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Finite Element Analysis and comparison of Split Core Transformer and Planar Spiral Coil Topologies for Underwater Wireless Power Transfer.

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***Abstract*— This paper presents a comparative analysis of two inductive wireless power transfer (IWPT) topologies, focusing on their application in underwater environments. The study compares the widely used planar spiral coil with an innovative split core transformer topology, employing finite element simulations to evaluate their performance, advantages, and disadvantages in near-field applications and underwater settings. The research addresses the challenges associated with underwater wireless power transfer (UWPT), such as misalignment, radiation losses, and high-pressure conditions. Different coil topologies are discussed, with an emphasis on their design considerations for efficient power transfer underwater. The study includes an overview of the IWPT circuit and design considerations for the underwater environment. Finite element method (FEM) studies are conducted for both planar spiral coils and split core transformers, assessing their efficiency, separation tolerance, and performance under increasing frequencies. The results highlight the strengths and limitations of each topology, providing valuable insights into their respective viabilities for underwater applications.**

Keywords— Underwater Wireless Power Transfer, Electromagnetic induction, Resonant Converters, Split core transformer, planar spiral coils

I. Introduction

The adoption of wireless power transfer (WPT) technologies is becoming widespread, particularly for charging applications like mobile phones, electric vehicles on land, and biomedical equipment [1]. Currently, there is ongoing research into applying this technology in underwater scenarios, such as charging underwater sensors and autonomous underwater vehicles (AUVs) [2]. This shift holds significant potential as it provides a means to power devices underwater, enhancing their operational efficiency and stability. Additionally, it reduces dependence on conventional charging methods, which often require the removal of these devices from the ocean environment for charging or battery replacement. This transformative technology holds great promise for underwater operations, including scientific exploration and various industrial tasks.

Several wireless power transfer methods exist, with inductive wireless power transfer (IWPT) being one of the most widely used for power charging. It utilizes time-varying electromagnetic fields for energy transfer between coils. WPT can be tightly or loosely coupled (Figure 1), providing a reliable option for near or medium distances underwater applications. Generally, the system's antenna inductance is resonated with capacitances to enhance the power transfer. In addition to this method, other approaches are used for different applications: capacitive, ultrasonic and optical wireless power transfer [2]. Capacitive wireless power transfer involves charging devices through an electric field. Ultrasonic WPT proves effective for transferring low-power signals by using ultrasounds. Optical wireless power transfer, relying on light for low-power transmission, presents a potential solution for precise underwater applications.

Within this context, this study will specifically focus on near-field wireless power transfer applications. It aims to compare circular planar spiral coil topologies with an innovative proposal, namely split core transformers (SCT). The primary objective is to assess and address the challenges of power transfer underwater through finite element simulations. The study will evaluate their viability and potential applications in an underwater setting by studying the devices in a finite element method software.

II. IWPT overview and design considerations

A. IWPT circuit.

Figure 2 showcases the Series-Series (SS) Inductive Wireless Power Transfer (IWPT) Converter. It comprises a full bridge inverter, transmitter (T_x) and receiver (R_x) resonant tanks, a diode bridge rectifier, and a battery. The full bridge inverter transforms DC into controlled high-frequency AC current in the form of a square wave at the resonant frequency required by the resonant tanks optimize power transfer efficiency. The diode bridge rectifier converts the received AC to DC to charge the battery.

The resonant tanks are a key part in any IWPT applications. Series or parallel resonant tank topologies are commonly used. On the receiver tank, series is preferable for lower load values and parallel for larger loads [3]. Other topologies like LLC or LCC have also been proposed in the literature for IWPT [4], [5]. In this study, the LLC topology has been selected for the SCT configuration to make it work as a regular LLC power supply, while the planar spiral coil is configured in a series-series arrangement.

