AGH University of Krakow

FIELD OF SCIENCE: ENGINEERING AND TECHNOLOGY

SCIENTIFIC DISCIPLINE: AUTOMATION, ELECTRONIC, ELECTRICAL ENGINEERING AND SPACE TECHNOLOGIES

SUMMARY OF DOCTORAL DISSERTATION

Modeling and Analysis of Magnetic Components used in High-Frequency Power Electronics Systems

Author: **Piotr Szczerba, MSc**

Supervisor: Cezary Worek, PhD, DSc, Associate Professor

Completed at: AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Institute of Electronics

Krakow, 2025

AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE

DZIEDZINA: NAUKI INŻYNIERYJNO-TECHNICZNE

DYSCYPLINA: AUTOMATYKA, ELEKTRONIKA, ELEKTROTECHNIKA I TECHNOLOGIE KOSMICZNE

AUTOREFERAT ROZPRAWY DOKTORSKIEJ

Modelowanie i Analiza Elementów Magnetycznych Pracujących w Wysokoczęstotliwościowych Układach Energoelektronicznych

Autor: **mgr inż. Piotr Szczerba**

Promotor rozprawy: dr hab. inż. Cezary Worek, prof. AGH

Praca wykonana: Akademia Górniczo-Hutnicza w Krakowie, Wydział Informatyki, Elektroniki i Telekomunikacji, Instytut Elektroniki

Kraków, 2025

Abstract

In many cases, power inductors are responsible for most of the power loss, volume, and cost when applied in high-frequency power electronic applications. It is desirable to optimize their design by proper calculation of winding and core losses. It allows for faster and cheaper commercial product release, a key issue for success in a highly competitive market. This is only possible if existing calculation techniques and technical data given by the core manufacturers are verified and correct; otherwise, the inductor optimization is less precise and requires several iterations to achieve good convergence.

One of the key challenges to solve are the complex permeability measurement and calculation techniques, which do not fully reveal how complex permeability is measured and fitted, or the fitting is oversimplified or overcomplicated. The fittings are based on not fully complete equivalent inductor models with several fitting variables, which can take arbitrary values and do not represent the physical behavior of the inductor. This approach cannot lead to the valid results needed for SPICE based simulation programs, commonly used in the industry to model electronic circuit behavior and quicken the time-to-market product release.

When it comes to the core loss, the ferrite-based core loss characteristics provided by the core manufacturers are designed to calculate the average power loss per unit volume or mass. The characteristics are estimated by the well-known original Steinmetz equation (OSE).

Unfortunately, the equation, despite its simplicity, does not account for non-sinusoidal excitation signals, such as rectangular waveforms and their DC bias, a situation that often prevails in modern SMPSs.

The rectangular excitation waveforms have a profound impact on the core loss, especially at the minimum and maximum values of the switching duty cycle. Therefore, to address this issue, various core loss models dedicated to non-sinusoidal excitations have been designed. These models attempt to predict the core loss accurately, but they often suffer from large numbers of hard-to-predict coefficients and overall method complexity.

Therefore, this research addresses existing and proposes improved calculation and measurement techniques regarding the complex permeability and the core power loss in ferrite-based magnetic components employed in SMPS.

The research begins with an overview of the up-to-date state-of-the-art techniques regarding power electronic converters, the properties of magnetic components, materials used in power electronics, the origin of winding and core loss mechanisms, along with the modelling of ferrite inductors to optimize their design.

Then, based on the overview, improved calculation techniques of complex permeability and the core loss are proposed.

The proposed complex permeability measurement and calculation technique is based on the inductor series equivalent model, with only one fitting variable, assuming that the inductance and the other quantities change along the frequency range according to the measured inductor impedance. This represents the physical behavior of an inductor, and only one fitting variable assures high fitting accuracy without the possibility of taking any arbitrary values by other quantities, which would otherwise be fitted. This allows for the accurate estimation of complex permeability regardless of inductor size, shape, winding structure, or frequency range.

The validation of the proposed model was done mathematically and by the test-bench measurements using an impedance analyzer. The results show that, if the inductor stray capacitor ESR loss tangent is correctly defined then it is possible to obtain a relative fitting error less than 2% along the entire frequency range.

Moreover, during the model validation it was revealed that the change in inductor inductance and other quantities is mostly due to the core's dimensional resonance and the windings' turn-to-turn and turn-to-core capacitance. The dimensional resonance also influences the inductor stray capacitance and its ESR values. The mechanism of how they originate is further investigated by test-bench measurements, calculations, and the FEM simulation, which are shown to be in good agreement. This has resulted in the proposal of an improved inductor equivalent model, which splits the stray capacitance into two parts: one related to the windings and one related to the core and frequency-dependent ESR of the stray capacitor.

This is significant because it might help in the development of improved inductor loss models and universal simulation models (e.g., SPICE models) that capture all AC loss mechanisms (core loss, winding loss, etc.), which do not yet exist, especially if we consider high-frequency power electronics applications.

