A Review on Charging Systems for Electric Vehicles in Smart Cities

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Abstract: An overview of types of electric vehicles and the variant batteries which the electric vehicles currently use is demonstrated. Different charging systems are presented. Plug-in charging system which is either on-board or off board is investigated. Moreover, fundamentals of wireless charging are analyzed for smart cities. Current market perspectives are provided. A hybrid charging system is also discussed. Different approaches for vehicle to vehicle charging either using plug or wireless charging are provided.

1 INTRODUCTION

Batteries are the main energy source of electric vehicles (EVs). However, some types of EVs also rely on other energetic components. Many systems have been developed for charging Electric Vehicles (EVs) batteries. The main two technologies are Plug-In (Turksoy, et al., 2018) and Wireless charging Systems (Bosshard, et al, 2016). Plug-in charging systems are hazardous and pose the danger of electric shocks (Freschi, et al, 2018); however, they are easier to implement and mostly have higher efficiency. Wireless Chargers, on the other hand, are safer and eliminate the inconvenience imposed by the bulkiness of the cables. Nonetheless, having the wired (plug-in) and wireless charging systems available at the same time is critical, especially before the wireless charging infrastructure is readily available (Chinthavali, et al, 2016).

Wireless power transfer (WPT) is a convenient way for electric and plug-in hybrid electric vehicle charging that has seen rapid growth in recent years for stationary and even dynamic applications. The size of the couplers in WPT systems can be reduced and the power transfer density increased by designing the systems to operate at higher frequencies. Higher operating frequencies also enable smaller power electronics associated with WPT systems (as shown in Figure 1) thanks to a decrease in energy storage requirements.

Today, real-time charging from the utility grid is recognized to be the mainstream way of ’fueling’ electric vehicles (EVs). However, since the current EV penetration rates are very limited, many of the problems such as increased distribution level peak demand. Studies show that residential EV charging will result in disruptive problems in the distribution grid of the future (Cuchý, et al, 2018), (Graber, et al, 2018), (Chentong, et al, 2019), (Luigi, et al, 2019), and (Veneri,et al, 2017). This indicates that residential EV charging must be accompanied by faster public stations to sustain the EV growth.

Vehicle-to-vehicle (V2V) Charge Sharing Network (CSN) philosophy can provide an alternative, more convenient, and flexible way of conducting EV charging. The design and implementation of V2V CSN will greatly reduce the range anxiety of EVs with minimal infrastructure cost (Ucer, et al, 2019).

This survey is organized into 7 sections. Section I provides a brief introduction to the topic this study is concerned with. An overview of types of EVs and batteries is given in section II. Section III discusses plug-in charging systems. Fundamentals of wireless power transfer and wireless charging systems along with market analysis is given section IV. Further, section V gives a unique overview of combining the wired and wireless charging systems. Section VI discuss the concept of vehicle to vehicle charging. The conclusion of this survey and possible future work is highlighted in section VII

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2 TYPES OF ELECTRIC VEHICLES

Batteries are the main energy source of EVs but some types of EVs also rely on other energetic components. Thus, there may be some EVs which work with electric propulsion alone while others also employ an Internal Combustion Engine (ICE). On that basis, the Technical Committee 69 of the International Electrotechnical Commission (IEC) has established the following classification of electric vehicles running with batteries:

- Battery Electric Vehicle (BEV). Power is inserted into the drive train exclusively by means of batteries.
- Hybrid electric vehicle (HEV). This refers to vehicles with two or more types of energy source or storage, providing one of them with electrical energy.
- Plug-in Hybrid Electric Vehicle (PHEV). This type of vehicle mainly uses the electrical power train to run.

Battery Technology in EVs. Batteries are the main storage element used in EVs. These elements make it possible to store energy in chemical form and convert it to electrical energy when required. The characteristics of the batteries, such as the density of energy and power, are defined by the technology used. Although many of them have characteristics that meet the criteria of electric vehicles, power is usually a limiting factor for some tasks such as acceleration and regenerative braking.