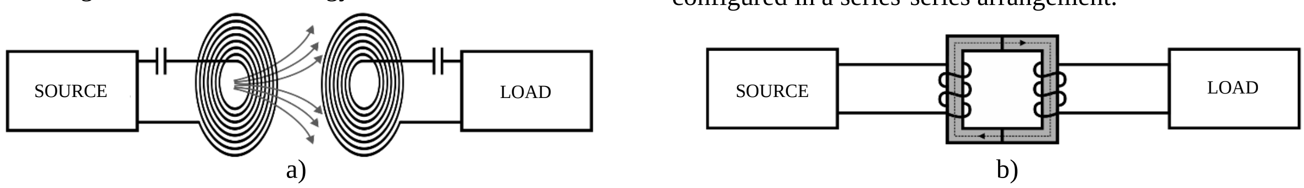
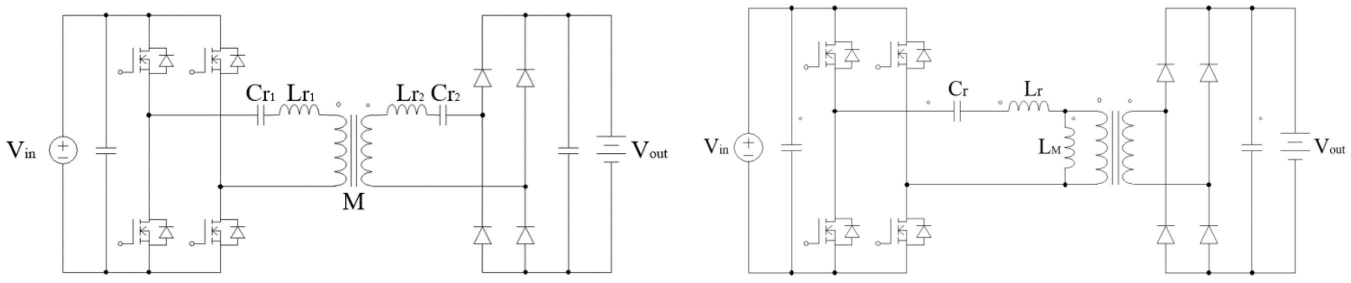


Figure 1. a) Loosely coupled IWPT diagram. b) Tightly coupled IWPT diagram.



a) b)

Figure 2. a) Series-Series IWPT electrical circuit. b) LLC IWPT electrical circuit.

In both cases, First Harmonic Approximation (FHA) has been employed to simplify the characterization of resonant tanks. This method involves considering only the first harmonic of the square wave in the calculation of the resonant frequency [6]. In series and LLC topologies, has a resonant frequency at:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \; [Hz] \tag{1}$$

Where L_r is the resonant inductance (H) and C_r (F) the resonant capacitance.

The main distinction between these topologies is that in the SS topology, the magnetizing inductance is much larger than the inductance of the resonant inductor, while the magnetizing inductance in LLC converter is around 3 to 8 times the resonant inductance [7], which is the leakage inductance of the coil got by introducing a small air gap in the transformer.

B. Design considerations underwater

The efficiency of underwater wireless power transfer (IWPT) systems faces significant challenges in the underwater environment. One primary concern is the misalignment between the transmitter and receiver caused by ocean currents [2], which can lead to increased losses in the conductive medium. Moreover, as the distance between the transmitter and receiver increases underwater, radiation losses become significant [8]. Electromagnetic waves spreading through the water result in higher energy dissipation. Eddy current losses introduce another layer of complexity to IWPT in underwater environments. The circulating currents induced by electromagnetic fields contribute to additional losses, reducing the overall efficiency of power transfer.

Additionally, communication becomes challenging in underwater environments. The conductive nature of water, combined with potential misalignments and radiation losses, makes establishing and maintaining a reliable communication link challenging. In addition to these concerns, the high-pressure conditions prevalent in underwater environments pose a substantial threat to the structural integrity and functionality of IWPT devices [2]. Designing devices capable of withstanding these pressures is essential to ensure their reliability and long-term operation.

C. Coil topologies

There are two main coil topologies: planar spiral coils and coaxial coils. An example of these is depicted in Figure 3. Planar spiral coils are a widely adopted topology in UWPT

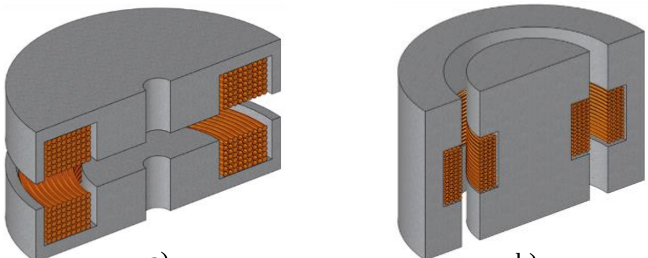
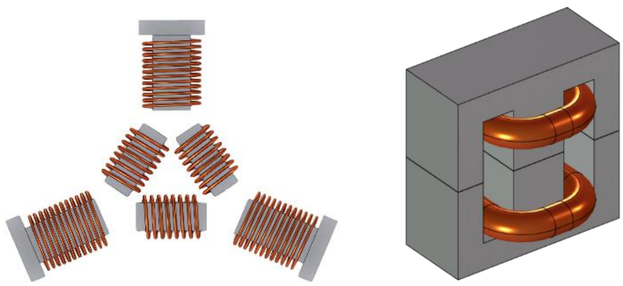

a) b)

