

Physical-Layer Security and Efficiency in Wireless Power Transfer: A Simulation-Based
Comparative Study of Self-Resonant Coil Geometries

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1. Description of the International Research Internship

1.1 Host Institution

The international research internship was carried out at École de technologie supérieure, a public engineering institution located in Montreal, Quebec, Canada. Is part of the Université du Québec network. Founded in 1974, ÉTS was created to address the growing need for engineers with strong practical and technological training capable of contributing to the technological and economic development of Québec [2].

The creation of ÉTS took place during Québec’s Quiet Revolution, when influential actors from business and industry promoted the establishment of a university institution dedicated to technology-oriented engineering education [2]. Since then, ÉTS has established itself as one of the leading engineering schools in Québec and Canada, ranking first among engineering faculties in Québec and second in Canada [2].

According to its institutional mission, “*École de technologie supérieure is dedicated to university education and research in applied engineering and technology for the technological and economic development of Québec. As part of our mission, and in conjunction with industry, we place special emphasis on co-operative education, applied research, and technology transfer*” [2].

The institution also maintains a strong collaborative research ecosystem. According to ÉTS, 60% of its research activities are conducted in collaboration with local, national, and international organizations and businesses, and more than 1,200 companies offer internships and academic collaborations each year [2]. In addition, ÉTS ranks fourth among Canadian universities in research intensity, reflecting its strong focus on applied and industry-oriented research [2].

1.2 Research Area or Laboratory

The research internship was in the Power Electronics and Industrial Control Research Group (GRÉPCI). GRÉPCI is a research group focused on applied research in collaboration with

industrial and academic partners in the fields of power electronics, renewable energy, smart systems, industrial control, simulation, and advanced electrical systems.

The research conducted during the internship was strongly connected to the group's research areas, particularly those related to power electronics, electromagnetic simulation, and modelling. The project focused on the simulation-based analysis of self-resonant coils for wireless power transfer (WPT) systems, including the evaluation of physical-layer security, efficiency, magnetic field leakage, and robustness under different operating scenarios.

As part of the research activities, electromagnetic simulations and comparative analyses were performed using ANSYS Maxwell, a software environment available through the laboratory infrastructure. In addition, simulation datasets were generated and processed for subsequent statistical and numerical analysis. The interdisciplinary and applied-research environment provided by GRÉPCI offered an appropriate framework for the development of advanced simulation methodologies and data-driven engineering analysis.

2. Objective and Justification of the Internship

2.1 General Objective

Investigate the trade-off between physical-layer security and efficiency in WPT systems through a simulation-based comparative study of self-resonant coil geometries, applying statistical and numerical methods to analyze the impact of different operating scenarios on system performance.

2.2 Specific Objectives

- Investigate the state of the art in physical-layer security for inductive WPT systems and self-resonant coil design, identifying gaps in the comparative analysis of geometries.
- Develop and validate simulation models of circular, octagonal, and figure-8 self-resonant coils in ANSYS Maxwell under equivalent operating conditions to enable consistent comparative analysis.

- Perform a simulation based comparative study under three scenarios: intruder, field leakage, and misalignment. Generating structured datasets of efficiency, siphoned power, leakage indices, and frequency shifts.
- Apply statistical analysis and numerical methods to the simulation datasets, including regression models to capture efficiency trends under misalignment, analysis of variance to test whether differences in efficiency across geometries are statistically significant, variance analysis to assess robustness under perturbations, interpolation and numerical integration to quantify field leakage, and multi-objective analysis to identify trade-offs between efficiency and security.

2.3 Justification

The internship allowed the integration of knowledge from Electronic Engineering and Applied Mathematics and Computer Science. From the engineering perspective, the project involved electromagnetic modelling, power electronics concepts, and WPT systems. From the computational and mathematical perspective, the work required data processing, statistical analysis, numerical methods, and multi-objective analysis techniques to evaluate efficiency–security trade-offs under different operating scenarios.

In addition to the technical aspects, the internship provided valuable experience in the research process itself, including problem formulation, methodology design, simulation planning, analysis of results, and scientific documentation. The interdisciplinary nature of the project contributed to the development of analytical thinking, problem-solving skills, and applied research competencies within an international academic environment.

3. Technical and Conceptual Framework

3.1 Technical Framework

Wireless Power Transfer (WPT) refers to the transmission of electrical energy without direct conductive contact between a power source and a load. Among the different WPT approaches, magnetic resonant coupling has become one of the most relevant for medium-range and high-

efficiency applications, particularly in systems where transmitter and receiver coils are tuned to operate at the same or similar resonant frequency. This principle allows energy to be exchanged through oscillating magnetic fields, making WPT suitable for applications such as electric vehicle charging, biomedical devices, industrial systems, and consumer electronics [6], [8].

In resonant inductive WPT systems, the performance of the link depends strongly on the electromagnetic interaction between the transmitter and receiver coils. Parameters such as inductance, resistance, coupling coefficient, resonant frequency, and quality factor influence the amount of power that can be transferred and the overall efficiency of the system. In self-resonant coils, the geometry of the conductor contributes directly to the electromagnetic behavior of the system, since the coil structure determines not only its inductive properties but also its distributed capacitive effects. Therefore, the design of the coil is not only a geometric decision, but a key factor in the electrical and magnetic response of the WPT link.

Circular coils are widely used due to their geometric simplicity, symmetry, and ease of implementation. However, alternative geometries have also been studied to improve field distribution, coupling stability, and spatial performance. In this context, octagonal coils represent an intermediate geometry between circular and polygonal structures, while figure-8 coils introduce two magnetically related lobes that can modify the spatial distribution of the magnetic field. Related bipolar and double-D structures have been studied in the WPT literature because of their potential to improve lateral tolerance and field shaping, although they may also introduce additional design complexity [6], [7]. Since this project focuses specifically on circular, octagonal, and figure-8 self-resonant coils, these geometries provide the technical basis for comparing how coil shape affects the behavior of WPT systems.

Figure-8 coils have been investigated for their effect on coupling behavior, voltage and current response, and lateral displacement performance in WPT systems [7]. These characteristics make figure-8 geometries relevant for comparative studies where the objective is not only to evaluate maximum efficiency, but also to understand how the magnetic field is spatially distributed by different coil shapes.

