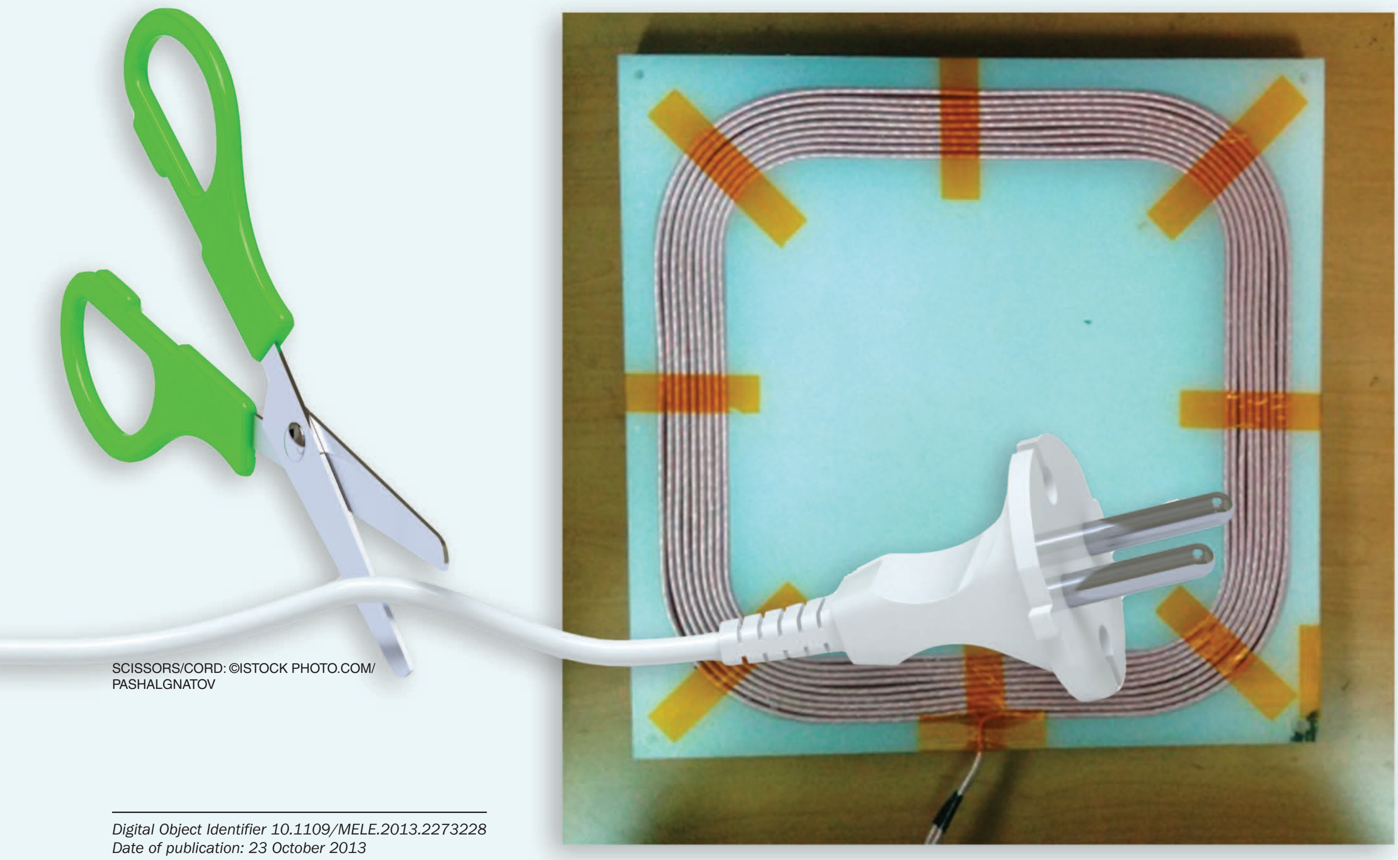
By Srdjan Lukic and Zeljko Pantic

Cutting the Cord

Static and dynamic inductive wireless charging of electric vehicles.

AMID GROWING CONCERNS ABOUT ENERGY security, environmental impacts, and resource limitations, both public and private-sector groups are calling for greater investments in renewable energy and alternative energy sources. However, despite calls to reduce the nation's dependence on oil, moving away from petroleum as an energy source has proven to be extremely difficult, especially in the energy-intensive transportation sector. Petroleum, with its high energy and power density, is ideally suited for transportation. To make matters worse, the number of vehicles worldwide is expected to increase dramatically in the coming years because of increased purchasing power in developing countries, leading to a higher portion of air pollution and greenhouse gases coming from transportation as well as greater competition for petroleum.

