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An Electric Roadway System Leveraging Dynamic Capacitive Wireless Charging

Furthering the continuous charging of electric vehicles.

WITH THE BLOOMING GROWTH OF ELECTRIC vehicles, the transportation system is in a critical stage of evolution and reformation. Due to their excellent flexibility and controllability, electric vehicles are becoming the solution for connected and automated vehicle technology. However, current transportation infrastructures are primarily designed for combustion engine vehicles and need improvements for electric vehicles. In highway scenarios especially, because the driving range of an electric vehicle is significantly limited by its battery capacity and charging rate, recent electric vehicles are not suitable for long-distance travel. Therefore, it is important to investigate their dynamic charging technology and improve the current roadway infrastructure to support more electric vehicles.

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The structure of an electric roadway system is shown in Figure 1, which mainly includes the following three major aspects:

1) *Diverse power sources*: The power grid provides the major power source for the electric roadway system. Meanwhile, the renewable sources in the outdoor environment, such as wind and solar power, are also adopted as supplements to improve power sustainability. In addition, energy storage units consisting of second-life battery banks could be used to manage the demand response.
2) *High-efficiency power electronics converters*: The power electronics converter is responsible for power conversion and directly supplies power to the electric roadway system. Usually, high-power and high-frequency converters are necessary. Because the converter determines the system power and efficiency, the next generation of wide-bandgap devices would be used to generate high-frequency ac voltages and currents for wireless charging. Advanced circuit topologies and the control method used for power converters are also important to regulate the charging power for multiple electric vehicles.
3) *Electric roadway structure based on reliable capacitive coupler*: The roadway structure is the key technology in dynamic charging system design, which directly determines the system power, efficiency, cost, reliability, and lifetime. The newly released capacitive power transfer (CPT) technology could be adopted to implement the electric roadway for power transfer.

The power electronics converter is responsible for power conversion and directly supplies power to the electric roadway system.

Figure 1 illustrates the working process of the proposed electric roadway system for dynamic charging. The diverse sources provide power to the power electronics converter, and the converter generates high-frequency excitation. Electric vehicles are equipped with wireless receivers that can interact with the transmitter and acquire sufficient power for electrification. In this way, dynamic power transfer is achieved to support vehicles in moving status.

Motivation of Dynamic Wireless Charging

There are more than five million electric vehicles on the roadway, and the target of the International Energy Agency is to increase the share of electric vehicles to 30% by 2030. It is expected that there will be significantly more electric vehicles in the next 10–20 years. Infrastructures need to be updated, including the stationary station and dynamic roadway. Charging station technology has been well studied before, but the dynamic charging system is still under development. The comparison between the fast-charging station and the dynamic roadway is depicted in Table 1.

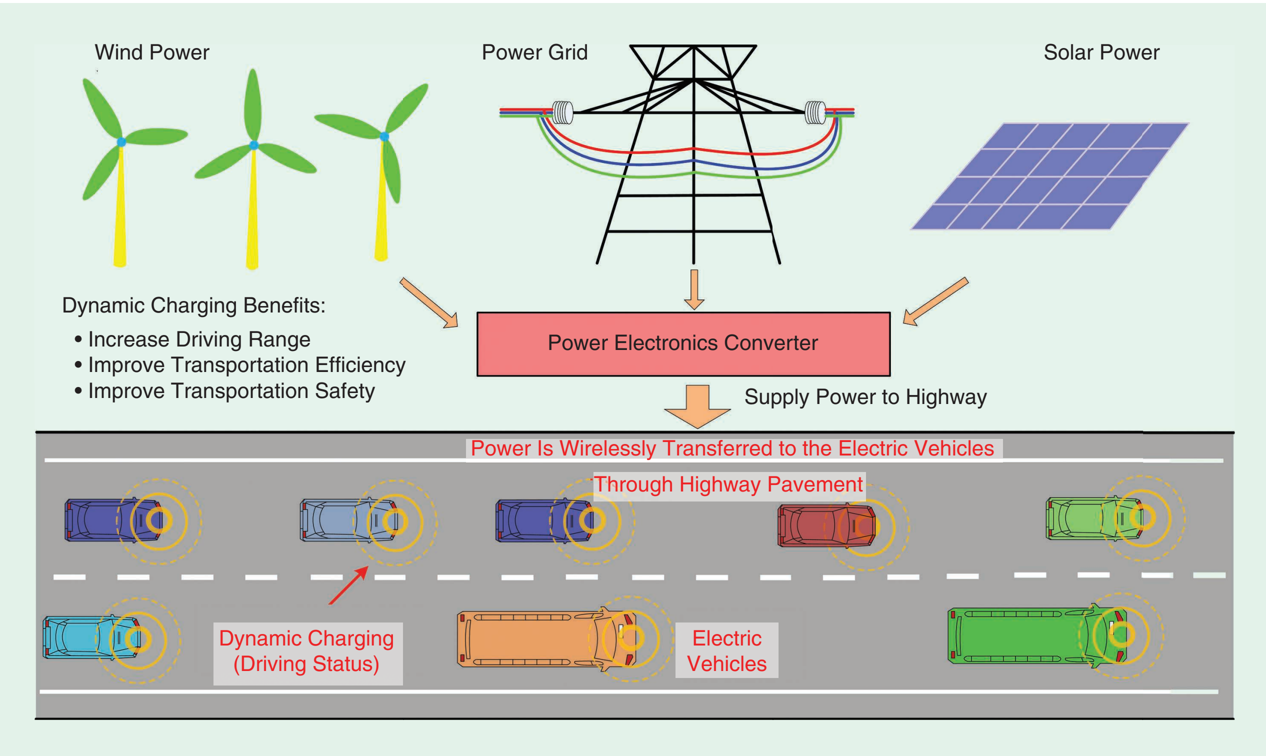

Figure 1. The electric roadway system with diverse renewable sources for electric vehicle charging applications.

