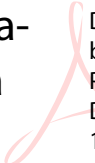


**FACULTY OF ELECTRONICS, TELECOMUNICATIONS AND
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PhD Thesis

SUMMARY

WIRELESS POWER TRANSFER SYSTEMS USING RESONANT COUPLING

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1. Introduction

A pressing issue of the current society is related to the losses that occur in the transfer and distribution of energy. As energy consumption increases, energy production increases, and with it, losses increase. Thus, the electricity transmission and distribution network must be in continuous development and refinement.

At the beginning of research and development of the electromagnetic phenomena, before the power distribution network was built, a special effort was made in the research and development of an energy transfer method without a dedicated transport environment, that is, without cables, but the result of the research did not meet the expectations. Solutions such as the use of omnidirectional antennas, which work exceptionally well in the transfer of information, are not suited to the transfer of energy because much of the energy is lost in free space. Directed electromagnetic radiation, such as the use of LASERs or unidirectional antennas, can be used to transfer wireless power even at a large distance, but requires the receiver to remain in the field of view of the transmitter, and possibly requires a complex tracking system if the receiver is mobile. The rapid development of autonomous electronic devices in recent years, such as laptops, mobile phones, robots, etc., is a good reason for resuming the study on wireless power transfer. Since today's power distribution network is supplying power almost anywhere in the world, wireless power transfer would be useful for powering autonomous electronic devices without requiring them to be wired to the grid and increase their autonomy level.

The project intends to contribute to the study and development of wireless power transmission equipment over short and medium distances. The transferred power may vary from a few watts to tens and hundreds of watts, and allow supplying power to multiple devices with varying voltage levels at different distances.

2. Importance and relevance of scientific content

The last decade has seen a significant increase in portable electronic devices. Everyday life of every person depends increasingly on such devices, whether we talk about devices used in communications such as mobile phones, tablets or laptops, be it medical devices such as hearing aids, pacemakers, etc. All of this requires a portable power supply with the possibility of recharging as quickly as possible or, if not, as convenient as possible. Wireless power transfer comes as an alternative to charging these devices without involving the end user. In other words, charging devices is not a problem unless it requires the user's attention.

Charging devices without using a physical connection also allows for complete isolation of the device from the outside environment. Construction of devices resistant to water, dust, acidic environment or sterile environment is much easier if there is no need for a physical connection of the power transfer device. The inclusion of a material between the transmitter and the receiver may have a negative effect on the power transfer. This paper also analyzes this aspect of power transfer in order to optimize the transfer for different insulating materials and also increase the efficiency of transfer by directing the magnetic field using ferromagnetic materials.

Using the finite element simulations method, it is possible to study in detail the power transfer between the transmitter and the receiver. It can also include different physical phenomena relevant to each system and allows the development of such systems in a short time and with a high efficiency. Simulations also highlight certain design and operating risks and offer the possibility of testing solutions to prevent such problems.

3. Current state

Since the construction of the first power grids, there has been a desire to remove the wires for power transmission, but technological limitations of that time have made it difficult to achieve practical transfer of wireless power. With the development of technology and significant price cuts for semiconductors, the development of wireless power transfer systems has increased. Numerous studies have been conducted regarding the quality factor of coils used in power transfer in an attempt to increase this factor Q as much as possible to improve system efficiency.

The position of the coupled coils is also critical in achieving high transfer yields, and there are studies in this direction. Methods of calculation have been proposed for determining the mutual inductance between two coils at a certain distance from each other. Also, in order to help designers, a number of approximations have been made to estimate mutual inductance and calculate a coupling factor. At the moment, a standardization of wireless power transfer systems is also underway, which is why the WPT abbreviated "Wireless Power Consortium" was set up, a body that is trying to develop an international standard for these systems.

Currently transmitted power levels are around tens of watts, generally used to charge batteries in mobile phones or tablets. However, there are studies to increase the power to hundreds of watts to charge the batteries in electric cars. The transmitter side may be positioned on the road so that the vehicles will pass over it, at which point the batteries would be recharged. By installing enough such systems, electric cars will be able to achieve theoretical infinite autonomy. Such a system is shown in Fig. 1.1.

