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Interoperability of Wireless Power Transfer

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ABSTRACT: This paper presents the results of investigations on the magnetic and electric interoperability of wireless power transfer (WPT) based on the magnetic coupling between two coils. A wayside installed coil transmits magnetic flux which is received by a vehicle side installed coil. The transferred power can be used to charge vehicle side batteries and/or power the propulsion system. The proof of interoperability is exclusively based on the transmitted and reflected magnetic flux characteristic and is independent of the impedance and the compensation design. Due to the focus on the description of interoperability by the magnetic coupled flux a wide range of the design details as coil geometry, voltage and current levels, electric impedances must not be standardized and can be kept under the responsibility of the individual design.

KEY WORDS: electric vehicle, wireless power transfer, interoperability, standardization.

1. INTRODUCTION

Wireless power transfer on the base of magnetic coupled coils is meanwhile used in various applications. First applications of dynamic (while vehicle is moving) power transfer where installed in Germany at various German vehicle manufacturing companies (1).

Fig. 1: Dynamic inductive power transfer, (automotive production line, P ≈ 3kW)

The worldwide biggest inductive power transfer for dynamic battery charging was installed 2004 at the TRANSRAPID maglev test facility in Lathen, Germany. At maglev vehicle speeds below about 100km/h inductive power transfer was used to power the levitation system instead of power rails. The transferred power rating is 2x 250 kW. The primary coil was designed with one winding w = 1 at a primary AC-current of 200Arms/20kHz, single phase system (4).

Fig. 2: TRANSRPID TR09, (dyn. inductive battery charging)

Based on the successful operation of the TRANSRAPID maglev battery charging system the dynamic power transfer technology was developed, implemented and tested for the operation of light rail systems without pantographs. The development was done in a cooperation of Bombardier and IMAB, Technical University of Braunschweig (Fig. 3 PRIMOVE). A primary 3-phase coil system located between the rails transmits electric power of 200kW (20kHz) to the light rail vehicle on the base of a traveling magnetic wave. The section length was designed between 20-100m.

In a later step this technology was modified for stationary battery charging of busses. This "emil" project in Braunschweig; Germany (2) is the first commercial use of wireless power transfer with a power rating of 200kW, 20 kHz worldwide.

Fig. 3: Dynamic Wireless Power Transfer (PRIMOVE, 200kW, 20 kHz)

The focus of all projects as described was the mainly the function of inductive power transfer. Technical details as operating frequency, design of the coil geometry, number of turns, voltage and current levels where under the responsibility of the individual designers. There was no need for standardization because the technology was unique within each project and developed, built and operated by one group of companies and engineers. Recent WPT-System deliveries benefit from the today's availability of fast switching power semi-conductors (SiC). Higher power rates can be transferred at harmonized operating frequency of 85 kHz.

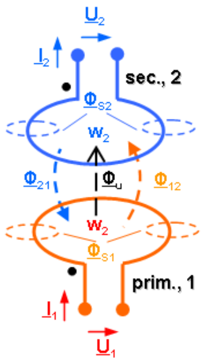
Fig. 4: INTIS' Stationary Wireless Power Transfer System (Slovenian Post, 2022), 22kW, 85 kHz.

2. THEORY OF INDUCTIVE WIRELESS POWER TRANSFER

Due to the worldwide general trend of e-mobility since about 2010 inductive wireless power transfer becomes more and more important as the key technology to transfer electric power to electric driven vehicles at specific places (static charging SWPT) and along roadways while the vehicles are running (dynamic charging DWPT). Standards developed by ISO, IEC, SAE, ITU describe the requirements for interoperability as operating frequency, air gap ranges, coil topologies by means of reference design, impedances, field emission levels as well as efficiency and safety aspects. Furthermore the different phases of charging sessions are described. The purpose of standardization is to ensure the system functionality and interoperability on the basis of as much freedom as possible regarding economical and commercial design aspects.

