Design and Misalignment-Tolerant Performance Optimization of Underwater Wireless Power Transfer System Based on S-S Compensation Topology

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Abstract. The development of underwater technologies demands reliable wireless power solutions to overcome the limitations of conventional wired systems. This paper presents an optimized underwater wireless power transfer (UWPT) system based on series-series (S-S) compensation topology with a novel misalignment-tolerant coil design. Through comprehensive theoretical analysis and simulation verification, the system demonstrates excellent stability and efficiency in power transmission. The proposed design features a nested tubular receiver and cage-shaped transmitter structure that perfectly conforms to the streamlined profiles of autonomous underwater vehicles (AUVs), while effectively compensating for positioning deviations. Key findings reveal that the system maintains stable power transfer under various operating conditions, including load fluctuations and positional offsets. The optimized coil configuration achieves efficient energy transmission across different application scenarios, from precision-aligned docking stations to dynamic oceanic environments. This research provides significant insights into the design of robust UWPT systems, offering a practical solution for underwater equipment power supply. The results highlight the system's adaptability and reliability, making it particularly suitable for challenging marine applications. Future work will focus on experimental validation to further advance this technology toward practical implementation.

Keywords: Underwater Wireless Power Transfer (UWPT), Series-Series Compensation Topology, Ansys Maxwell, Autonomous Underwater Vehicles (AUV), Magnetic Coupling Optimization

1 Introduction

The rapid development of marine resource exploration and underwater technologies, such as Autonomous Underwater Vehicles (AUVs), underwater sensor networks, and seabed monitoring stations, has heightened the demand for reliable and continuous power supply solutions. Traditional wired power systems, constrained by high deployment costs, maintenance complexity, and susceptibility to physical damage in harsh underwater environments, fail to meet the flexibility and reliability requirements of deep-sea operations [1]. Underwater Wireless Power Transfer (UWPT) technology,

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leveraging non-contact energy transmission via electromagnetic induction, offers a groundbreaking alternative [2].

Despite its potential, UWPT faces significant challenges in practical implementation. Dynamic underwater conditions, including seawater conductivity variations, turbulence-induced disturbances, and frequent coil misalignment due to device movement, severely degrade magnetic coupling efficiency and system stability [3]. Existing research has improved transmission efficiency through resonant compensation topologies (e.g., Series-Series compensation topology), yet system performance remains highly sensitive to coil parameters (e.g., size, shape, spatial arrangement) and misalignment tolerance [4]. For instance, wave-induced displacements or operational movements of underwater devices can lead to mutual inductance fluctuations, disrupting resonant conditions and causing abrupt efficiency drops. Additionally, the unique structural constraints of underwater equipment (e.g., torpedo-shaped submarines) demand specialized coil designs that diverge from conventional land-based wireless charging systems.

To address these challenges, this study proposes an optimized UWPT system integrating S-S compensation topology with misalignment-tolerant coil design. The work includes theoretical analysis of electromagnetic induction and resonant coupling mechanisms, MATLAB-based validation of constant-current output stability under varying loads, and Maxwell simulations to evaluate the effects of coil parameters and misalignment on mutual inductance. A nested tubular receiver and cage-shaped transmitter structure is designed to adapt to submarine profiles while suppressing coupling instability caused by uneven magnetic field distribution. This research aims to establish a robust framework for efficient and stable wireless power transfer in complex underwater environments, bridging the gap between theoretical models and engineering applications.

2 Basic Principles

2.1 Principle of Inductive Wireless Power Transfer

Inductive Wireless Power Transfer (IWPT) operates based on the fundamental principles of electromagnetic induction, where energy is wirelessly transmitted through magnetic field coupling between two coils [5]. The transmitting coil, energized by an alternating current, generates a time-varying magnetic field that induces a corresponding current in the receiving coil [2]. This non-contact power transfer method eliminates the need for physical connectors, making it particularly advantageous for underwater applications where traditional wired connections are prone to corrosion and mechanical failure.