The limitations of the fast-charging station are 1) although the charging power can reach 200 kW, the charging time is still relatively long, especially when more vehicles are waiting at peak hours, 2) it requires a large battery size, which increases the vehicle cost, 3) the cost of a fast-charging station is still very high. It requires a few megawatts of pulse power from the power grid, which is challenging to achieve, and 4) the traffic condition of the charging station is difficult to manage; therefore, it is necessary to develop dynamic charging technology.

The following are the major benefits of dynamic charging technology:

- *Increase driving range*: Because vehicles are continuously charged in moving status, the mileage-anxiety concern is completely eliminated, which cannot be achieved by any other existing technology and infrastructure. As a result, the adoption of green transportation is expected to increase dramatically.
- *Improve transportation efficiency*: Dynamic charging overcomes the limitation of the slow-charging rate. The extra transportation time caused by using the charging station and the waiting time during charging are both saved. During rush hour especially, it contributes to alleviating traffic congestion. The construction of fast-charging stations along the highway is reduced, and the possible waiting line around the stations is, therefore, lessened.
- *Improve transportation safety*: Because the vehicles could be charged more frequently, the size of the on-board battery pack is significantly reduced, resulting in less risk of explosion in accident scenarios. Furthermore, electric vehicles are conveniently connected and share traffic information, which contributes to avoiding potential accidents.
- *Alleviate the demand response from power grid*: The dynamic charging system is built along the roadway and the load is evenly distributed. Compared to a fast-charging station, the transient power requirement from the power system is reduced. It is convenient to have distributed energy resources along the roadway to reduce power demand from the grid.

The existing dynamic wireless power-transfer technology is mainly based on the inductive power transfer method presented in Figure 2. A long coil is embedded underneath the ground and works as the transmitter track. There is a relatively high current circulating in the transmitter to generate magnetic fields. However, the induced eddy-current loss may cause a temperature rise and fire hazards. Moreover, the conduction loss is significant when the coil size increases to 10 or even 100 s of meters for dynamic charging. In addition, the Litz wire and ferrites in coils are very expensive and fragile. When vehicles move on the top of the roadway, the coils cannot last long, which will reduce the system's lifetime and affect its maintenance.

TABLE 1. A comparison of stationary and dynamic charging.

Category	Fast Station	Dynamic
Waiting time	Long (>20 mins)	Zero
Battery size	Large	Small
Vehicle cost	High	Low
Infrastructure cost	High	High
Power grid effect	Negative	Positive
Traffic management	Negative	Positive

Structure of Dynamic Capacitive Wireless Charging

As an alternative method, Figure 3 depicts the structure of a dynamic CPT system. At the roadway side, there are conductive metal materials inside, which are directly connected to the terminal of a power converter. The metal materials could generate electric fields and work as the power transmitter. The voltage on the transmitter is in the kV range, and an insulation layer is needed to cover the metal surface to avoid potential electric shock or leakage.

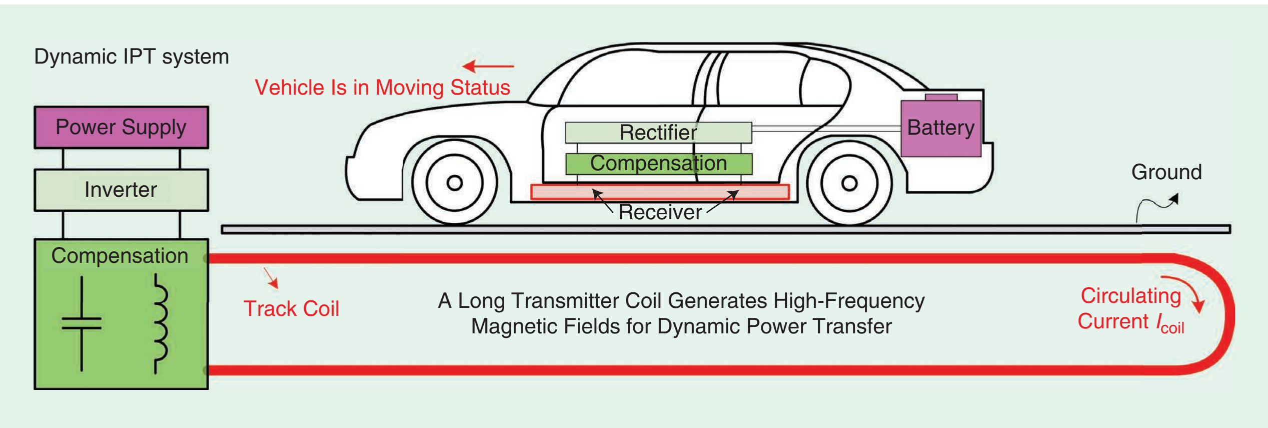

Figure 2. The structure of a dynamic inductive power transfer (IPT) system for the electric vehicle charging application using magnetic fields.

