FREQUENCY BASED INDUCTIVE RESONANT WIRELESS POWER TRANSFER FOR MAXIMUM OUTPUT POWER EFFICIENCY

BY

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ABSTRACT

Wireless Power Transfer (WPT) has been widely used in recent years for charging electric vehicles, powering gadgets, and activating inaccessible wireless devices. With the variety of existing technologies available, the power transferred to wireless electric vehicles, for example, is no longer an illusion. Inductive resonant technology has gained more popularity compared to their counterpart WPT technologies which are inductive and capacitive because it can transfer power over longer distances more effectively and safely. In inductive resonance, the power transferred to the load is maximized if the WPT link has a high-quality factor (Q) and the load impedance is matched properly to the system output impedance provided the WPT link works at the resonance frequency. The main considerations in inductive resonant WPT are to apply the equivalent circuit theory to the model theoretically and analyze the single load inductively coupled WPT system to ensure it works better at the resonance frequency. Therefore, this research focuses on the technique of how the resonance frequency of the inductive resonant WPT link can be estimated. In this research, the possibility of using total harmonic distortion (THD) in finding resonance frequency under varying link impedance conditions, is investigated. An experimental testbed to estimate the resonance frequency of inductive resonant WPT link was developed. Experimental data were obtained by measuring the transmitted and received voltages and then, analyzing them in the offline mode for THD estimates. The results are validated by calculating and comparing WPT performance using experimental data for relative power delivery in resonance, under-resonance, and over-resonance conditions. It has been shown that at the resonance frequency the power delivery reaches the highest point corresponding to the total harmonics distortion at the lowest peak and root mean square voltage (V_{RMS}) of the transmitted voltage (at the primary coil) at the highest peak. This suggests that the resonance frequency estimation of the inductive resonant WPT link can be implemented automatically and dynamically by measuring the transmitted voltage and finding the lowest THD peak and highest V_{RMS} peak using a specially developed algorithm or intelligent system. It is recorded that, at a distance of 0-5cm, the relative power transmitted to the load is increased by 45% at the estimated resonance frequency compared to the relative power delivered to the load at the best-fixed frequency. The result validated that the higher power is transferred to load provided the estimated resonance frequency is closer to the actual resonance frequency. Thus, it proves that it is possible to estimate the resonance frequency of the inductive resonant WPT link by finding the lowest THD value measured on the transmitter side. Therefore, the resonance frequency estimation for inductive resonant wireless power transfer using total harmonics distortion (THD) was successfully explored and employed in this research.

خلاصة البحث

في السنوات الاخيرة تم استخدام تقنية نقل الطاقة اللاسلكية WPT شكل واسع لشحن المركبات الكهربائية وتزويد الاجهزة والمعدات التي لا يمكن الوصول اليها بوسائل سلكية. لم تعد طاقة الرنين الحثي المنقولة لاسلكياُ إلى المركبات الكهربائية مجرد وهم بل اكتسبت المزيد من الشعبية مقارنة بالتقنيات المناظرة لها حيث يمكنها نقل الطاقة عبر مسافات أكثر مع المزيد من الفعالية والامان. في تقنية الرنين الحثي يتم نقل أكبر قدرة إذا كان عامل الجودة Q عالي مع تطابق معاوقة الحمل مع معاوقة خرج النظام بشرط ان تعمل عند تردد الرنين. لضمان عمل نظام WPT بشكل أفضل، يجب تحليل النظام المزدوج الأحادي الحمل باستخدام نظرية الدائرة المكافئة لنموذج نظري. لذلك ، يركز هذا البحث على كيفية تقدير تردد الرنين لتقنية الرنين الحثي WPT ديناميكيًا. في هذا البحث ، تم تطوير طريقة استخدام التشوه التوافقي الكلي (THD) في تحديد قيمة تردد الرنين في ظل تغير قيم معاوقة الارتباط المختلفة. كذلك تم تطوير اختبار تجريبي لتحديد قيم تردد الرنين المتغير لتقنية WPT. يتم الحصول على البيانات التجريبية عن طريق قياس الجهد المرسل والمستقبل ، وتحليل هذه البيانات في الوضع غير المتصل لتقدير قيمة THD. يتم التحقق من صحة النتيجة من خلال حساب ومقارنة أداء WPT باستخدام البيانات التجريبية للقدرة المرسلة لاسلكياً في ظل ظروف أقل من تردد الرنين و تردد الرنين و أعلى من تردد الرنين. من خلال النتائج يتضح انه يتم نقل أعلى قيمة للطاقة عند تردد الرنين في المقابل تكون قيمة التشوه التوافقي الكلي THD عند أدنى جهد ويكون مربع الجهد V_{RMS} للجهد المرسل في الملف الرئيسي عند أعلى قمة. نستنتج من هذا انه يمكن تقدير تردد الرنين عن طريق تحديد أقل قيمة لـ THD و أعلى ذروة للجهد المرسل V_{RMS}. علاوة على ذلك ، يشير هذا إلى أنه يمكن تقدير تردد الرنين لوصلة WPT بالرنين الحثي تلقائيًا وديناميكيًا عن طريق قياس الجهد المنقول وإيجاد أدنى ذروة THD وأعلى ذروة V_{RMS} باستخدام خوارزمية مطورة خصيصًا أو نظام ذكي. تم تسجيل أنه ضمن نطاق 0–4 سم ، تزداد الطاقة النسبية المنقولة التي يتم توصيلها إلى الحمل بنسبة 40٪ عند تردد الرنين المقدّر مقارنةً بالقدرة النسبية التي يتم توصيلها إلى الحمل عند أفضل تردد ثابت. يتم تحقيق نقل أعلى قيمة للطاقة المرسلة عندما يكون تردد الرنين المقدر أقرب إلى القيمة الفعلية لتردد الرنين. من خلال إيجاد أدنى قيمة THD يكون من الممكن تقدير تردد الرنين لنظام وبالتالي يتم بنجاح ارسال أعلى طاقة ممكنة باستخدام تقنية نقل الطاقة المرسلة لاسلكياً WPT وهي من أهم أهداف هذا البحث.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CT	Circuit Theory
DC	Direct Current
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
IHD	Individual Harmonic Distortion
IPT	Inductive Power Transfer
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
PF	Power Factor
PP	Parallel-to-Parallel
PS	Parallel-to-Series
PWM	Pulse Width Modulation
RMS	Root Mean Square
SP	Series-to-Parallel
SS	Series-to-Series
THD	Total Harmonic Distortion
WPT	Wireless Power Transfer

