ENHANCING WIRELESS POWER TRANSFER EFFICIENCY FOR POTENTIAL USE IN CARDIOVASCULAR APPLICATIONS

LUM KIN YUN

UNIVERSITI TEKNOLOGI MALAYSIA

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LUM KIN YUN

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Dedicated to my mum and dad,

my brother and sisters,

and my beloved friends.

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ABSTRACT

Left Ventricular Assist Devices (LVAD) are being used to assist blood circulation in heart failure patients. The requirement to have a continuous energy supply is deteriorating the patients' life quality since they need either to carry along two heavy battery packs or to attach a power cable. For this reason, a wireless power transmission (WPT) system is developed to power the LVAD. Within its effective charging region, the WPT system will offer an autonomous charging process which may lead to a smaller battery pack and cableless experience to the user. Previous WPT systems for cardiovascular applications are either compromised by poor transfer efficiency, short transmission distance or safety issues. To address these problems, an impedance matching WPT system is being designed. For increasing the overall transfer efficiency, both sides impedance matching technique and low loss matching networks are being worked on. In addition, efficiency specific design approach is being developed to reduce design complexity. As a result, the transfer efficiency and transmission distance of the impedance matched WPT have been increased by a factor of 7 and 6 times respectively. The conceptual idea for implementing such a system is also discussed in this thesis. Furthermore, safety measurements have been performed to ensure the system is safe to be used.

ABSTRAK

Pesakit lemah jantung memerlukan Peranti Pembantu Ventrikal Kiri (LVAD) untuk membantu pengepaman darah ke seluruh badan. Bekalan elektrik sama ada daripada bateri ataupun kabel elektrik adalah diperlukan untuk memastikan LVAD sentiasa berfungsi. Ini telah membawa banyak kesukaran kepada pengguna LVAD. Oleh yang demikian, sistem penghantaran kuasa tanpa wayar (WPT) telah direka bentuk demi memberikan kesenangan kepada pengguna. Dengan adanya sistem ini, bekalan elektrik yang beterusan boleh diberikan kepada pengguna. Ini akan menyumbang kepada penggunaan bateri yang lebih kecil. Sistem WPT yang digunapakai sebelum ini mempunyai masalah-masalah seperti kecekapan yang rendah, jarak penghantaran yang pendek dan isu-isu keselamatan semasa dipakai. Bagi menangani masalah-masalah ini, sistem WPT yang berasaskan prinsip kepadanan impedan telah dihasilkan. Teknik padanan impedan pada kedua-dua belah sistem dan teknik litar padanan yang bersifat kehilangan kuasa rendah telah direka bentuk demi meningkatkan kecekapan sistem WPT ini. Di samping itu, cara reka bentuk WPT yang lebih mudah telah dikeluarkan. Hasil kajian menunjukkan peningkatan kecekapan sistem sebanyak 7 kali ganda dan peningkatan jarak pemindahan sebanyak 6 kali ganda. Konsep pemasangan bagi sistem yang telah dicadang juga dibincang dalam tesis ini. Pengukuran dari segi keselamatan juga dilaksanakan bagi memastikan sistem ini bertugas mengikut penunjuk keselamatan yang sedia ada.

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LIST OF ABBREVIATIONS

AC	-	Alternating current
ADS	-	Advanced Design System
CMT	-	Coupled mode theory
DC	-	Direct current
FEM	-	Finite-element method
ICNIRP	-	International Commission on Non-Ionizing Radiation Protection
IJN	-	Institut Jantung Negara or National Heart Institute
IPT	-	Inductive power transfer
ISM	-	Industrial, Science, Medical
ITN	-	Impedance transformation network
KVL	-	Kirchhoff's Voltage Law
LVAD	-	Left ventricular assist device
MIT	-	Massachusetts Institute of Technology
PP	-	Parallel-to-parallel topology
PS	-	Parallel-to-serial topology
RF	-	Radio frequency
Rx	-	Receiver
SAR	-	Specific Absorption Rate
SP	-	Serial-to-parallel topology
SS	-	Serial-to-serial topology
TET	-	Transcutaneous Energy Transfer
Tx	-	Transmitter
VAD	-	Ventricular assist device
VNA	-	Vector Network Analyzer
WHO	-	World Health Organization
WPT	-	Wireless power transmission

LIST OF SYMBOLS

η	-	Transfer efficiency
ω	-	Angular frequency
C	-	Capacitance
f	-	Resonant frequency
I	-	AC Current
k	-	Coupling coefficient
L	-	Inductance
M	-	Mutual inductance
m	-	Impedance ratio
P	-	Power
Q	-	Quality factor
R_P	-	Parallel resistance
R_S	-	Series resistance
S_{11}	-	Reflection coefficient
S_{21}	-	Forward gain
V	-	AC Voltage
X	-	Reactant
Z	-	Impedance
Z_{in}	-	Input impedance
Z_{out}	-	Output impedance

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Heart disease is the major cause of death disease in Malaysia. It remains to be the leading cause of death for more than four decades and contributes to 30% of mortality. Due to donor shortages, left ventricular assist device (LVAD) is commonly used in Institut Jantung Negara (IJN) Malaysia for treating heart failure patients. It is an implanted mechanical pump which function is to assist the blood circulation. LVAD can be utilized as either bridge-to-transplant therapy or as the destination therapy.

