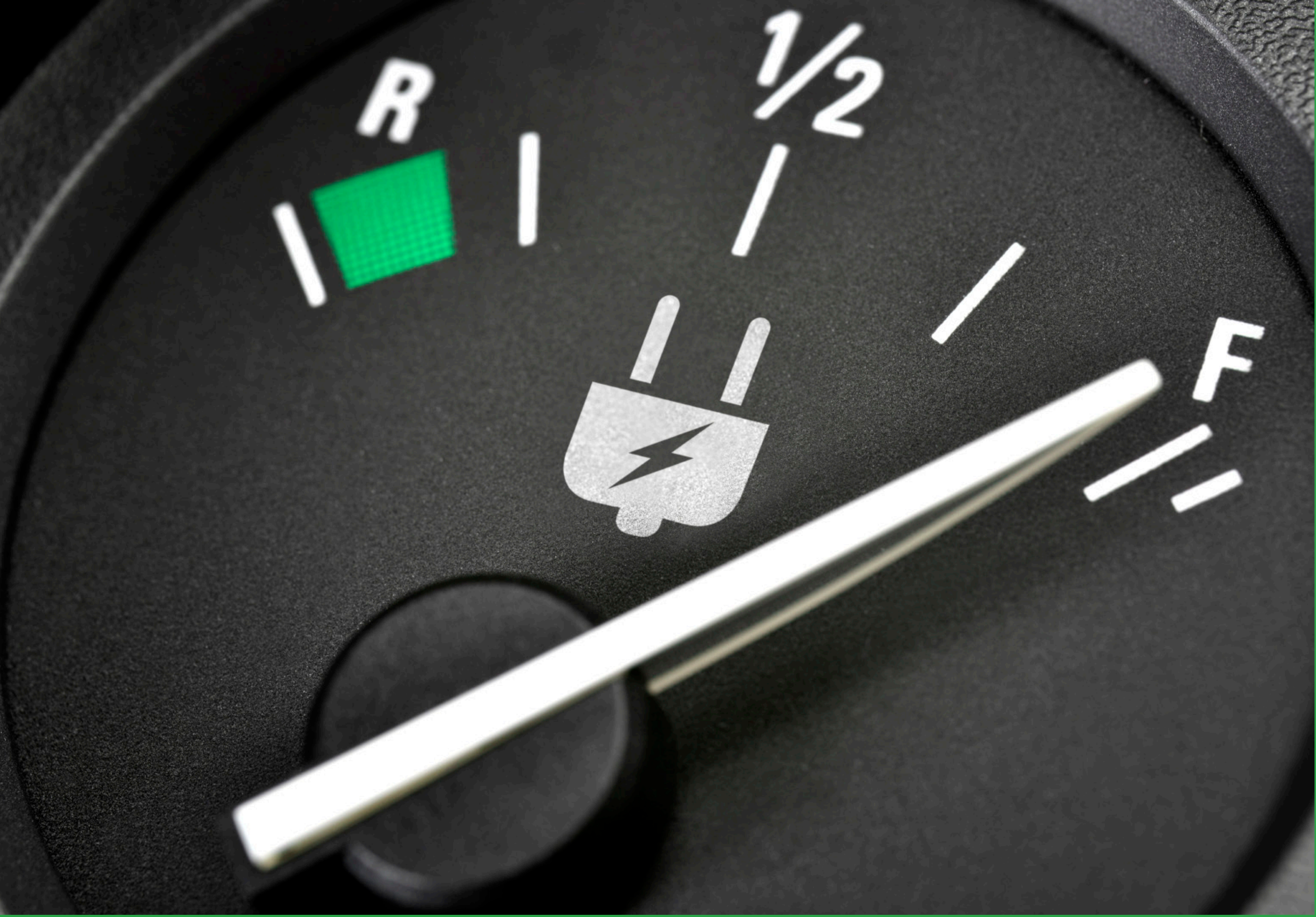


# SAFETY CONSIDERATIONS OF WIRELESS CHARGER FOR ELECTRIC VEHICLES – A REVIEW PAPER

# Safety Considerations of Wireless Charger for Electric Vehicles – A Review Paper

**White Paper by**
**Hai Jiang, Paul Brazis Jr., Mahmood Tabaddor and Joseph Bablo**
**Underwriters Laboratories LLC (UL)**
**Northbrook, IL USA**
**Hai.Jiang@ul.com**

