Wireless Charging for Electric Vehicles with its Boundary Conditions – A Contribution for Market Breakthrough

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Abstract
In this paper it is investigated what is necessary to bring Wireless Charging Systems for electric vehicles into the market. A power transfer can be realized easily. The challenges of shaping a Wireless Charging System to a series product in the market are the boundary conditions of the Automotive Environment. Especially the security and assistance systems as well as the interoperability which makes systems from manufacturer A with manufacturer B compatible are very important for the success of Wireless Charging. This paper shows the standard's impact on a successful product and which adjustments are supposed to be made additional to the Wireless Power Transfer setup.

1. Introduction
The ramp-up of electromobility with battery-electric vehicles and plug-in hybrids is to be supported and accelerated by governments. For many vehicle users today, however, a lack of convenience when charging the batteries and range anxiety, especially with battery-powered vehicles, are the main arguments for only driving a small number of purely electric kilometers. Inductive charging systems offer a solution to this problem, allowing the vehicle to be charged automatically and without any mechanical connection directly after parking. This increases the comfort for the vehicle user and at the same time lowers the inhibition threshold to start the charging process in the private, but also in the (semi) public application area. In order to create acceptance for inductive charging systems among the general public, it is necessary that the systems have all the essential safety functions and can be used interoperable and independently of manufacturers. Such boundary conditions are described via standards and must be incorporated into product development. In this paper, the boundary conditions from international standardization are addressed (Chapter 2). The application of safety and assistance systems (chapter 3) as well as interoperability (chapter 4) are considered for product development.
In Fig. 1 the concerned parts of a Wireless Power Transfer (WPT) system are depicted. The energy transfer begins at the PFC and continues over inverter, compensation, the magnetic circuit with the coil system as well as the secondary compensation, rectifier and battery. Additionally the positioning system, foreign and living objects as well as the communication setup and radiated emissions in form of electromagnetic interference are depicted.

![Diagram of Wireless Power Transfer System](image)

**Figure 1: Concerned parts of a Wireless Power Transfer System [1]**

2. **Boundary Condition in the Automotive Environment**

In this chapter the boundary conditions for Wireless Charging in the Automotive Environment are presented. When there are no laws, courts orient themselves at standards. For the certification process standards can be the starting point. But certification processes must be regarded for every country separately. Customer requirements can set higher bars than standards do.

2.1 **Laws**

Laws are the highest level of boundary conditions. Very often there are no or only a few laws for new technologies. For WPT there is e.g. for Germany the 26.BimschV [2]. In this law limitations for electromagnetic fields (EMF) are included. These limitations are very close to the ICNIRP recommended guidelines [3,4].

2.2 **Standards**

Standards are not legally binding but can be if there is a law which links to a standard. When there are no or few laws courts orientate in case of liability at the state of the art in the form of standards [5]. For the international standardization of WPT there are 4 big organizations.

In the SAE, IEC and ISO there is a big overlap of the committee members which leads to an ongoing harmonization process between these organizations.

![SAE, IEC, ISO, GB logos](image)

Figure 2: Logos from the standardization committees which have standards for Wireless Power Transfer Systems [Homepages from the committees]

For example there is a worldwide consensus for the tolerances in the driving and the transversal direction (see chapter 3.3. There is also a consensus that for different z-heights of vehicles different z-classes can be defined. In Tab. 1 a merged version of z-classes over the 4 big standardization committees is depicted.

<table>
<thead>
<tr>
<th>Distance class</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
<th>Z4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground clearance [mm]</td>
<td>100-150</td>
<td>140-210</td>
<td>170-250</td>
<td>&gt;250</td>
</tr>
</tbody>
</table>

The definition of z-classes is depicted as follows in Fig. 3.

![Z-Class definition in the standards](image)

Figure 3: Z-Class definition in the standards [6]

In Table 2 there is a merged version of all power classes from the 4 big standardization committees:

<table>
<thead>
<tr>
<th>Power class</th>
<th>WPT 1</th>
<th>WPT 2</th>
<th>WPT 3</th>
<th>WPT 4</th>
<th>WPT 5</th>
<th>WPT 6</th>
<th>WPT 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power [kVA]</td>
<td>≤ 3,7</td>
<td>≤ 7,7</td>
<td>≤ 11,1</td>
<td>≤ 22</td>
<td>≤ 33</td>
<td>≤ 66</td>
<td>&gt; 66</td>
</tr>
</tbody>
</table>
The resonance frequency is chosen in an ISM-band. These bands are free of approval and licences [18]. There is a worldwide consensus in the standards with a frequency between 79..90kHz, whereas GBT specifies a little more precisely to 85.5 kHz and SAE and IEC specify a nominal frequency of 85 kHz.