2.1. Equivalent Circuit

Magnetic and electric interoperability of the power components ensures the proper operation of power devices of for example from different manufacturers of the wayside and of the vehicle side coil systems, inverters and compensation networks. As inductive power transfer is in principle based on a transformer Fig. 5 shows the equivalent circuit of a WPT-transformer.



$\underline{U}_{1,2}$, $\underline{I}_{1,2}$: coil voltages currents,
$\underline{\Phi}_{12}$: transmitted magnetic flux,
$\underline{\Phi}_{21}$: reflected magnetic flux,
$\underline{\Phi}_{s1}$: prim. magnetic stray flux,
$\underline{\Phi}_{s2}$: sec. magnetic stray flux,
$\underline{\Phi}_{u}$: resulting. coupled magnetic flux,
$w_{1,2}$: no. of coil turns

Fig. 5: WPT Coil System

The physical coil system as shown in Fig.5 is shown in Fig.6 as the equivalent electric circuit (ohmic losses, harmonics neglected).

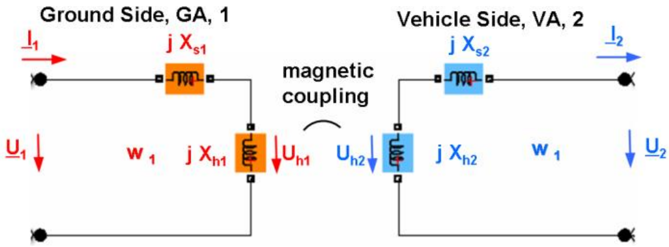


Fig. 6: General WPT Transformer (ohmic losses neglected)

The mesh equations of voltages are described by

$$\begin{aligned}\underline{U}_1 &= jX_{s1}\,\underline{I}_1 + jX_{h1}\left(\underline{I}_1 - \frac{w_2}{w_1}\underline{I}_2\right)\\ &= jX_{s1}\underline{I}_1 + jX_{h1}\underline{I}_1 - jX_M\underline{I}_2\\ &= j(X_{s1}+X_{h1})\underline{I}_1 - j\omega w_1\underline{\phi}_{21}\\ &= j(X_{s1}+X_{h1})\underline{I}_1 - \underline{U}_{i21}\end{aligned}$$

$$\begin{aligned}\underline{U}_{h1} &= jX_{h1}\underline{I}_1 - \underline{U}_{i21}\\ \underline{U}_{i21} &= j\omega w_1\,\underline{\phi}_{21}\\ \underline{\phi}_{21} &= X_M\,\underline{I}_2 = X_{h0}\,w_2\,\underline{I}_2\end{aligned} \quad (1)$$

$$\begin{aligned}\underline{U}_2 &= -jX_{s2}\,\underline{I}_2 - jX_{h2}\left(\underline{I}_2 - \frac{w_1}{w_2}\underline{I}_1\right)\\ &= -jX_{s2}\underline{I}_2 - jX_{h2}\underline{I}_2 + jX_M\underline{I}_1\\ &= -j(X_{s2}+X_{h2})\underline{I}_2 + j\omega w_2\underline{\phi}_{12}\\ &= -j(X_{s2}+X_{h2})\underline{I}_2 + \underline{U}_{i12}\end{aligned}$$

$$\begin{aligned}\underline{U}_{h2} &= -jX_{h2}\underline{I}_2 + \underline{U}_{12}\\ \underline{U}_{i12} &= j\omega w_2\,\underline{\phi}_{12}\\ \underline{\phi}_{12} &= X_M\underline{I}_1 = X_{h0}\,w_1\,\underline{I}_1\end{aligned} \quad (2)$$

