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Department of Electrical and Electronics Engineering

A PORTABLE ADAPTIVE WIRELESS POWER TRANSFER SYSTEM WITH INTELLIGENT MPPT CONTROL FOR RETROFITTING ELECTRIC VEHICLE CHARGING

Master Thesis

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Supervisor

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Turkish Abstract : Bu tezde, elektrikli araçlar için yüksek frekanslı kablosuz güç transferi (WPT) sistemi ve adaptif maksimum güç noktası izleme (MPPT) yöntemi incelenmiştir. Önerilen sistem, değişken manyetik kuplaj koşulları altında güç aktarım kapasitesini ve şarj performansını artırmak amacıyla Gri Kurt Optimizasyonu (GWO) tabanlı bir MPPT denetleyicisi kullanmaktadır. Kablosuz şarj sistemi, Seri–Seri (SS) kompanzasyon yapısına sahip rezonanslı endüktif güç transfer mimarisi ile gerçekleştirilmiştir. Çalışmada, önerilen WPT sistemi MATLAB/Simulink ortamında modellenmiş ve 3 cm ile 25 cm arasında değişen yedi farklı hava aralığı mesafesi

altında analiz edilmiştir. Sistemin doğal çalışma karakteristiklerini incelemek amacıyla farklı yük dirençleri altında maksimum güç aktarım davranışı değerlendirilmiştir. Daha sonra önerilen GWO tabanlı MPPT denetleyicisinin performansı, geleneksel Darbe Genişlik Modülasyonu (PWM) kontrol yöntemi ile karşılaştırılmıştır. Karşılaştırmalı analizler; aktarılan güç kapasitesi, batarya gerilimi, şarj akımı ve batarya doluluk oranı (SOC) parametreleri dikkate alınarak gerçekleştirilmiştir. Elde edilen sonuçlar, önerilen GWO tabanlı MPPT yönteminin tüm çalışma koşullarında geleneksel PWM kontrol yöntemine göre daha yüksek güç aktarımı, daha iyi gerilim kararlılığı ve daha gelişmiş şarj performansı sağladığını göstermektedir. Sonuç olarak, önerilen adaptif kontrol yaklaşımının değişken manyetik kuplaj koşulları altında çalışan kablosuz elektrikli araç şarj sistemleri için etkili ve güvenilir bir çözüm sunduğu doğrulanmıştır..

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Istanbul – 2026

DECLARATION

I hereby declare that in the preparation of this thesis, scientific ethical rules were followed, the works of other people were referenced in accordance with scientific norms, if used, there was no falsification in the used data, and no part of the thesis was submitted to this university or any other university as another thesis.

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SUMMARY

This thesis investigates an adaptive wireless power transfer (WPT) framework operating at high frequency for electric vehicle charging under variable magnetic coupling environments. To enhance energy delivery performance and charging effectiveness, a Grey Wolf Optimization (GWO)-driven maximum power point tracking (MPPT) strategy is incorporated into the proposed architecture. Wireless energy transmission is realized through a Series–Series (SS) compensated resonant network, which facilitates efficient power exchange between the transmitting and receiving coils.The developed system was implemented and evaluated in the MATLAB/Simulink environment across seven air-gap conditions extending from 3 cm to 25 cm. As an initial step, the influence of load resistance on transferred power was examined to characterize the system behavior under different coupling levels. Subsequently, the proposed GWO-based MPPT approach was benchmarked against a conventional pulse-width modulation (PWM) control method. The assessment focused on key performance indicators, including delivered power, battery voltage regulation, charging current behavior, and battery state-of-charge (SOC) evolution. Simulation outcomes revealed that the optimization-based controller provided consistently improved charging performance throughout the investigated operating range. The GWO algorithm demonstrated enhanced power extraction capability and more effective battery charging characteristics than the conventional PWM scheme. Furthermore, the results confirmed that stronger magnetic coupling, associated with reduced transmitter–receiver separation distances, significantly increased power transfer capability and overall charging efficiency. The obtained findings confirm the effectiveness of intelligent optimization-based adaptive control techniques for improving wireless EV charging systems operating under dynamically varying coupling conditions.

Keywords: Wireless Power Transfer, Electric Vehicles, Grey Wolf Optimization, MPPT, Magnetic Coupling, Wireless Charging Systems.

ÖZET

Bu tezde, elektrikli araçlar için yüksek frekanslı kablosuz güç transferi (WPT) sistemi ve adaptif maksimum güç noktası izleme (MPPT) yöntemi incelenmiştir. Önerilen sistem, değişken manyetik kuplaj koşulları altında güç aktarım kapasitesini ve şarj performansını artırmak amacıyla Gri Kurt Optimizasyonu (GWO) tabanlı bir MPPT denetleyicisi kullanmaktadır. Kablosuz şarj sistemi, Seri–Seri (SS) kompanzasyon yapısına sahip rezonanslı endüktif güç transfer mimarisi ile gerçekleştirilmiştir.Çalışmada, önerilen WPT sistemi MATLAB/Simulink ortamında modellenmiş ve 3 cm ile 25 cm arasında değişen yedi farklı hava aralığı mesafesi altında analiz edilmiştir. Sistemin doğal çalışma karakteristiklerini incelemek amacıyla farklı yük dirençleri altında maksimum güç aktarım davranışı değerlendirilmiştir. Daha sonra önerilen GWO tabanlı MPPT denetleyicisinin performansı, geleneksel Darbe Genişlik Modülasyonu (PWM) kontrol yöntemi ile karşılaştırılmıştır.Karşılaştırmalı analizler; aktarılan güç kapasitesi, batarya gerilimi, şarj akımı ve batarya doluluk oranı (SOC) parametreleri dikkate alınarak gerçekleştirilmiştir. Elde edilen sonuçlar, önerilen GWO tabanlı MPPT yönteminin tüm çalışma koşullarında geleneksel PWM kontrol yöntemine göre daha yüksek güç aktarımı, daha iyi gerilim kararlılığı ve daha gelişmiş şarj performansı sağladığını göstermektedir. Özellikle düşük hava aralığı mesafelerinde sistemin daha yüksek manyetik kuplaj sayesinde önemli ölçüde daha yüksek güç aktarım performansı elde ettiği gözlemlenmiştir. Sonuç olarak, önerilen adaptif kontrol yaklaşımının değişken manyetik kuplaj koşulları altında çalışan kablosuz elektrikli araç şarj sistemleri için etkili ve güvenilir bir çözüm sunduğu doğrulanmıştır.

Anahtar kelimeler: Kablosuz Güç Transferi, Elektrikli Araçlar, Gri Kurt Optimizasyonu, MPPT, Manyetik Kuplaj, Kablosuz Şarj Sistemleri.

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ABBREVIATIONS

AC	: ALTERNATING CURRENT
DC	: DIRECT CURRENT
DC–DC	: DIRECT CURRENT TO DIRECT CURRENT
EV	: ELECTRIC VEHICLE
GWO	: GREY WOLF OPTIMIZATION
HF	: HIGH FREQUENCY
IPT	: INDUCTIVE POWER TRANSFER
K	: COUPLING COEFFICIENT
L	: INDUCTANCE
M	: MUTUAL INDUCTANCE
MF	: MAGNETIC FLUX
MPP	: MAXIMUM POWER POINT
MPPT	: MAXIMUM POWER POINT TRACKING
P	: POWER
PS	: PARALLEL–SERIES
PWM	: PULSE WIDTH MODULATION
R	: RESISTANCE
RX	: RECEIVER COIL
SOC	: STATE OF CHARGE
SP	: SERIES PARALLEL
SS	: SERIES – SERIES
SSA	: SALP SWARM ALGORITHM
TX	: TRANSMITTER COIL
V	: VOLTAGE
WPT	: WIRELESS POWER TRANSFER
Ω	: ANGULAR FREQUENCY

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PREFACE

First and foremost, I would like to express my deepest gratitude to Allah the Almighty for His endless blessings, guidance, and mercy throughout my academic journey. Without His support, this work would not have been possible.

I would like to dedicate this achievement to my beloved parents, whose sacrifices, unconditional love, and continuous support have always been the foundation of my success. Their encouragement and belief in me have inspired me throughout every stage of my life.

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Finally, it is my sincere hope that the findings presented in this thesis will contribute to the ongoing advancement of wireless power transfer technologies and provide a useful reference for future researchers. I also hope that this work encourages aspiring scholars to pursue their goals with perseverance, confidence, and dedication.

CHAPTER ONE

GENERAL INTRODUCTION

1.1. Introduction

Growing concerns regarding energy sustainability and the environmental consequences of conventional fossil-fuel-based transportation have intensified global efforts to develop cleaner mobility solutions (Rehman et al., 2025). Among the available alternatives, electric vehicles (EVs) have become a key component of modern transportation strategies because of their high energy utilization efficiency, lower environmental footprint, and ability to integrate with renewable energy sources (Malik et al., 2025). Consequently, considerable attention has been directed toward enhancing EV technologies and establishing advanced charging infrastructures capable of satisfying the evolving requirements of future transportation networks (Nasri et al., 2025).

Despite the technological progress achieved in electric mobility, charging infrastructure continues to represent a significant barrier to the widespread deployment of EVs. Conventional charging approaches depend on physical electrical connections between the charging equipment and the vehicle battery through cables and connectors. Although such methods have been successfully adopted in many commercial applications, they are accompanied by several practical limitations, including connector wear, exposure to environmental stresses, operational safety concerns, and reduced suitability for automated charging. These challenges become increasingly important as transportation systems move toward higher levels of automation and intelligent operation.

In response to these limitations, wireless power transfer (WPT) technology has emerged as an attractive alternative for next-generation EV charging systems. Unlike conductive charging methods, WPT enables energy transmission without physical electrical contact by utilizing magnetic coupling between transmitter and receiver coils. This contactless charging approach offers several benefits, including enhanced operational safety, reduced maintenance requirements, improved user convenience, and greater compatibility with autonomous charging infrastructures. This technology offers several advantages, including enhanced user convenience, improved electrical

safety, reduced maintenance requirements, and better adaptability for autonomous and dynamic charging systems(Shovon et al., 2026). Among various WPT techniques, resonant inductive wireless power transfer has become one of the most widely adopted approaches for EV charging applications due to its high efficiency, operational flexibility, and capability of transferring power across moderate air-gap distances.

Despite the considerable progress achieved in wireless charging technologies, ensuring consistent and efficient power delivery remains one of the primary technical challenges in wireless EV charging systems. The amount of power transferred is highly sensitive to several factors, including coil misalignment, fluctuations in the magnetic coupling coefficient, load variations, operating frequency deviations, and, most importantly, the separation distance between the transmitting and receiving coils (Özüpak, 2024). Any deterioration in magnetic coupling conditions can negatively affect power transfer capability, increase energy losses, and degrade charging performance. Consequently, adaptive control mechanisms are essential for maintaining optimal operating conditions and maximizing power transfer efficiency under dynamic environmental and operational circumstances (Gao et al., 2025).

Recent developments in high-frequency wireless charging systems have highlighted the importance of combining advanced power electronic converters with intelligent control methodologies to improve both energy transfer efficiency and operational reliability (Ben Fadhel and Cardoso, 2025). Among the available control approaches, Maximum Power Point Tracking (MPPT) techniques have become widely adopted due to their ability to continuously adjust converter operating parameters in response to changing system conditions, thereby improving power extraction performance (Guanghua et al., 2025). In contrast, conventional fixed pulse-width modulation (PWM) controllers often exhibit limited adaptability when magnetic coupling conditions vary rapidly, which may result in lower efficiency and slower transient response characteristics.

In recent years, metaheuristic optimization methods have emerged as powerful tools for addressing nonlinear and highly dynamic optimization problems encountered in renewable energy and power electronics applications. One of the most prominent approaches is the Grey Wolf Optimization (GWO) algorithm, which has attracted significant research interest because of its effective exploration–exploitation balance,

rapid convergence behavior, computational simplicity, and robustness in complex operating environments (Dagal et al., 2025). Inspired by the hierarchical leadership structure and cooperative hunting strategy observed in grey wolf populations, the GWO algorithm offers an efficient search mechanism capable of identifying optimal operating points under continuously changing system conditions.

Motivated by these advantages, this thesis proposes an adaptive power transfer framework for high-frequency wireless EV charging systems based on the Grey Wolf Optimization algorithm. The proposed approach is designed to enhance transferred power capability, improve charging reliability, and maintain high system efficiency under different magnetic coupling scenarios and air-gap distances. To achieve these objectives, a resonant inductive wireless power transfer architecture is integrated with an intelligent converter control scheme that dynamically adapts to operating condition variations. The proposed methodology is validated through a comprehensive set of operating scenarios and benchmarked against conventional control techniques to assess its effectiveness in terms of power transfer performance, charging stability, and adaptability.

1.2. Motivation

Over the past decades, the increasing demand for electricity driven by population growth, urbanization, and the expansion of industrial and transportation activities has placed considerable pressure on global energy resources. Simultaneously, growing awareness of environmental challenges, including carbon emissions, resource depletion, and climate-related impacts, has encouraged the adoption of cleaner and more sustainable energy solutions. Within this context, electric vehicles (EVs) have emerged as a key component of modern transportation strategies due to their potential to reduce environmental impacts while improving overall energy utilization efficiency.

As EV adoption continues to accelerate, the development of efficient and dependable charging infrastructures has become a critical requirement for supporting large-scale deployment. Although conductive charging technologies remain the dominant commercial solution, they are associated with several operational constraints. Issues such as cable handling, connector deterioration, periodic maintenance requirements, and limited charging flexibility can negatively affect user experience and system reliability. Moreover, conventional plug-in charging

approaches are not ideally suited to the evolving landscape of autonomous mobility and smart transportation ecosystems, where automated, convenient, and uninterrupted charging processes are increasingly required.

Wireless Power Transfer (WPT) has gained considerable attention as an effective charging approach capable of addressing many of the shortcomings associated with conventional conductive charging systems. By utilizing resonant magnetic coupling between transmitting and receiving units, electrical energy can be delivered without direct physical contact. This contactless charging mechanism offers several practical benefits, including enhanced operational safety, improved user experience, lower maintenance demands, and greater compatibility with automated charging environments. In addition, the adoption of high-frequency resonant operation enables higher power density, more compact system configurations, and improved energy transfer capability compared with traditional charging solutions.

Although WPT technology offers substantial advantages, achieving reliable and efficient power delivery under dynamic operating conditions remains a critical challenge. System performance is strongly influenced by several factors, including the separation distance between coils, alignment accuracy, magnetic coupling variations, operating frequency deviations, and load fluctuations. Changes in these parameters can adversely affect power transfer effectiveness, resulting in reduced transferred power, voltage regulation issues, higher power losses, and diminished charging efficiency. Consequently, advanced adaptive control strategies are essential for continuously adjusting system operation and ensuring optimal energy transfer performance across a wide range of operating conditions.

The advancement of high-frequency wireless charging technologies has increased the demand for intelligent control frameworks capable of maintaining efficient and reliable power transfer. In this regard, the combination of modern power electronic converters with optimization-based control methodologies has proven to be an effective approach for enhancing both energy transfer efficiency and charging performance. A key component of such systems is the Maximum Power Point Tracking (MPPT) mechanism, which continuously regulates converter operating parameters to extract the highest possible power under varying system conditions. However, conventional control approaches based on fixed pulse-width modulation

(PWM) strategies often struggle to maintain optimal performance when subjected to nonlinear dynamics and rapidly changing operating environments, resulting in limited adaptability and slower response characteristics.

To address these challenges, metaheuristic optimization techniques have been increasingly adopted in renewable energy and power conversion applications due to their capability to handle complex optimization tasks without requiring detailed mathematical models. Among the available approaches, Grey Wolf Optimization (GWO) has emerged as a particularly attractive algorithm owing to its efficient exploration and exploitation capabilities, rapid convergence behavior, computational simplicity, and resilience in dynamic operating conditions. Inspired by the cooperative hunting strategy and hierarchical social structure of grey wolves, the algorithm provides an effective search mechanism for identifying optimal operating points within complex nonlinear systems. These characteristics make GWO a suitable candidate for adaptive power management and real-time control in wireless electric vehicle charging applications, where operating conditions may vary continuously during the charging process.

In response to the operational challenges associated with wireless electric vehicle charging and the growing demand for intelligent energy transfer solutions, this research proposes an adaptive power transfer framework based on the Grey Wolf Optimization (GWO) algorithm for high-frequency wireless charging applications. The proposed approach is designed to enhance power transfer performance, improve charging reliability, and sustain efficient system operation under varying magnetic coupling conditions and air-gap distances. By incorporating an optimization-driven control strategy within the wireless charging architecture, the framework seeks to dynamically adapt to changing operating environments and maintain favorable charging characteristics. Furthermore, this study aims to support the advancement of intelligent wireless charging technologies by providing a robust and adaptive solution capable of meeting the performance requirements of future electric transportation infrastructures.

1.3. Aims

The main objective of this research is to design and evaluate an adaptive power transfer framework based on the Grey Wolf Optimization (GWO) algorithm for high-

frequency wireless electric vehicle (EV) charging applications. The proposed framework is intended to enhance power transfer performance, improve charging reliability, and maintain high operational efficiency under dynamic magnetic coupling and varying charging conditions.

To achieve this objective, the study pursues the following specific goals:

• To develop a high-frequency resonant Wireless Power Transfer (WPT) architecture tailored for electric vehicle charging applications.

• To integrate a Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) strategy for adaptive converter control and optimal power extraction.

• To examine the influence of air-gap variations and magnetic coupling conditions on the operational behavior and energy transfer capability of the proposed system.

• To assess key performance indicators, including transferred power, voltage regulation characteristics, and battery charging performance.

• To conduct a comparative evaluation between the proposed GWO-driven control framework and a conventional Pulse Width Modulation (PWM) control approach.

• To enhance the efficiency, robustness, and adaptability of wireless EV charging systems operating under dynamic and uncertain conditions.

1.4. Thesis Contributions

This thesis contributes to the advancement of Wireless Power Transfer (WPT) technology and intelligent control methodologies for electric vehicle charging applications through several key achievements. The first contribution is the development of an adaptive power transfer strategy based on the Grey Wolf Optimization (GWO) algorithm for high-frequency wireless charging systems. The developed control framework is designed to enhance energy transfer performance while maintaining reliable charging operation under varying system conditions.