The 4 big standards also classify responsibilities for several technical solutions. For metallic foreign objects and living objects the primary side is responsible whereas for the energy transfer, communication and positioning assistance both sides are responsible. Therefore, a definition of interoperability has to be found.

2.3 Certification and Qualification
Certification process is necessary for official authorization of a product. The guidelines are different in different countries. Usually they are oriented at the state of the art in the form of standards. For a Tier1 it is a goal to have one system certificated in a lot of countries. Due to the different guidelines of the countries a system has to be designed with higher requirements for country A to also fit in country B.

2.4 Customer requirements
In the WPT for EV community it is usual that OEMs do not develop WPT-systems by themselves. Usually Tier1s develop the WPT-systems for the customers. Very often requirements from the OEMs are higher than the requirements from the standards and usually orientated very closely at the certification necessity. For example OEMs can claim lower limits in order to make certification for more countries possible.

The assembly space is usually individual for every OEM. An adjustment of the mechanic and the housing often leads to an adjustment of the shielding concept, which has an impact on the energy transfer and the security and assistance systems.
3. Wireless Power Transfer for Electric Vehicles under Boundary Conditions

Here it is shown which additional systems are necessary for power transfer of a Wireless Charging System in the automotive environment. The so-called security systems are necessary to prevent users and third parties from dangers (Foreign objects and living objects for people with active implants) and uncomfortable situations (high flux density to a healthy human being). For a high probability of a proper alignment a parking assistance system is necessary. Communication is necessary to exchange actual and target values of the energy transfer and for the accounting system. With electromagnetic interference it is meant that radiated emissions will be limited so that other electrical devices are not disturbed.

3.1 Metallic Foreign Objects

In the magnetic field in between the energy transferring coils it is possible that metallic objects heat up and e.g. cause hazards for persons who pick up the metallic objects (Fig. 4).

![Figure 4: Visualization of one potential hazard of metallic foreign objects at WPT-systems [1]](https://example.com/image)

There are two possible reasons for the heating of metallic objects. Materials with magnetization behaviour can cause hysteresis losses. This effect for dangerous heating and not detectable objects is negligible up to WPT3 class because of the magnitude of the magnetic field. The more interesting effect is the cause of eddy currents in expanded electric conductive objects. A fundamental work for this investigation was done in [1].

There are 3 different hazards that can occur. It has to be ensured that humans do not touch heated objects to prevent them from burns. It is also an objective that passive non-metallic foreign objects do not ignite and that there is no damage to the GA pad. The goals can be reached with a foreign object detection system (FOD-system).

3.2 Living Objects

In the first part of this chapter a general approach of body currents is made. Body currents can cause muscle reactions and ventricular fibrillation. The hazard occurs as a product of current and exposure time. In fig. 5 there is a hazardous table for AC / 50Hz
Figure 5: Dangerous body currents in zones for product of current and exposure time for AC/50Hz and adult persons [19], zone 1: no impact, zone 2: no hazard, zone 3: hazardous with muscle contractions or fibricular ventilation, zone 4: probable deadly, border lines a,b,c with different variants in c.

Because of the difficulty to measure body currents as a basis limit, a reference value is defined. With a voltage of 60 VDC and 25 VAC / 50 Hz it is ensured that in any worst case situation like wet hands there is no danger [19]. So, the reference values are set for worst case situations.

In WPT the only possibility to have currents in the human/animal body is via an induced voltage. If there is an expanded surface $A$ with an electric conductive material a voltage $U$ can be induced by the magnetic flux density $B$:

$$U = \frac{d\phi}{dt} = A \frac{d\sigma}{dt}$$  \hspace{1cm} (1)

Additionally a current flows only with a low electrical resistance on the expanded surface. The electrical resistance $R$ is dependent of the cross-sectional surface $A_{\text{quer}}$, the length $l$ and the electrical conductivity $\sigma$:

$$R = \frac{l}{\sigma A_{\text{quer}}}$$  \hspace{1cm} (2)

There are two possibilities where an expanded surface with electrical conductivity can occur in the body:
- A pacemaker opens a loop with copper or aluminium wires, approximately (very low $R$)

$$\sigma = 10^7 \ldots 10^8 \text{ S/m}$$  \hspace{1cm} (3)

- In the human body there are also electrical conductivities (high $R$) which are depicted in Fig. 7

$$\sigma = 10^{-3} \ldots 10^9 \text{ S/m}$$  \hspace{1cm} (4)

To assess the risk in the human body models have to be made and the electrical fields $E$ as the reason for the induced voltage $U$, which is the reason for body currents $I$.