## Summary

Abstract—Wireless power transmission is a promising technology which attracts attention in many fields and products. With mobile electronic products being prevalent, such as cell phones and PDAs, removing the power cord becomes a natural progression of achieving the ultimate mobility of the product. Wireless chargers for Electric Vehicles (EVs) would also be a convenient feature, avoiding any need to remember to plug in a power cord after parking the vehicle. Additional safety advantages may also be achieved due to eliminating exposed contacts. Nevertheless, wireless charging for EVs is an application requiring high electrical power (up to hundreds of kilowatts) and larger area of wireless power transmission which increases electromagnetic field exposure. Thus, application of wireless charging to an EV requires a comprehensive analysis to ensure consumer safety. This paper focuses on the safety considerations of wireless charging for EVs, including potential electrical shock hazards, magnetic field exposure hazards, fire hazards, etc. It provides a historical background of wireless charging, particularly for EVs. It also reviews two potential technologies applicable to wireless charging of EVs. The concept of Hazard Based Safety Engineering (HBSE) is applied to the problem and UL's training's program is introduced.

**Keywords:** Wireless charger; wireless power transfer; electric vehicle; safety standard; hazard based safety engineering (HBSE).

## Background

The concept of wireless power transmission can be traced back to the late 19th century, with Nicola Tesla. Tesla had promoted the idea of wireless power distribution for "wireless bulbs", where power was delivered through high frequency AC potentials between two plates or nodes[1]. However, at that time, such methods of wireless power transmission had generally not become a preferred method of power distribution. This was primarily due to their extremely low efficiencies, especially as the distances increase.

The technology of inductive charging has been in use for several decades, and has been commonly used for charging toothbrushes, shavers, and other small electrical appliances with lower power. Recently, inductive and resonant inductive chargers have become a hot technology mainly because of the emerging of massive mobile electronic products such as laptops, cell phones, PDAs, and other devices. For example, a laptop fitted with Bluetooth and/or Wi-Fi can be used without cables, except during recharging a battery. Therefore, removing the power charging cord is a natural progression of maximizing the mobility of the product. For most inductive chargers, the charging distance is less than one centimeter, requiring the mobile product to be placed on a charging pad. Novel concepts for inductive charging include embedding wireless charging into desktop surfaces or conference tables. However, such a system would likely require widespread implementation. Although the technology can make it happen the embedded charging has not become popular due to a lack of standards. Current products on the market tend to keep charging distance very small, with the primary utility arising from removing the need to plug the device in (e.g., the wireless Wii™ remote charger from Fu Da Tong Technology Company [2]), or for improving product aesthetics (e.g., the Palm® Touchstone™ charging dock for the Palm® Pre™ smartphone [3]).

Systems that are capable of delivering power over a larger distance such as the WiTricity system described in detail later in this paper (10 cm or more), or systems that deliver large amounts of power (100 W or more) open wireless charging to new business. One of these applications is the use of wireless charging for electric vehicles (EVs). Wireless charging of EVs has been used from the start of the General Motors EV1, where a Magne Charge paddle is inserted into an opening in the vehicle, similar to how a gasoline nozzle is inserted into a conventional vehicle for refueling [4]. In this application, the goal was to eliminate exposure of the operator to electrical contacts that are at high potential and able to deliver very high currents. Maximum power available from the Magne Charge was 6.6 kW, requiring 208-240 VAC and 32 A services.