Another contribution of this work lies in the extensive evaluation of wireless charging performance across multiple air-gap distances and magnetic coupling scenarios. This investigation provides a detailed understanding of the influence of coupling variations on power transfer behavior and charging effectiveness, while

demonstrating the ability of the optimization-based controller to sustain stable operation under dynamic conditions.

The research also presents a comparative assessment between the GWO-driven control scheme and a conventional Pulse Width Modulation (PWM) approach. The obtained results reveal noticeable improvements in transferred power, overall efficiency, voltage regulation characteristics, and adaptive response when the optimization-based strategy is employed.

Furthermore, this study expands the current understanding of integrating metaheuristic optimization techniques with high-frequency resonant wireless charging architectures. The findings confirm that intelligent optimization algorithms can effectively enhance converter control performance and improve the operational characteristics of wireless charging systems.

Finally, the proposed methodology offers a practical foundation for the realization of next-generation wireless charging infrastructures. The developed framework may support future advancements in autonomous charging platforms, dynamic wireless power transfer systems, smart transportation networks, and intelligent power electronic control applications.

1.5. Thesis Outlines

The structure of this thesis has been designed to provide a logical progression from the fundamental concepts of wireless power transfer to the development and evaluation of an adaptive charging framework. The study is organized into five integrated chapters that collectively address system modeling, optimization-based maximum power point tracking, and performance assessment of wireless electric vehicle charging systems operating under different magnetic coupling conditions.

Chapter II: presents the fundamentals of wireless power transfer systems, including magnetic coupling, mutual inductance, resonance conditions, and power transfer characteristics. It also comparatively analyzes the SS, SP, PS, and PP compensation topologies to identify the most suitable configuration for electric vehicle charging applications.

Chapter III**:** presents the proposed Grey Wolf Optimization (GWO)-based maximum power point tracking (MPPT) controller for optimizing the duty cycle of the

receiver-side DC–DC converter in the wireless power transfer system. It also explains the maximum power tracking formulation, duty-cycle update mechanism, and the conventional PWM control strategy used for performance comparison under varying air-gap conditions.

Chapter IV**:** presents the simulation implementation and performance evaluation of the proposed wireless power transfer (WPT) system under different operating conditions. It explains the MATLAB/Simulink configuration of the resonant wireless charging system and evaluates the proposed GWO-based MPPT controller in terms of transferred power capability, voltage and current characteristics, and battery state-of-charge (SOC) performance under varying air-gap conditions.

Chapter V**:** concludes the thesis by summarizing the main findings and contributions of the proposed wireless power transfer (WPT) system for electric vehicle charging applications. The obtained results confirm the suitability of the Grey Wolf Optimization (GWO)-based MPPT approach for adaptive wireless charging applications, showing its ability to sustain efficient power transfer and reliable charging behavior across a range of magnetic coupling scenarios. Furthermore, the outcomes of this research establish a basis for future investigations into advanced control methodologies and next-generation wireless electric vehicle charging systems.

CHAPTER TWO

WIRELESS POWER TRANSFER SYSTEM AND MODELING

2.1. Introduction

The growing emphasis on sustainable mobility solutions has accelerated the global transition toward electric transportation, positioning electric vehicles (EVs) as a central element of future transportation strategies (Satpathy et al., 2025). Increasing concerns regarding environmental sustainability, carbon emissions, and long-term energy security have further strengthened the shift away from conventional fossil-fuel-based transportation systems (Menyhart, 2024). As EV adoption continues to expand, the effectiveness of charging infrastructure becomes increasingly important for ensuring reliable vehicle operation and supporting integration with emerging smart-grid and intelligent transportation ecosystems (Okika and Musonda, 2025). Consequently, modern charging technologies are expected to deliver high energy efficiency, operational adaptability, reduced maintenance requirements, and seamless charging functionality suitable for automated transportation environments (Ramesh et al., 2025).

At present, most electric vehicles rely on conductive charging solutions in which electrical energy is supplied through a physical connection between the charging unit and the vehicle battery. Although this approach has achieved widespread commercial acceptance, several technical and practical challenges remain, including connector wear, exposure to adverse environmental conditions, and limitations in user convenience (Callen et al., 2000). In addition, the dependence on physical interfaces restricts the suitability of conductive charging systems for future autonomous and continuously connected transportation infrastructures (Leijon and Boström, 2022). To address these challenges, Wireless Power Transfer (WPT) technology has attracted growing research and industrial interest as a contactless charging alternative. By employing electromagnetic coupling between spatially separated transmitter (Tx) and receiver (Rx) coils, electrical energy can be transferred without direct electrical contact (Lee, 2024). This operating principle improves charging accessibility, enhances electrical safety, and minimizes mechanical degradation associated with conventional connectors. Furthermore, WPT systems can support both stationary and in-motion

charging scenarios, offering a practical pathway toward extending driving range and reducing concerns related to vehicle charging availability (Saraswathi and Vijayapriya, 2024).

Among the different WPT approaches, inductive wireless power transfer has attracted considerable research attention due to its relatively high efficiency and suitability for medium- and high-power charging applications (Shinohara, 2021). In inductive WPT systems, energy is transferred through a time-varying magnetic field generated by the transmitter coil and captured by the receiver coil (Hassan et al., 2017). The induced electrical energy is then processed through power electronic conversion stages to charge the EV battery (Aydin et al., 2022). Despite these advantages, maintaining stable and efficient power transfer under practical operating conditions remains a major technical challenge (Zhang et al., 2025).

The effectiveness of inductive wireless power transfer systems is largely governed by the strength of the magnetic interaction established between the transmitting and receiving coils (Kodeeswaran et al., 2024). Several parameters influence this interaction, including coil geometry, alignment accuracy, and the separation distance between the coupled coils (Aganti et al., 2025). In practical electric vehicle charging environments, maintaining a fixed separation distance is challenging due to factors such as vehicle positioning tolerances, suspension displacement, and variations in ground clearance (ElGhanam et al., 2021). As the distance between the coils increases, the magnetic coupling weakens, resulting in lower mutual inductance and a corresponding decline in power transfer capability (Dai et al., 2024). Moreover, fluctuations in coupling conditions may lead to impedance mismatches that adversely affect power delivery efficiency and system operating stability (Bi et al., 2016). The air-gap values investigated in this study were selected to represent both realistic charging scenarios and more demanding operating conditions. Distances between 5 cm and 10 cm reflect typical stationary EV charging applications, while larger separations were considered to assess the resilience of the proposed control approach under weak coupling environments (Van Mulders et al., 2022).

To mitigate the adverse effects associated with coupling variations, resonant compensation techniques are widely employed in wireless charging systems to minimize reactive power and sustain efficient resonance operation (Wu et al., 2026).

Numerous compensation arrangements have been reported in the literature, including Series–Series (SS), Series–Parallel (SP), Parallel–Series (PS), and Parallel–Parallel (PP) topologies (Li et al., 2023). Among these alternatives, the SS configuration has received extensive attention due to its structural simplicity, favorable resonance characteristics, and compatibility with loosely coupled power transfer applications (Aditya and Williamson, 2014). Furthermore, its ability to provide stable impedance reflection behavior under varying coupling conditions makes it particularly suitable for wireless charging systems intended for electric vehicles.

Beyond compensation network design, the control strategy employed within the power conversion stage significantly influences overall system performance (Guo, 2024). Conventional pulse-width modulation (PWM) control remains a common solution because of its straightforward implementation and dependable operation. Nevertheless, fixed-control PWM approaches often exhibit limited responsiveness when magnetic coupling conditions change as a result of air-gap variations. Consequently, system operation may shift away from the maximum power transfer region, leading to reduced energy delivery capability and lower charging effectiveness (Li et al., 2021). To overcome these limitations, Maximum Power Point Tracking (MPPT) techniques have been introduced to continuously adapt converter operating conditions and maintain optimal power transfer under changing coupling scenarios (Liu et al., 2024).

Among contemporary optimization methodologies, Grey Wolf Optimization (GWO) has attracted significant interest as a robust metaheuristic technique for solving nonlinear engineering optimization problems (Aganti et al., 2025). Owing to its efficient search mechanism, rapid convergence behavior, and relatively simple implementation, GWO has been successfully applied in various power electronics and renewable energy applications. Within wireless charging systems, a GWO-based MPPT controller can dynamically adjust the duty cycle of the receiver-side DC–DC converter to preserve operation near the optimal power transfer point despite fluctuations in magnetic coupling conditions. This adaptive behavior contributes to improved energy transfer performance and superior charging characteristics when compared with conventional fixed-control approaches (Gupta et al., 2025).

Although previous studies have explored the application of MPPT techniques in wireless charging systems, a comprehensive investigation of air-gap variation effects on both power transfer performance and battery charging behavior remains limited. In particular, the combined assessment of transferred power enhancement and battery state-of-charge (SOC) evolution under different magnetic coupling conditions has received relatively little attention. To address this research gap, this thesis presents a high-frequency inductive wireless charging system for electric vehicle applications incorporating a Grey Wolf Optimization-based MPPT controller operating with a 400 V battery. The developed system employs a Series–Series compensated topology and examines charging performance across seven air-gap distances ranging from 25 cm to 3 cm. In addition, a detailed comparison between the proposed GWO-driven MPPT strategy and a conventional PWM controller is conducted to evaluate improvements in power transfer capability and battery SOC performance under different coupling conditions.

2.2. System architecture

The developed Wireless Power Transfer (WPT) system is intended to deliver electrical energy to an electric vehicle battery through a contactless charging process while maintaining high efficiency and operational reliability (Aditya and Williamson, 2014). The overall architecture consists of several interconnected power conversion stages integrated with a resonant inductive coupling network that facilitates energy transfer across the air gap. As depicted in Fig. 1, power flows sequentially from the utility source to the battery charging unit through a series of conditioning and conversion stages.

The process begins with a three-phase AC supply, which is converted into a DC voltage using an AC–DC rectification stage. The resulting DC output forms the primary power bus and is subsequently fed to a DC–DC boost converter responsible for increasing and regulating the DC-link voltage. Proper regulation of this intermediate DC stage is important for maintaining stable system operation and ensuring consistent energy delivery to the subsequent conversion stages.

Following voltage conditioning, the DC-link output is supplied to a high-frequency inverter that generates an alternating voltage at the desired operating frequency. High-frequency operation is widely adopted in inductive wireless charging

systems because it enhances magnetic energy transfer and improves power transmission performance under resonant conditions [30]. The inverter output excites the transmitter (Tx) coil, which acts as the primary energy-emitting element of the wireless charging interface.

To improve energy transfer effectiveness and mitigate the impact of reactive power within the resonant circuit, a Series–Series (SS) compensation network is incorporated on both sides of the inductive link (Hassan et al., 2017). In this configuration, the compensation capacitors are selected such that resonance is achieved at the operating frequency, allowing the reactive components associated with the coil inductances to be effectively compensated. As a result, the equivalent circuit impedance is reduced, active power transfer is enhanced, and overall system efficiency is improved.

In addition, the SS compensation topology provides stable resonance characteristics under loosely coupled operating conditions, making it highly suitable for wireless EV charging applications. When energized by the high-frequency current, the transmitter coil generates a time-varying magnetic field that propagates across the air gap separating the transmitter and receiver structures. The receiver coil (Rx), positioned on the vehicle side, captures part of the generated magnetic flux and produces an induced AC voltage according to the principles of electromagnetic induction (Aydin et al., 2022). The voltage induced in the receiver coil depends largely on the strength of the magnetic coupling established across the wireless interface, with the separation distance between the coils representing one of the most influential factors. After energy is captured by the receiver (Rx) coil, the resulting high-frequency AC voltage is processed by an AC–DC rectification stage to produce a DC output suitable for battery charging applications. This DC power is then delivered to a DC–DC converter governed by a Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) strategy.

In contrast to conventional fixed-control Pulse Width Modulation (PWM) approaches, the proposed optimization-driven controller adaptively adjusts the converter duty ratio according to real-time operating conditions. This adaptive regulation enables the charging system to operate close to the optimal power transfer region despite variations in magnetic coupling caused by changes in air-gap distance

and other operating parameters. Consequently, improved energy transfer performance and more consistent charging behavior can be achieved across a wide range of wireless charging conditions.

. This adaptive control behavior improves the transferred power capability and enhances the battery charging performance under different air-gap distances. Finally, the regulated DC output is delivered to the 400 V EV battery to ensure stable charging operation. Through the integration of high-frequency power conversion, resonant inductive coupling, series-series compensation, and adaptive GWO-based MPPT control, the proposed WPT architecture achieves enhanced transferred power performance and improved charging characteristics under variable operating conditions.

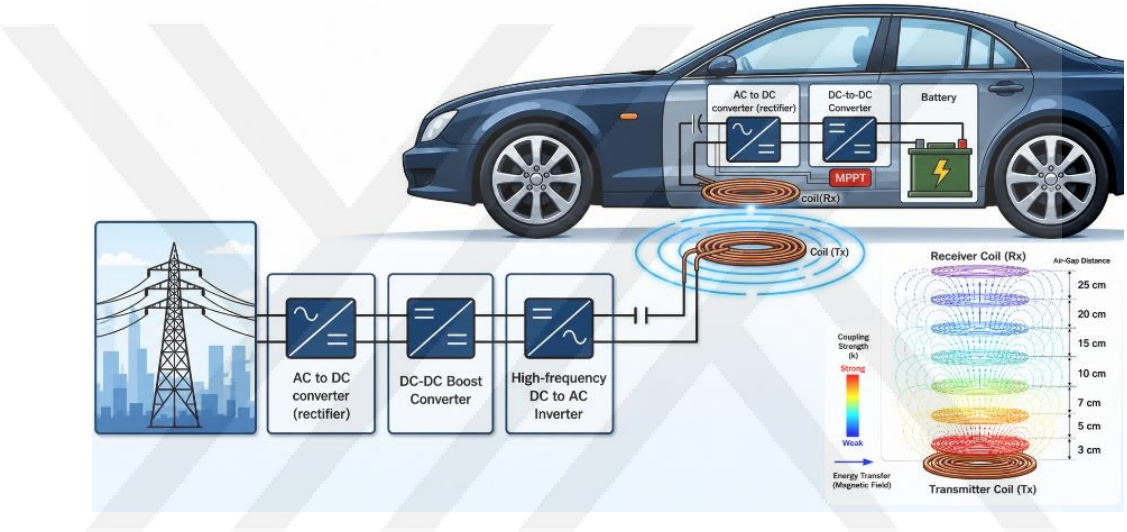


Figure 1. Proposed wireless EV charging system architecture.

2.3. Fundamental Principle of Inductive Power Transfer

Wireless power transfer (WPT) systems for electric vehicle applications operate based on inductive coupling between two physically separated coils, namely the transmitter (Tx) and receiver (Rx) coils (Zhang et al., 2025). At the transmitter side, the supplied electrical energy is converted into a high-frequency alternating signal, which generates a time-varying magnetic field around the transmitter coil. This magnetic field propagates across the air gap and induces an electromotive force in the receiver coil according to the principles of electromagnetic induction (Kodeeswaran et al., 2024). As a result, electrical energy can be transferred without direct electrical

contact, making inductive WPT technology highly suitable for electric vehicle charging applications (Maisnam et al., 2026).

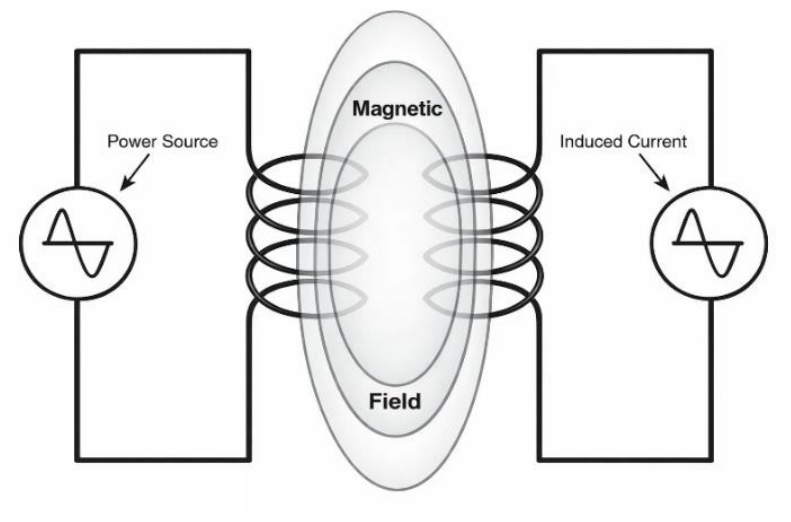


Figure 2. Magnetic coupling between the transmitter and receiver coils illustrating magnetic flux linkage.

As illustrated in Fig.2, the inductive coupling process is governed by the distribution of magnetic field lines and the magnetic flux linkage established between the transmitter and receiver coils. In practical inductive wireless power transfer systems, not all of the magnetic field produced by the transmitter coil contributes directly to energy transmission. A fraction of the generated magnetic flux successfully links the receiver coil and participates in power transfer, whereas the remaining flux disperses into the surrounding space as leakage flux. This phenomenon decreases the effectiveness of magnetic energy transfer and constitutes a major source of performance degradation in inductive charging systems.

The capability of a WPT system to deliver power is closely related to the degree of magnetic coupling established between the transmitter and receiver coils. This interaction is commonly quantified by the coupling coefficient, which reflects the proportion of magnetic flux shared by both coils. Parameters such as coil separation distance, positional alignment, and geometric configuration have a direct influence on the coupling strength. Deterioration in any of these factors reduces flux linkage, leading to a lower induced voltage at the receiver side and a corresponding reduction in transferable power. Consequently, preserving adequate magnetic coupling is a key

requirement for maintaining efficient and reliable wireless charging operation in real-world applications.

