 50 and 51 shows that the voltage from the grid is in phase with the inverter.
The green line represents the inverter’s voltage and the blue line represents the grid’s voltage.

The green line represents the inverter’s voltage, the blue line represents the grid’s voltage and the red line is the current through the grid.
Calculated Results:

Figure 52: LCL Low-pass Filter

Figure 52 represents the calculated LCL filter values with the desired bode plot shown on figure 53 below. The resonant frequency is set to 2 kHz, with minor quality factor.

Figure 53: LCL Bode Plot

Figure 54: LCL Low-Pass Filter Attached to H-Bridge Topology
The LCL filter above is connected to the H-bridge topology with the results shown on figure 55. Again, the switch decreases the time of transient response at the beginning of the simulation, it was not used for any other purposes. The green line represents the inverter’s voltage leading the grid’s voltage.

Figure 55: Calculated LCL Low-Pass Filter Result

Figure 51 shows a zoomed up version of the graph where slight distortion at the voltage peak of the inverter.
The green line represents the inverter's voltage, the blue line represents the grid's voltage and the red line represents the current across the voltage grid.

Similarly to the theoretical results, the grid's voltage is in the same phase as the inverter's voltage shown on the circuit below.

The inverter and the grid's voltage are in phase, where the green line represents the inverter's voltage and the blue as the grid's voltage. The inverter's voltage is slightly distorted at each peak.
Figure 58: In Phase Inverter and Grid Voltage

Figure 58 shows the green line represents the inverter’s voltage and the blue line represents the grid’s voltage.

Figure 59: In Phase Inverter and Grid Voltage and Current

Figure 59 shows the green line represents the inverter’s voltage, the blue line represents the grid’s voltage and the red line represents the current running through the grid.
ETAP Simulation:

Figure 60: Selected Vehicle Load

\[ S = \text{Apparent Power} = V \times I = 120V \times 16A = 1920VA \]

Use example under the red circled branch; the maximum apparent power the EV load’s capacity

Number of outlets \times Apparent Power \rightarrow 10 \times 1.92kVA = 19.2kVA

If the power is 19.2 kW, the reactive power will not be zero according to the equation below. By changing the power, the reactive power will also change as well. Shown below is an example if we did choose the power to 19.2 kW rather than 17 kW.
V2G:
Using the schematic shown in appendix the following waveform was produced in figure 61.
Figure 61 shows the voltage inverter leading the grid voltage which means that the power is being delivered to grid. Furthermore, the gray line represents the power (which remains positive for most of the time) going into the grid. Another important aspect of figure 61 shows that DC-link voltage remains 170V, even after 10ms when the Interface switch opened.

The DC-DC converter had an initial transient problem where the no-load current would then charge the low-side capacitor causing the voltage across the capacitor to slowly increase. When the inverter was added as a load, this drift was apparent again. To identify the problem, the grid angle was changed to increase inverter output power. It was suspected the drift was due to the transient response of the circuit in simulation. To fix this, a switch was used to interface the inverter and converter which sets the DC-DC converter initially to steady state.

Figure 62 shows the grid filter voltage (green waveform) and DC link voltage (blue waveform) during charge mode. The constant 170V was necessary to properly boost the voltage to 365V.

Figure 62: Bus Voltages
Figure 63 shows that power was delivered to the battery. The negative power spikes are due to the reverse recovery of the boost freewheel diode.

Figure 63: Power Delivered to the battery and diode current
**VI. Conclusion**

Using the bidirectional converter with sources tied to the high and low buses, the converter inductor current verified that power can be transferred to and from the battery. A bidirectional current-mode controller provided a feedback loop for the converter. Depending on the polarity of the reference voltage, the controller allowed a constant current output at each bus. Additional research showed that a multiphase interleave topology would provide a more efficient circuit for vehicle to grid applications.

The H-bridge topology was used to model the bidirectional inverter. The H-bridge topology was capable of converting the AC to DC using a full-bridge rectifier with four diodes in parallel with switches. The simulations showed the H-bridge produced a PWM signal while the rectifier produced a steady 170V DC signal.

The LCL filter is a bidirectional low pass filter that is inserted between the inverter and the power grid. The goal of the filter was to eliminate any harmonics from the inverter to grid without adding additional gain or loss or distortion. The elimination of the electromagnetic interference was dependent on the component values of the filter. Careful calculations were required to determine the component values when designing the filter. Overall, the LCL filter was able to filter out the unwanted harmonics from the PWM input signal. The output produced a 60Hz sinusoidal waveform with very little distortion.

