DESIGN OF A RELIABLE ALTERNATIVE CHARGING DEVICE TO ELECTRIC VEHICLE CHARGING STATIONS

Tennessee State University
Department of Electrical and Computer Engineering

Students: Justus Brown

Project Advisor: Dr. Sagnika Ghosh

Sponsor: GridEd by EPRI

ABSTRACT:

EV infrastructure is still in development and not yet up to par with combustion engine fueling stations. The purpose of this design project is to conceptualize, evaluate, develop and test a solar powered wireless charging system for EVs to compensate for the lack of charging stations. Several recommended and approved design tools are utilized to efficiently and effectively design the solar powered wireless charging system for EVs. These tools include the Pairwise Comparison Matrix, Weighted Decision-Matrix, and a physical system decomposition. Also, a multitude of figures depicting material breakdown and circuit analysis are displayed for educational purposes for their respective topics, such as components of a photovoltaic panel. For the entire system, five components were selected to complete the entire solar wireless power transfer system. These components include the following: solar panel, solar power regulator, controller, lithium-ion battery, and high-frequency inverter. Using various online retailers, three different alternatives were chosen for optimal selection of each device. Out of the three alternatives, only one is picked for the application of the system using a Pairwise Comparison-Matrix and a Weighted Decision-Matrix. Four criteria are chosen to determine the most appropriate solution. The device was tested in both a simulated and lab environment. The results showed that the system can generate, regulating and transferring power. The design also satisfied specifications and constraints such as portability, budget constraints, power requirements, feasibility and reliability.

INTRODUCTION:

Ever since the inception of the EV took hold in the minds of innovators and engineers, leaps and bounds in terms of scientific progress have been achieved for all aspects of these revolutionary machines. EV pioneers and entrepreneurs such as William Morrison and Elon Musk have catapulted the industry far beyond what was previously believed to be attainable. Even over the last decade or so, the share of EV's on many roadways has become increasingly noticeable. The Scottish immigrant and talented chemist, William Morrison, conducted research and experiments specifically on portable energy storage, i.e., batteries. Morrison's work would eventually lead to the invention of the first rudimentary Electric Vehicle in 1890 [1]. Since then, companies such as Tesla, Nissan and Volvo are at the forefront of humanity's new vehicle industry. Even in recent years, practically every other major car manufacturer has made promises to reduce carbon emissions by setting milestones for electric vehicle innovation and production. However, the heavyweight champion as it stands in the realm of Electric Vehicles is Tesla. The engineer turned entrepreneur, Elon Musk, essentially raised the bar for the Electric Vehicle industry in many ways, such as safety, customer satisfaction, reliability, and efficiency. Without Elon Musk's daring attempts to reinvent the way society perceives the Electric Vehicle industry, Electric Vehicles would remain as irrelevant as it did ten to fifteen years ago.

A. Problem Statement

Even though the Electric Vehicle industry has gained massive amounts of popularity and improvements over a short amount of time, the current infrastructure to support the utilization of these machines lags far behind their production compared to their fossil-fuel consuming counterparts. The EV industry is currently experiencing "growing pains" from cities not having the capability to support a newly introduced substantial load onto their electrical grids. When EV's need to be replenished of their energy source, their batteries need to be charged with electricity, like charging a cellphone at the end of the day before bedtime. Electric companies must predict the fluctuation of their city's electrical load for all hours of the day to optimally distribute power to different areas. Thankfully, human beings are predictable when it comes to power consumption, and electric companies can take advantage of this to reduce the strain on their equipment, such as transformers. However, since the recent boom in the EV industry, electric companies have faced challenges when operating their power grids. Unfortunately, several states and even other countries such as China have formed legislation to put a hold on developing infrastructure to support EV's to preserve their electrical grids [2, 3]. These roadblocks may deter people from switching from gasoline powered vehicles to electric and may ultimately stunt the growth of the EV industry.

B. Need Analysis

Since the increasing popularity of EV's took place in recent years, the development of infrastructure to support the EV industry has struggled to maintain the same pace. While EV's are widely regarded as the future of vehicular ownership and much more [4], there is concern that a lack of power stations will prevent future growth of the EV industry. This means that in the meantime, there is a demand for alternative methods of charging EV's. A simple and effective secondary means to charge an EV will undoubtedly be a necessary lifeline to sustain the future growth of the EV industry.

BACKGROUND AND THEORY:

The solar powered wireless charging system consists of only a few simple components. Several components create the solar panel powered wireless charging system. These components and their descriptive characteristics are as follows:

A. Solar Panel

Silicon is the primary material used in most panel systems. This is primarily due to the uniform geometric properties of silicon at the molecular level that gives it the unique ability to efficiently transfer light into energy [5]. Silicon is also one of the most abundant raw materials, making it a cost-effective choice for solar panel construction. The silicon "cells" are generally positioned to form a rectangular shape to maximize the area of the panel to capture and transfer as much light possible as possible. In Figure 2, a simple, effective breakdown of this system depicts the order in which each material is organized and constructed. The semi-conductor is not left exposed; it is encased within protective materials, such as aluminum and tempered glass.

