INVESTIGATING THE EFFECTS OF HUMIDITY AND TEMPERATURE FOR LCL COMPENSATION WIRELESS POWER TRANSFER

ISMAIL AHMAT MAHADI

A thesis submitted in
fulfilment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JUNE 2023

To my beloved parents, thank you.

ACKNOWLEDGEMENT

First and foremost, I thank Allah Almighty, the greatest, the merciful, the compassionate, the all-knowing, the first and the last for giving me the health, patience, and knowledge, I needed to complete this project.

I want to express my heartfelt gratitude and appreciation to my family, close friends, and everyone else who helped me complete my research. Dr. Jabbar Al-Fattah Bin Yahaya, my research supervisor, deserves special recognition for his creative ideas and encouragement in managing my studies, notably in opening doors of rescue whenever I needed it.

Furthermore, I would like to express my gratitude to the UTHM personnel in the Office for Research and Innovation Centre (RMC) and the Ministry of Higher Education (MOHE) for their invaluable assistance via the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2019/TK04/UTHM/03/14) VOT K192. In addition, my gratitude goes to the Faculty of Electrical and Electronic Engineering (FKEE) and the Center of Graduate Studies (CGS) for providing all the equipment needed to complete this research.

I am also grateful to all my friends for their unending moral support, encouragement, and inspiration.

ABSTRACT

In recent years, there has been much research in designing an inductive wireless power transfer system. The main challenge for this technology is the efficiency of the system. In designing a Wireless Power Transfer (WPT) system for long-distance applications, the gain bandwidth or Q-factor is a factor that should be considered as it affects the resonant coupling of the transmitter and receiver pads. An insufficient Q-factor will result in weak coupling or possible energy loss due to the attenuation characteristics of the environment, such as resistive and radiation losses. However, a system with too much Q-factor would cause the resonant coils to be very sensitive to the environment, such as temperature, humidity, and human proximity. Since wireless power transmission devices use power electronics technology, this technology is also affected by environment factors such as temperature and humidity. This research therefore, investigates the effect of temperature and humidity in LCL compensation wireless power transfer systems as well as study the safety of the magnetic field generated by the system. This project was carried out into two distinct phases: the first was a simulation analysis for the proposed system using JMAG-Designer software and the second phase was an experimental setup based on the simulated system. The hardware design was tested on the various temperature and humidity levels to observe the impact of the change in efficiency of the system. The results shows that the efficiency of both the simulation and experiment are high at 94.8% and 91.7% respectively, when the distance is low. However, as the distance increased, the efficiency decreased to 68.5% for simulation and 66.6% for experiment at 10 cm distance. Regarding the temperature and humidity setup, the temperature was set between 27-degree Celsius (room temperature) and 60-degree Celsius, while the humidity was set between 60% which is at room temperature and 99%. The result was showed that temperature and humidity have a very small changes on the efficiency of the system, with an error margin of 1%. Therefore, it was concluded that the efficiency can only be affected by the distance between the coils, load resistance, and frequency value.

