MULTIPLE COIL PAIR GEOMETRIC DESIGNS FOR INDUCTIVE WIRELESS POWER TRANSFER

BY

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ABSTRACT

The inductance coil of the transmitter and receiver coils plays a significant role in the inductive wireless power transfer (IWPT) charging system for electric vehicles (EVs). The dynamic wireless charging (DWC) system is based on the inductive coupling between an electrified road transmitter track and a receiver coil embedded underneath the EV chassis. Most researchers design the coil pair with the same coil geometric designs for the transmitter and receiver coils which is the conventional way of IWPT charging system. Hence, this research investigates a new coil pair combination that utilises different coil geometric designs to compare if the new proposed combination can be as efficient as the conventional coil pair. The proposed coil pairs are expected to show a slightly lower efficiency when compared to the established existing coil pair. The transmitter coil is made of double-D (DD) geometric, whilst the receiver coil is made of a circular geometric design. A 2000 mm long DD transmitter coil is designed along with five circular receiver coils with 400 mm outer dimensions (D_{out}). There are five proposed coil pairs (T-R1, T-R2, T-R3, T-R4, T-R5), all of which have the same dimension for the DD transmitter coil and circular receiver coils' outer diameter (D_{out}) but having different circular receiver coil inner diameter (D_{in}) among the five of them. These variations are significant as different EV manufacturers might have different preferences on designing and building inductance coils. Intensive calculations are done for coil parameters and geometric properties for the five proposed coil pairs. The coil parameters calculations are done to calculate the electrical parameters for the IWPT circuit's components. Meanwhile, the geometric properties calculations are done to calculate the suitable dimensions and coil turns number of the proposed coil pairs. For the performance analyses simulations, the power transmission efficiency (PTE), magnetic flux density (MFD), and transmitted power (P_{tx}) are analysed further using the JMAG Designer software. The compatibility of the proposed coil pairs is simulated for three different conditions, which are air-gap, lateral misalignment, and vertical movement conditions. All the proposed coil pairs showed a good result in terms of their compatibility. Each has a PTE greater than 60%, which follows a test conducted by UC Berkeley on the dynamic charging concept, and the MFD is within the standard limits. The MFD at several observation points under different conditions are analysed to meet the level defined in the ICNIRP standard. T-R4 has the best PTE, MFD, and P_{tx} performances, whereas T-R1 demonstrated the most unsatisfactory performances. When the performance analyses were completed, it was determined that all five proposed coil pairs exceeded or met the PTE and MFD performance standards. These results conclude that the DD transmitter coil and circular receiver coil are compatible to couple. This coil pair is a new combination of existing coil geometric designs that have never been reported in the literature. Thus, this study is establishing opportunities to improve this technology and investigating the feasibility of designing a coil pair that meets the preferred needs of multiple EV models in a more efficient and effective manner.