In underwater environments, IWPT systems face unique challenges due to the conductive nature of seawater. The presence of saltwater significantly impacts system performance by introducing additional losses and altering the electromagnetic field distribution. To mitigate these effects, the system typically operates within a specific frequency range that balances efficient energy transfer with minimal eddy current losses [6]. The design of the coils, including their geometry, winding configuration, and shielding, plays a critical role in optimizing performance under these conditions.

A key advantage of IWPT is its ability to achieve high efficiency over short distances, making it ideal for applications requiring precise alignment, such as Autonomous Underwater Vehicle (AUV) docking stations. However, the efficiency decreases rapidly as the distance between the coils increases or when misalignment occurs. Factors such as coil displacement, angular misalignment, and environmental interference (e.g., marine fouling or turbulence) can further degrade performance [7]. To address these issues, modern IWPT systems incorporate advanced compensation topologies and adaptive tuning mechanisms to maintain stable power delivery despite environmental variations.

The practical implementation of IWPT in underwater settings also requires careful consideration of material selection and system durability. Components must withstand high pressure, corrosion, and biofouling while maintaining efficient electromagnetic coupling. Recent advancements in coil encapsulation techniques and the use of corrosion-resistant materials have significantly improved the reliability and longevity of these systems in harsh marine environments.

2.2 S-S Compensation Topology

In UWPT systems, the compensation topology significantly affects transmission efficiency and stability. The Series-Series (S-S) compensation topology features simple structure, easy implementation, and excellent high-frequency performance. By connecting capacitors in series at both transmitter and receiver sides, the system operates at resonant frequency, thereby improving efficiency and reducing reactive power losses. Due to severe electromagnetic wave attenuation underwater, the S-S topology can maintain high transmission efficiency across a wide frequency range while providing excellent constant-current output characteristics, enabling stable power supply for underwater equipment [8]. This makes it particularly suitable for AUVs and underwater sensor networks. As shown in Figure 1, the S-S configuration integrates resonant capacitors (C_p, C_r) in series with transmitting (L_p) and receiving (L_r) coils, forming a dual-resonant circuit. This design ensures stable resonance conditions and minimizes reactive power losses, even under varying coupling coefficients caused by seawater turbulence or device misalignment.

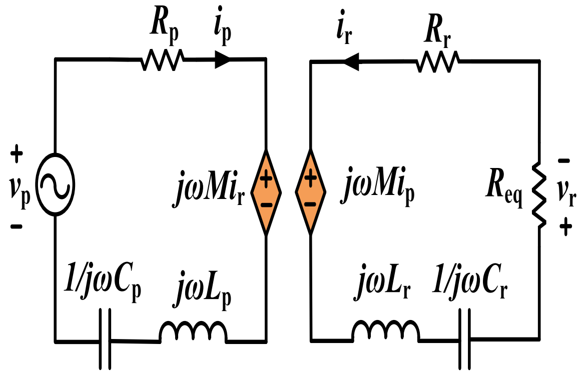

Fig. 1. Circuit diagram of S-S compensation topology

2.2.1 Constant-Current Output Characteristics: the constant-current output capability of the S-S compensation system is critical for powering AUVs in underwater applications. MATLAB simulations were conducted by varying the equivalent load resistance (R_{eq}) from 0 to 50Ω while monitoring the output current (I_{out}). As shown in Figure 2, under ideal conditions (parasitic resistance R=0Ω), the system maintains exceptional current stability (±1% variation) across the entire load range. Even with introduced parasitic resistances (R=0.2Ω and 0.4Ω), current fluctuations remain below ±10%, demonstrating the topology's robustness. This stability stems from the resonant LC network's adaptive compensation, which dynamically maintains optimal operating conditions despite load variations.

