

Coreless Inductors for Line Filters



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Abstract

The increasing integration of power-electronic converters in modern electrical grids has intensified the need for effective filtering solutions to maintain power quality. Conventional line filters typically employ magnetic-core inductors, which provide high inductance but are associated with core losses, saturation effects, nonlinear behavior, and increased weight and cost. This thesis investigates the feasibility of using coreless (air-core) inductors as an alternative in grid-connected converter applications, with particular focus on Active Dynamic Filter (ADF) systems developed by Comsys.

The study compares conventional and coreless inductors with respect to functionality, geometry, losses, thermal performance, magnetic field behavior, and practical implementation. Analytical calculations, electromagnetic simulations in COMSOL Multiphysics, and experimental testing of physically manufactured prototypes were conducted. Both solenoid and toroidal air-core geometries were evaluated to achieve a target inductance of 50 μH under specified operating conditions.

The results show that toroidal air-core inductors provide significant advantages over solenoid designs due to their ability to naturally confine magnetic fields and reduce electromagnetic interference. Simulations and measurements demonstrated good agreement for toroidal geometries, while thermal testing revealed that short and thick toroids offered improved manufacturability and cooling performance compared with long and thin configurations. Although air-core inductors require larger dimensions than magnetic-core counterparts, they eliminate core saturation and hysteresis losses while maintaining linear inductive behavior over a wide operating range. In addition, the investigated air-core design achieved a substantial mass reduction, with the three final toroidal inductors reducing the total mass by a factor of approximately 3–4 compared with the conventional three-phase iron-core inductor.

The findings indicate that air-core toroidal inductors are a technically viable solution for high-current line-filter applications and represent a promising alternative for future power-electronic systems operating at elevated switching frequencies.

Keywords: *Air-core inductor, Line filter, Power electronics, Active Dynamic Filter, Toroid, Electromagnetic interference, Power quality*

Preface

This master thesis was carried out during the spring semester of 2026 as a collaboration between the Division of Industrial Electrical Engineering and Automation (IEA) at the Faculty of Engineering at Lund University (LTH) and Comsys AB in Lund. This thesis constitutes the final part of our Master of Science degree in Electrical Engineering at LTH, with specialisations in Energy & Environment and Electrification, respectively.

We would like to acknowledge and thank the individuals who have made essential contributions to the completion of this master's thesis. First, we extend our sincere thanks to Nils Lundström at Comsys for initiating this master's thesis opportunity and for enabling us to conduct our research within the energy sector. We also extend our sincere gratitude to Getachew Darge for his invaluable assistance with laboratory equipment, troubleshooting electrical issues, and his practical support during the experimental work. Furthermore, we are deeply thankful to Mats Alaküla for undertaking the role of examiner. Finally, we express our deepest gratitude to our supervisor, Max Collins, for his invaluable guidance, constructive feedback, and unwavering support throughout this study.

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Abbreviations

AC	Alternating Current
ADF	Active Dynamic Filter
BESS	Battery Energy Storage System
CM	Common Mode
DC	Direct Current
DM	Differential Mode
EMI	Electromagnetic Interference
EV	Electric Vehicle
HV	High Voltage
LCR	Inductance, Capacitance, Resistance
LV	Low Voltage
PEC	Power Electronic Converter
PV	Photovoltaic
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
VFD	Variable Frequency Drive

Popular Science Summary

As society moves towards renewable energy sources such as solar power, battery storage systems, and electric vehicle charging, the number of power-electronic devices connected to the electrical grid continues to increase. While these technologies are essential for the energy transition, they can also introduce electrical disturbances that reduce power quality. To address this issue, electrical filters containing inductors are commonly used.

Most inductors used today contain a magnetic core made of iron or similar materials. These cores help create strong magnetic fields but also introduce disadvantages such as energy losses, increased weight, higher costs, and the risk of magnetic saturation. Air-core inductors address these limitations by eliminating the magnetic core, thereby reducing core-related losses and weight, although they typically require larger physical dimensions. This thesis explores whether this alternative inductor technology could be a practical solution for power-quality filter applications.

The work was carried out in collaboration with Comsys AB and focused on industrial power-quality filter applications. Different air-core inductor designs were studied through calculations, computer simulations, and laboratory experiments. Prototype inductors were manufactured using 3D printing and tested under realistic operating conditions.

The results showed that toroidal (ring-shaped) inductors performed significantly better than traditional solenoid-shaped designs because their magnetic fields remain largely confined within the structure. This reduces unwanted electromagnetic interference while maintaining the benefits of air-core technology. The study also identified design features that improve cooling and simplify manufacturing.

Although air-core inductors generally require more physical space than conventional magnetic-core inductors, they provide highly predictable and linear performance while eliminating saturation effects and core-related losses. The findings demonstrate that air-core toroidal inductors have strong potential for future high-power and high-frequency electrical systems, where efficiency, reliability, and power quality are becoming increasingly important.

