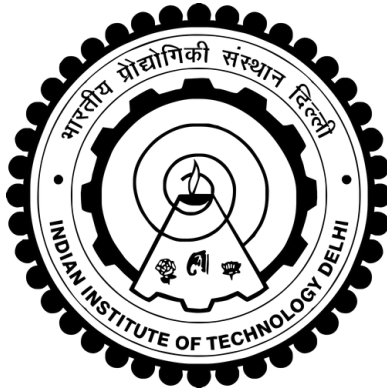


Misalignment Tolerant Control of a Bidirectional Wireless Power Transfer System for Electric Vehicle Charging

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Indian Institute of Technology Delhi
July 2025

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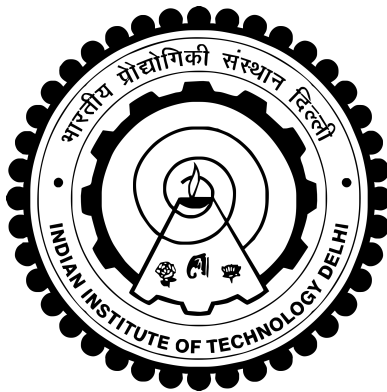
by

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DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

In fulfillment of the requirement of the Doctor of Philosophy
to the



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July 2025

Dedication

This thesis is dedicated to my mother

Mrs. Yakala Parvathi

Thesis Certificate

This is to certify that the thesis titled "**Misalignment Tolerant Control of a Bidirectional Wireless Power Transfer System for Electric Vehicle Charging**", submitted by **Yakala Ravi Kumar, 2018EE Z8149**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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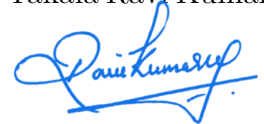
I extend my heartfelt gratitude to my supervisor, Dr. Sumit Kumar Pramanick, for his invaluable support, guidance, and encouragement throughout my research. His insights and mentorship at each stage have been instrumental in fostering both my personal and professional growth. His directions refined my technical and analytical skills, elevating the quality of this thesis and improving my ability to convey complex ideas clearly in presentations and technical papers. His trust in my abilities empowered me to engage with challenging projects, driving my growth in innovative ways. As I conclude this chapter, I carry forward the lessons and inspiration he imparted, which will undoubtedly guide me in future pursuits.

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Yakala Ravi Kumar



Abstract

Index Terms: Bidirectional Inductive Wireless power transfer, electric vehicle charging, Coil design, finit element method, ground assembly, vehicle assembly, misalignment, compensation networks, electrical resonance, Dual phase-shift control, Optimal efficiency, Dynamic modeling, Multi variable control, wireless communication, zero phase angle, full zero voltage switching.

This thesis presents the design, modeling, and optimization of a bidirectional inductive wireless power transfer (BWPT) system for electric vehicle (EV) charging, focusing on improving efficiency and ensuring robust control under varying conditions such as misalignment and load variations.

The shift toward EVs is a cornerstone of global efforts to reduce carbon emissions and foster sustainable development. Wireless charging has emerged as a preferred solution within this transformative landscape, offering a seamless and efficient alternative to conventional plug-in systems. Wireless charging enhances user convenience and reliability by eliminating cumbersome cables and connectors, addressing the challenges posed by incompatible charging standards. Beyond convenience, wireless power transfer (WPT) introduces a versatile "park-and-charge" capability, simplifying EV charging in residential, workplace, and commercial environments.

Moreover, the bidirectional functionality of WPT systems supports both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) power flow, enabling EVs to serve as mobile energy assets. These systems can feed surplus power back to the grid during peak demand, reducing reliance on extensive energy storage infrastructure and providing reactive power support. This integration of functionality not only improves energy utilization but also enhances grid stability. Consequently, BWPT systems are poised to revolutionize EV accessibility and energy management, paving the way for a more sustainable, resilient, and efficient energy ecosystem. Developing such systems requires a multidisciplinary approach encompassing power electronics, magnetic circuit design, and control strategies, with this thesis focusing on key advancements in magnetic design and robust control.