Because metal plates are used only to establish electric fields, there is no special requirement on the conductive property; commonly used aluminum and copper can be adopted to reduce the system cost. In Figure 3, the other terminal of the power converter is connected to the earth ground for protection. Meanwhile, the ground connection also provides the retuning loop for displacement currents in the capacitive system.

At the vehicle side, a metal plate is installed below the chassis as the receiver, which has continuous capacitive coupling with the transmitter. When the misalignment and distance between the transmitter and receiver varies, the capacitive coupling is not significantly affected, thereby maintaining system power.

Circuit Working Principle

The CPT system circuit topology is illustrated in Figure 4. A high-efficiency power electronic converter is required to connect the dc source. The compensation circuit, consisting of inductors and capacitors, works with the capacitive coupler and forms the resonant circuit. Because the permittivity of air is very small, the coupling capacitance is extremely small, usually in the 10-s of pF range. The circuit resonance contributes to establish high voltages in high frequency on the capacitive coupler to achieve a sufficient power transfer.

In a CPT system, the transfer power is proportional to the switching frequency, coupling coefficient, and voltages on the metal plates. For example, Figure 5 depicts the

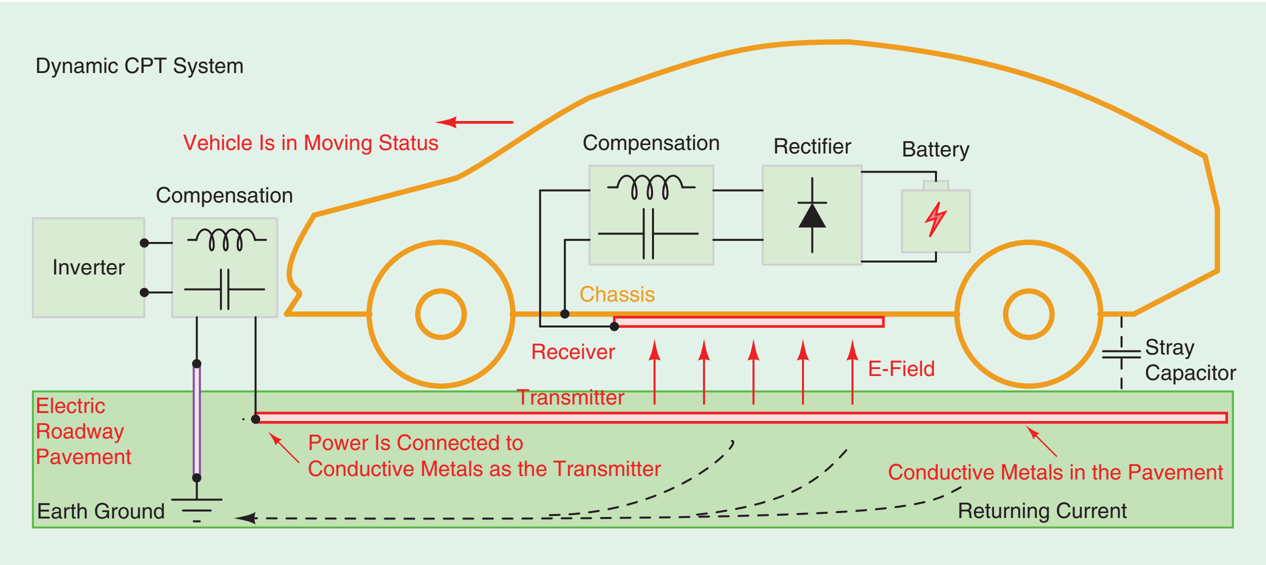

Figure 3. The structure of a dynamic CPT system for the electric vehicle charging application using electric fields.

