2021 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
VEA/CYBER TECHNICAL SESSION
AUGUST 10-12, 2021 - NOVI, MICHIGAN

Wireless Charging for Autonomous Electric Vehicles

Oly Jeon-Chapman, Ron Fiorello and Ronnie L. Wright, Ph.D.

DCS Corporation, Littleton, MA

ABSTRACT

Charging an autonomous electric vehicle can be a challenge using the traditional cable and connector approach. This paper explores various methods for the charging of batteries used in autonomous electric vehicles. One such method, an alternative to the traditional "contact" approach, utilizes a non-contacting power transfer technology that is based on magnetic induction and resonance principles. The paper examines various methods for the application of battery energy replenishment. A proposed charging station with design objectives is discussed, along with how well each of the battery energy replenishment methods would meet the proposed autonomous electric vehicle charging station requirements.

Citation: Oly Jeon-Chapman, Ron Fiorello and Ronnie L. Wright, Ph.D., "Wireless Charging for Autonomous Electric Vehicles", In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 13-15, 2021.

1. INTRODUCTION

As the battery electric vehicles (BEV) become more widely used, and as more autonomous vehicles are introduced, easy self-charging is likely to become necessary. The most common approach today for charging BEV's is to connect the vehicle to a charging station via an electro-mechanical connector. This is fine for manned BEVs whose driver would perform the task of connecting and disconnecting the vehicle to/from the charging station. However, for autonomous BEVs, the traditional direct connect approach would be difficult to implement. This paper surveys various methods for replenishing electric power provided by EV battery systems. The methods discussed include: (a) Battery Pack Replacement, (b) Direct Connect, and (c) Wireless Power Transfer (WPT). In addition to the BEV power replenishment method discussion, this paper presents the design objectives for a proposed BEV charge station, followed by a comparison and contrast of how well each of the surveyed charging methods meet the selected design criterion. The charging methods are introduced in the forthcoming sections.

2. BEV Power Replenishment Methods

BEVs are able to have their battery storage replenished by various means. The forthcoming sections will introduce a select few of these methods, consisting of Battery Pack Replacement, Direct Connect, and Wireless Power Transfer.

Battery Pack Replacement Method

The battery pack replacement method has been suggested as an alternative to alleviate the possibility of perceived long charge times. Using the battery replacement method, an EV enters a battery change station (or depot), and the total battery pack is replaced. This method averts the long vehicle down times, where there could be a substantial wait for a battery pack to be charged to (80-100)% SoC (*state of charge*). This method is simple/easy, and requires that a charged battery pack replacements be available, as well as the labor or automation to swap out/in the replacement battery packs. The vehicle is able to continue on its mission in a matter of minutes after a pack replacement, rather than a typical charge time of 30 min to hours (depending on vehicle battery capacity, battery temp, *etc.*). A fully automated station employing this method would require the use of robots to quickly replace an EV's small modular battery pack, allowing the vehicle to return to the road within a few minutes, similar to a gasoline fill-up.

The prospect of the battery pack replacement sounds attractive, but a variety of implementation concerns exist:

1) Storage facilities of battery packs and standardization of packs for various EV types.

2) Cost of storage areas, as well as the capital expense of sophisticated robotics needed.

3) Service and maintenance of facility.

4) Inventory of the battery packs necessary for the volume of vehicles requiring replacement.

5) Methods to charge the swapped-out battery packs are still needed.

6) For battery exchanging to completely replace gas stations — and, of course, recharging portals — as the refueling system of the future, it must be able to accommodate all cars from Ford to Ferrari. For that to happen, all the batteries needing a swap-out would have to be virtually identical.

From the previous list of concerns, it becomes quite apparent that the issues involved with storage, physical replacement (or battery swapping), battery inventory maintenance and battery standardization almost certainly prohibit the battery pack replacement method from being a cost effective or realistic approach for BEV Power Replenishment.

Direct Connect Method

The direct connect method involves the use of an external charger and/or an onboard charger that is part of the battery pack within the vehicle. For the purpose of charging, the vehicle must be manually plugged in via connector and cable.

Direct connect charging, shown in Figure 1, is the most common charging method used for today's commercial BEVs. The direct connect charging stations may also be referred to as electric vehicle charging station, electric recharging point, or charging point. Regardless of the name, this category of charging station requires that the vehicle under charge be physically plugged into (or directly connected to) a machine that supplies electric energy.

The direct connection requires the charge cable/plug to interface with the vehicle to initiate the charge process. Once charging is complete, it is necessary to physically unplug the vehicle from the charge station. The charge cable/plug has to be manually attached or installed by the user so automation of this process is not currently possible and would require a significant amount of capital investment and research in robotics to facilitate the full automation of this charge method.

