Publishable Summary for 16ENG08 MICEV
Metrology for inductive charging of electric vehicles

Overview

Inductive charging is a wireless charging technology that will be used with electric vehicles (EVs) in the near future. This offers many advantages over traditionally fuelled and other currently available EVs, such as charging whilst in motion, smaller batteries, high autonomy, and high-efficiency power transmission, all leading to the reduction of carbon dioxide (CO_2) and fossil fuel consumption. This project aims to advance inductive power transfer (IPT) for the charging of EVs by developing metrology techniques for measuring IPT efficiency as well as ensuring reliable demonstration of compliance with existing safety standards for human exposure.

Need

Air pollution is one of the major environmental concerns in the urban environment. Advancements in IPT can facilitate and hasten the growth of the EV industry directly benefiting the environment in terms of reducing CO_2 emissions and other pollution. However, IPT is a novel technology and, to a certain extent under development. Investing in this sector means to keep Europe at the forefront of associated research and industry.

IPT requires, among other things, accurate models and measurements that will clearly point out how electromagnetic emissions are compatible with any human exposure and also how one will be able to correctly bill the energy transferred on board EVs. Accurate measurement of electrical and magnetic quantities involved in IPT technology represents a challenge. In fact, the signal amplitudes are often as large as those of the energy distribution systems, while the frequency bandwidth involved is much wider. Since this technology is largely still under development, the corresponding required measurement capabilities have not been realised yet and given the types of application in question these traceable measurements are needed before the industry can develop further. By way of example, the waveform characteristics of the electric quantities that supply the EV inductive charging systems are quite specific and require dedicated measurement techniques. Such techniques have to include an adequate calibration of the transducers, especially as regards dynamic charging, where the supply of power to the vehicle involves a transient regime.

It is clear that reliable, accurate, traceable electric power, efficiency and magnetic field (MF) measurements are needed for IPT applications, specifically for manufacturers of electric vehicles or hybrid electric vehicles (not only in the automotive sector), their suppliers, certification bodies and electric companies, as they are subject to strict international requirements with respect to accuracy, safety and, in a near future, energy billing.

Objectives

In this project, high-accuracy calibration facilities will be developed to ensure traceability of electric and magnetic measurements with sufficient accuracy for the demands of EV industry. The specific objectives of the project are:

1. To develop and characterise a power measurement unit for static wireless power transfer for on-board measurement with a relative uncertainty in the direct current (DC) circuit of 10^{-3}, the frequencies of the alternating current (AC) transmission being up to 100 kHz – 150 kHz and powers up to 200 kW.
2. To develop methods to determine the efficiency of a static wireless power transfer system with a relative uncertainty of 10^{-3} and taking the relevant parameters, particularly airgap and misalignment between the coupled coils into account.
3. To define the requirements for a power measurement unit for dynamic wireless power transfer, identify the relevant parameters (e.g. traffic conditions, speed, vehicle dimensions, power converter state, coil configurations) and estimate their effect on the measurement of the power transferred to the vehicle and on the system efficiency.

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4. To set up a system for traceable calibration of magnetic field meters and gradiometers for 10 kHz to 150 kHz and up to 100 μT and field gradients up to 100 μT/m with both sinusoidal and non-sinusoidal waveforms. The target expanded uncertainty for the system is 5 %. To develop measurement protocols for the assessment of the human exposure to the electromagnetic fields generated by these technologies, in static and dynamic conditions, taking the compliance with the limits indicated by the guidelines of the International Commission on Nonionizing Radiation Protection into account.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain and end users and to provide metrology input and pre-normative research to the evolution of relevant international standards.

Progress beyond the state of the art

Static Inductive Power transfer. A power standard suitable for measuring electrical powers up to 200 kW, having the characteristics of the power transmitted to EV batteries, is not currently available in Europe. In the case of DC current affected by AC power ripple and harmonics up to 150 kHz, such a power standard will serve as a basis for measuring active and reactive power in IPT systems with high accuracy (maximum uncertainty of 10^{-3} relative). One output of this project is to build a facility, allowing manufacturers of sensors and power measurement technology to also have their instruments calibrated in this frequency range. The behaviour and efficiency of the IPT system will be preliminary estimated through a new model-based approach for the calculation of losses, especially in converters, which is based on the convergence of different modelling approaches validated by measurements.

