# ENHANCING WIRELESS POWER TRANSFER EFFICIENCY FOR POTENTIAL USE IN CARDIOVASCULAR APPLICATIONS

LUM KIN YUN

UNIVERSITI TEKNOLOGI MALAYSIA

# ENHANCING WIRELESS POWER TRANSFER EFFICIENCY FOR POTENTIAL USE IN CARDIOVASCULAR APPLICATIONS

## LUM KIN YUN

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Biomedical Engineering)

Faculty of Biosciences and Medical Engineering Universiti Teknologi Malaysia

**JULY 2016** 

Dedicated to my mum and dad,

my brother and sisters,

and my beloved friends.

### **ACKNOWLEDGEMENT**

First of all, I would like to say thank you to my supervisor, Dr Tan Tian Swee for all his given guidance and assistance throughout my whole PhD journey. Countless useful advice had been bestowed by him which were always directing me to the correct path.

Here would also like to express my sincerest gratitude to my co-supervisor, Professor Maria Lindén for allowing me to have a research attachment in Mälardalen University, Sweden. Professor Maria Lindén was always supportive in my work and she had opened the pathway to have future research collaboration in between Malaysia and Sweden.

At the same time, to all my colleagues and friends from Malaysia and Sweden, I am very fortunate to have you in my life for giving me all the beautiful unforgettable memories.

Last but not least, special dedication to my parents and brother, for the caring and financial support. They are always my backbone and I am not manage without them. Thank you.

#### **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. 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.

# TABLE OF CONTENTS

CHAPTER	TITLE		PAGE	
	DECL	ARATIO	N	ii
	DEDI	CATION		iii
	ACKN	OWLED	GEMENT	iv
	ABST	RACT		v
	ABST	RAK		vi
	TABL	E OF CO	NTENTS	vii
	LIST	OF TABL	ES	xi
	LIST	OF FIGU	RES	xii
	LIST	OF ABBR	EVIATIONS	xvi
	LIST	OF SYMB	BOLS	xvii
	LIST	OF APPE	NDICES	xviii
1	INTRODUCTION			1
	1.1 Background Study			1
	1.2	.2 Problem Statement		
	1.3	Objecti	ves	3
	1.4	Scope of	of the Study	4
	1.5	Organiz	zation of The Thesis	4
2	LITE	RATURE 1	REVIEW	6
	2.1	Magnet	tic Coupled Resonant WPT System	6
	2.2	Human	Safety Considerations	7
		2.2.1	Safety Guidelines	7
		2.2.2	Human Body Models	9
	2.3	WPT S	ystem for Cardiovascular Application	16
		2.3.1	Transcutaneous Energy Transmission	
			(TET) System	16
		2.3.2	Free-Range Resonant Electrical Energy	
			Delivery (FREE-D) System	16

	2.4	Impeda	ance Matching for Efficiency Improvement			
		of WP7	Γ System	17		
	2.5	Types of	of Impedance Matching Techniques	19		
		2.5.1	Four-coils System	19		
		2.5.2	Frequency Matching	19		
		2.5.3	Complex Conjugate Matching	21		
		2.5.4	Optimal Load Impedance Matching	22		
	2.6	Limitat	cions of Optimal Load Impedance Matching			
		Design		23		
		2.6.1	Overall Transfer Efficiency	23		
		2.6.2	Complex Design Steps	25		
		2.6.3	Lossy Impedance Transformation Net-			
			work	26		
	2.7	Backgr	ound Theories	28		
		2.7.1	Analysis Techniques	28		
		2.7.2	Scattering Parameters	30		
		2.7.3	WPT Topologies	31		
		2.7.4	Coil Coupling	32		
		2.7.5	Quality Factor	33		
	2.8	Chapte	r Summary	33		
3	RESE	ARCH M	ETHODOLOGY	35		
	3.1	Propos	ed WPT System	35		
		3.1.1	Grand Vision	35		
		3.1.2	System Design and Specifications	36		
	3.2	System	System Analysis			
		3.2.1	Efficiency Analysis	38		
			3.2.1.1 Series-Series Topology	39		
			3.2.1.2 Parallel-Parallel Topology	41		
			3.2.1.3 Series-Parallel Topology	43		
			3.2.1.4 Parallel-Series Topology	44		
		3.2.2	Two Port Network Analysis	47		
			3.2.2.1 Impedance Analysis	48		
			3.2.2.2 Resonant Frequencies Analysis	49		
		3.2.3	Duality of LC Resonant System	51		
	3.3	Propos	Proposed Solution 1 - Purely Resistive Both Side			
		Impeda	nnce Matching Technique	54		
		3.3.1	Design Background	54		
		3.3.2	System Design	55		