ملخص البحث

في نظام الشحن الاستقرائي لنقل الطاقة اللاسلكية (IWPT) للمركبات الكهربائية (EVs)، تلعب لفائف الحث للفائف المرسل والمستقبل دورًا مهمًا. يعتمد نظام الشحن اللاسلكي الديناميكي (DWC) على الاقتران الاستقرائي بين مسار مرسل الطريق المكهربة وملف المستقبل الموضوع أسفل هيكل EV. تستخدم معظم الدراسات نفس التصميمات الهندسية للملف لملفات المرسل والمستقبل، وهي الطريقة التقليدية لنظام الشحن IWPT. نتيجة لذلك، يدرس هذا البحث تركيبة زوج لفائف جديدة تستخدم تصميمات هندسية مختلفة للملف لمعرفة ما إذا كانت فعالة مثل زوج الملف التقليدي. عند مقارنتها بزوج الملف الحالي، من المتوقع أن يكون لأزواج الفائف المقترحة كفاءة أقل قليلاً. تم تصميم ملف الإرسال بنمط هندسي مزدوج (DD)، في حين أن ملف الاستقبال مصمم بنمط دائري. تم تصميم ملف إرسال DD بطول 2000 مم، وكذلك خمس ملفات استقبال دائرية بأقطار خارجية 400 مم (*Dout*). هناك خمسة أزواج ملفات مقترحة (T-R5 , T-R4 , T-R3 , T-R2, T-R1)، وكلها لها نفس ملف مرسل DD والأبعاد الخارجية لملفات الاستقبال الدائرية (*Dout*) لكن لفائف الاستقبال الدائرية كانت مختلفة القطر الداخلي (*Din*). هذه الاختلافات مهمة لأن الشركات المصنعة للمركبات الكهربائية المختلفة قد يكون لها تفضيلات متنوعة لتصميم وبناء ملف الحث. تخضع أزواج الملفات الخمسة المقترحة لحسابات مكثفة لعوامل الملف وخصائصها الهندسية. يتم حساب العوامل الكهربائية لمكونات دائرة IWPT باستخدام عوامل الملف. وفي الوقت نفسه، يتم حساب الخصائص الهندسية لأزواج الملفات المقترحة لتحديد الحجم المناسب وعدد لفات الملف. يتم فحص كفاءة نقل الطاقة (PTE)، كثافة التدفق المغناطيسي (MFD)، والقدرة المرسلة (*Ptx*) يتم فحصها بشكل أكبر باستخدام برنامج JMAG Designer لمحاكاة تحليل الأداء. يتم استخدام كل من فجوة الهواء، والخطأ الجانبي، وظروف الحركة العمودية لنمذجة توافق أزواج الملفات المقترحة. من حيث توافقها، كان أداء جميع أزواج الملفات المقترحة جيدًا. كل منها لديه PTE لأكثر من 60٪، بناءً على اختبار جامعة كاليفورنيا في بيركلي لمفهوم الشحن الديناميكي، وMFD ضمن الحدود القياسية. يتم تحليل MFD في نقاط مراقبة متعددة في ظل مواقف مختلفة لمعرفة ما إذا كان يفي بالمستوى القياسي ICNIRP. يتمتع T-R4 بأفضل نتائج PTE وMFD وPtx، في حين أن T-R1 كانت لديه نتائج غير مرضية. بعد الانتهاء من تحليلات الأداء، تم اكتشاف أن جميع أزواج الملفات الخمسة المقترحة قد تجاوزت أو استوفت معايير أداء PTE و MFD. تشير هذه النتائج إلى أن ملف الاستقبال الدائري وملف إرسال DD متوافقان للاقتران. زوج الملف هذا عبارة عن مزيج جديد من التصميمات الهندسية للملفات المنشورة مسبقًا. ونتيجة لذلك، فإن الهدف من هذا البحث هو إيجاد طرق لتحسين هذه التقنية ومعرفة ما إذا كان من الممكن تطوير زوج من الملفات يتوافق مع تفضيلات العديد من طرز المركبات الكهربائية بطريقة أكثر كفاءة وفعالية.

APPROVAL PAGE

I certify that I have supervised and read this study and that, in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Engineering.

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DECLARATION

I hereby declare that this thesis is the results 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 degree at IIUM or other institutions.

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For myself, my family, my loved ones and for the world…

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LIST OF ABBREVIATIONS

2D	2-Dimension
3D	3-Dimension
AC	Alternating Current
AWG	Additive Wire Gauge
CSC	Circular Spiral Coil
CT	Compensation Topology
CWPT	Capacitive Wireless Power Transfer
DC	Direct Current
DD	Double-D
DDC	Double-D Coil
DWC	Dynamic Wireless Charging
EMI	Electromagnetic Interference
EV	Electric Vehicle
FEM	Finite Element Method
FFH	Fundamental Flux Height
GMR	Giant Magnetoresistance
IMN	Impedance Matching Network
IWPT	Inductive Wireless Power Transfer
LCC-LCC	Inductor, Capacitor, Capacitor-Inductor, Capacitor, Capacitor
MFD	Magnetic Flux Density
NI	National Instrument
PFV	Petroleum-Fuelled Vehicle
PP	Parallel-Parallel
PS	Parallel-Series
PTE	Power Transmission Efficiency
RC	Rectangular Coil
RMS	Root Mean Square
SC	Square Coil
SDG	Sustainable Development Goals

SOC	State-of-Charge
SP	Series-Parallel
SS	Series-Series
SWC	Static Wireless Charging
T-R1	Coil Pair 1
T-R2	Coil Pair 2
T-R3	Coil Pair 3
T-R4	Coil Pair 4
T-R5	Coil Pair 5
VA	Volt-Ampere
VAR	Volt-Ampere Reactive
WPT	Wireless Power Transfer
ZPA	Zero Phase Angle