Dynamic Inductive Power transfer. In dynamic inductive charging no standards have been established and currently it is arduous to define a clear picture of the characteristics of the electrical parameters to be measured. The project aims to cover this gap. A modelling study has metrological relevance in that it may provide elements for the extension of the results of this project in the near future, for the realisation of a low uncertainty (10^{-3} relative) measurement systems in dynamic IPT (DIPT) stations.

Magnetic field exposure. Little information is publically available reporting results for the assessment of electric vehicle IPT systems from either modelling or measurements. Whilst manufacturers have modelled their electric vehicle designs, these contain proprietary information and are not publically available for the development of standards for safety assessment. This project will go beyond this state-of-the art by providing the required traceability for magnetic field sensors and gradiometers for sine wave and distorted waveforms. The project will also provide validated and comprehensive computer simulations and measurements of human exposure to EV IPT systems, and defined test protocols for field surveys and computational dosimetry for EV IPT systems (static and dynamic) that will form the basis of future standards for IPT stations.

Results

The MICEV consortium is currently developing a range of new measurement capabilities at National Metrological Institutes (NMIs) of direct relevance to manufacturers of current, voltage and magnetic field sensors for electric automotive and similar (forklifts, industrial automated electric vehicles) applications. In particular, a calibration facility for electrical quantities (voltage, current and power) is under construction, while a laboratory facility for the calibration of magnetic field meters and gradiometers is currently being designed for the frequency range between 10 kHz and 150 kHz. At the project end, facilities will be accessible to certification bodies, users and manufacturers of transducers.

Objective 1

A calibration facility for electrical signal transducers (current and voltage) used in AC and DC measurements in IPT systems has been designed and is currently being realised at PTB with the contribution of the consortium partners. The system is designed to generate real waveforms, recorded at charging stations. The laboratory facility is structured as a phantom power, with two independent circuits for current and voltage, and it operates with DC plus AC signals up to 150 kHz, simulating electric power up to 200 kW. The target relative uncertainty of the system is 10^{-3}.

The real waveforms reported in the literature for the charging stations are taken into account in the design and a first set of waveforms has been measured from a charging station powered at 85 kHz (resonant frequency). The two circuits for the generation of DC with an AC ripple (current and voltage) are being currently implemented. In particular, a first configuration of voltage chain for the phantom power, including a high frequency voltage injector, has been designed and realised. The voltage chain also includes a voltage calibrator providing the DC voltage and a power amplifier able to produce voltage “ripple” up to 150 kHz, overlapped to DC voltage, having amplitude up to 300 $V_{pk\text{-}pk}$. A self-calibration procedure for the voltage chain has been carried out, able to compensate the phase shift introduced by the amplifier and by the injector. The tuning of the voltage chain is nearly completed and the results will be presented in July 2018, at CPEM Conference in Paris.

A measurement unit archetype (PwMU) with relaxed accuracy has been designed and is currently under development for measurement on real charging stations. It will be characterised in the calibration facility aforementioned. The main components of the Power Measurement Unit (PwMU) were chosen, after a deep investigation of the technical requirements for wireless transmission of energy and based on commercial current transducers, voltage sensors and wideband power analysers made available by partners. The latter were calibrated at partners' laboratories. Besides, the control software is being developed to complete the PwMU.

The PwMU will be able to perform a number of efficiency measurements that will be carried out on real systems in order to provide an overall picture of the efficiency measurements, the uncertainty evaluation and the comparative (benchmarking) analysis between existing IPT systems. This last activity will also provide a precise reference on the state of the art, leading to clear protocols for the efficiency assessment.

Objective 2

A modelling tool (simulator) is being developed in order to support the prediction of the IPT system efficiency performance in any operating condition, and to quantify the impact of a device's circuit topology, harmonics, and physical and geometrical parameters (airgap, misalignment) on the measurement system.