		3.3.3	Verification	59
			3.3.3.1 Experimental Verification	60
			3.3.3.2 Computer Simulation	64
	3.4	Propos	ed Solution 2 - Efficiency Specified Ratio	
		Impeda	nnce Matching Design	69
		3.4.1	Design Background	69
		3.4.2	System Design	72
		3.4.3	Critical Coupling Point and Transmission	
			Distance	77
		3.4.4	Optimum Efficiency	79
		3.4.5	Verification	81
	3.5	Propos	ed Solution 3 - Purely Capacitive Low Loss	
		Impeda	ance Transformation Networks	83
		3.5.1	Design Background	83
		3.5.2	System Design	84
			3.5.2.1 Impedance Up Transformation	
			on Series System	85
			3.5.2.2 Impedance Down Transforma-	
			tion on Parallel System	86
		3.5.3	Verification	87
	3.6	Safety	Measure	92
	3.7	Chapte	r Summary	93
4	RESU	LTS AND	DISCUSSION	94
	4.1	Analys	is Results	94
		4.1.1	Efficiency Analysis	94
		4.1.2	Resonant Frequencies Analysis	98
	4.2	Experi	ment Results	100
		4.2.1	Results for Purely Resistive Both Side	
			Impedance Matching Technique	100
			4.2.1.1 Coupling Coefficient	100
			4.2.1.2 Transfer Efficiency	101
			4.2.1.3 Reflection Coefficient	103
			4.2.1.4 Fixed Frequency Verification	105
		4.2.2	Discussion for Purely Resistive Both Side	
			Impedance Matching Technique	106
		4.2.3	Results for Efficiency Specified Ratio	
			Impedance Matching Design	109

		4.2.4	Discussion for Efficiency Specified Ratio	
			Impedance Matching Design	112
		4.2.5	Results for Purely Capacitive Low Loss	
			Impedance Transformation Networks	114
			4.2.5.1 Transfer Efficiency	114
			4.2.5.2 Reflection Coefficient	115
		4.2.6	Discussion for Purely Capacitive Low	
			Loss Impedance Transformation Net-	
			works	116
	4.3	Safety 1	Measure	116
	4.4	Compa	rison with WPT System for Cardiovascular	
		Applica	ntion	118
	4.5	Comple	ete System Demonstration	118
	4.6	Chapte	r Summary	120
5	CONC	CLUSION		122
	5.1	Researc	ch Outcomes	122
	5.2	Contrib	outions to Knowledge	123
	5.3	Future	Works	124
	5.4	Chapte	r Summary	125
REFEREN(	CES			126
Appendices	A – F			135 – 157

# LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Recommended SAR value for frequencies above 100 kHz	
	(Kesler, 2013; Christ et al., 2013a)	9
2.2	Characteristics of each virtual family member (Christ et al.,	
	2013b)	10
2.3	Comparison among various impedance matching designs	24
3.1	Design Specification for wireless powering of LVAD	38
3.2	Comparison between series and parallel impedance transfor-	
	mation ratio	59
3.3	Measured values for each LC resonant circuit components	62
3.4	Design parameters for the L-match networks	63
3.5	Experiment Parameters	83
3.6	Matching Impedance	83
3.7	Design parameters for the proposed ITN (a) Impedance	
	up transformation on series system (b) Impedance down	
	transformation on parallel system	87
4.1	Benchmark with previous works	108
4.2	Comparison with FREE-D and TET WPT systems	118
5.1	Achievement	123
C.1	Coupling coefficient for equal coil size system	140
C.2	Coupling coefficient for different coil size system	141
C.3	$S_{21}$ Parameters for equal coil size system	142
C.4	$S_{21}$ Parameters for different coil size system	143
C.5	$S_{11}$ parameters for equal coil size system	144
C.6	$S_{11}$ parameters for different coil size system	145
C.7	$S_{21}$ fixed frequency verification for equal coil size system	146
C.8	$S_{21}$ fixed frequency verification for different coil size system	147
D.1	L-match ITN for parallel topology	148
D.2	L-match ITN for series topology	148
D.3	Results for Figure 4.13	149

