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Improving Efficiency and Power Transfer in Wireless Charging Systems Using Phase-Shift and Amplitude Control

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Abstract: Wireless power transfer (WPT) is an emerging technology with an increasing number of potential applications to transfer power from a transmitter to a mobile receiver over a relatively large air gap. However, its widespread application is hampered due to the relatively low efficiency of current Wireless power transfer (WPT) systems. This study presents a concept to maximize the efficiency as well as to increase the amount of extractable power of a WPT system operating in non-resonant operation. The proposed method is based on actively modifying the equivalent secondary-side load impedance by controlling the phase-shift of the active rectifier and its output voltage level. The presented hardware prototype represents a complete wireless charging system, including a dc–dc converter which is used to charge a battery at the output of the system. Experimental results are shown for the proposed concept in comparison to a conventional synchronous rectification approach. The presented optimization method clearly outperforms state- of-the-art solutions in terms of efficiency and extractable power.

Key Words: Wireless Power Transfer (WPT), Phase Shift Control, Amplitude Control, Power Efficiency Optimization, Inductive Charging, Maximum Power Extraction.

1. INTRODUCTION

Wireless Power Transfer (WPT) is an emerging technology that enables the transmission of electrical energy without the need for physical connectors or wiring. It operates on the principle of electromagnetic field coupling, allowing power to be transferred efficiently between a transmitting unit and a receiving device. With the rapid advancement of modern electronics, WPT has gained significant importance in applications such as consumer electronics, electric vehicles, and biomedical devices. This technology offers enhanced convenience, improved safety, and reduced mechanical wear compared to conventional wired systems. As a result, WPT is becoming a key research area in electrical and electronic engineering.

The concept of wireless power transmission dates back to the pioneering work of Nikola Tesla, who demonstrated the possibility of transmitting energy without wires using electromagnetic waves. The fundamental working principle of WPT is based on electromagnetic induction, discovered by Michael Faraday, where an alternating current in a transmitting coil generates a magnetic field that induces voltage in a nearby receiving coil. Modern WPT systems primarily use inductive and resonant inductive coupling techniques to achieve efficient power transfer over short to moderate distances. These methods are widely adopted in wireless charging pads and emerging electric vehicle charging systems.

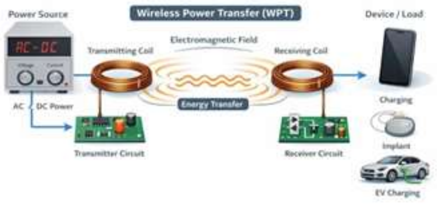

Fig: 1 wireless power transfer

Despite its advantages, wireless power transfer faces challenges such as limited transmission distance, efficiency losses, and dependency on coil alignment and operating frequency. Standardization protocols like the Qi standard ensure compatibility and safe operation among different devices, but also impose design constraints on system parameters. To address these limitations, advanced control techniques such as phase shift control, frequency tuning, and amplitude modulation are being explored to enhance efficiency and output power. Ongoing research focuses on optimizing WPT systems within standard constraints, making them more practical and scalable for real-world applications.

2. LITERATURE REVIEW

In another 2023 study, *Bole Ma et al.* introduced **“Pulse Width Modulation-Controlled Switching Impedance for Wireless Power Transfer”**, which focused on amplitude-related control using PWM techniques. The authors proposed a switching impedance control method to compensate for detuning caused by temperature variations and component tolerances. By dynamically adjusting the effective impedance, the system maintains resonance conditions and improves power transfer efficiency. This approach enhances system stability and ensures consistent power delivery under varying operating conditions. The work emphasizes that amplitude and impedance control play a crucial role in maintaining optimal efficiency in practical WPT systems.

Further advancements in combined phase and amplitude control were discussed in 2023 by *Da Li et al.* in **“Multi-Mode Joint Modulation of Array Wireless Power Transfer”**. This study proposed a multi-transmitter system using joint modulation techniques to control both phase and amplitude across multiple coils. The system utilized closed-loop control to switch between different transmissions modes, ensuring stable output and improved efficiency. The results demonstrated that coordinated phase and amplitude control can significantly enhance power delivery and spatial flexibility in WPT systems. This work is particularly relevant for applications requiring scalable and high-power wireless charging solutions.

