Study of Electric Field Emissions in Wireless Energy Transfer

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Abstract. The thesis focuses on the study of the electrical component of the electromagnetic field, radiated by the wireless energy transfer system into the adjacent environment. The wireless energy transfer and the wireless data transfer are studied simultaneously, focusing on the appropriate wireless communication channel between the transmitter and the receiver, so to make that channel improved. An implementation of a wireless energy transfer experimental prototype that operates simultaneously with a wireless data transmission is assembled. A computational application that allows tuning the operational frequency of the prototype to correspond to the resonant mode operation is developed.

Keywords: Wireless energy transfer · Wireless data transmission · Electromagnetic field · Electromagnetic interference

1 Introduction

The rational use of energy is associated with energy efficiency, which can be defined as the possibility of improving energy consumption, namely in the electricity and transport sectors, respectively. A mental and social shift towards energy consumption is urgently needed to mitigate the dependence on fossil fuels and to reduce greenhouse gas (GHG) emissions into the atmosphere. One way to mitigate the dependence on fossil fuels and GNG emissions in the transport sector is to promote further research into the development of electric vehicles (EV) and hybrids. EV/hybrids have advantages over internal combustion vehicles, namely, energy efficiency, mitigation of GHG emissions into the atmosphere, significantly lower maintenance costs. Thus, EV/hybrids can be considered as a measure of GHG emission mitigation and external dependence on primary energy [1–3].

However, there are still significant limitations on the use of EVs (land and air), particularly regarding batteries. The main disadvantages are the high price and reduced battery life. One way to overcome the disadvantage of battery life is to study new charging systems, namely using wireless energy transfer (WET) systems [1–3].

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1.1 Wireless Energy Transfer

There are two different WET methods, defined by physical phenomena of the electromagnetic (EM) fields' propagation: near field and far field. Between the main methods of near field, the inductive coupling, the capacitive coupling and the magnetic resonance coupling can be identified [3–9]. Far field methods, namely microwave and laser energy transfer with directional antennas could be used over long distances in space, in military industry or industrial applications [3–9].

1.2 Research Questions

The magnetic resonant coupling method presented by MIT team is recognized as the most suitable to achieve highly efficient wireless energy transfer for EV battery charging [8–13]. An important step is to combine power transfer with data transmission. Data transmission, such as vehicle identification, frequency, power values, user data are some examples of the required information.

Communication between Tx and Rx is important, especially when high intensity EM fields produced be WET system may have undesirable influence on the data channel. The strong EM fields produced by the WET system can not only negatively influence other adjacent electrical and electronic equipment, but also interact with living beings in the immediate vicinity of the EV while charging the battery with potentially harmful effects. The World Health Organization recommends that electrical/electronic devices must comply with the safety limits of human exposure to EM radiation. Safety limits are set primarily by the ICNIRP [14, 15] and the IEEE [16].

Considering the described aspects, the main research question chosen for this work is as follows:

Q1. How can be evaluated the impact of the high intensity EM field produced by the WET system on living beings and the communication channel between Tx and Rx?

The hypothesis proposed to solve this research question is as follows:

H1. In order to answer Q1 it is important to evaluate the values of the EM fields produced by the WET systems and to make a comparison with the safety limits set by the recognized international organizations. It is important to use computational simulations for exploring of EM field distribution and for comparing with the experimental results.

The proposed additional research questions are:

Q1a. Does the EM field produced by the WET system comply with established safety standards and secure?

Q1b. Can EM fields from the WET system influence or disturb the communication channel?

In order to find answers to research questions Q1a and Q1b the following steps should be taken into consideration:

- Measuring the intensity of the EM field produced by the WET system and comparing the results with the safety levels established by international organizations;
- Conducting Tx-Rx communications performance testing on the WET system to assess the impact of EM field emissions on the wireless data transfer channel.

The second research question chosen for this thesis is as follows:

Q2. How can the mode of operation of the WET system for the resonance regime be tuned?