# LIST OF FIGURES

FIGURE NO	c. TITLE	PAGE
2.1	A four-coils magnetic coupled resonant WPT system	
	proposed by MIT researchers	6
2.2	Virtual family anatomical human models (from left to right):	
	Duke, Ella, Eartha and Thelonious (Christ et al., 2013b)	10
2.3	Orientations of the coronal, axial and sagittal planes (Hui	
	et al., 2014)	11
2.4	Coil was placed 1cm from the model at orientation of coronal,	
	axial and sagittal (Christ et al., 2013b)	11
2.5	Localized SAR in the models Duke and Thelonious in two	
	sagittal planes (centered and 75 mm off center) for coronal	
	exposure (Christ et al., 2013b)	12
2.6	Coil current where the 2W/10g limit is reached Christ et al.	
	(2013b)	12
2.7	Peak 10 g averaged SAR in the TARO model when the	
	horizontal distance measured from the nose tip to the coils	
	is varied (Laakso et al., 2012)	13
2.8	Different WPT exposure locations on adult and child human	
	body models (Chen et al., 2014)	14
2.9	Normalized permissible B-field with respect to the ICNIRP	
	and IEEE guidelines ( $E_{ind-limit}$ and $psSAR_{limit}$ ) based on	
	the approximation results ( $E_{approx.}$ and $psSAR_{approx.}$ ) and	
	simulation results ( $E_{sim.}$ and $psSAR_{sim.}$ ) of a $d$ = 150 mm	
	coil at 5-mm distance; the vertical dashed lines indicate the	
	optimal frequencies to achieve compliance (Chen et al., 2014)	
		14
2.10	ICNIRP Reference levels	15
2.11	A Transcutaneous energy transmission (TET) systems	
	(HeartAssist, 2015)	16
2.12	Free-Range Resonant Electrical Energy Delivery (FREE-D)	
	System (Waters et al., 2012a)	17

2.13	Power delivered to a load as a function of $R_L$	18
2.14	Implementation of ITN on both ends of a WPT system.	27
2.15	A two-port network	29
2.16	Four WPT topologies	31
2.17	Series and parallel resonant circuits	33
3.1	Grand Vision to implement the WPT system	35
3.2	Proposed WPT system design	37
3.3	A complete schematic for a general SS WPT system	39
3.4	A complete schematic for a general PP WPT system	41
3.5	A complete schematic for a general SP WPT system	43
3.6	A complete schematic for a general PS WPT system	45
3.7	Plot of reactant vs frequency	50
3.8	Effect of frequency changing towards system efficiency	51
3.9	Interconversion between series and parallel resonant system	52
3.10	Added ITNs on both the transmitting and receiving end	55
3.11	Modeling of Figure 3.10.	56
3.12	Constructed coils for experiments	61
3.13	Experiment setup	64
3.14	Schematic setup for the simulations of equal coil size system	
	without ITN	65
3.15	Schematic setup for the simulations of equal coil size system	
	with proposed system using L-match ITNs	66
3.16	Schematic setup for the simulations of different coil size	
	system without ITN	67
3.17	Schematic setup for the simulations of different coil size	
	system with proposed system using L-match ITNs	68
3.18	Effect of different matching design towards the performance	
	of a WPT system	69
3.19	Conventional design flow	71
3.20	Proposed design flow	72
3.21	Schematic of WPT systems	73
3.22	Efficiency vs $k_{12_{critical}}$	80
3.23	A WPT system operating at different transfer efficiency	81
3.24	Experiment setup	82
3.25	Impedance transformation network designs	84
3.26	Impedance up transformation network on series system	85
3.27	Impedance down transformation network on parallel system.	86
3.28	Impedance up transformation using L-match network with	
	Q=50	88

3.29	Impedance up transformation using proposed ITN	89
3.30	Impedance down transformation using L-match network with	
	Q = 50	90
3.31	Impedance down transformation using proposed ITN	91
3.32	Magnetic field strength measurement	92
3.33	Electric field strength measurement	93
4.1	Analytical simulation on Efficiency vs $\log k_{12}$ using	
	MATLAB	95
4.2	Effect of different $Q$ towards system efficiency	96
4.3	Effect of different impedance set towards system efficiency	97
4.4	Comparison between analytical solution and simulation using	
	ADS	98
4.5	Frequency splitting on different coupling points	99
4.6	Analytical simulation without frequency tuning and with	
	frequency tuning.	100
4.7	Coupling coefficient measurement	101
4.8	$ S_{21} $ for the proposed technique and system without ITN	102
4.9	$S_{11}$ parameters for the proposed solution	104
4.10	$ S_{21} $ for the proposed technique on fixed resonant frequency	106
4.11	Simulation, analytical and experiment results for different	
	targeted efficiencies	110
4.12	Comparisons of impedance transformation ratios	111
4.13	Changes of transmission distance with different transfer	
	efficiency	112
4.14	$ S_{21} $ transfer efficiency for the proposed ITN and L-match	
	ITN	115
4.15	$ S_{21} $ transfer efficiency for the proposed ITN and L-match	
	ITN	115
4.16	Safety measurement and comparison with ICNIRP guideline	
	(a) Magnetic field strength (b) Electric field strength	117
4.17	Lighting a light bulb rated from a distance of 17cm away	119
4.18	Possible WPT implementation (a) Transmitter was placed	
	at the back of the chair (b)Wirelessly powered a light bulb	
	through human body	119
B.1	L-match ITN for impedance down conversion	138
B.2	L-match ITN for impedance up conversion	139
D.1	Simulation for SS topology	150
D.2	Simulation for SP topology	151
D.3	Simulation for PP topology	152