In Figure 1, as sunlight passes through the tempered glass and is subsequently absorbed by the silicon material, busbars that interconnect the cells are then energized with DC power. This power is then used by some external load or stored for a later use by an energy storage device, such as a battery.

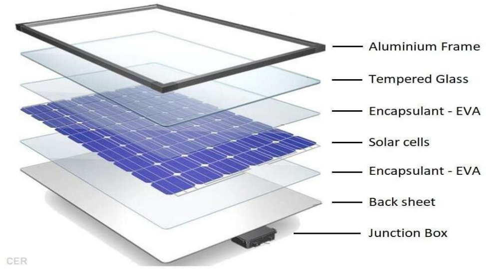

Figure 1. Solar Panel Material Breakdown [5]

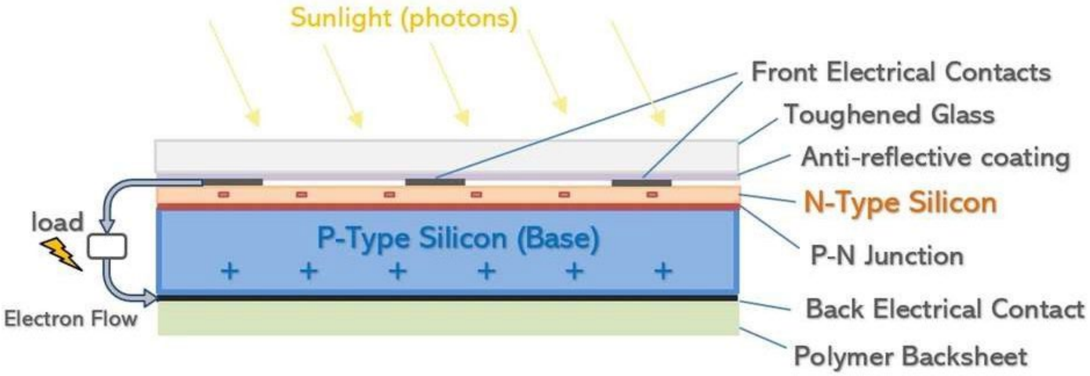

Figure 2. Solar Panel Component Functions [6]

B. Inverter

Since the solar panel is only capable of converting sunlight into DC power, another device called an inverter is introduced to the system to convert the DC power into AC power because the wireless transfer of electricity requires AC power. To convert the power for wireless distribution, the flow of the DC power must be redirected back and forth very rapidly to imitate AC current [9]. The power is then processed into a neat, uniform wave with electrical filtering devices that are regulated to produce a usable AC flow. There are a few different types of inverters to be considered, such as high and low frequency inverters. Low frequency inverters are much heavier due to the large iron core they use to withstand power surges. These inverters are appropriately used in an industrial application where several motors or other various inductors are connected. High frequency inverters are best suited for smaller applications, such as battery charging. The high frequency variant is not only much lighter than the low frequency counterpart, but also much cheaper. There are comparatively far smaller components in a high frequency inverter's circuitry than a low frequency inverter as shown in Figure 3.

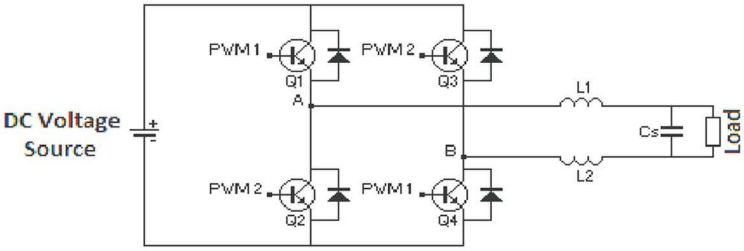

Figure 3. H-Bridge High Frequency Inverter Circuit Diagram [10]

An H-Bridge inverter uses four switches or transistors that reverse the polarity of the DC signal as the input control signal moves through its cycles. The transistors operate in pairs. During the first half of the control signal’s cycle, one pair of transistors will become active. After the first half of the cycle is complete, the first transistor pair will go offline, and the second pair will operate simultaneously through the second half cycle. This operation will repeat very quickly in a short period of time, thus allowing a DC signal to behave like an AC signal.

C. Controller

The previously mentioned components are essentially paperweight without the introduction of a device to control and facilitate the electricity produced by the solar panel. The controller prevents damage to other components, such as the battery by regulating the input voltage. Depending on the specifications of the battery, certain amperage to power ratios must be maintained to prevent the battery from overcharging [5]. There are two types of solar charge controllers: Pulse-Width Modulation and Maximum Power Point Tracking. The PWM controller was selected because it is affordable in comparison to the MPPT controller and will charge at the same rate no matter the array size. The PWM controller is also more appropriate for the application of charging car batteries. A PWM protects your battery by decreasing the amount of charge flowing into the battery as the battery reaches its maximum capacity. When the battery is at maximum capacity, the PWM enters a “trickle” charge mode that keeps the battery full without overcharging and damaging it. Figure 4 shows how one manufacturers device, BougeRV, will bridge the gap between your battery storage and your power generation device.

