

DESIGN AND DEVELOPMENT OF SQUARE SHAPE BASED COIL STRUCTURES FOR WIRELESS POWER TRANSFER SYSTEM

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JULY 2025

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DESIGN AND DEVELOPMENT OF SQUARE SHAPE BASED COIL STRUCTURES FOR WIRELESS POWER TRANSFER SYSTEM

by

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Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

CERTIFICATE

This is to certify that the thesis entitled “**Design and Development of Square Shape Based Coil Structures for Wireless Power Transfer System**” being submitted by **Mr.Pushpendra Yadav** in fulfillment of the requirements for the degree of **Doctor of Philosophy** in the Department of Electrical Engineering of Indian Institute of Technology Delhi, New Delhi.

Mr. Pushpendra Yadav has worked under my supervision and fulfilled the requirement for submission of the thesis, which to my knowledge reached the requisite standards. The matter embodied in this thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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ACKNOWLEDGEMENT

I would like to express sincere thanks and gratitude to my supervisor **Prof. M. Veerachary**, Department of Electrical Engineering, Indian Institute of Technology Delhi, India, for his valuable guidance, direction and constant encouragement throughout the period of doctoral program. His continual guidance and support contributed significantly in refining this research work.

I would also like to express gratitude and deep thanks to SRC members, **Prof. Amit Kumar Jain** and **Prof. Anandarup Das**, Department of Electrical Engineering, and **Prof. K. Ravi**, Department of Energy Science, IIT Delhi, for their valuable comments, constructive suggestions, and support during semester progress. I would also like to express my sincere thanks to Mr. Amit Kumar, Sr. Technical Superintendent, Mr. Borla Sagar, Technical officer of Power Electronics laboratory for providing research facility and assistantship during my research work.

I am also grateful to my seniors Mr. Nikhil Kumar, Mr. Varun Chitransh, Mr. Shrikant Misal, Mrs. Jyoti Prakash, Mr. Priyabrata Shaw, Mr. Punit Kumar, Mr. Ambuj Sharma, Mr. Devesh Malviya, and Mrs. Vasudha Khubchandani for giving me encouragement and motivation during the research work. I would also like to thank fellow research scholar Mr. Malay Ranjan Khuntiya, and my juniors Mr. Rahul, Mr. Satish, Mr. Nishant, Mr. Shreyansh, Mr. Venugopal, and Mr. Gaurav for their helpful discussions and support.

I would like to express thanks to my great uncle Mr. Bhole Singh, my parents Smt. Indervati and Shri Man Singh, my brother Amar, sister Upasana, parents-in-law Smt. Anita Yadav and Shri. Rakesh Yadav, brother-in-law Aayush, and my wife Mrs. Anjali Yadav for unconditional love and support. I would also like to thank my friends Mr. Anmol Singh, Mr. Rajat Sharma, Mr. Priyavrat Vats, Mr. Saran Chaurasiya, and Mr. Rajesh Kumar for cheering me up during this journey. I

convey profound gratitude to all individuals who contributed, both directly and indirectly in successful completion of this thesis.

Pushpendra Yadav

ABSTRACT

The work in this thesis mainly focuses on the design and development of new coil structures which provide high coefficient of coupling for large air-gaps, and low variations in output voltage, output power and efficiency under horizontal misalignment condition. Attaining high coupling coefficient for large air-gaps improves overall efficiency, output power transfer capability, low voltage stress across components, and lower leakage fields around the charging area. With conventional coils, achieving high coupling coefficient for large air-gaps (applications such as in drones and EVs) is quite challenging due to physical limits imposed due to space constraints. To increase the coupling factor, a single sided flux coupler is developed that enhances the nominal coupling factor, also yielding better flux density towards receiver (RX) coil. The proposed coupler is auxiliary coil based square coupler (AXBSC). The basis of AXBSC is conventional square coil which is evolved by adding auxiliary coil around ferrite core to enhance the flux linkages and collection by effectively magnetizing the ferrite cores. This thesis investigates the systematic design and geometric optimization using finite-element analysis (FEA) simulations. The performance comparison of AXBSC with existing coil structures (circular, square and DD coil) is presented in simulation in terms of self-inductance, mutual inductances and coupling factors against variation in vertical distances. To demonstrate the efficacy and suitability of AXBSC coupler in WPT systems, 150 W laboratory prototype is developed and simulations results are validated through experimentation.