Figure 1: Direct Connect Charging Station.

A common component found in direct connect EV charging stations is their use of an adapter (or connector). Today's EV charge stations are also characterized by their Charging Levels, which are based on their power distribution type and maximum power. The EV industry subscribes to three Charging Levels, outlined and discussed in the next section.

2.1.1 EV Charging Levels

EV charging consist of three levels or standards, which define the amount of power that the EV's battery pack can be charged to and as a consequence, the amount of power required from the charging station that is drawn from the utility.

Level 1 is the slowest type of charging equipment. L1 chargers plug directly into a standard 120VAC outlet supplying an average power output of 1.3kW to 2.4kW. This power output is equivalent to 3-5 miles of EV range per hour. An overnight charge will add 30-50 miles of range, which is sufficient for many commuters. A full charge for an empty EV battery can take over 24 hours.

Level 2 chargers operate at 208-240VAC and output anywhere from 3kW to 19kW of AC power. This power output translates to 18-28 miles of range per hour. An average EV can be fully charged in 8 hours or less [4].

Level 3 are the fastest chargers available with a maximum output of 350kW. Direct Current Fast Chargers (DCFCs) are designed to charge a typical EV battery to 80% in 20-40 minutes, and 100% in 60-90 minutes [4].

2.1.2 EV Connector Types

Charging stations and connector types will vary depending on the charger level types described in the paragraphs that follow. It is important to note that connectors will vary by electric vehicle and can be classified into two categories. The standard Level 1 and Level 2 connector, and the DC fast charging connectors. There are a multitude of connectors, with a few outlined below:

- **SAE J1772**

This connector is the industry standard for all electric vehicles performing Level 1 or Level 2 charging. Whether it's the cord provided with the purchase of your EV or the Level 2 charger, the SAE J1772 is going to be compatible.

- **CHAdeMO**

This is the first of three types of connectors currently present on EVs and first introduced. Originally it was implemented to be the industry standard, developed through the collaboration of five different Japanese automakers.

- **CCS**

After the CHAdeMO was introduced, a second connector called the Combined Charging System (CCS) was implemented as an additional charging standard.

- **Tesla Supercharger**

This proprietary connector exists on all Tesla models in North America, although it does offer CHAdeMO and CCS adapter for certain markets.

2.1.3 Direct Connect Charger Concerns

The main issues with wired chargers are

a) Non standardization of connector types.
b) User intervention is required *i.e.*; physical plugin and unplug of charger cable. Possible issues with forgetting to unplug charger
c) Dirty cords and plugs – EV owners complain that their charging system is the source of unwelcome grit and grime due to weather conditions and temperature exposure – this is also a very common perception owners.
d) Wear or damage to charge connector, due to multiple inserts/removals.
e) Maintenance of charging station.

Wireless Power Transfer Method

Wireless Power Transfer (WPT) allows the transfer of electric power to a device (BEV in this case) without any physical connection to the device being charged. This section will briefly discuss how the WPT energy transfer method can be applied to replenishing battery pack within BEV vehicles.

With the development of WPT, it is envisioned that a vehicle would pull into a charge station (see Figure 2) and without the need to provide a direct electrical connection to a charger, the battery pack would automatically be initiated. The typical system would consist of a charger mounted outside/alongside the charge station (housed in an enclosure similar to that of a circuit breaker panel). A charging pad that is located on the ground or under the surface on the ground of the charge station and a receiving pad located underneath the vehicle.

A visual pad alignment app would assist with the alignment of the vehicle to the pad so that the vehicle is parking appropriately above the ground pad in order to maximize the efficiency of power transfer. In an autonomous vehicle application it is envisioned that the alignment would be performed automatically by the use of the vehicle's onboard navigation system.

To date, WPT systems are currently in development for commercial vehicle applications and have been tested, where 15kW level charging of a battery pack within four hours has been demonstrated [6]. WPT-based autonomous EV charging stations could assist with military combat EVs by providing an efficient platform that recharges diminished EV battery storage systems, and does not require human interaction. Such a platform offers a viable technical approach for consideration in future Army Smart Motor pool concepts and solution exploration to enhance readiness.

Figure 2: Commercial wireless charging.

3. BEV Charge Station Objectives

The section outlines a proposed BEV charge station's design objectives, as well as a checklist of how well each of the previously discussed EV power replenishment methods match those objectives.