ABSTRAK

Dalam beberapa tahun kebelakangan ini, terdapat banyak penyelidikan dalam mereka bentuk sistem pemindahan kuasa tanpa wayar (WPT) induktif. Cabaran utama untuk teknologi tersubat adalah kecekapan sistem. Untuk sistem (WPT) yang digunakan dalam aplikasi jarak jauh, lebar jalur keuntungan atau faktor Q adalah faktor yang harus dipertimbangkan kerana ia mempengaruhi gandingan resonan pad pemancar dan penerima. Faktor Q yang tidak mencukupi hanya akan mengakibatkan gandingan yang lemah atau kemungkinan kehilangan tenaga disebabkan oleh kehilangan gelombang sinaran elektromagnet. Walau bagaimanapun, sistem dengan faktor Q yang terlalu banyak akan menyebabkan gegelung resonans menjadi sangat sensitif kepada persekitaran seperti suhu, kelembapan dan kedekatan manusia. Memandangkan peranti WPT menggunakan teknologi elektronik kuasa, teknologi ini turut dipengaruhi oleh persekitaran seperti suhu dan kelembapan. Penyelidikan ini mengkaji kesan suhu dan kelembapan dalam sistem WPT pampasan LCL serta mengkaji keselamatan medan magnet yang dihasilkan oleh sistem. Kerja-kerja ini dibahagikan kepada dua peringkat: analisis simulasi untuk sistem yang dicadangkan menggunakan perisian JMAG-Designer dan diikuti dengan persediaan eksperimen berdasarkan sistem simulasi. Reka bentuk perkakasan akan diuji pada pelbagai tahap suhu dan kelembapan untuk melihat kesan perubahan kecekapan sistem. Daripada keputusan tersebut, didapati bahawa kecekapan kedua-dua simulasi dan eksperimen adalah tinggi apabila jaraknya rendah iaitu masing-masing pada 94.8% dan 91.7%. Walau bagaimanapun, apabila jarak semakin bertambah kecekapan berkurangan kepada 68.5% untuk simulasi dan 66.6% untuk eksperimen pada jarak 10 cm. Bagi persediaan suhu dan kelembapan pula, suhu ditetapkan daripada 27- darjah Celsius kepada 60 darjah Celsius, dan kelembapan ditetapkan daripada 60% iaitu pada suhu bilik kepada 99%. Hasilnya diperhatikan bahawa suhu dan kelembapan mempunyai perubahan yang sangat kecil dengan margin ralat 1% pada kecekapan sistem. Oleh itu, disimpulkan

bahawa kecekapan hanya boleh dipengaruhi oleh jarak antara gegelung, rintangan beban, dan nilai frekuensi.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

B	-	Magnetic field density
$C_1 or C_p$	-	Primary capacitor
$C_2 or C_{ps}$	-	Secondary capacitor
D_{out}	-	Outer diameter
D_{in}	-	Inner diameter
E	-	Electric field
ε_0	-	Electricity permittivity of free space ($F.m^{-1}$)
f_r	-	Resonant frequency
$I_1 or I_p$	-	Primary current
$I_2 or I_s$	-	Secondary current
J	-	Current density
K	-	Coupling coefficient
$L_1 or L_p$	-	Primary inductor
$L_2 or L_s$	-	Secondary inductor
l	-	Length of the coil
M	-	Mutual inductance
μ	-	Permeability of a substance
μ_r	-	Permeability of the magnet of free space
μ_0	-	Permeability of the medium
N	-	Number of coils turns
η	-	Efficiency
P_L	-	Load power or output power
Q	-	Quality factor
$R_1 or R_p$	-	Primary resistor
$R_2 or R_s$	-	Secondary resistor
R_L or R_e	-	Load resistor
T	-	Spacing between turns

$V_1 or V_p$	-	Primary voltage
$V_2 or V_s$	-	Secondary voltage
w	-	Diameter of the wire
ω_0	-	Operating frequency
Zp *and* Zs	-	Primary and secondary impedance
∇	-	Curl which measures the strength of B

LIST OF ABBREVIATIONS

AC	-	Alternating current
ADC	-	Analog to digital converter
AWG	-	American wire Gauge
CCS	-	Code composer studio
CMRS	-	Coupled magnetic resonance system
CPT	-	Capacitive power transfer
CMT	-	Coupled mode theory
DC	-	Direct current
DSP	-	Digital signal processor
EMF	-	Electric and magnetic field
EM	-	Electromagnetic
EV	-	Electric vehicle
E-field	-	Electric fields
FCC	-	Federal Communications Commission
FEA	-	Finite Element Method
H-field	-	Magnetic fields
ICES	-	The International Committee on Electromagnetic Safety
ICNIRP	-	International Commission on Non-Ionizing Radiation Protection
IEEE	-	Institute of Electrical Electronic Engineers
IGBT	-	Insulated-gate bipolar transistor
IPT	-	Inductive power transfer
MMF	-	Magneto motive force
MF	-	Medium frequency
MOSFET	-	Metal–oxide–semiconductor field-effect transistor
PP	-	parallel-parallel
PS	-	Parallel-series
PWM	-	Paulse width modulation
Q-factor	-	Quality factor

RF	-	Radio frequency
SAR	-	Specific absorption rate
SS	-	Sries-series
SP	-	Series-parallel
VLF	-	Very low frequency
WPT	-	Wireless power transfer
ZVS	-	Zero voltage switching