The AXBSC coupler enhances the nominal coupling factor but rate of change of mutual inductance profile under misalignment conditions is very high, as a result the output voltage, output power and efficiency of system changes drastically even for small horizontal misalignment cases. To address misalignment issues, a new modified TX coil structure is evolved from

conventional square coil by adding tertiary coils. Initially, the improvement is achieved along y-axis only and later this concept is extended in other directions. Here, the concept of magnetic field shifting is adopted where magnetic field is shifted in the desired direction with the help of tertiary coils. Furthermore, coil polarity arranger (CPA) block and misalignment detection circuit (MDC) is proposed to implement this technique. The geometric design is carried out through FEA simulation and the performance comparison is carried out with existing coil structures. As compared to other structures, the proposed transmitter (TX) coil structure under misalignment scenarios outperforms the other WPT coil structures. The modified TX-coil structure is effective in mitigating the fluctuations in output power and voltage within 5% tolerance up to 60 mm against lateral misalignment (i.e. 30% of coil size). A 120 W laboratory prototype is designed and built to illustrate the functionality of the formulated TX-coil and misalignment detection circuit, for a 36 V input and a 48 V output. The system delivers an output power of 106 Watts with a nominal efficiency of 86% when operating under a 100 mm air-gap (half the size of the coil). The system upholds consistent efficiency, output power, and output voltage within a tolerance of 5% up to 60 mm of misalignment (a total range of 120 mm range) along y-and x-axis. The experiments are conducted for misalignments in diagonal directions and the results indicated that the range has reduced to 80 mm.

सार

इस शोध प्रबंध में मुख्य रूप से नई कुंडल संरचनाओं के डिजाइन और विकास पर ध्यान केंद्रित किया गया है जो बड़े वायु-अंतरालों के लिए उच्च युग्मन गुणांक प्रदान करती हैं, और क्षैतिज मिसलिग्मेंट की स्थिति में आउटपुट वोल्टेज, आउटपुट पावर और दक्षता में कम बदलाव प्रदान करती हैं। बड़े वायु-अंतरालों के लिए उच्च युग्मन गुणांक प्राप्त करने से समग्र दक्षता, आउटपुट पावर ट्रांसफर क्षमता, घटकों में कम वोल्टेज तनाव और चार्जिंग क्षेत्र के आसपास कम रिसाव क्षेत्र में सुधार होता है। पारंपरिक कुंडलियों के साथ, बड़े वायु-अंतरालों (ड्रोन और ईवी जैसे अनुप्रयोगों में) के लिए उच्च युग्मन गुणांक प्राप्त करना स्थान की कमी के कारण लगाई गई भौतिक सीमाओं के कारण काफी चुनौतीपूर्ण है। युग्मन कारक को बढ़ाने के लिए, एक तरफा फ्लक्स कपलर विकसित किया गया है जो नाममात्र युग्मन कारक को बढ़ाता है, साथ ही रिसीवर (RX) कुंडल की ओर बेहतर फ्लक्स घनत्व भी प्रदान करता है। प्रस्तावित कपलर सहायक कुंडल आधारित वर्गाकार कपलर (AXBSC) है। AXBSC का आधार पारंपरिक वर्गाकार कुंडल है जिसे फेराइट कोर के चारों ओर सहायक कुंडल जोड़कर विकसित किया गया है ताकि फेराइट कोर को प्रभावी ढंग से चुंबकित करके फ्लक्स लिंकेज और संग्रहण को बढ़ाया जा सके। यह शोध प्रबंध परिमित-तत्व विश्लेषण (FEA) सिमुलेशन का उपयोग करके व्यवस्थित डिजाइन और ज्यामितीय अनुकूलन की जाँच करता है। AXBSC की मौजूदा कुंडल संरचनाओं (वृत्ताकार, वर्गाकार और DD कुंडल) के साथ प्रदर्शन तुलना, ऊर्ध्वाधर दूरियों में परिवर्तन के विरुद्ध स्व-प्रेरकत्व, पारस्परिक प्रेरकत्व और युग्मन कारकों के संदर्भ में सिमुलेशन में प्रस्तुत की गई है। WPT प्रणालियों में AXBSC युग्मक की प्रभावकारिता और उपयुक्तता को प्रदर्शित करने के लिए, 150 W प्रयोगशाला प्रोटोटाइप विकसित किया गया है और सिमुलेशन परिणामों को प्रयोगों के माध्यम से मान्य किया गया है।

AXBSC युग्मक नाममात्र युग्मन कारक को बढ़ाता है, लेकिन मिसलिग्मेंट स्थितियों के तहत पारस्परिक प्रेरकत्व प्रोफाइल में परिवर्तन की दर बहुत अधिक होती है, जिसके परिणामस्वरूप आउटपुट वोल्टेज, आउटपुट पावर और सिस्टम की दक्षता छोटे