H2. In order to respond to Q2, it is necessary to implement the communication channel between Tx and Rx and to develop a computational application that allows coordinating the WET process and tuning the system operation mode to the resonance regime.

1.3 Approach

Since most studies are dedicated to the simulation and measurement of the magnetic field produced by the WET system, and there is a gap regarding the study of the electric field. Thus, it was decided in this thesis to investigate the electrical component of the EM field produced by the WET system.

In the simultaneous WET and wireless data transmission (WDT), to increase the efficiency of the WET process, it is necessary to quickly and securely exchange data between Tx and Rx. Thus, to increase the efficiency of the WET, a system is proposed not only for energy transfer, but also for WDT between Tx and Rx. The possibility of data transmission in a WET system provides interaction between Tx and Rx, facilitating the task of device detection and identification, and coordinating the battery charging process.

In the proposed WET system, a communication between Tx and Rx is implemented using microcontrollers (MCs). The use of MCs allows real time WDT and tuning the system operation mode to the resonance regime. The operation of the WET system in the resonance regime increases the system performance due to the communication capacity between Tx and Rx.

Wireless Data Transmission

Wireless communications have demonstrated potential in industrial and commercial applications, more precisely in the acquisition of data that can be collected and transferred for coordination and monitoring of technological processes.

The communication between Tx and Rx is indispensable for the coordination of energy transfer, so it is necessary to define a communication protocol between the MCs. In order to define proper Tx-Rx communication, it is necessary to analyze and compare the available wireless communication protocols, which can be linked to WET systems for battery charging and information exchange between Tx and Rx.

The EM field radiated by the Tx and Rx coils is the fundamental property of the WET system based on magnetic resonant coupling [17].

Studies show that EM fields are harmful and can have adverse effects on the human body [18, 19]. Although some works in the literature state that WET is safe for living beings [8], it is impossible to predict the impact of such exposure on human health over time. Electromagnetic compatibility (EMC) issues of WET systems are related to research and analysis of EM processes in the human body exposed to EM energy from them. Thus, measuring the intensity of the EM field produced by the WET system and comparing the results with the safety levels established by international organizations is important for assessing the impact of the field.

Data transmission between Tx and Rx via a communication channel is intended to coordinate the energy transfer process in the WET system. However, the high intensity EM field of the order of a few kW to the tens of kW of a WET system may have an undesirable influence on the communication channel that operates at tens of mW. In this case the transferred data may be influenced by transmitting erroneous information.

Thus, the performance of the communication channel between Tx and Rx exposed to the EM field produced by the WET system should be properly evaluated.

2 Technological Innovation for Life Improvement (TILI)

The TILI is a fundamental driver of economic and human progress [20]. The modern level of society development, success in the study and modeling of various technologies, processes and systems, allow developing revolutionary technologies in all areas of human activity, including medicine, education, agricultural industry, environment, transportation and communication systems. Technological innovation not only generates significant economic, environmental and social benefits, which contributes to the improvement of life, but also aids social advancement in all areas of human activity [21].

This WET technology could improve design and make products smarter, smaller and more effective, functionally and economically, improving human life. The WET systems with simultaneous data transmission are an example of the technological innovation as intelligent structure capable to optimize and integrate corresponding systems, to improve performance and service and to reduce resource consumption. The "smart" WET systems have a great potential and capability to completely transform the way devices and equipment are powered, what remarkably improves quality of life.

3 State of the Art

3.1 Magnetic Resonant Coupling

In the last decade, progress has been made in the area of WET using magnetic resonant coupling to increase system performance [8–10, 22]. Technological advances make magnetic resonant coupling WET very attractive for EV battery charging applications in either stationary or dynamic charging scenarios.

In the available literature research directions, approaches, and techniques are proposed including system architectures [10, 22–24], frequency splitting [10, 22, 25], adaptation impedance matching [10, 13, 26], frequency tuning models for the resonance regime [11, 25, 27], practical applications [9, 26].

3.2 Wireless Energy Transfer - Frequency Tuning

A key issue in WET systems is to maximize energy transfer efficiency [11, 25, 28]. The system configuration of the WET prototype studied in [11] is presented in Fig. 1.