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Electric and electronic appliances are typically powered by a wire that transfers electricity [1]. However, this is inconvenient for the following reasons: the incapability of moving the equipment while charging, broken cables, the necessity to establish an electrical connection during rainy weather conditions, and safety risks. Even though some of the equipment use battery for their mobility, there are some limitations with the batteries such as capacity, size, and efficiency which make them inconvenient and do not solve this limitation [2]. To overcome this limitation wireless power transfer (WPT) has been introduced in the past few decades. The benefit of WPT is that it transmits power from the primary windings to the secondary windings without any mechanical contact. WPT technology is used in various applications such as medical implants, mobile phones, and electric vehicles (EV) [3].

WPT technique is adopted rapidly in many sectors, including transportation and various other fields of approach in which certain parameters vary. For instance, the number of coils and their shape, compensation topologies, frequency control, and inverter design is being implemented to get the maximum power transfer efficiency [4].

Several approaches are used to build a WPT. They depend on the distance between the transmitter and receiver, the operating frequency, and the amount of transmitted power [5]. WPT has two types of fields: far-field and near-field. Table 1.1 shows the distinction between the two types of fields. Near-field WPT systems are classified into inductive and capacitive power transfer. The most often-used approach is inductive power transfer (IPT), which is based on magnetic induction. The IPT system has made significant contributions in theoretical development and industrial implementations for wireless power delivery [6], [7]. Hence, it was used in this research.

Table 1.1: Main differences between far-field and near-field [5]

WPT	**Far Field**	**Near Field**
Range	Long	Short-Mid
Phenomenon	Coupled mode theory	Induction theory
Frequency	Mega Hertz	Kilo Hertz
Efficiency	Low	High

The technique for wireless power transfer is that it eliminates the use of traditional wires. Instead, it transfers energy from the power supply to the targeted load via air. This technique consists of far-field and near-field transmissions. The far-field technique uses systems such as microwave, optical, and acoustic to transfer the energy from the source to the load. Whereas the near-field transmission uses electric and magnetic fields to transfer energy from the source to the load. It is noteworthy, that most of the WPT techniques use a near-field technique, which can be classified into two methods: i.e., magnetic induction (IPT) and electrostatic induction or capacitive power transfer (CPT) [8].

The reliability of electronic systems for operating in all types of environments has become a necessity. During operation, electronic components are exposed to a variety of stresses, including electrical, thermal, electrostatic discharge (ESD), EMI, and others. Temperature and humidity may impact the dependability of operation and be one of the causes of electronic component failure. There are numerous research articles and initiatives on electronic equipment like transformers and inductor, because thermal heat loss in electronic devices produces unexpected issues in system [10]. However, no active research on the effect of temperature and humidity on current WPT systems in the market has been done yet. The effect of temperature and humidity dissipation of a WPT system device can be minute if the machine deals with low power. However, when the system's power and frequencies increase, substantial power loss might occur because of the WPT system characteristics (such as proximity effects by many turns of wiring, and sensitivity to resonance frequencies).

This research proposed and investigated the effect of temperature and humidity which could negatively affect the efficiency and performance of any electronics device that includes WPT. As well as to model and design a WPT system using JMAG-designer, and to study the safety limits of the electromagnetic field produced by the coupling coil.

1.2 Problem Statement

To ensure the capability of energy transfer at longer distances, the resonance coupling must depends on a rate determined by the gain-bandwidth (Quality factor) [11]. Insufficient Q-factor simply results in weak coupling or possibly loss of energy due to the damping nature of the environment including resistive and radiative losses. However, too much Q-factor would result in the resonant coils being very sensitive to its surroundings i.e., temperature, humidity, and human proximity [12]. Although there are claims by certain researchers that the WPT system is immune to harsh environments, there are very few literature to support this claim.

Temperature and humidity are very important factors to consider when designing electronics appliances because any increase in temperature and humidity can reduce the lifespan of any electronic components and might even damage it. Besides that, they also have an impact on conventional charging as the device may take longer to charge when the temperature and humidity increase [13]. The WPT system uses a magnetic field to transfer power from one end to another, (that is, the magnetic coupling between a primary and a secondary winding). The electrical power can flow from the mains source to the load [14]. That magnetic field can be affected by the surrounding temperature and humidity.