Mesh Equations of the WPT Coil System

Prim. mesh and sec. mesh consist of inductive reactances $\mathbf{X_s}$ which represent the voltage drop at the stray inductance and of main inductances $\mathbf{X_h}$ which represent the magnetic coupling of the prim. and the sec. coil. The magnetic coupling is based on the resulting magnetization flux $\underline{\mathbf{\Phi}}_{\mathbf{u}}$ which is in proportion to the difference of the coil currents as magnetizing current $\underline{\mathbf{I}}_{\mathbf{u}} = \underline{\mathbf{I}}_{\mathbf{1}} - \mathbf{w_2/w_1}\ \underline{\mathbf{I}}_{\mathbf{2}}$. Due to the large gap between prim. and sec. coil the stray inductances $\mathbf{X_s}$ show high values compared with the main inductances. In addition $\mathbf{X_s}$ and $\mathbf{X_h}$ values change with the x, y, z position of both coils against each other.

Best magnetic coupling is achieved in center position Δx, $\Delta y = 0$ and $z = z_{min}$ of sec. coil 2 against prim. coil 1 while worst case coupling is achieved by Δx, Δy = max and $z = z_{max}$. The variation of magnetic coupling is about a factor of 2...3.

By separating the magnetizing current into coil currents the effect on the mesh voltages can be expressed by voltage drops at $\mathbf{X_h}\ \underline{\mathbf{I}}$ and voltage sources und voltage sinks $\underline{\mathbf{U}}_{\mathbf{i}} = \mathbf{j\omega\ w}\ \underline{\mathbf{\Phi}}$.

The voltage drop at the total coil inductance can be expressed as $\mathbf{(X_s + X_h)}\ \underline{\mathbf{I}}$ and usually will be compensated by a compensation network to prevent the power source (AC-inverter) and the power sink (battery rectifier) from large amounts of reactive power. The modified equivalent circuit based on (1), (2) including compensation networks is shown in Fig. 7.

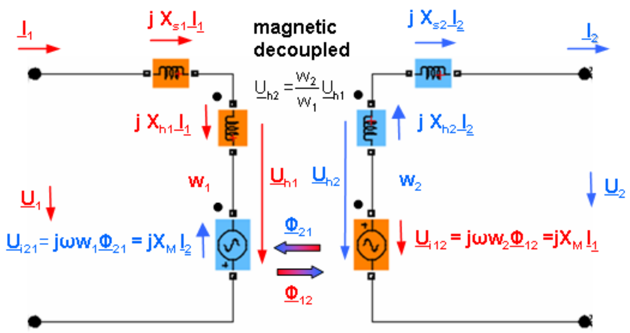


Fig. 7: Modified WPT Transformer

The prim. mesh consists of a compensation network, the total prim. reactance $\mathbf{X_1 = X_{s1} + X_{h1}}$ and the reflected (induced) voltage $\underline{\mathbf{U}}_{\mathbf{i21}}$ due to the reflected sec. magnetic flux $\underline{\mathbf{\Phi}}_{\mathbf{21}}$.

$\underline{\mathbf{U}}_{\mathbf{i12}}$ which is based on the transmitted prim. magnetic flux $\underline{\mathbf{\Phi}}_{\mathbf{12}}$.

The vector diagram in accordance to Fig. 7 is shown in Fig. 8 for non-compensation condition. On the sec. side the transmitted voltage $\underline{\mathbf{U}}_{\mathbf{i12}}$ presents the voltage source for the sec. load. Due to the non-compensated inductance $\mathbf{X_2}$ a voltage drop $X_2\ I_2$ will reduce the output voltage level of $\mathbf{U_2}$ significantly. Due to non-compensated condition the output current (load) $\underline{I}_2$ will be delayed with the consequence of a poor sec. power factor cos φ_2. The sec. load current $\underline{\mathbf{I}}_{\mathbf{2}}$ will generate a magnetic flux $\underline{\mathbf{\Phi}}_{\mathbf{21}}$ which will be reflected to the prim coil and which will generate a reflected voltage $\underline{\mathbf{U}}_{\mathbf{i21}}$ in the prim coil. The reflected voltage $\underline{\mathbf{U}}_{\mathbf{i21}}$ will be out of phase with the prim. current $\underline{\mathbf{I}}_{\mathbf{1}}$ and will reduce the prim. power factor. An additional reduction of the prim. power factor is caused by the non-compensated prim. inductance X_1. Caused by the large stray reactances compensation is required.