The wireless charging architecture considered in this study relies on electromagnetic induction as the fundamental mechanism for energy transfer. When an alternating current flows through the transmitter coil, a time-varying magnetic field is established around the coil structure. This varying magnetic field interacts with the receiver coil and induces an electrical voltage that can be utilized for power delivery (Rong et al., 2025). The electromagnetic relationship governing this process is described by Faraday's law of induction, which serves as the theoretical basis for inductive wireless power transfer systems and is expressed as follows:

$$V = -N\frac{d\Phi}{dt} \quad (1)$$

where V denotes the induced voltage, N is the number of coil turns, and Φ represents the magnetic flux linking the coil. Since the flux linkage is defined as:

$$\lambda = N\Phi \quad (2)$$

Faraday's law may also be reformulated as:

$$V = -\frac{d\lambda}{dt} \quad (3)$$

According to Faraday's law, the magnitude of the induced voltage is directly associated with the rate at which the magnetic flux linkage changes over time. As a result, the efficiency of energy transmission in wireless power transfer systems is closely related to the quality of the magnetic interaction established between the transmitting and receiving coils (Salgotra et al., 2021). The strength of this interaction is affected by multiple design and operational parameters, including the separation distance between the coils, lateral positioning accuracy, coil geometry, and the incorporation of magnetic shielding materials (Okika and Musonda, 2025).

To characterize the electromagnetic coupling between the two coils, the concept of mutual inductance is commonly employed. Mutual inductance, denoted by (M), represents the extent to which the magnetic field generated by one coil links with the other coil and contributes to energy transfer. Consequently, it serves as a key parameter in evaluating the performance and power transfer capability of inductive wireless charging systems and can be expressed as:

:

$$M = k\sqrt{L_1 L_2} \quad (4)$$

where L_1 and L_2 denote the self-inductances of the transmitter and receiver coils, respectively, while *k* is the coupling coefficient.

$$0 \leq k \leq 1$$

A higher value of *k* corresponds to stronger magnetic interaction and improved power transfer capability (Salgotra et al., 2021) (Rachid et al., 2022). However, in electric vehicle charging applications, the existence of a mechanical clearance between the ground charging pad and the vehicle underside generally results in loosely coupled operation (Okika and Musonda, 2025) . As the air-gap distance increases, the magnetic linkage decreases, causing a reduction in mutual inductance. This dependency may be represented as:

$$M(d) = k(d)\sqrt{L_1 L_2} \quad (5)$$

$$\frac{dM}{dd} < 0$$

where (*d*) denotes the distance separating the transmitter and receiver coils. It can be observed from the preceding relationships that enlarging the coil separation distance weakens the magnetic coupling mechanism, resulting in lower mutual inductance and reduced power transfer capability. For a magnetically coupled coil system, the flux linkages associated with the transmitter and receiver windings are expressed as follows:

:

$$\lambda_1 = L_1 i_1 + M i_2 \quad (6)$$

$$\lambda_2 = L_2 i_2 + M i_1 \quad (7)$$

where i_1 and i_2 are the instantaneous currents of the primary and secondary coils, respectively. Applying Kirchhoff's voltage law (KVL) yields the time-domain voltage equations of the coupled inductive system:

$$V_1 = R_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \quad (8)$$

$$V_2 = R_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} \quad (9)$$

where R_1 and R_2 are the winding resistances of the transmitter and receiver coils, respectively. Under sinusoidal steady-state operation, the above equations may be represented in phasor form as:

$$V_1 = (R_1 + j\omega L_1)I_1 + j\omega M I_2 \quad (10)$$

$$V_2 = (R_2 + j\omega L_2)I_2 + j\omega M I_1 \quad (11)$$

where I_1 and I_2 are the phasor currents, $j = \sqrt{-1}$, and the angular frequency is defined as:

$$\omega = 2\pi f \quad (12)$$

where (*f*) denotes the operating frequency of the wireless power transfer system. In many practical applications, the magnetic coupling established between the transmitter and receiver coils is relatively weak due to the physical separation and alignment constraints inherent to wireless charging environments. Under such conditions, achieving efficient energy transfer becomes increasingly challenging. To enhance power transmission performance and suppress the adverse effects associated with reactive power, resonant compensation circuits are commonly incorporated into the system architecture (Satpathy et al., 2025). By establishing resonance at the designated operating frequency, these networks facilitate more effective energy exchange between the coupled coils and improve overall system efficiency. The inductive and capacitive reactances associated with the resonant circuit can be expressed as:

$$X_L = \omega L \quad (13)$$

$$X_C = \frac{1}{\omega C} \quad (14)$$

At resonance, the reactive components are cancelled:

$$X_L = X_C \quad (15)$$

which leads to:

$$\omega_0 L = \frac{1}{\omega_0 C} \quad (16)$$

Hence, the resonant angular frequency is:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (17)$$

and the corresponding resonant frequency is:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{18}$$

Given that the coupling coefficient continuously varies with vehicle positioning and ground clearance, the transferred power cannot be assumed constant and instead exhibits dynamic variation (Menyhart, 2024), (Okika and Musonda, 2025). To account for this effect, the system is assessed over a range of air-gap distances, enabling a comprehensive evaluation of the influence of coupling conditions on charging performance. This modeling framework establishes the basis for deploying adaptive maximum power point tracking (MPPT) algorithms capable of accurately identifying and maintaining the optimal operating condition that maximizes the transferred power:

$$P_{MPP} = \max(V_{dc} I_{dc}) \tag{19}$$

or equivalently:

$$D^* = \arg\max_{D}(P_{out}) \tag{20}$$

where D^* denotes the optimal duty cycle of the receiver-side DC–DC converter used to maximize battery charging performance under varying coupling conditions.

2.4. Compensation Topologies in Inductive WPT Systems

Unlike conventional transformers, inductive wireless power transfer systems operate with a physical separation between the transmitting and receiving coils, resulting in reduced magnetic coupling and increased leakage inductance (Lee, 2024). These characteristics limit the effectiveness of energy transfer and can cause a considerable portion of the supplied energy to be associated with reactive power rather than useful power delivered to the load. Consequently, achieving high transfer efficiency becomes more challenging, particularly under loosely coupled operating conditions.

To address this issue, compensation circuits are incorporated into both sides of the wireless power transfer link. The primary function of these networks is to compensate for the reactive components introduced by the coil inductances and establish resonant operation at the desired frequency (Saraswathi and Vijayapriya, 2024). Operating under resonance conditions facilitates more efficient energy

exchange between the coupled coils, reduces reactive power circulation, and improves the overall power transfer capability of the system.

The primary role of the compensation network is to enhance the power transfer capability, provide voltage or current gain depending on the application requirements, reduce the apparent input impedance seen by the source, and improve the overall transfer efficiency (Saraswathi and Vijayapriya, 2024). In practical inductive wireless power transfer (WPT) systems, four fundamental compensation topologies are widely employed, namely: Series–Series (SS), Series–Parallel (SP), Parallel–Series (PS), and Parallel–Parallel (PP), as illustrated in Fig. 3. These topologies are classified based on the configuration of the compensation capacitors with respect to the transmitter and receiver coils.In the equivalent circuits shown in Fig. 3(a)–(d), L1and L2 denote the self-inductances of the transmitter and receiver coils, respectively, while R1 and R2 represent the internal winding resistances. The capacitors C1 and C2correspond to the compensation elements, RL denotes the load resistance, and the magnetic coupling between the coils is modeled by the mutual inductance (Leijon and Boström, 2022). The selection of the compensation topology significantly influences the input impedance characteristics, load sensitivity, voltage and current behavior, and ultimately determines the suitability of the WPT system for a given application.

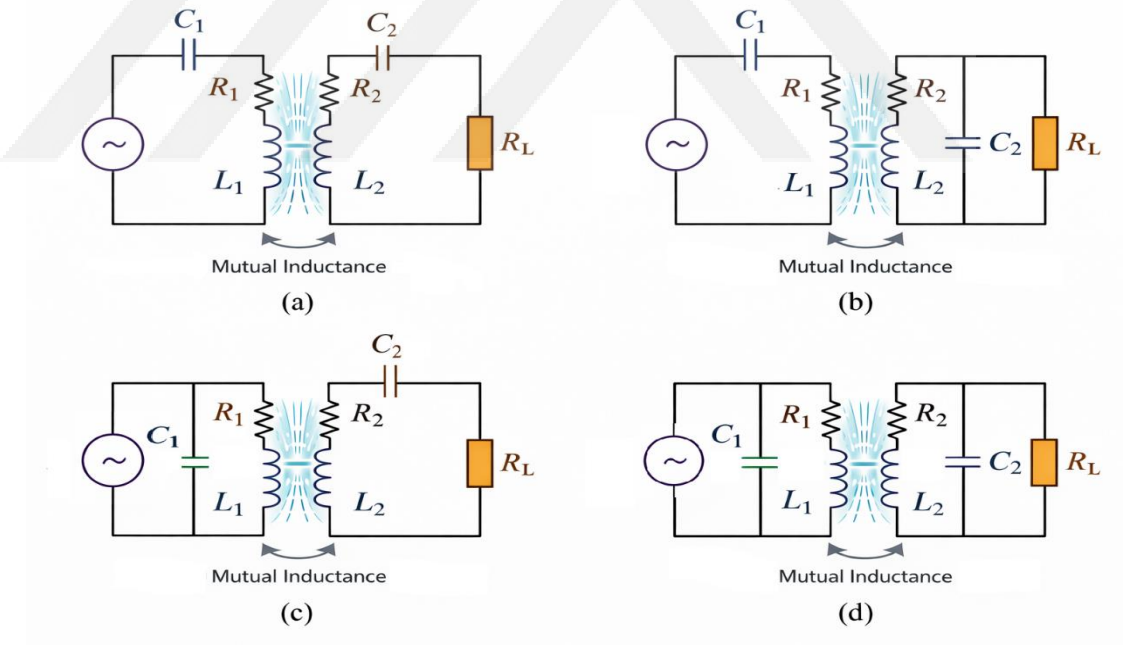


Figure 3. Compensation Topologies in WPT Systems.

2.4.1. Series–Series (SS) Compensation Topology

The Series–Series (SS) compensation topology, illustrated in Fig. 3(a), utilizes series-connected capacitors on both the transmitter and receiver sides. Under this configuration, the inductive reactances of the primary and secondary coils are effectively compensated at resonance, resulting in a reduction of the overall reactive impedance and an enhancement in the transfer of active power to the load (Corti et al., 2024).

The resonance conditions for both sides can be expressed as:

$$X_L = \omega L, \quad X_C = \frac{1}{\omega C} \tag{21}$$

At resonance:

$$X_L = X_C$$

$$\omega_0 = \frac{1}{\sqrt{LC}}, \quad f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{22}$$

One of the major advantages of the SS topology is its structural simplicity and suitability for medium- and high-power WPT applications (Ahire et al., 2022). Because both sides are series compensated, the current path is clearly defined, which simplifies circuit analysis and implementation (Sagar et al., 2023). In addition, the transferred voltage remains governed by the mutual coupling between coils:

$$V_2 = j\omega M I_1 \tag{23}$$

$$M = k\sqrt{L_1 L_2} \tag{24}$$

Another important characteristic of the SS topology is its relatively lower sensitivity to moderate load variations compared with several other compensation structures making it attractive for electric vehicle wireless charging where a stable power transfer path is required (Hassan et al., 2017) (Vishnuram et al., 2023). Moreover, high efficiency can be achieved under resonant operation, and the topology can be conveniently integrated with inverter-fed transmitter stages and rectifier-load receiver stages (Ahire et al., 2022). However, the SS topology also presents some limitations. Since the receiver side is series compensated, the secondary voltage may vary with coupling conditions and load changes (Zhu et al., 2022) .Therefore, an additional post-regulation stage is often required after rectification, particularly in battery charging applications where the charging voltage and current must be

controlled (Zavrel et al., 2024). Accordingly, practical EV charging systems commonly employ a DC–DC converter with an appropriate control algorithm after the SS compensated link, as adopted in the proposed system (El Ancary et al., 2025).

2.4.2. Series–Parallel (SP) Compensation Topology

The Series–Parallel (SP) topology, shown in Fig. 3(b), employs a series compensation capacitor on the transmitter side and a parallel compensation capacitor on the receiver side. In this configuration, the primary coil operates under series resonance, while the secondary side forms a parallel resonant network across the load (Wang et al., 2016). The primary-side resonant condition can be expressed as:

$$X_{L1} = \omega L_1, \quad X_{C1} = \frac{1}{\omega C_1} \tag{25}$$

At resonance:

$$X_{L1} = X_{C1}$$

which yields:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \tag{26}$$

A notable feature of the Series–Parallel (SP) compensation configuration is its ability to provide improved output voltage regulation owing to the parallel-compensated secondary network. Under appropriate operating conditions, this characteristic contributes to a more stable voltage profile at the load side (Lu et al., 2024). The equivalent impedance associated with the parallel-compensated secondary circuit can be expressed as:

$$Z_{sec} = \left(\frac{1}{R_L} + \frac{1}{j\omega C_2} + \frac{1}{j\omega L_2}\right)^{-1} \tag{27}$$

This feature makes the topology attractive in applications requiring voltage gain or voltage-source behavior at the receiver side (Li et al., 2023). From a circuit perspective, the series-compensated primary side still provides effective magnetic excitation, whereas the parallel-compensated secondary side modifies the output response compared with the SS topology (Shevchenko et al., 2019). The induced secondary voltage remains dependent on the mutual inductance:

$$V_2 = j\omega M I_1 \quad (28)$$

Because the load is connected in parallel with the resonant capacitor, the output characteristics become more sensitive to load variation and reflected impedance (Fang et al., 2017). Consequently, the resonant behavior of the SP topology is generally more load-dependent than that of the SS topology (Zhu et al., 2022). In addition, the receiver-side parallel branch may circulate relatively high reactive current, which can increase conduction losses and component stress if not properly designed. Therefore, although the SP topology is useful in medium-power and voltage-oriented applications, it is less commonly preferred than the SS structure in high-power EV wireless charging platforms (Li et al., 2023).

2.4.3. Parallel–Series (PS) Compensation Topology

The Parallel–Series (PS) topology, shown in Fig. 3(c), employs a parallel capacitor on the transmitter side and a series capacitor on the receiver side. In this configuration, the source excites a parallel resonant network at the transmitter, while the receiver remains series compensated. The transmitter-side admittance can be expressed as:

$$Y_{pri} = j\omega C_1 + \frac{1}{j\omega L_1} \quad (29)$$

and the resonant condition is:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \quad (30)$$

A distinguishing feature of the Parallel–Series (PS) compensation topology is the incorporation of a parallel resonant network on the transmitter side, which alters the input current characteristics compared with conventional series-compensated configurations (Wang et al., 2021). As a result, this topology is often considered advantageous in applications where the power source exhibits current-source behavior rather than voltage-source characteristics (Wang et al., 2021). Furthermore, the transmitter-side resonant branch can contribute to regulating and shaping the source current, thereby influencing the overall operating characteristics of the wireless power transfer system (Kazimierczuk and Cravens, 1995).

At the receiver side, a series compensation capacitor is employed to counterbalance the inductive reactance of the pickup coil and establish resonant

operation at the selected frequency. Under resonance conditions, the reactive component of the receiver circuit is significantly reduced, facilitating more effective power delivery to the load. The relationship governing the receiver-side series compensation can be expressed as:

$$X_{L2} = \omega L_2, \quad X_{C2} = \frac{1}{\omega C_2} \tag{31}$$

At resonance:

$$X_{L2} = X_{C2}$$

As a result, the PS compensation configuration combines the current-source characteristics provided by the transmitter-side parallel resonant network with the efficient power delivery associated with series compensation at the receiver side. Although this topology offers several operational benefits, its design and parameter optimization are generally more complex than those of the Series–Series (SS) configuration (Shu et al., 2023). The input impedance of the system can exhibit considerable sensitivity to variations in both magnetic coupling and load conditions, leading to changes in overall operating behavior. Moreover, the presence of the parallel resonant branch on the primary side may increase circulating currents within the compensation network, thereby imposing additional electrical stress on the power converter and associated passive components (Wu et al., 2024).

Because of these characteristics, the PS topology is typically considered for specialized applications in which source-current regulation or current-shaping capabilities are of particular importance. Nevertheless, for conventional wireless charging systems designed for electric vehicle applications, alternative compensation structures are generally preferred due to their simpler implementation and more predictable operating characteristics (Mansour et al., 2025).

2.4.4. Parallel–Parallel (PP) Compensation Topology

The Parallel–Parallel (PP) compensation configuration, illustrated in Fig. 3(d), incorporates parallel resonant networks on both the primary and secondary sides of the wireless power transfer system. As a result, the transmitter and receiver circuits exhibit parallel resonance characteristics, producing an electrical behavior that differs from the Series–Series (SS), Series–Parallel (SP), and Parallel–Series (PS) compensation arrangements. Owing to the presence of parallel compensation on both sides of the

inductive link, the impedance and current distribution within the system are governed by the admittance characteristics of the resonant branches. The admittance associated with each parallel-compensated circuit can therefore be represented as:

$$Y_{pri} = j\omega C_1 + \frac{1}{j\omega L_1} \tag{32}$$

$$Y_{sec} = j\omega C_2 + \frac{1}{j\omega L_2} + \frac{1}{R_L} \tag{33}$$

The resonant condition is obtained when:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{34}$$

The Parallel–Parallel (PP) compensation arrangement is commonly considered in wireless power transfer applications that favor current-source operation and require resonant behavior on both sides of the inductive link (Alam et al., 2022). Since parallel compensation is implemented at both the transmitter and receiver circuits, the overall electrical characteristics of the system become highly sensitive to factors such as operating frequency, magnetic coupling strength, and load variations. Consequently, changes in these parameters can significantly influence the equivalent impedance and power transfer behavior of the system.

One of the notable attributes of the PP topology is its capability to maintain satisfactory performance under light-load operating conditions while supporting relatively high resonant voltages across the compensated branches. Nevertheless, the existence of parallel resonance on both sides can lead to considerable reactive current circulation within the network, potentially lowering energy transfer efficiency and increasing electrical stress on the resonant capacitors and coil windings (Rezazade et al., 2022). The current flowing through an individual resonant branch may be represented as:

$$I_{branch} = I_L + I_C + I_o \tag{35}$$

where (I_L) denotes the current flowing through the inductive branch, (I_C) represents the capacitive branch current, and (I_O) corresponds to the load current. From both analytical and implementation perspectives, the PP compensation topology typically requires a more involved design process than the Series–Series (SS) configuration. The interaction between the parallel resonant networks on both sides of

the wireless link introduces additional sensitivity to parameter variations, making system tuning and optimization more challenging.