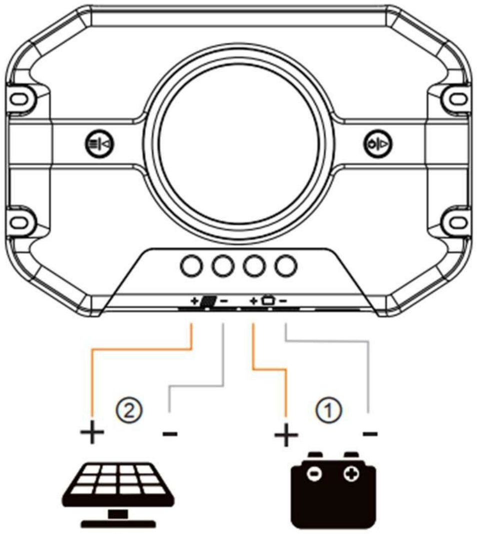

Figure 4. BougeRV Pulse-Width Modulator Controller [11]

An MPPT controller is better used in applications involving more than 12-to-24-volt systems. The efficiency of an MPPT is superior when the scale of the project is at least 170W [6].

D. Battery

By allowing the solar-panel system to charge a separate battery in case the EV is already at full charge, the system can utilize stored charge for later use and keep the charging system functional during periods of low light conditions. Lithium-Ion batteries are a popular choice for solar-charging systems due to the extended lifespan and compact size in comparison to other battery types such as lead-acid. Lithium-Ion batteries can also charge quicker and have a higher charge capacity than other battery types [7]. Lithium-Ion chemistry also holds a higher charge throughout the depth of discharge unlike Lead-Acid, which is graphically depicted in Figure 5.

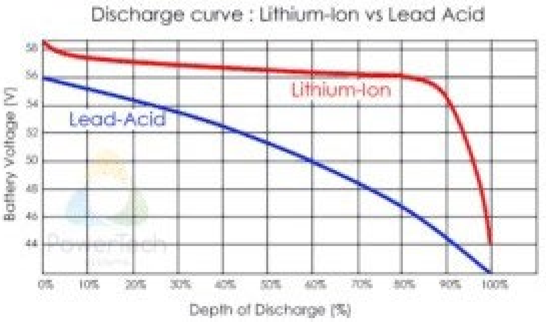

Figure 5. Lead-Acid and Lithium-Ion Discharge Rate [8]

During operation, a lithium-ion battery sends lithium-ions between an anode and a cathode within the lithium-ion cell. These ions move between a porous polymetric film that serves two purposes: to act as a barrier between both positive and negative terminals and to act as a median for the ions to travel across [9].

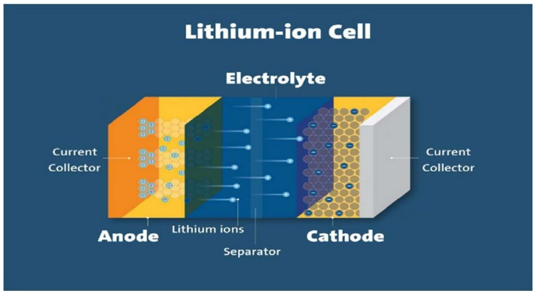

Figure 6. Lithium-Ion Cell [9]

The lead-acid battery variant uses a combination of metal and sulfuric acid to store electric charge. The use of large amounts of lead in these batteries is the primary reason for their increased weight and size compared to lithium-ion. Lead plates are submerged in sulfuric acid liquid in the battery housing. During operation, the molecular structure of the acid liquid splits apart and collects electrons from the lead plates. Through more chemical alteration at the molecular level, the gained electrons are deposited at the anode in connection with the positive DC source [10].

E. Power Regulator

As the intensity of sunlight fluctuates during the solar powered wireless transmitter system's operation, fluctuation in voltage being generated and delivered by the solar panel will also occur. Before the controller can be programmed to distribute the generated power to the user's desired specifications, a power regulator is a wise addition between the controller and the panel. A power regulator is a DC-to-DC converter that can either limit or boost the flow of generated power during times of high or low output, respectively. This device operates in a similar manner to aa AC transformer such that it can "step up" or "step down" the voltage source as it passes through the device [11]. In summary, a stable voltage output can be achieved by including and connecting this device directly after the solar panel. The simplicity of the buck-booster, DC-to-DC system is presented in Figure 7, with a voltage source, an inductor, a capacitor, a transistor, a diode and a load.