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1 Introduction

1.1 Background

The ongoing global energy transition imposes new demands on the power sector, necessitating a shift from traditional fossil-fuel-based generation toward renewable alternatives. This expansion is accelerating, and the International Energy Agency (IEA) projects a 4.6 TW increase in global renewable capacity by 2030, with solar photovoltaics (PV) accounting for nearly 80% of this growth [1]. Unlike conventional synchronous generators, these renewable sources are predominantly interfaced with the grid via power electronics. Consequently, power converters have emerged as the pivotal technology for enabling the scaling of renewables.

Comsys is a cleantech company founded in 2001 in Lund, Sweden, specializing in power quality solutions for grid-connected power electronic systems. The company develops Active Dynamic Filter (ADF) technology, which is used to mitigate current harmonics and improve overall power quality in electrical networks [2]. In the context of proliferation of power electronic converters and the resulting challenges in grid power quality, Comsys provides an industrial perspective for the present work and serves as the collaborating partner for this study.

Grid-connected power converters use line filters to suppress high-frequency current ripple generated during switching operations. Such filters are typically based on LCL topologies incorporating conventional inductors wound around a magnetic core material. Although magnetic cores enable higher inductance and confine the magnetic flux to the core, they introduce additional losses, saturation effects, and nonlinear magnetic behavior. Furthermore, core materials contribute significantly to component weight [3] and cost. Air-core inductors eliminate core saturation and magnetic hysteresis losses, making them attractive for high-power and high-frequency applications [4]. However, the absence of a magnetic core results in increased stray magnetic fields, creating new challenges related to component geometry and magnetic shielding. The feasibility and performance of air-core inductors in grid-connected converter applications therefore warrant further investigation. In particular, increasing the switching frequency is of considerable interest since it enables reductions in the size of magnetic components [5]. However, achieving both high power and high switching frequency presents significant challenges for conventional magnetic-core inductors, making air-core designs an attractive alternative.

1.2 Purpose

The purpose of this master's thesis is to investigate the feasibility of using coreless inductors in Comsys Active Dynamic Filter (ADF) products, with conventional core-based inductors serving as a reference rather than being included in a full experimental comparison. The study evaluates relevant performance metrics, including size, weight, linearity, and other key physical properties, to identify the relative advantages and disadvantages of coreless inductors. Furthermore, through analytical calculations and simulations, the thesis investigates suitable geometric designs and assesses their performance to provide design insights that can support future Comsys product development.

1.3 Limitations

The scope of this thesis is limited to a three-phase line filter based on coreless inductors, as this represents a typical application within Comsys. The study focuses on the analysis and comparison of inductor designs within this application context, and does not consider other converter topologies or filter configurations.

- **Rated current:** $80 A_{rms}$
- **Current spectrum:**
 - Baseband: 50-2500 Hz ($50 A_{rms}$)
 - Switching frequency: 5–25 kHz ($10 A_{rms}$)
- **Inductance:** $50 \mu\text{H}$

1.4 Research questions

In order to achieve the purpose, the following questions are answered:

- How do air-core solenoid and toroidal inductors compare in terms of magnetic performance, losses, thermal behavior, and suitability for use in a Comsys line filter?
- How accurately do theoretical calculations and COMSOL simulations predict the inductance and resistance of air-core inductors compared with experimental measurements?
- Which air-core inductor geometry offers the optimal balance between thermal performance, power losses, and compactness for high-current operation?

1.5 Related work

The design of inductive components for power filters is well established, with foundational contributions from Kolar [15] providing models for three-phase common-mode chokes, and Collins [11, p.163-165 & p.174-175] addressing high-power inductor design under demanding operating conditions. However, the application of air-core inductors in high-power grid-connected converters is an emerging field.

Recent research has addressed air-core inductor optimization for DC–DC converters [3], loss minimization through conductor geometry optimization [10], and thermal and electromagnetic interference (EMI) performance in inverter systems [8, 5]. Comparative studies [4] have shown that air-core reactors offer advantages in terms of linearity, absence of saturation, and reduced weight compared with iron-core designs, though they require larger physical volumes. Finite-element simulations have been validated against experimental measurements in several studies [9, 12], establishing COMSOL Multiphysics as a reliable modeling tool for predicting inductance, resistance, and magnetic field distribution in air-core geometries.

A clear gap remains in the literature regarding the use of air-core inductors as converter-side elements in LCL filters for active dynamic filters (ADFs) operating at high currents ($80 A_{rms}$) and

switching frequencies (5–25 kHz). This thesis addresses that gap by evaluating solenoid and toroidal air-core designs through analytical calculations, 3D finite-element simulations, and experimental testing of physically manufactured prototypes, with a focus on practical manufacturability, thermal performance, and integration into an existing ADF cabinet layout.