The pump is fed by two external batteries which are about 2kg in weight. The batteries can only last for less than 6 hours of continuous operations. It requires 4 to 5 hours to recharge a fully depleted battery on the given charging station. While sleeping, the patient is required to connect with a backup power cable in order to safeguard the LVAD operations. Consequently, the patient's freedom and mobility are greatly hindered.

Based on the feedbacks from the medical doctor of IJN, patients often forget to switch on the charging station after battery replacement. Other than that, frequent battery removal as well causes oxidation to the connector leads and results in a poor electrical connection.

For these reasons, a wireless power transmission (WPT) system is being proposed to improve patient's life quality. This system will charge the battery used to power the LVAD automatically as long as it is staying within its effective charging area. As a result, forgetful human interventions can be eliminated. The patient can now move freely without being entangled by the power cable. Since power is more readily available, a smaller battery can be used without replacement.

Previous attempts to implement the WPT system into the biomedical devices based on the concept of inductive power transfer (IPT) system did not demonstrate a good performance. For example, transcutaneous energy transfer (TET) system in AbioCor mechanical heart was having the issues on transfer efficiency, transmission distance, size and patient safety (Congdon, 2013; Dissanayake *et al.*, 2010; Hashimoto and Shiba, 2015). Another attempt based on the magnetic coupled resonant system was put in place to drive a LVAD. Despite its good transfer efficiency, high operating frequency does violate the safety regulation (Hui *et al.*, 2014). Besides, its practical implementation is also restricted by its space occupying multi-coils system.

The challenges to apply WPT system in driving the LVAD will be uncovered in this thesis and corresponding solutions were discussed in-depth.

1.2 Problem Statement

The following issues have to be considered altogether while designing a WPT system dedicated to power a LVAD.

1. **Efficiency** - Efficient WPT is required to ensure sufficient amount of power is delivered to the target. Additionally, efficient system is also intended to reduce the transmitting power which may lead to excessive tissue heating for safety considerations.
2. **Size and weight** - The WPT system should not burden the user who is wearing the system. Hence, it needs to be small in size and light in weight.
3. **Safety** (Christ *et al.*, 2013b) - The WPT system must be safe to be used in order to reduce any adverse health effect. In order to do so, the safety measure of the system should be studied along with the.

Existing WPT system failed to accomplish all the above-mentioned criteria. Even though high efficiency had been reported, they are either too bulky or unsafe to be used for biomedical application (Kim *et al.*, 2015; Kurs *et al.*, 2007). When it is bounded by all the above-mentioned criteria, the only feasible solution to have an efficient WPT system is by impedance matching (Pinuela *et al.*, 2013).

Nevertheless, current impedance matching solution did suffer from the following limitations:

1. **Both side matching** (Park *et al.*, 2011) - Due to the complexity of having a matching design on both transmitting and receiving end simultaneously, previous works are mainly focusing on single side matching or remaining to be a conceptual discussion. However, it is important to have both side matching in order to enhance the overall transfer efficiency of the WPT system.
2. **Efficiency specific design** (Awai and Ishizaki, 2012) - Previous studies have limited knowledge regarding the impedance matching design and the transfer efficiency. In order to avoid repeating trial and error design steps, it is important to relate the impedance matching design with the efficiency outcome.
3. **Power loss in the matching circuit** (Huwig and Wambsganss, 2013) - Conventional matching circuit used to transform the impedance into the optimal value suffers great power loss due to the lossy inductor. To maintain the overall transfer efficiency, it is required to have a low loss impedance transformation network.
4. **Coil size different** (Li *et al.*, 2012) - It is common to have the size disparity between the transmitter and receiver due to the smaller size of the implanted devices. The impedance matching design must cater for this working condition.
5. **Different WPT topologies** (Hannan *et al.*, 2014) - There is a total of four different WPT topologies based on the series and parallel combinations of the transmitter and receiver. Certain topology is preferable over the rest in some specific application (Guo and Jegadeesan, 2012; Ni *et al.*, 2013). The impedance matching design approach must not be only tackling on one or two topologies.

All the mentioned problems in this section and the relevant works will be examined in details in Chapter 2 of this thesis.