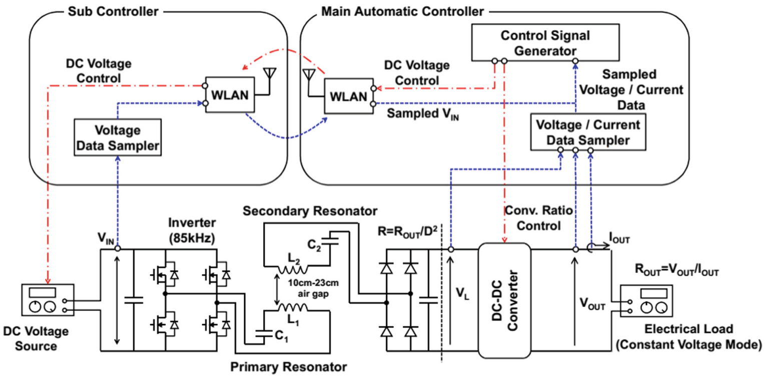


Fig. 1. System configuration of the WET prototype [11].

In [29] is proposed a frequency automatic tuning of the system in response to misalignments of Tx and Rx coils without using communication channel.

3.3 Wireless Energy Transfer and WDT

Different methods have been proposed in the literature for the simultaneous transfer of energy and data transmission in the WET systems, in order to increase efficiency and reliability.

In WET systems simultaneously with data transmission, the tuned resonant circuits can be used in a single operating frequency. In order to transmit the data simultaneously with the transfer of energy in these systems, the modulation of the signal sent by the Tx can be used. Thus, the carrier frequency has one of its parameters, namely amplitude, phase or frequency, modified according to the information to be transmitted. In [30–33] the WET systems running simultaneously with data transmission systems are studied, using different techniques of modulation of the transmitted signal, with the use of a single pair of Tx and Rx coils. In [30] the WET system is described. In [33] the data signal is binary phase-shift keying modulated with a carrier frequency.

However, the application of the modulation method in the WET systems reduces the energy transfer efficiency since the modulation operation of the signal decreases the average power of the modulated signal.

The WET and WDT system using two sets of coils is shown in [34, 35]. The geometry of data coils reduces the mutual coupling. Thus, the voltage induced in the data coils by the electromagnetic field of WET system can be reduced. The data transmission rate and power transfer efficiency are limited. In addition, the interaction between the power and data coil is complicated and cannot be completely eliminated [35].

The use of higher frequencies allows a higher data rate [36] and reduces the noise introduced by the WET on the data channel. In [36, 37] are proposed WET systems with data channel operating at 2.4 GHz. Thus, the energy and data can be transferred independently without affecting each other. The drawback of such systems is the complex paring between the Tx and Rx sides.

3.4 EM Emissions from WET Systems

Considering the limited number of studies in the available literature on the simultaneous operation of energy transfer and data transmission systems, the need for research in this area is even more evident [17].

In [14] it is mentioned that ICNIRP investigates and regulates procedures in the area of protection against non-ionizing radiation.

In [6] are presented techniques for reducing the EM fields generated by the underground cables and the EV itself. By applying a shield consisting of a metal plate mounted at the bottom of the EV and connected by a kind of brushes with the horizontal and vertical ground shields, the value of the EM field was significantly reduced. The results of the simulation and measurement of the radiated EM field values for EVs currently in service were also presented.

The EMC issues of the WET system increase the need for a detailed analysis of EM processes in the human body and other living beings exposed to radiated electromagnetic energy.

In [38] is presented the FEM modeling methodology and the simulation used in WET system.

4 Radiation Safety Limits for WET Systems

It is important to underline that the standardization of WET systems, equipment, components is relatively new. In recent years in all international and regional organizations related to WET systems, the WET systems regulatory regime is under development. As regards recommendations for exposure to EM fields in general, as the standard the ICNIRP 1998 recommendations [14], updated in 2010 [15], are globally recognized. In this thesis to evaluate exposure to EM fields irradiated by the TESC system, the ICNIRP recommendations [14, 15] were adopted.