Regarding the core loss, a new core loss model dedicated to rectangular AC voltages, which is based on the rectangular extension of the Steinmetz equation (RESE) and called here an improved RESE (iRESE), is proposed.

The iRESE unifies the Steinmetz-based core loss model with the small-signal complex permeability model to comprehensively complete the entire core loss characteristics regardless of the magnitude of the excitation signals, which was not earlier possible.

Moreover, it also considers the rectangular excitation of signals and the DC bias phenomenon commonly present in the SMPS, along with the magnetic permeability roll-off near the core saturation level.

The model is structured to be modular, meaning that each part of it can be used separately according to the intended application. This is a unique approach that provides engineers and scientists with all the required information at once regarding core loss, as well as the freedom of choice depending on the application they are working on.

The method was verified during extensive test-bench measurements supported by the SPICE simulations.

The results show a very good agreement between measurements and fitting results while the up-to-date SPICE simulation results are less precise, due to the incomplete non-linear magnetizing current model, which is scheduled as a future work.

Moreover, the method also discusses the nonlinearity of the inductor magnetizing current and its impact on the core losses in the small-signal domain. Thus, with an extra effort, the method can also be applied to the SPICE modelling and simulation, which is required by the industry for fast and precise estimation of the magnetic components' core loss.

The method is applicable but not limited to SMPS applications and can also be applied to any other arbitrary applications affected by DC bias and rectangular excitation waveforms, such as electric vehicle inverters and wireless power transfer systems.

Furthermore, a general error analysis has been performed, highlighting possible measurement and simulation errors and explaining their origins. The identification of these errors is crucial for a better understanding of possible measurement discrepancies and their magnitude in relation to the obtained results. It also indicates whether the assumed measurement approach and the test-bench setup are suitable for the expected measurement accuracy and are reasonable.

Abstrakt

W wysokoczęstotliwościowych impulsowych przekształtnikach energoelektronicznych (SMPS) elementy magnetyczne odpowiadają za większość straty mocy, a także za końcową objętość oraz całkowity koszt wprowadzanego na rynek przekształtnika. W związku z tym optymalizacja procesu projektowania oraz konstrukcji elementu magnetycznego poprzez możliwość dokładnego obliczenia strat mocy w uzwojeniach i rdzeniu jest rzeczą bardzo pożądaną.

Taka optymalizacja umożliwia szybsze wprowadzenie produktu na rynek, co jest czynnikiem decydującym, jeśli chodzi o jego sukces komercyjny, a także początkowe koszty implementacji.

Jest to tylko możliwe, jeśli istniejące techniki obliczeniowe oraz dane techniczne dostarczane przez producentów elementów magnetycznych są zweryfikowane i poprawne. W innym wypadku optymalizacja nie spełnia zakładanych oczekiwań, co prowadzi do nadmiernych iteracji projektowych w celu osiągnięcia założonych celów projektowych i kosztowych.

Jednym z głównych wyzwań w optymalizacji elementów magnetycznych stosowanych w przetwornicach impulsowych (SMPS) jest dokładny pomiar i obliczanie zespolonej przenikalności magnetycznej, która jest niezbędna do poprawnej oceny mało-sygnałowej rezystancji rdzenia, a także zbudowanie poprawnego mało-sygnałowego modelu obwodowego elementu magnetycznego. Niestety, istniejące techniki nie w pełni wyjaśniają sposób pomiaru i dopasowania zespolonej przenikalności magnetycznej. Niektóre metody nadmiernie upraszczają ten proces, podczas gdy inne przesadnie go komplikują. Dodatkowo, wiele metod dopasowania opiera się na niepełnych modelach zastępczych dławika, obejmujących zbyt wiele zmiennych dopasowania, które mogą przyjmować dowolne wartości i nie odzwierciedlają fizycznego zachowania elementu magnetycznego. W efekcie, metody te nie dostarczają wiarygodnych danych, które mogłyby być wykorzystane przez symulatory obwodowe oparte na SPICE, a które są powszechnie używane w przemyśle do modelowania układów elektronicznych co znacząco przyspiesza wprowadzenie produktu na rynek.

Jeśli chodzi o straty w rdzeniu, charakterystyki strat rdzeni ferrytowych dostarczane przez producentów rdzeni są dedykowane do obliczania średniej mocy strat na jednostkę objętości lub masy. Charakterystyki te są szacowane za pomocą dobrze znanego oryginalnego równania Steinmetza (OSE). Niestety, równanie to, pomimo swojej prostoty, nie uwzględnia niesinusoidalnych sygnałów wzbudzenia, takich jak przebiegi prostokątne i ich składowa stała (DC), co jest często spotykane w przekształtnikach energoelektronicznych. Trzeba nadmienić, że przebiegi prostokątne mają znaczący wpływ na straty w rdzeniu, zwłaszcza przy minimalnych i maksymalnych wartościach współczynnika wypełnienia przełączania.