3.2 Conceptual Framework

- **Physical-Layer Security:** Refers to the ability to control and limit undesired electromagnetic interactions during power transmission. [5].
- **Power Transfer Efficiency:** Represents the ratio between the power successfully delivered to the receiver and the total transmitted power. Efficiency is strongly influenced by factors such as coil geometry, magnetic coupling, resonant conditions, operating frequency, and alignment between transmitter and receiver coils [6], [8].
- **Magnetic Field Leakage:** Is the portion of the electromagnetic field that extends beyond the intended power transfer region. Leakage fields may contribute to unwanted electromagnetic exposure, interference, or unintended energy transfer outside the desired coupling area [3].
- **Receiver Misalignment:** Occurs when the transmitter and receiver coils are displaced relative to each other. In resonant inductive WPT systems, misalignment can reduce magnetic coupling, modify field distribution, and decrease overall system efficiency [6], [7].
- **Robustness:** Describes the ability of a WPT system to maintain stable performance under variations or perturbations in operating conditions.
- **Unintended Receiver / Intruder:** Is an external conductive or resonant element capable of interacting with the magnetic field generated by a WPT system. Such interactions may alter the electromagnetic behavior of the system or extract part of the transmitted energy through unintended coupling mechanisms.
- **Performance Metrics:** Quantitative indicators used to evaluate the behavior of WPT systems under specific operating conditions.

- Comparative Analysis: Systematic evaluation of different system configurations under equivalent operating conditions.
- Simulation-Based Evaluation: Consists of analyzing the behavior of electromagnetic systems using computational modelling tools. [1].
- Multi-Objective Analysis: Involves the simultaneous evaluation of multiple performance criteria that may present conflicting behaviors.

4. Description of the Problem or Research Topic

4.1 Background and Context

Research on WPT systems has expanded considerably during the last decade due to the growing demand for flexible and contactless energy transfer technologies. Resonant inductive coupling has become one of the most widely studied WPT approaches because of its ability to achieve efficient power transfer while operating over moderate transmission distances [6], [8].

Conventional circular coils are commonly used in resonant inductive WPT systems because of their geometric simplicity and symmetric magnetic field distribution. However, alternative geometries have been investigated to improve specific electromagnetic characteristics such as coupling stability, tolerance to displacement, and spatial field distribution. Bipolar and figure-8 related structures have attracted attention in the literature due to their ability to modify magnetic field patterns and improve lateral performance under certain operating conditions [3], [7]. Although these configurations may also introduce additional design complexity and different electromagnetic trade-offs [3].

4.2 Problem Statement

Recent research has highlighted the importance of electromagnetic field management in WPT systems. The geometry of the transmitter and receiver coils plays a fundamental role in determining magnetic field distribution, coupling behavior, and power transfer efficiency. As

a result, the design of coil geometries has become an important research topic in the development of high-performance WPT systems.

Topics such as magnetic field leakage, unintended electromagnetic interactions, shielding techniques, and robustness under perturbations have become increasingly relevant as WPT systems are considered for larger-scale and higher-power applications [5], [3]. These concerns are important in this study related to physical-layer security, where the spatial distribution of electromagnetic fields may influence both system efficiency and susceptibility to unintended interactions.

Although previous studies have investigated efficiency improvement, field shaping, shielding, and misalignment tolerance independently, fewer works have addressed the combined influence of coil geometry. By analyzing circular, octagonal, and figure-8 coils within a unified framework, this work contributes to a broader understanding of the trade-offs that may exist between efficiency, robustness, and electromagnetic field distribution in WPT systems.

5. Methodology

5.1 Simulation Environment and Model Setup

5.1.1 Software and Tools

The electromagnetic simulations used during this research internship were ANSYS Electronics, specifically the Maxwell environment for the analysis of inductive coupling, magnetic field behavior, and resonant structures.

Different simulation setups were employed throughout the project, including magnetostatic and eddy current analyses. Magnetostatic simulations were used mainly for the visualization and qualitative evaluation of magnetic flux density distributions, while eddy current simulations were employed to extract quantitative electrical and electromagnetic parameters such as coupling coefficient, impedance behavior, induced losses, and efficiency-related indicators under different operating scenarios.

The simulation workflow also incorporated MATLAB and Python for data processing, statistical analysis, numerical post-processing, and multi-objective evaluation. MATLAB scripts were used to compute derived metrics related to robustness, field leakage, interpolation-based analyses, and Pareto representations. Python was employed for dataset preprocessing, statistical validation, and hypothesis testing, including normality analysis, variance analysis, and comparative statistical evaluation across geometries.

All simulations and post-processing stages were organized through structured datasets generated from the electromagnetic models, enabling reproducible comparative analyses under equivalent operating conditions.

5.1.2 Coil Geometry Design

Three self-resonant coil geometries were designed and evaluated during the development of this project: circular, octagonal, and figure-8. The geometries were selected to compare different magnetic field distributions and coupling behaviors under equivalent WPT operating conditions. All electromagnetic models were developed using copper conductors embedded within a surrounding air domain to allow the propagation and visualization of the magnetic field generated by the resonant structures. The dimensions of the air domain were selected to minimize boundary effects and avoid artificial field distortions during the simulations.

To ensure a fair comparative analysis, the geometries were designed under comparable operating conditions, including equivalent excitation frequency, similar transfer distances, and consistent electromagnetic simulation environments. The models were developed directly in ANSYS Maxwell, where the geometrical parameters of each structure were adjusted iteratively to obtain stable resonant behavior and comparable coupling conditions.

The circular geometry was used as a baseline reference due to its widespread use in conventional inductive WPT systems. The octagonal geometry was introduced as a polygonal alternative intended to modify magnetic field distribution while preserving a similar overall structure. Finally, the figure-8 geometry was incorporated because of its

magnetic behavior and its relevance in previous studies related to field confinement, misalignment response, and security-oriented WPT analysis.

