University of British Columbia department of Engineering

ENGR 459 - Term Project
Dynamic Wireless Power Transfer

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Abstract

Nicola Tesla's desire for power transfer through wireless means improves every year with the advancements in understanding the fundamental parameters for optimization of WPT systems. For designers of WTP systems, the choice of near-field WPT systems consists of inductive, capacitive, and mixed type configurations. Inductive systems are preferred over capacitive systems because lower harmful radiation is less harmful than electric radiation [23]. In addition, applying the fundamental electromagnetism principles while including strongly coupled resonance designed techniques, designers can achieve efficient safe wireless power transfer systems that provides a net social benefit to all users.

Contents

List of Figures

1 Introduction

Nicola Tesla's initial desire for power transfer through wireless means improves every year with the advancements in understanding the fundamental parameters for optimization of WPT systems. For designers of WTP systems, the choice of near-field systems consists of inductive and capacitive options. Inductive systems are preferred over capacitive systems because magnetic radiation is less harmful than electric radiation [23]. In addition, the efficiency of the energy transferred wireless should be foremost in the mind of designers. By using the fundamental principles electrodynamics and other theories such as strongly coupled coils, and resonance circuits, and highly efficient and human-safe wireless power transfer system is achievable.

2 Types of Wireless Power Transfer Systems

A 2017 "News and View" article in the journal Nature was the initial inspiration the topic for my term report. In particular, 2.1: Two WPT methods, tweaked my curiosity into the efficiency vs distance relationship. coils relationship. Article [1] was a review of [2], an article on nonlinear parity time-symmetric circuits (Figure 1b), my curious drew me to figure 1a, a WPT system with an efficiency vs. distance profile of an inverted parabola, shift to the right. My initial instinct was that the most efficient distance between transmitter and receiver would be zero. My initial thought was at a distance of zero, all the magnetic flux flowing out of the transmitter would pass to the receiver, provided the transmitter and receiver coils are aligned.

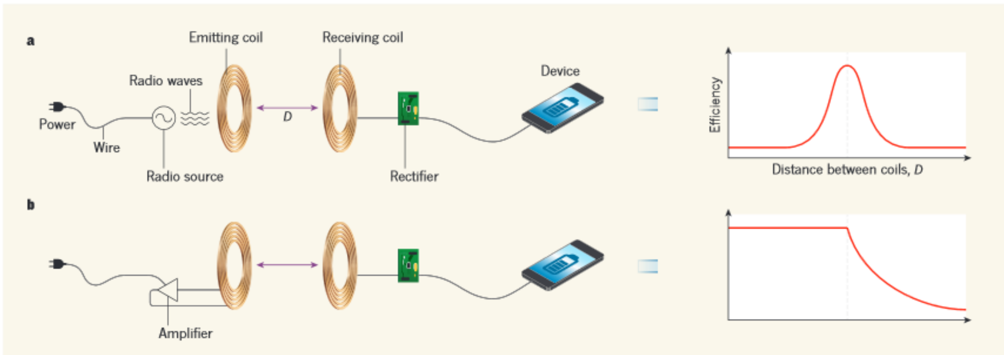

Figure 2.1: Wireless power transfer, two possible methods

Wireless Power Transfer (WPT) systems can be classified into one of two categories: Near- and far-field WTP systems. A WPT system is near-field if the distance between the transmitter and receiver coils is less than the wavelength of the energy signal, whereas, a WPT system is termed far-field when the distance between the transmitter and receiver is greater than the signal wavelength. Examples of near-field WPT systems are:

- Inductive power transfer,
- magnetic power transfer, and
- mixed WPT systems.

The following dives further into the near-field WPT systems with the goal of better understanding the optimal design parameters for maximum power transfer efficiency.