The first objective of this research is to optimize the IWPT coil design for im-

proved energy transfer efficiency while minimizing copper usage. Circular coils are explored due to their ease of alignment and adaptability. A Type-1 IWPT system coil is optimized using 3D finite element method (FEM) analysis, considering parameters like vertical offset and coil misalignment to maximize coupling efficiency. Additional optimization reduces coil weight, copper usage, and losses, ensuring compliance with SAEJ2954 standards and ICNIRP guidelines.

The second objective is to develop an accurate and dynamic model for the BWPT system using Generalized State Space Averaging (GSSA) and Extended Describing Function (EDF) methods. This model integrates multiple control variables and accounts for their interdependencies, which is essential for advanced strategies like the dual-phase shift (DPS) method. A novel input reactive power control strategy for S-S compensated BWPT systems is also introduced, improving efficiency by managing reactive power without compromising stability. However, analysis and experimental results reveal that DPS control with multiple output variables introduces a cross-coupling effect, degrading the system's dynamic performance. A relative gain array (RGA) analysis is performed to find the degree of cross-coupling due to the interdependencies formed by the multiple control and output variables.

To address this issue, a unified control approach is proposed, utilizing a single vehicle assembly (VA) side PI controller. This minimizes cross-coupling and ensures stable bidirectional power flow by controlling the VA side phase shift for constant output power and the ground assembly (GA) side phase shift for a zero power factor angle (ZPA). This approach achieves high efficiency even under misalignment. Additionally, due to its symmetry on both sides, this method provides simple bidirectional power flow control of the BWPT system. The final objective aims to improve system efficiency under varying load and misalignment conditions by evaluating performance under ZPA and full zero voltage switching (FZVS) modes. This research identifies the conditions necessary to achieve FZVS and ZPA operation, establishing optimal operating parameters to maximize efficiency. A comprehensive mathematical analysis of the trade-offs between ZPA and FZVS is conducted, utilizing a detailed loss model of the system across different operating scenarios to provide valuable insights into their influence on overall system performance.

Overall, this thesis contributes a comprehensive framework for designing and controlling BWPT systems, achieving high efficiency, stability, and performance under challenging conditions, thereby advancing wireless EV charging technology and paving the way for future innovations.

संक्षेप

सूचकांक शर्तें: द्विविध प्रेरणीय वायरलेस पावर ट्रांसफर, विद्युत वाहन चार्जिंग, कॉइल डिज़ाइन, परिमित तत्व विधि, ग्राउंड असेंबली, वाहन असेंबली, विसंरेखण, क्षतिपूर्ति नेटवर्क्स, विद्युत अनुनाद, द्वि-चरण शिफ्ट नियंत्रण, गतिशील मॉडलिंग, इष्टतम दक्षता, बहु-चर नियंत्रण, वायरलेस संचार, शून्य चरण कोण, पूर्ण शून्य वोल्टेज स्विचिंग।

यह शोध प्रबंध विद्युत वाहनों (EV) के चार्जिंग के लिए एक द्विविध प्रेरणीय वायरलेस पावर ट्रांसफर (BWPT) प्रणाली की डिज़ाइन, मॉडलिंग और अनुकूलन प्रस्तुत करता है, जिसका उद्देश्य दक्षता में सुधार करना और विसंरेखण एवं लोड में परिवर्तन जैसी विभिन्न परिस्थितियों में मजबूत नियंत्रण सुनिश्चित करना है।