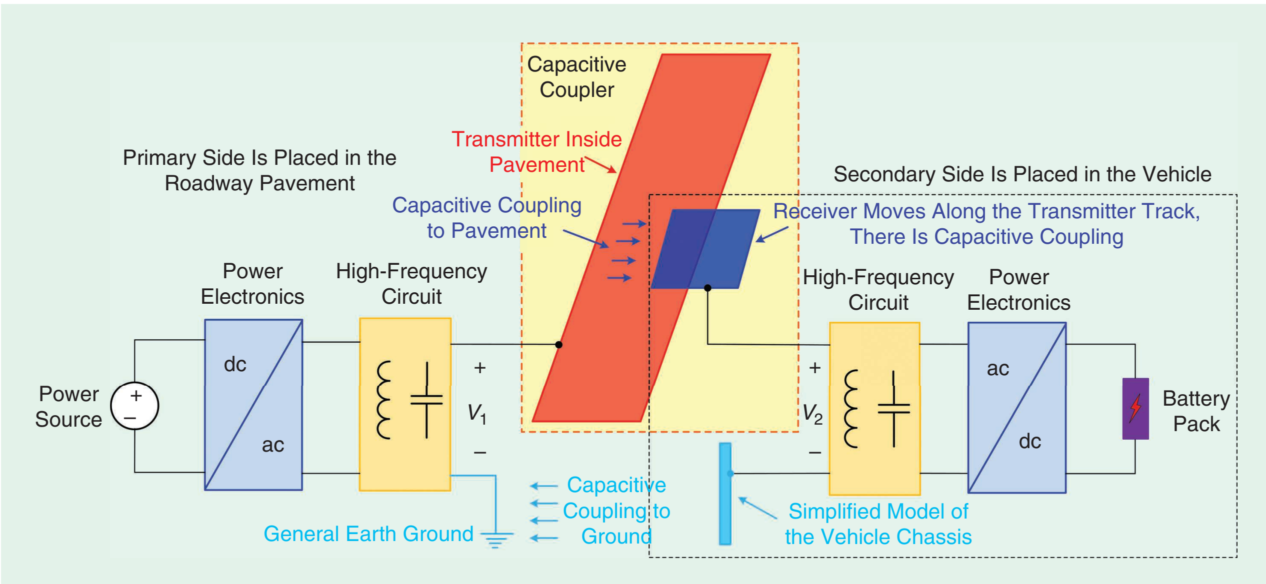

Figure 4. A simplified and equivalent circuit model used for an electric roadway system for dynamic charging.

system power when the coupling capacitance is 50 pF. It demonstrates that the power increases with the voltage and frequency. When the voltage is 5 kV and the frequency is 2 MHz, the system power can reach 15 kW, which is sufficient to charge an electric vehicle in moving status.

The transfer efficiency of a CPT system is provided in Figure 6, indicating the relationship with the coupling coefficient k_C and the component quality factor (Q). Increasing both k_C and Q contribute to improving the efficiency. For example, as long as k_C is larger than 0.1, the transfer efficiency can easily achieve 90%.

The compensation circuit, consisting of inductors and capacitors, works with the capacitive coupler and forms the resonant circuit.

Meanwhile, the chassis voltage on the vehicle side is also an important concern for practical applications. Based on IEEE Standard C95.1, the root mean square value of the current flowing through a human body should be limited to below 16.7 mA at the frequency range of 100 kHz–110 MHz. If the contact resistance from the human body to ground is 500 Ω, the chassis voltage should be lower than 8.35 V for safety concerns. Therefore, the chassis voltage is estimated, as illustrated in Figure 7. In this analysis, considering the physical size of an electric vehicle, the mutual capacitance is 50 pF and the stray capacitance from vehicle to ground is 10 nF. This estimation shows that for a 15-kW system, the chassis voltage is maintained below the safety requirement when the frequency is higher than 2 MHz.

High-power, long-distance, and high-efficiency CPT technology has been realized and implemented. For example, a grounded CPT prototype has been built in the laboratory, as displayed in Figure 8. The top plate acts as the chassis, and the bottom plate is connected to the ground. The stray capacitance from the chassis to ground provides the current-returning path. Experiments demonstrate that high power is achieved at high efficiency and at a safe chassis voltage.

The following are advantages of CPT technology:

- *Low cost and low weight*: The CPT system only requires metal materials to generate electric fields. Its shape, size, and thickness have no significant influence on the transferred power and efficiency. It provides flexibility in the installation.
- *High reliability and long lifetime*: Considering the vehicle's weight on pavement, metal plates are much more reliable than coils made by Litz wire and ferrite.

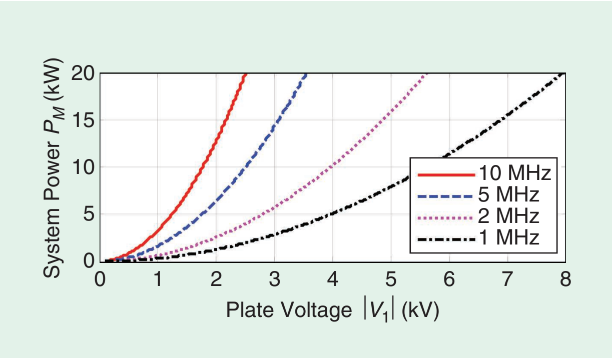

Figure 5. System power P_M at different voltage and frequency conditions when the coupling capacitance $C_M = 50$ pF.

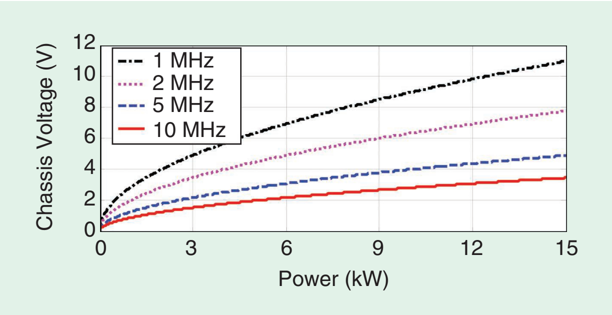

Figure 7. The chassis voltage at different power and frequency conditions. When the mutual capacitance $C_M = 50$ pF, the chassis stray capacitance is 10 nF.