3 Fundamental Principles of Strongly Coupled Magnetic Resonance Systems

Article [4] in the journal Science, submitted by the department of physics at MIT, came up with a novel idea for wireless energy transfer using direct coupling between the transmitter and receiver coils. The research was novel because it used open ended, helix shaped transmitter and receiver coils that floated in air. The transmitter coils is excited by a one-loop resonator and the receiver coil received the energy inductively. This system used Strongly Coupled Magnetic Resonant (SCMR) system that can be analyzed using an RLC.

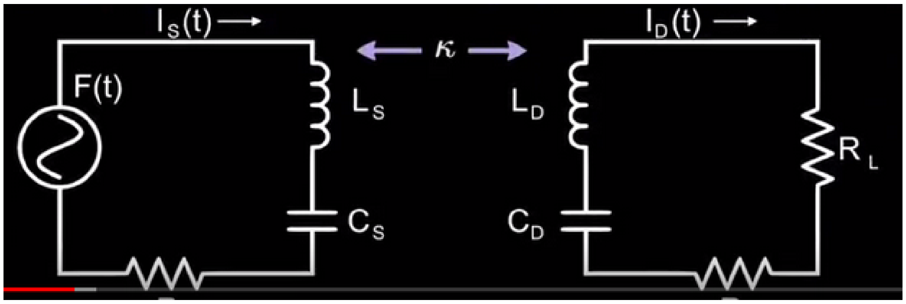

Figure 3.1: Ideal model for SCMR RLC circuit [21]

RLC circuits have a resonant frequency that is related to the inductive and capacitance of their respective circuit. The resonant frequency of the circuit is found using:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{3.1}$$

For the MIT system, the resonant frequency was about 9.9 MHz, and it was at this frequency that maximum energy transmitted was achieved.

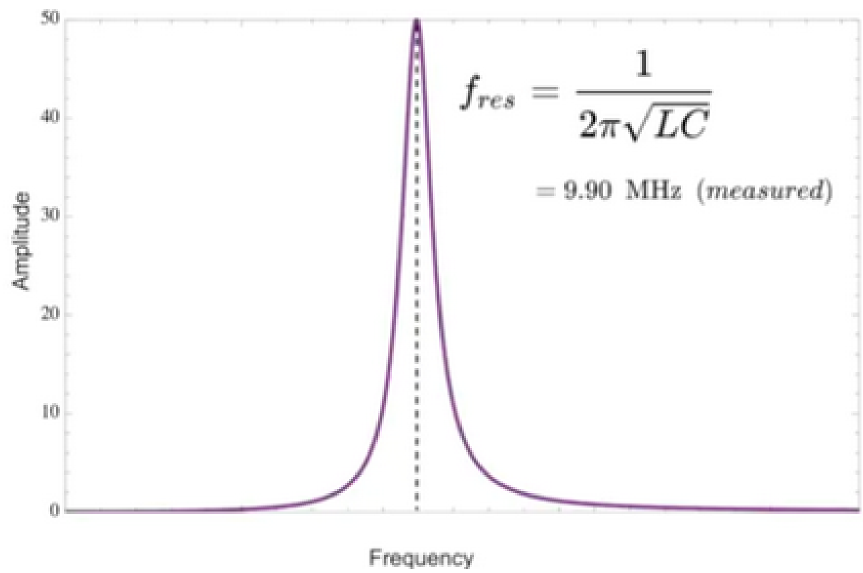

Figure 3.2: Maximum amplitude achieved at resonant frequency [21]

3.1 Optimal Design Parameters

In article [22], a similar WPT system was used article [4] with the goal of analyzing the optimal design parameters for resonance magnetic configuration. For a SCMR based system, optimal energy transfer occurs when the Q-factor is maximum.

Like [4], [22] used open-ended helix shaped transmitter and receiver coils, and the transmitter coil was excited by a single loop resonator. The optimal design parameters is summarized by the Q-factor of the RLC circuit:

$$Q = \frac{w_r L}{R} = \frac{2\pi f_r L}{R} \tag{3.2}$$

where $f_r = f_{res}$ from equation 3.1.