Do tej pory zaprojektowano szereg modeli strat mocy w rdzeniach magnetycznych dedykowanych dla wzbudzeń niesinusoidalnych. Mimo, że modele te starają się dokładnie przewidzieć straty mocy, jednakże często cierpią na dużą liczbę trudnych do obliczenia współczynników oraz ogólną złożoność metody. Co więcej metody te nie uwzględniają wszystkich czynników wpływających na straty mocy na raz, mianowicie (i) wielkości sygnału wzbudzającego, (ii) częstotliwości wzbudzenia, (iii) wpływu temperatury, (iv) kształtu sygnału wzbudzającego, (v) podmagnesowania składową stałą (DC).

Bazując na powyższym niniejsza praca badawcza dotyczy istniejących oraz proponuje nowe, ulepszone techniki pomiaru i obliczeń zespolonej przenikalności magnetycznej oraz strat mocy w ferrytowych rdzeniach magnetycznych, stosowanych w impulsowych przekształtnikach energoelektronicznych (SMPS).

Badania rozpoczynają się od przeglądu najnowszych technik w zakresie przekształtników energoelektronicznych, właściwości elementów magnetycznych, materiałów magnetycznych stosowanych w elektronice mocy, mechanizmów powstawania strat w uzwojeniach i rdzeniach oraz modelowania dławików ferrytowych w celu optymalizacji ich konstrukcji.

Następnie, na podstawie przeglądu, zaproponowane zostały ulepszone techniki obliczeniowe zespolonej przenikalności magnetycznej oraz strat mocy w rdzeniach.

Zaproponowana metoda pomiaru i obliczania zespolonej przenikalności magnetycznej opiera się na szeregowym modelu zastępczym dławika, z jedną zmienną dopasowującą, zakładając, że indukcyjność i inne wielkości zmieniają się wraz z częstotliwością zgodnie ze mierzoną impedancją dławika. Takie podejście pozwala na wierne i fizyczne odwzorowanie zachowania elementu magnetycznego, a użycie jednej zmiennej dopasowującej zapewnia wysoką dokładność, jednocześnie zapobiegając przyjmowaniu przez inne parametry dowolnych, nie fizycznych wartości. W rezultacie metoda umożliwia precyzyjne obliczenie zespolonej przenikalności magnetycznej, niezależnie od rozmiaru, kształtu, konfiguracji uzwojenia czy częstotliwości pracy dławika.

Weryfikacja zaproponowanego modelu została przeprowadzona matematycznie oraz za pomocą pomiarów na testowym stanowisku laboratoryjnym z użyciem analizatora impedancji. Wyniki pokazują, że jeśli tangens strat równoważnej rezystancji szeregowej (ESR) pojemności pasożytniczej dławika jest prawidłowo określony to możliwe jest uzyskanie względnego błędu dopasowania poniżej 2% w całym zakresie częstotliwości.

Ponadto podczas weryfikacji modelu wykazano, że zmiana indukcyjności dławika i innych wielkości wynika głównie z rezonansu wymiarowego (dimensional resonance) rdzenia oraz pojemności międzyzwojowej i pojemności zwój-rdzeń. Rezonans wymiarowy wpływa również na pojemność pasożytniczą dławika oraz wartości jej ESRa. Mechanizm ich powstawania został także zbadany za pomocą pomiarów, obliczeń i symulacji MES, które wykazały dobrą zgodność. W rezultacie zaproponowano ulepszony model zastępczy dławika, który dzieli pojemność pasożytniczą na dwie części: jedną związaną z uzwojeniami oraz drugą związaną z rdzeniem i częstotliwościowo zależną wartością ESR kondensatora pasożytniczego.

Te wyniki badań są istotne, ponieważ mogą pomóc w opracowaniu ulepszonych modeli strat dławików oraz uniwersalnych modeli symulacyjnych (np. modeli SPICE). Modele te będą obejmować wszystkie mechanizmy, które do tej pory nie zostały uwzględnione, a które pochodzą od wymuszeń zmiennoprądowych (straty w rdzeniu, straty w uzwojeniach itd.), co ma szczególne znaczenie w zastosowaniach wysokoczęstotliwościowej energoelektroniki mocy.

Jeśli chodzi o straty w rdzeniu, niniejsza praca proponuje nowy model obliczania strat dedykowany prostokątnym sygnałom wzbudzenia, oparty na prostokątnym rozszerzeniu metody Steinmetza (RESE), zwanym tutaj ulepszonym RESE (iRESE).

Model iRESE rozszerza RESE poprzez unifikację modelu strat w rdzeniu opartym na równaniu Steinmetza z modelem małosygnałowym zespolonej przenikalności magnetycznej, aby kompleksowo opisać charakterystyki strat w rdzeniu bez względu na amplitudę sygnałów wzbudzenia, co wcześniej nie było możliwe.

Dodatkowo zaproponowana metoda uwzględnia prostokątne sygnały wzbudzenia wraz ze składową stałą, co jest zjawiskiem powszechnie występującym w przekształtnikach energoelektronicznych, spadek przenikalności magnetycznej w pobliżu nasycenia rdzenia oraz wpływ zmian temperatury na straty.