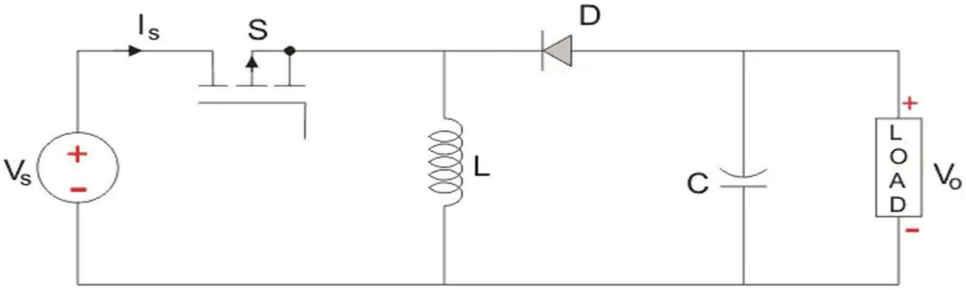

Figure 7. A Typical Buck-Boost Converter Diagram [17]

With a solid-state device such as a transistor or, in this case, a MOSFET, the voltage source that is directly connected will either open or close the switching device. During periods of low voltage conditions, the MOSFET will act as an open switch, releasing stored energy within the inductor's coil which then acts as another voltage source, providing a boosted voltage level. During higher than desired voltage conditions, the MOSFET enters a closed switch or short-circuited state while the diode prevents the extra voltage from entering the load and redirects the unwanted excess voltage back to the input source [11].

DESIGN GOAL AND OBJECTIVES:

The project goal is to provide EV drivers with a safe, affordable, effective, and reliable alternative to charging EV's without a charging station nearby. To achieve the goal, several objectives must be established. A device must be designed to be portable so that the EV operator may transport it within their EV which is intended to prevent the driver from having a dead battery with no way to charge it if they are not near a charging station. A device must be built and subsequently tested to observe and measure its ability to provide ample charge to an EV battery.

A. Design Specifications

Several design requirements must be established prior to researching an alternative to EV charging. The following specifications must be considered:

1. The device shall be integrable with the existing EV charging 12-volt system.
2. The device shall be portable and able to be stored within the EV.
3. The device shall be able to charge the EV during operation.

B. System Decomposition

The solar powered device with a wireless transmitter is broken down into its most basic functions and capabilities. A solar panel comprised of photovoltaic cells made of semi-conductive material absorbs light emitted from the Sun. Many factors, including obstruction from clouds and other objects will constantly alter how much power the solar panel will generate. Because of this, a device called a power regulator, or buck-booster, will alleviate any issues of power fluctuation directly after the source. Then, after stable power is maintained by the power regulator, a battery can retain the generated power for later usage and to power other devices in the system. When a load, such as an EV, needs the external power supply, power from the battery is distributed through the inverter initially to convert the DC power into wirelessly transferrable AC power, which is then transferred through the transmitter coil. The last device shown in Figure 8 is the controller, which will facilitate the flow of power to the regulator, battery and the inverter, simultaneously. Figure 2 visualizes the flow of power through the devices as a collective system.

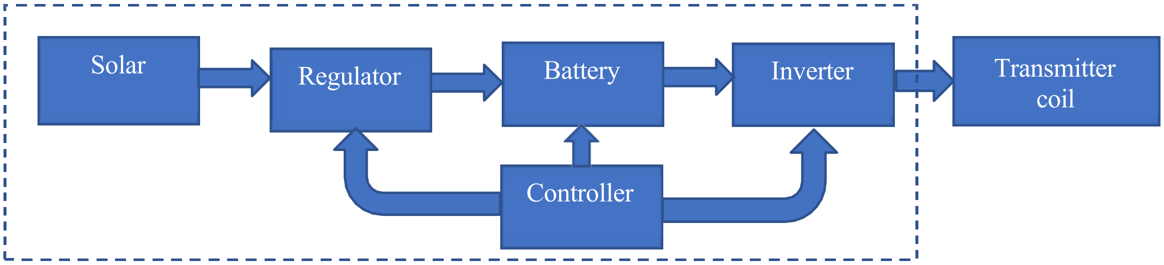

Figure 8. Solar Powered Wireless Transmitter Device System Decomposition

DESIGN IMPLEMENTATION AND TEST EVALUATION:

Simulink was utilized for the purpose of creating an ideal and realistic simulated model of the EV charging device. The components were implemented according to the block diagram in Figure 2. Creating a simulated model of the device serves to establish a fundamental understanding of the components working as a system and how the components affect one another during operation. The circuits shown in Figures 9, 10, and 11 are only rudimentary replicas of the manufacturers' components but will nevertheless represent how the device will operate with great accuracy for educational and research purposes. Figure 10 displays the entire solar powered wireless charging device as an interconnected system in Simulink.