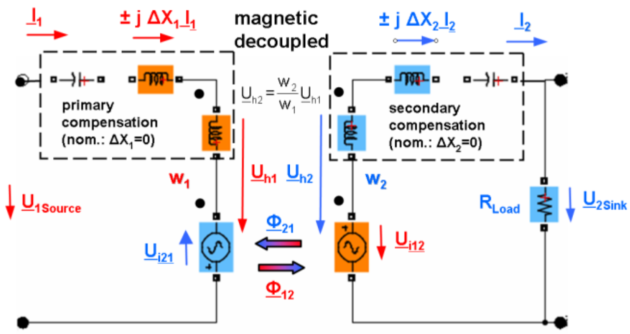


Fig. 9: WPT Transformer incl. Compensation Network

The prim. and sec. compensation networks will compensate the voltage drops of X_1, X_2. A remaining inductive or capacitive reactance $\pm jΔX_1$,

$ΔX_2$ has to be considered because x1, X2 values will be effected by the relative positioning of prim. and sec. coil.

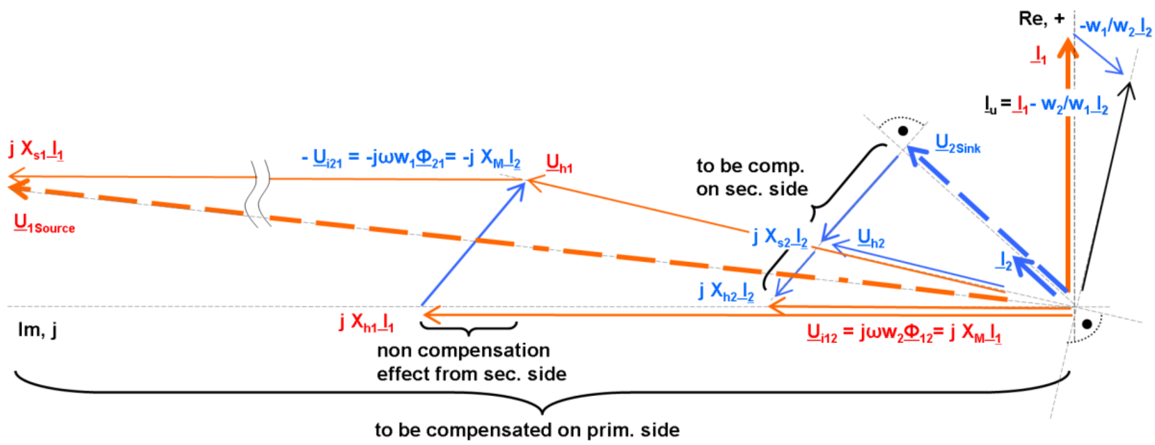


Fig. 8: Vector Diagram WPT Transformer (Fig. 7)

Fig. 10 shows the vector diagram of the compensated coil system. Usually for compensation series capacitors are used. At best compensation condition of the sec. coil system the sec. current $\underline{\mathbf{I}}_{\mathbf{2}}$ and the transmitted voltage $\underline{\mathbf{U}}_{\mathbf{i12}}$ are in phase. Depending on the sec.

faulty compensation range (due to positioning deviation) $\underline{\mathbf{I}}_2$ will be out of phase related to $\underline{\mathbf{U}}_{i12}$. The magnitude of $\underline{\mathbf{I}}_2$ might also vary due to the load condition.