	EV Power Replenishment Method		
BEV Charge Station Objective	***Battery Swap***	***Direct Connect***	***Wireless Power Transfer***
Power transfer efficiency > 93%	N/A	√	√
100% Automation	X	X	√
Various Battery Chemistries	√	√	√
Level 3 Charge	N.A	√	√
Charge time < 4 hrs.	√	√	√

Vehicle size	√	√	√

Table 1: Replenishment Method Compare.

Based on a very simple list (Table 1) of objectives for a BEV charge station, the Wireless Power Transfer method stands out as a favorite, mainly because it has the potential to be fully automated and will not require human interaction.

In addition, a very important feature of WPT is that the energy transfer efficiencies, a key requirement for charge station design, have been shown to match that of a direct connection method. It has also been reported in [1] that WPT energy transfer efficiencies have been measured in the 88% to 93% range under most operating conditions.

4. WPT Charge Station Design Concept

A possible solution for wirelessly charging autonomous BEVs is to embed these WPT coils below the surface of the parking stall, as depicted in Figure 2. The autonomous BEV will be positioned over the buried transmitter coil, and energy transfer to the BEV's receiver coil will follow. This will greatly simplify the positioning of autonomous vehicles to connect to the power source for charging.

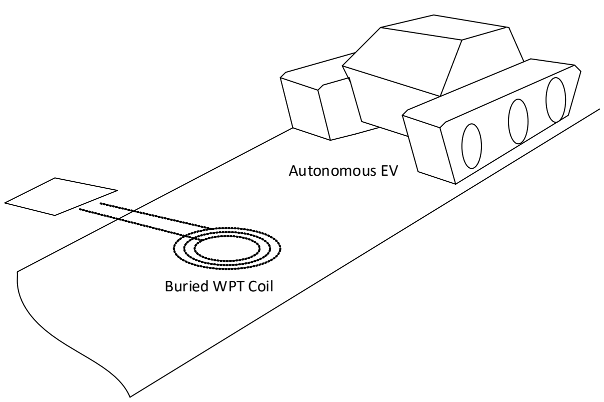

Figure 3: WPT Charging.

The commercial WPT technology has made great advancements in the recent decade. For example, power transfer efficiencies claimed to be in the 90% range with demonstrated power levels above 11kW, and growing [1]. The design feature directly responsible for the power transfer efficiency is the energy coupling formed between the Receiver and Transmitter coils. Transmission and receiving coil coupling can be represented as shown in Figure 4, where the transmitting and receiving coils are simplistically represented, along with the mutual coupling and leakage field between the two coils (dotted red line). The transmit coil can be thought of as the primary and the receive coil can be considered the secondary of the WPT coil arrangement.

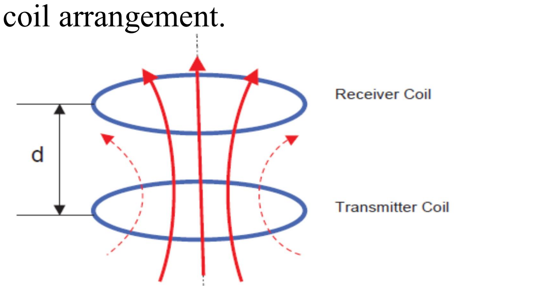

Figure 4: Energy transmission/reception coils.

For resonant WPT, the basic representation for an LC resonant circuit is described by Figure 5. This circuit is central to the proposed wireless energy transfer system, which is based on two inductively coupled resonant circuits that are separated by an air gap. L_S represents the transmission coil inductance and L_D, represents the receiving coil inductance. Capacitors C_S and C_D are part of the impedance matching network and are required to provide maximum power transfer at the resonant frequency of operation.

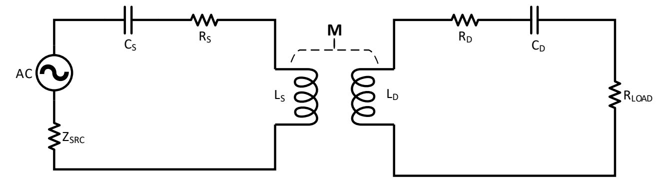

Figure 5: Equivalent circuit for coupled resonator system.

The two coils are tuned to operate at a fixed *resonant* frequency (ω), described by Eq. (1), which promotes maximum coupling and power transfer at that particular frequency (≈80kHz). The power transfer can occur within some allowed positional misalignment between coils (X, Y and Z spatial orientation). Unlike inductive power transfer (IPT), the position of the coils in not as dependent.

$$\omega = \frac{1}{\sqrt{L_S \cdot C_S}} \quad (1)$$

$$\kappa = \frac{M}{\sqrt{L_S \cdot L_D}} \quad (2)$$

The resonant frequency of operation can be adjusted to fit the application and typically would be lowered for higher power applications to minimize power stage component switching losses.