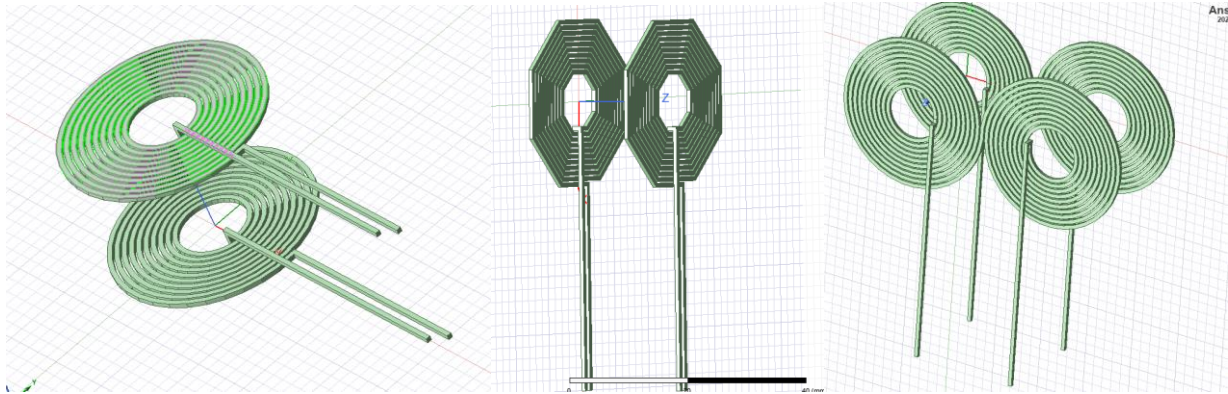


Figure 5.1. Self-resonant coil geometries: (a) circular configuration, (b) octagonal configuration, and (c) figure-8 configuration.

5.2 Resonance Calibration and Model Validation

5.2.1 Frequency Sweep and Resonance Identification

Frequency sweep analyses were performed in ANSYS Maxwell using the Eddy Current solver to evaluate the electromagnetic behavior of each coil geometry across different operating frequencies. The sweeps allowed the identification of resonance regions and the extraction of electrical quantities associated with inductive WPT performance.

During the simulations, parameters such as inductance, reactance, impedance magnitude, and magnetic coupling behavior were monitored as functions of frequency. These analyses were used to verify the consistency of the electromagnetic responses and to identify operating regions where stable resonant behavior could be achieved for each geometry.

The resonance identification process was conducted iteratively, combining electromagnetic simulation results with post-processing analysis of the extracted datasets. The selected operating region for the comparative study was centered near 100 kHz, which enabled

comparable operating conditions among the circular, octagonal, and figure-8 self-resonant coil configurations.

5.2.2 Geometry Adjustment for Comparable Conditions

After identifying the resonance regions of each configuration, the geometrical parameters of the coil models were adjusted iteratively to obtain comparable operating conditions across the different WPT structures.

The adjustment process involved modifications to coil dimensions, number of turns, and structural proportions. These adjustments were performed while maintaining equivalent excitation conditions, simulation environments, and operating frequency ranges throughout the study.

5.3 Definition of Study Scenarios

5.3.1 Intruder Scenario (Power Siphoning)

The intruder scenario was designed to evaluate the susceptibility of the WPT link to unintended electromagnetic coupling with external conductive structures. In this scenario, an additional coil acting as an unintended receiver, referred to as the intruder, was introduced near the primary TX–RX system to analyze power siphoning effects and security-related perturbations in the wireless link.

Two intruder configurations were considered during the simulations: a passive intruder and an active intruder. In the passive configuration, the intruder coil was not externally excited and interacted with the system only through induced electromagnetic coupling. In the active configuration, the intruder was modeled as an externally excited conductive structure, allowing the evaluation of stronger perturbation and interference conditions within the WPT system.

The simulations were performed using the Eddy Current solver in ANSYS Maxwell under equivalent operating conditions for the circular, octagonal, and figure-8 geometries. A distance parameter was introduced to control the relative position between the intruder and

the primary wireless power transfer link, enabling the generation of comparative datasets under different coupling conditions.

This electromagnetic and power-related quantities were extracted during the simulations, including transmitted power, power received by the intended receiver, power coupled toward the intruder, magnetic field distributions, and efficiency-related indicators.

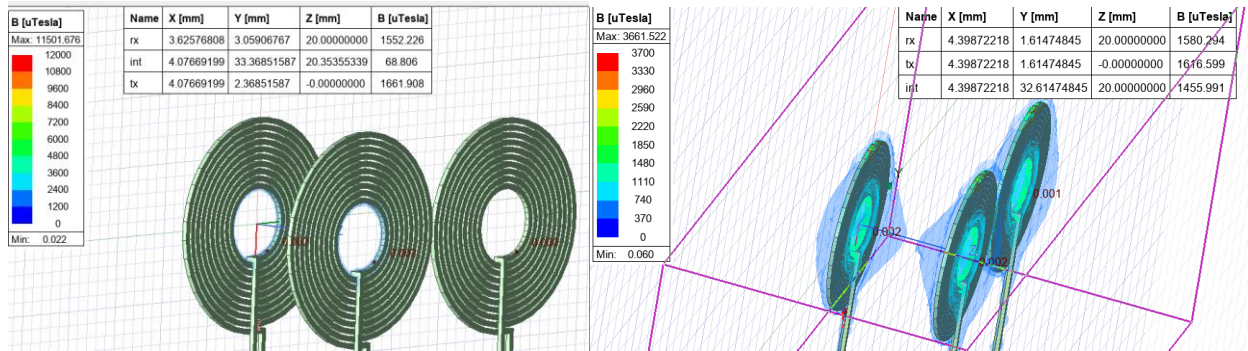


Figure 5.3. Representative magnetic field distribution for the passive and active intruder using the circular geometry.