Although wireless power transmission offers numerous advantages, it also poses a possible safety issue due to human and animal exposure to the leaky magnetic field, which may have a negative effect on the general public's health. Due to the high power and frequency, a greater magnetic field is created when there is an air gap between the transmitter and receiver pads. This implies that the leaking magnetic field's frequency and amplitude must be carefully controlled to meet industry standards for safety [15].

Therefore, this study aims to model and design a WPT system that can transmit energy from the transmitter to the receiver as well as investigate the effect of temperature and humidity on wireless power transfer, and study the safety risk of electromagnetic exposure of the system to the general public.

1.3 Objectives

1. To design and model a wireless power transfer system (WPT) using FEM JMAG-Designer.
2. To analyse the effect of load and input volt on the efficiency of the system.
3. To investigate the effect of temperature and humidity in WPT.
4. To study the safety and electromagnetic limits based on the specific absorption rate (SAR).

1.4 Scope of Study

The main purpose of this research was to analyze the effect of temperature and humidity on coil systems using inductive wireless charging systems which comprises of; efficiency vs distances (mm), efficiency vs resonant frequency, specific absorption rate, and design topologies.

(i) This project entails the design of a wireless power transfer system that can transfer low voltage to a maximum of 200V.

(ii) Frequency values are used to identify a suitable resonant frequency range between (10 kHz to 20 kHz) for different airgaps.

(iii) The airgap used is between 0 to 100mm

(iv) The design and analysis are carried out using JMAG-Designer ver16.0.01.

(v) A prototype of WPT will be implemented based on the software specification, focusing on the transmitter and receiver pads.

(vi) The study of electromagnetic exposure risk is based on the ICNIRP standard for magnetic field safety consideration.

(vii) The temperature and humidity test are only performed on the experimental part due to lack of these parameters in the software.

1.5 Significance of Study

In this study, an investigation of the effect of temperature and humidity on LCL topology WPT system was introduced. The finding of this study would help to understand how load affect the efficiency of the system, as well as to understand the effect of temperature and humidity on WPT system for a variety of applications such as laptops, scoters, etc... Therefore, the result of this study will contribute to the knowledge related to pad design using LCL compensation topology, and the safety risk of electromagnetic exposure to human body.

1.6 Thesis Outline

This section briefly outlines the structure of this thesis, it will be divided into five chapters as explained below.

Chapter One: Introduction

Chapter one is the introduction of this research thesis which includes the background of the study, problem statement, objectives, and scope, limitations, significance of study and finally, chapter summary.

Chapter Two: Literature Review

Chapter two consists of a review of related literature regarding the current issue of wireless power transfer. This section also includes the types of WPT that have been studied before and the mathematical derivation of the formula of the system. Moreover, it also explains more about the research problem that will be addressed in this project.

Chapter Three: Research Methodology

This chapter clarifies the method used to achieve the result of this study. It consists of an introduction, and simulation method which describes the software used in this project and the design parameters of the system. Furthermore, this chapter also describes the experimental method which includes the design parameter of the system, equivalent circuit, devices, and components used to obtain the result.

Chapter Four: Results and Discussion

This chapter comprises of the results of the research from both simulation and experimental methods, as well as analyses the result and compares the simulation vs experiment of the system.

Chapter Five: Conclusion and Recommendation

The last chapter of the research concludes the findings of the study in relation to the study's objective. In addition, it also discusses the implication of the results and recommendations for future research.

REFERENCES

[1] N. Chawla and S. Tosunoglu, “State of the Art in Inductive Charging for Electronic Appliances and its Future in Transportation,” *2012 Florida Conf. Recent Adv. Robot.*, no. August 2016, pp. 1–7, 2012.

[2] J. Huang, Y. Zhou, Z. Ning, and H. Gharavi, “Wireless Power Transfer and Energy Harvesting: Current Status and Future Prospects,” *IEEE Wirel. Commun.*, vol. 26, no. 4, pp. 163–169, 2019.

[3] J. Shin, S. Shin, Y. Kim, S. Lee, B. Song, and G. Jung, “Optimal current control of a wireless power transfer system for high power efficiency,” *Electr. Syst. Aircraft, Railw. Sh. Propulsion, ESARS*, pp. 6–9, 2012.