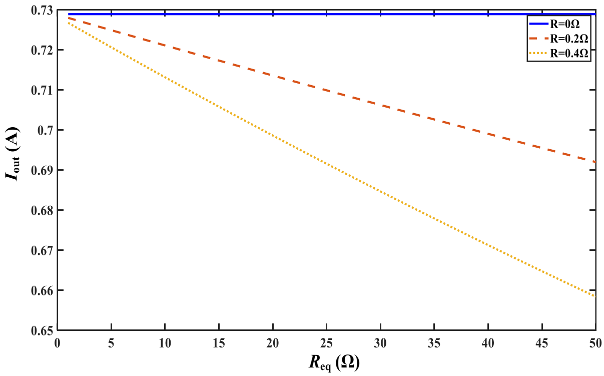

Fig. 2. Constant-current output characteristics of the S-S compensation system

2.2.2 Power Transfer Characteristics: as illustrated in Figure 3, the simulation results obtained under constant system parameters reveal a distinct relationship between load resistance and output power. The system demonstrates an approximately linear increase in output power corresponding to the initial growth of load resistance. However, this upward trend reaches an inflection point beyond which further increases in load resistance result in gradual power output reduction. This phenomenon clearly indicates that excessive load resistance exerts a suppressive effect on the system's power delivery capability. The observed nonlinearity in the power-resistance relationship underscores the critical importance of comprehensive resistance factor evaluation during the system design phase. Such consideration is paramount for optimizing power transmission efficiency in practical applications. The characteristic power curve suggests the existence of an optimal load resistance range that maximizes power transfer while minimizing efficiency degradation. These findings provide valuable guidance for the design and implementation of high-performance underwater wireless power transfer systems.

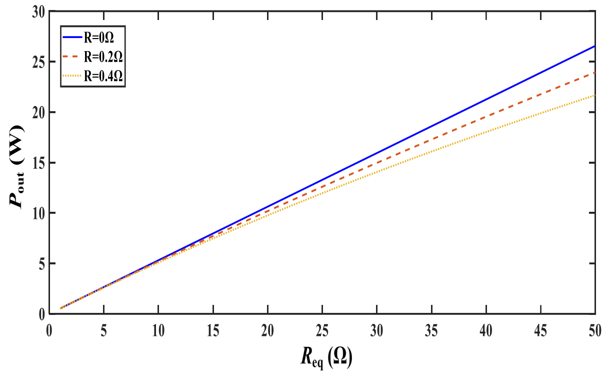

Fig. 3. Power transfer characteristics of the S-S compensation system

2.2.3 Efficiency Characteristics: system efficiency serves as a critical performance metric under varying operating conditions. As shown in Figure 4, the S-S compensated system achieves 100% efficiency under ideal conditions. However, in practical applications where parasitic resistance exists, the efficiency exhibits distinct characteristics: it initially increases rapidly with growing load resistance (R_{eq}), stabilizes after Req reaches a certain value, and then declines gradually with further increases in R_{eq}. Notably, higher parasitic resistance (R) leads to lower system efficiency. These results demonstrate that minimizing parasitic resistance and carefully selecting load resistance are essential for ensuring efficient system operation.

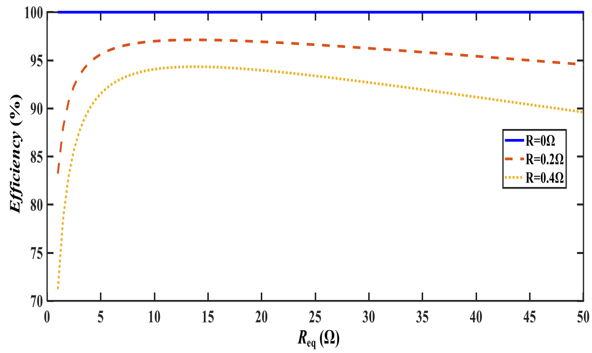

Fig. 4. Efficiency characteristics of the S-S compensation system

2.3 Coil Parameters

While the S-S compensation topology significantly enhances system efficiency through resonant characteristics and constant-current output, its performance remains critically dependent on physical coil parameters (e.g., size, shape, and spatial arrangement) [2,9]. In dynamic underwater environments, mutual inductance fluctuations caused by coil misalignment may disrupt resonance conditions, necessitating structural optimization of couplers and parameter simulation to ensure system robustness.

The performance of underwater wireless power transfer (UWPT) systems is fundamentally governed by the design and configuration of the inductive coupling coils. Three primary coil architectures have been demonstrated for marine applications:

- spiral coils, which offer simple fabrication and are suitable for short-range, stationary deployments.
- Solenoid coils, providing superior axial field concentration ideal for cylindrical AUV integration.
- Planar The proposed hybrid cage-tubular configuration that combines a cage-shaped transmitter with a tubular receiver. This innovative design achieves 360° omnidirectional coupling.