Transportation systems powered by electricity can help to reduce the consumption of petroleum. In the case of personal electric transportation, vehicles would be plugged into the grid, and their onboard energy-storage systems would be recharged using clean, renewable electricity. If properly



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managed, plug-in vehicles could be charged during low demand periods (at night) when there is excess capacity on the grid, minimizing the strain on the grid and obviating major generation and transmission infrastructure additions.

In this article, we present an emerging technology—inductive power transfer (IPT)—that holds the key to more convenient charging by means of contactless or wireless power transfer through induction. We review the fundamentals of the IPT technology and its history and also present some considerations for designing IPT systems for static and dynamic vehicle charging.

Tesla's experiments demonstrate the majority of modern IPT design concepts.

Moving Toward Better Electric Transportation

An electric transportation model requires on-the-vehicle (onboard) energy storage capable of supplying the energy and power demands of the vehicle. Unfortunately, the currently available energy-storage devices, with lithium-ion (Li-ion) batteries being the most promising, need substantial performance improvements to effectively compete with petroleum. The main issues with the state-of-the art Li-ion batteries are 1) their low energy density (200 Wh/kg versus 12,000 Wh/kg for petroleum), 2) their high initial cost (up to US$1,000/kWh with a long-term goal of US$300/kWh), 3) charge rate limitations due to their internal electrochemical processes, 4) degradation that limits the acceptance of battery-powered vehicles due to hard-to-predict component life, and 5) the environmental costs associated with producing and disposing of electrochemical batteries.

Given the limitations of onboard energy storage, drivetrain hybridization and battery swapping concepts have been proposed as possible approaches to mitigate the limitations of state-of-the-art batteries. In the case of hybridization, an internal combustion engine (ICE) is added to the electric vehicle (EV) drivetrain to make a plug-in hybrid EV (PHEV). The ICE is then used only when the battery is sufficiently depleted. While hybridization enables a longer driving range, it also increases the vehicle weight, cost, and complexity, in addition to introducing the use of hydrocarbons. In the case of battery swapping, the vehicle battery is exchanged at a specialized station that stores an equivalent replacement battery. This concept brings with it the issues of battery ownership and standardization, the need for additional battery packs for swapping, and significant swapping infrastructure costs.

An alternative hybridization method to extend the utility of PHEVs and EVs is to enable a power exchange between the vehicle and the grid while the vehicle is moving. This concept has been referred to as *dynamic charging, move-and-charge,* or *roadway powered EVs*. Dynamic charging can mitigate the high initial cost of plug-in EVs by allowing the vehicle energy-storage system to be substantially downsized. In addition, dynamic charging can provide a very effective utilization of the installed infrastructure, since a large number of vehicles use the same road segments that can be dynamic-charge enabled. In essence, dynamic charging would represent a hybridization of the EV with the electric grid. Importantly, dynamic charging is compatible with other methods of extending the EV range, such as vehicle hybridization and battery swapping.

Wireless charging makes stationary EV charging more convenient by allowing the charging to take place automatically without the user having to provide a physical contact path between the utility power supply and the vehicle battery. The longer-term vision for wireless charging is to enable the power transfer between the grid infrastructure and the vehicle while the vehicle is moving.

Some examples of dynamic charging systems are shown in Figure 1. The stationary wireless charger can replace the conductive charger used today, with a single inverter powering multiple charging pads. Contactless charging can also be used to deliver power to a bus while passengers embark and disembark. The concept can be used to continuously power a lane of a highway or to power a section of the roadway in the vicinity of high-congestion areas, such as traffic lights, where the vehicle speed is low.

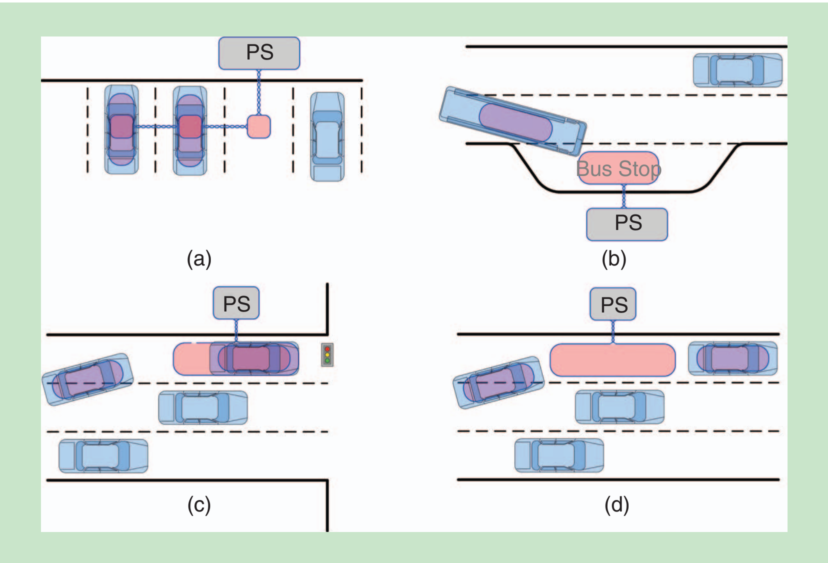

Figure 1. IPT systems for vehicle applications: (a) an IPT-powered parking deck, (b) an IPT-powered bus stop, (c) an IPT section placed at a traffic light in an urban environment, and (d) a track section on a highway powering multiple vehicles (PS stands for IPT power supply).