The Q-factor coincides with the natural, resonance, frequency of the RLC circuit. The Q-factor, therefore, can be thought of as the natural maximum possible parameter configuration. In order for the entire system to have a *global* maximum Q-factor, the transmitter and receiver coils should have the same individual Q-factor values. This allows the system, as a whole, to have maximum resonance. With the Q-factor determined, the designer can now determine the radius r_{max} of the transmitter and receiver coils, and the frequency,f_{res}, of oscillation of the transmitter coil.

Based on my research, Coupled Mode Theory is based on defining electromagnetic power that is independent and separate from other electromagnetic power is an electromagnetic mode [16]. The benefit of designing a WPT system that incorporates strong coupling between transmitter and receiver coils is improved energy transfer. Fundamentally, coupled-mode theory suggests that the efficiency of power transfer is equal to that of wired circuit [16]. Another type of WPT system that research suggests that almost ideal voltage and current transfer is possible is Inductive Power Transfer (IPT) systems.

3.2 IPT Circuits

During my research, numerous article on inductive power transfer system where found. One such article [15] described the efficiency possibility from compensative IPT system:

> *By appropriate selection of the topology and resonant scheme of the compensation circuit, the IPT could be equivalent to either an ideal voltage source or an ideal current source*

The purpose of the compensation circuit, refer to Figure 3.3, is to improve the power factor of the system, and eliminate reactive power the results from loosely coupled transfer and receiver coils.

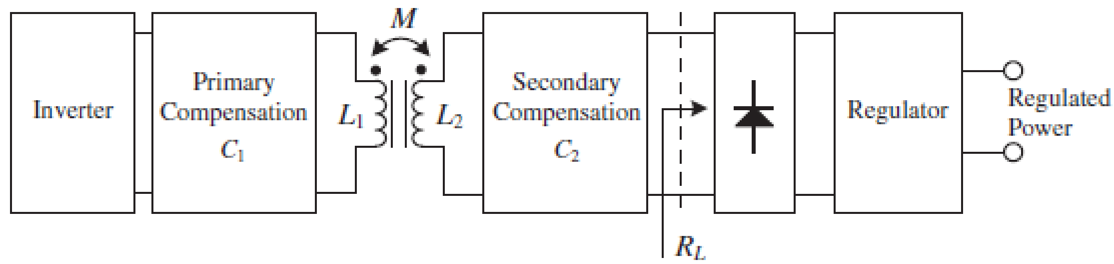

Figure 3.3: General configuration of an IPTS [15]

The compensation circuit can be arranged in one of eight possible configuration:

- (V-SS) - voltage source with transmitter series, receiver series
- (V-SP) - voltage source with transmitter series, receiver parallel
- (V-PS) - voltage source with transmitter parallel, receiver series
- (V-PP) - voltage source with transmitter parallel, receiver parallel
- (I-SS) - current source with transmitter series, receiver series
- (I-SP) - current source with transmitter series, receiver parallel
- (I-PS) - current source with transmitter parallel, receiver series
- (I-PP) - current source with transmitter parallel, receiver parallel

These eight different configurations were compared for their power transfer efficiency properties using a normalized angular frequency ω_η