Figure 3. a) Planar Spiral Coil. b) Coaxial coil.

systems due to their efficient and compact design. These coils consist of a flat, spiral-shaped conductor that is laid out in a planar configuration. The design offers advantages such as ease of fabrication and a relatively large surface area, contributing to enhanced coupling efficiency. Planar spiral coils are suitable for applications with space constraints, as they can be easily integrated into various underwater devices.

Coaxial coils, with their concentric arrangement of conductors, represent another key topology. In this configuration, an inner conductor is surrounded by an outer conductor, forming a coaxial structure. The outer and inner conductors serve as the transmitter and receiver coils, with the inner coil placed in the AUV and the outer coil in the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docking platform where the device is charged.

Figure 4. a) Three-phase multi-coil [12] b) SCT topology.

Several other topologies have been proposed in the literature to improve different aspects of UWPT. Arc shaped coils are an option that combine planar and coaxial topologies to get a converter that is easily integrated in the AUV and less sensible to misalignment [9], [10]. Self-latching coils are a proposal that try to maintain the coil always in the optimal position to reduce losses [11]. Finally, multicoil arrangements (Figure 4a) have the potential to reduce dissipation losses due to misalignment and could allow the parallel charge of several AUV [12].

III. FEM STUDIES AND RESULTS

A. General choices

The study was conducted for three different topologies and was focused on the effects in efficiency of distance between T_x and R_x and frequency variations. To compare the topologies equally, all the coils were tested at a 0.3 T saturation flux density, as ferrite materials usually have a saturation value between 0.3-0.45 T [13]. To achieve this, the current was modified for each measurement to equal the saturation current:

$$I_{sat} = \frac{(B_{sat} \cdot A_e)}{\sqrt{(A_L \cdot L)}} [A] \quad (1)$$

Where I_{sat} is the saturation current, B_{sat} is the saturation flux (T), A_e core effective area (m^2), L the inductance (H) and A_L the inductance per turns^2 ($\frac{H}{N^2}$).

The FEM model had some common parameters to all topologies, presented in Table I. The study was conducted as an electromagnetic model, including a simplified series-series circuit for the spiral coils Figure 5 and LLC circuit for the SCT. Both models were based on FHA. The test was conducted for 100-1000 kHz. The capacitances were readjusted for each frequency to always keep resonance.

Table I. FEM model parameters.

Parameter	Seawater	Copper	Ferrite
Relative permeability	1	1	5000
Relative permittivity	80	1	1
Conductivity (S/m)	5.5	$6 \cdot 10^7$	$1 \cdot 10^{-6}$

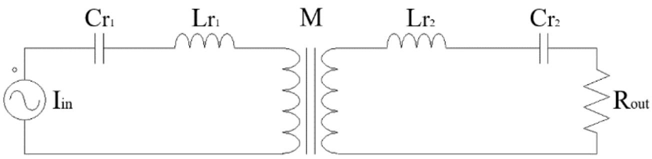

Figure 5. FHA of a SS resonant circuit.

B. Regular planar spiral coil

The planar spiral coil was constructed using a 200W WPT development kit from Infineon and Würth Elektronik [14]. Modeled as a multiturn coil, its geometry is depicted in Figure 6, and its parameters are provided in Table II.

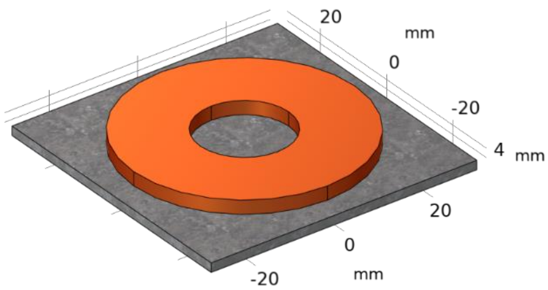

Figure 6. Planar spiral coil geometry for FEM simulation.