1.6 Thesis outline

- Chapter 2 - Theory
- Chapter 3 - Methodology
- Chapter 4 - Results
- Chapter 5 - Discussion
- Chapter 6 - Main findings and possible future research directions

2 Theory

This chapter introduces important theoretical concepts in order to understand the results of this study.

2.1 Electromagnetic fundamentals

Electromagnetics describes the interaction between electric and magnetic fields. The basic source of a magnetic field is electric charge in motion [6, p.719]. The reason magnetic fields arise from moving charges can be further explained using Einstein's theory of relativity, which is beyond the scope of this study. A net flow of charge carriers constitutes an electric current, and a constant current produces a constant magnetic field. For a straight current-carrying conductor, the magnetic field generated around it depends on both the current and the distance from the conductor. The magnetic field intensity H is described by Ampère's law, which relates the field to the current enclosed by a circular path surrounding the conductor.

$$\oint H \cdot dl = I \quad (1)$$

The magnetic flux density B and the magnetic field intensity H are related by

$$B = \mu H \quad (2)$$

where μ represents the magnetic permeability of the material through which the magnetic field propagates. For air, the permeability is approximately equal to the permeability of free space.

If a current-carrying wire is formed into a multiturn coil, the magnetic field is greatly intensified, particularly if the coil is wound around an iron core [6, p.719]. The direction of the magnetic field produced by the coil can be determined using the right-hand rule. The magnetic flux density inside an ideal solenoid can be approximated by combining Eq. (1) and Eq. (2) which yields

$$B = \frac{\mu NI}{l} \quad (3)$$

where N is the number of turns, I is the current through the coil, and l is the length of the coil. The magnetic flux is given by

$$\Phi_B = \int_A B \cdot dA \quad (4)$$

The total magnetic flux passing through a coil with N turns is called the flux linkage λ [6, p.722] and is given by

$$\lambda = N\Phi_B \quad (5)$$

2.2 Inductance

Inductance is the property of an electrical conductor that opposes the change in the current flowing through it by generating a magnetic field around it. Inductance can be seen as an equivalent electrical inertia similar to the mechanical inertia which opposes the change of motion of an object. When the current flowing through a conductor changes the magnetic field induces an electromotive force (EMF) according to Faraday's law of electromagnetic induction whose polarity is such that it opposes the change according to Lenz's Law [6, p.163, p.723].

$$\varepsilon = -\frac{d\Phi_B}{dt} \quad (6)$$

The constant of proportionality between the voltage and current is the inductance, usually denoted by the letter L .

$$v(t) = L \frac{di(t)}{dt} \quad (7)$$

The unit of inductance is Henry (H), which is equivalent to volt seconds per ampere. Every wound coil of some kind has the ability to induce an emf in itself, i.e. a self-inductance (L), when the current through it changes. The self-inductance is defined directly from Eq. (7). For a wire with N turns the self-inductance is given by

$$L = \frac{\lambda(t)}{i(t)} \quad (8)$$

The mutual inductance, commonly denoted by the letter M , refers to when the magnetic field from a primary coil induces an emf in another nearby (secondary) coil. It can be defined as

$$V_2 = M \frac{di_1(t)}{dt} \quad (9)$$

Where V_2 is the voltage induced in the secondary coil due to the rate of change of current ($\frac{di_1(t)}{dt}$) in the primary coil [6, p.172]. The magnetic flux produced by one coil can either aid or oppose the flux produced by the other coil.

Induced voltages also usually occur in the core (or other conductors nearby) by the changing magnetic fields and give rise to so called eddy currents. As the eddy currents flow in the core they dissipate energy, giving rise to core losses and additional heating, hence why they are undesired. An inductor is usually constructed by coiling a wire around some type of magnetic material such as iron or iron oxides that increases the magnetic flux for a given current [6, p.162-163]. Iron cores are often composed of thin sheets called laminations that are electrically insulated from one another and oriented in a way to interrupt the flow of eddy currents [6, p.170, p.740]. The energy stored in an inductor is given by Eq. (10) and of which is released back into the circuit when the current through the inductor changes back to zero [6, p.164-165].

$$w_L(t) = \frac{1}{2} Li^2(t) \quad (10)$$

2.2.1 Solenoid

Inductors usually come in the form of a solenoid, see Figure 1 below.

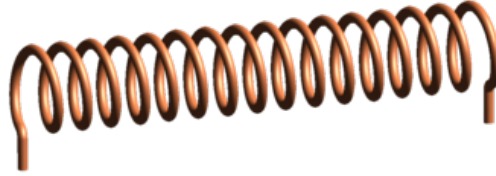


Figure 1: Solenoid.