The electric field exposure limits by ICNIRP [4, 15, 39] is shown in Fig. 2.

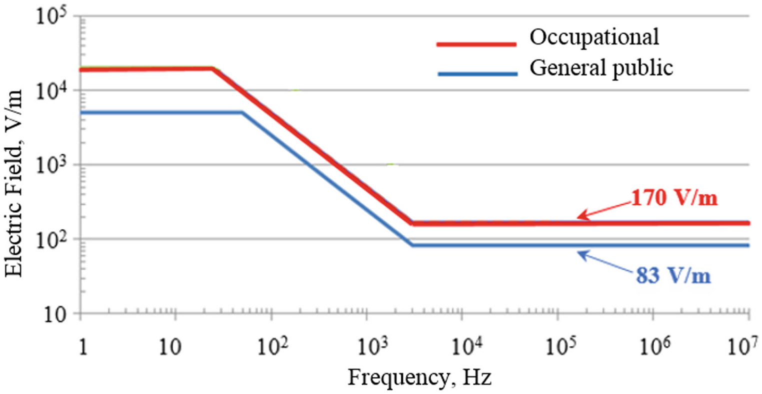


Fig. 2. Electric field exposure limits by ICNIRP [15]

5 Prototype Modeling and Implementation

The WET system with capacitor compensation in series with the coils is shown in Fig. 3(a), (b) and is used in Case Study_1, Case Study_2 and in the developed experimental prototype.

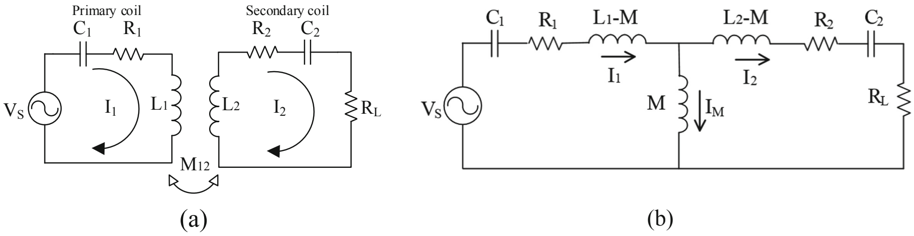


Fig. 3. (a) Configuration; (b) Circuit of the WET prototype

The WET equivalent circuit [12, 40] is shown in Fig. 3(b).

The topology of prototype and Tx and Rx circuit parameters was shown already by the authors in [12, 40] and is shown in Fig. 4 and is in Fig. 5.

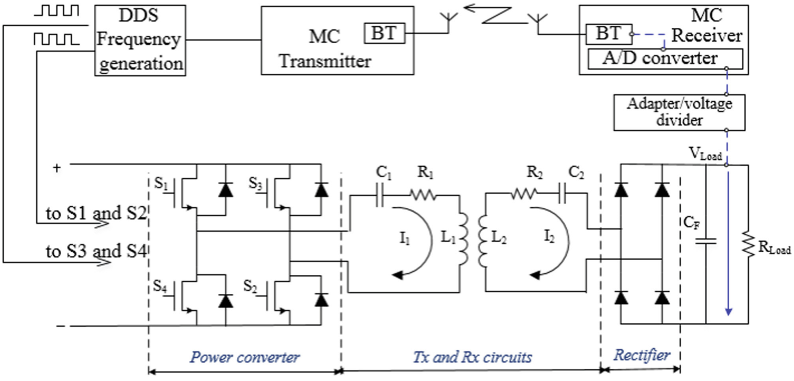


Fig. 4. Topology of the implemented prototype

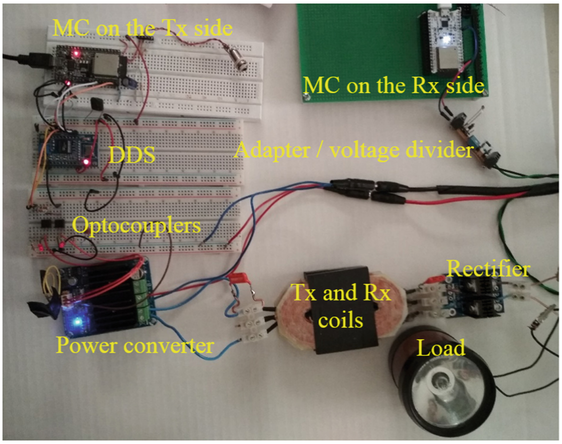


Fig. 5. WET prototype

The process of tuning operating frequency f_{curr} to resonant frequency f_{res} is organized according to flowchart shown in Fig. 6.