Table II. COMSOL model coil geometry.

Turns	Extern. Ø	Intern. Ø	Coil thickness	Ferrite lenght	Ferrite thickness
20	25 mm	10 mm	3 mm	60 mm	2 mm

The model was tested 0, 10, 20 and 40 mm distance. The following results were obtained for 250 kHz and 0 mm (Figure 7) and 250 kHz and 10 mm (Figure 8).

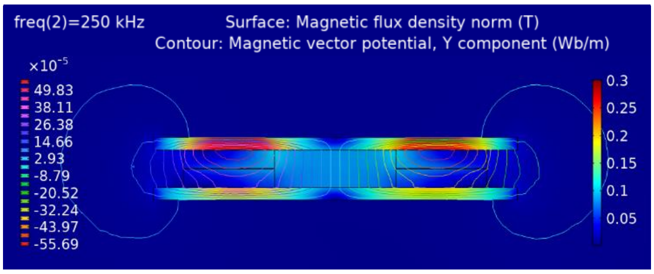

Figure 7. Planar spiral coil: FEM results for 250 kHz and 0 mm.

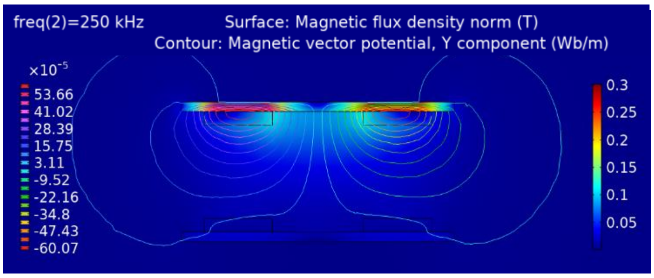

Figure 8. Planar spiral coil: FEM results for 250 kHz and 10 mm.

For all the distance and frequency values, the power transfer efficiency was computed, with a maximum power value around 570 W at a flux density of 0.3 T. The efficiency curves in Figure 9 were obtained.

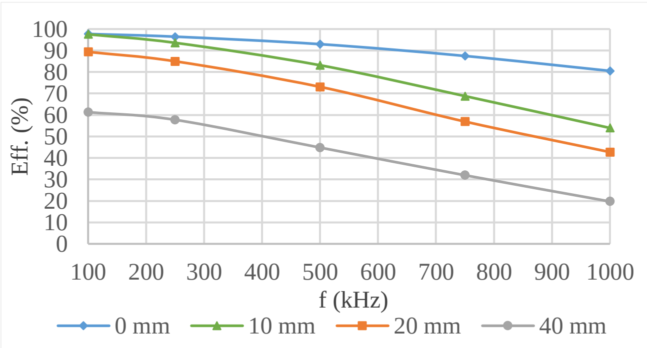

Figure 9. Planar spiral coil study: efficiency values.

The device kept an efficiency over 85 % for 100 kHz and 250kHz frequency values below 40 cm distance. In all cases, the efficiency was reduced for higher frequency values.

C. Enclosed planar spiral coil

The same coil was tested but enclosed in the ferrite core as depicted in Figure 10.

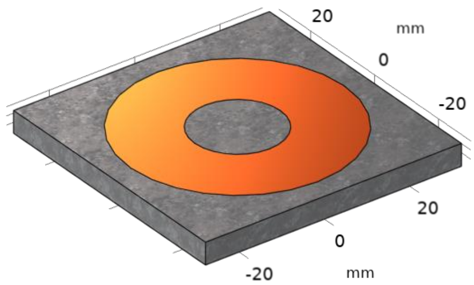

Figure 10. Enclosed planar coil geometry for FEM simulation.

The model was tested 0, 10, 15 and 20 mm distance. The following results were obtained for 250 kHz and 0 mm (Figure 11) and 250 kHz and 10 mm (Figure 12).

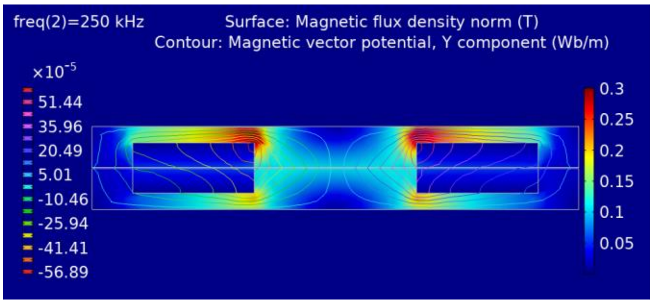

Figure 11. Enclosed coil: FEM results for 250 kHz and 0 mm.