Oprócz tego, model zbudowany jest modułowo, co oznacza, że każda jego część może być użyta niezależnie, w zależności od zamierzonego zastosowania. Jest to unikalne podejście, które dostarcza inżynierom i naukowcom wszelkich niezbędnych informacji dotyczących strat w rdzeniu, a jednocześnie daje swobodę wyboru metody w zależności od konkretnej aplikacji, nad którą pracują.

Zaproponowana metoda została zweryfikowana podczas rozległych pomiarów laboratoryjnych z wykorzystaniem oscyloskopowej metody dwuzwojowej opisanej w oraz wsparta symulacjami typu SPICE.

Metoda porusza także nieliniowość prądu magnesującego dławika i jego wpływ na straty rdzenia w dziedzinie mało- i wielkosygnałowej. Dzięki temu przy dodatkowym wysiłku może być stosowana do modelowania i symulacji SPICE, co jest wymagane przez przemysł w celu szybkiej i dokładnej oceny strat w rdzeniu dla projektowanych elementów magnetycznych.

Dodatkowo przeprowadzono ogólną analizę błędów, wskazując możliwe błędy pomiarowe i symulacyjne oraz wyjaśniając ich źródła. Identyfikacja tych błędów jest kluczowa dla lepszego zrozumienia potencjalnych rozbieżności pomiarowych i ich wielkości względem uzyskanych wyników. Analiza wskazuje również, czy przyjęte podejście pomiarowe i konfiguracja stanowiska testowego są odpowiednie dla oczekiwanej dokładności pomiarów i mają sens.

Wyniki wykazują bardzo dobrą zgodność pomiarów z wynikami dopasowania, jednak bieżące wyniki symulacji obwodowej (SPICE) są mniej precyzyjne z powodu niekompletnego nieliniowego modelu prądu magnesującego, co jest planowane jako rozwój dalszych prac.

Zaproponowana metoda, chociaż opracowana z myślą o zastosowaniach w impulsowych przekształtnikach energoelektronicznych, może być szeroko stosowana w innych systemach elektronicznych, w których występuje składowa stała oraz niesinusoidalne przebiegi wzbudzenia, w tym między innymi w przetwornicach pojazdów elektrycznych i systemach bezprzewodowego przesyłu energii.

1. Research Background.

Modern lifestyles demand the use of a wide range of electronic devices, such as computers, mobile phones, and household appliances, all of which are predominantly powered by the electricity derived from the fossil fuels. Simultaneously, there is a rising concern over an air pollution and global warming, primarily driven by the greenhouse gas emissions resulting from the combustion of the coal and the oil. In response, global authorities are promoting the transition to green energy sources, including electric vehicles and renewable energy solutions such as solar and wind power. However, the effective integration and operation of these technologies would not be possible without the implementation of highly efficient power electronics systems.

Power electronics systems, while essential to modern energy infrastructure, face several critical challenges. Foremost among these are the growing market and consumer expectations for devices that combine high efficiency with compactness, affordability, and reliability. Meeting these demands requires a fragile trade-off between minimizing power losses and reducing physical size. As devices shrink, power density, defined as the power handled per unit volume increases, leading to greater losses and intensified thermal stress. As a result, the maximum permissible operating temperature becomes a key factor limiting the continued miniaturization of power electronic components.

Recent advancements in semiconductor switching technologies, particularly the adoption of wide-bandgap materials like silicon carbide (SiC) and gallium nitride (GaN), have partially addressed the challenge of low conversion efficiency in high-frequency switch-mode power supplies (SMPS). These materials offer significant advantages over traditional silicon-based devices, including superior switching speed, higher breakdown voltage, and enhanced thermal conductivity. However, while these improvements significantly boost semiconductor performance, they are not sufficient to eliminate overall efficiency limitations in power converters. This is largely due to the losses associated with the magnetic components, such as inductors and transformers, which often dominate total power loss in high-frequency operation and remain a major constraint.

These components are a key element in power electronic systems, responsible for a significant portion of the power losses and the overall volume of the final power supply system solutions. For this reason, it is advisable to expand knowledge about them and be able to optimize their design. Contemporary knowledge in the field of magnetic components, although very broad, is very dispersed, and selected phenomena are described using analytical equations, empirical formulas, or complex numerical models. For example, copper losses are described by Dowell's, Ferreira's, and modified Kazimierczuk's equations or, for a specific case, simulated using the FEM method. This makes the design process much more difficult as the designer has to go through different solution concepts and calculations to find a sufficiently accurate match. This is a highly inefficient process, both in terms of the resources used and the time needed to reach a solution.

The better visualization of the above is shown in Figure 1. If an inductor is not well optimized, at least two outcomes might happen. One of the outcomes is the oversizing. In this case, an inductor is made larger than its optimum size. The larger inductor requires more material and takes up more space on the printed circuit board (PCB) than is actually needed. It is contrary to the market requirements for a small and inexpensive device. This outcome represents the material waste and the waste of space.