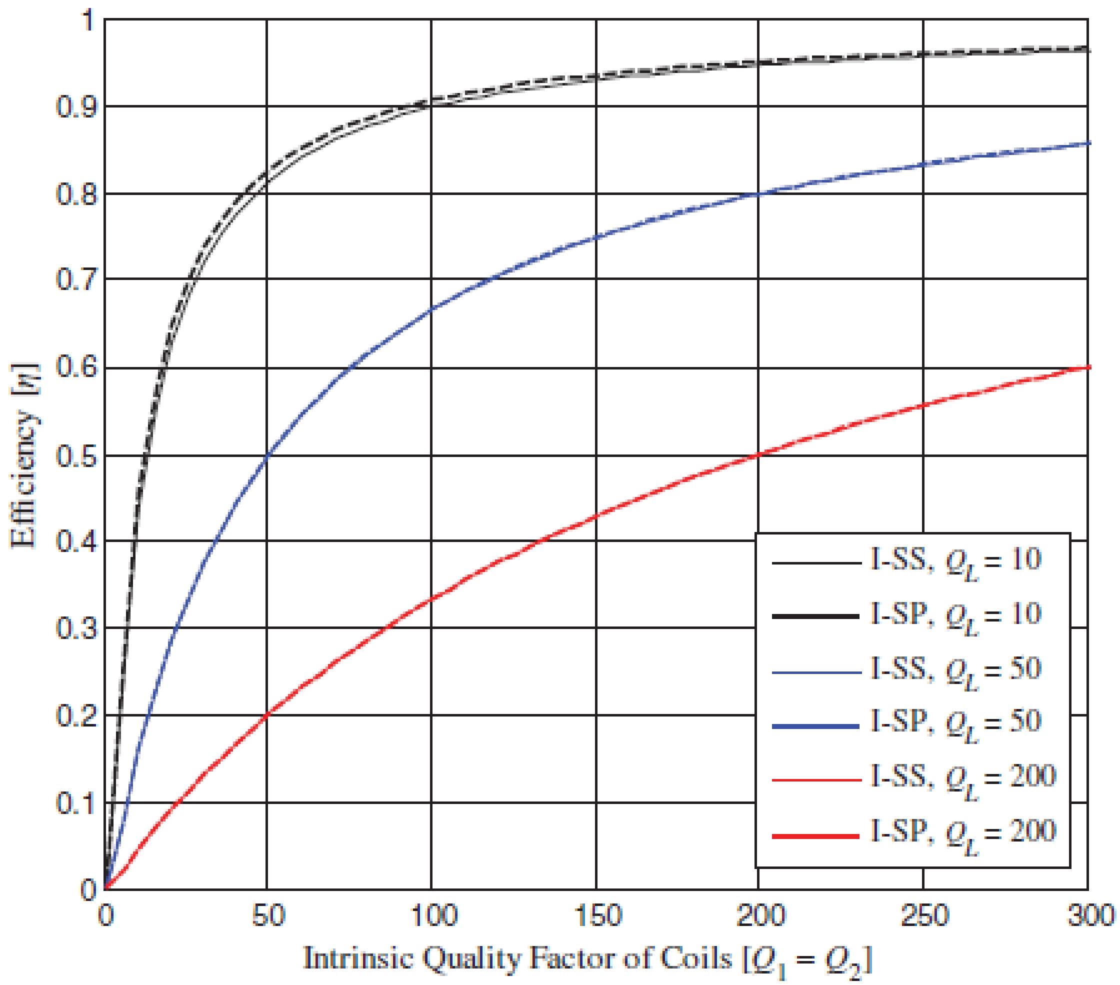

Figure 3.4: Efficiency η versus the normalized angular frequency ω_η when k = 0.3 and Q1 = Q2 = 150 [15]

The conclusion from this evaluation is that maximum efficiency is occurs at the second resonant angular frequency ω_η, irrespective of Q_L, the Q-factor of the load (receiver side) circuit.

4 Dynamic Charging Challenges

Charging of electric devices is performed using static or dynamics charging systems. Static systems, such as electric toothbrushes and smartphones, are less complex due the fact the spacial separation between transmitter and receiver remains fixed during charging. In contract, dynamic charging systems, such as charging electric vehicle, is more complex due to changing orientation and distance between transmitter and receiver systems. From the end-user perspective, dynamic charging system provides greater freedom. For example, dynamic electric vehicle charging offers the ability to extend the duration between full charging. This in turn has a secondary benefit of allowing electric vehicles to have small, and therefore overall lower battery weight, resulting in more efficient travel.

Wireless Power Transfer (2014) provided a review of electric vehicle wireless charging technology. In this article magnetic coupling systems were used to illustrate how wireless transfer charging of electric vehicles can be accomplished.