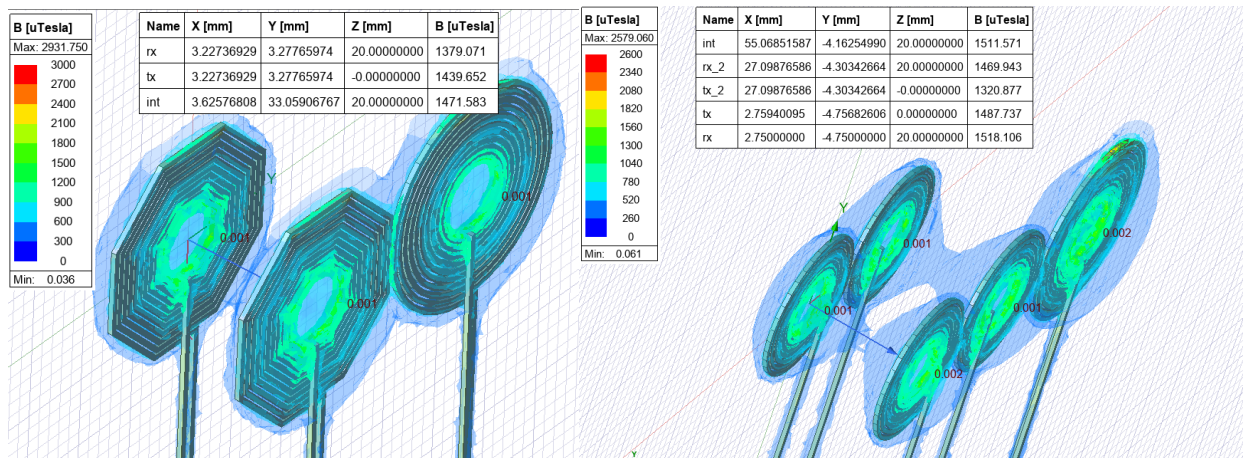


Figure 5.4. Magnetic field distribution for the active intruder scenario using the octagonal and figure-8 geometry.

5.3.2 Field Leakage Scenario

The field leakage scenario was developed to evaluate the propagation of magnetic fields outside the intended WPT region. This scenario focused on analyzing the spatial distribution of magnetic flux density around the receiver area and quantifying the extent to which coil geometry confined or dispersed electromagnetic energy into the surrounding environment.

Observation regions were defined around the receiver area to extract magnetic field distributions and evaluate leakage-related behavior under comparable conditions. Magnetic field maps and numerical field distributions were exported from the simulations for subsequent post-processing and numerical analysis. In addition to qualitative visualization of the field propagation patterns, numerical leakage indicators were computed using processed magnetic field data extracted from the simulation environment.

The field leakage analyses also contributed to the evaluation of security-related aspects associated with unintended field exposure and energy propagation outside the useful transfer region.

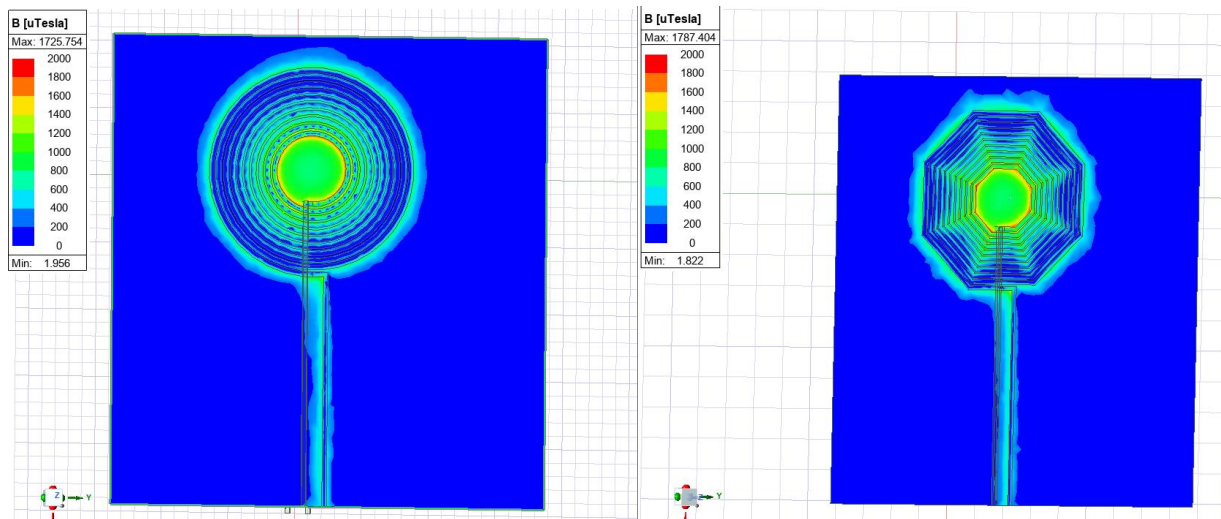


Figure 5.5. Magnetic field leakage distribution for the circular and octagonal geometry.

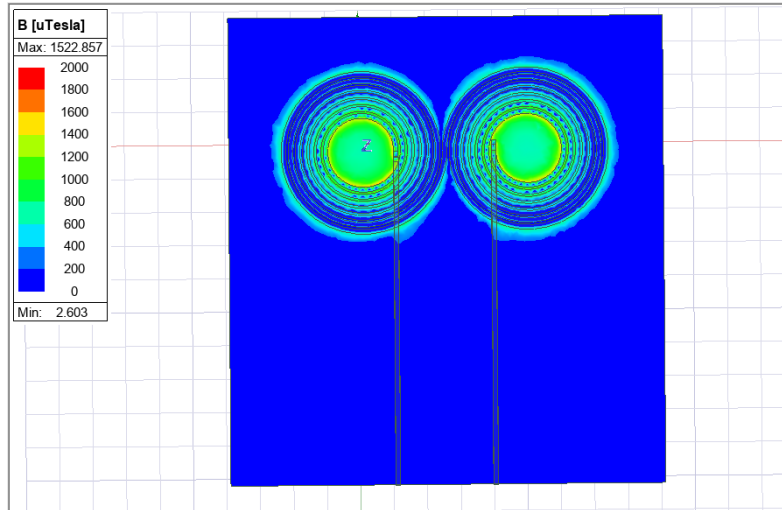


Figure 5.6. Magnetic field leakage distribution for the figure-8 geometry.

5.3.3 Misalignment Scenario

The misalignment scenario was designed to evaluate the robustness of the WPT link under spatial displacement between the transmitter and receiver coils. This scenario focused on analyzing the degradation of coupling behavior and power transfer performance caused by lateral displacement of the receiver with respect to the transmitter.

A displacement parameter was introduced to progressively shift the receiver position along the horizontal axis while maintaining the remaining simulation parameters constant. This approach enabled the evaluation of the sensitivity of each geometry to positional perturbations.