For this reason, the PP topology is not widely employed in high-power wireless charging applications, particularly those intended for electric vehicle systems. In most practical implementations, designers tend to favor the SS configuration because of its simpler design procedure, predictable operating characteristics, and ease of control. Consequently, the adoption of PP compensation is generally restricted to specialized applications where its unique impedance properties offer distinct operational advantages that justify the increased design complexity (Vishnuram et al., 2023).

2.4.5. Comparative Discussion and Topology Selection

Based on the comparative evaluation of various compensation topologies discussed in the previous section, the Series–Series (SS) compensation topology is selected for the proposed wireless power transfer (WPT) system. This topology is widely adopted in inductive wireless charging applications due to its structural simplicity, predictable resonant characteristics, and robust performance under loosely coupled conditions(Corti et al., 2024). To illustrate the adopted configuration, Fig. 4 presents the equivalent circuit model of the SS-compensated WPT system, where both the transmitter and receiver sides are equipped with series compensation capacitors.

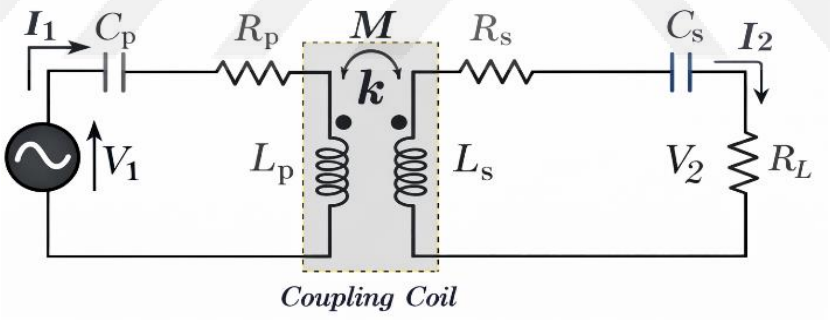


Figure 4. SS-Compensated WPT Equivalent Circuit.

In this topology, the primary-side capacitor C_p is connected in series with the transmitter inductance L_p, while the secondary-side capacitor Cs connected in series with the receiver inductance Ls. The two coils are magnetically coupled through the mutual inductance M, which depends on the coupling coefficient k. The system is driven by an AC voltage source V_1, producing a current I_1in the primary circuit, while

the induced voltage V_2drives the secondary current I_2 through the load resistance R_L This configuration enables both the primary and secondary circuits to resonate at the operating frequency. Under resonant operating conditions, the reactance introduced by the coil inductances is effectively counterbalanced by the compensation capacitors, resulting in a substantial reduction in the reactive component of the circuit impedance. As the system approaches resonance, power transfer becomes more efficient because a larger proportion of the supplied energy is delivered as useful active power rather than being dissipated through reactive circulation within the resonant network. This operating characteristic is one of the principal reasons for the widespread adoption of Series–Series (SS) compensation in wireless charging applications. Another notable advantage of the SS configuration is its ability to maintain satisfactory performance when magnetic coupling conditions vary. In practical electric vehicle charging environments, changes in vehicle position, ground clearance, and air-gap distance can alter both the coupling coefficient and mutual inductance. By establishing resonance on both the transmitter and receiver sides, the SS topology helps reduce the sensitivity of the system to these variations, thereby supporting more consistent power transfer behavior over a range of operating conditions. The SS compensation structure also aligns effectively with the architecture developed in this study. On the transmitter side, a high-frequency inverter energizes the resonant network and generates the alternating magnetic field required for wireless energy transmission. The power received at the secondary side is subsequently converted into DC form through a rectification stage and then processed by a DC–DC converter governed by a Maximum Power Point Tracking (MPPT) controller. This multi-stage configuration enables efficient energy conversion and appropriate power conditioning before delivery to the battery charging unit.

Furthermore, the SS topology exhibits favorable operating characteristics under changing load conditions, which is particularly beneficial for electric vehicle charging applications where battery demand varies throughout the charging cycle. Considering its resonance stability, adaptability to coupling variations, compatibility with converter-based control schemes, and ability to support efficient energy transfer, the Series–Series compensation topology was selected as the preferred compensation method for the proposed wireless charging system.

CHAPTER THREE

MAXIMUM POWER TRANSFER CHARACTERISTICS UNDER VARIABLE LOAD RESISTANCE AND AIR-GAP CONDITIONS

3.1. Introduction

A comprehensive load-variation study was conducted to evaluate the fundamental performance characteristics of the proposed wireless power transfer (WPT) architecture. For each investigated air-gap distance, the equivalent load resistance was swept over a wide operating range, while the output power was continuously monitored. The resulting data were used to assess the influence of load conditions on power transfer behavior and to identify the operating regions associated with maximum power delivery under different magnetic coupling scenarios.

The results obtained from the load-resistance analysis are summarized in Fig. 5, which depicts the variation of transferred power as a function of the equivalent load resistance for different coil separation distances. The plotted characteristics reveal a nonlinear relationship between load resistance and transferred power, with each air-gap condition exhibiting a distinct operating profile and a corresponding maximum power point (MPP). This behavior indicates that the power transfer capability of the system is influenced by both the electrical loading conditions and the degree of magnetic coupling established between the transmitter and receiver coils (Toluwaloju et al., 2022).

The observed trends further demonstrate that the proposed wireless charging system does not behave as a fixed-voltage or fixed-power source. Instead, its operating characteristics vary according to the interaction between the resonant network parameters and the prevailing coupling conditions, resulting in a dynamic power-transfer response (Xiong et al., 2023). Under weak coupling conditions associated with larger air-gap distances, such as 20 cm and 25 cm, the amount of transferred power remains comparatively low across the investigated resistance range. This reduction can be attributed to the decrease in mutual inductance and magnetic flux linkage as the separation between the coils increases, which limits the efficiency of energy transfer through the wireless link.

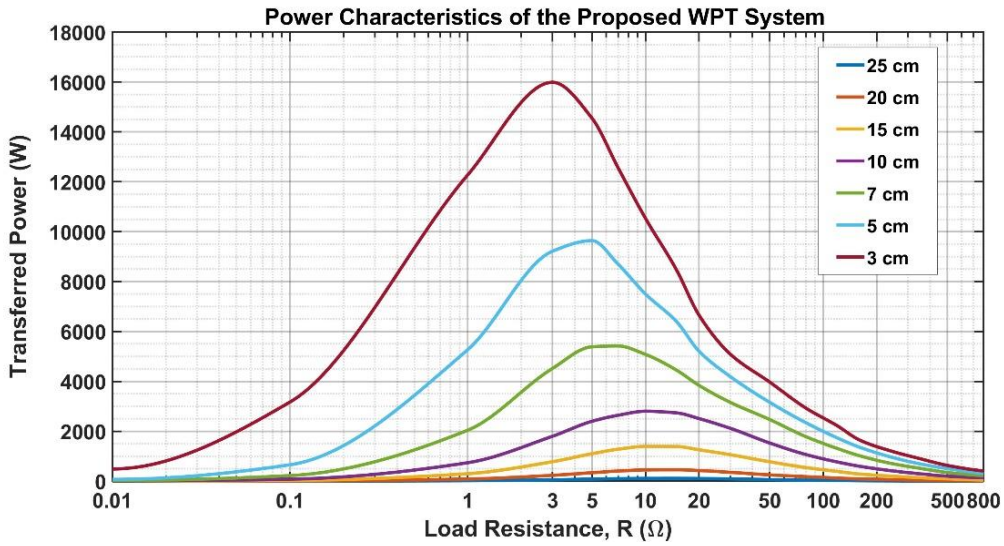


Figure 5. Power Transfer vs Load Resistance under Different Air-Gaps.

The observed reduction in transferred power at larger coil separation distances can be explained by the deterioration of magnetic coupling, which results in lower mutual inductance and increased magnetic flux leakage (Guan et al., 2024). As the air gap decreases, the coupling coefficient increases, strengthening the electromagnetic interaction between the coils and enabling more effective energy transfer (Leng et al., 2023). Consequently, the highest power transfer levels are obtained at shorter separation distances, particularly at 3 cm and 5 cm, where stronger flux linkage allows a greater portion of the transmitted energy to be delivered to the load.

The results also reveal that the load resistance associated with the maximum power operating point is not constant but varies according to the magnetic coupling conditions. Under stronger coupling scenarios, maximum power transfer is achieved at relatively lower resistance values, whereas weaker coupling conditions produce lower peak power levels and alter the location of the optimal operating point. This behavior reflects the impedance-reflection phenomenon inherent in resonant inductive power transfer systems, where the effective load observed from the primary side depends on both the coupling coefficient and the secondary-side loading conditions (Koh and Beh, 2014).

These findings emphasize the necessity of employing adaptive Maximum Power Point Tracking (MPPT) techniques within the proposed wireless charging framework. Since the optimal operating point changes in response to variations in magnetic coupling, fixed-control strategies may be unable to maintain maximum energy transfer

efficiency under all operating conditions. An intelligent optimization-based controller is therefore required to continuously adjust the converter operating parameters and identify the most favorable duty-cycle value for each charging scenario.

Overall, the presented results confirm the strong dependence of system performance on magnetic coupling conditions and provide a clear foundation for the comparative assessment of the optimization algorithms investigated in the subsequent sections of this thesis.

3.2. Effect of Air Gap on Power Transfer Performance

The distance separating the transmitter (Tx) and receiver (Rx) coils is one of the most influential parameters affecting the performance of inductive wireless power transfer systems. Variations in this distance directly alter the magnetic coupling strength between the coils and, consequently, the amount of power that can be transferred through the wireless link. As the air gap becomes larger, the magnetic field produced by the transmitter coil spreads over a wider region, reducing the fraction of magnetic flux intercepted by the receiver coil. This decline in flux linkage decreases the mutual inductance and weakens the electromagnetic interaction responsible for energy transfer.

The effect of coil separation on system performance is illustrated in Fig. 6, where a clear increase in maximum transferred power can be observed as the air-gap distance decreases. Stronger magnetic coupling at shorter distances enables more efficient energy exchange between the transmitter and receiver coils, resulting in higher power delivery capability. Conversely, larger air gaps reduce coupling effectiveness, thereby limiting the amount of power that can be transferred to the load. These results highlight the strong dependence of WPT system performance on coil separation distance and emphasize the importance of maintaining adequate magnetic coupling to achieve efficient wireless charging operation.

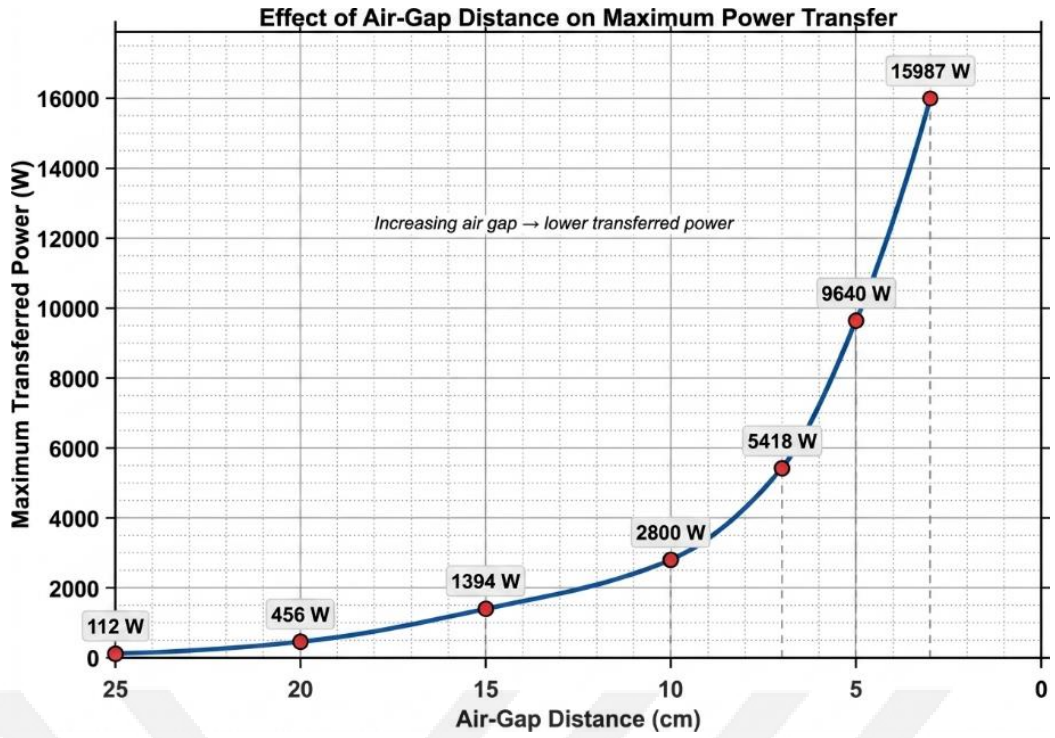


Figure 6. Maximum Power vs Air-Gap Distance.

When the transmitter and receiver coils are positioned closer to one another, a greater proportion of the magnetic field generated by the transmitter intersects the receiver coil. This enhanced flux linkage strengthens the electromagnetic interaction between the two coils, resulting in higher induced voltage levels and increased power delivery to the load. In contrast, increasing the coil separation distance reduces the amount of magnetic flux captured by the receiver coil because the magnetic field becomes distributed over a larger spatial region. Consequently, both the induced current and the transferred power decrease as the coupling strength deteriorates.

The results presented in Fig. 6 further indicate that the relationship between transferred power and air-gap distance is not linear. While moderate reductions in power are observed at relatively short separation distances, a much steeper decline occurs as the coils become farther apart. This behavior reflects the inherent characteristics of loosely coupled inductive power transfer systems, where the coupling coefficient decreases nonlinearly with increasing distance. Since mutual inductance is directly related to the coupling coefficient, any substantial reduction in magnetic coupling leads to a pronounced decrease in transferable power. These findings emphasize the importance of maintaining adequate magnetic coupling in

wireless charging systems and explain the significant performance differences observed between short and large air-gap operating conditions.

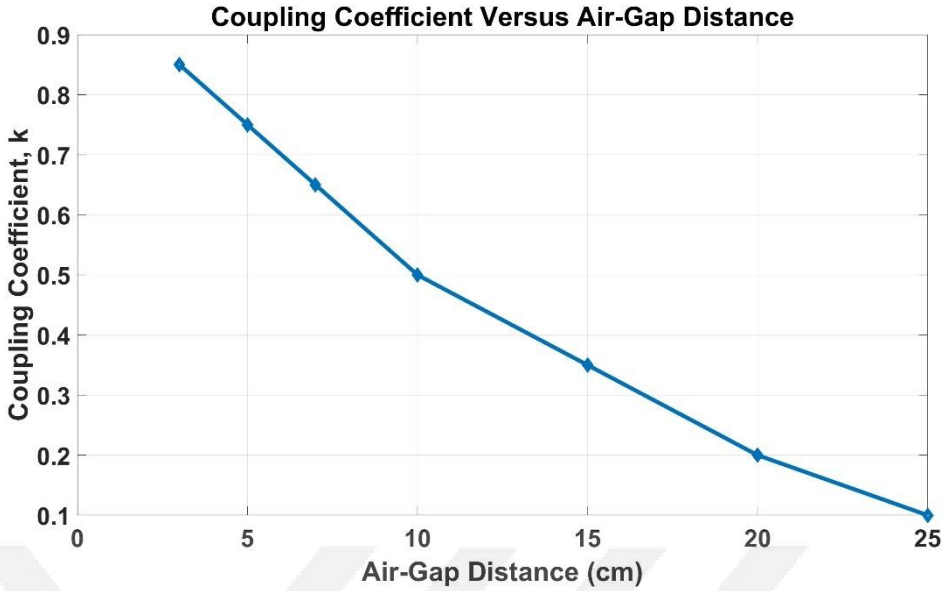


Figure 7. Coupling Coefficient vs Air-Gap Distance.

Figure 7 illustrates the variation in maximum transferred power achieved by the proposed wireless power transfer system for different air-gap distances. The results reveal a strong dependence of power transfer capability on the separation distance between the transmitter and receiver coils. As the air gap decreases, the magnetic interaction between the coils becomes stronger, leading to improved mutual inductance and enhanced flux linkage. These conditions facilitate more effective energy transmission across the wireless interface and result in higher power delivery to the load.

The observed characteristics also indicate that the system operates with greater effectiveness under short-distance coupling conditions, where the electromagnetic link remains sufficiently strong to support efficient power transfer. In contrast, increasing the separation distance weakens the coupling mechanism, reducing the amount of energy that can be transferred through the inductive link. Beyond a certain distance, the deterioration in magnetic coupling becomes the dominant factor governing system performance, causing a pronounced decline in the achievable power level.

These findings demonstrate the critical influence of air-gap distance on the overall performance of wireless EV charging systems and confirm the importance of

maintaining adequate magnetic coupling to achieve high power transfer efficiency. Moreover, the results highlight the need for adaptive control mechanisms capable of responding to coupling variations. Intelligent optimization-based MPPT techniques can continuously adjust converter operating conditions, enabling the system to remain close to its optimal operating point despite changes in magnetic coupling strength.

3.3. Control Strategy of the Proposed WPT System

The performance of inductive wireless power transfer systems is closely related to the strength of the magnetic coupling established between the transmitter and receiver coils (Leng et al., 2023). Because the coupling coefficient changes with variations in air-gap distance, the amount of power that can be transferred through the wireless link is not constant and varies according to the prevailing operating conditions (Benalia et al., 2024). Consequently, operating the system near its maximum power point (MPP) is crucial for maximizing energy transfer efficiency and maintaining effective battery charging performance.

To achieve this objective, the proposed wireless electric vehicle charging system employs an adaptive control strategy in which the duty cycle of the receiver-side DC–DC converter is continuously adjusted based on real-time voltage and current measurements obtained from the rectifier output. By monitoring these electrical variables, the controller can evaluate the instantaneous power delivered through the wireless interface and modify the converter operating conditions accordingly. The instantaneous transferred power at the receiver side is determined by:

$$P = V_{dc} I_{dc} \tag{35}$$

where Vdc and Idc represent the rectified output voltage and current, respectively. The objective of the proposed control strategy is to determine the optimal converter duty cycle corresponding to the maximum transferred power operating condition. In this work, a Grey Wolf Optimization (GWO)-based maximum power point tracking (MPPT) controller is implemented and compared with a conventional pulse-width modulation (PWM) control strategy in order to evaluate the effectiveness of adaptive optimization-based control under varying air-gap conditions.