An Incomplete History of EV Wireless Charging

The history of the wireless power transfer began in 1891 when Nikola Tesla invented his famous Tesla coil or magnifying transmitter. The system contains two loosely coupled and tuned resonant circuits: a primary and a secondary. The coils were built using large, single-layer solenoids, which significantly reduces the coil resistance and increases the quality factor. The primary and secondary coils were tuned using an external capacitor and the parasitic self-capacitance, respectively. Periodic spark gap discharges were used to short out the primary resonant circuit and initiate the power transfer. Even with the significant spark losses, the Tesla coil was able to transfer power with 85% efficiency. Tesla's experiments demonstrate the majority of modern IPT design concepts: 1) Tesla applied the strongly coupled resonant circuit to enhance the power transfer capability of the system, 2) he used the self-capacitance to tune the secondary and to obtain a high quality factor, and 3) he used the spark discharge over the air gap to control the power in the resonant circuit, similar to how modern resonant converters use electronic switches.

The next milestone in vehicle dynamic charging took place in 1894, when Hutin and LeBlanc filed a patent that describes a transformer for powering streetcars without contact. The proposed system included a single-wire elongated primary coil carrying 2-kHz ac and coupled by multiple secondary windings. They used ferromagnetic materials and suspension systems that lower the receivers to increase the coupling. Although the proposed topology has some similarities to modern solutions, because of component limitations at the time, the system was not a commercial success.

In the 1990s, researchers at the University of California, Berkeley, built a proof-of-concept roadway-powered 35-passanger electric bus. The complete infrastructure was built for a 213-m-long test track with two 120-m powered sections. The bipolar primary track was supplied with 1,200-A, 400-Hz ac current and coupled to a receiver with an area of 4.3 m^2, at a distance of 7.6 cm. The system efficiency was around 60%. These results proved the potential of the technology but were limited by the size of the system due to the very low operating frequency.

The longer-term vision for wireless charging is to enable the power transfer between the grid infrastructure and the vehicle while the vehicle is moving.

Researchers at Auckland University laid the theoretical groundwork in the 1990s for much of the research that is presently ongoing in the design of wireless chargers. It is worth noting their recent achievement in designing the optimal pad for the stationary charging of EVs. One of the designs is a 766 mm × 578 mm pad that delivers 7 kW of power with more than 90% efficiency at a distance of 20 cm. They also proposed using multicoil track designs for dynamic charging applications.

Starting in 2008, researchers at the Korea Advanced Institute of Science and Technology (KAIST) have built several prototypes of roadway powered EVs, which they named online EVs. Three generations of IPT systems have been developed, and three different vehicles have been tested, with system efficiency peaking at about 70%. In each generation, a different structure of the ferromagnetic material and a different track layout has been designed.

Components of the IPT System

A typical IPT system consists of two physically detached subsystems with power transfer through induction. Typically, the system supplying the power is stationary and is named the *primary, transmitter,* or *source*. The system receiving the power is attached to a movable frame and is named the *secondary, pickup,* or *receiver*. The power is transferred via induction between two magnetically coupled coils, much like in a transformer. The coupling medium between the coils is air, which has a much higher magnetic reluctance than do the ferromagnetic materials used in transformers. As a result, the coupling coefficient is in the range of 0.1–0.2 for stationary charging applications and less than 0.1 for midrange resonant applications. Therefore, these systems are usually referred to as loosely coupled systems to distinguish them from the tightly coupled transformer coils.