On the other hand, the second outcome is downsizing. The inductor is made smaller than its optimum. In this case, the inductor must carry an excess amount of power through a limited volume of space. This means the higher power density requires additional thermal management to address the associated hot spots. The hot spots might easily cause the entire electronic system the inductor is part of to fail, or simply the device will not meet the customer's or the standard-based requirements regarding thermal management. Both outcomes provide for one point: the waste of time and money for an already poorly designed magnetic component, and another waste of time and money, which will be incurred in the future to undertake another iteration of the entire design process to achieve the desired optimal solution.

The power electronics industry has already foreseen these issues, pointing out that the design optimization of magnetic components is the key challenge at present, as shown in Figure 2.

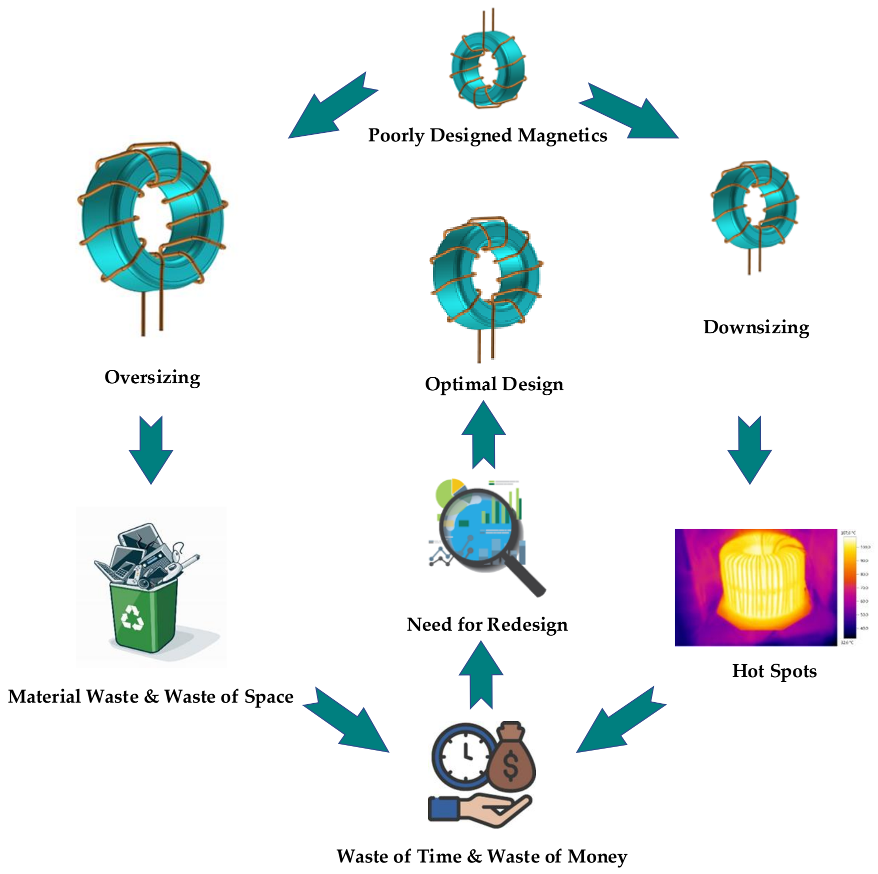

Figure 1: Magnetic Component Design Optimization Issues.

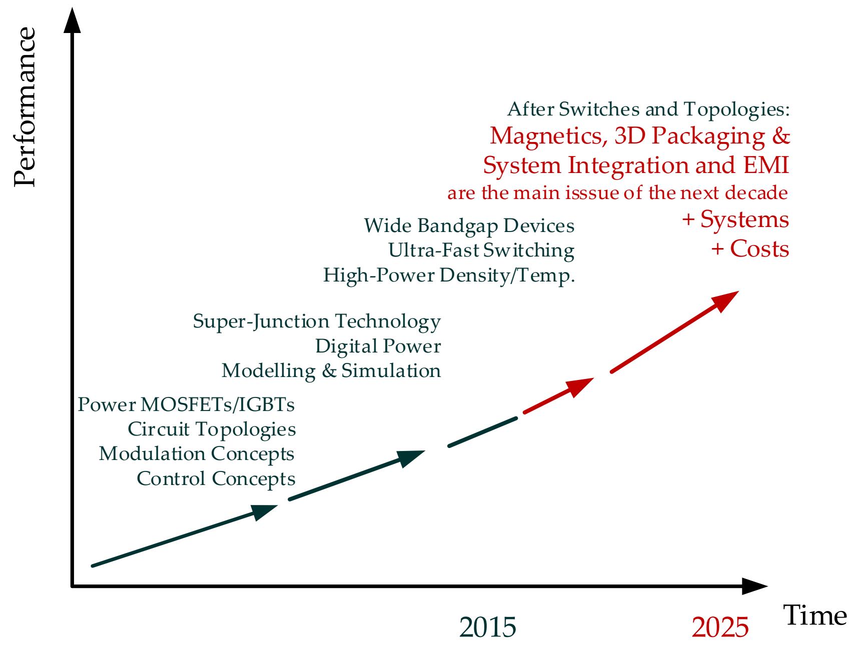

Figure 2: Power Electronics Industry Road Map and Challenges.