More recent wireless charging technologies for EVs describe charging the vehicle without the need to plug in a charger, through the use of coils or small antennas embedded in the floor of a garage, parking space, or even in the street at intersections or along the roadway [5, 6]. This paper describes approaches to wireless power transfer technology with a focus on large-power applications, inductive and magnetic resonant wireless chargers for electric vehicles, and then discusses key safety concerns and potential areas that may need specialized testing standards development. The concept of Hazard Based Safety Engineering (HBSE) is applied to the problem and UL's training program is introduced.

## Wireless Charging Technology

In this paper, we discuss two wireless charging technologies applicable for EVs. One technology uses an inductive coupling method, also known as the inductive power transfer (IPT) system. As shown in Figure 1, such a system is composed by a primary coil, a secondary coil, and a rectifier to convert the AC power into DC power. The secondary coil is placed on and carried by the EV and the primary coil is embedded in the floor of a garage, parking space, or in the street.

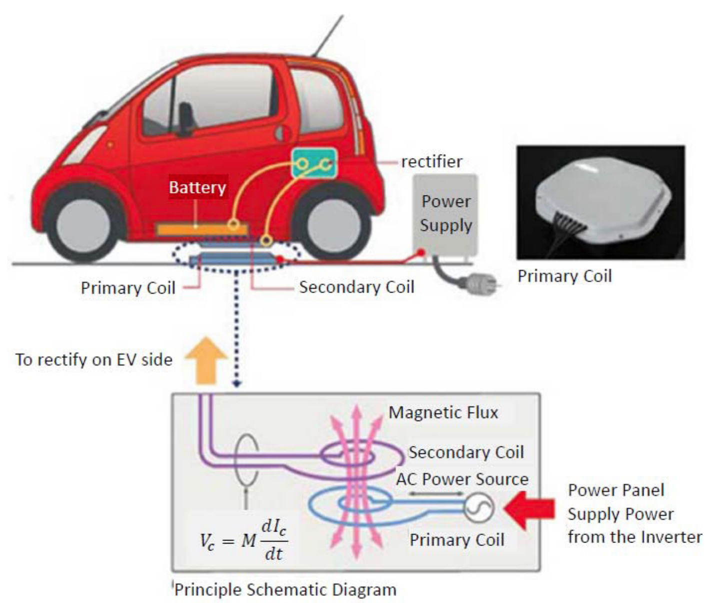


Figure 1. Schematic Diagram of Inductive Power Transfer System for EVs.

In 2009, Huang, Boys, Covic, and Budhia from the University of Auckland proposed an IPT system with a design of the power regulator ensuring continuous power flow at high efficiency, considering the fact that the separation could be increased as a result of variation in the vehicle to ground heights [7]. In 2010, Huang, Boys, Covic, and Budhia [8] presented a charging system with dynamic demand control in assisting frequency stabilization of the electrical power grid. Recently, HaloIPT [10] (acquired by Qualcomm) reported the IPT system that can take place at a distance of 400 mm and to a power level of 60 kW. Another wireless charging system for EVs has been announced by Showa Aircraft Industry (SAI) in Japan, collaborated with Waseda University [11, 12]. In their most recent results [13], it claims a delivery of 30 kW over a distance of approximately 100 mm.

Disadvantages for IPT include a limited transferring distance and the efficiency is relatively low when there is misalignment between the primary and secondary coils. An alternative technology that largely circumvents both issues is defined as magnetic resonant coupling (MRC), a "nonradiative" wireless energy transfer method [13]. This technique gained significant attention through the work of A. Karalis and colleagues at the Massachusetts Institute of Technology (MIT) [14-16]. The concept uses four coils instead of two coils, and the power is wirelessly delivered between the four coils using resonant electromagnetic states over distances that are moderately large (i.e., ten times larger than the diameter of the disk or coil used). It is noted that the outer two coils have only one turn and the two inner coils have multiple turns as the IPT system. By using four coils (two extra), the power efficiency is improved for achieving better impedance matching between the transmitter coil and receiver coil. The extra coils primarily provide an extra degree of freedom in tuning the impedance of the coils to achieve better impedance matching.