The V2G system was simulated by connecting the DC-DC converter, inverter, and LCL filter. With little interfacing, the results showed the system was capable of bidirectional power flow transfer.
VII. Further Works and Implementation

DC-DC Converter

As mentioned earlier a half-bridge interleaved bidirectional DC-DC converter would be a better choice for this application. For high-power applications, a single converter requires multiple devices in parallel to handle high currents. It is desirable to have more phase legs to allow reduction of either voltage or current stress, and thus better efficiency.\(^{[11]}\)

A three-phase bidirectional dc-dc converter is shown in Figure 60 where the phase switch is controlled with 120-degree phase shift from each other. The ripple on the total current will become relatively small, so a small capacitance is enough in both low and high sides for acceptable voltage ripple.\(^{[21]}\)

![Figure 64: Bidirectional Three-Phase DC-DC Converter](image)

The following topology has the following features:

1. Zero-voltage switching and thus high efficiency at high load conditions
2. Interleaving phase-leg currents to eliminate the ripple current going into the sensitive voltage source.
3. Compact inductor size with discontinuous conduction mode operation.
4. Compact bus capacitor size with ripple cancellation.\(^{[22]}\)
Bi-Directional Inverter

1. Implementing feedback loop which controls the inverter by monitoring grid voltage and phase.
2. System protection by responding to grid disturbances such as faults and non-utility sources.

An improvement to the H-Bridge inverter is to use an integrated circuit to send in a desired carrier frequency and control frequency to the comparator. Ideally, a positive and negative voltage rail will power the IC so that realistic components may be used when building the physical product.

The next phase should consider the NPC topology where it has a number of advantages such as reduced switching loss. With two separate voltage sources, only half of the voltage has to switch, therefore there is half the amount of switching loss on the transistors. There are also smaller ripple current in comparison to the H-Bridge topology and with half the output voltage transient, it reduces the complexity of filter required. Furthermore, with the total positive and negative supply voltage shared, the positive and the negative voltage supports the serial connection of DC capacitors without the problem of leakage compensation. Again, there are disadvantages to the NPC topology and it is a newer topology so there is not as many sources as there are with the H-Bridge topology.
The two capacitors will divide the one DC source into two, where $C_1$ will convert the DC voltage to a positive waveform and $C_2$ will convert the second half to a negative waveform with the middle point as the ground.
Filter

The low-pass LCL filter is preferred more than any other filter to connect a power electronic convert to the grid system.

An alternate option is to use the NPC topology where an inductor alone may be a filter. Although an inductor alone may be a filter, the LCL is still preferred to connect between the inverter and the grid system. When building the filter, also take in the consideration of the grid’s impedance as well.
**ETAP Simulation**

The electric vehicle loads are each limited to a certain amount of power. The electric vehicle load may handle a limit amount of power due to the reactive power. An improvement to this problem estimate until the capacity of the electric vehicle power load is reached with minimal reactive power.

Testing multiple real life circuits is preferable rather than testing one circuit on ETAP. Testing multiple circuits will increase the probability that attaching an electric vehicle will be safe for the grid. Unfortunately, ETAP donated a school version ETAP program to California Polytechnic State University of San Luis Obispo which limits the students from using the full access of ETAP such as limiting the number of busses that may be used. A full version of ETAP is recommended with call in technical support.

**Battery**

With the actual battery characteristics, more accurate current, voltage, and power ratings, can be used for the design. Since the requirements of this project is to create a simple V2G system that charge and discharge the battery. The current battery model suffices in modeling and proving that the system is capable of charging and discharging. If more precise simulations are required in terms of the battery's reaction to the system, a more accurate model can be created in the next phase. This can be done by having the voltage and internal resistance of the battery changing in respect to the state of charge. Additional research should be used to understand how to simulate a battery.
IX. Appendix A

PHEV plug in electric vehicle
V2G vehicle to grid

DC-DC Converter:

- $V_{\text{grid}}$: voltage of the grid
- $V_{\text{battery}}$: voltage of the battery
- $F_{\text{sw}}$: switching frequency
- $T$: period
- $I_{\text{boost}}$: maximum input current when boosting
- $D$: duty cycle
- $L_{\text{c}}$: critical inductor (the inductor’s lowest value in a parameter)
- $C_2$: output capacitor value when boosting
- $C_1$: output capacitor value when bucking
- $M_1$: buck switch
- $M_2$: boost switch