1.3 Objectives

This study aims to fill up the research gap by solving the problems mentioned in the previous section. Therefore, the objectives of this study are:

1. To design an innovative purely resistive both side impedance matching technique to enhance the overall transfer efficiency of the WPT system.
2. To simplify designing steps of the WPT system by having an efficiency specified ratio impedance matching design.
3. To design a purely capacitive low loss impedance transformation networks dedicated to reduce the power loss during the impedance transformation process.

At the same time, all the proposed techniques must be applicable to the system with different coil size and different WPT topologies.

1.4 Scope of the Study

The design of the WPT system for biomedical devices is limited to the following scopes:

1. **Power** - Maximum transmissible power must not be over 30 Watts which is confined by the safety regulations.
2. **Frequency** - The operating frequency must be lower than 1 MHz bounded by the ISM bandwidth and safety concerns.
3. **Compact** - Two-coil WPT system is used instead of the four-coils WPT system to reduce the size and weight of the system.
4. **Efficiency** - The WPT system should be able to have at least 60% transfer efficiency.
5. **Distance** - The transmissible distance should be more than one coil diameter or about to be 12cm.
6. **Target Device** - Thoratec HeartMate II® LVAD and HeartWare® LVAD.

1.5 Organization of The Thesis

Chapter 1 is briefly introducing the motivation for the study and those challenges for having a WPT system in powering the LVAD. This research is aimed at improving the transfer efficiency of the WPT system by impedance matching. Hence, limitations in current studies for having an impedance matched WPT system to drive the LVAD has been highlighted in the problem statement section. The objectives are formulated to address the research gaps. Finally, job scopes for this study are being listed.

Chapter 2 is all about the literature studies. Reviews on the WPT technologies and their applications on cardiovascular applications have been done. Then, the safety measure is being reviewed thoroughly. For improving the efficiency of the WPT system, impedance matching technique is used. There is critical reviews section focus on how to fill up the research gap in designing an impedance matched WPT system for driving a LVAD. Some relevant theories are also part of this chapter.

The methodologies for having a WPT system in driving a LVAD are presented in Chapter 3. It is first showing the idea for integrating the WPT system in a big picture. The system framework is shown and the design specifications are being listed. In-depth analyses are carried out to understand the working principle of the WPT systems. Then, the three proposed solutions to improve the transfer efficiency of a WPT system are organized to follow the order of the objectives. All the proposed solutions are being verified by mathematics models, software simulations, and experimental prototypes for consistency and correctness of the design. To indicate the safeness of the WPT system, safety measurements are also carried out to the readied designed system.

Chapter 4 is showing all the results from the previous chapter accompanies by discussions. The results to be shown are consisting of the system analyses, three proposed solutions and safety measurements. The results are oriented to improve the transfer efficiency and the matching of the impedances. Benchmarking with previous literature is being included. Safety test results are portrayed alongside with the exposure guidelines. After that, the advantages offer by the proposed WPT system as compared to other two systems used in cardiovascular applications are shown.

Chapter 5 is concluding all the findings from this study with respect to the research objectives. Knowledge contributions are also listed out along the way. Possible expansion to the current study is also mentioned as the future works.

1. Since frequency matching tends to violate the safety regulation, it is not encouraged to be used in practical especially from the biomedical perspective. However, it remains to be the simplest approach to tune the system to work efficiently in the over coupled regime. To solve this problem, researchers are coming out with the adaptive matching technique to match the impedance at different operating distance. However, the proposed system is over complicated due to the requirement of complex tracking and feedback systems. The added complexity is mainly due to the considerations to take care of every single possible operating distance, which results in a significantly large amount of matching set. In order to address this problem, a limited set of matching systems can be used and consequently lead to a much simpler control system. Examining Figure [fig:DiffEff], there exists overlapping between each matching set. By properly setting the matching set combination, there will be only 5 to 6 sets of matching circuit required. Hence, a much simpler adaptive impedance matching circuits can be yielded.
2. This study can be further extended to drive multiple receivers in order to power up several medical devices at the same time. However, cross coupling among the receivers will hinder the power received by each individual receiver. In order to avoid the happening of the over-power or under-power condition, proper tuning of the load impedance can be the next study.
3. The issue of coils misalignment is not being studied in this work. This is one of the practical implementation issues when used to drive a LVAD. Even though it is commonly known that misalignment will lower the coupling coefficient and consequently lead to a poor transfer efficiency, it is recommended to perform the experimental study to get the better understanding of the system limitations.

5.4 Chapter Summary

This chapter is concluding the research findings with respect to the research objectives in chapter 1. At the same time, knowledge contributions by this work has been mentioned. Some possible future works to extend this study are also being presented.

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