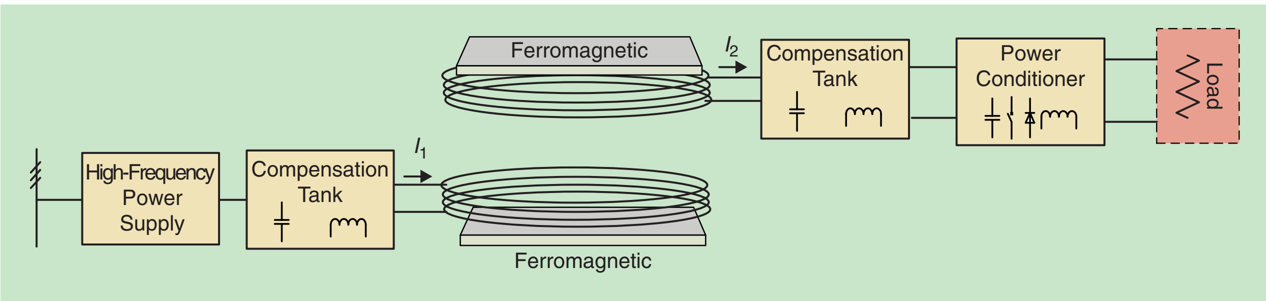

Figure 2. The typical topology of a high-power IPT system.

The components of the state-of-the-art IPT system are shown in Figure 2. The characteristics of each block are discussed in detail in the following sections. In addition to the components described below, the primary and secondary are equipped with all necessary sensors and control circuits to generate the firing signals for the switches and to control the transferred power. Additionally, communication modules are used to add a further level of intelligence and controllability to the system and ensure safe and efficient power transfer.

An alternative hybridization method to extend the utility of PHEVs and EVs is to enable a power exchange between the vehicle and the grid while the vehicle is moving.

Primary Converter and Compensation Circuit

On the primary, a power supply delivers high-frequency current and voltage at its output by using modern switching elements and converter topologies. Although direct ac–ac conversion from the grid input to the high-frequency output is possible through the use of matrix converters, most topologies are based on the well-known two-stage ac–dc–ac conversion. A unity power factor stage or three-phase line filters might be considered at the input to reduce the reactive power exchange and harmonic pollution of the grid. Modern IPT systems make use of voltage-fed full-bridge resonant topologies, taking advantage of modern metal–oxide–semiconductor field-effect transistor (MOSFET) and insulated-gate bipolar transistor (IGBT) switches. Although IGBTs are more suitable for high-power systems, paralleling MOSFET devices can provide higher operating frequencies and lower losses but typically at a higher price.

Since the primary coil is dominantly inductive, the increase in the signal frequency will linearly increase the volt–ampere (VA) ratings required to drive the current into the unloaded coil, increasing the VA ratings of the inverter. As a result, a compensation circuit is placed between the inverter and the primary coil. The compensation circuit consists of one or more reactive elements (inductors and capacitors) that are arranged in a particular formation to achieve different design goals. The commonly used primary compensation topologies include series compensation with matching transformer, series-parallel inductor–capacitor (LC) compensation, and series-parallel inductor–capacitor–capacitor (LCC) compensation (Figure 3). The series compensation with matching transformer, shown in Figure 3(a), makes use of the series capacitor to eliminate the reactive power flow, and the transformer for galvanic isolation and impedance matching. The main limitations of the topology are that it fails to keep the track current constant in face of load variations and that the capacitor VA rating is quite high. The series-parallel LC compensation topology distributes the VA rating over two elements, reducing the stress on individual components. In addition, the current in the coil is controlled by the magnitude of the input voltage source, making the coil current load independent. Another variant of this topology, shown in Figure 3(c), includes a series capacitor that can be used as an additional degree of freedom to control the VA rating of the inverter or to ensure zero-current-switching in the inverter.

Inductively Coupled Coils

The design of the coupled coils has a profound impact on system efficiency, and their design is therefore a critical component of the IPT system. The coil conductors are typically made using Litz wires because of their small resistance at high frequencies. At very high frequencies and for designs with special requirements, planar and tubular conductors have also been considered. Ferromagnetic material is commonly used to improve the coupling coefficient and to contain the magnetic flux. In the case of stationary wireless chargers, a combination of ferromagnetic material and aluminum is used to maximize the coupling coefficient while ensuring that the produced flux is fully contained underneath the vehicle, even when there is a misalignment between the source and the receiver. In the case of weakly coupled coils, the use of ferromagnetic materials to

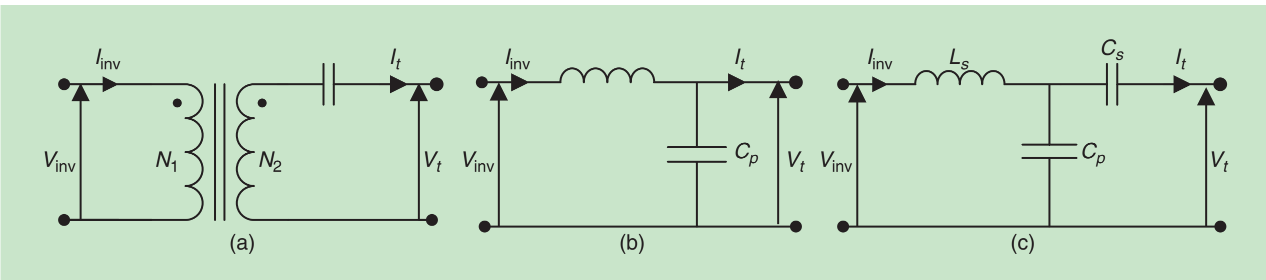

Figure 3. The IPT primary compensation circuits: (a) a series compensation circuit with matching transformer, (b) a series parallel LC compensation circuit, and (c) an LCC compensation circuit.