D.4 Simulation for PS topology

153

## 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

xvii

## LIST OF SYMBOLS

 $\eta$  - Transfer efficiency

 $\omega$  - Angular frequency

 ${\cal C}$  - Capacitance

*f* - Resonant frequency

I - AC Current

k - Coupling coefficient

L - Inductance

Mutual inductance

m - Impedance ratio

P - Power

 ${\it Q}$  - 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

# LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Derivation for Resonant Frequency Analysis	135
В	The Design of L-match ITN	138
C	Results of Proposed Solution 1	140
D	Experiment Parameters and Results of	
	Proposed Solution 2	148
E	Derivation for Purely Capacitive Low Loss ITN	154
F	List of Publications	157

### **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<sup>®</sup> LVAD and HeartWare<sup>®</sup> 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. Indepth 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.

#### REFERENCES

- Ahn, D. and Hong, S. (2013). A study on magnetic field repeater in wireless power transfer. *IEEE Transactions on Industrial Electronics*. 60(1), 360–371.
- Ahn, D. and Hong, S. (2014). A transmitter or a receiver consisting of two strongly coupled resonators for enhanced resonant coupling in wireless power transfer. *IEEE Transactions on Industrial Electronics*. 61(3), 1193–1203.
- Ahuja, N., Eshaghian-Wilner, M. M., Ge, Z., Liu, R., Pati, A. S. N., Ravicz, K., Schlesinger, M., Wu, S. H. and Xie, K. (2016). WIRELESS POWER FOR IMPLANTABLE DEVICES: A TECHNICAL REVIEW. Wireless Computing in Medicine: From Nano to Cloud with Ethical and Legal Implications, 187.
- Alexander, C., Alexander, C. K. and Sadiku, M. N. (2006). *Fundamentals of electric circuits*. Urban Media Comics.
- Awai, I. and Ishizaki, T. (2011). Superiority of BPF theory for design of coupled resonator WPT systems. In *Asia-Pacific Microwave Conference Proceedings* (*APMC*). IEEE, 1889–1892.
- Awai, I. and Ishizaki, T. (2012). Transferred power and efficiency of a coupled-resonator WPT system. In *IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS)*. IEEE, 105–108.
- Awai, I. and Komori, T. (2010). A simple and versatile design method of resonator-coupled wireless power transfer system. In *International Conference on Communications, Circuits and Systems (ICCCAS)*. IEEE, 616–620.
- Barman, S. D., Reza, A. W., Kumar, N. and Anowar, T. I. (2015a). Two-side Impedance Matching for Maximum Wireless Power Transmission. *IETE Journal of Research*, 1–8.
- Barman, S. D., Reza, A. W., Kumar, N., Karim, M. E. and Munir, A. B. (2015b). Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications. *Renewable and Sustainable Energy Reviews*. 51, 1525–1552.
- Beh, T. C., Imura, T., Kato, M. and Hori, Y. (2010). Basic study of improving efficiency

- of wireless power transfer via magnetic resonance coupling based on impedance matching. In *IEEE International Symposium on Industrial Electronics (ISIE)*. IEEE, 2011–2016.
- Beh, T. C., Kato, M., Imura, T., Oh, S. and Hori, Y. (2013). Automated impedance matching system for robust wireless power transfer via magnetic resonance coupling. *IEEE Transactions on Industrial Electronics*. 60(9), 3689–3698.
- Bou, E., Alarcon, E. and Gutierrez, J. (2012). A comparison of analytical models for resonant inductive coupling wireless power transfer. *Session 2P4 Near to Mid-range Wireless Power Transfer Technology: Principles and Applications* 2, 389.
- Chen, C.-J., Chu, T.-H., Lin, C.-L. and Jou, Z.-C. (2010). A study of loosely coupled coils for wireless power transfer. *IEEE Transactions on Circuits and Systems II: Express Briefs*. 57(7), 536–540.
- Chen, L., Liu, S., Zhou, Y. C. and Cui, T. J. (2013). An optimizable circuit structure for high-efficiency wireless power transfer. *IEEE Transactions on Industrial Electronics*. 60(1), 339–349.
- Chen, X. L., Umenei, A. E., Baarman, D. W., Chavannes, N., De Santis, V., Mosig, J. R. and Kuster, N. (2014). Human exposure to close-range resonant wireless power transfer systems as a function of design parameters. *IEEE Transactions on Electromagnetic Compatibility*. 56(5), 1027–1034.
- Cheon, S., Kim, Y.-H., Kang, S.-Y., Lee, M. L., Lee, J.-M. and Zyung, T. (2011). Circuit-model-based analysis of a wireless energy-transfer system via coupled magnetic resonances. *IEEE Transactions on Industrial Electronics*. 58(7), 2906–2914.
- Christ, A., Douglas, M., Nadakuduti, J. and Kuster, N. (2013a). Assessing human exposure to electromagnetic fields from wireless power transmission systems. *Proceedings of the IEEE*. 101(6), 1482–1493.
- Christ, A., Douglas, M. G., Roman, J. M., Cooper, E. B., Sample, A. P., Waters, B. H., Smith, J. R. and Kuster, N. (2013b). Evaluation of wireless resonant power transfer systems with human electromagnetic exposure limits. *IEEE Transactions on Electromagnetic Compatibility*. 55(2), 265–274.
- Congdon, M. (2013). AbioCor Artificial Heart.
- Dionigi, M. and Mongiardo, M. (2012). A novel coaxial loop resonator for wireless power transfer. *International Journal of RF and Microwave Computer-Aided Engineering*. 22(3), 345–352.
- Dissanayake, T. D., Budgett, D. M., Hu, P., Bennet, L., Pyner, S., Booth, L., Amirapu,