The same system used in motor vehicles can be extended in the case of distribution robots inside factory halls or in the case of power supplying of drones. The lack of cables and physical connection between the mobile equipment and the docking system reduces both maintenance costs and design costs for an efficient physical connection.

Other studies include finite element simulations to determine the electromagnetic field generated by these coils. In case of power transfer, the inductive coupling is preferred, and the transfer takes place by magnetic field, but there are also studies for power transfer using electric field and capacitive coupling. Simulations with the finite element method were also made and some shortcomings related to the capacitive coupling in the case of wireless power transfer were identified.

Due to the significant worsening of the transfer efficiency with increasing distance between the two inductively coupled coils, it was attempted to intercalate resonant L-C circuits between the transmission and receiving circuits to increase the transmission distance. Experiments were done in published in scientific literature.

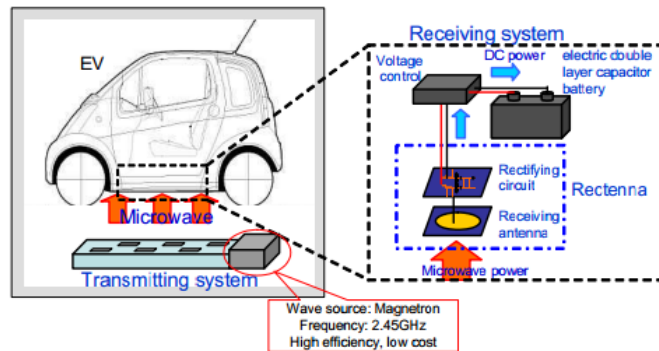


Fig. 3.1 Car charging system using wireless power transfer

There is also the power transfer using a domino resonating network. In this case, the operating frequency has been set around 500 kHz, the frequency used for switching converters. By placing the resonant coils at a small distance from one another, high coupling factors and high transfer efficiency can be achieved. Moreover, by arranging the coils, it is possible to transfer both in a straight line and in Y, curved or even a closed circle.

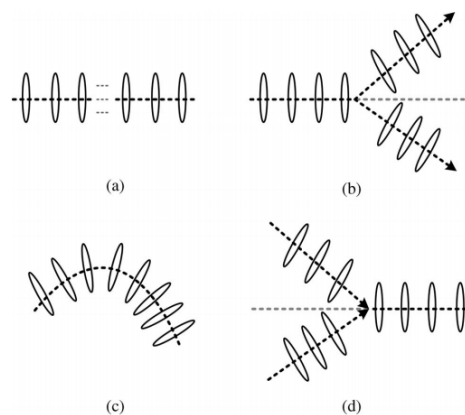


Fig. 3.2 Domino wireless power transfer network a) in straight line, b) in Y by splitting, c) in curved format, d) in Y by fusion of emission

4. The purpose of the thesis

This thesis aims at studying electrical energy transfer systems without using wires but by resonating coupling between two or more inductive elements. The study is focused on the finite element method, building a more accurate model of the transfer system for use in later design of such systems. Also, the use of finite element simulations allows a careful analysis of the electromagnetic field generated around the inductive elements to optimize power transfer and reduce induced disturbances in the rest of the circuit.

The elaboration of the thesis involves a high degree of interdisciplinary, requiring knowledge of power electronics, radio frequency and wave propagation, mathematical analysis, etc.

The main objectives of the thesis are:

- Studying the methods of transferring wireless power, focusing on the resonant coupling;
- Elaboration of calculation sheets for determining the transfer parameters in case of such systems;
- Construction of finite element simulation methods for power transfer systems with two or more inductively coupled resonant elements and at distances from one another;
- Constructing equivalent schematics based on the results obtained from the finite element simulations and simulation of these schematics in design environments dedicated to electronic circuits;
- Studying the magnetic field and the electric field generated by the resonant coils and adjusting it to reduce emissions and increase the transferred power;
- Finite element modeling of a single resonant coil and evaluation of the electric field generated by it in order to obtain plasma at atmospheric pressure.

The objectives of this PhD thesis related to documentation, analysis, design, modeling, implementation, comparative study, practical implementation and improvement of the proposed battery charging system using wireless energy transfer systems create prerequisites for technical creativity in the field of conversion and transport of electricity.