Bi-directional Inverter

- PWM: Pulse Width Modulator
- $m_a$: amplitude modulation
- $V_{dc}$: DC voltage
- $f_{\text{carrier}}$: carrier frequency (triangular waveform)
- $f_{\text{control}}$: control frequency (sinusoidal waveform)
- $V_{\text{control}}$: control voltage (sinusoidal waveform)
- $V_{\text{triangle}}$: carrier voltage (triangular waveform)

LCL Filter

- $f_c$: cutoff frequency from the RLC filter
- $L_1$: converter-end inductance of the LCL filter
- $L_2$: network-end inductance of the LCL filter
- $n$: coefficient that increases the number of waveforms
- $R_j$: ESR of the capacitor
- $G(s)$: transfer function of the LCL filter
- $L_{g}$: induction from the grid
- $L_{\text{d}}$: total inductance of the LCL filter
- $\omega_{\text{res}}$: resonant frequency
- $C_f$: capacitor
- $V_{\text{dc}}$: DC-link Voltage
- $h$: hysteresis-band
- $L_{\text{min}}$: minimal required total inductance
- $k$: ratio of inductances of the LCL filter
- $m$: coefficient value to determine $k$
- $\alpha$: coefficient value to determine $L_d$
Q quality factor
NPC neutral point clamped
EMI electromagnetic interference

**ETAP Simulation**

S maximum apparent power at the EVload
P power from the EV to EVload
Q reactive power from the EV to EVload
X impedance line between the EV and EVload bus
V\textsubscript{1} voltage from inverter bus
V\textsubscript{2} voltage from EVload bus
\(\delta\textsubscript{1}\) angle from inverter bus
\(\delta\textsubscript{2}\) angle from EVload bus
\(\frac{r}{x}\) typical reactance values given from ETAP
X. Appendix B

Calculated Section:

DC-DC Converter Calculations

Given:

- The low side or grid voltage
  \[ V_{grid} = 170V \]

- The high side or battery voltage
  \[ V_{bat} = 365V \]

- Switching Frequency and Period
  \[ f_{sw} = 300kHz \quad T_s = \frac{1}{300kHz} = 3.33\mu s \]

- The maximum load current
  \[ I_{max} = 16A \]

- The minimum current in ccm at 10% of load current
  \[ I_{ccm} = 16 \times 0.10 = 1.6A \]

- The output ripple voltage
  \[ \Delta V_o = 1\% \cdot (365) = 3.65V \]

Boost Calculations:

- Duty Cycle
  \[ D = 1 - \frac{Vin}{V_{out}} = 0.53 \quad (1) \]

- Critical Inductance
  \[ L_c = \frac{D(1-D)^2}{2f_{sw}} \frac{V_o}{I_{ccm}} = \frac{0.5342(1-0.5342)^2(365)}{2(300k)(6.4)} = 11.6\mu F \quad (2) \]
Output Capacitance

\[ C_{boost\_out} = C_2 = \frac{DI}{f \cdot \Delta V_o} = \frac{(0.5342)(6.4)}{(300k)(365)(.01)} = 3.12\mu F \] (3)

Inductor Current Ripple

\[ \Delta I_L = \frac{D(Vin)}{L_c \cdot f_{sw}} = \frac{0.5342(170)}{44\mu \cdot 300k} = 6.879A \] (4)

Buck Calculations:

Ideal On-time of the switch

\[ t_{on} = \frac{V_{grid}}{V_{battery}} \cdot T_s = \frac{170}{365}(3.33\mu) = 1.56\mu s \] (5)

Critical Inductance

\[ L_c = \frac{(V_{battery} - V_{grid})}{2I_{ccm} \cdot t_{on}} = \frac{(365 - 170)}{2(6.4)} = 156\mu = 23.76\mu H \] (6)

Inductor Current Ripple

\[ \Delta I_L = \frac{D(Vin - Vout)}{L_c \cdot f_{sw}} = \frac{0.5342(365 - 170)}{L_c \cdot f_{sw}} = 10.85A \] (7)

Output Capacitance

\[ ESR = \frac{\Delta V_c}{\Delta I_L} = 322.5m\Omega \] (8)

Assuming using Electrolytic Capacitor whose ESR*C=65μs

\[ C_{buck\_out} = C_1 = \frac{65 \cdot 10^{-6}s}{ESR} = 201.863\mu F \] (9)
Switch Ratings

\[ V_{DS1} = V_{DS2} = V_{omax} = 365V \rightarrow \text{Choose } V_{DS} > 400V \]

\[ I_{D1} = I_{D2} = I_{omax} = 0.5342 \cdot 16A = 8.54 \rightarrow \text{Choose } I_D > 10.256A \]