3.4. Grey Wolf Optimization (GWO)-Based MPPT Controller

The Grey Wolf Optimization (GWO) algorithm is a population-based metaheuristic optimization technique inspired by the leadership hierarchy and hunting mechanism of grey wolves in nature (Yetkin and Bilginer, 2020). In the GWO algorithm, candidate solutions are classified into four hierarchical groups referred to as alpha (α), beta (β), delta (δ), and omega (ω) wolves. The search process is guided by the best three candidate solutions, while the remaining search agents update their positions according to the hunting behavior mechanism of grey wolves. The position update equation of the GWO algorithm can be expressed as follows:

$$\boldsymbol{X(t+1)} = \frac{\boldsymbol{X_\alpha + X_\beta + X_\delta}}{\boldsymbol{3}} \tag{35}$$

where X_α, X_β and X_δ denote the three best candidate solutions that guide the optimization process toward the optimal operating point. In the proposed wireless power transfer system, the candidate solution corresponds to the duty cycle of the receiver-side DC–DC converter, whereas the fitness function corresponds to the measured transferred power. The proposed GWO-based MPPT controller continuously adjusts the converter duty cycle to maintain operation near the maximum power point under varying magnetic coupling conditions. This adaptive behavior improves the transferred power capability and enhances the battery charging performance under different air-gap distances. The operational flow of the proposed GWO-based MPPT controller is illustrated in Fig. 8. The controller continuously measures the rectified output voltage and current, calculates the transferred power, evaluates the fitness function, and updates the search agents according to the GWO optimization mechanism. The optimal duty cycle generated by the algorithm is then applied to the receiver-side DC–DC converter in order to maximize the transferred power delivered to the 400 V EV battery.

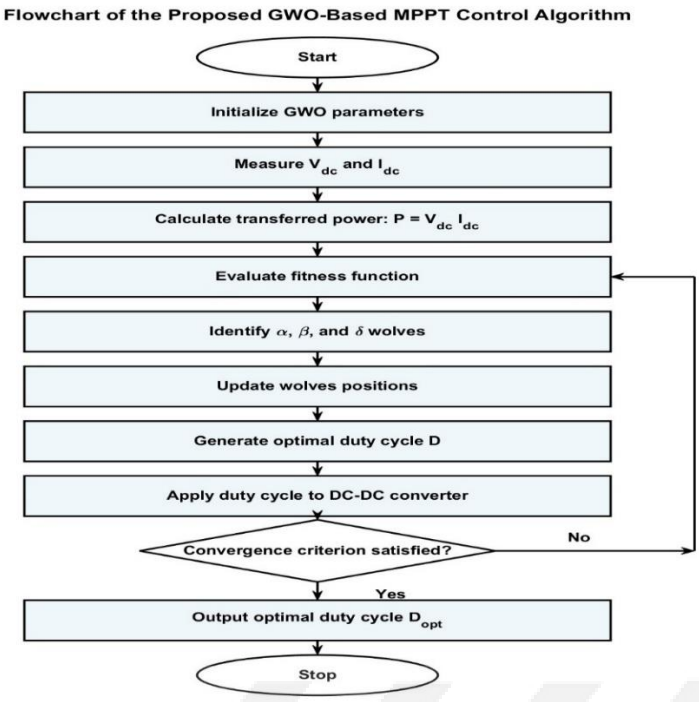


Figure 8. GWO-Based MPPT Control Flowchart.

The proposed GWO controller is implemented after the receiver-side rectifier stage of the wireless power transfer system. During operation, the controller dynamically regulates the duty cycle according to the transferred power variations caused by changes in magnetic coupling conditions. Compared with conventional fixed-duty-cycle control approaches, the proposed optimization-based controller provides improved adaptability under nonlinear and time-varying operating conditions.

3.5. Conventional PWM Control

For benchmarking purposes, a conventional Pulse Width Modulation (PWM) control scheme is incorporated into the proposed wireless electric vehicle charging system. PWM-based control remains one of the most commonly adopted techniques in power electronic converters due to its straightforward implementation, predictable switching behavior, and suitability for practical hardware realization (Batkhishig et al., 2025). Within this control framework, converter operation is regulated by adjusting the switching duty ratio according to a predefined control reference, thereby influencing the output voltage or current delivered by the converter (Matsushita et al., 2020).

Unlike optimization-based MPPT approaches, the PWM controller does not actively search for the operating point associated with maximum power transfer. Instead, system performance depends primarily on the selected control settings and operating conditions. As a result, variations in magnetic coupling or air-gap distance may cause the converter to operate away from the optimal power transfer region, potentially reducing charging effectiveness under dynamic conditions. The switching duty ratio employed in the PWM control strategy is defined as:

$$\boldsymbol{D = \frac{T_{on}}{T_s}} \tag{36}$$

where Ton represents the switch on-time and Ts denotes the switching period. For the boost converter employed in the proposed system, the ideal voltage gain is expressed as follows:

$$V_o = \frac{V_{in}}{1-D} \tag{37}$$

Accordingly, varying the duty cycle directly modifies the converter output voltage and operating condition. In the proposed system, PWM control is applied to the receiver-side DC–DC converter located after the rectifier stage of the wireless power transfer link. The duty cycle also influences the effective input impedance observed at the secondary side of the inductive coupling system, which can be expressed as follows:

$$R_{in} = R_L(1-D)^2 \tag{38}$$

where (R_L) denotes the equivalent load resistance connected to the converter output. In wireless inductive charging systems, efficient energy transfer is closely associated with the impedance relationship between the primary and secondary circuits. Consequently, the selected converter duty cycle has a direct influence on the operating point of the system and, therefore, on the amount of power delivered to the load (Lee, 2024).

In contrast to the proposed Grey Wolf Optimization (GWO)-based MPPT strategy, the conventional PWM controller does not possess a mechanism for continuously identifying and tracking the maximum power operating region when magnetic coupling conditions change. As a result, variations in air-gap distance or coupling strength may shift the optimal operating point while the converter continues to operate at a non-optimal duty ratio. This mismatch can lead to a reduction in power

transfer effectiveness and lower charging performance, particularly under weak-coupling conditions associated with larger coil separation distances. Consequently, the ability of the PWM controller to maintain maximum power transfer becomes increasingly limited as operating conditions deviate from their nominal design values.

3.6. Simulation Setup

To evaluate the proposed wireless power transfer (WPT) system under conditions representative of practical electric vehicle charging applications, a comprehensive simulation model was developed in MATLAB/Simulink using the Simscape Electrical environment. The implemented architecture consists of a sequence of interconnected power conversion stages, including a three-phase AC–DC rectifier, a DC–DC boost converter, a high-frequency inverter, a Series–Series (SS) compensated inductive power transfer link, and a receiver-side DC–DC converter responsible for regulating battery charging. The system operates at a switching frequency of 10 kHz, which was selected to achieve an effective balance between power transfer performance and converter switching constraints. Although higher operating frequencies can improve magnetic coupling characteristics and reduce the physical size of passive components, they are often accompanied by increased switching losses and electromagnetic compatibility challenges. Accordingly, a frequency of 10 kHz was adopted as a practical operating point for medium- and high-power wireless EV charging applications. A DC-link voltage of approximately 400 V is maintained throughout the system to support efficient energy transmission and ensure compatibility with typical electric vehicle battery voltage levels. Maintaining this voltage level also contributes to stable inverter operation and facilitates adequate power transfer across the inductive coupling stage under different magnetic coupling conditions. To establish resonant operation within the wireless charging interface, both the transmitter and receiver coils were designed with inductance values of 200 μH. When combined with appropriately selected compensation capacitors, these inductances enable resonance at the designated operating frequency. This design approach improves impedance matching between the coupled circuits, promotes efficient power transfer, and supports stable operation of the SS compensation network. The principal simulation parameters adopted throughout this study are summarized in Table 1.

Table 1 . Key Electrical Parameters of the Proposed WPT system.

Parameter	Symbol	Value
Input three-phase voltage	V_{in}	140 V
DC bus voltage	V_{BOOST}	400 V
Operating frequency	f	10 kHz
Transmitter resistance	R_1	1 m Ω
Receiver resistance	R_2	1 m Ω
Transmitter inductance	L_1	200 μH
Receiver inductance	L_2	200 μH
Compensation capacitor (Tx)	C_1	1.266 μF
Compensation capacitor (Rx)	C_2	1.266 μF

To ensure a consistent and reliable assessment of system performance, all simulations were conducted under predefined numerical conditions. A fixed-step discrete solver with a sampling interval of 5 μs was employed to accurately represent the switching behavior of the power electronic converters operating at 10 kHz. A low coil resistance value (1 mΩ) is assumed in this study to represent a highly efficient conductor configuration, such as Litz wire, and to emphasize the influence of magnetic coupling conditions and control strategy performance. In practical implementations, higher resistance values are typically observed due to conductor characteristics as well as high-frequency effects, including skin and proximity phenomena. This temporal resolution was selected to capture the high-frequency dynamics of the system while maintaining an acceptable computational cost. For all investigated cases, the simulation duration was fixed at 10 s to provide a uniform basis for performance comparison. This observation period was sufficient to capture the complete operating response of the wireless charging system, including startup transients, controller convergence characteristics, and steady-state operation. Moreover, the selected time horizon enabled the evaluation of short-term battery state-of-charge (SOC) variations during the charging process. Given the switching frequency adopted in the converter stages, the simulation interval encompassed a large number of switching cycles, thereby providing a dependable representation of system behavior and power transfer performance. The developed model incorporates practical operating considerations, including converter switching actions, parasitic effects, and nonlinear phenomena associated with power electronic components. Initial conditions were defined to

represent a realistic startup sequence in which the charging system evolves from an unenergized state toward its normal operating condition. In addition, the Grey Wolf Optimization (GWO)-based MPPT controller was implemented using a fixed update period synchronized with the operation of the receiver-side DC–DC converter to ensure stable duty-cycle adjustment and reliable controller performance. Before evaluating the proposed optimization-based control strategy, the intrinsic electrical characteristics of the wireless power transfer system were examined through a load-sweep analysis. A variable resistive load was connected at the receiver side and gradually adjusted over a broad operating range, extending from near short-circuit conditions to relatively high resistance values. For each operating point, the corresponding output voltage, output current, and transferred power were recorded. This procedure allowed the identification of the maximum power point (MPP) associated with each loading condition and provided insight into the relationship between load resistance and power transfer capability. To investigate the effect of magnetic coupling on system performance, the same analysis was repeated for multiple air-gap distances. Variations in coupling conditions were represented by modifying the mutual inductance between the transmitter and receiver coils according to their spatial separation. The mutual inductance values adopted for each investigated air-gap distance are listed in Table 2 and were used to emulate the corresponding magnetic coupling conditions throughout the simulation study.

Table 2 . Mutual Inductance vs Air-Gap Distance.

Air gap (cm)	**Mutual inductance (M)**
3	170 μH
5	150 μH
7	130 μH
10	100 μH
15	70 μH
20	40 μH

Air gap (cm)	Mutual inductance (M)
25	20 μH

To ensure a fair and consistent evaluation, the proposed Grey Wolf Optimization (GWO)-based MPPT controller and the conventional PWM control strategy were implemented under identical operating conditions within a unified simulation environment. The duty cycle of the receiver-side DC–DC converter was selected as the primary control variable because it directly affects the effective input impedance of the wireless power transfer link and consequently influences the transferred power capability of the system. The duty cycle was constrained within a predefined operating range in order to maintain stable converter performance and avoid undesirable operating conditions. During simulation, the proposed GWO-based MPPT controller continuously adjusted the converter duty cycle according to real-time measurements of the receiver-side output voltage and current with the objective of maximizing the instantaneous transferred power . The configuration parameters of the Grey Wolf Optimization (GWO) algorithm, including the population size and the maximum number of iterations, were carefully selected to achieve an appropriate balance between optimization accuracy and computational efficiency. Furthermore, the execution of the optimization routine was synchronized with the dynamic response of the receiver-side DC–DC converter to ensure stable duty-cycle regulation and reliable tracking of the maximum power operating point under changing system conditions.
To provide a meaningful performance benchmark, a conventional Pulse Width Modulation (PWM) control scheme was also incorporated into the simulation framework. In contrast to the adaptive optimization-based controller, the PWM approach operates using a predetermined duty ratio and does not actively respond to variations in magnetic coupling strength or power transfer conditions. Consequently, the PWM controller serves as a reference case for quantifying the benefits achieved through the proposed GWO-based MPPT strategy. The proposed wireless power transfer system was evaluated under multiple operating scenarios to examine its sensitivity to changes in magnetic coupling. Seven air-gap distances were considered, namely 3 cm, 5 cm, 7 cm, 10 cm, 15 cm, 20 cm, and 25 cm. These distances represent

a wide range of coupling conditions extending from strongly coupled operation at short separations to weakly coupled operation at larger distances. Since the magnetic coupling coefficient and mutual inductance vary with coil separation, each air-gap condition produces a distinct power transfer environment that influences the overall charging performance of the system. All performance assessments were conducted using a 400 V battery model in order to represent a high-power electric vehicle charging scenario. To ensure consistency and fairness in the comparison process, both the GWO-based MPPT controller and the conventional PWM controller were tested under identical operating conditions for each investigated air-gap distance. System performance was primarily evaluated using transferred power and battery state-of-charge (SOC) as the key performance indicators, enabling a comprehensive assessment of the ability of each control strategy to maintain effective charging performance under varying magnetic coupling conditions.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

This section presents the simulation outcomes and performance assessment of the proposed wireless power transfer (WPT) system developed for electric vehicle charging applications. Particular emphasis is placed on evaluating the effectiveness of the Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) strategy under different magnetic coupling conditions. The analysis focuses on the controller's ability to enhance power transfer capability and maintain effective battery charging performance as operating conditions vary.

To examine the effect of magnetic coupling, the system was evaluated at seven different transmitter–receiver distances: 3 cm, 5 cm, 7 cm, 10 cm, 15 cm, 20 cm, and 25 cm. These distances were selected to cover a wide range of operating conditions, from strong coupling at short separations to weak coupling at larger gaps. The chosen values reflect both realistic wireless charging scenarios and more challenging conditions commonly reported in EV charging applications.

In practice, air-gap distances between 5 cm and 10 cm are typical for stationary wireless charging systems, as they align with vehicle ground clearance while maintaining sufficient coupling. The selected distance points are also distributed to allow a clear observation of how system performance changes as the coupling condition gradually weakens..

All investigations were performed using a 400 V battery model to represent a high-power electric vehicle charging scenario. The performance of the proposed GWO-based MPPT controller was benchmarked against a conventional Pulse Width Modulation (PWM) control approach under identical operating conditions. The comparison was conducted using transferred power and battery state-of-charge (SOC) characteristics as the primary evaluation metrics. Through this analysis, the capability of the adaptive optimization-based controller to sustain efficient charging operation and improve system performance under varying coupling conditions can be comprehensively assessed.

4.2. Steady-State Behavior of the WPT System

To validate the proper operation of the proposed wireless power transfer (WPT) system, the steady-state characteristics of both the transmitter and receiver stages are initially examined. The analysis is performed under nominal operating conditions corresponding to a 400 V battery and a transmitter–receiver separation distance of 10 cm. For this preliminary evaluation, a conventional Pulse Width Modulation (PWM) control strategy is employed to establish a baseline operating condition prior to the implementation of the optimization-based control approach. Investigating the steady-state response under these conditions provides valuable insight into the electrical behavior of the resonant wireless charging system and confirms the correct functionality of the power conversion stages before comparative performance assessments are conducted.

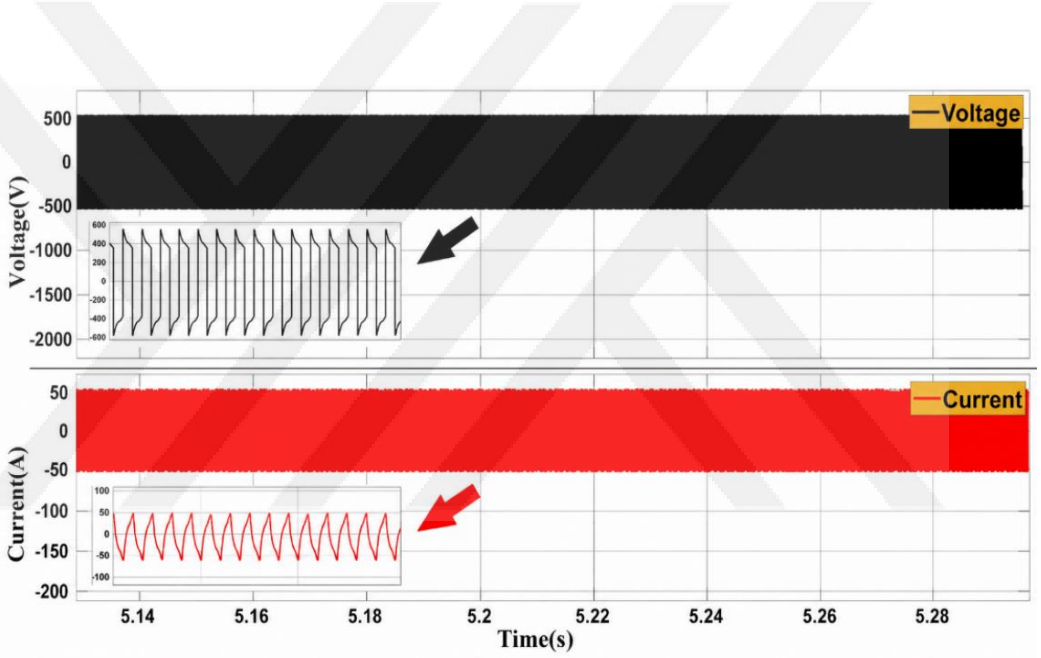


Figure 9. Voltage and current waveforms of the coil (Tx).