3. PROPOSED SYSTEM

The proposed wireless power transfer (WPT) system focuses on optimizing the overall performance from the DC input source to the battery charging stage at the output. Unlike conventional approaches that primarily concentrate on isolated subsystems, this work considers the complete power transfer chain, including the transmitter, coupling interface, active rectifier, and DC–DC converter. Existing studies, such as Qi-compliant systems and dual-mode receivers supporting Qi and Rezence standards, mainly utilize fixed configurations or commercially available components without incorporating advanced optimization strategies. As a result, their efficiency and extractable output power remain limited, especially under varying operating conditions. The proposed system addresses these limitations by integrating intelligent control techniques to enhance both efficiency and power transfer capability across the entire system.

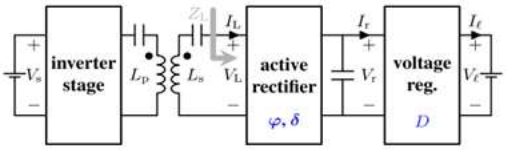

Fig 2: Schematic diagram of WPT system with inverter-driven primary resonance and secondary rectifier DC–DC converter stage.

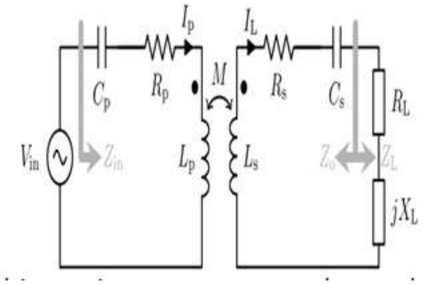

Fig 3: Equivalent circuit model of a series-series tuned WPT system based on the first harmonic approximation.

3.1Theoretical Analysis

This section presents a circuit-based modelling approach to analyse the behaviour of the wireless power transfer (WPT) system and determine the conditions for achieving maximum efficiency and power transfer. The analysis is based on the first harmonic approximation, where only the fundamental component of the input voltage is considered. The active rectifier and DC–DC converter are simplified as equivalent load impedance. This approximation is valid for high-quality resonant systems operating near their resonance frequency and enables effective steady-state analysis.

The system is modelled as a series–series compensated WPT topology, where a sinusoidal RMS input voltage drives the primary resonant circuit. The primary and secondary sides include parasitic resistances and compensating capacitors that define the resonance condition. The coupling between the coils is represented by mutual inductance, which depends on the coupling factor and physical alignment. The primary and secondary impedances are expressed as follows:

$$Z_p = R_p + j\left(\omega L_p - \frac{1}{\omega C_p}\right), \quad Z_s = R_s + j\left(\omega L_s - \frac{1}{\omega C_s}\right)$$

The equivalent load impedance represents the combined effect of the receiver-side components, including the rectifier, DC–DC converter, and battery load. Based on this model, the input and output impedances can be derived to evaluate system performance. This simplified analytical framework allows optimization of both resistive and reactive components of the load to maximize efficiency and extractable power in the WPT system.

3.2 Overview of proposed system

3.2.1 Control Strategy and Optimization of Wireless Power Transfer System

This section presents the control techniques used to enhance the efficiency and power transfer capability of the wireless power transfer (WPT) system. Initially, synchronous rectification is reviewed, followed by the proposed concept based on phase-shift and amplitude control. The system is analysed using simulation parameters based on the Qi standard operating at 140 kHz with a resonance frequency of 100 kHz. The objective is to optimize the equivalent load impedance seen by the receiver to maximize efficiency and extractable output power.

3.2.2 Synchronous Rectification

Synchronous rectification is a widely used technique where the switches of the active rectifier are controlled based on the zero-crossings of the rectifier input current I_L. This ensures that the input voltage V_L and current I_L is in phase (ϕ=0), resulting in purely resistive load behaviour:

3.2.3Proposed Phase-Shift and Amplitude Control

To overcome the limitations of synchronous rectification, the proposed method introduces a phase-shift ϕ between the rectifier input voltage and current. This allows simultaneous control of both resistive and reactive components of the equivalent load impedance. The equivalent impedance is derived from the first harmonic components as:

$$Z_L = \frac{V_L^{(1)}}{I_L^{(1)}} = R_L + jX_L$$

Where $V_L^{(1)}$ and $I_L^{(1)}$)are the fundamental components of voltage and current. Unlike conventional methods, varying the phase-shift affects V_L and I_L both providing greater flexibility for system optimization.