Eq. ((2) describes the WPT (coupled resonator system) equivalent circuit (Figure 5) model's coupling coefficient (k), which is expressed as a fractional number between 0 and 1, that characterizes the amount of inductive coupling (*i.e.* transfer of energy) that exists between two coils (L_S / L_D). M is the mutual inductance between the transmission (L_S) and receiver (L_D) coils, which is attributed to current flow in one coil (say L_S) that induces a voltage in the adjacent coil (L_D), as a result of a changing magnetic field, similar to the operation of a transformer.

The wireless energy transfer stage of the WPT charge station concept can be viewed as a set of power converters that transforms AC Main electrical power and inductively transfers this energy to a nearby coil, separated by an air-gap. The block diagram shown in Figure 6 illustrates the WPT charge station's power stage, where it shows an AC/DC converter followed by an amplifier driving the device side coils and on the receiving side, a rectifier for AC/DC conversion.

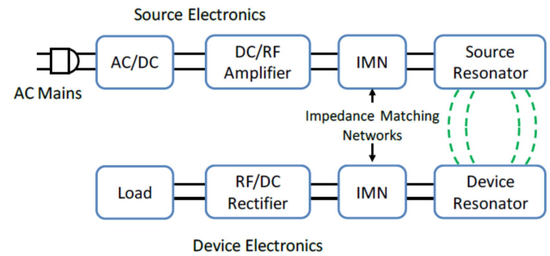

Figure 6: Power stage functional blocks.

The feedback system elements are not depicted, but would be required to regulate power (V/I) delivered to the device side (battery load). The AC/DC stage is not shown in the power flow diagram in Figure 7, but this stage would generate the high voltage bus that drives the amplifier. This converter would typically be a boost *power factor correction* stage. The function of this stage is to convert the AC input to a regulated DC bus. Additionally, this stage would provide power factor correction to reduce the reactive power drawn from the AC line.

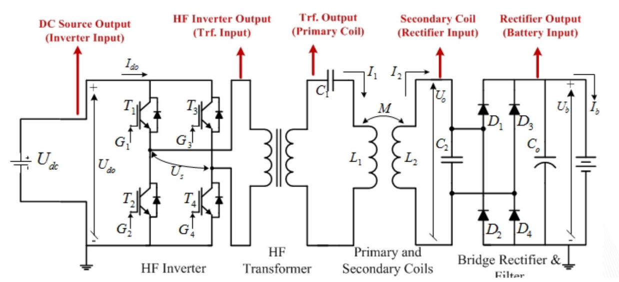

Figure 7: System power flow schematic.

The next stage is the RF amplifier, optimized for low loss by (inductive) operation in the class DE mode. In this mode, the switches turn on using *zero-voltage-switching* so as to reduce the power loss. This mode of operation can be maintained over an operating load by a slight change in the amplifier operating frequency or by dynamically adjusting the matching network. This combination will drive the source resonator which couples the energy to the device side resonator on the "secondary" side of the system. On the rectifier side (in Figure 7) it is shown as a passive rectifier but can be designed using active components in order to reduce potential losses.

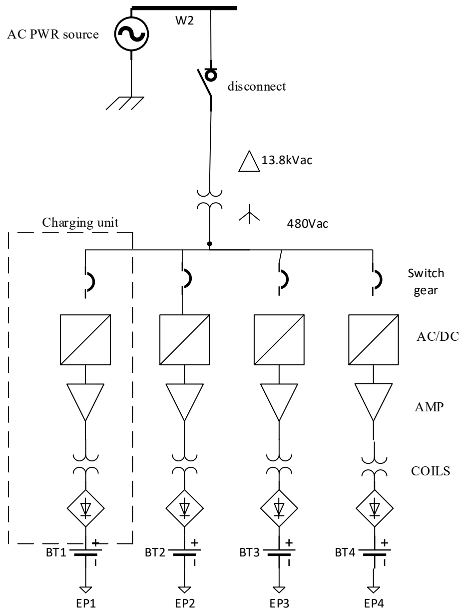

Figure 8: Level 3 WPT charging station power distribution.

A power distribution system view for a possible WPT charge station implementation capable of supporting multiple simultaneous vehicle charges is illustrated in Figure 8. This diagram is representative of how a typical Level 3 charger's power distribution system might be designed. Multiple WPT stalls/stations are shown powered by a 480VAC bus, where for higher power applications, requires Level 3 charging capability and associated power optimization algorithms.