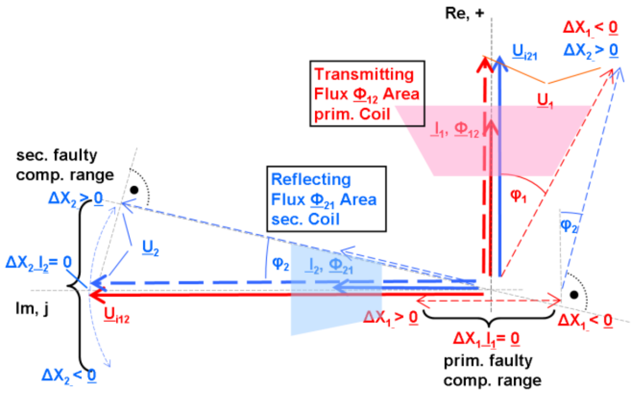


Fig. 10: Vector Diagram of compensated WPT Transformer

As a consequence of faulty sec. compensation condition the reflected voltage $\underline{\mathbf{U}}_{i21}$ will vary which results in additional lag of transmitted active power and prim. power factor.

<u>Transmitted and received Power:</u>

sec. Coil System:

apparent power: $S_2 = U_{i12}\ I_2$
active power: $P_2 = U_{i12}\ I_2 \cos\varphi_2$
reactive power: $Q_2 = U_{i12}\ I_2 \sin\varphi_2$

prim. Coil System:

apparent power: $S_1 = U_{i21}\ I_1$
active power: $P_1 = U_{i21}\ I_1 \cos\varphi_1$
reactive power: $Q_1 = U_{i21}\ I_1 \sin\varphi_1$

3. COMPENSATION TOPOLOGIES

The large amount of magnetic stray flux requires additional reactive power but does not contribute to the transferred active power. To minimize reactive power usually compensation networks are assigned to the coil systems.

3.1 Series Compensation

The concept of series compensation is to compensate the voltage drop along the inductances $X_{1,2}$ by series capacitors.

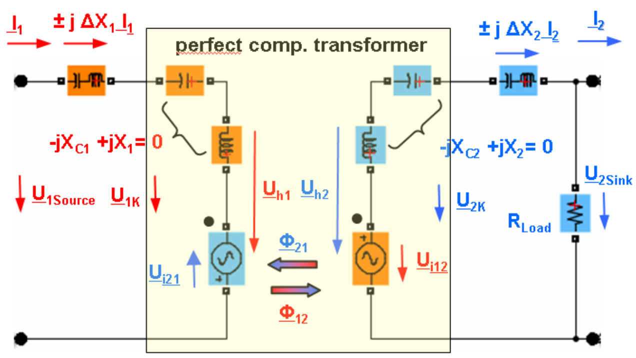


Fig.11: Series Compensation

Under perfect compensation conditions (-jXc+jX=0) the induced and the reflected voltages are equal to the applied voltages ($\underline{U}_{1Source}$ = $\underline{U}_{1K}$, $\underline{U}_{2Sink}$ = $\underline{U}_{2K}$). However usually a certain amount of compensation deviation $\pm j\Delta X_{1,2}$ has to be considered due to lateral and vertical positioning tolerances. As a consequence a certain amount of phase shift $\varphi_{1,2}$ has to be considered at the source and sink voltages. In principal the compensation topology as shown in Fig. 11 acts as an L_C_L gyrator impedance transformation design.

3.2 Parallel Compensation

The concept of parallel compensation is to compensate reactive current by a parallel capacitor. This strategy can be combined with the necessity of serial inductances which are required to decouple the primary inverter and the secondary rectifier from these parallel capacitors.