[4] A. Elahi, A. A. Amin, U. T. Shami, M. T. Usman, and M. S. Iqbal, “Efficient wireless charging system for supercapacitor-based electric vehicle using inductive coupling power transfer technique,” *Adv. Mech. Eng.*, vol. 11, no. 11, pp. 1–10, 2019.

[5] M. A. Z. Aslina Abu Bakar, Azreme Idris, Ahmad Rashidy Razali, “Wireless Power Transfer through Inductive Coupling,” *Recent Adv. Circuits*, vol. 10, no. 1, pp. 115–118, 2015.

[6] Y. Yusop, Z. Ghani, S. Saat, H. Husin, and S. K. Nguang, “Capacitive power transfer with impedance matching network,” *Proceeding - 2016 IEEE 12th Int. Colloq. Signal Process. its Appl. CSPA 2016*, no. March, pp. 124–129, 2016.

[7] C. K. Chang, G. G. Da Silva, A. Kumar, S. Pervaiz, and K. K. Afridi, “30 W capacitive wireless power transfer system with 5.8 pF coupling capacitance,” *2015 IEEE Wirel. Power Transf. Conf. WPTC 2015*, pp. 30–33, 2015.

[8] Z. Zhang, H. Pang, A. Georgiadis, and C. Cecati, “Wireless Power Transfer - An Overview,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1044–1058, 2019.

[9] L. Sun, D. Ma, and H. Tang, “A review of recent trends in wireless power transfer technology and its applications in electric vehicle wireless charging,” *Renew. Sustain. Energy Rev.*, vol. 91, no. March, pp. 490–503, 2018.

[10] K. Hwang, S. Chun, U. Yoon, M. Lee, and S. Ahn, “Thermal analysis for temperature robust wireless power transfer systems,” *2013 IEEE Wirel. Power Transf. WPT 2013*, pp. 52–55, 2013.

[11] K. DOWNEY, “Why your phone’s battery charging slows down during hot summer months - Komando.com,” 05-Jul-2017. [Online]. Available: https://www.komando.com/smartphones-gadgets/why-your-phones-battery-charging-slows-down-during-hot-summer-months/405637/. [Accessed: 05-Dec-2021].

[12] V. Shevchenko and I. Kondratenko, “Coil Design for Wireless Power Transfer with Series-Parallel Compensation,” *2019 IEEE 2nd Ukr. Conf. Electr. Comput. Eng.*, pp. 401–407, 2019.

[13] H. Jiang, P. B. Jr, M. Tabaddor, and J. Bablo, “Safety Considerations of Wireless Charger For Electric Vehicles – A Review Paper,” 2012.

[14] M. T. Nguyen *et al.*, *Electromagnetic field based WPT technologies for UAVs: A comprehensive survey*, vol. 9, no. 3. 2020.

[15] F. Pellitteri, M. Caruso, V. Castiglia, R. Miceli, C. Spataro, and F. Viola, “Experimental Investigation on Magnetic Field Effects of IPT for Electric Bikes,” *Electr. Power Components Syst.*, vol. 46, no. 2, pp. 125–134, 2018.

[16] F. Lu, H. Zhang, and C. Mi, “A review on the recent development of capacitive wireless power transfer technology,” *Energies*, vol. 10, no. 11, 2017.

[17] C. E. Theses and S. R. Daida, “ODU Digital Commons A Design of Inductive Coupling Wireless Power Transfer System for Electric Vehicle Applications,” 2019.

[18] J. Dai and D. C. Ludois, “A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications,” *IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6017–6029, 2015.

[19] C. Xia, Y. Zhou, J. Zhang, and C. Li, “Comparison of power transfer characteristics between CPT and IPT system and mutual inductance optimization for IPT system,” *J. Comput.*, vol. 7, no. 11, pp. 2734–2741, 2012.

[20] Tark Altahr Ahmed Farnana, “Analysis and comparison of classical compensation topologies for inductive power transfer for electrical vehicles,” *Вестник Росздравнадзора*, vol. 4, pp. 9–15, 2017.

[21] M. A. Houran, X. Yang, and W. Chen, “Magnetically coupled resonance wpt:

Review of compensation topologies, resonator structures with misalignment, and emi diagnostics," *Electron.*, vol. 7, no. 11, 2018.