3.2.4 Optimization Strategy

The optimization of the WPT system aims to achieve maximum efficiency for a given output power P_{out} . Two approaches are considered: (1) direct optimization of resistive and reactive impedance components, and (2) optimization using measurable parameters such as phase-shift and rectified voltage. The first method involves determining the optimal values of R_L and X_L using constrained optimization:

$$\max\ \eta \quad \text{subject to} \quad P_{out} = \text{constant}$$

Weak coupling conditions. It also overcomes the limitation of conventional methods that optimize only a single operating point.

3.2.5 Optimization Using Phase-Shift and Rectified Voltage

The second method utilizes measurable parameters ϕ and Vr to achieve optimal performance. The system is modelled as a two-port network, and the efficiency is maximized by minimizing input power P_{in} for a fixed output power:

$$\eta = \frac{P_{out}}{P_{in}}$$

Using Lagrangian optimization, the optimal rectifier current is derived

$$I_{L,opt} = I_{L,opt}^{R} + jI_{L,opt}^{I}$$

From this, the optimal load impedance can be calculated for maximum efficiency. Experimental validation results showed as simulations results the variation of rectified voltage and duty cycle with output power, confirming the effectiveness of the proposed control strategy.

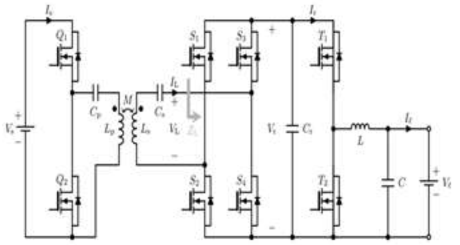

Fig.4: Schematic of FPGA-controlled MOSFET experimental setup with digital control

A key feature of the proposed approach is the active control of both the resistive and reactive components of the load impedance. Traditional methods adjust only the resistive part, neglecting the reactive component, which leads to suboptimal performance over a wide operating range. In contrast, this system employs an advanced control strategy based on phase-shift and amplitude modulation to dynamically regulate impedance characteristics. This enables optimal power transfer while maintaining high efficiency, even under detuning or parameter variations. Additionally, the use of an active rectifier and adaptive DC–DC converter ensures effective energy conversion and battery charging. Overall, the proposed system provides a robust and efficient solution for maximizing extractable power in wireless charging applications compliant with modern standards such as the Qi standard.

4. SIMULATION MODEL AND RESULTS

The proposed wireless charging system using phase-shift and amplitude control demonstrates significant improvement in overall efficiency and extractable output power compared to conventional methods. Simulation and analysis results show better impedance matching, reduced losses, and enhanced power transfer capability across varying operating conditions. The approach effectively adapts to system variations, ensuring stable performance and higher efficiency over a wide power range.

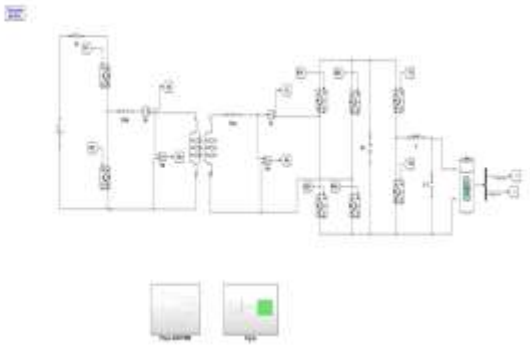

Fig 5: Schematic illustration of the key waveforms of the proposed method

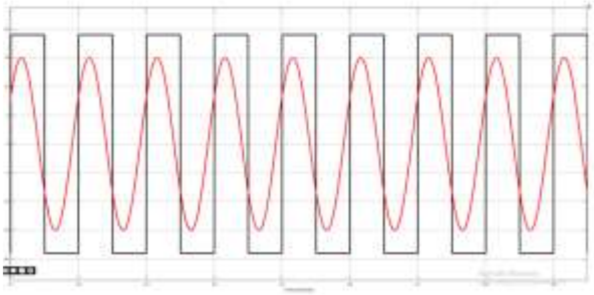

Fig. 6: Phase-shift control output showing voltage $V_L$and current $I_L$at the rectifier input using duty cycle control.