improve the coupling is relatively limited; however, it may still be used to contain the flux in the vicinity of the source and the receiver. The design of the magnetic link is probably the most challenging part of the IPT system optimization. Although the use of finite element modeling software provides a method of evaluating the system performance, it requires substantial time and iterations to achieve a satisfactory design.

Secondary Compensation Circuit and Power Conditioner

The power transferred to a receiver coil of an IPT system is directly proportional to the product of the open-circuit voltage and its short-circuit current. Since the open-circuit voltage increases proportionally, while the short-current decreases proportionally with the number of turns, generally, changing the number of turns does not directly lead to better coupling or improved power transfer capability. However, by using the compensation circuit and the resonance phenomenon at the secondary, the power capability and efficiency can be increased in proportion to the quality factor of the resulting resonant circuit. The typical configuration of the secondary compensation circuit (resonant tank) is similar to that of the primary compensation circuit, but the criteria that lead to an optimal structure and design are different. Since the receiver load is typically a battery, the high-frequency power is rectified and controlled using a rectifier and a dc-voltage regulator. The dc regulator essentially controls the quality factor of the receiver and delivers a constant power to the load in face of changes in the coupling coefficient between the source and the receiver. The design of the dc regulator is a function of the compensation circuit structure, with the buck or boost topologies employed in most applications.

If only 1% of the roadway is powered in urban environments, most vehicle types can easily meet the 300-m target range with the relatively small battery pack.

Health and Safety Concerns Related to the Leaking Magnetic Flux

Because of concerns about the long-term health effects of exposure to magnetic fields, wireless charging designs must comply with the well-established standards on magnetic emissions. These standards limit the maximum power and distance at which energy can be transferred using induction. For example, for the 3–100-kHz frequency range, the International Commission on Non-Ionizing Radiation Protection electromagnetic field exposure guideline specifies the maximum level for occupational exposure to be 100 μT and the maximum level for general public to be 27 μT. In general, minor system-design modifications are needed to contain the magnetic field to meet the pertinent standards. Frequently, aluminum metal shields are used at the back of the pickup pad to protect the interior of the vehicle, while aluminum rings are used on both the primary and secondary pads to limit the stray field in the lateral direction.

IPT Systems for EV Charging

Stationary Wireless Charger for EVs

Although it is challenging to match the efficiency of the conductive (wired) charger, which is a significant drawback,

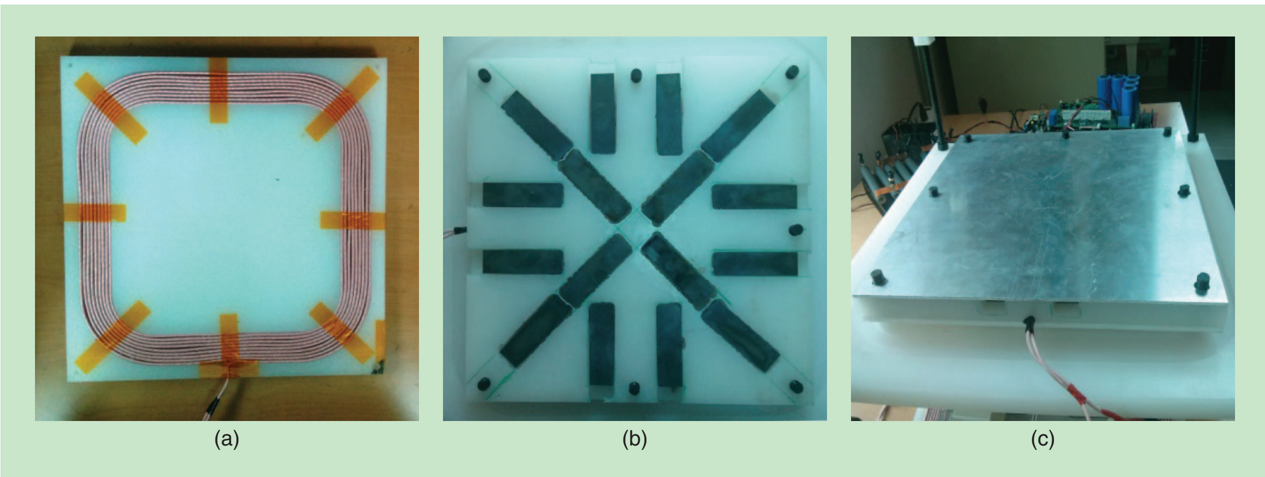

Figure 4. An implementation of the wireless charger receiver: (a) the coil winding made of Litz wire, (b) ferromagnetic material embedded in a plastic holder above the coil, and (c) a cross section of the receiver design, showing the final assembly including the aluminum shield.