**Compensation Network Calculations**

Choosing Crossover frequency

\[ f_{co} = 0.2 \cdot f_{sw} = 0.2 \cdot 300kHz = 60kHz \]

From bode plot on figure gain and phase at \( f_{co} \) [converter gain]

\[ Gain = -34dB; \ \phi = -91.1dB \]

Gain should = 1 or 0dB at crossover

\[ 34dB = \frac{53}{v} \rightarrow \text{Choose } \frac{R_2}{R_1} = \frac{53k}{1k} \] (10)

Choosing \( K \) factor = 3. For a phase margin > 45°

phase shift \( \theta_{co} = -217^\circ \)

\[ 360^\circ - 217^\circ - 90.53^\circ = 52.47^\circ \]

Determining Capacitors \( C_1 \) and \( C_2 \)

\[ C_1 = \frac{K}{2\pi \cdot R_2 \cdot f_{co}} = \frac{K}{2\pi \cdot 57\mu \cdot 60kHz} = 139.61pF \] (11)

\[ C_2 = \frac{1}{k \cdot 2\pi \cdot R_2 \cdot f_{co}} = \frac{1}{3 \cdot 2\pi \cdot 57\mu \cdot 60kHz} = 15.512pF \] (12)

**LCL Filter**

*Calculated:*

The calculated component values of the LCL filter with the minor harmonics is shown below.

\[ V_{dc} = \sqrt{2} \times 120rms = 170Vpp \] (13)
The hysteresis-band is 10% of the current

\[ h = 10\% \times I = 10\% \times 16A = 1.6 \] (14)

The maximum switching frequency is 2.5 kHz.

\[ L_{\text{min}} = \frac{V_{dc}}{8 \times h \times f_{\text{max}}} = \frac{170V}{8 \times 1.6 \times 2.5kHz} = 0.0053125 \, H \] (15)

\[ Z_{\text{base}} = \frac{V}{I} = \frac{120}{16} = 7.5 \Omega \] (16)

\[ L_d = L_1 + L_2 = \text{the total inductance} \]

\[ L_d = \alpha \times L_{\text{min}} \text{ where } \alpha \leq \frac{0.1(P.U.)}{L_{\text{min}}(P.U.)} \] (17)

\[ \alpha \leq \frac{0.1}{0.00690625/7.5\Omega} = 108.6 \text{ therefore pick } \alpha = 1.3 \] (18)

\[ L_d = 1.3 \times 0.0053125 = 6.90625 \, mH \] (19)

\[ m = 2\pi(f_{\text{res}})\sqrt{L_d \times C} \rightarrow \text{pick } C \]

When picking the capacitor value, keep in mind that it will affect the resonant frequency shown by the equation below.
Pick $C = 80 \mu F$ & resonant frequency = 2 kHz

$$m = 2\pi (2 \text{ kHz})\sqrt{6.906 \text{ mH} \times 80 \mu F} = 9.3406$$ (21)

$$k^2 - (m^2 - 2)m + 1 = 0 \rightarrow \text{solve for } k$$ (22)

$$k = 28.2 \quad k = -28.2$$

$$L_1(1 + k) = L_d \rightarrow L_1(1 + 28.2) = 6.906 \text{ mH} \rightarrow L_1 = 0.236 \text{ mH}$$ (23)

$$\frac{L_2}{L_1} = k \rightarrow \frac{L_2}{0.236 \text{ mH}} = 28.2 \rightarrow L_2 = 6.669 \text{ mH}$$ (24)

The capacitor comes with an internal resistance known as the ESR and is calculated with the equation shown below.

$$R_d = \frac{1}{2} [(f_{res} \times C \times \pi)] \rightarrow R_d = \frac{1}{2} [(2 \text{ kHz} \times 80 \mu F \times \pi) = 0.2513 \Omega$$ (25)

**ETAP Simulation**

$$S = \text{Apparent Power} = V \times I = 120V \times 16A = 1920VA$$ (26)

Use example under the red circled branch; the maximum apparent power the EV load’s capacity

**Number of outlets \times Apparent Power \rightarrow 10 \times 1920VA = 19200VA**

The equation below is the apparent power where we may adjust the power and reactive powers of the battery to be equal or less of the EV load’s capacity.
\[ \sqrt{P^2 + Q^2} = S \]  