4.1 Vehicle Applications

The basic concept of dynamic electric vehicle systems is to bury the transmitter under the road surface, and locate the receiver connected to the bottom side of the vehicle. In addition, detection and communication systems are required. Article [13] provides one possible *futuristic* dynamic charging systems, see Figure 4.1.

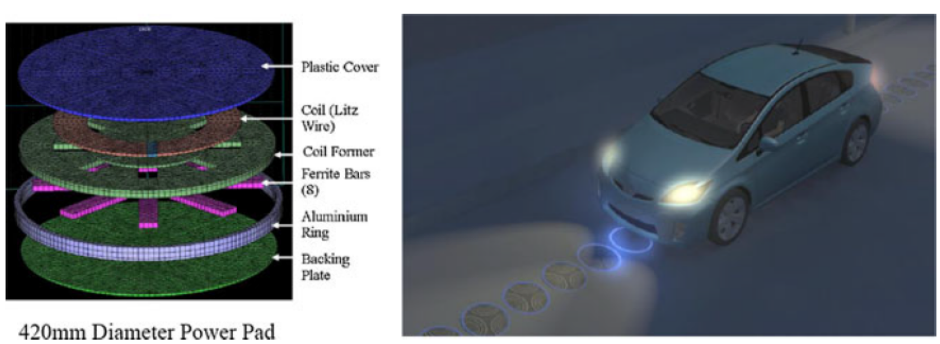

Figure 4.1: Diagram and vision of the power pad design from the University of Auckland [13]

As the vehicle travels over a road, a coordinated communication system would track the vehicle and turn on and off charging pads to correspond with the location of the vehicle. This type of system is inherently complex, and would require signification private and public sector collaboration to implement. From a futuristic perspective, it is very interesting possibility.

4.1.1 ICNIRP Guildlines

A question was raised during my presentation regarding the potential risks associated with exposure to magnetic field radiation. The International Commission on Non-ionizing Radiation Protection organization (ICNIRP) provides a guideline for limiting exposure to time-varying electric and magnetic fields (1 Hz - 100 kHz) [23]. The ICNIRP is an independent organization that provides scientific advice to "protection against all established adverse health effects."[23]. Under the *Protective Measures* section within the ICNIRP guidelines, the first recommended step is to engineering systems such that EM field exposure is limited. EM field exposure was something I failed to address during my presentation, this was a mistake on my part, and something I'll be sure to consider moving forward (pun intended :) .

5 Conclusion

Nicola Tesla‘s initial desire for power transfer using wireless means improves every year with the advancements in understanding the optimization parameters of WPT systems. For designers of WTP systems, the choice of near-field systems consists of inductive and capacitive options. Inductive systems are preferred over capacitive systems due to their lower human harming radiation. In addition, incorporating coupling and resonant properties within WPT systems provides the best topology for systems to operate at peak efficiency. Key components of efficient resonant design are: geometric parameters of the transmitter and receiver coils, the LC properties of the respective transmitter and receiver coils. Finally, the distance between the transmitter and the receiver coils considered when designing WPT systems.

The future of WTP provides many exciting opportunities for the improvement of the quality of life of users of mobile devices and electric vehicles through the ubiquitous charging of their device/car. As governments develop legislative changes in energy use, they will be instrumental in helping to accelerate gains in WPT efficiency by providing increased research opportunities to further explore these principles.

References

[1] Lerosey,Geoffry. *Wireless power on the move*. Nature, Vol. 546, June 15 2017.

[2] Sid Assawaworrarit1, Xiaofang Yu1 & Shanhui Fan1. *Robust wireless power transfer using a nonlinear paritytime-symmetric circuit*. Nature, Vol. 546, June 15 2017.

[3] Jawad, A. M. et al. *Opportunities and Challenges for Near-FieldWireless Power Transfer: A Review*. Energies, doi:10.3390/en10071022, 2017.

[4] Kurs, Andre et al. *Wireless Power Transfer via Strongly Coupled Magnetic Resonances*. Science, Vol. 317, July 6 2007.