The battery technology used in electric vehicles has evolved over time, especially in recent years with the emergence of large vehicle manufacturers in this market. Lead-acid batteries were the first type of battery used to start the internal combustion engines in vehicles. Some manufacturers, such as Toyota and General Motors, have tested this technology in BEVs. However, the low energy density of this kind of battery does not make them suitable for pure EVs. ZEBRA batteries, also known as molten salt batteries, have been used for some vehicle concepts and urban bus models (O'Sullivan, et al, 2006). These batteries have a good energy density, but they need to operate at high temperatures (between 270 and 350 C). This restriction means that this technology is only viable in vehicles with a continuous operation in order to maintain the working temperature.

NiMH technology has been widely used in the market (Iclodean, et al, 2017). Despite the low efficiency of this technology and a slightly higher weight than others, its good energy and power density combined with its simplicity, low cost and useful lifetime make it a good solution for HEVs and PHEVs. However, Lithium-ion or simply Li-ion batteries are the market leaders thanks to their electrical features. Within this group of batteries, we find a wide variety of different types. The types of Li-ion batteries vary according to the specific chemical combination found at the anode and the cathode. Although the combination most widely used in consumer applications is Lithium-Cobalt Oxide (LCO), its use does not extend to electric vehicles due to safety concerns. Instead, the most common solutions for automotive applications are lithium-nickel-manganese-cobalt (NMC), lithium-nickel-cobalt-aluminum (NCA) and lithium-iron phosphate (LFP). Table 1 summaries the main electrical features of the batteries discussed above (Kumar, et al, 2017).

Table 1: Comparative Table of Electric Vehicle Batteries.

	Nominal Voltage(V)	Power (Wh/Kg)	Life Cycle	Production Cost/60 KWh
Lead acid	2	180	1000	$4,800
Nickel-metal Hybrid	1.2	200-300	<3000	$20,000
ZEBRA	2.6	155	>1200	$19,600
Li-ion	3.6	200-430	2000	$12,000
Li-iron Phosphate	3.2	2000-4500	>1200	$28,000

3 PLUG-IN CHARGING SYSTEMS

This section gives a quick overview of plug-in battery charging systems for electric vehicles. Battery Chargers can be categorized into two main categories, on-board and off-board, with the two options of unidirectional and bidirectional power transfer, this is decided according to the place where the charger is installed (Turksoy, et al., 2018).

Battery chargers are a kind of power converter that supplies power from the network to the battery pack. The charger usually creates a non-linear load in the power system. Charging the battery with high efficiency is not the only concern of a well-designed charger, but also to meet the international standards (Pan, et al, 2017). The comparisons of on-board vs. off-board battery charger features are given in Table 2.

Table 2: The comparison of On-board vs. Off-board battery chargers.

On Board Battery Charger	Off-Board Battery Charger
Generally lower KW charging	Generally higher KW charging
Battery management system is managed by on-board rectifier	Battery management system is more complicate
Less concern about battery heating	Battery heat must be controlled
Add weights to vehicle	Removes weight from vehicle
Slow and semi-fast charging	Fast charging

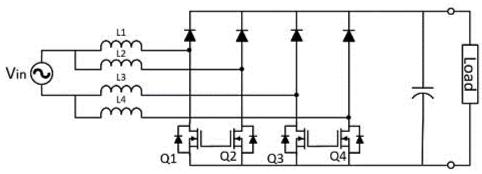

Figure 1: Circuit topology of bridgeless interleaved boost PFC. (Turksoy, et al., 2018).

Unidirectional charger is a power converter with simple control structure where the power is supplied in only one direction from the network to the battery pack; while bidirectional battery chargers are power converters that charge the battery pack from the network and transmit this power to the grid when the network needs it (Tashakor et al, 2017). The characteristics of the battery charger affects the battery life and charge time.

The first stage of a two-stage EV battery charger carries out the AC DC conversion with power factor correction (PFC). The second stage is DC-DC converter which is convert the output DC voltage level of AC-DC PFC converter to the battery DC voltage level (Chen, et al, 2011). Figures 1 and 2 show the topologies of a PFC and a DC-DC converter.

The safety of EVs users may be challenged by the vehicle's increased operating voltages, at different frequencies, possibly making the protection against direct and indirect contacts more complex. As a result, plug-in EVs must meet minimum safety requirements. Consumer safety may be affected by various hazards associated with human interaction with these vehicles, including chemical, collision, electrical, and fire risks. The chemical hazard is associated with a given battery technology and stems from the potential chemical release of the battery's reactive constituents, with which people may come into con-tact (Freschi, et al, 2018).