For each displacement condition, some electromagnetic and performance-related quantities were extracted, including coupling coefficients, transmitted and received power, efficiency indicators, and normalized robustness metrics. The resulting datasets were subsequently processed using interpolation techniques, comparative statistical analysis, and robustness-oriented evaluations to characterize the operational stability of the different geometries under perturbation conditions.

5.4 Data Generation and Processing

5.4.1 Simulation Data Extraction

The electromagnetic simulations generated multiple outputs. These outputs were extracted from ANSYS Maxwell using both field visualization tools and numerical report generation methods available within the simulation environment.

Depending on the scenario under analysis, different electromagnetic quantities were extracted from the simulations. For the resonance calibration stage, parameters such as inductance, reactance, impedance magnitude, and frequency-dependent responses were obtained from Eddy Current analyses. In the intruder scenario, transmitted power, received power, induced losses, and coupling-related quantities associated with the unintended receiver were extracted. For the field leakage scenario, magnetic flux density distributions and field intensity maps were exported for subsequent numerical processing. In the misalignment scenario, efficiency-related quantities and coupling coefficients were extracted for multiple receiver displacement conditions.

The extracted data were exported into structured CSV and spreadsheet-based formats to facilitate subsequent processing and comparative analysis.

5.4.2 Dataset Construction

The datasets included both directly extracted electromagnetic quantities and additional derived metrics computed during the post-processing stage. Data preprocessing and consolidation were performed using Python and MATLAB scripts developed specifically for the project. These scripts were used to normalize geometry labels, standardize numerical variables, clean inconsistent entries, organize displacement and distance parameters, and generate unified datasets for comparative analysis.

5.5 Statistical and Numerical Analysis

5.5.1 Statistical Analysis (ANOVA and Regression)

Statistical analysis techniques were applied to the generated datasets to evaluate differences between geometries and characterize the behavior of the WPT system under the considered perturbation scenarios.

Prior to the comparative analyses, the datasets were evaluated to verify statistical consistency and suitability for parametric analysis. Normality tests and homogeneity of variance analyses were performed using Shapiro–Wilk and Levene-type procedures before applying analysis of variance methods to the efficiency-related datasets.

Analysis of variance (ANOVA) was used to evaluate whether the observed differences in efficiency and robustness-related metrics across the circular, octagonal, and figure-8 geometries were statistically significant under the analyzed operating conditions. The statistical analyses enabled comparative evaluation of geometry-dependent behavior while reducing the influence of isolated numerical variations generated during the simulations.

Regression-based analyses were also applied to the misalignment datasets to characterize efficiency degradation and coupling behavior as functions of receiver displacement. These analyses allowed the identification of robustness trends and comparative sensitivity patterns associated with positional perturbations in the WPT link.

The statistical processing stage contributed to transforming the simulation outputs into interpretable comparative indicators, supporting the quantitative evaluation of efficiency–security trade-offs across the different self-resonant coil geometries.

5.5.2 Numerical Methods

Numerical methods were applied during the post-processing stage to analyze the electromagnetic datasets generated throughout the simulations. These methods were implemented mainly in MATLAB and were used to construct derived metrics, evaluate

leakage behavior, characterize robustness trends, and support the comparative analysis of the different coil geometries.

Interpolation techniques were applied to the misalignment datasets to obtain continuous representations of efficiency and coupling behavior as functions of receiver displacement. These interpolated responses facilitated comparative visualization and robustness-oriented analysis under positional perturbations.

Numerical integration procedures were also employed during the field leakage analysis to estimate magnetic energy propagation outside the intended transfer region. Leakage-related indicators were computed from processed magnetic flux density distributions exported from the electromagnetic simulations. Integration-based indices associated with magnetic field intensity and field energy distribution were used to quantify the environmental electromagnetic behavior of each geometry.

Additional numerical post-processing procedures were used to compute normalized performance metrics and robustness indicators derived from the simulation datasets. These analyses enabled consistent comparison between geometries under equivalent operating conditions and facilitated the construction of global comparative metrics used in the subsequent multi-objective analysis stage.

5.5.3 Multi-Objective Analysis

A multi-objective analysis framework was developed to evaluate the trade-offs between efficiency, robustness, and security-related behavior across the different self-resonant coil geometries. Since WPT systems may exhibit conflicting performance characteristics under different operating conditions, the analysis was designed to compare geometries using multiple normalized metrics simultaneously rather than relying on a single performance indicator.

Global performance and security indices were computed from the processed datasets using MATLAB-based post-processing workflows. These indices enabled the generation of comparative Pareto representations used to identify geometries exhibiting favorable trade-

offs between efficiency and security-related performance metrics under the evaluated scenarios.

The multi-objective analysis stage constituted the final integration layer of the computational workflow, combining the electromagnetic simulations, structured datasets, statistical analyses, and numerical methods into a unified comparative evaluation framework.

6. Results and Outcomes

6.1 Technical or Academic Results

The comparative analyses revealed that the three self-resonant coil geometries exhibited distinct behaviors under perturbation conditions, particularly in terms of efficiency stability, magnetic coupling robustness, and security-oriented performance indicators.

The misalignment analyses showed different degradation patterns as the receiver displacement increased. Figure 6.1 presents the efficiency evolution as a function of lateral offset for the circular, octagonal, and figure-8 geometries. The figure-8 configuration maintained the highest average efficiency values throughout most of the evaluated displacement range, while the circular and octagonal geometries exhibited greater local variations under increasing offset conditions.

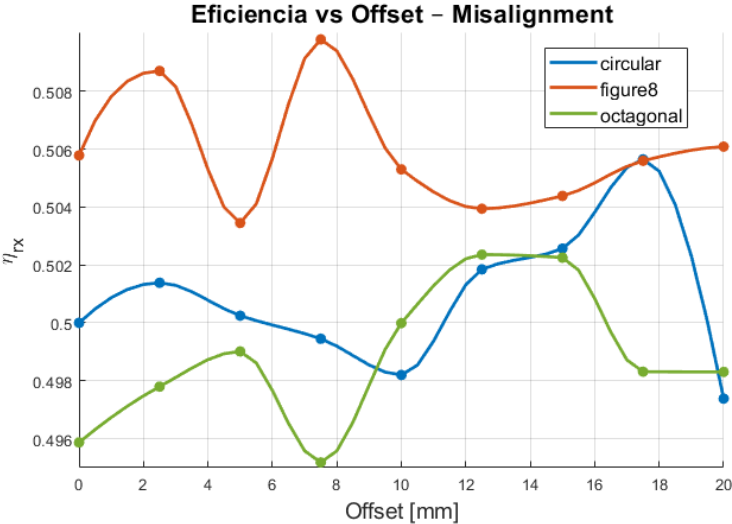


Figure 6.1. Efficiency behavior as a function of receiver misalignment for the evaluated geometries.