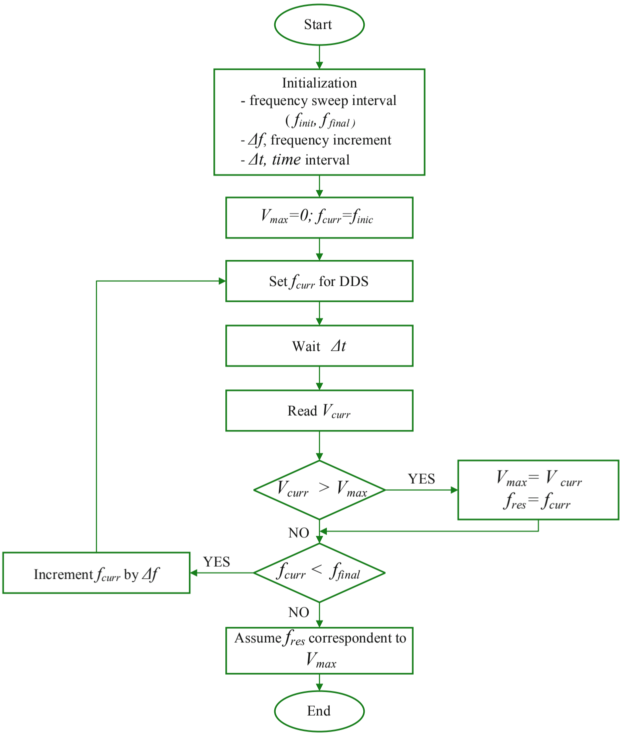


Fig. 6. Flowchart of the frequency tuning process.

A video showing the tuning to the resonant frequency reported in this paper can be found in https://www.youtube.com/watch?v=KAsASXtZrt0.

6 Experimental Results

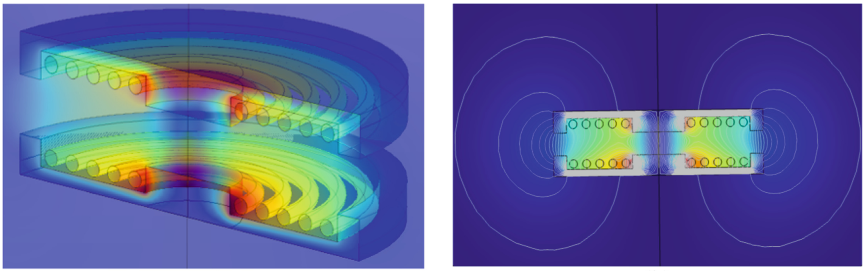
This thesis deals with the topic of simulation and measurement of electric fields irradiated by WET systems [6, 29, 44].

Simulations and measurements of the electric field are exposed in two case studies.

Case Study_1

The purpose of Case Study_1 is the simulation and measurement of electric field intensities produced by the prototype of the Technical University of Sofia.