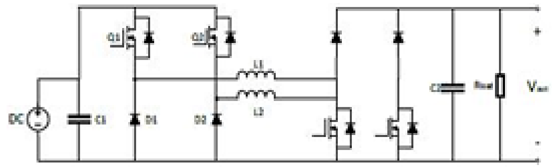

Figure 2: Interleaved Buck-boost DC-DC converter (Turksoy, et al., 2018).

4 WIRELESS CHARGING SYSTEMS

4.1 Fundamentals of Wireless Power Transfer

Wireless power transfer is supported by an electromagnetic wave travelling from the power emitter to the power receiver. In WPT systems, the electromagnetic field is exclusively generated to transfer power. Conversely, energy harvesting techniques make use of the electromagnetic waves generated to transfer information to acquire energy to power devices. Thus, energy harvesting techniques are restricted to the requirements imposed by the information transfer, which are not present in WPT technologies.

The behavior of an electromagnetic wave is defined by Maxwell's equations. Simplification of these equations is possible when some conditions hold, leading to the near-field and far-field operation. Both scenarios are described next.

Near-field Operation or Non-radiative Propagation. Three conditions must be satisfied to work in this kind of scenario. They are:

- The size of the transmitter element, L, is much smaller than the wavelength λ.
- The distance between the energy emitter and the receiver is much smaller than the wavelength λ.
- The distance between the transmitter and the receiver is much smaller than $(2L^2)= \lambda$.

Far-field Operation or Radiative Propagation. This is based on the electric field of the electromagnetic wave. In this case, the conditions are:

- The distance between the energy emitter and the receiver is greater than the wavelength λ.
- The size of the transmitter element LDEV is more than 10 times greater than the wavelength λ.

1) Inductive WPT: Inductive WPT is realized with the magnetic field of the electromagnetic wave. The

operation principle is explained by the interaction of the magnetic and electrical behavior described by Ampere's` Law and Faraday's Law. According to Ampere's` Law, a current-carrying wire generates a magnetic field around it. The intensity of the magnetic field and its orientation depend on the topology of the wire. Specifically, Ampere's` Law (1) states that:

$$\oint \bar{H}\ dl = I \quad (1)$$

where H is the magnetic field intensity of the magnetic field generated by the electric current I and dl is the differential element of length along the path on which the current travels.

Unlike simple wires, coils are able to concentrate, to a higher degree, the magnetic field around the area in which they are defined. As described by Ampere's` Law, when a time-varying current passes through a coil, a time-varying current magnetic field is generated around this element. If that time-varying magnetic field traverses a different coil, a voltage (e_{ind}) is induced in its terminals. This effect is described by Faraday's Law as follows (2):

$$e_{ind} = -\frac{d\phi}{dt} \quad (2)$$

where is the flux of the magnetic field passing in the area limited by the coil. Inductive WPT technology requires a pair of coils referred to as the primary and secondary coils.

2) Magnetic Resonance WPT: Magnetic resonance or resonant WPT can be considered an improvement on inductive WPT in which the electrical system is forced to work under resonant conditions. To meet this requirement, the pair of coils is connected to structures composed of reactive elements such as capacitors or additional coils. These structures are referred to as the compensation networks.

The most simple compensation topologies consist of a single capacitor, which may be connected to the primary and the secondary in series or in parallel. These networks are referred to as mono-resonant compensation topologies. Alternative, more complex compensation topologies are also an option. These are identified as multi-resonant compensation topologies.

4.2 Wireless Chargers for Electric Vehicles

Due to the current environmental crisis, there is great interest in developing new trends in the sustainable transportation sector. In this context, EVs are expected to significantly decrease greenhouse gas emissions and, in turn, lead to a healthier living \environment. A number of facts support this prediction. According to the United States Environmental Protection Agency, nearly 28.9% of the greenhouse gas emissions of the United States in 2017 were derived from the transportation sector (US EPA, 2015), (Sato, et al, 2016).

4.3 Wireless Power Transfer Market Perspectives

Presented below is a review of a number of technology providers that lead the EV-WPT market (Choi, et al, 2015):

-**WiTricity:** WiTricitys 3.6–11 kW EV charging products show an overall system efficiency of 90–93%. WiTricity works actively with global standardization agencies such as SAE International and IEC/ISO. The WiTricity EV wireless products offer several charging rates varying from 3.6 to 11 kW to meet different EV battery needs and with a single system design.