EVs की ओर झुकाव वैश्विक स्तर पर कार्बन उत्सर्जन को कम करने और सतत विकास को बढ़ावा देने के प्रयासों का एक प्रमुख आधार है। वायरलेस चार्जिंग इस परिवर्तनशील परिदृश्य में एक पसंदीदा समाधान के रूप में उभरी है, जो पारंपरिक प्लग-इन प्रणालियों का एक सहज और कुशल विकल्प प्रदान करती है। यह उपयोगकर्ता की सुविधा और विश्वसनीयता को बढ़ाती है, क्योंकि यह भारी केबल और कनेक्टरों को समाप्त करती है और असंगत चार्जिंग मानकों से उत्पन्न चुनौतियों का समाधान करती है। इसके अलावा, वायरलेस पावर ट्रांसफर (WPT) “पार्क-एंड-चार्ज” जैसी बहुउद्देश्यीय सुविधा प्रदान करता है, जो आवासीय, कार्यस्थल और वाणिज्यिक वातावरण में EV चार्जिंग को सरल बनाता है।

इसके अतिरिक्त, WPT प्रणालियों की द्विविध कार्यक्षमता ग्रिड-से-वाहन (G2V) और वाहन-से-ग्रिड (V2G) दोनों प्रकार के पावर फ्लो का समर्थन करती है, जिससे EVs को चलायमान ऊर्जा संसाधनों के रूप में उपयोग किया जा सकता है। ये प्रणालियाँ चरम मांग के समय ग्रिड को अधिशेष ऊर्जा वापस भेज सकती हैं, जिससे बड़े पैमाने की ऊर्जा भंडारण अवसंरचना पर निर्भरता कम होती है और प्रतिक्रियाशील शक्ति समर्थन प्राप्त होता है। इस प्रकार की कार्यात्मकता का एकीकरण ऊर्जा उपयोग को बेहतर बनाता है और ग्रिड की स्थिरता में वृद्धि करता है। परिणामस्वरूप, BWPT प्रणालियाँ EV की पहुँच और ऊर्जा प्रबंधन में क्रांतिकारी बदलाव लाने की क्षमता रखती हैं, जिससे अधिक सतत, लचीला और कुशल ऊर्जा पारिस्थितिकी तंत्र संभव होता है। ऐसे प्रणालियों का विकास पावर इलेक्ट्रॉनिक्स, चुंबकीय परिपथ डिज़ाइन और नियंत्रण रणनीतियों सहित एक बहुविषयक दृष्टिकोण की मांग करता है, और यह शोध प्रबंध चुंबकीय डिज़ाइन और मजबूत नियंत्रण में प्रमुख उन्नतियों पर केंद्रित है।

इस अनुसंधान का पहला उद्देश्य उच्च ऊर्जा ट्रांसफर दक्षता प्राप्त करते हुए तांबे के उपयोग को न्यूनतम करने के लिए IWPT कॉइल डिज़ाइन का अनुकूलन करना है। संरेखण में आसानी और अनुकूलनशीलता के कारण वृत्ताकार कॉइल का चयन किया गया है। टाइप-1 IWPT प्रणाली कॉइल को 3D सीमित अवयव विधि (FEM) विश्लेषण का उपयोग करके अनुकूलित किया गया है, जिसमें ऊर्ध्वाधर विस्थापन और कॉइल विसंरेखण जैसे मापदंडों को यथासंभव युग्मन दक्षता प्राप्त करने

हेतु ध्यान में रखा गया है। इसके अतिरिक्त अनुकूलन से कॉइल का वजन, तांबे की खपत और नुकसान कम होते हैं, जिससे यह SAEJ2954 मानको और ICNIRP दिशानिर्देशों के अनुरूप रहता है।

दूसरा उद्देश्य GSSA (सामान्यीकृत राज्य अंतरिक्ष औसत) और EDF (विस्तारित वर्णन फंक्शन) विधियों का उपयोग करते हुए BWPT प्रणाली के लिए एक सटीक और गतिशील मॉडल विकसित करना है। यह मॉडल विभिन्न नियंत्रण चर और उनके परस्पर संबंधों को एकीकृत करता है, जो DPS (दोहरी चरण पारी) जैसी उन्नत रणनीतियों के लिए आवश्यक है। एस-एस क्षतिपूर्ति BWPT प्रणालियों के लिए एक नवीन इनपुट प्रतिक्रियाशील शक्ति नियंत्रण रणनीति प्रस्तुत की गई है, जो स्थिरता से समझौता किए बिना प्रतिक्रियाशील शक्ति का प्रबंधन करके दक्षता में सुधार करती है। हालांकि, विश्लेषण और प्रयोगात्मक परिणाम दर्शाते हैं कि बहु-आउटपुट चर के साथ डी पी एस नियंत्रण प्रणाली के गतिशील प्रदर्शन को बिगाड़ता है, क्योंकि यह क्रॉस-कपलिंग प्रभाव उत्पन्न करता है। इस क्रॉस-कपलिंग की डिग्री को निर्धारित करने हेतु RGA (सापेक्ष लाभ सरणी) विश्लेषण किया गया है।