stationary wireless charging has its merits. First, stationary wireless charging systems can be completely autonomous, requiring minimal action from the driver. This feature can maximize opportunity charging since the user often forgets or chooses not to charge when the vehicle is parked for short periods of time. In addition to convenience, wireless charging improves the safety of the charging process. By removing cords and cables, the trip hazard associated with wired chargers is nonexistent. The chargers are vandal proof and have no risk of electric sparks. Low maintenance requirements increase the reliability of the charger. On the other hand, the electromagnetic emissions of the charger must be considered in the system design. The magnetic field can present a hazard when an object is placed in the magnetic link. Therefore, the system must have a robust foreign-object identification system that turns the system off when there is an obstruction in the magnetic link.

In addition to one-for-one replacements of conductive chargers, wireless charging technology is ideally suited for opportunity charging scenarios, where the vehicle is parked at a predetermined location for a short period of time. The concept is particularly well suited for mass transit applications, where the wireless charger can be installed at bus stops, allowing the vehicle to charge while the passengers are embarking and disembarking from the bus. This concept is being used successfully for two lanes of public transportation in Turin, Italy, and many other cities.

The design of a stationary charger consists of a primary pad buried in the ground and a pickup pad mounted on the underside of the vehicle. The primary pad is typically sealed in rubber or covered with plastic to prevent the coil from flooding and/or other hazardous situations. It frequently contains ferromagnetic materials to shape the magnetic field, and metal rings or plates that reduce the leakage of the magnetic field. An implementation of the system is shown in Figure 4, with a representation of the system in Figure 5. A similar pad structure to the one shown in Figure 4 is attached on the underside of the vehicle. The primary pad might sometimes be elevated by several centimeters to reduce the vertical distance between the coils. An automatic guidance system can be installed in the vehicle to help the driver align the vehicle directly above the primary pad. The charging station and the vehicle exchange data by using the inductive link or other short-range communication methods. This feature allows the charging station to adjust the charging procedure according to the condition of the battery or the driver's preferences.

Dynamic Charging of EVs

First, we look at the infrastructure requirements for dynamic wireless charging. These results were first reported in a previous publication [1]. We considered three vehicle types (compact car: Honda Insight; large car: Chevrolet Impala; and SUV: Ford Explorer) fitted with small battery packs (8, 11, and 15 kWh, respectively) operating on three types of driving cycles [low-demanding urban driving cycle (UDDS), highway driving cycle (HWFET), and highway driving in a mountainous region (HW-MTN)]. Our simulations show that the vehicles have a very short driving range, never exceeding 50 mi (see Table 1). We then determined the section of the roadway that needs to be IPT-enabled to extend the vehicle range to 300 mi. The results, when the optimization algorithm tries to minimize the length of the roadway that needs to be powered, are summarized in Table 2. Figure 6 shows a graphical representation of

TABLE 1. Driving Range Without IPT (in Miles).

	UDDS	HWFET	HW-MTN
Insight (8 kWh)	38.17	37.14	22.99
Explorer (15 kWh)	36.09	33.00	18.83

TABLE 2. IPT Coverage Required for 300-mi Range (30 kW Delivered to Vehicle).

	Insight	Impala	Explorer
	UDDS		
Coverage (%)	0.46	0.91	1
	HWFET		
Coverage (%)	17	27.3	43.8
	HW-MTN		
Coverage (%)	17.2	35.4	64.3

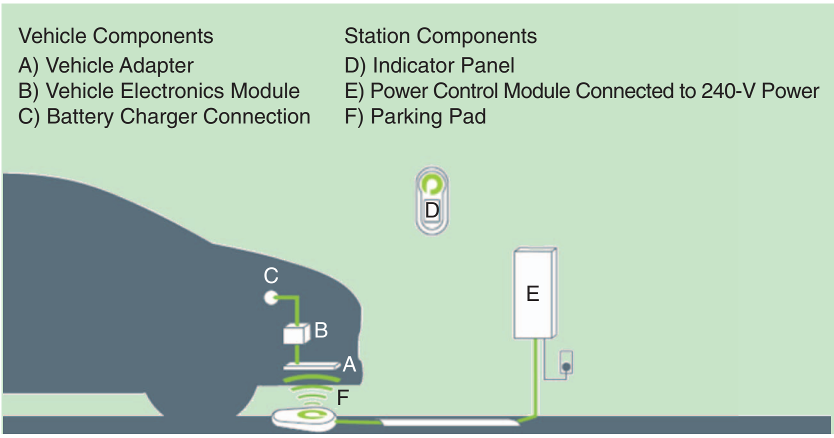

Figure 5. An illustration showing the setup of stationary wireless chargers. (Image courtesy of Evatran Inc.)