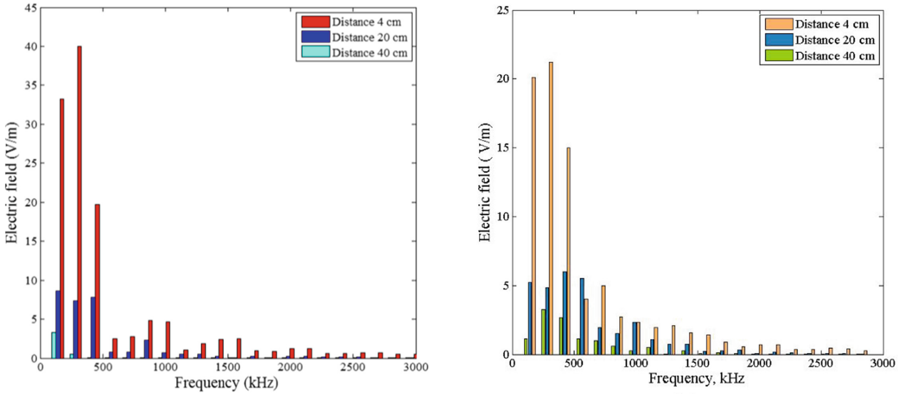
The modelling, simulation and measurements of electric field (E-field) produced by the prototype of the Case Study_1 is presented in [4, 39, 41]. In Fig. 7 are shown the 3D Model and the result of E-field simulation for Case Study_1.



(a) (b)

Fig. 7. (a) 3D model: Case Study_1; (b) Distribution of electric field lines.

The E-field harmonics generated by the WET system with Pout of 800 W (a) and 228 W (b) are shown in Fig. 8.

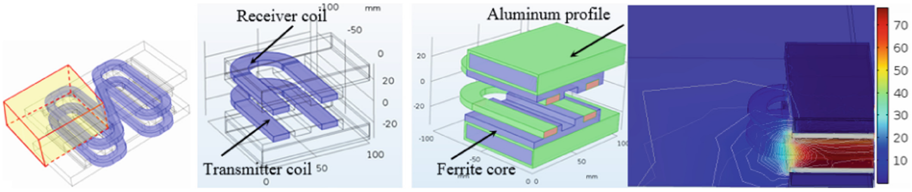


(a) (b)

Fig. 8. E-field harmonics generated by the WET system with Pout of 800 W (a) and 228 W (b).

Case Study_2

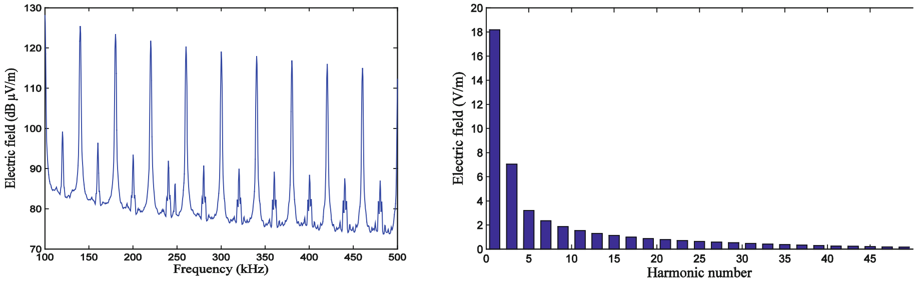
Simulation and measurement of E-field intensities produced by the prototype of Universidade Nova de Lisboa. The modelling, simulation and measurements of E-field produced by the prototype of the Case Study_2 is presented in [42, 43]. In Fig. 9 are shown the 3D Model and the result of E-field simulation (V/m) for Case Study_2.



(a) (b)

Fig. 9. (a) 3D model: Case Study_2; (b) Distribution of electric field lines.

The harmonics generated by the WET with output power value of 262 W and with air gap of 20 mm [12, 45] are shown in Fig. 10.



(a) (b)

Fig. 10. Harmonic generation from the WPT.

7 Conclusions

In this thesis the emissions of the electrical component of the EM field of the WET system in two case studies are also studied. 2D and 3D models are created and prototype modeling of Case Study_1 and Case Study_2 is performed using the finite element analysis using the Comsol Multiphysics computational application. The computational simulation of the E-field produced by the prototypes of Case Study_1 and Case Study_2 working at a frequency of 142 kHz and 20 kHz, respectively, is performed.

The performance evaluation of the developed experimental prototype revealed the tuning capacity of the implemented system for the resonance regime under the conditions of distance variation and misalignment between the coils Tx and Rx, increasing the system yield.

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