The MRC technology is also described by Intel [17] for wireless laptop applications. Zhu et al. experimentally demonstrated the feasibility of the MRC technology in 2008 [18] but no application was involved. Imura, Uchida, and Hori experimentally studied the efficiency, resonant frequency and air gap of the MRC wireless charging system for EVs using a helical antenna [19], which has the advantages of high gain, smaller size electrically and circular polarization. These researchers also [20] studied the performance of the system with respect to misalignment between the charger and the EV, and [21] proposed the equations for the relationship between maximum efficiency and air gap length in magnetic resonant coupling using the Neumann formula and the equivalent circuit method. Beh, Imura, Kato, and Hori proposed an MRC system improving the efficiency of power transfer by using an impedance matching (IM) circuit to tune the resonant frequency of the antenna to match the frequency of the power sources [22].

Recently, many research groups have been studying the MRC system for various applications. In the recent 2012 IEEE Antenna and Propagation Symposium, a session named "Wireless Power Transfer" is organized and many designs of the transfer system were presented for different applications [23-33]. The reports [23-29] focus on investigation and improvement of the power transfer efficiency. It is noted that these reports may be applicable to any wireless power transfer application including electrical vehicles, because most of them are general discussions on how to improve the efficiency of the WPT system. Previous work on MRC system has used loops, spirals, coils or lumped circuits to realize the two resonators (two inner parts of the system), in [23] SRRs are introduced in the SCMR system and they achieve excellent efficiency performance (nearly 90%). In [24], an MRC system with spiral resonators in air concrete interface is analyzed, and the efficiency of wireless power transmission from a source in air to a device embedded in concrete via SCMR is reported. In [25], the previous reported system using helical antennas is studied for its efficiency to the impact of pitch and ground plane on those helical antennas. In [26], instead of using a helical antenna with multiple turns, an array of coils are proposed to replace the helical antenna, and it claimed that it will reduce the phase cancellation problem and increase the system efficiency as a whole. In [27], a tri-loop configuration is proposed for the receiver enabling better impedance matching and frequency tuning. In [28], an adaptive impedance matching method using a multi-loop feeding is studied. The multi-loop can consist of two or more loops and each loop has a RF switch such as a PIN diode. Thus, the multi-loop can act as several different feeding loops and can be reconfigured for impedance matching at a certain distance. In [29], analysis of misalignment effects between resonators in efficiency of midrange wireless power transmission is presented, and some interesting phenomena of the nullification of the power transfer regarding the misalignments have been experimentally discovered. In [30-31], the near fields were discussed for the WPT system. In [32-33], the human body effects on the power transmission efficiency were discussed.

## Hazard Based Safety Engineering

Although wireless charging systems has many advantages for EV charging, the technology also poses potentially significant safety concerns such as electrical shock due to the high electrical power, high magnetic field exposure to the general public that may exceed standards and FCC regulations, and potential fire hazards. These concerns are primarily due to the presence of large power levels, large electromagnetic fields, and operation in potentially hazardous locations (for example, operation in garages with flammable materials). The Hazard Based Safety Engineering (HBSE) approach is an engineering process that focuses on the causes of injury and anticipating them. HBSE aims to equip engineers with a set of tools to anticipate specific hazards so that safeguards can be incorporated early on, rather than a reactive approach of seeking solutions that would tend to bog down the safety compliance design process at a later stage of the production cycle. Specifically, the tools assist design engineers in balancing safety requirements against other parameters such as performance, appearance and cost. Manufacturers benefit by increasing the chance for successful product evaluation, thereby gaining product certification and market acceptance in less time and at less cost.

As shown in Figure 2, HBSE primarily concerns three areas: hazardous energy sources, the transfer mechanism, and a body part [22]. The key of HBSE is to quantify hazardous situations based on the three-block model. We can predict the probability of a potential hazard, or even whether or not injury will occur, if we can quantify the energy sources, the transfer mechanism, and the effects on the body. HBSE can be applied to different types of hazards, which typically are thermal hazards, electrical shocks, and fire hazards. HBSE can also be used to enable safer designs through a relatively simple, straightforward process that can be applied to virtually any product or situation.