2 Research Objectives.

The research goal is to introduce innovative design and calculation procedures for calculating losses in magnetic components that are part of power electronic systems. Proven design procedures, which are based on analytical equations, empirical formulas and numerical models are a necessary condition, closely related to technical progress and the need to meet technical requirements in advanced commercial projects.

Research goals include, but are not limited to:

- Theoretical, analytical, and experimental verification of complex permeability.
- Theoretical, analytical, and experimental verification of the core loss and the core resistance.
- The design and development of the FEM models for simulation-based verification of the magnetic components' equivalent circuit models.
- The design and development of SPICE-based models for simulation-based verification of magnetic components' power loss and core resistance.
- The design of the test bench for experiments.
- Verification of presented methods and determination of their practical usefulness.
- Tools development for calculation and design of magnetic components (VBA, SMath) – verification of created tools and assessment of their practical usefulness.

3 Scope of the Dissertation.

The thesis consists of seven chapters with the content shown in Figure 3 and described as follows:

Chapter 1 briefly discusses the background of the research and the challenges that face power electronic systems regarding market requirements for reliability, size, cost, efficiency, and associated power loss and thermal management issues. The key objectives and scope of the thesis are then defined.

Chapter 2 describes the most common topologies of SMPS converters, along with the requirements of the magnetic components used in commercial designs. The state-of-the-art power loss calculation techniques of the ferrite-based magnetic components are also discussed.

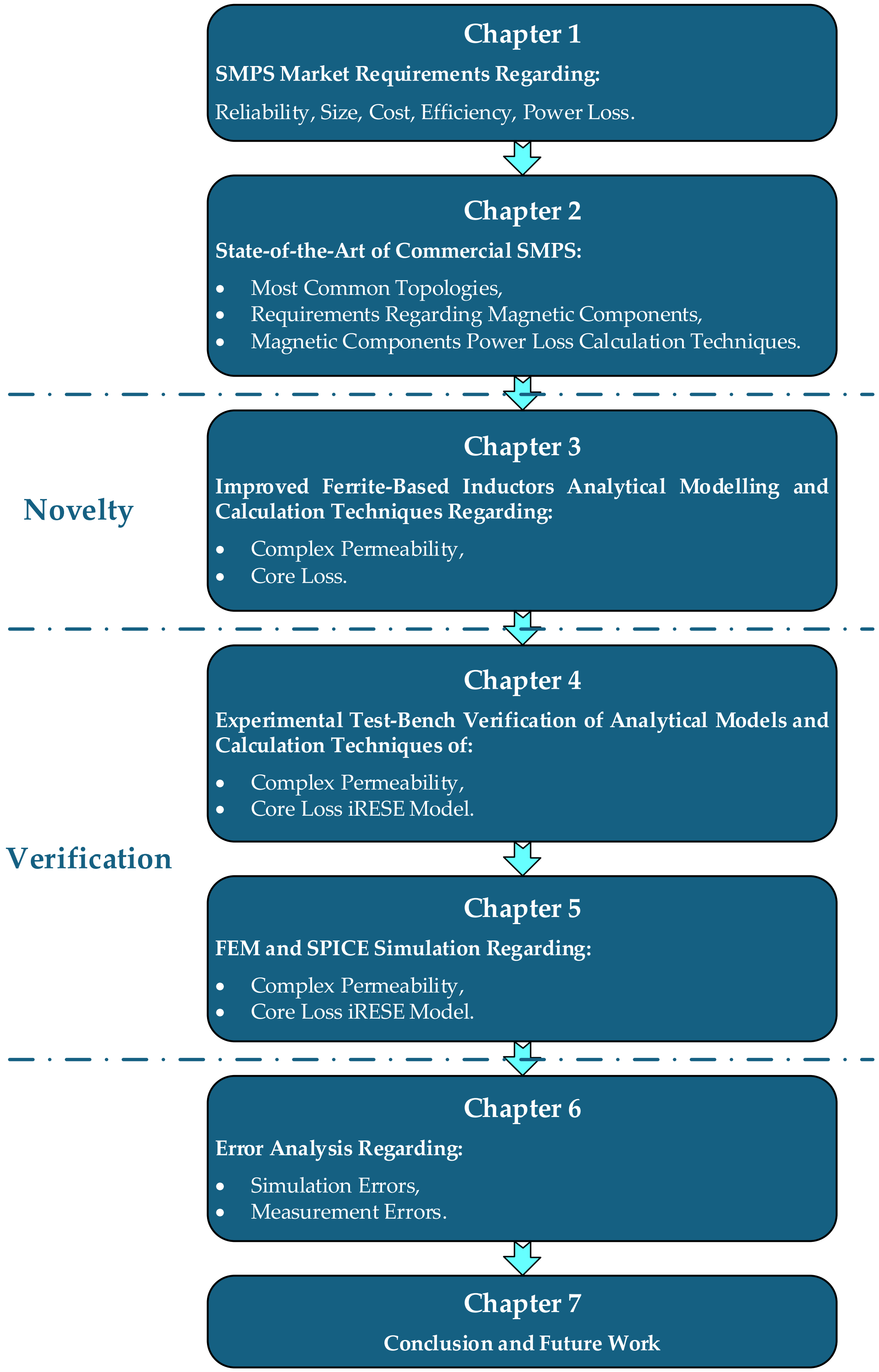

Figure 3: Structure of the PhD Dissertation.