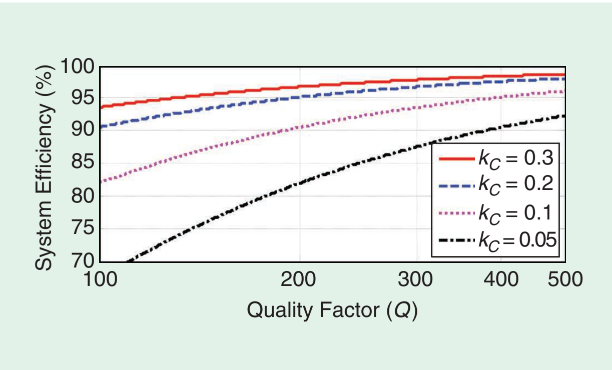

Figure 6. The efficiency of a CPT system at different coupling coefficient k_C and component Q.

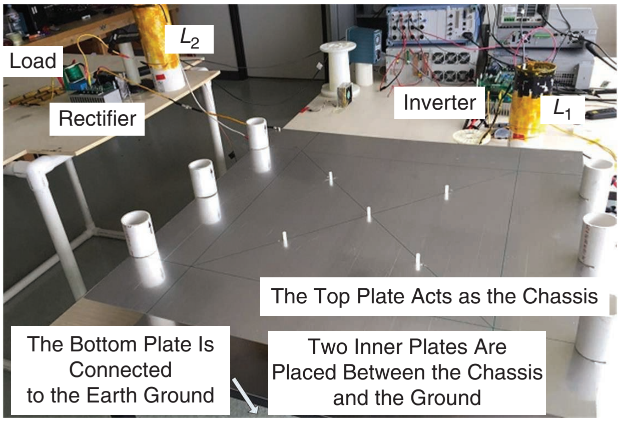

Figure 8. A lab-based prototype of a grounded CPT system used for high-power electric vehicle-charging applications.

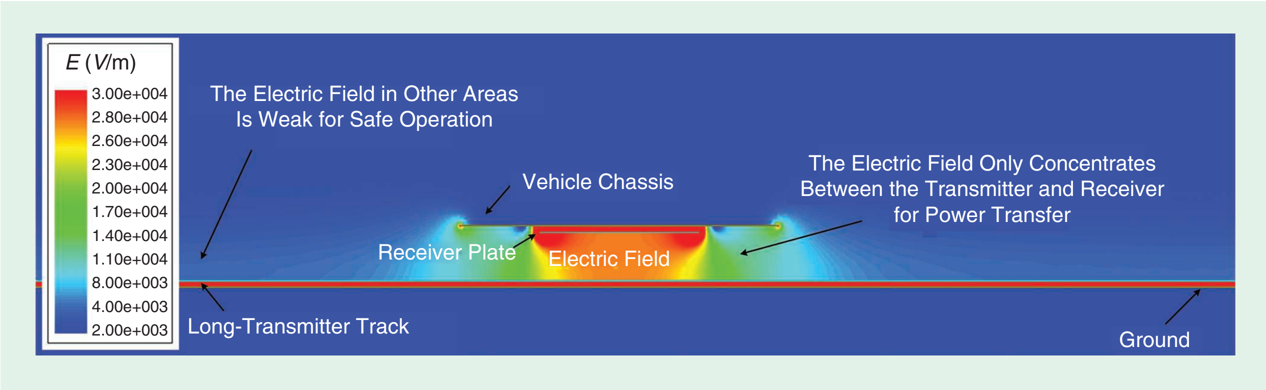

Figure 9. A simulated electric field distribution in a dynamic CPT system, demonstrating its safe operation.

With a good insulation layer on the plate surface, the corrosion and aging of the plate can also be limited.

- *High efficiency and safety performance*: In a dynamic CPT system, long-transmitting coils are eliminated. To achieve high power, the voltage is increased and the current is reduced to limit the conduction loss and improve efficiency. Moreover, because the electric field does not generate any eddy-current loss in metals, there is no concern for overheating.

Electric Field Emission in a Dynamic CPT System

Applying a voltage excitation up to a few kilovolts on the capacitive coupler, a finite element method (FEM) analysis provides the simulated electric field distribution depicted in Figure 9. A long metal track is used at the primary side as the transmitter, and a relatively small plate is used at the secondary side as the receiver. The ground plate and vehicle chassis are both included in the simulation model to emulate the practical scenario. The simulation model demonstrates that most of electric fields concentrate between the transmitter and receiver, and the electric-field strength in other areas along the transmitter track is relatively weak, which is good for safety.

Because the voltage on the vehicle chassis is limited to a low value (<8.35 V), it acts as the shielding to the electric field emission. Figure 9 also shows that the field strength above the chassis is significantly reduced. In a practical vehicle, this means that the electric field inside the vehicle is reduced, and the dynamic CPT system would be safe for the driver and passengers in the vehicle.