Figure 2 Block diagram of Hazard Based Safety Engineering

Underwriters Laboratories (UL) LLC was licensed to organize the HBSE training, which aims to help engineers integrate safety compliance early in the product design cycle. IBM, Dell, and the like are among those who have increasingly embraced the HBSE approach. The earlier manufacturers understand the Hazard Based Safety Engineering (HBSE) concept, the faster they can meet the challenges and transition to the new standard smoothly. For more information regarding UL HBSE training, please refer to [42].

## Potential Safety Concerns for EV WirelessCharging

The following list of potential safety concerns for an under-the-car EV charging system are not to be considered allinclusive, or imply that such hazards exist for such a charging system. They are to provide background for the safety standards and testing method for EV charging systems for which UL has been concerning [35] and can provide the solutions [36]. Similar considerations also may be applicable for other wireless systems capable of transmitting large amounts of power.

### *A. Electromagnetic Fields Exposure*

Electromagnetic field (EMF) exposure is a major concern for wireless charging for EVs. EMF exposure need to be rigorously analyzed to be within acceptable levels specified by safety standards, both under normal conditions as well as unusual conditions such as during abnormal operation, presence of a human under the vehicle, potential abuse, etc. For the driver and passengers in the car, the radiation hazard may be less concerned due to the shielding of metal on the chassis of the car. However, there is a possibility that humans or animals may be present underneath the car during charging and therefore be exposed to high levels of electromagnetic radiation. The "radiation zone" of the wireless charger for EV is in the near field of the electromagnetic wave, since both IPT and MRC operate in the near field of the EMF source versus far field which is used for transmitting signals/information for antennas. Exposures in the near field are more difficult to specify because both E and H fields must be studied or measured separately, and because the field patterns are more complicated. Apparently, the most hazardous radiation zone is right between the two coils, and secondary hazardous zone is around the coils (not right over the coils but still under the car). These areas are the most hazardous zones but it is noted that they are not directly exposed to humans or animals at all time. Comparing with these areas, another important hazardous zone in need of consideration is near the charger and around the car (not under the car), and it exposes to the general public directly. This area along with the two hazardous areas under the car needs to be considered during the design cycle.

There are two international groups that set standards/Guidelines for Human Exposure to Electromagnetic field (EMF): one is the International Committee on Electromagnetic Safety (ICES) under the Institute of Electrical Electronic Engineers (IEEE) [37], and the other one is International Commission on Non-ionizing Radiation Protection (ICNIRP) [40]. The radiation restrictions set differently for general public and occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions. More stringent exposure restrictions are adopted for the public than for the occupationally exposed population, because individual members of the public cannot reasonably be expected to take precautions to minimize or avoid exposure. Also, the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals.

**IEEE Standard C95.1**

According to IEEE Standard C95.1-2005 [37], below 100kHz only the electrostimulation limits apply, above 5 MHz only the thermal limits apply, and both sets of limits apply in the transition region between 100kHz to 5MHz. The two types of recommendations for IEEE are expressed in terms of basic restrictions (BRs) and maximum permissible exposure (MPE) values. The BRs are also referred as in situ electric field or internal fields in the human. MPEs, which are derived from the BRs, are limits on external fields (outside the human body) and induced and contact current. From [37], assuming the frequency employed by the wireless charger is 50 kHz (usually between 10 kHz to 100 kHz for current mainstream wirelesscharger for EV), the BR limits are calculated as shown in Table 1.

| | Action Level | Persons in Controlled Environment |
|---|---|---|
| Exposed tissue | Eo (rms) (V/m) | Eo (rms) (V/m) |
| Brain | 14.725 | 44.25 |
| Heart | 282.3 | 282.3 |
| Extremities | 31.3 | 31.3 |
| Other tissues | 10.5 | 31.3 |

Table 1. Basic restrictions applying to various regions of the body at the frequency of 50 KHz

As given in [37], the “safety factors” incorporated in the MPEs are generally greater than the “safety factors” in the BRs. Thus, as long as the external fields meet MPE limit, the BRs are met automatically. From [37], the Magnetic permissible exposures (MPEs) between 3KHz and 5 MHz is 163 A/m for magnetic field strength (H field of rms value), and 0.205 mT for Magnetic flux density (B field).