The observed efficiency variations were directly associated with differences in magnetic coupling behavior between the geometries. As shown in Figure 6.2, the circular and octagonal configurations preserved positive coupling values throughout the evaluated displacement interval, whereas the figure-8 geometry exhibited stronger sensitivity to positional perturbations.

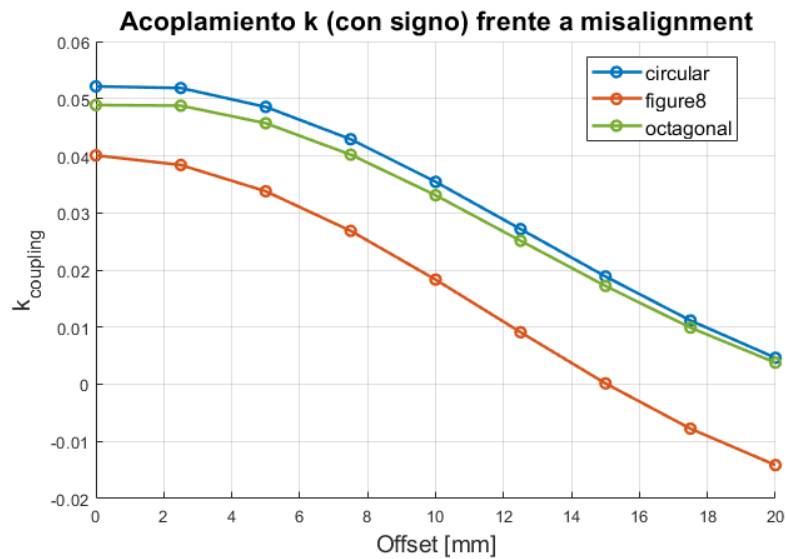


Figure 6.2. Coupling coefficient behavior under receiver misalignment.

Additional robustness-oriented indicators derived from normalized efficiency behavior revealed different stability trends among the geometries. Figure 6.3 shows the evolution of the normalized security-related index associated with efficiency stability under displacement conditions. The octagonal geometry exhibited comparatively stable behavior over a broader displacement interval, while the figure-8 geometry showed larger local oscillations associated with its more complex magnetic field distribution.

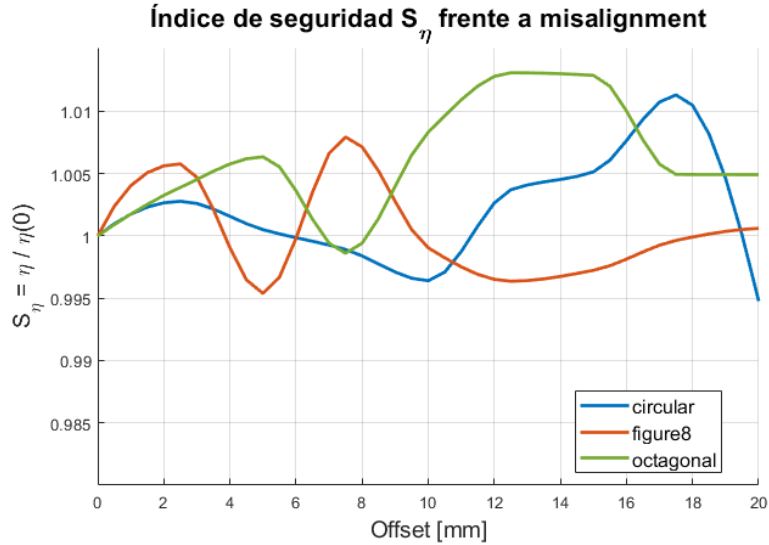


Figure 6.3. Normalized efficiency-security index under receiver misalignment.

The statistical distribution of efficiency values across geometries is summarized in Figure 6.4. The figure-8 configuration achieved the highest median efficiency values, while the circular and octagonal geometries exhibited slightly lower central tendencies but more stable distributions under perturbation conditions. The observed distributions confirmed the existence of geometry-dependent operational trade-offs between efficiency and robustness.

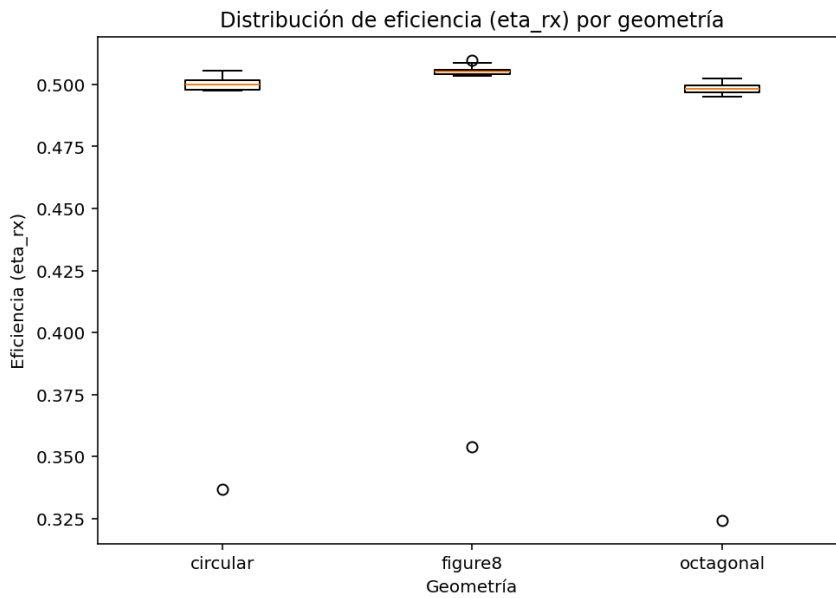


Figure 6.4. Statistical distribution of efficiency values across geometries.