[22] Y. Wang, Y. Yao, X. Liu, and Di. Xu, "S/CLC compensation topology analysis and circular coil design for wireless power transfer," *IEEE Trans. Transp. Electrif.*, vol. 3, no. 2, pp. 496–507, 2017.

[23] C. Jiang, K. T. Chau, C. Liu, and C. H. T. Lee, "An overview of resonant circuits for wireless power transfer," *Energies*, vol. 10, no. 7, 2017.

[24] X. Mou, D. T. Gladwin, R. Zhao, and H. Sun, "Survey on magnetic resonant coupling wireless power transfer technology for electric vehicle charging," *IET Power Electron.*, vol. 12, no. 12, pp. 3005–3020, 2019.

[25] V. Shevchenko, O. Husev, R. Strzelecki, B. Pakhaliuk, N. Poliakov, and N. Strzelecka, "Compensation topologies in IPT systems: Standards, requirements, classification, analysis, comparison and application," *IEEE Access*, vol. 7, pp. 120559–120580, 2019.

[26] S. Kuzey, S. Balci, and N. Altin, "Design and analysis of a wireless power transfer system with alignment errors for electrical vehicle applications," *Int. J. Hydrogen Energy*, vol. 42, no. 28, pp. 17928–17939, 2017.

[27] R. Bosshard, J. Muhlethaler, J. W. Kolar, and I. Stevanovic, "Optimized magnetic design for inductive power transfer coils," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, pp. 1812–1819, 2013.

[28] J. O. Mur-Miranda *et al.*, "Wireless power transfer using weakly coupled magnetostatic resonators," *2010 IEEE Energy Convers. Congr. Expo. ECCE 2010 - Proc.*, pp. 4179–4186, 2010.

[29] M. Elwalaty, M. Jemli, and H. Ben Azza, "Modeling, Analysis, and Implementation of Series-Series Compensated Inductive Coupled Power Transfer (ICPT) System for an Electric Vehicle," *J. Electr. Comput. Eng.*, vol. 2020, 2020.

[30] P. S. R. Nayak and D. Kishan, "Performance analysis of series/parallel and dual side LCC compensation topologies of inductive power transfer for EV battery charging system," *Front. Energy*, vol. 14, no. 1, pp. 166–179, 2020.

[31] K. Aditya and S. S. Williamson, "Comparative study of Series-Series and Series-Parallel compensation topologies for electric vehicle charging," *IEEE Int. Symp. Ind. Electron.*, pp. 426–430, 2014.

[32] C. Zheng *et al.*, "High-efficiency contactless power transfer system for electric

vehicle battery charging application," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 3, no. 1, pp. 65–74, 2015.

[33] Q. Zhu, L. Wang, Y. Guo, C. Liao, and F. Li, "Applying LCC Compensation Network to Dynamic Wireless EV Charging System," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6557–6567, 2016.

[34] W. Zhang and C. C. Mi, "Compensation topologies of high-power wireless power transfer systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4768–4778, 2016.

[35] L. Chen, S. Liu, Y. C. Zhou, and T. J. Cui, "An optimizable circuit structure for high-efficiency wireless power transfer," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 339–349, 2013.

[36] C. Sen Wang, G. A. Covic, and O. H. Stielau, "Investigating an LCL load resonant inverter for inductive power transfer applications," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 995–1002, 2004.

[37] X. Mou and H. Sun, "Wireless power transfer: Survey and roadmap," *IEEE Veh. Technol. Conf.*, vol. 2015, no. 646470, 2015.

[38] "Finite Element Modeling and Analysis of High Power, Low-loss Flux-Pipe Resonant Coils for Static Bidirectional Wireless Power Transfer _ Enhanced Reader."

[39] Y. Li *et al.*, "Wireless energy transfer system based on high Q flexible planar-Litz MEMS coils," *8th Annu. IEEE Int. Conf. Nano/Micro Eng. Mol. Syst. IEEE NEMS 2013*, vol. 1, no. L, pp. 837–840, 2013.

[40] F. Wen and X. L. Huang, "Human exposure to electromagnetic fields from parallel wireless power transfer systems," *Int. J. Environ. Res. Public Health*, vol. 14, no. 2, 2017.