-**Qualcomm:** This technology offers a power rate ranging from 3.3 to 20 kW at an overall efficiency greater than 90%. Qualcomm technology uses patented innovative technology that enables highly efficient power transfer even when the charging pads are not completely aligned.

-**Evatran:** Evatran offers a 7.2 kW-production plugless system charging a BMWi3 across 254mm of clearance. The charging time of different systems is presented in Table 3.

Table 3: Comparative table of charging times.

		WiTricity	Qualcomm	EVATRAN
BMW 530e	Charge Time/hours	0.84-2.6	0.46-2.8	1.28
Audi e-tron	Charge Time/hours	3.5	4.75-28.8	13.2
Toyota Prius	Charge Time/hours	0.8-2.4	0.44-2.67	1.22
Nissan Leaf	Charge Time/hours	3.6-10.97	1.975-11.96	5.49

4.4 Wireless Charging Systems

The industry has experienced huge progress in inductive WPT technology for stationary charging of EVs the past decade (Bosshard, et al, 2016). In today's market, stationary chargers are already available. However, for magnetic flux guidance and shielding, inductive WPT systems require ferrite cores. This makes them expensive and bulky. The operating frequencies are kept under 100 KHz to limit the losses in the ferrites. This results in low transfer power densities and larger coils. The high cost and low power transfer density pose huge challenges for dynamic WPT, as these systems need to have very high power capability in order to deliver sufficient energy to the vehicle during its very brief time passing over a charging coil.

For these reasons dynamic inductive WPT is yet to become commercially viable, although a few experimental systems have been demonstrated (Choi, et al, 2015) (Onar, et al, 2013). The inductive WPT is shown in Figure 3.

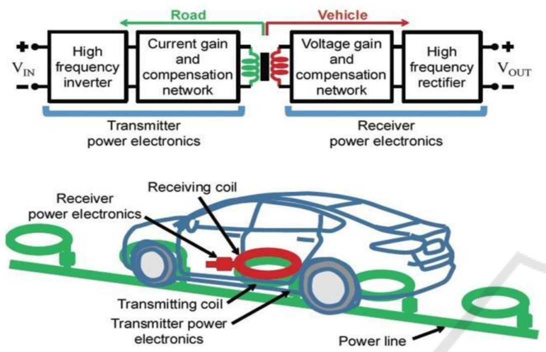

Figure 3: Inductive WPT using plates coupled through electric fields (Choi, et al, 2015).

Achieving effective power transfer limits WPT systems' operating frequency to be close to the resonant frequency of the resonant tank formed by the reactances (capacitive and inductive) of the coupler and compensating network. However, the coupler reactance depends on the vehicle's road clearance, and varies as the vehicle moves across the charger. A reduction in power transfer and WPT system efficiency is then caused by the drift between the resonant and operating frequency.

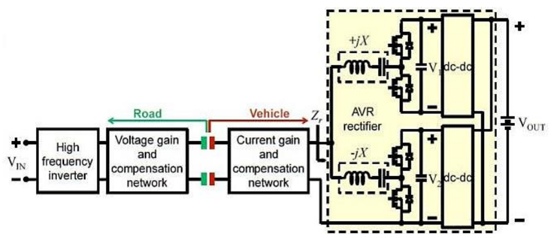

Figure 4: A capacitive wireless power transfer (WPT) system with an active variable reactance (AVR) rectifier that can provide continuously variable compensation by controlling the voltages V_1 and V_2 (Regensburger, et al, 2017).

Adaptive impedance matching techniques include the use of saturable and variable inductors (James, et al, 2005), but these techniques reduce system efficiency and do not scale well with power. An example of a high frequency rectifier and inverter architecture, that compensate for coupling variations , while operating at fixed frequency and maintaining high efficiency is the active variable reactance (AVR) rectifier shown in Figure 4.

By appropriately controlling the output voltages of its two coupled rectifiers, the AVR can provide continuously variable compensation while maintaining optimum soft switching to ensure high efficiency. This compensation architecture ensures that the output power of the WPT system is maintained at a fixed level across wide variations in coupling and is applicable to both capacitive and inductive WPT systems.