The robustness analysis further highlighted differences in operational stability under perturbation scenarios. As shown in Figure 6.5, the figure-8 geometry achieved the lowest variability under intruder-related conditions, whereas the circular and octagonal configurations exhibited comparatively higher variability levels depending on the evaluated scenario.

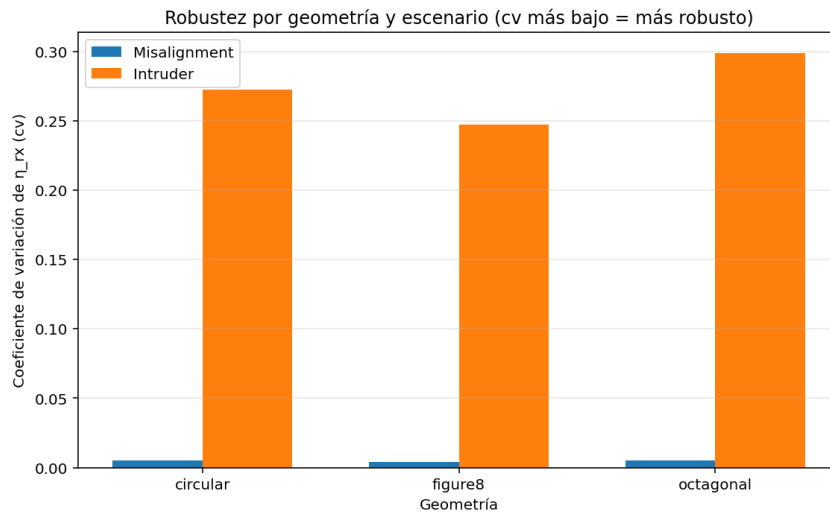


Figure 6.5. Comparative robustness analysis across geometries and perturbation scenarios.

The multi-objective analyses demonstrated that no single geometry simultaneously maximized all performance and security-related indicators. Figure 6.6 presents the trade-off between global performance and robustness under receiver misalignment. The circular and octagonal geometries achieved higher robustness-oriented indicators, whereas the figure-8 geometry achieved higher overall performance values at the expense of reduced robustness.

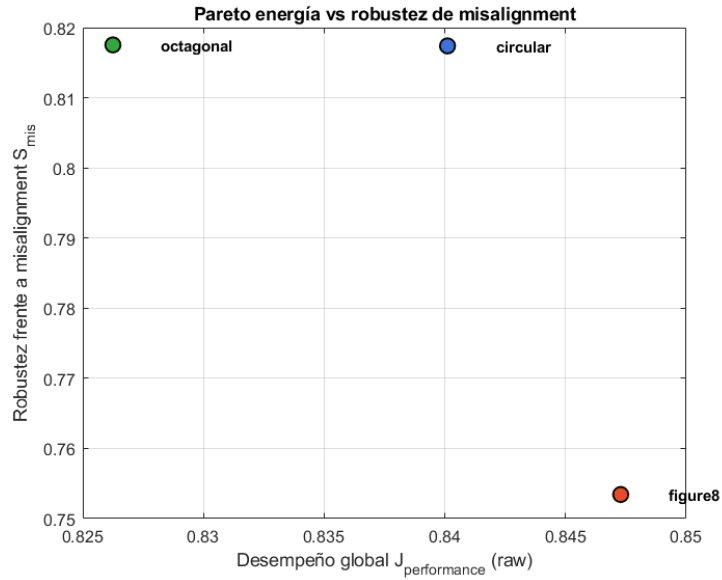


Figure 6.6. Pareto representation of performance versus misalignment robustness.

The operational security analysis shown in Figure 6.7 revealed similar trade-off behavior under combined intruder and misalignment conditions. The circular geometry achieved comparatively balanced behavior between performance and operational security, while the figure-8 geometry prioritized performance over robustness-related indicators.

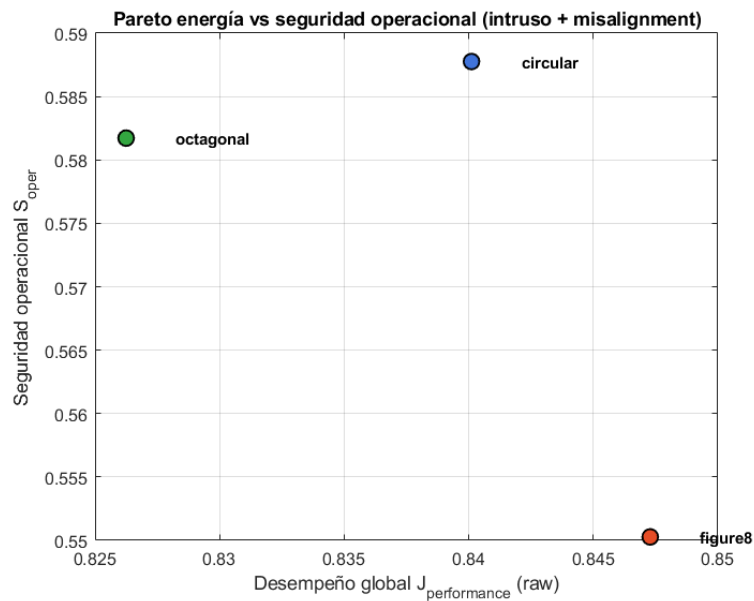


Figure 6.7. Pareto analysis of performance versus operational security.

Environmental electromagnetic behavior also differed significantly across geometries. Figure 6.8 shows the trade-off between performance and environmental security-related indicators associated with field leakage behavior. The octagonal geometry achieved the highest environmental security indicator, whereas the figure-8 geometry presented the lowest leakage-related security performance among the evaluated configurations.