[41] C. Panchal, S. Stegen, and J. Lu, "Review of static and dynamic wireless electric vehicle charging system," *Engineering Science and Technology, an International Journal*, vol. 21, no. 5. pp. 922–937, 2018.

[42] N. N. Nanda, S. H. Yusoff, S. F. Toha, N. F. Hasbullah, and A. S. Roszaidie, "A brief review: Basic coil designs for inductive power transfer," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 20, no. 3, pp. 1703–1716, 2020.

[43] N. This, "Guidelines For Limiting Exposure To Time-Varying Electric And Magnetic Fields (1 Hz to 100 kHz) International Commission on Non-Ionizing Radiation Protection *," pp. 818–836, 2002.

[44] H. Kanai, I. Chatterjee, and O. P. Gandhi, "Human Body Impedance for Electromagnetic Hazard Analysis in the VLF to MF Band," *IEEE Trans. Microw. Theory Tech.*, vol. 32, no. 8, pp. 763–772, 1984.

[45] N. Doumit, B. Danoumbé, S. Capraro, J. P. Chatelon, M. F. Blanc-Mignon, and J. J. Rousseau, "Temperature impact on inductance and resistance values of a coreless inductor (Cu/Al2O3)," *Microelectron. Reliab.*, vol. 72, pp. 30–33, 2017.

[46] F. O. R. Limiting, E. To, and M. Fields, "Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz TO 100 kHz)," *Health Phys.*, vol. 99, no. 6, pp. 818–836, 2010.

[47] R. Matthes, J. H. Bernhardt, A. F. McKinlay, and International Commission on Non-Ionizing Radiation Protection., *Guidelines on limiting exposure to non-ionizing radiation : a reference book based on the guidelines on limiting exposure to non-ionizing radiation and statements on special applications*, vol. 74, no. 4. 1999.

[48] Health Council of the Netherlands: ELF Electromagnetic Fields Committee, "Exposure to electromagnetic fields (0 Hz - 10 MHz)," 2000.

[49] D. Patil, M. Sirico, L. Gu, and B. Fahimi, "Maximum efficiency tracking in wireless power transfer for battery charger: Phase shift and frequency control," *ECCE 2016 - IEEE Energy Convers. Congr. Expo. Proc.*, 2016.

[50] Vidya Muthukrishnan, "Q Factor: What is it? (And How Do You Measure It?) | Electrical4U," *https://www.electrical4u.com/*, 11-Oct-2020. [Online]. Available: https://www.electrical4u.com/q-factor/. [Accessed: 01-Apr-2021].

[51] C. Cai *et al.*, "Resonant wireless charging system design for 110-kV High-voltage transmission line monitoring equipment," *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 4118–4129, 2019.

[52] X. Shi, C. Qi, M. Qu, S. Ye, and G. Wang, "Effects of coil locations on wireless power transfer via magnetic resonance coupling Effects of Coil Locations on Wireless Power Transfer via Magnetic Resonance Coupling," no. January 2017, 2016.

[53] Y. C. Hsieh, Z. R. Lin, M. C. Chen, H. C. Hsieh, Y. C. Liu, and H. J. Chiu, "High-Efficiency Wireless Power Transfer System for Electric Vehicle Applications," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 64, no. 8, pp. 942–946, 2017.

[54] J. Zhou, B. Zhang, W. Xiao, D. Qiu, and Y. Chen, “Nonlinear Parity-Time-Symmetric Model for Constant Efficiency Wireless Power Transfer: Application to a Drone-in-Flight Wireless Charging Platform,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 5, pp. 4097–4107, 2019.

[55] M. Rehman, P. Nallagownden, and Z. Baharudin, “Efficiency investigation of SS and SP compensation topologies for wireless power transfer,” *Int. J. Power Electron. Drive Syst.*, vol. 10, no. 4, pp. 2157–2164, 2019.

[56] Y. Jiang, S. Member, L. Wang, S. Member, and J. Fang, “A High-Efficiency ZVS Wireless Power Transfer System for Electric Vehicle Charging With Variable Angle Phase Shift Control,” vol. 9, no. 2, pp. 2356–2372, 2021.