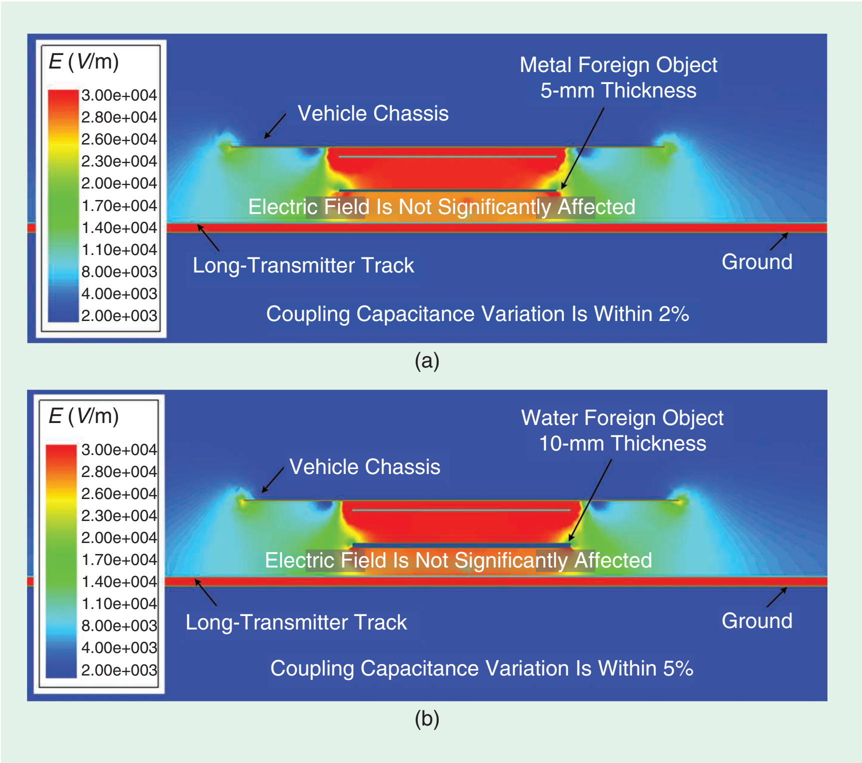

Figure 10. The impact of conductive and dielectric foreign objects on electric fields in a dynamic CPT system. (a) A metal foreign object and (b) a water foreign object.

It is also common to have foreign objects existing between the transmitter and receiver that could affect the power-transfer process. In different weather conditions, such as wind, rain, and snow, there could be leaves, water, and ice on the roadway surface. These foreign objects can be divided into two categories: metal and dielectric materials. The FEM analysis is used to study the impact, and simulation results are presented in Figure 10.

For the conductive material, a piece of aluminum is analyzed, and the electric field can pass through it. For the dielectric material, water is adopted to represent the severe weather condition. When the water thickness is 10 mm, the simulation indicates that the power-transfer process is not affected. For different foreign objects, the coupling capacitances are also simulated. Further experiments are also consistent with the FEM analysis simulation. Therefore, it can be concluded that the proposed dynamic CPT system is robust to foreign objects and can be applied in different conditions.

Transfer to Practice

With the development of CPT technology in the past few years, it has been well prepared for application to dynamic charging on electric roadways. In practical implementations, to reduce the construction cost, the width of the electric pavement can be limited (e.g., to 20 in). Because CPT technology has very good misalignment capability (the effective charging width can reach 40 in), which is sufficient to maintain effective power transfer to moving vehicles. As metal plates have high reliability and are well connected inside the roadway, they do not need frequent maintenance.

The practical implementation of the proposed electric roadway system is depicted in Figure 11. On the low-speed electric roadway, vehicles can easily pick up power in slow-moving status. In addition, the high-power stationary charging system can be combined with the dynamic system at the traffic-light position, and the vehicle can acquire extra power in waiting status. In this way,