On the other hand, the experimental development of the proposed system, based on the knowledge gained through applied research, can have a significant impact on the technical progress of the manufacturing processes of such products.

The challenge of the project is to correlate existing ideas in the field with the aim of innovating and applying new methods that practically result in an original prototype that includes all the technical qualities and functional characteristics of the desired product.

5. Methodology of the thesis

The main objective of the PhD thesis is the study of the wireless power transfer systems, resonant coupling and the simulation of these systems with the finite element method in order to optimally design them. Finite element simulation is required in the analysis of several concomitant physical phenomena and the evaluation of the actual distribution system operation. Due to some limitations related to the complexity of finite element simulations, simulation programs for specific areas have been used to simulate some system elements. The simulation programs used were Comsol Multiphysics, LTSpice, PSIM, and Mathcad was used to develop the mathematical model. Comsol Multiphysics includes several modules for finite element simulation, and the main modules used were the electric field and magnetic fields, the electric circuit and the radio frequency.

Original contributions include the realization of finite element simulation methods, the results of which are confirmed by experimental tests as well as the analysis of the electromagnetic field created by these systems. Also, several simulations have been made for different systems with a variety of resonant coupled coils and different coil positions to highlight yield change and to carefully analyze the magnetic and electric field generated by the coils. The simulation results were validated through experimental measurements using prototypes.

The results were disseminated in 7 papers at international conferences and ISI indexed journals with impact factor.

6. Organization of the thesis

The thesis includes two major studies, the first part, chapters 2, 3, 4 and 5 being related to the magnetic field generated by the inductive-resonant coupled coils and Chapter 6 related to the electric field generated by a single resonant coil. Using the finite element method simulations, the magnetic and electric field distribution around the bobbin and the influence of the resonance frequency were carefully studied. If, in the case of the magnetic field, the emphasis was placed on the power transfer between two or more coils, in the case of the electric field study, the emphasis was on increasing the intensity of the field to obtain the plasma in the open air.

Chapter 2 includes a brief history of power transfer systems without using conductive wires. It is noticed that such systems are not a novelty at concept level, with different experimental devices being developed since the 1900s and enjoying a certain success. Due to technological limitations at the time, however, the use of such systems on an industrial scale was limited. As the materials used in electronics have improved, the idea of transferring power without the use of wires has reemerged in present days, and nowadays enjoys increased attention.

The chapter also presents a classification of the best known methods of wireless power transfer as well as the advantages and limitations of each method. The focus is on resonant inductive transfer, it is presented how to determine the performance of such a system, one of the parameters being yield and the other being the ratio of transfer. As will be seen, a high-yield system implies a low transfer rate, and a high-transfer rate system will have a low return.

The chapter continues with the presentation of the basic topologies for inductive resonance transfer as well as the advantages and disadvantages of each topology. The block structure of a resonant system is also presented.

Chapter 3 starts with a mathematical analysis of a resonant system for a better understanding of such a system and includes the losses that occur in such systems. If the first part of the analysis is done on any resonant system, the next step analyzes a resonant electric circuit used in the power transfer. It follows from the calculations that an important role in the transfer of power is played by the mutual inductance of the inductively coupled coils. The value of the mutual inductance depends on the physical distance between the coils and the angle between the coils.

To limit the effect of the distance between the coils on the mutual inductance, there is a possibility to include resonant circuits between the transmitter circuit and the receiver circuit, a more detailed analysis being made in the following chapters. In the case of the angle between the coils, the preferred method is to somehow direct the magnetic field generated by the emitter coil to close through the receiving coil. The first system uses a ferrite bed with three primary infiltrations and depending on the windings that are activated, the magnetic field can be directed so that the maximum intensity corresponds to the position of the receiving coil on the ferrite bed. However, for the transfer to exist, it is necessary for the receiving coil to be horizontally on the ferrite bed.