As an analogy to the body currents for touch hazards (e.g. AC / 50 Hz) a reference value like the voltage has to be found. This reference value can be defined as the flux density $B$. In the product standard ISO 14117 [21] $15 \mu\text{T} / 85 \text{ kHz}$ are defined for new pacemakers as a safety level. For human beings with no pacemaker the ICNIRP guideline recommends $27 \mu\text{T} / 85 \text{ kHz}$ as a safety level.

The $27 \mu\text{T} / 85\text{kHz}$ are a very conservative approach considering the low electric conductivity in the human body and with that a high resistance for a body current. For example a TENS device (Fig. 8) for the healing of muscles has much higher body currents @approx. 200 Hz than with $27 \mu\text{T} / 85 \text{ kHz}$ would be possible.
The zones from Fig. 5 can be a little different for other frequency ranges. The zones exist in every frequency range, but may vary. These TENS devices work actively in zone 2 from Fig. 5. WPT (for a transformed zone for the frequency range) always occurs in a low area of zone 1.

For long term impact recently a very interesting study was made on 80 mice over 10 months with 20 kHz and $360 \, \mu T$ as equivalent to a human with $27 \, \mu T$ [22]. In this study no significant issues were found.

For product certification it is necessary to have a charging system below the addressed values. If this is not possible a detection system for living objects needs to be installed in areas where the values can be guaranteed for the regions where human beings stay.

### 3.3 Parking Assistance

When a car is going to be parked it must be ensured that the vehicle is parked in the tolerance band of the standards. In ISO/IEC/SAE [6-10] the following tolerances are defined (Tab 3)

<table>
<thead>
<tr>
<th>Tolerance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving direction X</td>
</tr>
<tr>
<td>Transversal direction Y</td>
</tr>
</tbody>
</table>

Figure 8: Device for transcutaneous electrical nerve stimulation (TENS) for healing of muscles via electrical activation, frequencies in the range 100...200 Hz [mtrplus.com]

Figure 9: Parking process of a public space

Table 3: Tolerance for EV-parking for WPT-systems in the standards
Therefore, an assistance system is necessary. In the near future it is possible that the parking assistance is completely integrated in the vehicle’s autonomous/assistance driving system.

### 3.4 Communication

For the control of the system it might be useful to exchange target and actual values between GA and VA. Alignment check and start stop functions of the charging process are absolutely necessary. Furthermore accounting functions can be integrated.

### 3.5 Electromagnetic Interference (EMI)

In WPT not only the fundamental wave is regarded also the harmonics have to be taken into account. In WPT for EV the principles of evanescent field coupling is used. With a coupling factor $k$ between 0.05 and 0.35 it is meant that 5% to 35% of the magnetic field is coupled in the near field whereas 65% to 95% exists as a localized stored energy. The only possibility for radiation is in combination with an antenna that matches to the frequency which is not the scope of WPT. For this reason the amount of radiated power is insignificantly small so that WPT can be categorized as existing power electronic devices like motor inverters for washers, cooking tops, conductive charging stations or even conductive switching power supply for smartphones or notebooks. In Fig.9 and 10 a typical measurement environment is shown.

![Figure 9: Typical EMC-measurement](image)

![Figure 10: Typical EMC-measurement Test Setting: drawing (left) [6], picture (right) [24]](image)
4. Interoperable Wireless Power Transfer Systems

Wireless Charging is a system which consists of two galvanically separated sides with the Ground Assembly (GA) and the Vehicle Assembly (VA). Both sides must be standardized like a plug and a socket from the energy transferring grid. The four critical parts for interoperability of a WPT system are presented here with the solution. A basic idea for interfaces is the independence of manufacturers and license-free systems. So that every new manufacturer has the possibility to introduce their product to the market.

4.1 Coil System

In the standards from SAE, ISO and IEC [6,9,10] it is consensus that there must be a freedom of operation. A coil can be designed very individually by manufacturer but has to be compatible with the given reference designs. The verification is done by measurements as described in the next section. There are two proposals for coil design in the standards, the so-called circular and DD-coils. Figure 11 shows an exemplary set of coils for the power class WPT3 with the VA coils of the distance class Z2. The coils are not shown to scale as in practice the GA coil exceeds the VA coil in the x-y direction, so that there is a higher tolerance to misalignment. The sizes of the coils are listed in Table 4 along with the magnetic properties, which are position dependent due to the use of ferrite and aluminium [25].