इस समस्या के समाधान के लिए एक एकीकृत नियंत्रण दृष्टिकोण प्रस्तावित किया गया है, जिसमें एक ही VA (वाहन असेंबली) पक्ष PI नियंत्रक का उपयोग किया गया है। यह क्रॉस-कपलिंग को न्यूनतम करता है और द्विदिश शक्ति प्रवाह को स्थिर बनाए रखता है, जहाँ VA पक्ष फेज शिफ्ट को निरंतर आउटपुट पावर के लिए नियंत्रित किया जाता है और GA (ग्राउंड असेंबली) पक्ष को शून्य पावर फैक्टर कोण (ZPA) बनाए रखने के लिए नियंत्रित किया जाता है। यह दृष्टिकोण विसंरेखण की स्थिति में भी उच्च दक्षता प्राप्त करता है। इसके अतिरिक्त, दोनों पक्षों पर इसकी समरूपता के कारण, यह BWPT प्रणाली के द्विदिश शक्ति प्रवाह नियंत्रण को सरल बनाता है। अंतिम उद्देश्य विसंरेखण और लोड में परिवर्तन की स्थितियों में प्रणाली की दक्षता सुधारना है, जिसके लिए ZPA और पूर्ण शून्य वोल्टेज स्विचिंग (FZVS) मोड में प्रदर्शन का मूल्यांकन किया गया है। यह शोध FZVS और ZPA ऑपरेशन प्राप्त करने के लिए आवश्यक स्थितियों की पहचान करता है और अधिकतम दक्षता प्राप्त करने हेतु इष्टतम संचालन मापदंड निर्धारित करता है। विभिन्न परिचालन परिस्थितियों में विस्तृत लॉस मॉडल का उपयोग करते हुए ZPA और FZVS के बीच ट्रेड-ऑफ का एक व्यापक गणितीय विश्लेषण किया गया है, जो प्रणाली के समग्र प्रदर्शन पर इनके प्रभाव की उपयोगी अंतर्दृष्टि प्रदान करता है। कुल मिलाकर, यह शोध प्रबंध BWPT प्रणालियों की डिजाइन और नियंत्रण के लिए एक व्यापक ढांचा प्रदान करता है, जो कठिन परिस्थितियों में भी उच्च दक्षता, स्थिरता और प्रदर्शन प्राप्त करता है। यह वायरलेस EV चार्जिंग तकनीक को आगे बढ़ाता है और भविष्य के नवाचारों के लिए मार्ग प्रशस्त करता है।

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Acronyms

AC	Alternating Current
BWPT	Bidirectional Inductive Wireless Power Transfer
DC	Direct Current
DPS	Dual-phase Shift Control
DSP	Digital Signal Processor
EV	Electric Vehicles
EMC	Electromagnetic Compatability
EMF	Electromotive Force
EMI	Electromagnetic Interference
ESL	Equivalent Series Inductance
ESR	Equivalent Series Resistance
FEM	Finite Element Method
FHA	First order Harmonic Analysis
FOD	Foreign Object Detection
FZVS	Full Zero Voltage Switching
GA	Ground Assembly
GA	Ground Assembly Converter
G2V	Grid to Vehicle
ICNIRP	International Commission on Non-Ionisation Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IITD	Indian Institute of Technology, Delhi
ISO	International Organization for Standardization
IWPT	Inductive Wireless Power Transfer
LCV	Light Commercial Vehicles
LIOC	Load Independent Output Current
LIOV	Load Independent Output Voltage
MEPT	Maximum Efficiency Power Transfer
MIMO	Multi Input Multi Output
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PWM	Pulse Width Modulation
PP	Parallel Parallel