This figure illustrates the phase difference (ϕ) between voltage and current, enabling control of both resistive and reactive components. It improves power transfer efficiency and maintains stable system performance under varying load conditions.

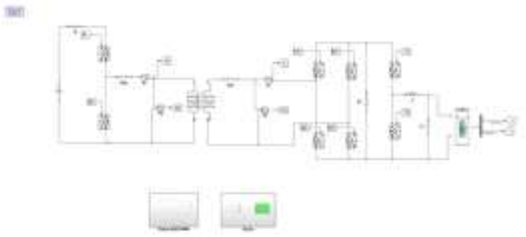

Fig 7: Schematic Illustration of the Key Waveforms Of The Proposed Method

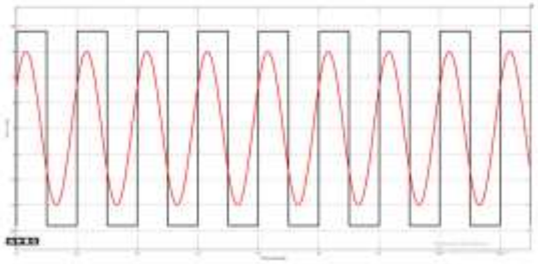

Fig 8: Phase-shift control output showing V_L and $_{IKat}$ the rectifier input with duty cycle control of Vr.

The phase difference (ϕ) between voltage and current enables control of both resistive and reactive components. This improves power transfer efficiency and ensures stable operation under varying load conditions.

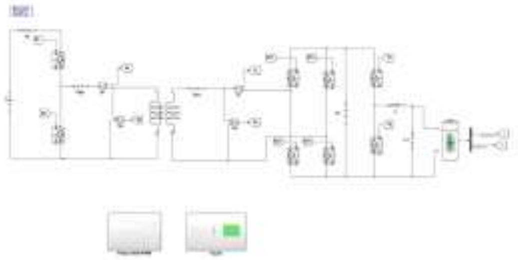

Fig 9: Schematic illustration of the key waveforms of the proposed method

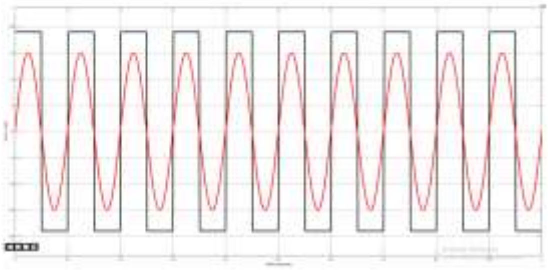

Fig: 10 Voltage V_L and current I_L at the input of the rectifier

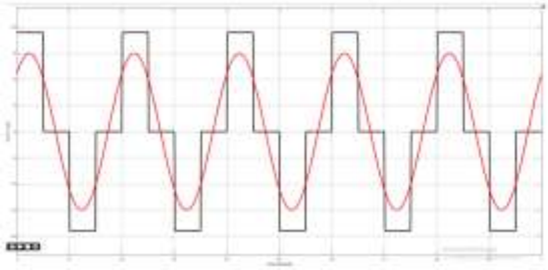

Fig 11: Extension (FOPID)

5. CONCLUSION

This study presents an effective method to optimize efficiency and enhance power transfer capability in inductive power transfer (IPT) systems. The proposed approach dynamically adjusts the equivalent load impedance using phase-shift and rectified voltage control, enabling improved system performance. At resonance, the system behaves like a synchronous rectifier with purely resistive impedance characteristics, while under off-resonance conditions; it significantly enhances performance by compensating reactive components. Simulation and experimental results based on a Qi standard compliant prototype validate the effectiveness of the proposed method. The system achieves higher efficiency across the entire operating range and increases the maximum extractable output power, particularly at lower coupling factors.

FUTURE SCOPE:

In the future, this work can be extended by incorporating intelligent control techniques such as adaptive optimization for real-time performance enhancement. Additionally, the proposed approach can be applied to high-power applications, including wireless charging systems for electric vehicles, to further improve scalability and efficiency.

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