The steady-state investigation was conducted to evaluate the electrical characteristics of the resonant wireless power transfer interface and to verify stable operation under continuous high-frequency excitation. Analysis of the voltage and current waveforms also provides valuable insight into the resonance behavior of both the transmitter and receiver circuits during the wireless energy transfer process.

Figure 9 shows the steady-state voltage and current behavior of the transmitter coil. The resonant network on the transmitter side is driven by a high-frequency

inverter operating at approximately 10 kHz, generating an alternating signal that enables wireless energy transfer.The choice of 10 kHz provides a practical balance between achieving stable resonant operation and limiting switching losses and electromagnetic interference. At this frequency, the system operates with realistic component values, particularly for the inductors and compensation capacitors, while maintaining stable performance. Although higher operating frequencies are typically adopted in commercial EV wireless charging systems to enhance power density and coupling efficiency, the selected frequency is adequate for analyzing the system behavior and evaluating the proposed control strategy under varying coupling conditions.

With the Series–Series (SS) compensation topology, the inductive and capacitive effects are effectively balanced at resonance, which minimizes the reactive component of the impedance. As a result, the transmitter circuit appears predominantly resistive from the inverter point of view.As a consequence, the transmitter current exhibits a waveform that closely resembles a sinusoidal profile despite the switching nature of the inverter. This characteristic indicates effective resonance operation and reduced harmonic content within the resonant circuit, allowing electrical energy to be transferred more efficiently to the magnetic coupling interface. Furthermore, the measured voltage and current waveforms demonstrate stable and repetitive periodic behavior, confirming that the transmitter-side resonant network operates under well-established steady-state conditions throughout the wireless charging process.

The obtained results confirm proper resonant operation of the transmitter-side circuit and demonstrate the effective coordination between the high-frequency inverter and the SS compensation network under the selected operating conditions.

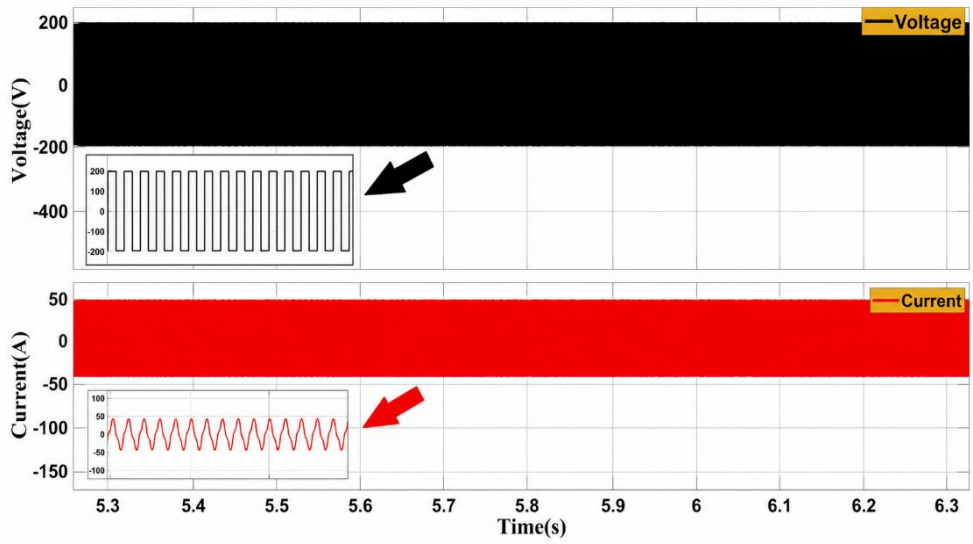


Figure 10. Voltage and current waveforms of the coil (RX).

Figure 10 depicts the voltage and current responses observed at the receiver side of the proposed wireless power transfer system. The induced voltage waveform follows the operating frequency established by the transmitter-side inverter, demonstrating the successful transfer of energy through the magnetic coupling interface. The magnitude of the induced voltage is directly related to the coupling strength between the transmitter and receiver coils and therefore reflects the effectiveness of energy transfer at the investigated air-gap distance. The corresponding receiver-side current exhibits a smooth periodic waveform with characteristics consistent with resonant operation. This response indicates that the secondary resonant circuit remains properly tuned at the operating frequency, enabling efficient energy extraction from the coupled magnetic field. The observed behavior also confirms that the Series–Series (SS) compensation network effectively supports resonance on both sides of the wireless link, thereby facilitating favorable impedance characteristics and reducing the influence of reactive power within the system. As a result, a greater proportion of the transferred energy is delivered as useful active power to the load.

The steady-state responses obtained from the transmitter and receiver circuits collectively verify the stable operation of the proposed wireless charging architecture at the designated resonant frequency. The waveform characteristics further demonstrate the ability of the compensation network to mitigate undesirable reactive effects and sustain efficient energy transfer through the inductive coupling channel. Moreover, the strong correlation between the primary- and secondary-side electrical

responses confirms the proper functioning of the magnetic coupling mechanism under the selected operating condition. These results provide a reliable reference operating point that serves as the foundation for the subsequent assessment of the proposed MPPT control strategy under different magnetic coupling scenarios.

4.3. Duty-Cycle Response of the Proposed GWO-Based MPPT Controller

In addition to evaluating power transfer and battery charging performance, the dynamic response of the proposed MPPT controller was examined through the variation of the converter duty cycle during operation. Figure 11 illustrates the duty-cycle trajectory generated by the Grey Wolf Optimization (GWO)-based MPPT controller under a strong magnetic coupling scenario corresponding to an air-gap distance of 3 cm. The results show that the controller continuously modifies the converter duty ratio over a defined operating range to maintain the system in the vicinity of the maximum power transfer region.

Unlike conventional Pulse Width Modulation (PWM) approaches that rely on predetermined control settings, the optimization-based strategy adjusts the converter operating point in real time according to the prevailing electrical conditions of the wireless charging system. This adaptive behavior enables the controller to respond effectively to changes in transferred power and resonant circuit conditions, thereby improving overall energy transfer performance.

The recorded duty-cycle response further demonstrates the capability of the GWO algorithm to rapidly identify and follow favorable operating points. The observed duty-cycle variations reflect the ongoing optimization process, in which the controller continuously evaluates system performance and updates the converter operating conditions to maximize transferred power. Despite these adjustments, the duty-cycle values remain within the allowable operating range of the DC–DC converter, indicating stable controller behavior and practical suitability for wireless electric vehicle charging applications. The results therefore confirm both the effectiveness of the optimization mechanism and the robustness of the proposed control framework under strong magnetic coupling conditions.

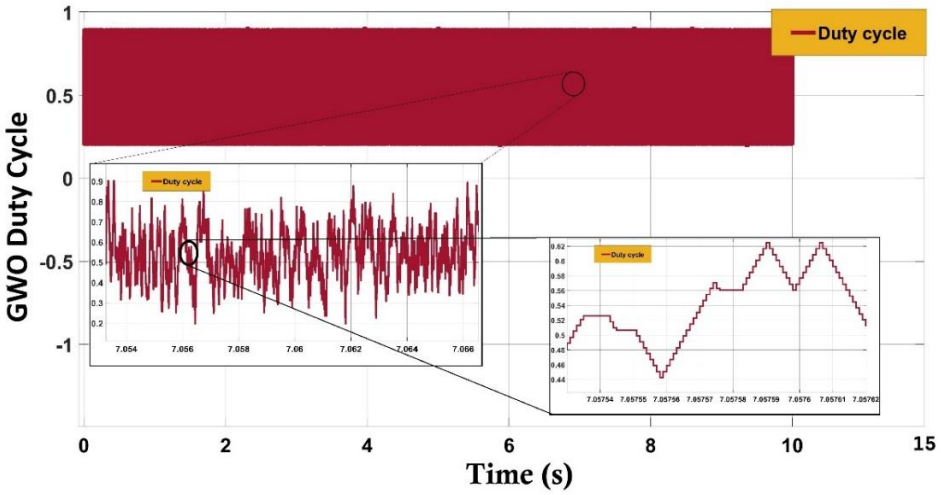


Figure 11. Duty-Cycle Response at 3 cm Air-Gap.

Taken together, the obtained results confirm the effectiveness of the Grey Wolf Optimization (GWO)-based MPPT strategy in adaptively regulating converter operation and maintaining favorable wireless charging performance under varying operating conditions. By continuously adjusting the converter duty cycle in response to changes in system behavior, the proposed controller is able to sustain efficient power transfer and support stable battery charging, demonstrating its suitability for high-frequency wireless electric vehicle charging applications.

4.4. Influence of air-gap distance on power transfer

To examine the effect of magnetic coupling on the power transfer capability of the proposed wireless power transfer (WPT) system, a comprehensive air-gap analysis was performed by varying the separation distance between the transmitter and receiver coils from 3 cm to 25 cm. These distances were selected to represent a broad range of coupling conditions, spanning from strongly coupled operation at short separations to significantly weaker coupling at larger air gaps.

For this investigation, the electric vehicle battery was replaced with a variable resistive load to enable precise characterization of the power transfer characteristics of the system. The load resistance was systematically adjusted over a wide operating range, and the corresponding output voltage, output current, and transferred power were recorded for each operating point. This procedure allowed the maximum power point (MPP) associated with each air-gap condition to be accurately identified.

The results summarized in Table 3 indicate that the location of the maximum power operating point changes with magnetic coupling conditions. This observation demonstrates that the optimal electrical operating condition of the wireless charging system is not constant but varies according to the degree of coupling established between the transmitter and receiver coils.

A pronounced relationship between air-gap distance and power transfer capability can also be observed. As the separation distance decreases, stronger magnetic coupling results in higher mutual inductance and improved magnetic flux linkage, enabling more effective energy transfer across the wireless interface. Conversely, larger air gaps weaken the electromagnetic interaction between the coils and limit the amount of transferable power. For instance, the maximum transferred power increases from approximately 111.51 W at an air-gap distance of 25 cm to approximately 10.12 kW at 10 cm and reaches its highest value under the strongest coupling conditions. These results clearly illustrate the dominant influence of magnetic coupling on overall system performance.

Another important finding is the variation of the optimal load resistance with coupling strength. Under strong coupling conditions, maximum power transfer is achieved at lower resistance values, whereas weaker coupling scenarios shift the optimal operating point toward different load conditions. This behavior is consistent with the impedance-reflection phenomenon observed in resonant inductive power transfer systems, where the effective impedance seen by the primary circuit depends on both mutual inductance and the loading condition at the receiver side. Consequently, a fixed operating point cannot guarantee maximum performance across all coupling scenarios, highlighting the need for adaptive control strategies capable of continuously adjusting system operation in response to changing magnetic coupling conditions.

The results clearly demonstrate that the performance of the proposed wireless power transfer system is strongly influenced by the prevailing magnetic coupling conditions. Variations in air-gap distance alter the coupling coefficient, mutual inductance, and power transfer characteristics, causing the optimal operating point of the system to shift continuously. As a consequence, control approaches based on fixed

operating parameters are unable to maintain maximum power transfer performance across all operating scenarios.

These observations highlight the importance of employing adaptive Maximum Power Point Tracking (MPPT) techniques capable of responding to changes in coupling conditions in real time. By continuously identifying and adjusting the operating point associated with maximum power transfer, such strategies enable the wireless charging system to sustain high power transfer efficiency and stable charging performance despite variations in coil separation distance and magnetic coupling strength.

Table 3. MPP Values vs Air-Gap.

Air-Gap Distance (cm)	Optimal Load Resistance (Ω)	Voltage (V)	Current (A)	Maximum Power (W)
25	15	41.3	2.7	111.51
20	15	82.9	5.5	455.95
15	10	118.1	11.8	1393.58
10	10	167.8	16.7	2802.26
7	7	194.9	27.8	5418.22
5	5	219.6	43.9	9640.44
3	3	219	73	15987

4.5. Performance evaluation of the proposed GWO-based MPPT3 controller

This section provides a detailed assessment of the dynamic performance of the proposed wireless power transfer (WPT) system under a range of magnetic coupling conditions. The Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller is evaluated and compared with a conventional Pulse Width Modulation (PWM) control scheme using a 400 V battery and seven transmitter–receiver air-gap distances extending from 3 cm to 25 cm.

The analysis focuses on determining the ability of the proposed adaptive control framework to sustain efficient power transfer and effective battery charging as the magnetic coupling strength changes. To achieve this objective, the battery voltage and charging current responses are examined for each investigated air-gap condition, providing insight into the dynamic behavior of the wireless charging system and its response to coupling variations.

In addition to voltage and current characteristics, battery state-of-charge (SOC) performance is analyzed to quantify the charging effectiveness achieved by each control strategy. By examining transferred power capability together with SOC progression, a comprehensive evaluation of the charging performance under different magnetic coupling scenarios can be established.

To ensure consistency in the comparison process, both controllers were tested under identical operating conditions. This approach enables the performance improvements achieved by the optimization-based controller to be accurately quantified relative to the conventional PWM method and provides a clear assessment of its capability to maintain favorable charging performance across a wide range of operating conditions.

4.5.1. Battery Voltage and Current Characteristics

This subsection examines the battery voltage and charging current responses of the proposed wireless power transfer (WPT) system under different magnetic coupling conditions. A comparative analysis is performed between the Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller and a conventional Pulse Width Modulation (PWM) control strategy to assess the impact of adaptive converter regulation on wireless charging performance.

The evaluation is conducted using a 400 V battery model and seven air-gap distances ranging from 3 cm to 25 cm. These distances represent a broad spectrum of magnetic coupling conditions, extending from strongly coupled operation at short coil separations to weakly coupled scenarios at larger air gaps. Variations in coupling strength directly influence the transferred power capability and consequently affect the charging characteristics of the battery.

The battery voltage and charging current waveforms obtained under each operating condition are analyzed to investigate the dynamic behavior of the charging process and the ability of the control strategies to respond to coupling variations. Particular attention is given to voltage regulation performance, charging current characteristics, and their influence on overall energy transfer effectiveness. Through this analysis, the impact of magnetic coupling on wireless charging performance can be clearly identified, while the benefits of the proposed optimization-based controller can be quantitatively assessed across different operating scenarios.

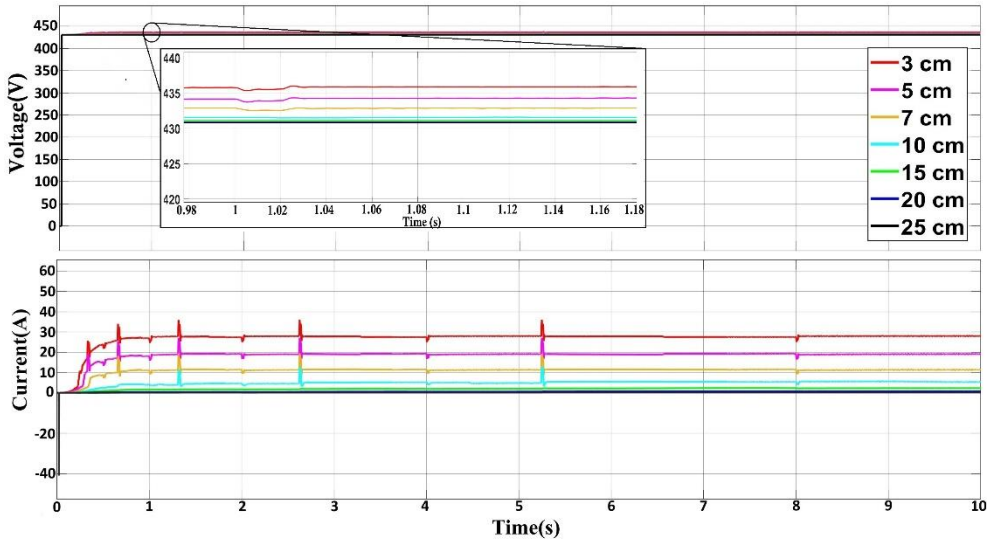


Figure 12. Battery Response under PWM vs Air-Gap.

Figure 12 illustrates the battery charging characteristics of the proposed wireless power transfer (WPT) system when operated using the conventional Pulse Width Modulation (PWM) control strategy under seven different air-gap distances ranging from 3 cm to 25 cm. The upper plot depicts the battery voltage response, while the lower plot presents the corresponding charging current profiles over the 10 s simulation period.

The voltage responses indicate that the battery voltage remains within a relatively narrow operating range across all investigated coupling conditions. Following an initial transient period, the voltage gradually approaches a steady-state value of approximately 430–435 V, demonstrating the ability of the PWM-controlled converter to provide acceptable voltage regulation throughout the charging process. Nevertheless, the final voltage level exhibits a noticeable dependence on magnetic coupling strength. Stronger coupling conditions associated with shorter air-gap distances produce slightly higher voltage values, whereas larger coil separations lead to a modest reduction in the achievable battery voltage due to lower energy transfer capability.

The influence of magnetic coupling becomes more pronounced when examining the charging current characteristics. At the beginning of the charging process, all current responses exhibit transient dynamics before gradually reaching steady-state operation. The largest charging current is observed under the strongest coupling condition corresponding to a 3 cm air gap, where the current stabilizes at

approximately 27–30 A. Similarly, the 5 cm operating condition maintains relatively high current levels, reflecting the enhanced energy transfer capability achieved under strong magnetic coupling.

As the separation distance between the coils increases, a progressive reduction in charging current can be observed. The responses corresponding to 7 cm and 10 cm maintain moderate current levels, whereas substantially lower current values are obtained at 15 cm, 20 cm, and 25 cm. This trend is directly related to the reduction in mutual inductance and magnetic flux linkage that accompanies weaker coupling conditions, thereby limiting the amount of power delivered to the battery.

Another notable observation is the presence of current oscillations during the charging process, particularly under strong coupling conditions. These fluctuations are associated with the fixed operating nature of the PWM controller, which lacks the capability to continuously adapt its operating point in response to variations in power transfer conditions. Consequently, the converter may not always operate at the most favorable duty-cycle value, resulting in reduced utilization of the available transferable power.

Overall, the results demonstrate that the conventional PWM control strategy is capable of sustaining stable charging operation across a range of air-gap distances. However, its ability to fully exploit the available power transfer capability diminishes as coupling conditions vary, particularly under weak magnetic coupling scenarios. These limitations motivate the adoption of adaptive Maximum Power Point Tracking (MPPT) techniques. Accordingly, the same operating conditions are subsequently evaluated using the proposed Grey Wolf Optimization (GWO)-based MPPT controller to assess the benefits of adaptive duty-cycle regulation on charging performance and power transfer capability.