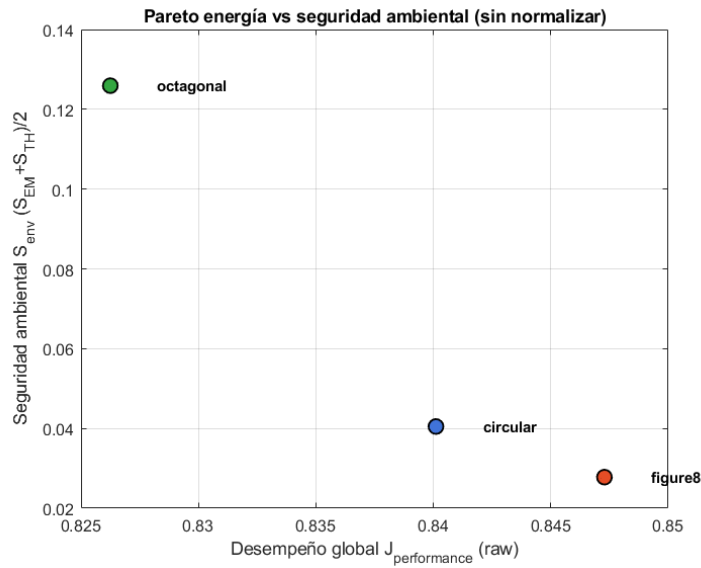


Figure 6.8. Pareto analysis of performance versus environmental electromagnetic security.

The global efficiency–security trade-off obtained from the normalized comparative framework is presented in Figure 6.9. The results indicate that the octagonal geometry achieved the best overall security-oriented performance, whereas the figure-8 geometry prioritized global transfer performance at the expense of security-related metrics. The circular geometry exhibited intermediate behavior between both extremes.

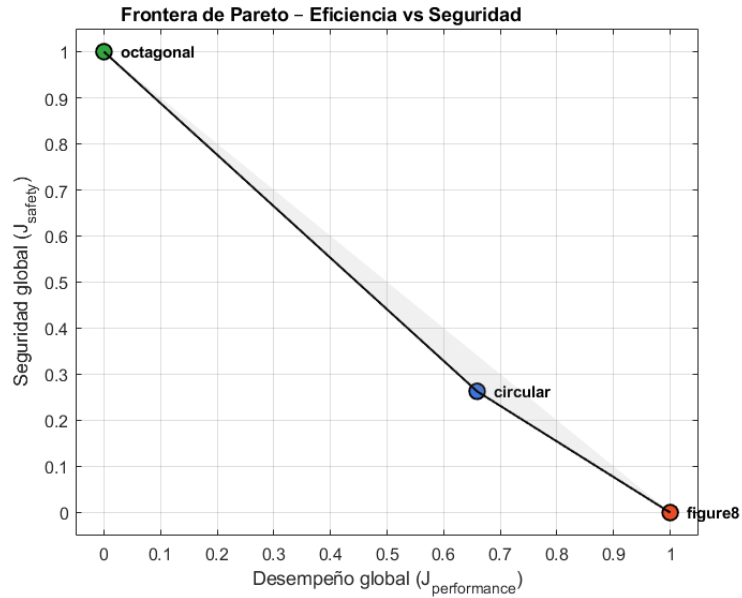


Figure 6.9. Global Pareto frontier between performance and security-related indicators.

Finally, the global radar-based comparative analysis shown in Figure 6.10 summarizes the multidimensional behavior of the evaluated geometries across the different perturbation scenarios. The figure highlights the existence of clear trade-offs between performance, robustness, and vulnerability depending on the selected geometry, confirming that coil geometry significantly influences both efficiency and physical-layer security behavior in WPT systems.

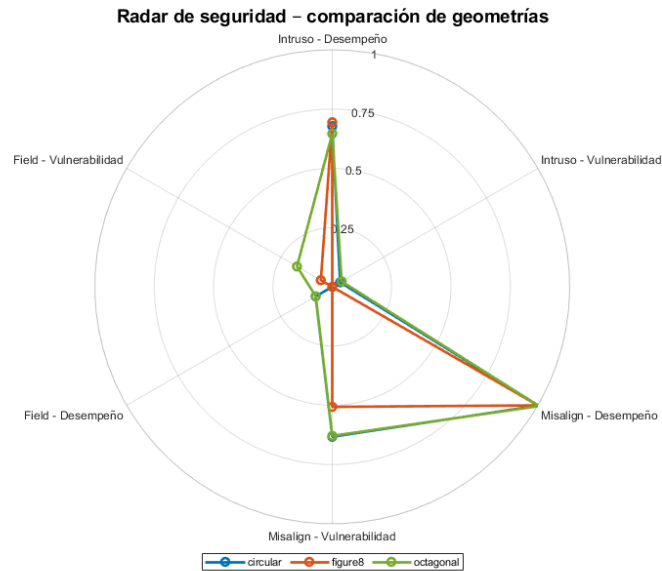


Figure 6.10. Radar-based comparative analysis of performance and vulnerability indicators across geometries.

Overall, the obtained results allowed the fulfillment of the general and specific objectives, providing a comparative evaluation of self-resonant coil geometries under different wireless power transfer operating scenarios.

6.2 Educational Impact

The international research internship represented a transformative academic and personal experience that significantly contributed to the development of technical, analytical, and professional competencies. Beyond the technical outcomes of the project itself, the experience provided direct exposure to the complete research process, from the initial identification of a research problem and state-of-the-art review to the design, simulation, analysis, and interpretation of results within a real research environment.

One of the most valuable aspects of the internship was the opportunity to work on a topic that was initially unfamiliar, which made the entire learning process more challenging and enriching. Developing the project progressively, refining the models, validating the simulations, and continuously improving the analysis framework strengthened problem-

solving abilities, adaptability, and independent research skills. The experience also reinforced the importance of persistence and iterative development in scientific and engineering research.

Professionally and personally, the experience provided the opportunity to interact daily with doctoral students, master's students, researchers, and professors within a highly research-oriented engineering environment. Being immersed in an institution strongly focused on science, technology, and innovation broadened the understanding of academic research and international collaboration while also strengthening communication, autonomy, and critical thinking skills.

7. Limitations and Opportunities for Improvement

While a four-month internship may initially appear to be a sufficient period, research projects involving simulation, modelling, data generation, analysis, and scientific documentation require extensive planning and iterative development processes. For that, time management became a critical factor for the internship.

In some cases, delays in communication and institutional procedures reduced the amount of time available to focus exclusively on research activities. Since international research internships involve academic, administrative, and logistical coordination between institutions, more streamlined communication processes could improve the overall research experience and reduce interruptions during the development of the project.

Additionally, having clearer guidance before the beginning of the internship regarding the academic expectations, expected deliverables, and institutional requirements associated with the research stay could help students prepare more effectively and organize their work more efficiently from the early stages of the internship. Overall, the international research internship represented a highly valuable academic and personal experience.

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