(27)

The equation below represents the power the battery supplies to the electric vehicle load. The additional bus bar is used to adjust the power by changing the angle. \( V_1 \) is the voltage on the bus from the inverter and \( V_2 \) is the voltage from the load. \( X \) is the line impedance given in between the load and the additional bus bar.

\[ P = \frac{V_1 \times V_2}{X} \sin (\delta_1 - \delta_2) \]  

(28)

\[ P = \frac{201V \times 202V}{1} \sin[24.3^\circ - (-0.29^\circ)] = 16901.8 \, W \]

\[ Q = \frac{V_1^2}{X} \sin(\phi_z) - \frac{V_1 \times V_2}{X} \sin [90 - (\delta_1 - \delta_2)] \]

(29)

\[ \phi_z = \tan^{-1}\left(\frac{Y}{X}\right) \]

(30)

\( \frac{Y}{X} \rightarrow \text{typical reactance values given on ETAP} \)

\[ \phi_z = \tan^{-1}\left(\frac{19.5}{1}\right) = 87.06^\circ \]

\[ Q = \frac{201^2}{1} \sin(87.06^\circ) - \frac{(201 \times 202)}{1} \sin[90 - (24.3 - (-0.29))] = 3431.02 \, \text{VAR} \]

\[ S = \sqrt{16901.8^2 + 3431.02^2} = 17246.5 \, \text{VA} \]

The calculated apparent power is less than the given maximum power of 19200VA.
The ideal power supplied from the battery is 19200 W and the reactive power is 0 VAR.

Unfortunately, we tried to calculate the power to 19200 W by picking the desired angles, but that will also change the reactive power as well.

**Derivation for Q:**

\[ I_{12} = \frac{v_1 \angle \delta_1 - v_2 \angle \delta_2}{Z \angle \phi_z}, \quad (31) \]

\[ S_{12} = v_1 \angle \delta_1 \times \left( \frac{(v_1 \angle - \delta_1) - (v_2 \angle - \delta_2)}{Z \angle \phi_z} \right), \quad (32) \]

\[ S_{12} = \frac{V_1^2 \angle \phi_z}{Z} - \frac{V_1 \times V_2 \angle (\delta_1 - \delta_2 + \phi_z)}{Z}, \quad (33) \]

*Assume Z = lXl \angle 90° when R=0;*

\[ Q_{12} = \frac{V_1^2 \angle \phi_z}{Z} - \frac{V_1 \times V_2 \angle (\delta_1 - \delta_2 + 90°)}{Z}, \quad (34) \]

\[ Q_{12} = \frac{V_1^2}{X} - \frac{V_1 \times V_2}{X} \sin (90 + \delta_1 - \delta_2) \quad (35) \]

*When R ≠ 0;*

\[ Q = \frac{V_1^2}{X} \sin(\phi_z) - \frac{V_1 \times V_2}{X} \sin [90 - (\delta_1 - \delta_2)] \quad (36) \]
XII. Appendix C

Figures:

DC-DC Converter:
Bi-directional Inverter

H-Bridge Configuration
H-Bridge Configuration
V2G System Buck Mode
V2G System Boost Mode
Summary of Functional Requirements

The bidirectional V2G system is modeled to send a 170V AC source from the grid to charge a 365V DC battery source and be able to discharge the 365V DC battery source to the 170V AC power grid under one circuit.

Primary Constraints

DC-DC Converter

The bidirectional inverter design has been the most significant source of problems. Although it was easy to show the power stage fully capable of providing bidirectional power flow with one source and a resistive load, the system needed to be simulated with both high and low side buses connected using a source and being able to show power being exchanged across the two busses. Therefore it was difficult to figure out a controller for the converter.

LCL Filter

The filter design was more complicated than most others. The filter must function between two sources rather than the usual one source and one load. There were problems with the filter...
calculating the components and understanding the component values. Many references used different approaches to calculate the component values, where additional computer programs are used to calculate the component values. Multiple attempts were made to calculate the component values. When the inverter is in phase with the grid, both waves look sinusoidal whereas when the inverter is leading the grid, the inverter’s waveform is non-sinusoidal.

**ETAP Simulation**
Finding the correct equations to calculate the power and the reactive used in ETAP was the most difficult trend for ETAP. The calculated values shown on the ETAP simulation are the rounded values.