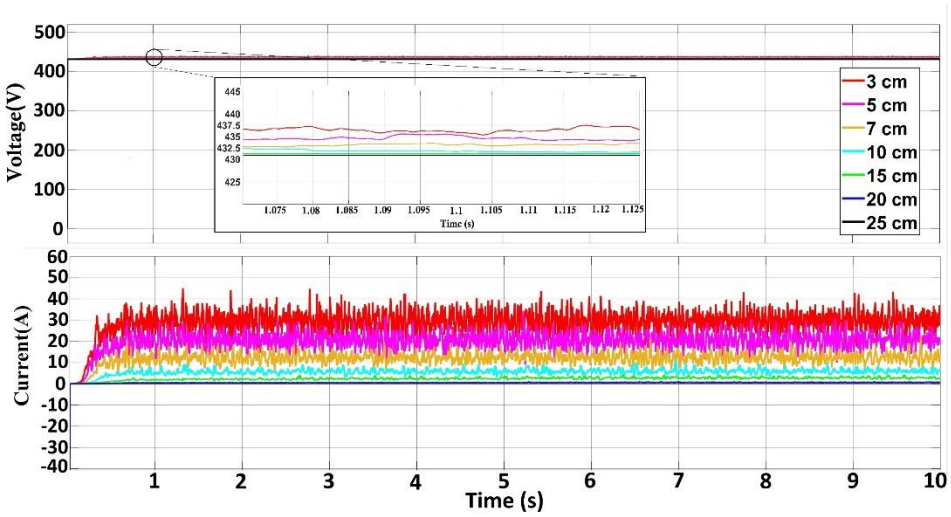


Figure 13. Battery Response under GWO-MPPT.

Figure 13 presents the charging characteristics of the proposed wireless power transfer (WPT) system when the Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller is employed under seven different air-gap distances ranging from 3 cm to 25 cm. The upper plot depicts the battery voltage response, while the lower plot illustrates the corresponding charging current profiles throughout the 10 s simulation period.

The voltage responses indicate stable charging operation across all investigated coupling conditions. Following a brief transient interval, the battery voltage converges toward a steady operating range of approximately 430–436 V. The rapid convergence and limited steady-state fluctuations demonstrate the ability of the GWO-based controller to maintain effective converter regulation despite variations in magnetic coupling strength. The relatively smooth voltage profiles further indicate that the optimization process does not introduce undesirable instability into the charging system.

A comparison of the voltage characteristics under different air-gap distances reveals a modest dependence on coupling conditions. Stronger magnetic coupling associated with shorter coil separations results in slightly higher steady-state voltage levels, whereas larger air gaps produce lower voltage values due to reduced mutual inductance and weaker electromagnetic interaction between the transmitter and receiver coils. Nevertheless, the voltage remains well regulated across all investigated operating scenarios.

The charging current responses provide a more direct indication of the influence of magnetic coupling on power transfer performance. All current waveforms exhibit an initial transient phase before settling into steady-state operation. The largest charging current is obtained at the shortest air-gap distance of 3 cm, where the current stabilizes within the range of approximately 30–35 A and briefly exceeds 40 A during the transient period. Such behavior reflects the strong magnetic coupling and enhanced energy transfer capability achieved under short-distance operating conditions. Similarly, the 5 cm case maintains relatively high current levels, confirming efficient power transfer under favorable coupling conditions.

As the transmitter–receiver separation increases, the charging current progressively decreases. The responses corresponding to 7 cm and 10 cm continue to provide moderate current levels and stable charging operation, which is consistent with practical wireless EV charging conditions. In contrast, the current magnitude declines considerably at 15 cm, 20 cm, and 25 cm due to the reduction in magnetic flux linkage and mutual inductance. Under these weak-coupling conditions, the amount of transferable power becomes increasingly constrained, resulting in lower charging capability.

The results demonstrate that the proposed GWO-based MPPT controller is capable of continuously adjusting the converter operating point according to the available transferable power under different coupling conditions. This adaptive behavior enables the system to maintain effective charging performance over a wide range of air-gap distances while preserving stable operation.

When compared with the conventional PWM strategy, the proposed optimization-based controller consistently delivers higher charging current levels and improved power transfer performance, particularly under strong and moderate coupling conditions. In addition, the GWO-based approach exhibits more effective dynamic regulation and better utilization of the available power transfer capability, highlighting the advantages of adaptive maximum power point tracking for wireless electric vehicle charging applications.

4.5.2. State of Charge (SOC) Analysis

This subsection examines the battery state-of-charge (SOC) behavior of the proposed wireless power transfer (WPT) system under different magnetic coupling

conditions. A comparative assessment is performed between the Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller and the conventional Pulse Width Modulation (PWM) control strategy to evaluate the impact of adaptive power optimization on battery charging effectiveness.

The analysis was carried out using a 400 V battery model and seven transmitter–receiver air-gap distances ranging from 3 cm to 25 cm. To ensure a consistent basis for comparison, the initial battery state-of-charge was fixed at 50% for all investigated operating scenarios, and the charging process was monitored over a simulation period of 10 s. This approach enables the influence of magnetic coupling variations on battery charging performance to be examined under identical initial conditions.

Battery SOC was selected as a key performance metric because it directly reflects the amount of energy delivered to the battery during the charging process. By comparing the SOC progression achieved by the two control strategies, the effectiveness of the proposed optimization-based controller in utilizing the available transferred power can be quantitatively evaluated. The resulting SOC characteristics therefore provide valuable insight into the charging capability of the wireless EV charging system and its ability to maintain effective energy transfer under different magnetic coupling conditions.

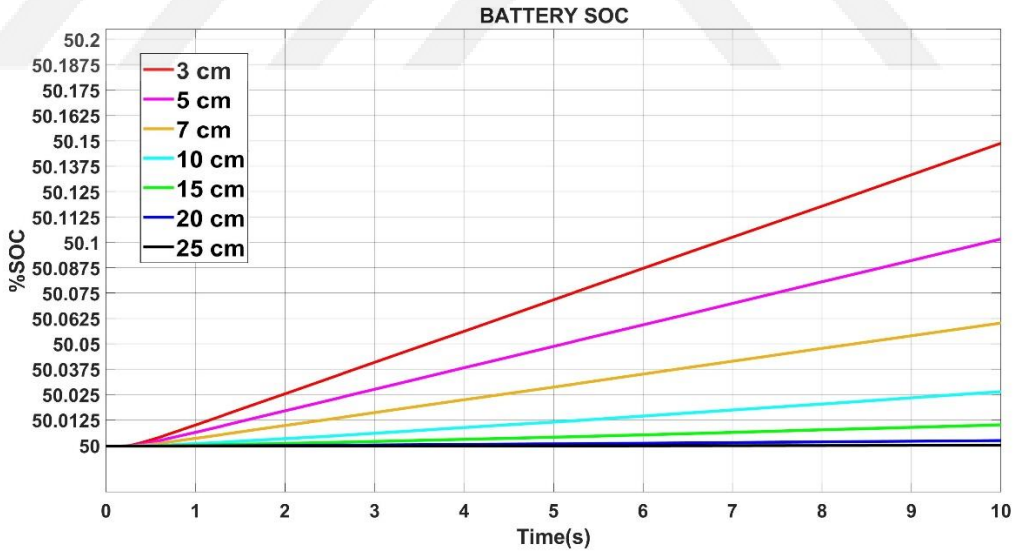


Figure 14 . SOC under PWM at Different Air-Gaps.

Figure 14 presents the battery state-of-charge (SOC) responses obtained using the conventional Pulse Width Modulation (PWM) control strategy for seven different air-gap distances ranging from 3 cm to 25 cm during the 10 s charging period.

The results indicate that the battery SOC increases progressively over time for all investigated operating conditions, confirming that energy is successfully transferred to the battery throughout the charging process. However, the rate of SOC growth varies considerably with the magnetic coupling condition. Stronger coupling, associated with shorter transmitter–receiver separation distances, enables higher power transfer capability and consequently leads to a greater increase in battery charge during the simulation interval.

The most pronounced SOC enhancement is achieved at the shortest air-gap distance of 3 cm, where the battery state-of-charge rises from approximately 50% to about 50.15%. This improvement is directly related to the higher charging currents and increased power transfer capability achieved under strong magnetic coupling conditions. A similar trend is observed at 5 cm, where effective energy transfer continues to support a noticeable increase in battery charge.

As the air-gap distance becomes larger, the SOC growth rate gradually declines. The responses corresponding to 7 cm and 10 cm still exhibit measurable charging progress, whereas significantly smaller SOC increments are observed at 15 cm, 20 cm, and 25 cm. This behavior can be attributed to the reduction in magnetic flux linkage and mutual inductance associated with weaker coupling conditions, which limits the amount of power delivered to the battery and consequently slows the charging process.

Another notable observation is the smooth evolution of the SOC curves throughout the simulation period. The absence of significant oscillations indicates stable converter operation and consistent battery charging behavior under PWM control. Nevertheless, the charging effectiveness remains strongly dependent on the prevailing magnetic coupling condition because the PWM controller operates with a predetermined duty-cycle strategy and lacks the capability to continuously adjust its operating point in response to changing power transfer conditions.

Overall, the results demonstrate that the conventional PWM approach is capable of maintaining stable battery charging across all investigated air-gap distances. However, its charging effectiveness decreases noticeably as coupling conditions

deteriorate, resulting in reduced SOC improvement under larger separation distances. These observations highlight the limitations of fixed-duty-cycle control and provide a strong motivation for employing adaptive Maximum Power Point Tracking (MPPT) techniques. Accordingly, the Grey Wolf Optimization (GWO)-based MPPT controller is evaluated under the same operating conditions to determine its ability to improve power transfer utilization and enhance battery charging performance.

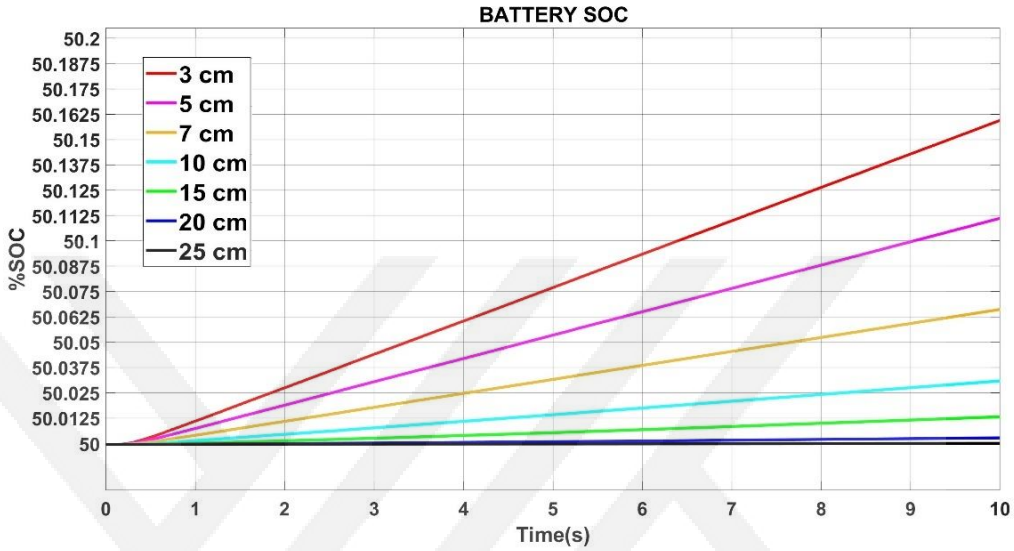


Figure 15 . SOC under GWO-MPPT at Different Air-Gaps.

Figure 15 presents the battery state-of-charge (SOC) profiles obtained using the Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller for seven different air-gap distances ranging from 3 cm to 25 cm over a 10 s charging period.

The results demonstrate a continuous increase in battery SOC under all investigated operating conditions, confirming the ability of the proposed controller to sustain effective charging operation across a wide range of magnetic coupling scenarios. Nevertheless, the magnitude of the SOC improvement remains closely related to the coupling strength between the transmitter and receiver coils. Stronger coupling conditions associated with shorter air-gap distances enable greater power transfer capability and consequently produce faster battery charging rates.

The largest SOC enhancement is achieved at the 3 cm air-gap distance, where the battery state-of-charge increases from approximately 50% to 50.16% during the

simulation interval. This improvement is attributed to the high charging current and enhanced power transfer capability achieved under strong magnetic coupling conditions. Similarly, the 5 cm operating condition exhibits a noticeable increase in SOC, indicating that efficient energy transfer is maintained when adequate magnetic coupling is available.

As the separation distance between the coils increases, the rate of SOC progression gradually declines. The cases corresponding to 7 cm and 10 cm continue to exhibit meaningful charging progress, whereas the SOC increments become considerably smaller at 15 cm, 20 cm, and 25 cm. This trend is consistent with the reduction in mutual inductance and magnetic flux linkage associated with weaker coupling conditions, which limits the amount of energy delivered to the battery during the charging interval.

A further observation is the smooth and monotonic behavior of the SOC curves throughout the simulation period. The absence of significant fluctuations indicates stable controller performance and effective regulation of the converter operating point. By continuously adjusting the duty cycle according to the available power transfer conditions, the GWO-based MPPT algorithm is able to maintain operation close to the optimal power transfer region despite variations in magnetic coupling strength.

When compared with the conventional PWM strategy, the proposed optimization-based controller consistently achieves greater SOC enhancement across all investigated air-gap distances. These results demonstrate that adaptive maximum power point tracking enables more effective utilization of the available transferable power and contributes to improved battery charging performance. Consequently, the findings confirm the suitability of the GWO-based MPPT approach for wireless electric vehicle charging systems operating under variable magnetic coupling conditions.

4.6. Performance Comparison

This subsection provides a comparative assessment of the conventional Pulse Width Modulation (PWM) controller and the proposed Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) strategy under a range of magnetic coupling conditions. The comparison focuses on two primary performance indicators, namely transferred power capability and battery state-of-charge (SOC)

progression, in order to quantify the benefits of adaptive power optimization in wireless electric vehicle charging applications. To ensure consistency in the evaluation process, both control approaches were tested under identical operating conditions using a 400 V battery and seven transmitter–receiver air-gap distances ranging from 3 cm to 25 cm. These distances encompass a broad spectrum of coupling scenarios, extending from strongly coupled operation at short separations to weakly coupled conditions at larger air gaps. Such variations provide a suitable framework for examining the influence of magnetic coupling on system performance and controller effectiveness. The comparative results enable a quantitative determination of the performance gains achieved by the proposed optimization-based controller relative to the conventional PWM approach. Particular attention is given to the ability of each controller to utilize the available transferable power under changing coupling conditions and to sustain effective battery charging performance. Through this analysis, the role of adaptive duty-cycle regulation in enhancing energy transfer efficiency and improving overall wireless charging performance can be clearly identified.

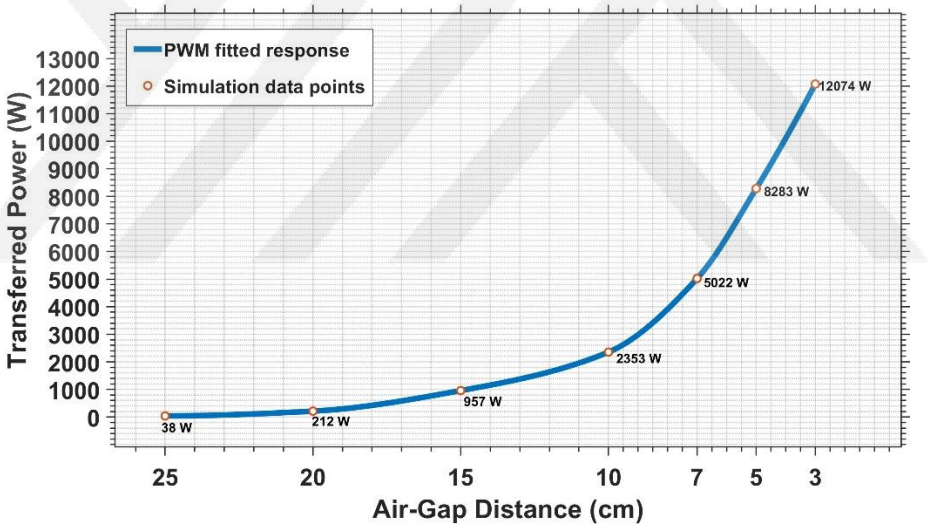


Figure 16 .Transferred Power under PWM vs Air-Gap.

Figures 16 and 17 present the transferred power responses obtained using the conventional Pulse Width Modulation (PWM) controller and the proposed Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller, respectively, under different air-gap distances. For both control approaches, the transferred power exhibits a strong dependence on magnetic coupling conditions. As

the separation distance between the transmitter and receiver coils decreases, the coupling coefficient and mutual inductance increase, enabling more effective energy transfer and higher power delivery capability.

Although both controllers follow the same general trend, the GWO-based MPPT strategy consistently delivers higher transferred power levels across all investigated operating conditions. This performance enhancement arises from the controller's ability to continuously adapt the converter operating point according to the prevailing coupling conditions. By dynamically regulating the duty cycle, the optimization algorithm maintains operation closer to the maximum power transfer region, allowing more effective utilization of the available transferable power.

The difference between the two control strategies becomes particularly evident under strong and moderate coupling conditions, where greater amounts of power are available for transfer. Under these scenarios, the adaptive controller is able to exploit the improved magnetic coupling more effectively than the fixed-duty-cycle PWM approach, resulting in higher power delivery to the load. Even under weak-coupling conditions associated with larger air-gap distances, the proposed controller maintains a performance advantage by continuously seeking a more favorable operating point.

Overall, the transferred power characteristics confirm the effectiveness of the GWO-based MPPT strategy in enhancing the power transfer capability of the wireless charging system. The results demonstrate that adaptive duty-cycle regulation enables superior utilization of the inductive power transfer link and contributes to improved system performance across a broad range of magnetic coupling conditions.