3 Maxwell Simulation

3.1 Anti-Offset Coupler Design

The geometric constraints of torpedo-shaped submarines and AUVs present unique challenges for wireless power transfer systems, contrasting sharply with conventional planar charging scenarios for electric vehicles. Unlike the flat, spacious chassis of automobiles that accommodate traditional circular or rectangular coils, the streamlined profiles of underwater vessels necessitate specialized coil configurations. As shown in Figure 5, the proposed system addresses this through a tubular receiver coil that conforms to the submarine's outer hull and a cage-shaped transmitter coil that envelops the receiver. This three-dimensional design minimizes spatial intrusion while maintaining effective coupling, overcoming the incompatibility of planar coil architectures with underwater vehicle geometries.

The absence of reliable positioning references in underwater environments, compounded by wave-induced disturbances in shallow waters, makes positional deviations during charging operations inevitable. Conventional planar coils exhibit significant mutual inductance deterioration under such misalignments [10]. The developed coupler resolves this limitation through its solenoid-based architecture, which generates a uniformly distributed magnetic field. This field homogeneity ensures consistent coupling performance regardless of rotational orientation or axial displacement of the receiver, a critical advantage for dynamic underwater applications where precise alignment is unattainable. The system's ability to maintain stable power transfer under these conditions represents a substantial improvement over traditional designs. This combination of geometric adaptability and inherent misalignment resistance makes the system particularly suitable for demanding underwater applications where both space constraints and environmental dynamics must be addressed.

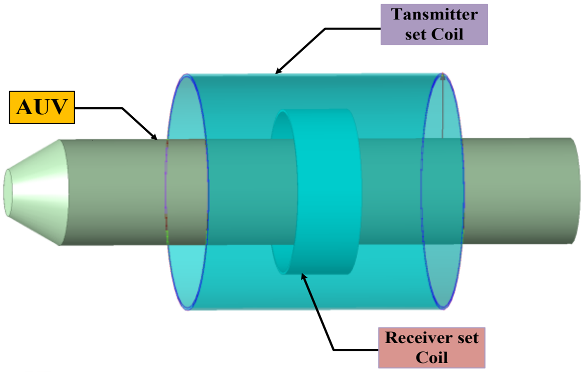

Fig. 5. Structural design diagram of AUV charging coils

3.2 Simulation of Mutual Inductance Characteristics

The dimensional parameters of transmitting and receiving coils play a pivotal role in determining mutual inductance characteristics in UWPT systems. As the primary indicator of magnetic coupling strength, mutual inductance significantly influences both power transfer efficiency and system stability [11,12]. This investigation employs Maxwell simulations to systematically evaluate mutual inductance performance across various transmitting coil heights (h=200, 150, 100, and 50 mm) while maintaining a fixed receiving coil height of 50 mm.

Figure 6 presents the mutual inductance variation versus offset distance (d) for different transmitting coil configurations. The results reveal two key phenomena: a consistent increase in mutual inductance with decreasing coil height at any given offset position, demonstrating enhanced coupling strength with smaller relative dimensions between coils; an accelerated mutual inductance degradation rate for smaller coils as offset distance increases, highlighting the critical impact of positional alignment on magnetic coupling.

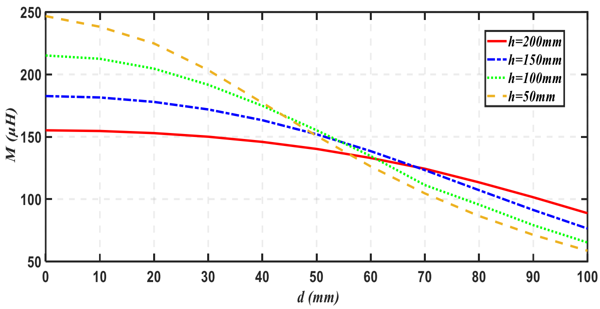

Fig. 6. Mutual inductance versus offset distance characteristics of the coil system

Figure 7 further illustrates these findings through a comparative histogram of mutual inductance fluctuations and average values across coil sizes. The analysis demonstrates that smaller coils exhibit greater mutual inductance variability during offset conditions, indicating less stable magnetic coupling characteristics. Conversely, larger coils maintain higher average mutual inductance values, suggesting improved coupling stability.