- S., Wu, Y. and Malpas, S. C. (2010). A novel low temperature transcutaneous energy transfer system suitable for high power implantable medical devices: performance and validation in sheep. *Artificial organs*. 34(5), E160–E167.
- Duong, T. P. and Lee, J.-W. (2011). Experimental results of high-efficiency resonant coupling wireless power transfer using a variable coupling method. *IEEE Microwave and Wireless Components Letters*. 21(8), 442–444.
- Ean, K. K., Chuan, B. T., Imura, T. and Hori, Y. (2012). Impedance matching and power division algorithm considering cross coupling for wireless power transfer via magnetic resonance. In *IEEE 34th International Telecommunications Energy Conference (INTELEC)*. IEEE, 1–5.
- Elixmann, I., Köny, M., Bertling, S., Kiefer, M. and Leonhardt, S. (2012). Transcutaneous Energy Transfer System Incorporating a Datalink for a Wearable Autonomous Implant. In *Ninth International Conference on Wearable and Implantable Body Sensor Networks (BSN)*. IEEE, 1–5.
- Falavarjani, M. M., Shahabadi, M. and Rashed-Mohassel, J. (2014). Design and implementation of compact WPT system using printed spiral resonators. *Electronics Letters*. 50(2), 110–111.
- Fu, M., Zhang, T., Zhu, X. and Ma, C. (2013). A 13.56 MHz wireless power transfer system without impedance matching networks. In *IEEE Wireless Power Transfer* (WPT). IEEE, 222–225.
- Fu, W., Zhang, B. and Qiu, D. (2009). Study on frequency-tracking wireless power transfer system by resonant coupling. In *IEEE 6th International Power Electronics and Motion Control Conference (IPEMC'09)*. IEEE, 2658–2663.
- Fu, Y., Hu, L., Ruan, X. and Fu, X. (2015). A transcutaneous energy transmission system for artificial heart adapting to changing impedance. *Artificial organs*. 39(4), 378–387.
- Guideline, I. (1998). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Phys.* 74(4), 494–522.
- Guo, Y.-X. and Jegadeesan, R. (2012). Efficient Inductive Power Transfer for biomedical applications. In *IEEE International Workshop on Electromagnetics*; *Applications and Student Innovation (iWEM)*. IEEE, 1–2.
- Hannan, M. A., Mutashar, S., Samad, S. A. and Hussain, A. (2014). Energy harvesting for the implantable biomedical devices: issues and challenges. *Biomed. Eng. Online*. 13.