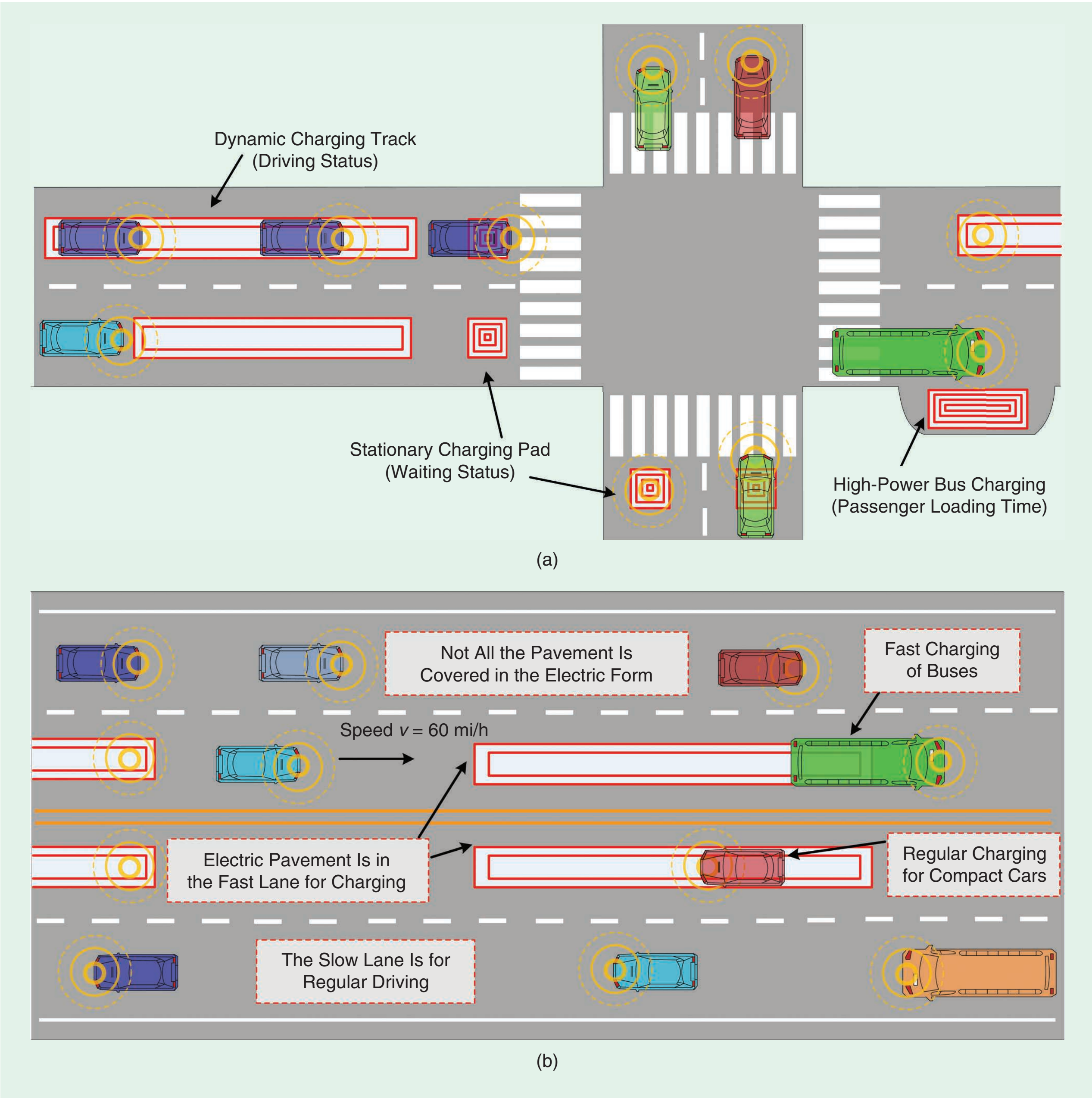

Figure 11. The practical implementation of the proposed electric roadway system used to achieve dynamic CPT charging for electric vehicles. (a) A low-speed electric roadway with a traffic light system and (b) a high-speed electric roadway on a highway system.

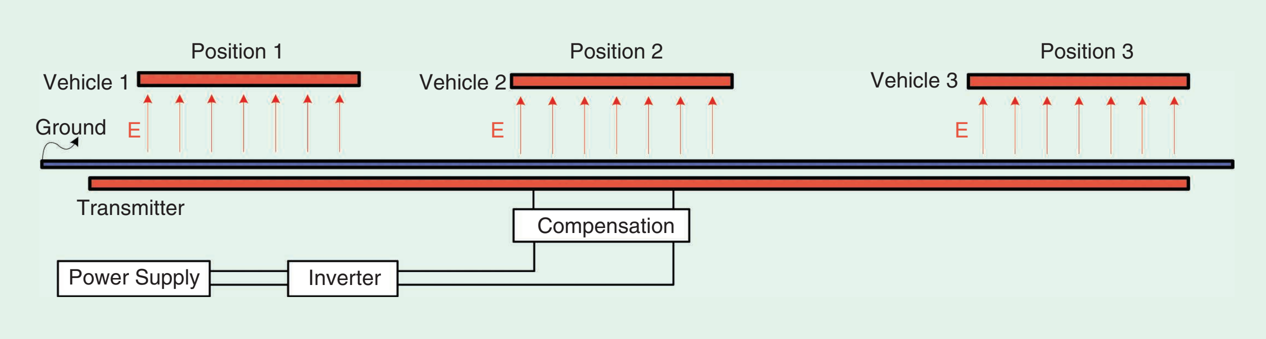

Figure 12. A long-transmitter track with multiple vehicles at different positions.

the traveling time can be fully utilized and transportation efficiency is also improved.

On the high-speed electric roadway, it is not necessary to cover all the pavement with the charging system. For example, the segmented transmitter structure can be adopted, and each track length is set at 50 m. When the vehicle speed is 60 mi/h, the effective charging time is roughly 1.86 s. The working frequency of the CPT system is in the MHz range, and the transient response time of the high-frequency resonant circuit is in the μs range. Therefore, there is sufficient time for the dynamic charging system to respond to high-traveling rates of speed.

Considering the vehicle's weight on pavement, metal plates are much more reliable than coils made by Litz wire and ferrite.

Challenges in Dynamic CPT Systems

In practical applications, there are three major challenges in a long-track dynamic CPT system:

1) The self-inductance of the transmitter plate affects the power-transfer process at different positions.