क्षैतिज मिसलिग्मेंट मामलों में भी नाटकीय रूप से बदल जाती है। मिसलिग्मेंट समस्याओं के समाधान के लिए, तृतीयक कुंडलियों को जोड़कर पारंपरिक वर्गाकार कुंडल से एक नई संशोधित TX कुंडल संरचना विकसित की गई है। प्रारंभ में, सुधार केवल y-अक्ष के अनुदिश प्राप्त किया जाता है और बाद में इस अवधारणा को अन्य दिशाओं में विस्तारित किया जाता है। यहां, चुंबकीय क्षेत्र स्थानांतरण की अवधारणा को अपनाया जाता है जहां तृतीयक कॉइल की मदद से चुंबकीय क्षेत्र को वांछित दिशा में स्थानांतरित किया जाता है। इसके अलावा, इस तकनीक को लागू करने के लिए कॉइल पोलरिटी अरेंजर (CPA) ब्लॉक और मिसलिग्मेंट डिटेक्शन सर्किट (MDC) का प्रस्ताव है। ज्यामितीय डिजाइन FEA सिमुलेशन के माध्यम से किया जाता है और प्रदर्शन की तुलना मौजूदा कॉइल संरचनाओं के साथ की जाती है। अन्य संरचनाओं की तुलना में, मिसलिग्मेंट परिदृश्यों के तहत प्रस्तावित ट्रांसमीटर (TX) कॉइल संरचना अन्य WPT कॉइल संरचनाओं से बेहतर प्रदर्शन करती है। संशोधित TX-कॉइल संरचना पार्श्व मिसलिग्मेंट (यानी कॉइल आकार का 30%) के खिलाफ 60 मिमी तक 5% सहिष्णुता के भीतर आउटपुट पावर और वोल्टेज में उतार-चढ़ाव को कम करने में प्रभावी है। यह प्रणाली 100 मिमी वायु-अंतराल (कुंडली के आधे आकार) में संचालित होने पर 86% की नाममात्र दक्षता के साथ 106 वाट की आउटपुट शक्ति प्रदान करती है। यह प्रणाली y और x-अक्ष के अनुदिश 60 मिमी तक के मिसलिग्मेंट (कुल 120 मिमी परास) तक 5% की सहनशीलता के भीतर एकसमान दक्षता, आउटपुट शक्ति और आउटपुट वोल्टेज बनाए रखती है। विकर्ण दिशाओं में मिसलिग्मेंट के लिए प्रयोग किए गए और परिणामों से पता चला कि परास घटकर 80 मिमी रह गया है।

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LIST OF ABBREVIATIONS

AXBSC	Auxiliary Coil Based Square Coupler
BP	Bipolar
CPA	Coil Polarity Arranger
DD	Double D
EV	Electric vehicle
EMF	Electro Motive Force
EMI	Electromagnetic Interference
FEA	Finite Element Analysis
FEM	Finite Element Method
FHA	Fundamental Harmonic Analysis
KCL	Kirchoff's Current Law
KVL	Kirchoff's Voltage Law
MMF	Magneto Motive Force
MCU	Microcontroller Unit
MDC	Misalignment Detection Circuit
PI	Proportional and Integral Controller
PID	Proportional, Integral and Derivative Controller
DDQ	Quadrature double D
RX	Receiver
RMS	Root Mean Square
SS	Series-Series

SAE	Society of Automotive Engineers
TX	Transmitter
UAV	Unmanned Aerial Vehicle
WPT	Wireless Power Transfer
ZPA	Zero Phase Angle
ZVS	Zero voltage switching
SD	Standard Deviation
COV	Coefficient of variation

LIST OF SYMBOLS

V_{in}	DC input source voltage
I_{in}	Input source current
V_o	Output Voltage
I_o	Output current
R_L	Load resistance
I_1	Current in transmitter coil
I_2	Current in receiver coil
L_T	Self-inductance of transmitter coil
L_R	Self-inductance of receiver coil
M_{TR}	Mutual inductance between transmitter and receiver coil
k	Coefficient of coupling/coupling factor
C_T	Compensation capacitor in transmitter side
C_R	Compensation capacitor in receiver side
R_T	Equivalent series resistance of transmitter side
R_R	Equivalent series resistance of receiver side
N_T	Number of turns in transmitter coil
N_R	Number of turns in receiver coil
Z_{in}	Input impedance
f_o	Resonant frequency
f_s	Switching frequency of inverter
ω_o	Resonant angular frequency
η	Efficiency
P_o	Output power
d	Vertical distance between transmitter and receiver coil
w_c	Cross-sectional width of Litz wire
p	Pitch between turns
A_o	Outer half dimension of the coil
A_i	Inner half dimension of the coil
ρ_c	Resistivity of copper

l_t	Mean length of turn
N_s	Total number of strands
d_s	Diameter of strand
B_{peak}	Peak magnetic field density
$\mathcal{R}$	Reluctance