Chapter 3 introduces new, author-based analytical modelling and calculation techniques regarding complex permeability and core loss in ferrite-based inductors. A complex permeability iterative curve fitting technique is proposed, followed by an in-depth explanation of inductor resonance and the origin of parasitic components in the inductor equivalent model. This leads to the proposal of an improved equivalent model for the inductor, which can be further utilized in simulation software. Next, the improved RESE (iRESE) core loss model is proposed. It considers the influence of the DC bias, sinusoidal and non-sinusoidal excitation signals, permeability roll-off near saturation, and also combines two core loss models, which originate from the small- and large-signal domains. Moreover, the iRESE is structured in a modular manner, which is a unique approach. This means that each part can be used separately, according to the application it is intended for, giving engineers and scientists freedom of choice depending on the application they work on.

Chapter 4 introduces the experimental test-bench verification of the analytical models shown in Chapter 3. The chapter is split into two parts: (i) the first part deals with the small-signal measurement and calculation techniques of complex permeability using an impedance analyzer as a main tool, and (ii) the second part verifies the claims regarding the iRESE model. Firstly, verification is performed in the small-signal domain again, with the help of an impedance analyzer. At this stage, the unification of the complex permeability and Steinmetz-based core loss models occurs. Then, the model is verified in the large-signal domain by measuring the core loss of the tested inductors in a temperature-controlled environment, such as an oil bath. This is done using a two-winding method. Based on the results, curve fittings are performed to mathematically express the core loss characteristics and unify the proposed core loss model, regardless of the type of excitation signal and DC bias.

Chapter 5, through FEM and SPICE simulations, verifies the assumptions and claims made in Chapters 3 and 4, respectively. The FEM simulation has been used to verify the origin of the inductor stray capacitance; the information is required to build a precise equivalent inductor model. The SPICE simulation is used to verify the assumptions regarding the non-linear behavior of the core resistance and the core loss. This information is required to build a precise inductor SPICE model for circuit simulations.

Chapter 6, in its general form, highlights possible measurement and simulation errors and explains their origin. The identification of these errors is crucial for a better understanding of potential measurement discrepancies and their magnitude in relation to the obtained results.

Chapter 7 summarizes the dissertation, provides the final conclusion to the presented research work and describes potential areas for future development.

4. Main Research Contributions.

This research presents improved measurement and calculation techniques for the complex permeability of ferrites, one of the fundamental parameters that define inductor behavior in the frequency domain. This advancement is significant, as it supports the development of more accurate inductor loss models and universal simulation tools (e.g., SPICE models) capable of capturing all AC loss mechanisms, including core and winding losses. Such comprehensive models are currently unavailable, particularly in the context of high-frequency power electronics applications.

The proposed method is based on the inductor equivalent model, enabling the direct estimation of complex permeability values from impedance measurements. Importantly, the method remains valid regardless of the inductor's size, geometry, winding structure, or operating frequency range. The results demonstrate high accuracy not only in the low-frequency complex permeability values, e.g., the values of the imaginary part stripped of the influence of 'windings' resistance, but also in the permeability peak values existing in the vicinity of the resonance. This information would be otherwise hidden or diminished by parasite components, of which the real inductor is made.

The method is also simple and intuitive to process, assuming the frequency dependence of most inductor model components, and thus overcomes some of the limitations and complexity of other methods.

Furthermore, this work introduces an improved core loss measurement technique—termed the improved Rectangular Extension of the Steinmetz Equation (iRESE). The iRESE model extends the traditional RESE approach into both the small-signal and near-saturation large-signal domains. It unifies the Steinmetz-based core loss model with the small-signal complex permeability model to comprehensively complete the entire core loss characteristics regardless of the magnitude of the excitation signals.

This unification of both models would be beneficial: (i) because it more accurately reflects the actual behavior of inductors, and (ii) because it enables the use of a single model across both small- and large-signal domains – an integration which was not possible before.

The iRESE model also considers rectangular excitation of signals and the DC bias effects commonly encountered in switch-mode power supplies (SMPS), as well as the magnetic permeability roll-off near core saturation. Its modular structure allows each component of the model to be used independently, depending on the application. This flexibility provides engineers and researchers with a complete and adaptable framework for core loss analysis.

Additionally, the model accounts for the nonlinearity of the inductor's magnetizing current and its impact on core losses in the small-signal domain. With further refinement, the method can be adapted for use in SPICE modelling and simulation—an essential requirement for industry, where rapid and accurate core loss estimation of magnetic components is critical.