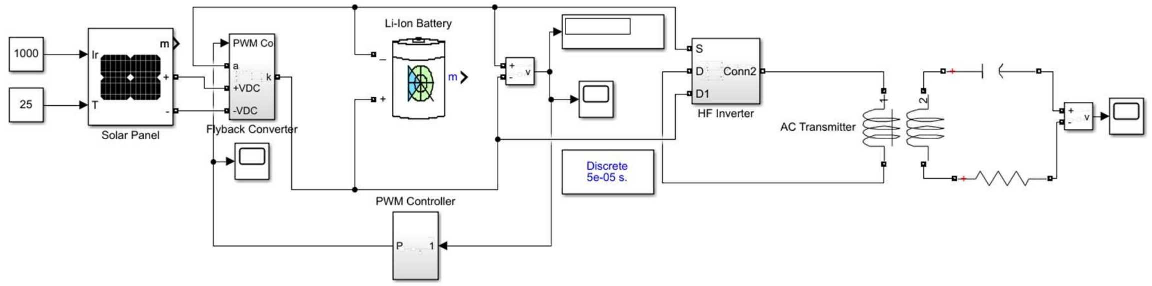

Figure 9. Simulated Solar Powered Wireless Charging Device

The PV array is first in connection with the flyback (buck-boost) converter which receives signals from the Pulse Width Modulation controller simultaneously. The PWM controller will take output from the buck-booster as input and compare the buck-booster's output to a programmed reference value. In this case, for optimal and safe battery charging, the reference voltage is set to 14VDC. The PWM controller will send a corrective output to be read as input to the buck-booster which will facilitate a stabilized voltage pulsing through the system from the PV array to the lithium-Ion battery. In Figure 10, the converter is shown as its own subsystem. A MOSFET is a switch that operates depending upon the amount of voltage coming in from the source. As the voltage level increases, the larger the medium for the passage of electrons becomes, and the inductors become magnetized. The diode prevents unnecessary feedback, and the capacitor isolates the desired signal for transmitted power.

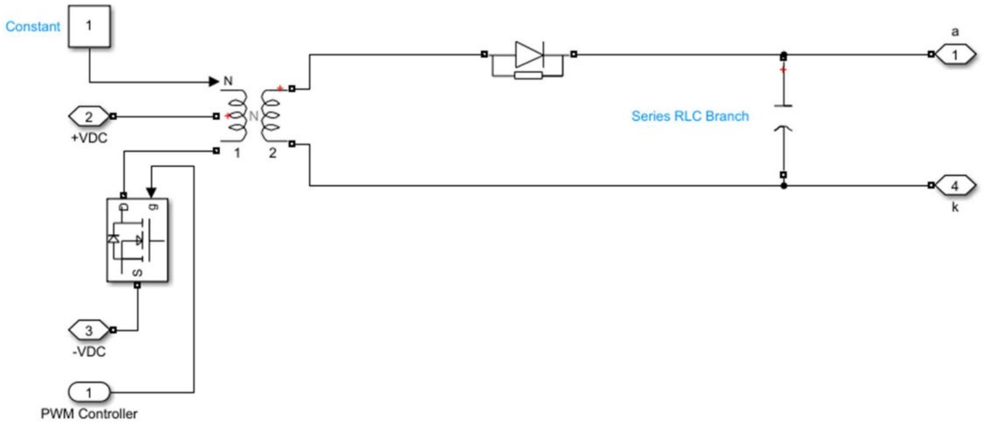

Figure 10. Simulated Flyback Converter (Buck-Booster)

After DC power is generated from the PV array and optimized by the controllers, the device can wirelessly transfer power to a battery in an EV with a high-frequency inverter and a transmitter. The high-frequency inverter is shown in Figure 11, which displays two pairs of MOSFETs that synchronously operate. As one pair allows the passage of current, the other restricts it, simultaneously. This process occurs very rapidly, forcing the DC signal input to behave as an AC signal output to the mutual inductor. DC power cannot be wirelessly transferred as it does not emit an electromagnetic field, hence the need for its conversion to AC power. Once the conversion takes place, properties of AC power allow it to be transferred, using the air as a medium, to a receiver that is not physically connected to the wireless charging device.

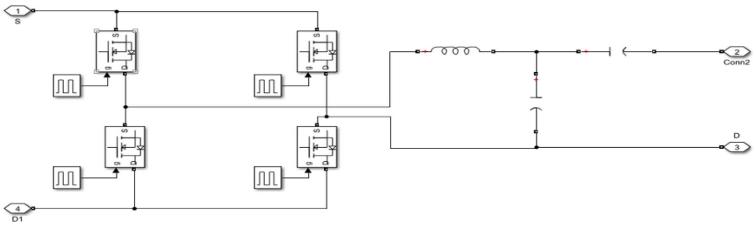

Figure 11. Simulated High-Frequency Inverter

Figures 12-14, display useful data produced from the simulated solar powered wireless charging system. In figure 13, Simulink can produce visuals of the discharge rate of the Lithium-Ion battery available in the software. A load drawing a current of 5.2 amps will drain the battery through its useful voltage range in approximately 2 hours. Different amperages will vary the rate of discharge.