**ICNIRP Guidelines**

For ICNIRP, the two types of recommendations are “Basic Restrictions”, and “Reference Levels”. The reference level in ICNIRP is similar to the maximum permissible exposure (MPE) values. In terms of basic restriction comparing with the IEEE standard, ICNIRP uses current density J (mA/m2) as the unit. The relationship between the current density J and the internal electric field by Ohm’s Law: $J=\sigma E$, where $\sigma$ is the electrical conductivity of the medium/body tissue. Assuming homogeneous $\sigma$ of 0.2 S m-1 [42], the comparison between IEEE standard and ICNIRP is given by Figure 3, where Fs is the safety factor used by ICES and ICNIRP. It is noted that the ICNIRP has only one general limit for BR, but the ICES (IEEE) has multiple limits for different parts of body tissue such as the Brain and other tissue demonstrated in the figure. As shown in Figure 3, the BR from ICNIRP recommendation for general public is much more conservative between 10 to 100 kHz (range of wireless charger). Basic restrictions are the key to harmonize of ICNIRP and ICES. The ICNIRP reference level for general public exposure to time-varying electric and magnetic fields is found as 6.25μT [40]. It is noted that the recommended magnetic field level is 6.25μT which is much lower than the ICES level.

**Recent Publications and Activities**

To the authors' current knowledge, few publications were presented on simulation results of the magnetic field radiation for wireless charger for EVs, and experimental results have not been presented so far.

In [7], Huang et al. discusses the need to meet stringent electromagnetic field exposure regulations for human and livestock by ICNIRP. The frequency employed in Huang's charger is in the range of 5 kHz to 50 kHz. At the frequency used the limit of general public exposed to magnetic field intensity is regulated to be 6.25 μT by ICNIRP. Huang uses a particular design of the magnetic structure to constrain the leakage flux outside of the pad to lower the fields. This distributed ferrite structure was suggested for EV charging applications [9]. With this structure, most of the flux is contained within its cylindrical area. Outside the charger pad the magnetic flux density drops rapidly as presented by Huang. The results suggest that at 140mm away from the edge of the charger pad, the flux density is dropped to the limit of 6.25 μT. This battery charging system is designed to be installed underneath the vehicle, and consequently the magnetic flux density outside the vehicle area will meet the 6.25 μT reference level specified by ICNIRP [40]. It is noted that only the simulation results are shown in this paper, and there is no measurement or experimental results to support the simulation results. Moreover, for the most hazardous zones, the radiation is still over the standard limits, and special control system needs to be defined for these areas.

The magnetic resonant coupling (MRC) technology generally uses frequency above 100kHz (mainly between 1MHz to 10MHz). This is much higher than the IPT technology and the radiation restriction is much more stringent as the frequency increases. Moreover, the SAR evaluation is required by the standard. The technology at this frequency is hard to meet the reference level. Intel collaborated with IT'IS for investigation of near fields and SAR value in 2011 [44] with the simulation tool, "SEMCAD (part of IT'IS)". It is noted that it shows only the normalized SAR calculation results for four different in the models Duke and Thelonious in two sagittal planes but it did not release the real data without normalization. Some detailed results are also given in a separate presentation at CE4A workshop in April 2012 [45]. In this presentation, the max currents are presented for the results of 1g, 10g and whole body SAR evaluation for the respective SAR limits. The max current from 0.8 to 1.2A(rms) are used based on different anatomical model in order to meet the SAR limit of 2W/kg for 2g SAR exposure. The wireless charger for EV will require higher current (several tens of amperes) to obtain a reasonable charging time (not too long to be unrealistic), so the radiation level for such a WPT system will not meet the safety standard.