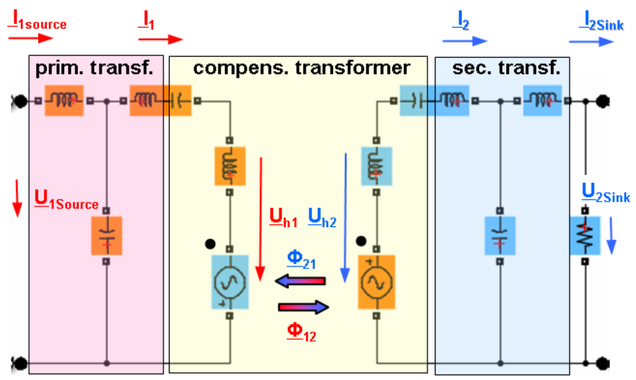


Fig. 12: Parallel Compensation

The L_C_L gyrator design of the additional inductance, the parallel capacitor and the partly compensated coil inductance can be used to transform impedances in accordance to

$$Z = \frac{X^2}{R}$$

R: load impedance,
Z: input impedance
X: gyrator impedance

The parallel compensation offers additional possibilities to transform impedances depending on the coil design, harmonics and inverter design. Also a mixed design of series and parallel compensation is possible.

4 SYSTEM INTEROPERABILITY

4.1 Magnetic and Electric Interoperability

<u>Requirements:</u>

- The prim. coil system must be able to transmit a specified amount of magnetic flux $\underline{\mathbf{\Phi}}_{12}$ to the sec. coil system,
- the sec. coil system must be able to reflect a certain amount of magnetic flux $\underline{\mathbf{\Phi}}_{21}$ to the prim coil system,
- transmitted and reflected flux values have to be ensured under specified positioning, load and compensation conditions.

Design:

- The transmitted flux is given by $\underline{\boldsymbol{\phi}}_{12} = \boldsymbol{X_{h0}}\ \boldsymbol{w_1}\ \underline{\boldsymbol{I}}_1$.

  The main inductance X_{ho} is defined by specified geometric parameters while the prim. ampere turns w_1 I_1 are design free,
- the received flux is given by $\underline{\boldsymbol{\phi}}_{21} = \boldsymbol{X_{h0}}\ \boldsymbol{w_2}\ \underline{\boldsymbol{I}}_2$.

  The main inductance X_{ho} is defined by specified geometric parameters while the sec. ampere turns w_2 I_2 are design free.

Verification:

- The verification of the prim. and sec. coil system design can be accomplished by exiting the coil system with current and measuring the transmitted (received) flux with a gauge device or reference device in terms of measuring the induced voltage under the specified positioning conditions,
- the verification of transferred (received) power can be accomplished by exiting the coil system with current and measuring the transmitted (received) power with reference device under the specified positioning and power conditions,
- the calculation and measuring of the transformed load impedance including the compensation devices can be used for system verification,
- considering the effects of faulty compensation and impedance transformation (gyrator...) the calculation (and measuring) of the resulting impedances is used.

4.2 Operation and Power Control

System interoperability includes mainly the aspects of operation control, power. Operation control handles the switch ON_OFF procedure depending on vehicle status messages including failure management. Power control handles the amount of active power respectively primary current value and the control strategy. The modes "power control" and "current control" depend on the vehicle side installed control devices. According messages might have to be exchanged between vehicle side and wayside installed control devices. If multiple vehicles are powered by one single primary power source the primary mode "constant current control" will decouple the power flow between multiple vehicle loads. If only one vehicle load is powered by one wayside device the mode "primary power control" might be advantageous regarding cost and complexity. Operation control and power control concepts do affect the power system and the control system design. In addition the requirements of the power and control systems for conductive power transfer interoperability might have to be considered.

Interoperability of WPT-systems with components from different manufacturers requires harmonization of several individual activities of a static WPT charging session. Some of these activities are described in the following chapters.