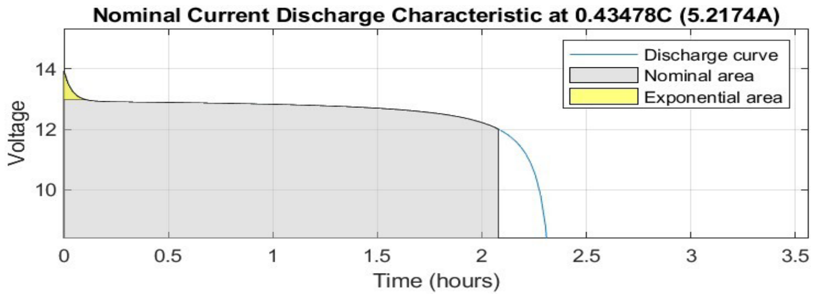

Figure 12. Simulated Lithium-Ion Battery Discharge Rate

Figure 14 plots the voltage level through 10 seconds of discharging power to the inverter. This signal is currently behaving as direct current but will subsequently be transformed into alternating current after it reaches the next device. The power stored from the photovoltaic panel and regulator steadily approaches 0 as time increases, but the battery can be programmed to exclusively store power while the charged system is at full capacity.

The DC signal passes through the inverter, and the MOSFETS begin the process of rapidly switching the direction of the electrons. The DC signal then becomes an AC signal and produces the following plot depicted in Figure 15. The signal produced is seen rapidly and periodically fluctuating between roughly -10 and +10 volts.

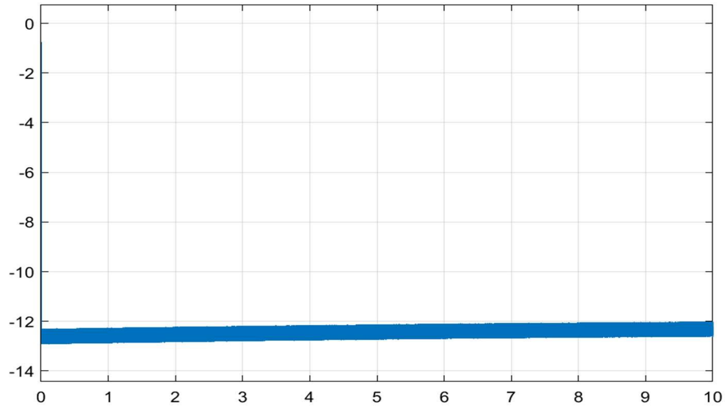

Figure 13. Lithium-Ion Battery Voltage Discharge to Inverter.

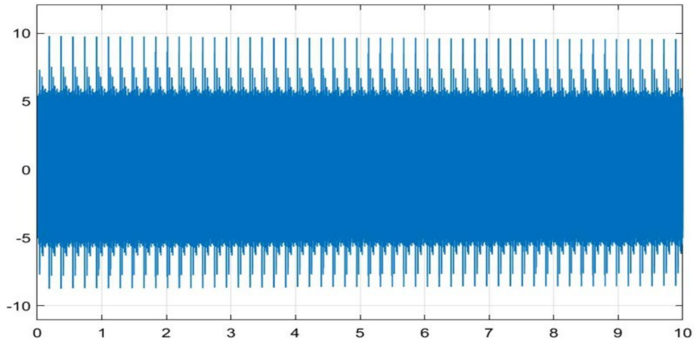

Figure 14. Simulated High-Frequency Inverter Output

Measurements including real and reactive power, current and voltage are to be measured before the inverter at the battery for the purpose of collecting data. It is shown in Figure 15 that the real power of the Simulink system maintains approximately 400W while reactive power remains near 0.5 VAR. Voltage behaves the same as it does in Figure 13.

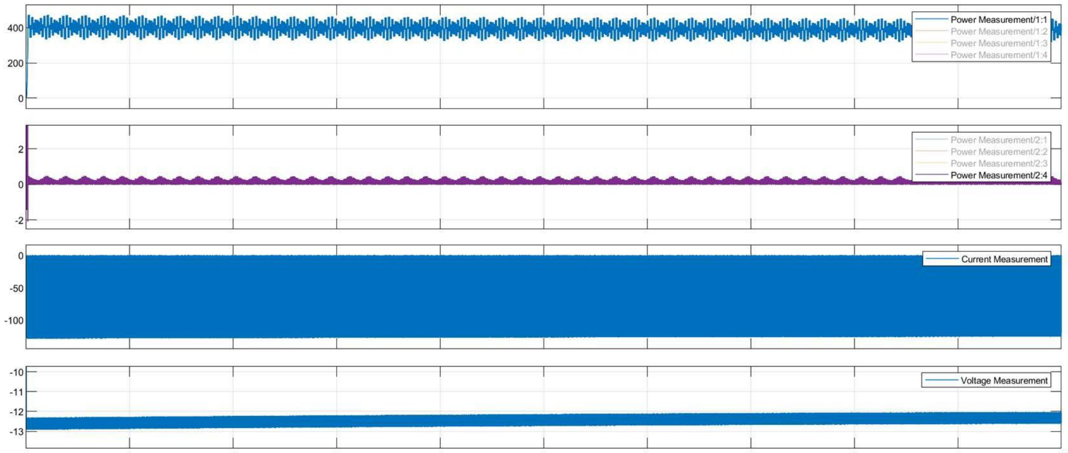

Figure 15. Real Power, Reactive Power, Current and Voltage Measured at Battery

The effects of temperature on a PV design can cause a severe decrease in efficiency, as shown in Figure 16. The standard reference temperature used is 25° Celsius, meaning that when a panel has a temperature coefficient of -0.5/°C, for every degree past 25, the PV array will be 0.5 percent less efficient in energy production. Figure 16 shows at varying temperatures how the simulated PV array will decrease in power production.