The "Standard Reference Man" [39], if not grounded, has a resonant absorption frequency close to 70 MHz, meaning maximum coupling efficiency, and therefore maximum heating, when a human is exposed to a field at this frequency. For taller individuals the resonant absorption frequency is somewhat lower. If a wireless charger system for EVs such as the MRC adopting MHz frequency, the radiation exposure

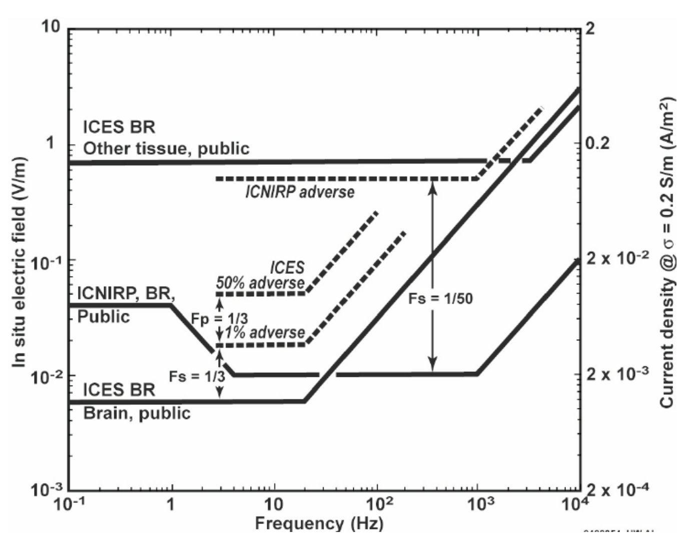


Figure 3 Basic Restrictions of ICES (IEEE) & ICNIRP for General Public [42]

should definitely be concerned and examined either in the designing cycle or the certification of such a product.

Except direct coupling to the body, indirect coupling may also occur in certain circumstances. For example, one potential EMF exposure hazard is the coupling of EMF to medical devices worn by, or implanted in, an individual [39]. Another potential indirect coupling hazard is that when the body is in physical contact with an object exposed to the field, where the object transfers electric currents through the body [40]. Transient discharges and sparks can also occur when an individual and a conducting object exposed to a strong field come into close proximity [39].

***B. Electrical Shock***

A wireless charger for an electric vehicle could deliver 100kW or more, and could utilize large voltages (for a household installation, likely 240 VAC) and high currents (up to 100 A). Voltage potentials across the primary and/or secondary coils may greatly exceed the supply voltage. The magnetic coil therefore would need to be physically sealed to prevent exposure of humans and animals to the conductors, under normal operation under a wide range of environmental conditions (for example, arctic cold, desert heat, extended periods of dry weather, immersion, seismic activity, etc.). The National Electrical Code would also likely need to be updated should such large power charging systems proliferate hazards, since wireless charging systems may be permanently installed into the floor of a garage or parking space.

***C. Fire Hazards***

The presence of high power is a potential fire hazard in the event of an insulation fault or other electrical failure. Current flow or excessive heating may need to be electrically monitored for faults, including shorting, poor energy transfer, arc or ground faults, or other events that may lead to a fire hazard. Performance of insulation materials used in the construction of the charging coils need to be evaluated for long-term resistance to elevated temperatures and environmental exposure to ensure materials degradation will not likely create a fire hazard.

## Conclusions

Safety and performance standards for wireless charging for EVs are currently under development. The automotive industry and other organizations are developing the technology and improving it not only from a performance perspective, but also from a safety standpoint. Due to the large area of electromagnetic field exposure between the car and the primary coil and high electrical power involved in this application, the product or system needs to be designed accordingly in order to meet the safety standard. Under such condition that safety is certified, efficiency and charging cycle are also required to meet the customer's expectation. As discussed, the standard test should cover electrical shock, electromagnetic field exposure level and fire hazard. In our current research, both simulation and experimental tools is being used to evaluate the near magnetic fields for EV's wireless charger system.

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