LIST OF SYMBOLS

avg	Average
C	Capacitance
C_p	Primary Capacitor
C_s	Secondary Capacitor
I	Current
k	Coupling Coefficient
L	Inductance
L_p	Primary Inductor
L_s	Secondary Inductor
P_{rms}	Root Means Square Power
R_x	Resistor X
V_{rms}	Root Means Square Voltage
V_s	Input Voltage
V_o	Output Voltage
W	Watt
Z_{in}	Input Impedance
Z_{out}	Output Impedance

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

In general, the concept of energy transfer through an air gap is not a new piece of new knowledge. Historically, it has been around since humans knew that magnetic coils could be used to induce an electric field. The term wireless power transfer (WPT) which is used to describe the technology to transfer energy/power to an electric load without having physical contact or medium, has been experimented with by Nicolas Tesla in the late 19th century through conducting several experiments (Shidujaman, Samani, & Arif, 2014). For example, Nicola tesla set up a large laboratory in Manhattan to conduct further experiments to realize his dream of supplying megawatt power wirelessly to ships without the need for a physical cable. He had raised a huge tower bearing a coil to provide power to the ship without requiring the ship to approach the shipyard. Unfortunately, studies in this area have been almost forgotten since Tesla's death, and some failed experiments by some pioneering works appear in the period after Tesla's death. Although Tesla was very ambitious, his work did not get much attention at the time until recently research in wireless power transfer was given a new breath, with newer research directions and interests.

With the development of electric appliances and applications, research in the wireless power transfer area has become a popular area lately. In addition, the recent research on wireless power transfer has contributed to new dimensions and aspects in the field of contactless power transfer applications (X. Lu, Wang, Niyato, Kim, & Han, 2016). For example, Electric Vehicles, which are now a reality in the very near future in metropolitan transportation, are transforming into the Park-and-Charge concept right away from now. Further, RFID and IoT devices are other areas, where passive device activation or battery charging via non-contact devices is an obvious area for wireless charging applications. Other applications of wireless power transfer are autonomous underwater vehicles, public transport, for example, monorail, industrial automation, and robot manipulation and maneuvering of autonomous objects and unmanned aerial vehicles. Similarly, powering devices buried in civil structures for monitoring the purpose of physical parameters or activation of implants for the measurement of biological or biomedical parameters are areas where wireless power transfer has proven to be the only means of application (S. R. Khan, Pavuluri, Cummins, & Desmulliez, 2020).

Inductive resonant wireless power transfer is one of the most popular areas of wireless power transfer research. However, one of the main challenges in inductive resonant WPT is the loss of energy on the way from the energy source to the target device. There is a lot of work reported to overcome or reduce power loss throughout power transmission. Work addressing research parameters such as coil design, geometry or shape, resonance frequency channel parameters, or the effect of gap separation in the form of coupling coefficients has been widely reported. On top of that, there are other works reported, for example, fine-tuning the primary or/and the secondary capacitor for tuning and conditioning reasons; fine-tuning the primary or/and the secondary coils; and load impedance matching, to name a few.