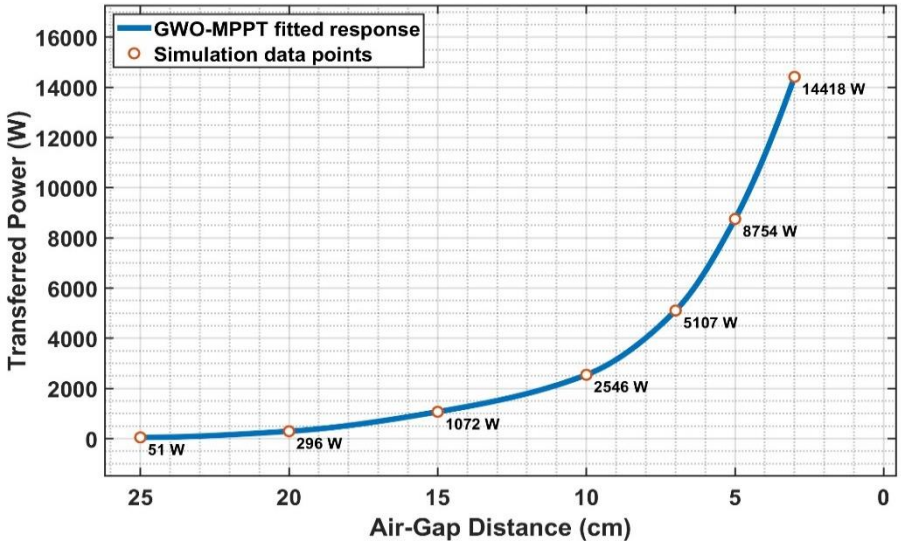


Figure 17 . Transferred Power under GWO-MPPT vs Air-Gap.

Under weak magnetic coupling conditions, particularly at air-gap distances of 25 cm and 20 cm, the proposed GWO-based MPPT controller demonstrates a clear advantage over the conventional PWM strategy. At 25 cm, the transferred power increases from approximately 38.08 W to 50.77 W, corresponding to an enhancement of about 33.33%. Likewise, at 20 cm, the transferred power rises from 211.60 W to 296.31 W, yielding an improvement of approximately 40.03%. These results indicate that adaptive maximum power point tracking becomes increasingly beneficial when magnetic coupling deteriorates, as the controller is able to identify more favorable operating conditions despite the limited transferable power available under weak-coupling scenarios.

As the transmitter–receiver separation distance decreases, stronger magnetic coupling leads to a substantial increase in the power transfer capability of both control strategies. At an air-gap distance of 15 cm, the proposed controller delivers approximately 1071.96 W compared with 957.26 W obtained using PWM control, representing an improvement of about 11.98%. This result confirms that the optimization-based controller continues to provide measurable performance gains even when the available transferable power increases significantly.

The same trend is observed at 10 cm and 7 cm, where both controllers operate within a relatively high-power region. Although the difference between the two approaches becomes less pronounced under these stronger coupling conditions, the GWO-based MPPT controller consistently maintains a higher power transfer

capability. This improvement is attributed to its ability to continuously adjust the converter duty cycle and maintain operation closer to the optimal power transfer region.

The largest power transfer levels are achieved at the shortest air-gap distance of 3 cm, where magnetic coupling between the transmitter and receiver coils is strongest. Under this condition, the conventional PWM controller delivers approximately 12.07 kW, whereas the proposed GWO-based MPPT strategy reaches approximately 14.42 kW. This corresponds to a power enhancement of about 19.41%, demonstrating the capability of the adaptive controller to effectively exploit favorable coupling conditions and maximize the utilization of the wireless power transfer link.

Overall, the comparative results indicate that the proposed GWO-based MPPT controller provides superior power transfer performance across all investigated operating conditions. The observed improvements confirm the effectiveness of adaptive duty-cycle regulation in maintaining operation near the maximum power transfer point and highlight its importance for wireless EV charging systems operating under both strong and weak magnetic coupling conditions.

Table 4. PWM vs GWO-MPPT Power Comparison vs Air-Gap.

Air-gap Distance	PWM Power (W)	GWO Power (W)	Improvement (%)
25 cm	38.079	50.772	33.33
20 cm	211.600	296.310	40.03
15 cm	957.264	1071.961	11.98
10 cm	2353.310	2545.800	8.18
7 cm	5022.452	5107.200	1.69
5 cm	8282.864	8753.500	5.68
3 cm	12074.430	14418.400	19.41

Table 4 presents a quantitative comparison of the transferred power achieved using the conventional Pulse Width Modulation (PWM) controller and the proposed Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) strategy, together with the corresponding percentage improvements for each investigated air-gap distance. The results demonstrate that the optimization-based

controller consistently outperforms the conventional PWM approach across all magnetic coupling conditions considered in this study. Regardless of the transmitter–receiver separation distance, the adaptive control strategy is able to utilize the available transferable power more effectively by continuously adjusting the converter operating point in response to changing system conditions.

Table 5 summarizes the battery state-of-charge (SOC) values obtained after a 10 s charging interval for both control strategies. The comparison reveals that the proposed GWO-based MPPT controller achieves higher SOC progression than the conventional PWM controller under all investigated operating scenarios. Although the absolute SOC increments remain relatively small because of the limited simulation duration, the observed differences clearly reflect the improved energy transfer capability achieved by the adaptive control framework.

The enhanced SOC performance can be directly associated with the higher transferred power levels and improved charging current characteristics obtained using the proposed controller. By maintaining operation closer to the maximum power transfer region, the GWO-based MPPT strategy enables a greater amount of energy to be delivered to the battery during the charging period, thereby improving charging effectiveness under both strong and weak magnetic coupling conditions.

Taken together, the results presented in Tables 4 and 5 provide clear evidence of the benefits of adaptive maximum power point tracking in wireless electric vehicle charging applications. The proposed GWO-based controller not only increases the power transfer capability of the wireless charging system but also contributes to improved battery charging performance, demonstrating its effectiveness as an advanced control solution for operation under varying magnetic coupling conditions.

Table 5. SOC Comparison: PWM vs GWO-MPPT (10 s).

Air-gap Distance	Time (s)	PWM SOC (%)	GWO SOC (%)
25 cm	10	50.000001	50.000037
20 cm	10	50.002300	50.002700
15 cm	10	50.010000	50.013100
10 cm	10	50.026300	50.030800
7 cm	10	50.060200	50.066100
5 cm	10	50.101500	50.111100
3 cm	10	50.148800	50.159400

Overall, the obtained results confirm that the proposed GWO-based MPPT controller significantly improves the transferred power capability and battery charging performance of the wireless power transfer system under varying magnetic coupling conditions compared with the conventional PWM control strategy. The adaptive duty-cycle regulation capability of the proposed controller enables continuous operation near the maximum transferred power condition, thereby enhancing charging effectiveness and improving system performance under both strong and weak magnetic coupling scenarios.

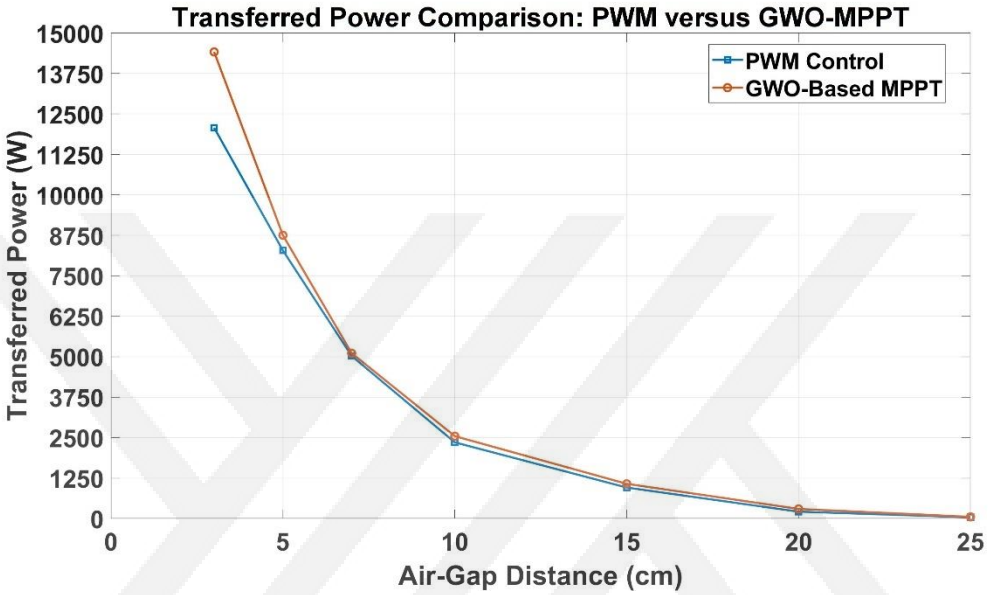


Figure 18. Power Comparison: PWM vs GWO-MPPT**.**

Figure 18 compares the transferred power performance of the conventional Pulse Width Modulation (PWM) controller and the proposed Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) strategy across the investigated air-gap distances. The comparison reveals a consistent performance advantage for the optimization-based controller under all magnetic coupling conditions considered in this study. As the air-gap distance decreases and the magnetic coupling strength improves, both control approaches exhibit an increase in transferred power capability. However, the GWO-based MPPT controller consistently delivers higher power levels because it continuously adjusts the converter operating point according to the prevailing system conditions. This adaptive behavior enables more effective utilization of the available transferable power and allows the system to operate closer to the optimal power transfer region. The difference between the two

control strategies becomes particularly evident at air-gap distances where coupling conditions vary significantly. Under both weak- and strong-coupling scenarios, the proposed controller maintains a measurable performance advantage over the conventional PWM approach, demonstrating its ability to respond effectively to changes in magnetic coupling and system operating conditions.Overall, the results presented in Figure 18 highlight the benefits of adaptive maximum power point tracking for wireless electric vehicle charging applications. The superior transferred power capability achieved by the GWO-based controller confirms its effectiveness in improving energy transfer performance and maximizing the utilization of the wireless charging link across a wide range of operating conditions.

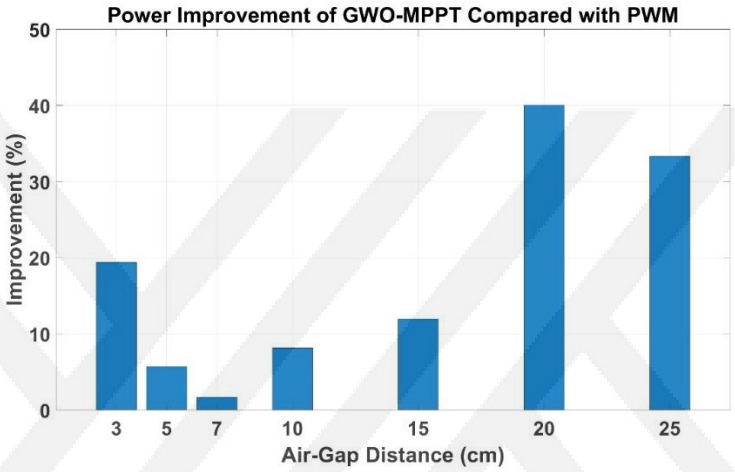


Figure 19. Power Improvement (%) of GWO-MPPT over PWM.

Fig. 19 illustrates the percentage improvement in trans ferred power achieved by the proposed GWO-based MPPT controller relative to the conventional PWM control strategy under different magnetic coupling conditions. The obtained results indicate that the proposed adaptive controller consistently improves the transferred power capability across all investigated air-gap distances. The highest improvement percentages are observed under weak magnetic coupling conditions, particularly at 20 cm and 25 cm, where the adaptive duty-cycle regulation capability of the proposed controller enables more effective tracking of the maximum transferred power condition compared with the conventional fixed-duty cycle PWM appro.

4.7. Comprehensive Performance Analysis and Discussion

The results obtained from the simulation study reveal the strong influence of magnetic coupling on the performance of the proposed wireless power transfer (WPT)

system. Variations in air-gap distance directly affect the mutual inductance and magnetic flux linkage between the transmitter and receiver coils, which in turn determine the amount of transferable power available for battery charging. Stronger coupling conditions achieved at shorter separation distances facilitate more efficient energy transfer, resulting in higher charging currents and improved charging effectiveness. Conversely, increasing the air-gap distance reduces coupling strength, limiting power transfer capability and slowing the charging process.

The comparative evaluation further demonstrates the advantages of the Grey Wolf Optimization (GWO)-based Maximum Power Point Tracking (MPPT) controller over the conventional Pulse Width Modulation (PWM) approach. By continuously adjusting the converter duty cycle according to the prevailing operating conditions, the proposed controller is able to maintain operation closer to the maximum power transfer region. This adaptive capability enables improved utilization of the available transferable power and contributes to enhanced charging performance across all investigated coupling scenarios.

The benefits of the proposed control strategy are particularly evident under favorable magnetic coupling conditions, where the highest power transfer levels and the most pronounced battery state-of-charge (SOC) progression are achieved. Although both controllers benefit from improved coupling at shorter air-gap distances, the optimization-based approach consistently extracts a greater proportion of the available power, leading to superior charging current characteristics and more effective battery charging performance. In contrast, the fixed-duty-cycle nature of the PWM controller restricts its ability to respond to changing coupling conditions, resulting in lower overall charging effectiveness.

Analysis of the voltage and current responses also confirms stable system operation throughout the charging process. The battery voltage remains well regulated under both transient and steady-state conditions, while the charging current profiles clearly reflect the influence of magnetic coupling on power transfer capability. These characteristics verify the stable interaction between the resonant wireless power transfer stage and the proposed control framework.

Overall, the findings confirm that the GWO-based MPPT controller provides an effective adaptive control solution for wireless electric vehicle charging applications.

The ability to continuously optimize converter operation under varying magnetic coupling conditions enhances power transfer capability, improves charging performance, and strengthens the operational robustness of the wireless charging system.

CONCLUSION AND RECOMMENDATIONS

This study introduced an adaptive wireless power transfer (WPT) framework for electric vehicle charging based on a Grey Wolf Optimization (GWO)-driven Maximum Power Point Tracking (MPPT) strategy. The proposed architecture combines a Series–Series (SS) compensated resonant inductive link with a receiver-side DC–DC converter to enhance energy transfer performance under varying magnetic coupling conditions.

A detailed MATLAB/Simulink investigation was performed using a 400 V battery model and seven air-gap distances ranging from 3 cm to 25 cm. The performance of the proposed controller was assessed under both strong and weak coupling conditions and benchmarked against a conventional Pulse Width Modulation (PWM) control approach. The evaluation considered transferred power capability, charging current characteristics, voltage regulation behavior, and battery state-of-charge (SOC) progression.

The results revealed that magnetic coupling plays a dominant role in determining the charging capability of the wireless power transfer system. Reducing the air-gap distance strengthened the electromagnetic interaction between the transmitter and receiver coils, leading to higher mutual inductance, improved flux linkage, and greater power transfer capability. Under the strongest coupling condition (3 cm), the proposed GWO-based MPPT controller delivered approximately 14.42 kW compared with 12.07 kW achieved by the PWM controller, corresponding to an improvement of 19.41%. Furthermore, under weak-coupling conditions (20 cm), the proposed strategy increased the transferred power from 211.60 W to 296.31 W, representing an enhancement of approximately 40.03%.

The comparative analysis demonstrated that adaptive duty-cycle optimization enables the converter to operate closer to the maximum power transfer region across different coupling scenarios. Consequently, the proposed controller achieved higher charging currents, improved power utilization, enhanced SOC progression, and more effective charging performance than the conventional PWM approach. The observed voltage and current responses also confirmed stable resonant operation and reliable system behavior during both transient and steady-state conditions.

From an application perspective, the proposed framework highlights the potential of integrating intelligent optimization algorithms with resonant wireless charging architectures to improve charging robustness and adaptability in practical electric vehicle environments. The ability to sustain effective power transfer under coupling variations makes the proposed approach a promising candidate for future wireless charging infrastructures requiring high efficiency, operational flexibility, and reliable performance.

Future work will focus on experimental validation of the proposed system using real-time embedded controllers and hardware prototypes. In addition, further investigations may consider the impact of lateral coil misalignment, the implementation of dynamic wireless charging scenarios, and efficiency improvement under higher power levels. The integration of advanced artificial intelligence techniques for multi-objective optimization and intelligent energy management will also be explore.

The comparative evaluation demonstrated that the proposed optimization-based control strategy effectively maintained system operation in the vicinity of the maximum power transfer region through continuous duty-cycle adaptation. As a result, higher charging current levels, improved voltage regulation, enhanced dynamic response, and greater battery state-of-charge (SOC) progression were achieved across all investigated operating conditions. Furthermore, the voltage and current characteristics confirmed stable resonant operation of the wireless power transfer system during both transient and steady-state periods, indicating reliable interaction between the resonant network and the adaptive control framework.

From a practical standpoint, the proposed approach highlights the potential of combining intelligent MPPT techniques with resonant inductive wireless charging architectures to improve charging reliability under variable magnetic coupling conditions. The ability to sustain effective power transfer despite air-gap variations enhances the suitability of the system for real-world electric vehicle charging applications, where coupling conditions may change during operation. Consequently, the proposed framework offers a promising pathway toward the development of next-generation wireless charging infrastructures requiring adaptive control, operational robustness, and efficient energy transfer performance.

Future research will focus on validating the proposed methodology through real-time experimental implementation using embedded digital controllers and hardware prototypes. Additional studies may investigate the effects of lateral coil misalignment, dynamic wireless charging scenarios, and efficiency enhancement under higher power operating conditions. Moreover, the incorporation of advanced artificial intelligence and hybrid optimization techniques may further improve control performance and support multi-objective energy management strategies for future wireless electric vehicle charging systems.

Recommendations for Future Work

Future research may investigate the implementation of the proposed adaptive wireless charging framework under dynamic electric vehicle operating conditions involving coil misalignment and moving charging scenarios. Additional investigations may also focus on integrating advanced artificial intelligence techniques and hybrid optimization algorithms in order to further improve adaptive charging performance and real-time energy management capability.

Moreover, future studies may consider experimental hardware implementation of the proposed WPT system in order to validate the obtained simulation results under practical operating environments. The integration of renewable energy sources, bidirectional energy transfer capability, and multi-coil charging architectures also represents promising research directions for next-generation intelligent wireless EV charging infrastructures

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