It is attempted to solve this problem by constructing a system of three primary windings positioned perpendicular to each other, the idea being to direct the electric field to the receiving coil regardless of the angle it makes with the three coils in the primary. Here comes the finite element method simulation that allows us to evaluate both the power transfer rate from primary to secondary and to visualize the magnetic field lines generated by the emitting coils and the way they are closed by the receiver coil. From the simulation, it can be seen that it is possible to transfer power between the coils regardless of the angle between the receiving coil and the emitting coils.

Chapter 4 is dedicated to investigating the mutual inductance and coupling factor between two or more coils as well as the effect of the coupling factor on the power transfer. Starting from the exact calculation of the coupling factor between two randomly positioned coils, the result is used as a reference and compared with the results obtained from the finite element method simulation. In the case of simulations two methods of coil modeling have been approached, the former considering the coil as a thin filament through which all the current flows from the coil, and the second method considers the coil as a bundle of spirals tightly connected to each other. It is found that for a theoretical approach coil shaping as a filament is preferred, but for a practical approach it is preferable to model the coil as bundles of turns. Having small errors between the simulated model and the calculated results, we can consider the simulation model as approaching quite a lot to the real case, and we can proceed to the simulation of square-shaped coils. The simulation can be extended for coils with different geometric shapes and the determination of the coupling factor in situations where the mathematical calculation for such coils can be complicated.

With the coupling factor evaluation one can simulate and evaluate the power transferred between the coils and the influence of the distance between the coils on the coupling factor. Going forward, it is attempted to increase the power transfer distance by interposing LC resonant circuits between the transmitter coil and the receiving coil. The study considers two resonant circuit system located between the receiving coil and the emitting coil. With the finite element method simulations, system performance can be evaluated. We analyze the coupling factor between all system coils and adjust these factors so that the power transfer is optimal. A simulation under identical conditions is made for a power transfer system using only two coils, and by comparing the results, an improvement in the transfer for the four-circuit system is observed under the conditions that the coupling factor ratio is one. The idea of including resonant circuits in the power transfer system also has drawbacks, one of which is the power losses on each resonant circuit added.

Chapter 5 presents a detailed analysis of a two coil power transfer system. As a practical model used to compare the results obtained by simulation with experimental measurements, the BQTesla development board was used. For simulation with the finite element method, the emphasis was put on accurate modeling of the two coils used in the power transfer. Both the dimensions of the coils and their position and materials used have been modeled to produce the most conclusive results. As elements are added to the finite element method simulation, the degree of complexity of the simulation increases and the calculation times become longer. The compromise solution is to analyze the coupling between the coils and determine the coupling factor, and these results can be used in electronic circuit simulation environments such as LTSpice for a rapid system evaluation.

Comparing the results obtained by finite element simulation and LTSpice results with the measurements made on the real system, it is noted that the simulations are approaching with reality. Thus, the finite element method simulation can be used for a rapid evaluation of the unit power transfer system with results close to reality.

Chapter 6 aims to study the electric field generated by a single resonant coil for generating outdoor plasma at relatively low powers. The device is designed to be portable, with as little power consumption as possible, for use in field for spectral measurements. The coil used in plasma generation is helical type and can be approximated in operation with a waveguide. If the coil length is equal to $\lambda / 4$ of the resonance frequency, it is possible to generate an electric field of sufficient intensity to ionize the gas and produce plasma. If the beginning of the chapter

summarizes the use of plasma and ways to obtain it, the second part presents the mathematical analysis for the design of a plasma generator coil and the modeling of such a coil for simulation with the finite element method.

Using finite element simulation, several coils of different sizes and resonance frequency can be evaluated, leaving a single coil for testing and measurement. Values obtained by simulation are compared with the results of the measurements. With the simulation model close to the experimental result, other parameters that are more difficult to measure experimentally, such as peak spike voltage to obtain plasma, can be evaluated and simulated.

Here again, the impedance matching circuit added between the generator and the helical coil is evaluated. Using data obtained by simulating the finite element method and making a simplified circuit for plasma generation, it is possible to quickly evaluate circuit operation as well as the possibility of testing some changes to improve the plasma generator.

Chapter 7 presents the studies made in each chapter and summarizes the personal contributions made. Being a vast field of study, in the end are listed some research directions that can be followed in order to extend the scientific horizon.