PS	Parallel Series
RMC	Reactive power Measurement Circuit
RMS	Root Mean Square
SAE	Society of Automotive Engineers
Si	Silicon
SiC	Silicon Carbide
SP	Series Prallel
SS	Series Series
V2G	Vehicle to Grid
VA	Vehicle Assembly
VAC	Vehicle Assembly Converter
VSI	Voltage Source Inverter
WBG	Wide Band Gap
ZPA	Zero Power factor Angle
ZVS	Zero Voltage Switching

Notation

1ϕ	Single phase
P_{sw_on}	Turn-on switching losses
P_{sw_off}	Turn-off switching losses
P_{cm}	MOSFET conduction losses
P_{cd}	Diode conduction losses
V_{bat}	Battery voltage
i_p	Instantaneous GA coil current
i_s	Instantaneous VA coil current
v_{ab}	Instantaneous GAC voltage
v_{cd}	Instantaneous VAC voltage
C_{oss}	MOSFET output capacitance
θ_{db}	Dead band in degrees
θ_{db_min}	Minimum Dead band in degrees
f_{sw}	switching frequency
V_{DC}	GAC input DC bus voltage
S_{in}	Input Apparent power
Q_{in}	Input Reactive power
P_{in}	Input Active power
$\vec{V}_{ab}$	RMS GAC voltage
$\vec{V}_{cd}$	RMS VAC voltage
$\vec{I}_p$	RMS GA coil current
$\vec{I}_s$	RMS VA coil current
R_p	GA parasitic resistance
R_s	VA parasitic resistance
X_p	GA reactive impedance
X_s	VA reactive impedance
R_L	Battery equivalent load resistance
R_{eq}	VAC input reflected equivalent resistance
X_{eq}	VAC input reflected equivalent reactance
R_{eq_opt}	VAC optimal input reflected equivalent resistance
X_{eq_opt}	VAC optimal input reflected equivalent reactance
Q_p	GA coil quality factor
Q_s	VA coil quality factor
U	Figure of merit
k	Coupling coefficient
α	Phase shift angle between leg a and b of GAC
β	Phase shift angle between leg c and d of VAC
θ	Phase shift angle between leg a and c

ϕ_p	GAC power factor angle
ϕ_s	VAC power factor angle
ϕ_{pp}, ϕ_{ss}	Self fluxes
ϕ_{ps}, ϕ_{sp}	Mutual fluxes
v_p, v_s	EMF induced due to flux linkages
L_p, L_s	Self inductances
L_{lp}, L_{ls}	Leakage inductances
M	Mutual inductance
k	Coupling coefficient
K_p	Proportional gain
K_i	Integral gain
C_p, C_s	Compensation capacitors
Z_{in}	Input impedance
Z_r	Reflected impedance
Z_o	Output impedance
ω_p	GA resonance frequency
ω_s	VA resonant frequency
ω_n	Normalized angular frequency
η_s	Efficiency
Q_{LP}	Load quality factor for parallel compensation
Q_{LS}	Load quality factor for series compensation
N_S, N_P	GA and VA coil turns
D_{in}, D_{out}	Inner and outer diameter of the coil
D_{cd}	Central diameter of the coil
G_v	Voltage gain
G_I	Current gain
P_{out}	Output power
B_{max}	maximum flux density
$E_{on} \text{ and } E_{off}$	Switch turn on and Off energy losses
$v_{cp} \text{ and } v_{cs}$	Voltage across the compensation capacitors
i_{1p}	GAC input current
i_{2s}	VAC output current
$\Lambda[G(s)]$	Relative gain array (RGA)
$\Im(Z_{in})$	Imaginary part of input impedance
$\Re(Z_{in})$	Real part of input impedance