Wireless power charging systems are unique with specific challenges. A key performance challenge for the proposed WPT charge station design will be power transfer efficiency. Optimizations to improve WPT power transfer efficiency are discussed in the next section.

5. WPT Charge Station Optimizations

Power transfer efficiency is a key design objective for the proposed WPT charge station, with the key performance objective for the WPT charging station being the achievement of power transfer efficiency of 93% or better. For the purposes of our analysis, power transfer efficiency is simply calculated as the power delivered to the load (battery system) divided by the input power, at resonant frequency (ω), as shown in Eq. (3).

$$\eta = \frac{P_{LOAD}}{P_{IN}} \tag{3}$$

The simplistic view of power transfer efficiency coincides with the power system efficiency block diagram which highlights typical efficiencies for individual systems internal power conversion stages (shown in Figure 9).

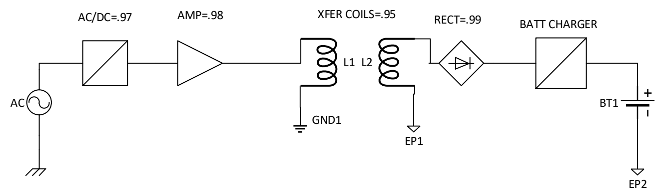

Figure 9: Power Stage's typical system efficiency breakdown.

DC input to DC output conversion efficiency is typically in the neighborhood of 88% to 90% for high power applications, and represents an area were significant performance improvements could be applied. Power efficiency in the DC/DC conversion can be improved by employing methods to reduce or lower power losses, such as minimization of source or device impedance.

Another area shown in the system efficiency breakdown diagram such that performance improvements could provide an overall system impact is the transmission/receiver coil stage, where efficiency is shown to be around 95%. Improvements to the transmission and receiver coil stages could include optimizing and/or minimizing the coil air-gap separation, as too large of an air-gap between the transmission and receiver coils could result in a lower coupling factor (k). This reduced coupling in turn could result in a lower mutual inductance (M) between the coils and as a consequence, more leakage flux between the coils. As a result, the power transfer operation is less efficient and is accompanied by increased losses due to higher reactive current, leading to a need for higher power rated power converters used in the power train electronics.

This condition could exist in an EV charging application where the source and device coils are separated by a larger or sub-optimal air-gap distance. In this example the transmission coil may be floor-mounted and the receiving coil is mounted beneath the vehicle's undercarriage (similar to Figure 2). However, the coil air-gap separation could be in the 10 to 20 cm range [1]. This variation in air-gap separation(s) can coincide with different vehicle classes or types, *i.e.* sports car vs. sedan vs. SUV. During WPT charging, coil air-gaps in the 10 to 20 cm range are subject to lower coupling factors, which would result in more reactive power circulation within the circuitry, and lead to increased circuit losses. Because of the reduced coupling, higher reactive power rated tuning or matching capacitors and power components in the inverter stage would be necessary.

One method or solution to address the variability in transmission/receiver coil air-gap distance(s), due to vehicle height variations, is to dynamically adjust the coil's placement, by raising the transmission coil closer to the vehicle's receiver coil, so as to minimize the distance between the coils once charging has been initiated.

As mentioned earlier, coil air-gap separation minimization techniques and/or improvements to transmission and receiver coil physical characteristics (*i.e.* width, length, turns ratio) lead to improvements in magnetic coupling. Further optimization methods implemented in the operating mode, AC/DC bridge converter switching (PWM vs. Soft) techniques, power semiconductors (wide bandgap devices) selection and active vs passive rectification can increase the overall power conversion efficiency by minimizing power losses. Thus, enabling WPT power transfer efficiency to possibly meet and exceed 93%.

6. CONCLUSION

This paper examined three methods for battery energy replenishment in electric vehicles: Battery Pack Replacement, Direct Connect, and WPT. These replenishment methods were compared against the objectives for a proposed autonomous BEV charging station, where it was determined that WPT has the greatest potential to address all EV charging criterion, with the key criteria being 100% automation, power transfer efficiency > 93% and Level 3 charging capability. A Level 3 WPT power distribution diagram for multiple vehicle charging was introduced. Additionally, optimization methods for improving the proposed WPT's power transfer performance were discussed, and shown to mainly depend on improving the coupling between the receiver and transmitter coils, which is really a function of the distance between the coils. Other power transfer improvements were centered around increasing the overall AC to DC power conversion stage by the use of improved power conversion methods and wide band gap semiconductors (WBG), such and GaN and other state of the art power semiconductors to reduce switching and conduction losses, as well as improvements in operating mode and physical improvements (width/length, turns-ratio) to transmission and receiver coils.

7. REFERENCES

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