[5] Mude1 K.N., Outeiro M.T., Carvalho A., and Vidyapeetham A. V. *In-motion Wireless Power Transfer: Technology, Infrastructure, challenges and Market scenario*. IEEE, 2017.

[6] COLLADO A., DASKALAKIS Spyridon-Nektarios , Kyriaki NIOTAKI2, and Ricard MARTINEZ3, Ferran BOLOS, Apostolos GEORGIADIS. RadioEngineering, VOL. 26, NO. 2, JUNE 2017.

[7] V. V. Konotop, D. A. Zezyulin *Stochastic parity-time-symmetric coupler* OPTICS LETTERS, VOL. 39, NO. 5, March 1, 2014.

[8] D.C Giancoli, *Physics for Scientists & Engineers with Modern Physics*, New Jersey: Pearson Prentice Hall, 2008, pp. 385-387.

[9] Wireless Charging. (2017). Available: `https://powerbyproxi.com/wireless-charging/#how-does-wireless-charging-work`

[10] Resonance Induction Coupling. (2017). `https://en.wikipedia.org/wiki/Resonant_inductive_coupling`.

[11] C. Li, H. Zhang, and X. Jiang, "Parameters Optimization for Magnetic Resonance Coupling Wireless Power Transmission," *The Scientific World Journal*, vol. 2014, no.321203, 8 pages, May 13, 2014.

[12] A. Costanzo, M. Dionigi, F. Mastri, M. Mongiardo, J. A. Russer, and P. Russer, "Rigorous network modeling of magnetic-resonant wireless power transfer," *Wireless Power Transfer,* vol. 1, no. 1, pp. 27-34, 2014.

[13] T. M. Fisher, K. B. Farley, Y. Gao, H. Bai, and Z. T. H. Tse, "Electric vehicle wireless charging technology: a state-of-the-art review of magnetic coupling systems" *Wireless Power Transfer*, vol. 1, no. 2, pp. 87–96, 2014.

[14] A. Abdolkhani and A. P. Hu, "Magnetic coupling coefficient determination of IPT systems under operating conditions," *Wireless Power Transfer*, vol. 1, no. 2, pp. 83-86, 2014.

[15] Rim, Chun T. *Wireless Power Transfer for Electric Vehicles and Mobile Devices.* John Wiley & Sons, 2017. Web. 24 Oct. 2017.

[16] *Coupled-mode Theory.* Youtube `https://youtu.be/pZ_alesCCPo`

[17] *Resonant inductive coupling.* Retrieved from `https://en.wikipedia.org/wiki/Resonant_inductive_coupling#cite_note-WitrityWhitePaper-19`

[18] *Resonant inductive coupling.* Retrieved from `https://www.digikey.ca/en/articles/techzone/2016/aug/inductive-versus-resonant-wireless-charging`

[19] *Magnetic Resonance and Magnetic Induction - What is the best choice for my application?.* Retrieved from `https://www.wirelesspowerconsortium.com/technology/magnetic-resonance-and-magnetic-induction-making-the-right-choice-for-your-application.html`

[20] O. Jonah, Student Member, IEEE, Stavros V. Georgakopoulos, Senior Member, IEEE, and Manos M. Tentzeris, Fellow, IEEE. *Design Parameters for Wireless Power Transfer by Resonance Magnetic.* IEEE Antennas and Wireless Propagation Letters, Vol. 11, 2012.

[21] *Wireless Power Transfer via Coupled Resonators.* Youtube `https://youtu.be/DB98cBp1UeU`

[22] O. Jonah, S. V. Georgakopoulos, M. M. Tentzeris. *Optimal Design Parameters for Wireless Power Transfer by Resonance Magnetic*. IEEE Antennas and Wireless Propagation Letters, Vol. 11, 2012.

[23] *The International Commission on Non-ionizing Radiation Protection*. Retrieved Dec 1, 2017 `https://www.icnirp.org/`