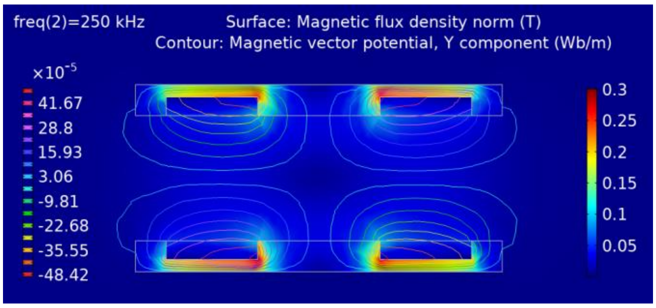

Figure 12. Enclosed coil: FEM results for 250 kHz and 10 mm.

For all the distance and frequency values, the power transfer efficiency was computed, with a maximum power value around 256 W at a flux density of 0.3 T. The efficiency curves in Figure 13 were obtained.

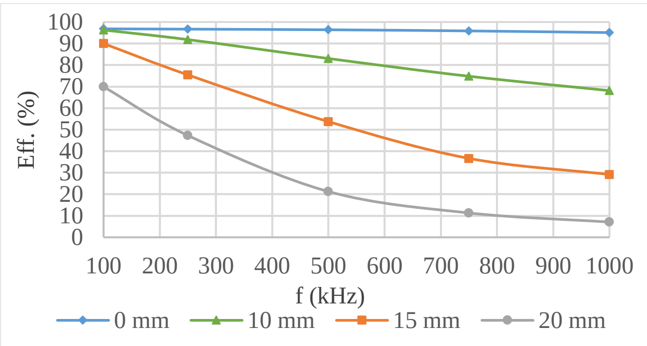

Figure 13. Enclosed coil study: efficiency values.

When the device was tightly coupled at 0 mm, the device kept a very high efficiency (around 95 %) for all frequency values. In the rest of the cases, efficiency dropped when frequency was increased. The efficiency was maintained for 100 kHz and 250 kHz at 0 and 10 mm distance. When the separation was increased over 15 mm, efficiency started to drop for frequencies over 250 kHz and for 20 mm separation efficiency is relatively low even for 100 kHz.

D. *Split core transformer*

The SCT topology was built based on a regular transformer, featuring two E-shaped cores as illustrated in Figure 4b. The transformer model was tested in two conditions: first, with the full coil immersed in seawater, and second, with a portion of the core exposed while the winding remained inside an air recipient. Each of the coils had a single spire, and the measurements for their cores are depicted in Figure 14.

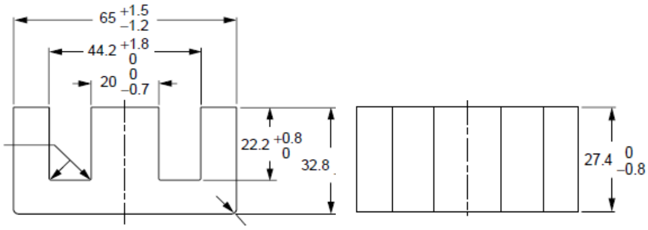

Figure 14. Measurements of one split core.

The model was only tested for 0 and 10 mm distance, as it already showed a great reduction in efficiency. The following results were obtained for 250 kHz and 0 mm and 250 kHz and 10 mm in direct underwater connexion and inside a recipient (Figure 15-Figure 18).

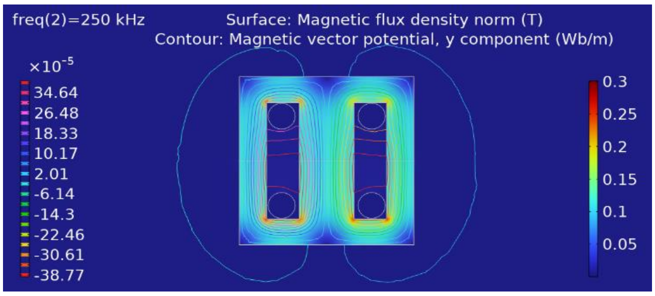

Figure 15. SCT in air: FEM results for 250 kHz and 0 mm.