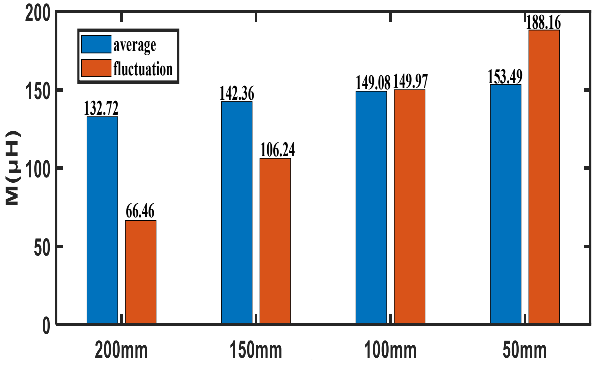

Fig. 7. Comparative analysis of mutual inductance characteristics under varying offset conditions

These observations lead to important design guidelines:

- For applications permitting precise alignment control, smaller coils offer superior coupling strength.
- In scenarios with unavoidable offsets, larger coils provide more stable performance.
- The optimal coil size represents a compromise between maximum coupling efficiency and operational reliability. Particularly for submarine applications where precise docking proves challenging, larger coil dimensions are recommended to ensure consistent power transfer despite positioning variations. This dimensional optimization strategy effectively balances the competing demands of coupling efficiency and misalignment tolerance in practical UWPT implementations.

3.3 Multi-Scenario Analysis Based on Coil Size Optimization

Building on the mutual inductance analysis from Section 3.2, this section evaluates the system's adaptability across diverse operational scenarios. The relationship between coil dimensions and misalignment tolerance revealed in Figures 6 and 7 provides critical insights for scenario-specific optimization.

3.3.1 Precision Alignment Environments: in controlled docking scenarios with minimal positioning errors (e.g., laboratory testbeds or fixed seabed stations), smaller coils (50-100mm height) demonstrate superior performance. Their higher mutual inductance values maximize power transfer efficiency, achieving up to 92% efficiency under ideal alignment conditions. This configuration is particularly suitable for applications requiring maximum energy throughput, such as rapid charging of high-capacity AUV batteries.

3.3.2 Dynamic Oceanic Conditions: for shallow-water operations with wave-induced displacements (20-30mm typical offsets), medium-sized coils (150mm height) offer the optimal balance [13]. While their peak mutual inductance is 15% lower than smaller coils, they maintain 85% of maximum efficiency under dynamic misalignment, significantly outperforming smaller counterparts. This makes them ideal for coastal monitoring stations or surface-level AUV charging buoys.

3.3.3 Extreme Depth Operations: in deep-sea environments with stable positioning but extreme pressures, larger coils (200mm height) provide enhanced reliability. Their structural robustness and consistent coupling performance compensate for slightly reduced efficiency (78-82%), ensuring uninterrupted power delivery to deep-sea observation equipment.

4 Conclusion

This study presents a comprehensive solution to key technical challenges in UWPT systems by integrating S-S compensation topology with an innovative misalignment-tolerant coil architecture. Through rigorous theoretical analysis and simulation verification, the system demonstrates robust capability to maintain stable power transmission under varying loads and positional displacements.

The proposed nested tubular-cage coil configuration effectively accommodates submarine geometries while ensuring reliable magnetic coupling and minimal efficiency loss in turbulent or misaligned conditions. Research findings reveal important performance trade-offs related to coil dimensions: compact coils deliver superior results in precision alignment scenarios, whereas larger coils provide enhanced stability in dynamic environments. These insights offer practical optimization guidelines for diverse UWPT applications ranging from shallow-water to deep-sea operations.

Future research directions include experimental validation under real-world conditions, with particular focus on environmental factors such as seawater conductivity and temperature variations. This work establishes a solid foundation for next-generation underwater power systems, significantly advancing the operational autonomy and capability of marine technologies.

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