5 COMBINED WIRED AND WIRELESS CHARGING SYSTEMS

This section gives a unique overview of combining the wired and wireless charging functionalities as presented in (Chinthavali, et al, 2016). As the number of EVs increase, the market is in continuous need for reduction in cost size while increasing the efficiency and the power rating of on-board chargers. Further, on- and off-board plug-in chargers pose the hazard of electric shock along with the heavy weight and large size of cables. Implementing WPT, ergo having wireless chargers seems to solve these problems; however, having the wired (plug-in) and wireless charging systems available at the same time is critical, especially before the wireless charging infrastructure is readily available. Achieving the integrated system using same components for both charging systems substantial cost benefits could be achieved (Chinthavali, et al, 2015).

Figure 5 shows the overall proposed integrated system. The topology five stages of power conversion from the wall to the vehicle battery in the wireless charging mode and four stages in the wired charging mode.

5.1 Wireless Charging Mode

Figure 6 demonstrates the circuit topology for the wireless mode of operation. Utility ac power is converted to controllable dc voltage by the active front-end rectifier with power factor correction (PFC). Adjustable dc voltage is applied to the input of the high frequency (HF) full-bridge inverter with a controlled duty ratio.

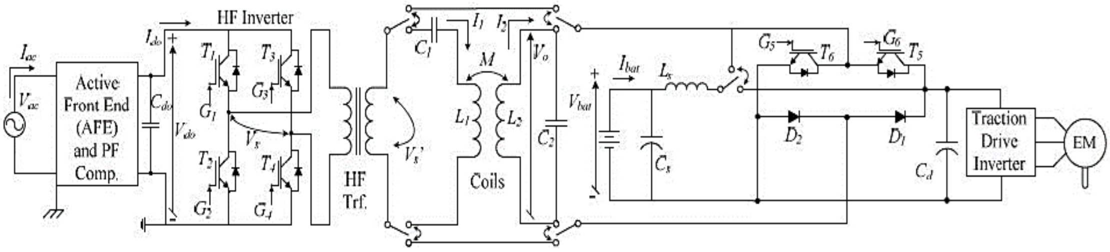

Figure 5: Integrated system topology on the circuit level. (US EPA, 2015).

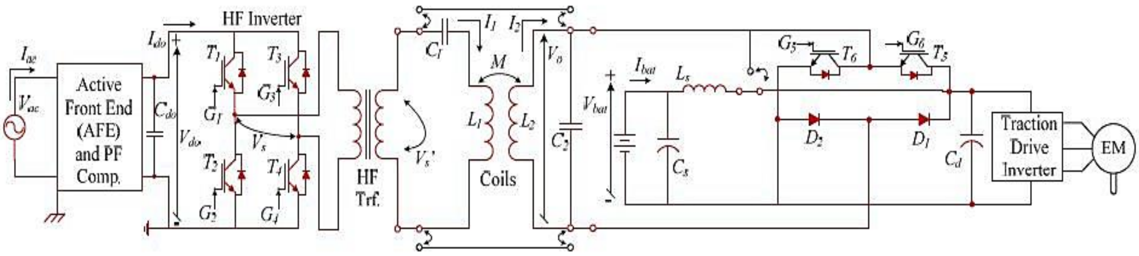

Figure 6: Wireless charging system topology on the circuit level. (US EPA, 2015).

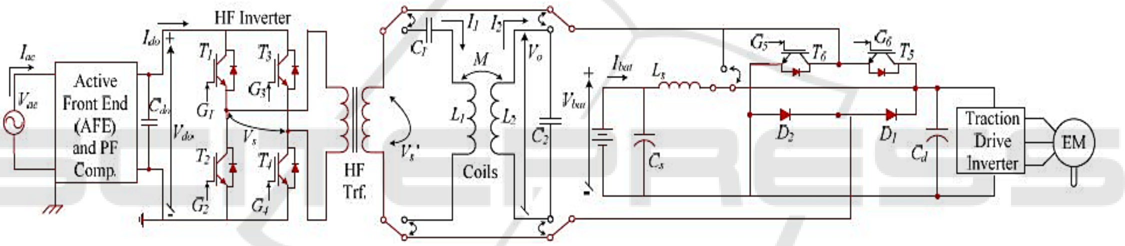

Figure 7: Wired charging system topology on the circuit level. (Chinthavali, et al, 2015).