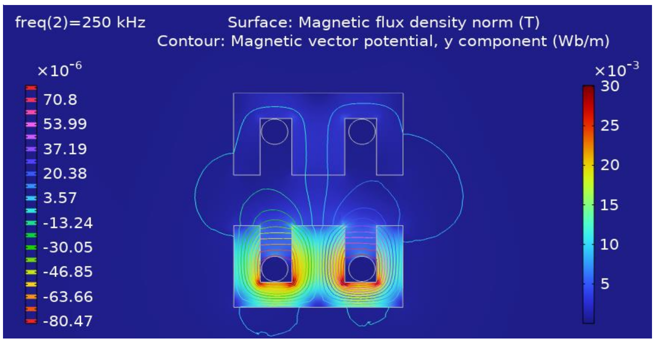

Figure 16 SCT in air: FEM results for 250 kHz and 10 mm.

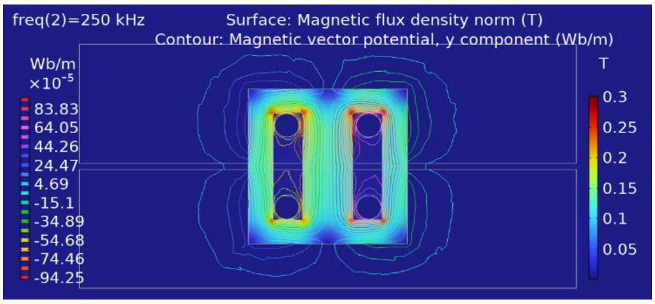

Figure 17. SCT in seawater: FEM results for 250 kHz and 0 mm.

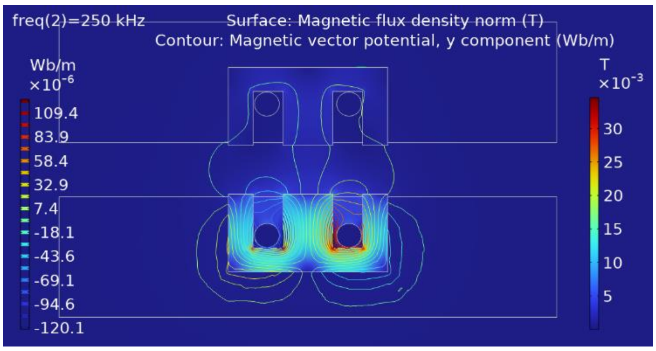

Figure 18. SCT in seawater: FEM results for 250 kHz and 10 mm.

For all the distance and frequency values, the power transfer efficiency was computed. The maximum power value in 0 mm was around 1059 W in seawater and 1447 W in air. When the distance was increased to 10 mm, power was very low, up to 36 W, as the WPT link was highly reduced.

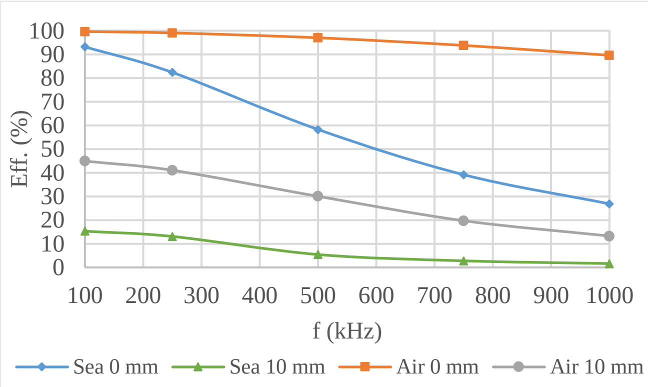

Figure 19. SCT study: efficiency values.

As presented in Figure 19, efficiency was kept over 90 % for all the frequency values if the device was kept inside the recipient and with a 0 mm separation. In direct seawater connection, the efficiency was only over 90 % for 100 kHz and then quickly dropped. In both cases, the device should be very firmly coupled to be able to transfer high power at high efficiency.

IV. Comparison of FEM results

To compare all the results, the maximum power reached for each topology at 0 mm is presented in Table III. In this case, the split core transformer in air was the optimal topology as it could transfer up to 1447 W, while the enclosed spiral coil reached saturation for low power values around 254 W.