It is possible to have a transmitter length of 10 s of meters. The connection position of the primary compensation circuit affects the current-flowing path on the transmitter track. It is better to connect in the middle of the track to shorten the path of the current. There could be multiple receivers moving along the transmitter track. The positions of electric vehicles are used to illustrate the influence of the transmitter track-parasitic inductance, as depicted in Figure 12.

Receiver 2 is placed in the middle of the transmitter track, just on top of the compensation circuit connection. The other receivers are placed at the edge of the transmitter, and the currents must travel a long distance to reach the receiver. The FEM simulation indicates that the self-inductance can reach 10 s of μH, which affects the circuit resonance and reduces power. When the switching frequency is in the MHz range, the influence of plate self-inductance can be much more significant. It is, therefore, meaningful to study the self-inductance of the transmitter plate to reduce its side effects.

2) At a very high frequency, the radiated loss from the transmitter plate to the free space can be significantly increased, which affects system efficiency and safety.

In a CPT system, increasing the frequency f_{sw} contributes to increasing the system power and reducing the size of the passive component. With the development of modern wide-bandgap semiconductor materials, the switching frequency of a high-power device is expected to reach as high as 100 MHz. When f_{sw} increases, the wavelength λ of the generated electromagnetic wave is reduced. According to $c = \lambda \cdot f_{sw}$, where c is the speed of light, the quarter-wavelength $\lambda/4$ is calculated, as depicted in Figure 13. It demonstrates that when the switching frequency is as high as 1 MHz, the quarter-wavelength is $\lambda/4 = 75$ m. If the switching frequency increases to 100 MHz, the quarter wavelength decreases to 0.75 m. If the transmitter track length is close to or larger than $\lambda/4$, the transmitter will behave as an antenna to radiate a large amount of system power to the free space. In this case, the system power and efficiency will be significantly reduced. Meanwhile, the radiated power is also a critical safety issue to the general public. Based on this concern, the working frequency of a dynamic CPT system should be within the MHz range.

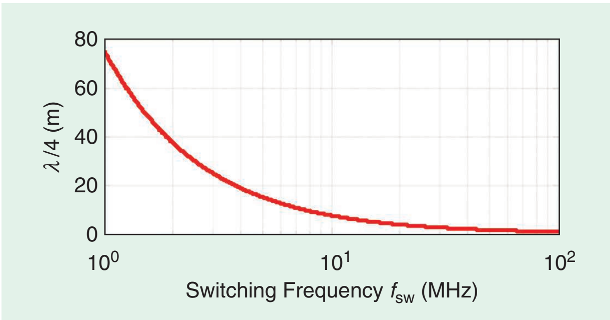

Figure 13. The relationship between switching frequency f_{sw} and quarter-wavelength $\lambda/4$ of the electromagnetic wave.

3) The high cost of infrastructure and the economic benefits affect feasibility in the practical transportation system.

The cost of the proposed electric roadway system mainly includes the one-time infrastructure cost and the long-time operation cost. The infrastructure consists of the power grid upgrade, power converter installation, and pavement reconstruction.

With respect to investment recovery, the electric highway pavement could be first adopted on toll roads, and the operator could charge costumers based on their electricity usage. In the future, with more electric vehicles on electric roadways, it is expected that the return-on-investment time will be acceptable to both government and industry partners.

At a very high frequency, the radiated loss from the transmitter plate to the free space can be significantly increased, which affects the system efficiency and safety.

Other CPT Technologies

In addition to the aforementioned technology in which the ground is utilized as the current-returning path, there are other potential CPT topologies that can be used to realize the electric roadway system, including four- and six-plates and other structures. The four-plate coupler structure is more popular and has been utilized in stationary CPT systems. Two plates are placed at the ground side as the transmitter, and the other two plates are attached on the vehicle chassis as the receiver. Transmitter plates are connected with the power electronic inverter and are insulated from the ground. The receiver plates are also insulated from the vehicle chassis. The advantage of this is that the vehicle chassis and ground are not involved in the power-transfer process, and the stray capacitance between them does not need to be considered. However, the electric field emission of the four-plate coupler could be a critical safety concern.

Then, the six-plate coupler structure is proposed to reduce the electric field emission. Two large metal plates are added at the ground and vehicle sides as the shielding to electric fields. At the ground side, the shielding plate is connected to the ground. Due to the symmetry of the coupler structure, the vehicle chassis is also equivalently grounded. In this way, the field emission to the surrounding environment is significantly reduced.

The capacitive coupler structure relates to the transfer power, efficiency, electric field emission, weight, cost, and other properties of a CPT system. Recently, there have been more studies focusing on the improvements of the coupler structure. With further development of the CPT technology, the application of dynamic charging for electric vehicles will be promoted in the future.

Conclusions

This article introduced the motivation, feasibility, and technical details of electric roadway systems for the dynamic CPT charging of electric vehicles. It demonstrated that electric vehicles could be continuously charged when they move along electric roadways. System power, efficiency, voltage stress, safety issues, and electric field emissions were all considered, indicating that it could be a potential technology used to promote the wide adoption of electric vehicles. In addition, the practical implementation and associated challenges were also discussed.

For Further Reading

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