The HF stage delivers excitation current to a series tuned primary coil for magnetic field generation that is linked to the secondary coil on the vehicle across the air gap. Voltage induced at the secondary is rectified, filtered, and delivered to the vehicle HV battery.

5.2 Wired Charging Mode

The HF transformer solution also provides the flexibility of using the system as a wired charger. This can be achieved by simply using a relay system that can be operated to disconnect the resonant coil system and connect the output of the HF transformer to the on-board section of the integrated charger system. The wired charging mode of operation has four power conversion stages. This mode of operation will enable the EV users to use the plug-in charger wherever there is no wireless charging option. Figure 7 shows the topology for the wired mode of operation (Chinthavali, et al, 2015).

6 VEHICLE TO VEHICLE CHARGING SYSTEMS

In the near future, the concept of vehicle to X (V2X), that is transmitting electricity from an on board battery to infrastructure, is expected to spread. V2X is a collective term for such as, vehicle to live (V2L), vehicle to home (V2H), and vehicle to grid (V2G) (Panchal, et al, 2018). For example, this can be used as an emergency power source to charge electric appliances (Izumi, et al, 2014). V2H and V2G technologies have started to be put to practical use. However, in this section the main purpose is to study the vehicle-to-vehicle technology.

The energy transfer between EVs will be through a bidirectional DC-DC converter in a conductive way which can take place at parking lots of workplaces, campuses, or residential premises and highways. As proposed by (Cuchý, et al, 2018) the (V2V) Charge Sharing Network (CSN) philosophy shall provide an alternative, more convenient, and flexible way of conducting EV charging.

V2V charging requires an analysis in terms of how to match suppliers to receivers with efficient matching algorithms and how to enable energy exchange with current EV charging technologies (Mou, et al, 2018). Three different approaches for V2V energy transfer have been compared in (Sousa, et al, 2018): vehicle-to-grid and grid-to-vehicle (V2G+G2V), V2V over direct ac interconnection (acV2V), and V2V over dc interconnection (dcV2V). It was concluded that dcV2V is more efficient than the other options due to reduced number of energy conversions.

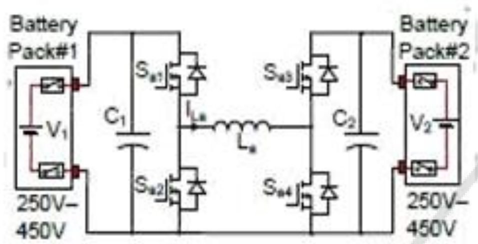

Figure 8: Bidirectional DC-DC converters for V2V charger (Cuchý, 2018).

The dc-dc converter topologies investigated in this paper are non-isolated as there is no grid connection requirement (Cuchý, et al, 2018). One of the candidate solutions to this operation is known as bidirectional dc-dc converters is shown in Figure 8. As a practical industry example, there is a V2V charging realized by Andromeda Power using 'Orca Inceptive' (Andromeda Power, 2020).

7 CONCLUSIONS

In this survey, different EV battery charging systems are discussed, along with the various battery types used for different EVs. A theoretical overview on the various WPT techniques is provided. Multiple WPT systems are discussed for smart cities. The overview of each topology is presented. Research is still needed on the health effects of long-term exposure to weak electric and magnetic fields, methods to determine optimal charger power levels and spacing for cost effectiveness and approaches to analyze impacts of large-scale WPT system deployment on the electric grid.

As for future applications, 3 main concepts shall be considered. First, Wireless vehicle to grid (W-V2G) which can offer a solution alongside advanced scheduling for charging and discharging to the distribution network.

Secondly, in Wheel wireless charging system (IW-WCS) where receiver coils are placed in a parallel combination inside the tire. This technology can rectify air-gap problems. It has been developed for both stationary and dynamic applications. The third application is wireless vehicle-to-vehicle charging technology structure, where the transmitter coil and the receiver coil are embedded in the front and rear of the car, respectively. With a limited number of charging stations, this technology can be used to increase charging opportunities through vehicle-to-vehicle (V2V) charging. At present, charging stations require regular maintenance and service to ensure the equipment is working properly. The wireless V2V charging system can help to solve this issue. The main issue with the wireless V2V charging technology is the angular offset due to the change in the location of the vehicle and the reduced battery size.

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