An electromagnetic numerical model of a charging system has been created, which includes the transmitter-receiver coils and the shielding structures like aluminium and ferrite concentrator blocks.. Then, it has been implemented and validated. The model has been used to retrieve the equivalent circuit parameters needed for the system-level simulations. The self and mutual inductances have been evaluated, taking into account some significant variations of the geometrical and physical parameters of the system. Specifically, the behaviour of such inductances has been studied letting the following parameters vary: i) chassis conductivity; ii) vertical distance between receiver and transmitting coils; iii) misalignment of coils along an axis in the coil plane; iv) reciprocal rotation of the coils around the vertical axis. These results are processed in view of building the behavioural models of the converters.
Also, a circuital simulation model of a real IPT system has been built, based on information collected on the transmitter inverter, the coils and the receiver rectifier of the IPT system. The results of simulation models have been compared with results of experimental measurements, under different steady-state load conditions. The comparison has led to the validation of the simulation models and has highlighted directions for further investigations. Based on the information collected on the semiconductor modules, a system-level behavioral model of the inverter has been developed, tailored for fast simulations in dynamic conditions, based on a genetic programming approach. The results will be presented at SMACD2018 conference, to be held in Prague, CZ, in July 2018.

Objective 3

Numerical and experimental analysis will be carried out to gain a greater understanding of the measurement problems related to IPT and DIPT. In particular, the loss of power in semiconductor devices used in conversion systems and their dependence on the operating conditions will be assessed, in order to map and predict the distribution of losses among the transmitter and the receiver sections.

The PwMU will be utilised to collect experimental data useful in assessing the measurement uncertainty and to determine the requirements of future measurement systems for DIPT. A modelling approach will be applied to the investigation of the effects of different traffic conditions and car misalignments on the performances of the PwMU in the dynamic IPT.

Objective 4

The project team will perform extensive computer simulations involving numerous scenarios of static and dynamic vehicle IPT structures for different systems, concerning electric quantities behaviour and towards the exposure of the vehicle passengers and bystanders.

The consortium has compared the results and performances of different numerical codes applied to a benchmark problem, consisting of a realistic IPT system (including a conductive shield and a ferrite flux concentrator), with axisymmetric geometry resulting in a more than satisfactory agreement. The comparison has been extended to 4 canonical problems, obtained from a unique configuration considering two different operating conditions and two different frequencies. The dosimetric analysis (induced electric field within an anatomical human model) has been applied to a bystander exposed to the stray magnetic field produced when the receiving coil is open or operating. A first preliminary comparison of dosimetric results from different partners provided satisfactory results.

Two simplified generic vehicle bodies have been developed and set up for the purpose of assessing exposure of the vehicle passengers to magnetic fields. In order to assess human exposure near inductive power transfer systems, adequate modeling methodologies have to be developed. The level of exposure is highly dependent on various parameters: shape of coils, geometrical characteristics of the system, materials properties, possible misalignment between transmitter and receiver, and the position of the human body. In this case, the introduction of stochastic tools allows dealing with the variability of all the parameters describing the electromagnetic problem. A first comparison between different stochastic methods in a simplified configuration was performed when investigating the compliance of IPT systems with international standards regarding the human exposure. Non-intrusive methods have been combined with a 3D finite element method to build surrogate models and manage the uncertainties of the several different parameters (affecting geometry or materials). Some results of this activity will be presented at the Conference on Electromagnetic Field Computation (CEFC), in Hangzhou, China, in October 2018.

Measurement and simulation surveys will allow the definition of measurement protocols for the assessment of the human exposure to the electromagnetic fields in IPT and DIPT systems.

Moreover, a facility for traceable calibration of magnetic field meters and gradiometers for 10 kHz – 150 kHz and up to 100 μT and field gradients up to 100 μT/m with both sinusoidal and non-sinusoidal waveforms will be developed. The target expanded uncertainty for the system is 5 %. Companies and laboratories will have access to this facility.

A calibration procedure and a gradient verification for high intensity magnetic field probes working in the frequency range of interest has been proposed.

Impact

Impact on industrial and other user communities

The project will develop new measurement capabilities at NMIs of direct relevance to accredited laboratories, manufacturers of magnetic field meters and manufacturers of electric current, voltage and power meters. Manufacturers of electric vehicles and their component suppliers, manufacturers of forklift and automatic vehicles in the industrial environment will also be interested in the project achievements.

In particular, specific calibration facilities will be created for the transducers used in IPT systems, able to take into account the actual waveforms registered in applications. Laboratories, users and manufacturers of transducers will have access to these facilities.

A specific calibration facility will be created for the measurement of power and frequency levels required by these applications (ripple up to 150 kHz, uncertainty of the reference power standard of the order of 10^{-3} relative) with associated new measurement capabilities accessible to companies and laboratories, especially manufacturers of electric current, voltage and power meters and electric companies interested in IPT.