This research addresses the optimization of power transfer through resonance frequency adjustment as well as focuses on techniques on how the resonance frequency of the inductive resonant WPT link can be estimated through simpler implementation efforts. In other words, this research is about proposing, validating, and verifying resonance frequency estimation techniques for inductive resonant wireless power transfer (WPT).

1.2 RESEARCH QUESTION

The inductive resonant wireless power transfer efficiency can be maximized by ensuring the operating frequency as close as possible to the secondary coil resonance frequency. If the system is at the resonance frequency of the secondary coil, then the quality factor (Q) of the system is high. This ensures that almost all power at the primary coil is transferred to the secondary coil. Therefore, the major research question of this research is about devising a technique to estimate the resonance frequency with accuracy, making it a reason for estimating the coupling coefficient (k) of the inductive resonant WPT link. The open research question is whether such a technique can be reliably used to estimate the resonance frequency of inductive resonant wireless power transfer. Will the technique in stand-alone mode prove sufficient or require other parameters in the association? Exploring this work onward will pave the way into areas of automatic resonance frequency tracking and self-tuning research activities.

1.3 RESEARCH PHILOSOPHY

In general, almost all inductive resonant wireless power transfers rely on the square waves generated to run the DC-to-DC network in the form of an H-bridge as the voltage source. The voltage source in the form of a square wave is injected into the transmitter unit mutually coupled with the receiver unit. Depending on the resistance and reactance of the inductive resonant WPT system, the transmitted voltage is the result of a square wave signal modified by the inductive resonant WPT link response. In general, the resulting transmitted voltage depends on the frequency of the square wave injected into the WPT link, as well as the resonance frequency of the WPT link. The operating frequency or period of the injected square wave should be kept close to the resonance frequency of the WPT link to ensure that the source finding the chain of the device mounted on the receiving unit appears to be a purely resistive load. The objective of this thesis is to estimate the resonance frequency of inductive resonant wireless power transfer by analyzing the transmitted voltage. Initially, total harmonics distortion (THD), Crest Factor, and VRMS were suggested as parameters to be used in estimating resonance frequency.

1.4 RESEARCH HYPOTHESIS

The hypothesis of the research is:

"It is possible to develop a method to estimate the resonance frequency of inductive resonant wireless power transfer links."

The research hypothesis is based on:

1- Assuming an inductive resonant wireless power transfer link is like a bandpass filter.

2- Assuming the inductive resonant WPT link allows the frequency components within its passband and discriminates all other frequency components.

3- Assuming that the resonance frequency of the inductive resonant WPT link can be estimated by the frequency response of the transmitting voltage across its primary coil.

1.5 PROBLEM STATEMENTS

In the resonant inductive wireless power transfer system, the energy from the primary coil is transferred inductively through the air gap to the secondary coil. This is usually implemented with purposely designed transformers. As with a wired power transmission system, power transmission efficiency in a wireless power transfer system is highly dependent on the capability of energy delivered from the primary coil to the secondary coil. It has been observed that ensuring high power transmission efficiency is one of the most popular branches of research in wireless power transfer technology as well as the most challenging field for researchers.

Several factors are affecting the amount of power delivered to load. The most prominent factor is the coupling coefficient between the two coils. In contrast to the conventional transformer, the WPT coils are placed apart or/and aligned at some angle orientation. The farther the secondary coil is from the primary coil, the lower the amount of magnetic flux produced by the primary coil cutting through the secondary coil (Q. Li & Liang, 2015). As a result, the lesser the coupling coefficient between the two coils and the lesser power is delivered to load. The situation is the same if the two coils are aligned at an angle, the power transfer is maximum if the coils are arranged coaxially with the plane of the coils parallel to each other.

Another factor influencing the amount of power transfer is the quality factor (Q) of the secondary resonant coil. Where the ratio of energy store to energy loss is determined by the system quality factor which in other words, active or effective power gets wasted due to the presence of reactive power. Therefore, the presence of reactive power in the system must be reduced to improve power transfer. One way to address this wastage of power is to use tuning capacitors coupled to coils on both sides. Therefore, power transfer can be maximized by ensuring that the inductive resonant WPT works at the resonance frequency determined by the inductive and capacitive elements of the system. In (W. Zhang & Mi, 2016), the resonance frequency of the system has been proven to be determined by the resonance frequency of the receiving coil. For these reasons, the resonance frequency of the primary and secondary coils is practically set to operate at the same frequency.

However, the resonance frequency of the WPT is not regulated primarily by the capacitance and inductance of the system. The resonance frequency of the WPT also