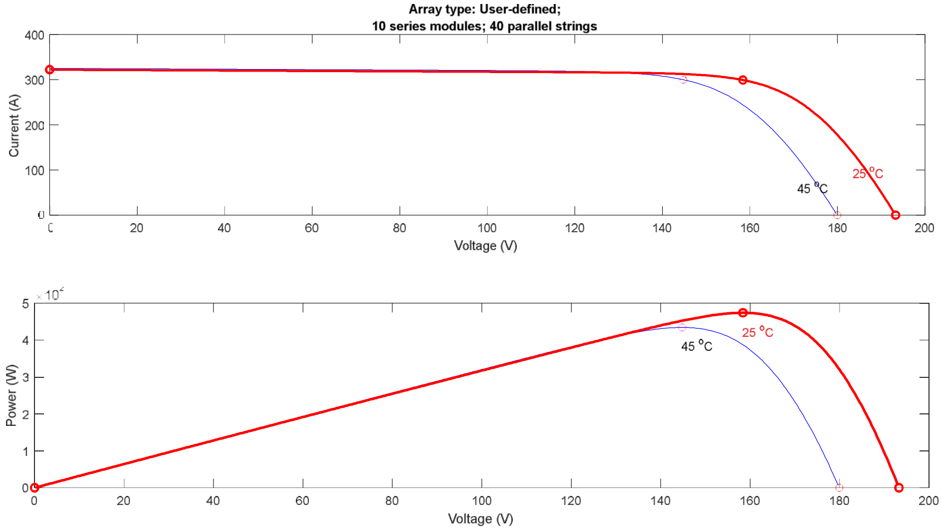

Figure 16. Temperature Coefficient Effect on PV Array

G. Lab Testing and Results of Solar Powered Wireless Charging Device

The device was tested with a substitute for the PV array due to a lack of time needed to wait for the solar panel to power the system and produce quick results. For demonstration purposes, a power source connected via a wall outlet was connected instead. This power source has functions that allow variable voltage throughout the charging sequence which should closely resemble the changing output from a PV array as the intensity of radiance varies throughout the day. To monitor and record voltage and current at the battery, an ammeter and a voltmeter were both connected to the circuit. The oscilloscope reads output at the receiver to verify power is successfully transferring between the inductors. The inductors were made by hand with simple wires and capacitors for the sake of simplicity and convenience. Figure 17 includes all components of the solar powered charging system in a testing and experimental environment.

The power source is constantly adjusting the voltage and current output throughout the charging process. However, the charge regulator directly to the right of the power source is tuned to allow a maximum of approximately 14V to be distributed to the battery to prevent overcharging. The output of the energy storage device to the inverter is also regulated to approximately $11V_{DC}$ by the small device seen between the battery and the inverter shown in Figure 17. This is to protect the MOSFETs and ICs within the inverter due to previous failure during testing where some equipment was damaged. A fan is used to dissipate heat from the MOSFETs as well. The regulator and a cooling system would typically integrated into one device with the inverter, but for demonstration purposes, these components were separate. Through an oscilloscope, a sine wave is generated and measured at the receiver. The 50kHz (high frequency) inverter was able to successfully transfer power as required by the design specifications. In Figure 18, the voltage is shown as 30V, but the distance between the transmitter and receiver has a significant effect. When the distance is increased, the voltage fluctuates until a certain length is passed which results in the loss of the magnetic coupling altogether.