[57] X. Shu, W. Xiao, and B. Zhang, “Wireless Power Supply for Small Household Appliances Using Energy Model,” *IEEE Access*, vol. 6, pp. 69592–69602, 2018.

[58] Z. Li, C. Zhu, J. Jiang, K. Song, and G. Wei, “A 3-kW Wireless Power Transfer System for Sightseeing Car Supercapacitor Charge,” *IEEE Trans. Power Electron.*, vol. 32, no. 5, pp. 3301–3316, 2017.

[59] Y. Li *et al.*, “High Efficiency WPT System for Electric Vehicles with LCL-S and SS compensation,” *2019 IEEE 4th Int. Futur. Energy Electron. Conf. IFEEC 2019*, pp. 1–4, 2019.

[60] A. Ridge, K. K. Ahamad, R. McMahon, and J. Miles, “Development of a 50 kW Wireless Power Transfer System,” *2019 IEEE PELS Work. Emerg. Technol. Wirel. Power Transf. WoW 2019*, pp. 406–409, 2019.

[61] Texas Instruments, “C2000 ™ DIMM100 Experimenter ’ s Kit Overview,” no. October. Texas Instruments Incorporated, pp. 1–8, 2017.

[62] H. A. Wheeler, “Simple inductance formulas for radio coils,” vol. 16, no. 10, pp. 1398–1400, 1928.

[63] S. S. Mohan, M. Hershenson, S. P. Boyd, and T. H. Lee, “Simple Accurate Expressions for Planar Spiral Inductances,” *iEEE J Solid-State Circuits Solid-State Circuits*, vol. 34, no. 10, pp. 1419–1424, 1999.

[64] J. L. Villa, “Optimal Design of ICPT Systems Applied to Electric Vehicle Battery Charge,” *IEEE Trans. IND*, vol. 56, no. 6, pp. 2140–2149, 2009.

[65] J. M. Miller and A. Daga, “Elements of Wireless Power Transfer Essential to High Power Charging of Heavy Duty Vehicles,” *IEEE Trans. Transp. Electrif.*, vol. 1, no. 1, pp. 26–39, 2015.

[66] W. A. Shah, “Analysis and Design of Inductive Power Transfer Systems for Automotive Battery Charging Applications,” Near East University, 2016.

[67] M. Hediehloo and M. Akhbari, “New approach in design of planar coil of induction cooker based on skin and proximity effects analysis.”

[68] C. R. Sullivan, R. Y. Zhang, and C. Sci, “Simplified Design Method for Litz Wire,” pp. 2667–2674, 2014.

[69] M. Budhia, S. Member, J. T. Boys, G. A. Covic, and S. Member, “Development of a Single-Sided Flux Magnetic Coupler for Electric Vehicle IPT Charging Systems,” vol. 60, no. 1, pp. 318–328, 2013.

[70] R. Bosshard, J. W. Kolar, and B. Wunsch, “Accurate Finite-Element Modeling and Experimental Verification of Inductive Power Transfer Coil Design,” *IEE Conf. Publ.*, pp. 1648–1653, 2014.

[71] K. Aditya, S. S. Williamson, and S. Member, “Design Guidelines to Avoid Bifurcation in a Series-Series Compensated Inductive Power Transfer System,” *IEEE Trans. Ind. Electron.*, vol. PP, no. c, p. 1, 2018.

APPENDIX A

LIST OF PUBLICATIONS

Conference Proceedings

1. Mahadi, I. A., & Yahaya, J. A. F. (2022, August). Performance Analysis of Different Shielding Material for A 100W Wireless Power Transfer System. In *Journal of Physics: Conference Series* (Vol. 2319, No. 1, p. 012006). IOP Publishing.
2. Coil Design Analysis and Performance Using Series-Parallel Inductive Power Transfer. (ICON3E 2021). Presented, but not published yet.

Journal Articles

1. Mahadi, I. A., & Yahaya, J. A. F. (2023). Performance analysis of inductive power transfer using JMAG-designer. Bulletin of Electrical Engineering and Informatics, 12(1), 33-41.
2. Evaluation Performance of Wireless Power Transfer System Using LCL Compensation Topology Under the Influence of Temperature and Humidity. Have not submitted yet (ISI journal).