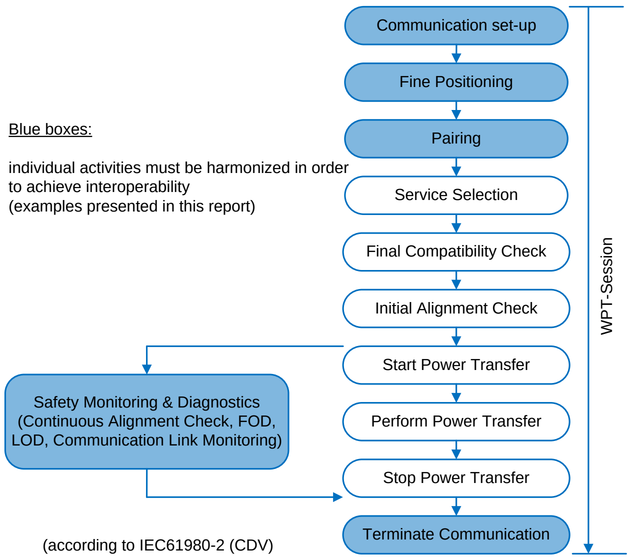


Fig. 13: individual activities for a WPT charging session

4.3 Vehicle positioning assistance and Pairing

A vehicle positioning assistance mean shall continuously provide alignment information to the vehicle/ the driver while approaching the wayside coil. Vehicle positioning shall ensure that the vehicle is finally positioned over the wayside coil within a coil alignment tolerance area around the pair of coils specific center alignment point. For pairs of reference coils the center alignment point is specified e.g. IEC- and ISO-standards.

Several fine positioning methods are implemented in the standards. The methods range from "Manual" (e.g. by visually detecting of specified marking or other characteristics with an automatic parking system, cameras or physical blocks), over low frequency RF signal, emitted by the EV, low frequency RF signal, emitted by the infrastructure/ wayside coil, LPE (see further below) up to proprietary methods.

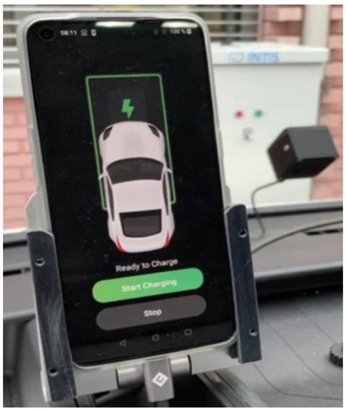


Fig. 14: HMI for fine positioning support using LPE (INTIS)

The methods require data exchange, Data exchange messages and parameters are described in relevant standards, e.g. ISO 15118. Installations at infrastructure- and vehicle side shall be interoperable, if they accommodate one or more of the above described methods and the corresponding data exchange requirements.

4.4 Living Object Protection and Foreign Object Detection

The execution of a Hazard Analysis and Risk Assessment (HARA) is essential for wireless power transfer systems in order to identify potential hazards and to categorize them according to their severity, probability, and controllability.

Living Object Protection (LOP):

Living objects shall not be exposed to hazardous electromagnetic fields above the limits from applicable EMF guidelines (e.g. ICNIRP) and cardiac implantable electronic devices (CIED) shall not malfunction due to the operation of a wireless power transfer system.

The standards for wireless power transfer systems distinguish between different physical regions around and/ or inside a vehicle. The highest electromagnetic field levels are expected near to the two power transfer coils underneath the vehicle. In order to prevent exposures exceeding the limits from EMF guidelines the system manufacturer is requested to implement active or passive access control, to implement a technical mean for the protection of living objects in that region, leading to a shut-down prior to living object ingress or shall make sure that applicable EMF limits are not exceeded in the region.