Table III. Maximum Tx power for different FEM studies.

Topology	Spiral	Enclosed	SCT Sea	SCT Air
P_{out} (W)	570	254	1059	1447

In Figure 20, the efficiency of all the topologies is compared for a 0 mm separation. All the topologies could maintain an efficiency over 90 % for 100 kHz. Additionally, the enclosed coil and the SCT inside the air recipient could keep an efficiency over 90 % for all frequency values. On the other hand, the SCT in a seawater environment was not able to maintain an operation at higher frequencies than 100 kHz.

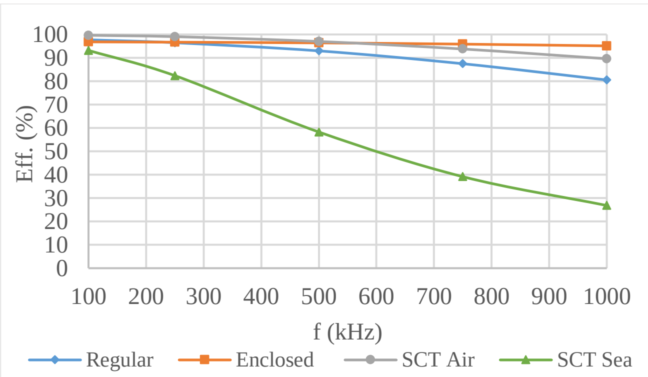

Figure 20 FEM studies: efficiency comparison at 0 mm.

In Figure 21, the efficiency of all the topologies is compared for a 10 mm separation. Both planar topologies could maintain an efficiency over 90 % for 100 kHz and 250 kHz. In the case of SCT, such a small separation significantly reduced efficiency, showing the requirement of a very precise operation. However, the only topology capable of tolerating separations up to 20-40 mm was the regular planar topology, making it the most separation-tolerant among those tested.

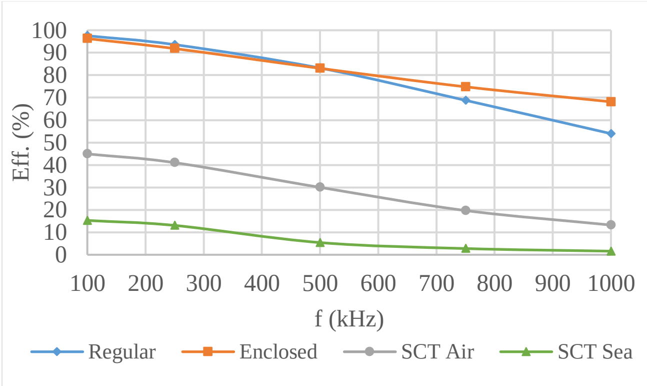

Figure 21. FEM studies: efficiency comparison at 10 mm.

To consolidate the findings discussed in this section, Table IV is presented.

Table IV. FEM studies: summary of all the results.

Study	Separation tolerance	High freq. operation	Maximum power
Spiral coil	High	Medium	Medium
Enclosed coil	Medium	High	Low
SCT Sea	Low	Low	High
SCT Air	Low	High	High

V. Conclusion

The comparative analysis of planar spiral coils and split core transformers for underwater inductive wireless power transfer (IWPT) underscores some of the required considerations in designing efficient systems for underwater environments. The study revealed distinctive characteristics and trade-offs associated with each topology, offering valuable insights for the development of robust and effective underwater wireless power transfer systems.

The planar spiral coil demonstrated notable separation tolerance and efficiency, particularly in lower frequency ranges. However, limitations arise in terms of maximum power transfer efficiency. Extending the core allowed for higher frequency operation but further compromised maximum power. On the other hand, the split core transformer exhibited the highest efficiency when tightly coupled and fully isolated, achieving maximum power transfer values over 1 kW. However, its performance proved highly sensitive to separation distances, requiring precision in alignment, and a robust attachment. In any case, for separations beyond 40 mm, none of the devices exhibited sufficient efficiency, emphasizing the importance of designing devices to operate as tightly as possible.

As underwater wireless power transfer continues to gain importance for devices like Autonomous Underwater

Vehicles (AUVs), this comparative study provides valuable insights. Future work should concentrate on refining these topologies, addressing their respective limitations, and subjecting them to experimental setups, particularly in the case of SCT, given its novel approach to underwater wireless power transfer.

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