7. Personal contributions

1. **Modeling and finite element simulation of a wireless power transfer system consisting of three transmitting coils in perpendicular planes and a receiving coil in the immediate vicinity of the system.** The structure allows direction control of the magnetic field towards the receiver coil to maximize power transfer. The simulation environment also allows viewing magnetic field lines and their path through the receiver coil so that the transfer system can be optimized. It is found that this system permits a power transfer to the secondary coil regardless of the angle the receiver coil makes with the coils of the emitting coils.
2. **Coil modeling by filament current method and multiturn coil method and use of finite element method simulation for determining mutual inductance and coupling factor between two coils.** The results of the simulations were compared with analytically obtained results and a comparison was made between the two coil modeling modes. It is noted that the filament current method is a more theoretical approach that does not take into account the geometrical dimensions of the coil, and the multiturn method is a more practical approach considering also the magnetic field that closes between the turns of the coil.
3. **Finite element method simulation of a wireless power transfer system by resonating coupling, composed of four coils.** The simulation demonstrates that through the use of intermediate resonant circuits a higher power transfer can be achieved than with a simple two resonant coil system as long as the ratio of the coupling factors of the adjacent coils remains close to the value of one. The simulation also highlights how field lines are routed through intermediate resonant circuits from the generating coil to the receiving coil.
4. **Modeling and finite element simulation of the BQTesla resonant power transfer system.** The simulation takes into account both the dimensions of the coils used in the transfer, the used materials and the relative position of the two coils. From the information obtained from the finite element simulation, it was possible to model the system in LTspice. The simulation results were compared with measurements made on the real system.

5. Modeling and construction of a helical coil for plasma production in the open air.

In order to obtain the plasma, the helical coil must behave like a waveguide of $\lambda / 4$ length so that the field strength at the tip of the coil is very high. Finite element simulation allowed quick evaluation and adjustment of coil size for optimum yield as well as visualization of electric field distribution around the bobbin to ensure that field strength is maximal at the tip of the coil. Based on simulation results, a coil was built and plasma was generated. A simplified simulation model of the plasma generator circuit was built to evaluate the impedance matching network between the generator and the helical coil.

List of publications

ISI indexed journals with impact factor 1.114

E1. **Dan-Sebastian Filip**, Dorin Petreus, „Study and Implementation of an Atmospheric Pressure Plasma Generator Based on Helical Coil”, Revue roumaine des sciences techniques Série Électrotechnique et Énergétique, Vol. 64, Nr. 2, Pp. 9 – 15, 2019

ISI Proceedings articles in IEEE Xplore Digital Library

E2. **Dan-Sebastian Filip**, Dorin Petreus, „Wireless energy transfer using resonant induction”, Proceedings of the 2014 37th International Spring Seminar on Electronics Technology, Dresden, Germania, Mai 2014, DOI: 10.1109/ISSE.2014.6887598

E3. **Dan-Sebastian Filip**, Dorin Petreus, „Simulation of an inductive coupled power transfer system”, IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, Florența, Italia, Dec. 2016, DOI: 10.1109/IECON.2016.7793628

E4. **Dan-Sebastian Filip**, Dorin Petreus, „Simulation of a Resonant Inductive Wireless Charger”, 2017 40th International Spring Seminar on Electronics Technology (ISSE), Sofia, Bulgaria, Mai 2017, DOI: 10.1109/ISSE.2017.8000947

E5. **Dan-Sebastian Filip**, Dorin Petreus, „Simulation of a Four Resonant Coil Power Transfer System”, 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), Brasov, Romania, Iulie 2017, DOI: 10.1109/OPTIM.2017.7974970

E6. Radu Etz, Dorin Petreus, Toma Patarau, Cristian Orian, **Dan-Sebastian Filip**, „Life cycle test bench for LiFePO₄ batteries”, 2017 40th International Spring Seminar on Electronics Technology (ISSE), Sofia, Bulgaria, Mai 2017, DOI: 10.1109/ISSE.2017.8000934

Other articles

E7. **Dan-Sebastian Filip**, Dorin Petreus, „Medium Power Buck-Boost Converter for Solar Application”, 36th International Spring Seminar on Electronics Technology, Alba Iulia, Romania, Mai 2013