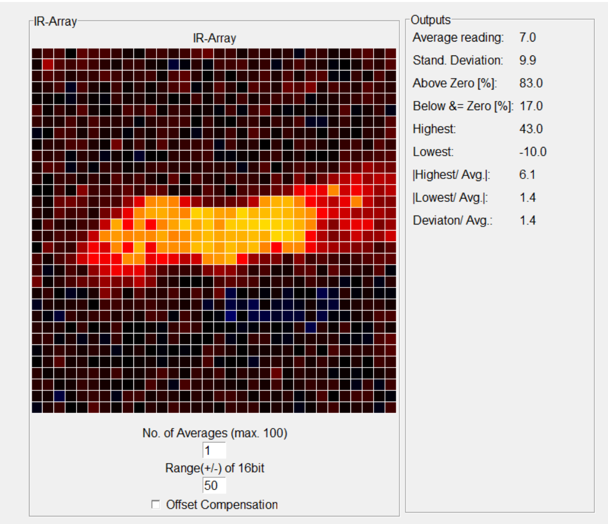


Fig. 15: LOD observation in airgap between WPT-coils (32 x 32 infrared array image, INTIS)

In other regions (around the vehicles periphery and inside the vehicle) applicable EMF limits shall never be exceeded. Relevant standards do not demand one or more specific methods for the detection/ protection of living objects. However testing criteria for the validation of living object detection systems are incorporated in these standards.

Detection of Foreign Objects:

Touch or fire hazards from heating of foreign objects are to be avoided when operating wireless power transfer systems. Appropriate technical means or specific operational procedures are described in applicable standards and must be implemented accordingly, if foreign objects risk the exceedance of temperature limits during power transfer or for more than 10 seconds after power transfer has finished. Standards define temperature limits for different materials. Furthermore test objects and different test methods for touch and fire hazard prevention are defined herein.

Specific methods for foreign object detection are not defined in the standards. The manufacturer may chose a method, where the power density is low enough to not cause test objects to exceed temperature limits or implements a technical mean, which suspends power transfer until a foreign object has been removed or properly reduces the power transfer level in case of foreign object detection. In any case the manufacturer has to prove fitness of purpose of the chosen method with the defined test objects and according to the testing procedures for touch and fire hazard prevention.

Safety Monitoring and Diagnostics:

The protection of living objects and the detection of foreign objects are to be accompanied by safety monitoring and diagnostics. A system for safety monitoring and diagnostics must include communication link monitoring, continuous system anomaly monitoring and failure condition reporting. Safety Monitoring and Diagnostics is to be activated during the preparation of the power transfer and shall not be stopped prior to the end of the power transfer. In accordance to standards (e.g. ISO15118 or IEC 61980-2), data exchange parameters and messages in conjunction with the protection of living objects and the detection of foreign objects have to be incorporated in the diagnostics during power transfer.

4.5 Wireless Communication

Interoperability of WPT also includes the communication issues between the vehicle side and the wayside system. Communication requirements, messages and parameters are defined in the standards (e.g. ISO15118 or IEC61980-2). For static charging applications with up to 22kW charging power WLAN has been chosen for wireless data exchange between vehicles and the wayside components. Point-to-point signaling (P2PS) by means of low frequency technology is optionally permissible, especially for the accommodation of Fine Positioning and Pairing. P2PS implementations do not foresee any signal modulation and therefore data exchange is not possible via P2PS.Interoperability and safety requirements for high power wireless power transfer systems (HWPT) and for dynamic wireless power transfer systems(DWPT)are currently being developed, including all relevant matters for wireless communication/ data exchange between the vehicles and the wayside components. WLAN technology may also be used for future HWPT-systems, while 5G technology is a candidate for future DWPT-wireless communication.

5. CONCLUSION

The proposal of interoperability on the base of the transmitted and the reflected magnetic flux offers a wide range of design aspects of WPT coil systems. The primary coil system can be designed as a high voltage system or as a high current system (5,6). Any compensation topology can be used and the impedance values do not have to be standardized. As a consequence a maximum of freedom is possible following physical and economically aspects at the stage of designing a new WPT system. With regard to the improving demand of electric driven vehicles in the near future and the progressive development of materials, electronic components and technical solutions (7) it is important to keep the standardization requirements with wide freedom for the development of new WPT systems.

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