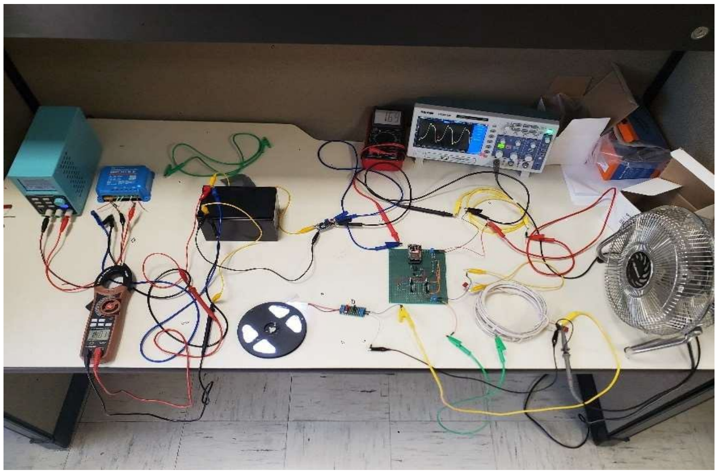

Figure 17. Wireless Solar-Powered Charging System

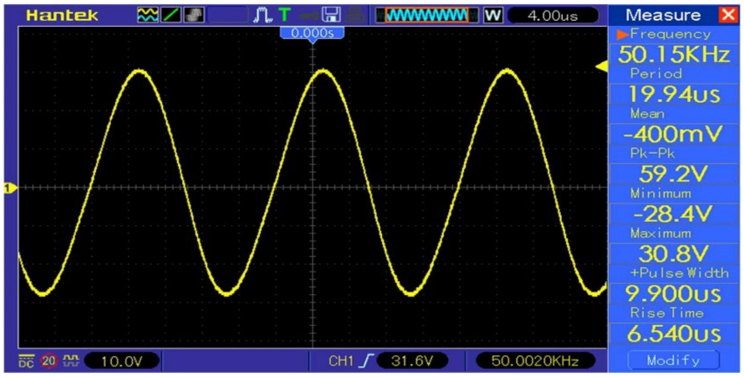

Figure 18. Oscilloscope Measurement at Receiver

The results include successfully powering a load wirelessly with the PV system as well. A small load of 3W connected after the receiver and rectifier was energized while the device was generating power. The load used was a strip of LED’s, which allowed quick and simple verification of successful power transmission on the receiving end of the system. Regardless of the power source being on or off, provided the battery has sufficient charge, the power to the load was maintained as well.

H. Risk Assessment

The project and device are on a small-scale, so the potential risks involved are limited and manageable. Potential risks involve a lack of sufficient charging due to low sunlight intensity for a variety of reasons such as time of day, light obstruction from various objects and weather. There is also a low yet notable possibility of the occurrence of electrical faults within the device, which was observed during testing and remedied with the introduction of corrective hardware. A Risk Assessment Matrix was utilized to identify, analyze and mitigate the previously mentioned potential risks. The potential risks are given a rating based on the likelihood that the risk will occur and the severity of the effects.

In the event of case one, lack of charging due to periods of low sunlight intensity, the likelihood of this occurrence is classified as "occasional" as radiance from sunlight is not always going to be at a maximum level. It is commonly known that areas of low light conditions will greatly reduce the effectiveness of any PV device, so it is assumed that any potential user will assess that their environment is suitable for the device. An area with at least average to moderate sunlight exposure throughout the year is considered in reference to case one. The impact or severity of low light exposure has a potential to significantly impact the performance of the solar powered device, which puts case one in zone 3 in Table 1.

In the event of case 2, which involves a short or electrical fault within the solar powered charging system, the system can potentially go completely offline permanently as a worse-case scenario. However, the likelihood of this outcome occurring is extremely minimal if all the necessary components are present and correctly tuned to their respective values. For instance, tuning the charge controller to approximately 14V prevents overcharging of the battery from the PV or power source. Similarly, the regulator between the battery and the inverter regulates the voltage further to protect the components in the inverter, and a fan dissipates heat from the inverter's MOSFETs. This means that while the outcome of the event of an electrical fault has a potential to be highly problematic, the probability of such an event is almost irrelevant under the assumed condition that all hardware requirements are met, which places case two in region 3 in Table 1.

Table 1. Risk Assessment Matrix

				PROBABILITY					
				A	B	C	D	E	F
SEVERITY	Category	Descriptive Word	Loss of Points	Frequent	Reasonably Probable	Occasional	Remote	Extremely Probable	Impossible
	1	Catastrophic	Total Loss	1	1	1	2	3	3
	2	Critical	Majority	1	1	2	3	3	3
	3	Marginal	25%	2	2	3	3	3	3
	4	Negligible	0%	3	3	3	3	3	3

CONCLUSIONS AND RECOMMENDATIONS

A. Conclusion

The results gathered from the Simulink simulation and lab-tested system conclude that the solar powered wireless charging device is both conceptually and physically feasible. The device serves primarily to act as a wireless, eco-friendly and portable back-up charger for an EV. The Simulink simulation and lab test results prove that the system can successfully generate, store and transfer power to a load. The use of a renewable energy source would categorize this device as an "environmentally friendly" EV charger since solar power does not produce harmful carbon by-products. Also, this device is small and light enough to be easily moved or stored, but it is much more useful when always deployed during EV operation.

While running the simulation, battery charging and discharging was verified with the help of the measuring tools provided in the software. The system in the simulation closely mirrored the physically implemented device to ensure feasibility and accuracy, which the simulation provided with plots including power, current and voltage at the battery terminals, battery discharge rates at varying temperatures and amperages, and voltage measurements at the receiver.

During lab testing, voltage was measured at the PV output and the charge controller output to verify the correction of excess voltage levels. Voltage was also measured at the battery to verify charging while the PV was in operation and discharging when it was off. A small load was applied to the battery during and after PV operation which verified that power was successfully transmitted through a mutual inductor.

B. Recommendations

Although the device is intended to be easily removable and portable as per the one of the design specifications, the user will experience far greater results in terms of charging capabilities if the solar-powered charging device is always left in operation possible. Since sunlight is at peak intensity for a small period each day and moderately intense for slightly longer, the device should always remain deployed to the vehicle and only removed if necessary. However, leaving the option for quick and easy removal is a unique and invaluable quality of the device.

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