LIST OF SYMBOLS

η	Power Transmission Efficiency (PTE)
B	Magnetic Flux Density (MFD)
C_1	Capacitor 1
C_2	Capacitor 2
C_3	Capacitor 3
C_4	Capacitor 4
C_p	Transmitter capacitance
C_s	Receiver capacitance
d	Distance between two parallel straight wires of different D coil
D_{in}	Circular receiver coil inner diameter
D_{ℓ}	D coil length
$D_{\ell_{in}}$	D coil inner length
D_{out}	Circular receiver coil outer diameter
D_{w}	D coil width
$D_{w_{in}}$	D coil inner width
DD_{ℓ}	DD coil length
DD_{w}	DD coil width
I_p	Transmitter current
$I_{p_{RMS}}$	Transmitter RMS current
I_s	Receiver current
$I_{s_{RMS}}$	Receiver RMS current
k	Coupling coefficient
k_c	Critical coupling coefficient
ℓ	Length
L_{DD}	DD coil total inductance
L_{sc}	D coil self-inductance
L_p	Transmitter coil self-inductance
L_s	Receiver coil self-inductance

L_{f1}	Compensated inductance for LCC (transmitter side)
L_{f2}	Compensated inductance for LCC (receiver side)
M	Mutual inductance
M_{sc}	DD coil mutual inductance
N	Coil turns number
N_R	Receiver coil turns number
N_T	Transmitter coil turns number
P	Power
P_{rx}	Received power
P_{tx}	Transmitted power
Q_s	Receiver quality factor
r	Radius of coil wire
R_L	Load resistance
R_p	Transmitter internal resistance
R_s	Receiver internal resistance
U_1	AC voltage for inverter
U_2	AC voltage for rectifier
V_p	Transmitter voltage
$V_{p_{RMS}}$	Transmitter RMS voltage
V_s	Receiver voltage
$V_{s_{RMS}}$	Receiver RMS voltage
ω	Operating frequency
w	Width
ΔMFD	MFD difference or MFD loss
ΔPTE	Percentage difference or PTE loss

CHAPTER ONE

INTRODUCTION

1.1 RESEARCH BACKGROUND

A wireless power transfer (WPT) system is a system where the transmission of electrical power from one object to another is possible through an air-gap without any physical contact. There are different approaches to wireless power transfer (WPT), either Capacitive Wireless Power Transfer (CWPT) or Inductive Wireless Power Transfer (IWPT) (Ko & Jang, 2013). CWPT relies on the coupling of two plates that produce an electric field. The alternating voltage of the transmitter plate will create the electrostatic field on the receiver plate caused by the induced EMF from the oscillating electric field (Huang & Hu, 2015). The CWPT can only be used for low power applications, such as drone charging or mobile charging. This CWPT approach is obviously less suitable for charging electric vehicles (EVs) (Silva & Petry, 2015; Vincent et al., 2018).

However, this approach might be able to be implemented for the EV if a proper design of compensation network is utilised (Elekhtiar et al., 2018). Meanwhile, in IWPT, the field created from the coupling of the two inductance coils is referred to as the magnetic field. The magnetic field is created in between the transmitter and receiver coils as they are inductively coupled during the EV charging process. The magnetic field produced results from obeying Ampere's Law and Faraday's Law (Patil et al., 2017). The source generates an alternating current that creates an oscillating magnetic field at the transmitter coil. The magnetic field produced is then passed through to the receiver coil, producing the induced alternating current to flow in the load of the circuit, which is typically the EV battery.

The implementation of the IWPT system to the EV has hugely evolved after the issue related to the depletion of energy resources, especially petroleum, started to get global attention. Besides that, the fact that petroleum gas emission has contributed to air pollution is also one of the factors that lead to EV development (Bauer, 2019). This development is seen to receive favour from the consumers since the EV does not emit any harmful gasses as it utilises energy from battery packs to move. Fortunately, this arising issue is supported by the willingness of car manufacturers to be involved in this green technology as well.

The implementation of WPT has contributed tremendously to the transportation industry, especially the IWPT concept. IWPT uses the power transmission coil principle to transfer electrical power from the main grid source to energise EVs. This IWPT concept is also referred to as EV wireless charging. People have started to pay attention to the depletion of energy resources, especially petroleum since EV technology was introduced. This depletion is due to the increase in population, contributing to an increase in vehicle usage on the road. This increment might assist in economic and social development since people are able to travel everywhere to meet anyone. However, this increment is a barricade to the preservation of petroleum sources. Hence, electric propulsion is likely to be the main source in the future as it does not create pollution. It is also a part of renewable energy sources (Liang Chen et al., 2014).