the results of the third row of Table 2, depicting the IPT coverage required on the UDDS drive cycle. Figure 6 shows the velocity versus time plot of the UDDS on the left y-axis. On the right y-axis, the distance versus time plot is shown for the same driving cycle, for the three vehicles of interest. The three plots are offset from each other for clearer viewing. The black lines on the distance versus time plot signify the sections of the driving cycle that were chosen (using an optimization routine) as optimal sites for installing the dynamic charging system. The power transfer to the vehicle is considered to be 30 kW. The results of this simplified study show promising results: if only 1% of the roadway is powered in urban environments, most vehicle types can easily meet the 300-m target range with the relatively small battery pack described earlier. The assumptions and details of the study can be found in [1], along with other interesting results that, for brevity, are not repeated here.

Currently available energy-storage devices, with lithium-ion (Li-ion) batteries being the most promising, need substantial performance improvements to effectively compete with petroleum.

Dynamic Charging System Implementation

As described earlier, a dynamic charging system consists of a source coil embedded in the road, and a receiver system attached to the vehicle chassis. As a result of the vehicle movement, the receiver of a dynamic charging system moves laterally and longitudinally in a plane parallel to the source coil. The source coil designs can be categorized as *single-coil* designs, where the source coil is substantially larger than the receiver, or *segmented* coil designs where the source is made of multiple lumped coils that are commeasurable in size with the receiving coil.

Considering the single-coil designs, an obvious advantage is a reduction in system complexity due to the simplified system control, reduced number of converters, and relatively constant coupling between the source and the receiver. The demerits of the approach are that 1) the resulting coupling coefficient between the source and the receiver is relatively low because of the large uncoupled flux of the source coil; 2) field emissions in the uncoupled sections of the coil need to be contained to ensure safety; and 3) the large inductance of the coil for which the distributed capacitors must compensate to limit the voltage at the coil terminals.

Because of their simplicity, single-coil designs are quite popular in practical implementations of dynamic charging systems, as evidenced in the systems developed by researchers at Bombardier and KAIST. An example of the elongated track is illustrated in Figure 7. The receiver system in this application is similar to the one used in stationary chargers, with multiple receiver pads used for higher-power applications. For example, KAIST's second-generation IPT-supplied bus carries ten 6-kW pickups. On the source side, however, the lumped coil used for stationary wireless chargers is replaced with an elongated conductive cable buried in the road. Some implementations, including the ones mentioned earlier, make use of ferromagnetic material at the primary to direct the magnetic flux, reduce magnetic reluctance, and minimize the field emissions when the receiver coil does not couple with a section of the source coil.

Although the systems using single-coil designs achieve acceptable efficiency, peaking at around 70%, there is still substantial room for improvement, given that stationary chargers attain 90% efficiency. Because of an increased misalignment during dynamic charging, it is reasonable to expect lower system-level efficiency compared to stationary applications. In theory, the efficiency

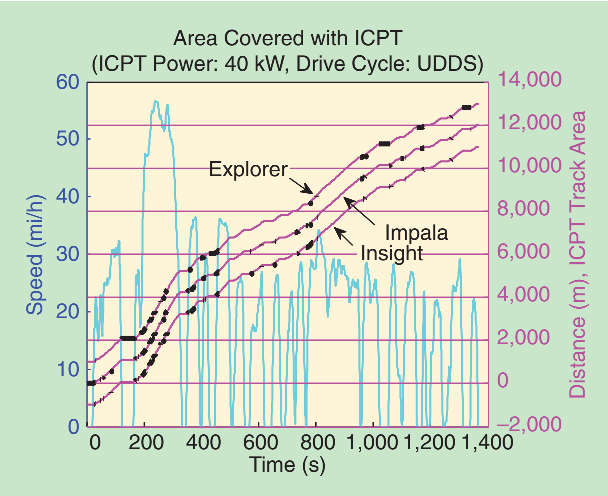

Figure 6. The area covered with IPT—optimization for different cars. (Reproduced from [1].)