- Hasgall, P., Neufeld, E., Gosselin, M., Klingenbock, A. and Kuster, N. (2012). IT'IS Database for thermal and electromagnetic parameters of biological tissues. *IT'IS Foundation website*.
- Hashimoto, I. and Shiba, K. (2015). Analysis of low leakage magnetic field transcutaneous energy transfer for ventricular assist devices. In 2015 IEEE Biomedical Circuits and Systems Conference (BioCAS). IEEE, 1–4.
- HeartAssist, R. (2015). Dualis MedTech and ReliantHeart Partner on Fully Implantable TET System for the HeartAssist® LVAD. Available from: <a href="http://reliantheart.com/2015/04/07/dualis-medtech-and-reliantheart-partner-on-fully-implantable-tet-system-for-the-heartassist5-lvad">http://reliantheart.com/2015/04/07/dualis-medtech-and-reliantheart-partner-on-fully-implantable-tet-system-for-the-heartassist5-lvad</a> [Accessed: 3 June 2016].
- HeartWare, Inc. (2014). HeartWare® Ventricular Assist System Instructions for Use.
- Ho, J. S., Kim, S. and Poon, A. S. (2013). Midfield wireless powering for implantable systems. *Proceedings of the IEEE*. 101(6), 1369–1378.
- Huang, X. L., Tan, L. L., Li, H. and Qiang, H. (2011). Frequency splitting and distance boundary condition in magnetic resonance coupled wireless power transfer system. In *Advanced Materials Research*, vol. 308. Trans Tech Publ, 1349–1352.
- Hui, S. Y. R., Zhong, W. and Lee, C. K. (2014). A critical review of recent progress in mid-range wireless power transfer. *IEEE Transactions on Power Electronics*. 29(9), 4500–4511.
- Huwig, D. and Wambsganss, P. (2013). Digitally controlled synchronous bridge-rectifier for wireless power receivers. In *Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE, 2598–2603.
- Imura, T. and Hori, Y. (2011). Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula. *IEEE Transactions on Industrial Electronics*. 58(10), 4746–4752.
- Jang, B.-J., Lee, S. and Yoon, H. (2012). HF-band wireless power transfer system: Concept, issues, and design. *Progress in electromagnetics research*. 124, 211–231.
- Jiang, H., Zhang, J. M., Zhou, S. Y., Liou, S. S. and Shahnasser, H. (2010). A rotating-magnet based wireless electrical power transfer for biomedical implants. In 3rd International Conference on Biomedical Engineering and Informatics (BMEI), vol. 4. IEEE, 1409–1411.
- Jung, Y.-K. and Lee, B. (2013). Design of adaptive optimal load circuit for maximum wireless power transfer efficiency. In Asia-Pacific Microwave Conference Proceedings (APMC). IEEE, 1221–1223.

- Karalis, A., Joannopoulos, J. D. and Soljačić, M. (2008). Efficient wireless non-radiative mid-range energy transfer. *Annals of Physics*. 323(1), 34–48.
- Kesler, M. (2013). Highly resonant wireless power transfer: safe, efficient, and over distance. *WiTricity Corporation*.
- Kiani, M., Jow, U.-M. and Ghovanloo, M. (2011). Design and optimization of a 3-coil inductive link for efficient wireless power transmission. *IEEE Transactions on Biomedical Circuits and Systems*. 5(6), 579–591.
- Kim, J., Kim, D.-H. and Park, Y.-J. (2015). Analysis of Capacitive Impedance Matching Networks for Simultaneous Wireless Power Transfer to Multiple Devices. *IEEE Transactions on Industrial Electronics*. 62(5), 2807–2813.
- Kim, J., Son, H.-C., Kim, K.-H. and Park, Y.-J. (2011). Efficiency analysis of magnetic resonance wireless power transfer with intermediate resonant coil. *IEEE Antennas and Wireless Propagation Letters*. 10, 389–392.
- Kim, J.-H., Son, H.-C., Kim, D.-H. and Park, Y.-J. (2013). Impedance matching considering cross coupling for wireless power transfer to multiple receivers. In *IEEE Wireless Power Transfer (WPT)*. IEEE, 226–229.
- Kim, N., Kim, K., Choi, J. and Kim, C.-W. (2012a). Adaptive frequency with power-level tracking system for efficient magnetic resonance wireless power transfer. *Electronics letters*. 48(8), 452–454.
- Kim, N. Y., Kim, K. Y., Ryu, Y.-H., Choi, J., Kim, D.-Z., Yoon, C., Park, Y.-K. and Kwon, S. (2012b). Automated adaptive frequency tracking system for efficient midrange wireless power transfer via magnetic resonanc coupling. In *42nd European Microwave Conference (EuMC)*. IEEE, 221–224.
- Kim, Y. and Ling, H. (2007). Investigation of coupled mode behaviour of electrically small meander antennas. *IET Electronics Letters*. 43(23), 1250–1252.
- Knecht, O., Bosshard, R. and Kolar, J. W. (2015). High-efficiency transcutaneous energy transfer for implantable mechanical heart support systems. *IEEE Transactions on Power Electronics*. 30(11), 6221–6236.
- Knecht, O. and Kolar, J. (2015). Impact of Transcutaneous Energy Transfer on the Electric Field and Specific Absorption Rate in the Human Tissue.
- Koh, K. E., Beh, T. C., Imura, T. and Hori, Y. (2014). Impedance matching and power division using impedance inverter for wireless power transfer via magnetic resonant coupling. *IEEE Transactions on Industry Applications*. 50(3), 2061–2070.
- Kurs, A. (2007). *Power transfer through strongly coupled resonances*. Ph.D. Thesis. Massachusetts Institute of Technology.

- Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P. and Soljačić, M. (2007). Wireless power transfer via strongly coupled magnetic resonances. *science*. 317(5834), 83–86.
- Kusaka, K. and Itoh, J.-i. (2012). Input impedance matched AC-DC converter in wireless power transfer for EV charger. In 15th International Conference on Electrical Machines and Systems (ICEMS). IEEE, 1–6.
- Laakso, I., Tsuchida, S., Hirata, A. and Kamimura, Y. (2012). Evaluation of SAR in a human body model due to wireless power transmission in the 10 MHz band. *Physics in medicine and biology*. 57(15), 4991.
- Lee, S.-H. and Lorenz, R. D. (2011). Development and validation of model for 95%-efficiency 220-W wireless power transfer over a 30-cm air gap. *IEEE Transactions on Industry Applications*. 47(6), 2495–2504.
- Lee, W.-S., Son, W.-I., Oh, K.-S. and Yu, J.-W. (2013). Contactless energy transfer systems using antiparallel resonant loops. *IEEE Transactions on Industrial Electronics*. 60(1), 350–359.
- Li, X., Tsui, C.-Y. and Ki, W.-H. (2015). A 13.56 MHz wireless power transfer system with reconfigurable resonant regulating rectifier and wireless power control for implantable medical devices. *Solid-State Circuits, IEEE Journal of.* 50(4), 978–989.
- Li, X., Zhang, H., Peng, F., Li, Y., Yang, T., Wang, B. and Fang, D. (2012). A wireless magnetic resonance energy transfer system for micro implantable medical sensors. *Sensors*. 12(8), 10292–10308.
- Lim, Y., Tang, H., Lim, S. and Park, J. (2014). An adaptive impedance-matching network based on a novel capacitor matrix for wireless power transfer. *IEEE Transactions on Power Electronics*. 29(8), 4403–4413.
- Lima, B., Mack, M. and Gonzalez-Stawinski, G. V. (2015). Ventricular assist devices: The future is now. *Trends in cardiovascular medicine*. 25(4), 360–369.
- Lin, J. C. (2013). Wireless power transfer for mobile applications, and health effects [telecommunications health and safety]. *IEEE Antennas and Propagation Magazine*. 55(2), 250–253.
- Linlin, T., Xueliang, H., Hui, L. and Hui, H. (2010). Study of wireless power transfer system through strongly coupled resonances. In *International Conference on Electrical and Control Engineering (ICECE)*. IEEE, 4275–4278.
- Liu, S., Chen, L., Zhou, Y. and Cui, T. J. (2014). A general theory to analyse and design wireless power transfer based on impedance matching. *International journal*

- of electronics. 101(10), 1375–1404.
- Low, Z. N., Chinga, R. A., Tseng, R. and Lin, J. (2009). Design and test of a high-power high-efficiency loosely coupled planar wireless power transfer system. *IEEE Transactions on Industrial Electronics*. 56(5), 1801–1812.
- Lum, K. Y., Lindén, M. and Tan, T. S. (2014). Impedance matching wireless power transmission system for biomedical devices. *Studies in health technology and informatics*. 211, 225–232.
- Luo, Y. T., Yang, Y. M. and Chen, Z. S. (2013). Network Analysis and Impedance Matching Methods for Wireless Power Transfer via Coupled Magnetic Resonances. In *Applied Mechanics and Materials*, vol. 437. Trans Tech Publ, 301–305.
- Mur-Miranda, J. O., Fanti, G., Feng, Y., Omanakuttan, K., Ongie, R., Setjoadi, A. and Sharpe, N. (2010). Wireless power transfer using weakly coupled magnetostatic resonators. In *IEEE Energy Conversion Congress and Exposition (ECCE)*. 4179–4186.
- Ni, B., Chung, C. and Chan, H. L. (2013). Design and comparison of parallel and series resonant topology in wireless power transfer. In 8th IEEE Conference on Industrial Electronics and Applications (ICIEA). IEEE, 1832–1837.
- Niknejad, A. M. (2007). Electromagnetics for high-speed analog and digital communication circuits. Cambridge University Press.
- Ogawa, K., Oodachi, N., Obayashi, S. and Shoki, H. (2012). A study of efficiency improvement of wireless power transfer by impedance matching. In *IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS)*. IEEE, 155–157.
- Park, J., Lee, S., Tak, Y. and Nam, S. (2012). Simple efficient resonant coupling wireless power transfer system operating at varying distances between antennas. *Microwave and Optical Technology Letters*. 54(10), 2397–2401.
- Park, J., Tak, Y., Kim, Y., Kim, Y. and Nam, S. (2011). Investigation of adaptive matching methods for near-field wireless power transfer. *IEEE Transactions on Antennas and Propagation*. 59(5), 1769–1773.
- Pinuela, M., Yates, D. C., Lucyszyn, S. and Mitcheson, P. D. (2013). Maximizing DC-to-Load efficiency for inductive power transfer. *IEEE Transactions on Power Electronics*. 28(5), 2437–2447.
- RamRakhyani, A. K., Mirabbasi, S. and Chiao, M. (2011). Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants. *IEEE Transactions on Biomedical Circuits and Systems*. 5(1), 48–63.