**Battery**
The battery cell characteristics manufactured by LG Chem is not release to the public. An addition problem was simulating a battery on LTSpice. The battery must be not only be a voltage source with a resistor in series, the battery must behave like an actual battery where it charges and discharges. With the battery cell characteristics, modeling an actual battery on LTSpice is possible, but it requires a separate circuit that must be interface to the DC-DC converter. It may also be easily programmed on other simulations such as SIMULINK except interfacing between two programs will be difficult.

**Economics (Per Person)**
*There is no additional or estimated component cost because the project was mainly simulation.

*Original Estimated Time:*

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<th>Hours</th>
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<td>Research</td>
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<td>Trouble Shooting</td>
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Writing the Report: 32 Hours
Total Estimate Time: 145 Hours

Actual Development Time:

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<td>Total Estimate Time</td>
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</table>

If Manufactured on a Commercial Basis

Given the following assumptions:
- 100,000 units are to be sold each year for the first 5 years (based on demand of EVs).
- The costs to manufacture is $1000 (Based the average price of DC-DC converter and grid-tie inverter, including highly efficient components and low volume.)
- Each unit is expected to be sold at 150% of manufacturing cost for the first 5 years.

If we were to consider the start-up costs and production times and employee costs and the fact that we’re not expecting the system to reach market popularity until the EV market grows rapidly, we would most likely break even.

Environmental

If the product is physically built, the product will affect the environment by shaving off the peak loads and controlling whether or not to charge or discharge the battery from a vehicle. The increased demand of EV’s means cleaner air due to the reduced amount of pollutants from fossil fuel based cars.
**Manufacturability**

The product may be challenging to manufacture because the components must not be heavy or too big. Additional size to the components will affect the efficiency of the vehicle. If the product is too heavy, the vehicle may require more energy to move. If the product is too big, it may not fit in the vehicle correctly. The manufacturing process may be limited to the amount of parts are available. Since it is desired to have high efficient components, there may be restrictions if these components are to become unavailable.

**Sustainability**

The design of the product is not physically built, so there are no challenges to maintain the completed device or system. However, simulating the circuit on LTSpice may take several hours due to the large file and number of components used in the system.

This project is based off of research and development through simulation to improve the sustainable use of resources, the next phase to the project is to build the product. If the product is physically built, the product will improve the sustainable use of resources by controlling whether or not to charge or discharge the battery to the power grid.

There are other topologies known that will convert the 170V AC to 365V DC and vice versa, and are slightly more efficient than the topologies used in this project. The problem with the more efficient topologies is that it is consist of more component parts, the complexity of the component parts requires additional research, and the cost of the product will skyrocket. Other topologies such as the NPC (Neutral Point Clamp) may be used to convert DC to AC but additional component parts are used and the NPC is much more complex than the H-Bridge topology.
When used inside a V2G application, this product has the potential to become highly sustainable. Since the energy stored can be transferred via our system, energy can be reused somewhere else as opposed to being dissipated elsewhere, such as heat.

**Ethical**

The ethical implications to designing the project were purely based off on simulations therefore there are no short cuts to designing the product. The simulation program simulates the product, and if the product does not work, the results will be unexpected. There are no misuses of the product because the product is made to assist the utility companies and peak load, and assist consumers as well.

**Health and Safety**

Like all high voltage applications, extra precautions should be taken when dealing with such circuitry. Since the design has grid-tie capabilities, it should follow UL standards, and comply with NEC. Additional recommendations should be advised upon further implementation.

**Social and Political**

Socially, V2G is not a common concept to society. The idea of the grid drawing power from a car’s battery when parked may come across as an unwanted entity when consumers are able to purchase the product. However, this can be overcome when consumers are thoroughly educated on this topic knowing that the long term effects of V2G can promote energy sustainability. Another concern consumers may face is the battery life. Even though battery life and characteristics are expected to increase in efficiency throughout the coming years, the effects of charging and
discharging a battery are unavoidable. A design that can maximize battery life characteristics will be desired to overcome this.

**Development**

This project allowed us to become more fluent in LTSPICE. The simulation software can be a very powerful program if used properly and effectively. Linear Technology offers a yahoo group where users are able to share simulated designs. This served as an excellent resource for efficient designing as well as properly modeling device parameters.

Furthermore, since the majority of the topics discussed in the paper were not covered in undergraduate studies, extensive research was conducted in order to determine a viable solution for the design. The IEEE explore database was our main resource for literature.
XIV. References


[18] M. Tavakoli Bina, E. Pashajavid, An efficient procedure to design passive LCL-filters for active power filters, K.N. Toosi University of Technology, Iran