<table>
<thead>
<tr>
<th>Coil</th>
<th>Circular GA</th>
<th>Circular VA</th>
<th>DD GA</th>
<th>DD VA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size X x Y [mm x mm]</td>
<td>500 x 650</td>
<td>320 x 320</td>
<td>630 x 580</td>
<td>419 x 260</td>
</tr>
<tr>
<td>Inductance [μH]</td>
<td>35.1 … 38.1</td>
<td>43.1 … 44</td>
<td>68.3 … 72.3</td>
<td>44.7 … 48.2</td>
</tr>
<tr>
<td>Coupling Factor [-]</td>
<td>0.210 … 0.088</td>
<td>0.385 … 0.160</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 11: Proposals for Coil Design using the example of the WPT3/Z2-system. The coils are not to scale](https://doi.org/10.51202/9783181023846-459)
When combining coils of different topologies, for example circular GA and DD VA, a natural offset between the centres of the coil is required to reach a sufficient magnetic coupling [26]. A fundamental investigation for the coupling of the circular and the DD-coils was made in [25]. Here it is shown that it is recommended to have the circular coil as an infrastructure coil and on the vehicle side it can be chosen between circular and a DD-coil. In the SAE the circular coil is defined as a reference coil whereas the DD-coils are listed in the informative annex.

### 4.2 Impedance Matching/Operating Point Design

For efficient power transfer at the coupling factors in Table 4, reactive power compensation on both sides is required. Analogous to the coil designs, there is also a reference design for each power and distance class. In Fig. 12, this is again shown as an example for the WPT3/Z2-class with all relevant parts for power transfer (see Fig. 1). The capacities C1a, C1b and C2 on both sides form the Impedance Matching Network (IMN), which are used to properly couple the resonators to the equivalent battery load and to the driving inverter. System operation with high efficiency over a wide range of battery voltages and offset positions within the tolerances in Table 3 is reached by the active components jXGA and jXVA, the so-called Tunable Matching Network (TMN) [30].

![Figure 12: Electric circuit of the reference design exemplary for the WPT3/Z2-system](image)

Table 5: Electrical Parameters of the reference design in Fig. 12

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ground Assembly (GA)</th>
<th>Vehicle Assembly (VA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>C1a, C2, jXGA/2</td>
<td>C1a, C2, jXVA/2, L1a, L1b, L2a, L2b</td>
</tr>
<tr>
<td>Value</td>
<td>320 nF, 270 nF, 4 to 16 Ω</td>
<td>270 nF, 145 nF, -15 to 0 Ω, 54 μH</td>
</tr>
</tbody>
</table>
The product GA or VA from a manufacturer should be compatible with the respective counterpart. For full interoperability (Class I), a product GA shall cover the input power range up to 11.1 kW as well as the battery voltage range of 280 to 420 V at full output power over the full ground clearance range (Z1 to Z3 in Table 1) and within the positioning tolerances in Table 3. For a primarily specific application, a Class II is defined in which not all the named requirements have to be fully met. For details, please refer to the standard [6]. For a product VA, the Z range and the output voltage shall be specified by the manufacturer and therefore it does not need to be classified by Z-Class. A Product VA is tested with the GA reference design and shall operate within the same positioning tolerances according to Table 3. For all tests, an efficiency greater than 85% in the centered position and at least 80% at maximum offset is required.

Investigations on the measurement of interoperable systems and the necessary test bench setup can be found in [27] and [28]. Results of the measurement of complete systems are presented in [29].

4.3 Communication

In the standardization it is consensus that the ISO 15118 [31] layer is used [8,32]. This can be implemented e.g. with Wi-Fi as a communication network.

4.4 Positioning Systems

The tolerances for parking in x and y-direction are defined (see chapter 2.2). Over the years there have been a lot of proposals for an assistance system. Yet there is no consensus for a positioning assistance in the standardization committees. It is very difficult to have an assistance procedure which guarantees the freedom of operation, which is highly claimed in the standards. For this purpose, MAHLE has started a funding project together with other partners where amongst other technical purposes a standardized positioning procedure is a goal.
5. Summary and Outlook

If a WPT system is designed additional to fundamentals of the power transfer the requirements of the automotive environment have to be taken into account. Especially interoperability has to be regarded (for manufacturer independent systems). A holistic consideration of the system is required. This also includes Safety, assistance systems, certification, and customer wishes.

In this paper it is shown that Wireless Charging is feasible. There are no technological barriers. With Wireless Charging a battery in an EV can be kept full due to automized charging while parking and with no necessity of a user interaction. There is also the advantage that with a continuous grid connection the load management ca be improved.

Wireless Charging is the key enabler for autonomous driving with its support for automized valet parking and for the general automatization in the vehicle. If all considerations for the system design from this paper are implemented a wireless charging system for electric vehicles will be shaped into a successful product with a high probability for a market breakthrough.

References


[18] Frequenzplan gemäß § 54 TKG über die Aufteilung des Frequenzbereichs von 0 kHz bis 3000 GHz auf die Frequenznutzungen sowie über die Festlegungen für diese Frequenznutzungen, Bundesnetzagentur, Bonn, 2021.