The proposed model has five degrees of freedom regarding the core loss in the ferrite materials and includes dependency on: (i) the magnitude of the magnetic flux density, (ii) frequency of the excitation, (iii) temperature variations, (iv) the shape of the excitation signal, and (v) DC bias.

Although developed with SMPS in mind, the method is equally applicable to other systems affected by DC bias and rectangular excitations, such as electric vehicle inverters and wireless power transfer systems.

5. Main Research Limitations.

The limitation of the complex permeability measurement method is that it was tested with single-layer inductors only and might not be applicable to inductors with multilayer, multiturn windings. Furthermore, due to the complex and implicit relationship between the core and the windings, the stray capacitance ESR value is not fully defined. This leads to an incomplete small-signal equivalent inductor model, which might not give as accurate results as expected if applied to a SPICE simulation.

The primary drawback of the iRESE core loss calculation methodology is its time-consuming nature, particularly during the measurement and computation phases. Each measurement requires an accurate calculation of magnetic flux density, as detailed in Chapter 6, and any error may necessitate repeated testing. Moreover, the process of converting oscilloscope data into a format compatible with LTSpice simulations is labor-intensive, ensuring data fidelity but contributing to the overall complexity. The model also involves numerous coefficients, which can make the implementation appear daunting. However, this complexity is a necessary trade-off to achieve a high-fidelity fit between the measured characteristics and their mathematical representation.

6. Future Work.

As mentioned in the dissertation, the inductor self-resonant frequency depends on the windings and core apparent capacitance. However, the relationship between the core and the windings is complex and explicit; therefore, there is limited evidence as to what the correct relationship is between their capacitances and the capacitances' ESRs. This should be further investigated regarding an improvement of the proposed small-signal inductor model.

Furthermore, the proposed technique should be additionally tested when applied to multi-winding, multilayer inductors with substantial inter-winding capacitance. Simultaneously, the FEM simulations should be enhanced by incorporating more accurate material models for both the core and its insulating coating. This improvement would enable a more precise representation of the interaction between the core and windings, leading to more accurate modelling of the inductor's stray capacitance and its associated ESR.

Despite producing strong results in core loss prediction, there remains potential for further improvement in the iRESE methodology. For example, the research demonstrates that the measured core resistance does not follow a double-logarithmic straight-line trend, but rather curves upward. This is due to the fact that core resistance is a function of two variables: magnetic flux density (B_m) and the magnetizing current (I_m), the latter of which is absent from the original Steinmetz model. To address this, I_m was measured during both: impedance sweeps and large-signal experiments, then incorporated into the model. This resulted in an $R_c(I_\mathrm{m})$ relationship, which more closely aligns with the observed core resistance behavior at higher excitation levels.

As shown in the research results, the core resistance values measured under large-signal conditions were added and correlate well with those obtained via impedance analyzer.

This resolves the open question stated in the dissertation regarding the upward-bending nature of R_c, confirming that it is a nonlinear function of current—a behavior not captured by Steinmetz. Furthermore, because this function is also temperature-dependent, the proposed model should be reformulated as a nonlinear and temperature dependent function of the magnetizing current.

The resulting model shows promise as a more accurate representation of core losses for integration into electrical circuit simulators such as LTspice, as demonstrated in Chapter 5 of the dissertation. However, its implementation demands precise measurements of extensive datasets and significant test bench modifications—efforts that are well-suited to future development work.

7. Author's List of Publications.

1. Szczerba, P.; Worek, C., *Improved rectangular extension of Steinmetz equation including small and large excitation signals with DC bias*, Electronics, vol. 14, issue 14, MDPI, 18 July 2025. [CrossRef]
2. Szczerba, P., Ligenza, S., Worek, C., *Measurement and calculation techniques of complex permeability applied to Mn-Zn ferrites based on iterative approximation curve fitting and modified equivalent inductor model*, Electronics, vol. 12, issue 19, MDPI, 22 September 2023. [CrossRef]
3. Szczerba, P.; Raczko, W.; Ligenza, S.; Worek, C., *Analytical PFC boost inductor power loss calculation method in CCM*, 2021 21st International Symposium on Power Electronics (Ee), 27-30 October 2021, Novi Sad, Serbia. [CrossRef]
4. Szczerba, P.; Raczko, W.; Ligenza, S.; Worek, C., *Analytical design optimization of PFC boost inductor in CCM*, 2021 21st International Symposium on Power Electronics (Ee), 27-30 October 2021, Novi Sad, Serbia. [CrossRef]
5. Szczerba, P.; Ligenza, S.; Worek, C., *Inductor AC resistance extraction method from an impedance measurement based on complex permeability model*, In the Proceedings of 19th International Power Electronics and Motion Control Conference, Gliwice, Poland, 25–29 April 2021. [CrossRef]
6. Szczerba, P.; Ligenza, S.; Trojan, P.; Worek, C., *Practical design considerations of inductor AC resistance calculation methods*, 20th International Symposium on Power Electronics (Ee), Novi Sad, Serbia, 2019. [CrossRef]