This measure is introduced to improve transportation energy and economic and social development to achieve sustainability in all aspects (Foundation et al., 2018). Since transportation is fuelled by energy, this effort is directly linked to Sustainable Development

Goals 7 (SDG 7). The goal is to achieve affordable and clean energy, which also interlinks with all 17 SDGs. This is why the alternative to petroleum to power up the vehicle is slowly changing to electrification, commonly known as EV. With electric propulsion, no unwanted gasses are released from driving an EV and thus, pollution can be reduced. People today are more aware of the importance of a green environment and its impact on human health. Hazardous gas from burning petroleum is not good for humans. It can cause some diseases, such as asthma, eye irritation, and cancer (Afridi, 2018). Fortunately, this arising issue is also supported by the willingness of car manufacturers to involve in producing clean and sustainable vehicles. The shifting of internal combustion engine vehicles to electrified engine vehicles is also positively growing. This shift is expected to improve gradually as the EV is becoming more accessible and affordable to all as it is critical for sustainable development (Foundation et al., 2018).

Thus, in 2013, Malaysia's government introduced the first EV in Malaysia, which is Mitsubishi i-MiEV (Shah, 2013). Nonetheless, even though the Malaysian government has granted a full tax exemption for the EV, the price still reaches almost RM 136 118.50 without insurance. Thus, resulting it fails to catch people's attention due to its expensive price (Shah, 2013). Until today, the EVs in Malaysia are still not seen regularly on the road. This is due to its travel range limitation. In Malaysia, not all petrol stations provide the EV charger. However, the Malaysian government aims to build a 3,000 EV charging station infrastructure to help increase the market for EVs (Zakariah, 2018).

The EV charging process can be either wired charging or wireless charging to fuel the power source of the vehicle. The wired charging concept utilises the same concept as fuelling petroleum to a vehicle which is done through a cable. The wired charging concept for EV is seen as the conventional way of charging and has become inconvenient in today's transportation industry due to the long hours of charging time. Besides that, it is also dangerous to leave the charging cable inserted into the EV's tank unattended. For that reason, tremendous efforts to enable the EV to be recharged wirelessly have been implemented. This research focuses on wireless charging that utilises the IWPT principle.

In the wireless charging process, the transmitter coil is the inductance coil embedded underneath the road. Whilst the receiver coil is the inductance coil installed underneath the EV chassis. The transmitter coil will transmit the electrical power to the receiver coil through an air-gap that is linked by the electromagnetic coupling once the transmitter and receiver coils are on top of each other. For the two inductance coils to be electromagnetically or inductively coupled, the system starts by getting a direct current (DC) input from the power supply. The DC voltage is then converted to the AC voltage induced by the AC current. The change in current through the transmitter coil creates a changing magnetic field. Then, this changing magnetic field induces an electromotive force (EMF) in the receiver coil.

With the fast growth of the EV market and the attraction of new technology to recharge the EV battery, the IWPT technology has now moved from static wireless charging (SWC) to dynamic wireless charging (DWC) (Ahmad et al., 2017). In SWC, the wireless charging process of an EV is done while the EV is parked on top of the transmitter coil. On the other hand, DWC operation offers to recharge the EV battery while EV is moving. The dynamic IWPT system uses the coupling power transmission principle to transfer electrical power from the stationary transmitter coil to energise the moving receiver coil embedded underneath the EV chassis (Grant A. Covic & Boys, 2013). It means that

EVs will not need to consume time to stop and park at the designated area just to wait for at least 4 hours of full charging before continuing the journey. In other words, DWC is able to extend the range of the EV by applying the IWPT technique. On top of that, this new technology also offers benefits in terms of overall battery capacity reduction, which may lead to the reduction of overall EV cost. Furthermore, it is expected that in 30 years from now, the demand for EVs will be high as it is much more environmentally friendly. That is the main reason for this research to design the coil pair that could help achieve the world's future goals while exploring its versatility.

The IWPT principle is not just applied to the EV but also supply power to the household appliances, biological implants, and other means of transportation, such as buses and shuttle vehicles (Ahn & Kim, 2011; Miller, Jones, et al., 2015; Na et al., 2015; Suh et al., 2011). Currently, most researchers focus on the power transmission efficiency (PTE), coil geometric designs, coupling coefficient, misalignment tolerance, and air-gap between the inductively coupled coil (Deshmukh & Talange, 2015; Vaka & Kumar, 2018; Xiang et al., 2018). Countless studies are executed on different geometric designs to guarantee good coupling even in conditions of misalignment. There is no discussion yet related to the coupling coil compatibility that utilises different geometric designs at both transmitter and receiver sides.

Therefore, this research will investigate several basic coil geometric designs commonly used for EV applications. In this research, the coil pair will be made coreless, which means no ferrite core is involved. Hence, there will be no discussions on other coils geometric, such as E-type, U-type, W-type, I-type, and S-type, as these geometric dominate the use of ferrite, which leads to higher cost. The analysis of the basic coil geometric