- Sample, A. P., Meyer, D., Smith, J. R. *et al.* (2011). Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer. *IEEE Transactions on Industrial Electronics*. 58(2), 544–554.
- Shimamoto, T., Iwahashi, M., Sugiyama, Y., Laakso, I., Hirata, A. and Onishi, T. (2016). SAR evaluation in models of an adult and a child for magnetic field from wireless power transfer systems at 6.78 MHz. *Biomedical Physics & Engineering Express*. 2(2), 027001.
- Silay, K. M., Dondi, D., Larcher, L., Declercq, M., Benini, L., Leblebici, Y. and Dehollain, C. (2009). Load optimization of an inductive power link for remote powering of biomedical implants. In *IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 533–536.
- Student, U. (2015). WiTricity-Wireless Power Transfer by Non-radiative Method.
- Sun, Y., Moritz, J. and Zhu, X. (2011). Adaptive impedance matching and antenna tuning for green software-defined and cognitive radio. In *IEEE 54th International Midwest Symposium on Circuits and Systems (MWSCAS)*. IEEE, 1–4.
- Thomas, E. M., Heebl, J. D., Pfeiffer, C. and Grbic, A. (2012). A power link study of wireless non-radiative power transfer systems using resonant shielded loops. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 59(9), 2125–2136.
- Thoratec Europe Limited (2007). *HeartMate II*<sup>®</sup> LVAS Left Ventricular Assist System Operating Manual.
- Waffenschmidt, E. and Staring, T. (2009). Limitation of inductive power transfer for consumer applications. In 13th European Conference on Power Electronics and Applications (EPE'09). IEEE, 1–10.
- Waters, B., Sample, A., Smith, J. and Bonde, P. (2011). Toward total implantability using free-range resonant electrical energy delivery system: achieving untethered ventricular assist device operation over large distances. *Cardiology clinics*. 29(4), 609–625.
- Waters, B. H., Mahoney, B. J., Lee, G. and Smith, J. R. (2014a). Optimal coil size ratios for wireless power transfer applications. In *IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2045–2048.
- Waters, B. H., Reed, J. T., Kagi, K. R., Sample, A. P., Bonde, P. and Smith, J. R. (2013). A Portable Transmitter for Wirelessly Powering a Ventricular Assist Device Using the Free-Range Resonant Electrical Energy Delivery (FREE-D) System. In Wirelessly Powered Sensor Networks and Computational RFID. (pp. 235–247). Springer.

- Waters, B. H., Sample, A. P., Bonde, P. and Smith, J. R. (2012a). Powering a ventricular assist device (VAD) with the free-range resonant electrical energy delivery (FREE-D) system. *Proceedings of the IEEE*. 100(1), 138–149.
- Waters, B. H., Sample, A. P. and Smith, J. R. (2012b). Adaptive impedance matching for magnetically coupled resonators. *PIERS Proc*, 694–701.
- Waters, B. H., Smith, J. R. and Bonde, P. (2014b). Innovative free-range resonant electrical energy delivery system (FREE-D system) for a ventricular assist device using wireless power. *ASAIO Journal*. 60(1), 31–37.
- Xue, R.-F., Cheng, K.-W. and Je, M. (2013). High-efficiency wireless power transfer for biomedical implants by optimal resonant load transformation. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 60(4), 867–874.
- Zhang, W., Wong, S.-C., Tse, C. K. and Chen, Q. (2014a). Load-independent current output of inductive power transfer converters with optimized efficiency. In *International Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA)*. IEEE, 1425–1429.
- Zhang, X., Ho, S. and Fu, W. (2011). Quantitative analysis of a wireless power transfer cell with planar spiral structures. *IEEE Transactions on Magnetics*, 47(10), 3200–3203.
- Zhang, Y., Zhao, Z. and Chen, K. (2013). Load matching analysis of magnetically-coupled resonant wireless power transfer. In *IEEE ECCE Asia Downunder (ECCE Asia)*. IEEE, 788–792.
- Zhang, Y., Zhao, Z. and Chen, K. (2014b). Frequency decrease analysis of resonant wireless power transfer. *IEEE Transactions on Power Electronics*. 29(3), 1058–1063.