A system for traceable calibration of MF meters and gradiometers up to 100 μT and field gradients up to 100 μT/m (for 10 kHz – 150 kHz, with both sinusoidal and non-sinusoidal waveforms) will be developed. Accredited laboratories, manufacturers of magnetic field meters will have access to this facility.

The project will produce specific theoretical investigations and measurements on power losses in the IPT chain. Future payment systems in public charging systems and stations will take advantage from this research data making it clear what the consumer pays for, the transmitted or received energy.

The measurement supply chain (accredited laboratories) and end users (e.g., industry, electrical service providers, instrumentation companies, certification bodies) will realise the uptake of the developed measurement infrastructure. An advisory group (Stakeholder Committee) has been established consisting of ten industrial stakeholders including instrument manufacturers, automotive engineering companies, a local transport company, an electric company and some SME's. Two car companies participate also in the project as stakeholders. The Committee met at the beginning of April 2018. Stakeholders exchange information with the consortium and ensure that the project is delivering relevant information for end users. The Stakeholder Committee will interact with the project partners through a new project website that is currently being created. Knowledge will also be disseminated to end users through a dedicated training course. A stakeholder workshop will be organised at the end of the project.

Impact on metrology and other scientific communities

A phantom power standard will be realised in this project, achieved by the cooperation of the metrology institutes participating in this consortium, for DC currents affected by harmonics determining AC power up to 150 kHz. This power standard will serve as a basis for the measurement of active and reactive power in IPT systems. The metrology institutes involved will be able to expand their measurement capability claims in this power and frequency range by tracing them to this standard.

This consortium will develop a new calibration system for the traceable calibration of magnetic field meters and gradiometers. This system, located at NPL, will increase the European calibration capabilities from 25 µT to 100 µT at 100 kHz, extending the range up to 150 kHz. In addition, a low frequency field gradients calibration system will be achieved up to 100 µT/m with both sinusoidal and non-sinusoidal waveforms.

A measurement unit archetype will be set up and characterised, and a benchmarking exercise will be carried out by comparison to the measurement systems previously developed. Specific measurement guidelines, taking into account conversion losses and input for new standard, will be drawn up, including a specific study on dynamic IPT, enabling NMIs or calibration laboratories to extend their services in the near future.

The consortium will present the project's results at conferences and in scientific journals.

Impact on relevant standards

The European Commission (EC) submitted the following Standardisation requests: "M/468 Standardisation Mandate addressed to CEN and CENELEC and ETSI concerning the charging of electric vehicles", and "M/533 Standardisation Request addressed to the European Standardisation Organisations, to draft European standards for alternative fuels infrastructure". This project will support this standardisation effort by the participation in seven working groups at DKE, EURAMET, IEA, IEC and ISO level.

The project will develop an example measurement system and a benchmarking activity, both valuable to produce data for contributing to guidelines and standards. A relaxed accuracy measurement unit archetype (PwMU), conceived for power, efficiency and magnetic field measurement on real plants will be set up and characterised.

Longer-term economic, social and environmental impacts

The global sales of IPT charging units for electric vehicles is estimated to be ~352,000, by 2020, with an estimated value of $1.4 billion, with production mainly in Europe and America. This project will help maintain Europe's world-leading position in research and production of inductive systems for electric vehicles.

The EU is committed to reducing greenhouse gas emissions by 2050 to a level which is 80–95 % below the 1990 levels. In the 2050 Energy Roadmap a key goal amongst others will include "no more conventionally-fuelled cars in cities". Actions aimed at increasing the use of electric transport will directly contribute to these objectives. In this context, this project is certainly centred in EU political strategies concerning transports.

In the future, payment systems will be widely spread in inductive public charging systems and stations. It must then be exactly clear what the consumer pays for, the transmitted or received energy. Successful completion of the objectives proposed here will facilitate the implementation of wireless charging for electric vehicles on public roads and highways providing public assurance on the safety and the cost of using inductive charging technologies.

Project start date and duration:	1st September 2017, duration 36 months	
Coordinator: Mauro Zucca, PhD Researcher - Istituto Nazionale di Ricerca Metrologica (INRIM), Tel: +390113919827 E-mail: m.zucca@inrim.it Project website address: https://www.inrim.eu/research-development/quality-life/metrology-energy-and-environment/micev-16eng08		
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