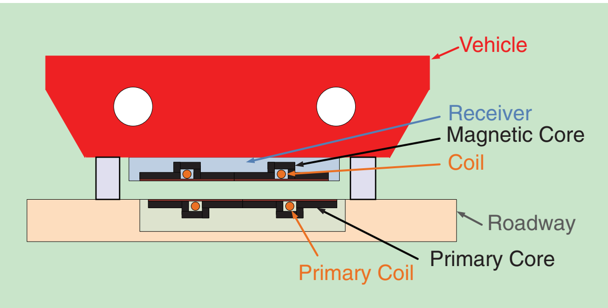

Figure 7. An illustration of the dynamic charging concept.

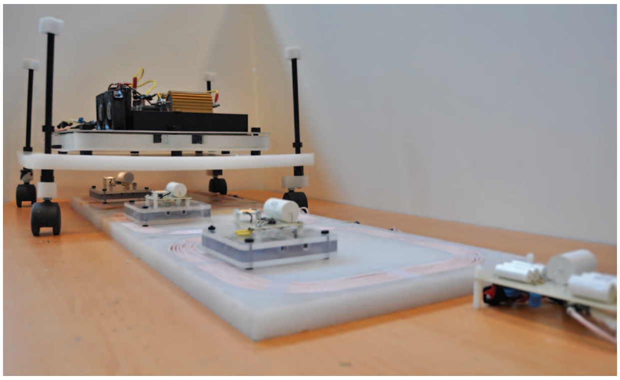

Figure 8. A scaled-down testbed for dynamic wireless charging.

of the dynamic chargers could reach that of stationary chargers if the optimized segmented source coils designed for stationary charging are used, and the system transfers power only when the misalignment is within prescribed limits that guarantee 90% or higher efficiency.

Considering the segmented source coil design, the issues of field containment, large source–coil self-inductance, and difficulties with coil impedance compensation are easily addressed. However, developing a strategy for powering the coupled segments is challenging, since it requires complex receiver position feedback as well as a method to energize and de-energize coils as needed. Further reduction in the size of each segment exacerbates the issues and advantages associated with coil segmentation: small coils can further contain the leakage flux of nonenergized coils, thus improving the coupling, but result in a complicated design with many bypass switches and sensors.

Figure 8 shows a test-bench implementation of a dynamic charging system, built in North Carolina. The system consists of three source coils, identical to the receiver coil, with small indicator receivers placed on each segment of the source coil that are used as qualitative gauges of the strength of the magnetic field present in the coil. The source–coil segments are powered by a common inverter, with the compensation capacitors located at the inverter. The goal of the test-bench demonstration was to show the ability of a novel method of focusing the field produced by the source–coil underneath the receiver. The system uses a single inverter to power multiple coil segments, by connecting each segment in parallel to the inverter. The power is limited by compensating the coil segments so that the coil resonance occurs at a frequency offset from the system operating frequency. Because of the large reactive impedance, the current in given coil segments is limited when the coil is uncoupled, resulting in a relatively weak field in the uncoupled segments of the sectionalized source coil. By designing the receiver to reflect a large reactance back onto the source coil section, the magnetic field of the source coil is automatically increased when the receiving coil becomes aligned with that particular segment of the source coil. This way, the field produced by the segmented source coil can be controlled by the position of the receiver.

Conclusions

In this article, we have reviewed the state of the art of IPT systems and have explored the suitability of the technology to wirelessly charge battery powered vehicles. The review shows that the IPT technology has merits for stationary charging (when the vehicle is parked), opportunity charging (when the vehicle is stopped for a short period of time, for example, at a bus stop), and dynamic charging (when the vehicle is moving along a dedicated lane equipped with an IPT system). In the case of stationary chargers, the products are reaching maturity, with pertinent standardization initiatives taking place. The opportunity charging systems have also been implemented in bus charging applications, with systems installed on many commercial lines throughout the world. Dynamic charging is a concept that is still in its infancy, and there is a lot of work ahead that is needed for the systems to reach their full potential. The main stumbling blocks for this technology, beyond the technical challenges and efficiency concerns, are safety and infrastructure costs.

On the other hand, dynamic wireless charging holds promise to partially or completely eliminate the overnight charging through a compact network of dynamic chargers installed on the roads that would keep the vehicle batteries charged at all times, consequently reducing the range anxiety and increasing the reliability of EVs. Dynamic charging can help lower the price of EVs by reducing the size of the battery pack. Indeed, if the recharging energy is readily available, the batteries do not have to support the whole driving range but only supply power when the IPT system is not available. Depending on the power capability, the use of dynamic charging may increase driving range and reduce the size of the battery pack.

For Further Reading

Z. Pantic, S. Bai, and S. M. Lukic, “Inductively coupled power transfer for continuously powered electric vehicles,” in *Proc. Vehicle Power and Propulsion Conf.*, 7–10 Sept. 2009, pp. 1271–1278.

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