The self-inductance, L , for an ideal solenoid with N turns is given by Eq. (8). Combining it with Ampere's Law (Eq. (1)), the B-H relation (Eq. (2)) and the formula for magnetic flux (Eq. (4)) while assuming that $r \ll l$ and that the magnetic field is uniform inside the coil and zero outside, gives the following expression

$$L = \frac{\mu N^2 A}{l} \quad (11)$$

where

- N is the number of turns
- μ is the absolute permeability of the core material.
- l is the length of the solenoid.
- A is the cross-sectional area of the solenoid.
- r is the radius of the cross-sectional area.
- $n = N/l$ is the number of turns per unit length.

2.2.2 Toroid

An ideal toroid with a rectangular cross-section and with N turns is shown in Figure 2 below.

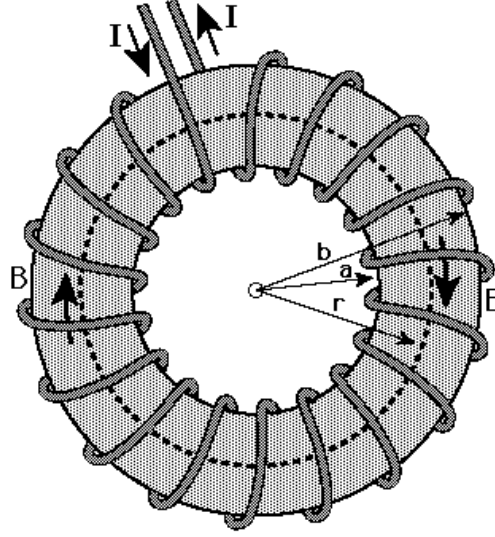


Figure 2: Toroid.

Following the same procedure as in the solenoid case the expression for the self-inductance for a toroid is derived to be

$$L = \frac{\mu_0 N^2 h}{2\pi} \ln\left(\frac{b}{a}\right) \quad (12)$$

where

- h is the height (thickness) of the toroid
- a is the inner radius
- b is the outer radius

From Eq. (11) and Eq. (12) it can be concluded that the self-inductance is determined by the inductor's geometry and the permeability of the surrounding medium. Furthermore, the self-inductance is proportional to the square of the number of turns (N), making it the most determining factor. Additionally, the self-inductance is not a function of the current I (for a constant medium permeability) and the qualification that the coil be closely wound is to minimize the linkage flux around the individual turns of the wire [7, p.270]. In a toroid the generated magnetic field gets naturally confined within the cross-section due to the arrangement of the current path. This quality mitigates the electromagnetic interference (EMI) which is desired in power electronic applications. Experimental testing have proved that various air-core inductor designs can operate in close proximity to sensitive control electronics without requiring external magnetic shielding or causing EMI-related disruptions [8].

2.2.3 Circuit model for a real inductor

All practical circuit elements including inductors possess parasitic effects in addition to the desired properties. They can cause the components' behavior to depart from that of their ideal behavior. A circuit model for a real inductor is illustrated in Figure 3.

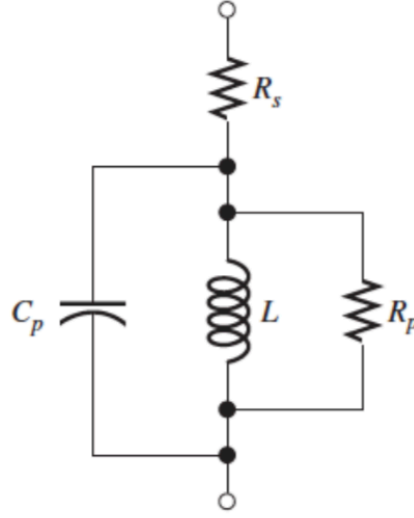


Figure 3: Circuit model for a real inductor including several parasitic elements.

The series resistance R_s is caused by the resistivity of the material composing the wire, it can be avoided by using wires composed of superconducting materials which have zero resistivity [6, p.171]. The parallel resistance R_p represents core loss due, in part, to eddy currents in the core. This parasitic effect is theoretically nonexistent in the case of aircore inductors. The parallel capacitance C_p (interwinding capacitance) arises naturally between any two conductors that are separated by an insulator due to the electric field present there. The inductance (L) and parasitic capacitance (C_p) form a parallel resonant circuit where the self-resonant frequency (f_{SRF}) is given by

$$f_{SRF} = \frac{1}{2\pi\sqrt{LC_p}} \quad (13)$$

Above f_{SRF} , the inductor behaves more as a capacitor while below it it behaves more as an inductor. The interwinding capacitance is usually unwanted and is mostly mitigated at low operating frequencies while becoming more apparent as frequency increases. The parasitic capacitance is often the factor limiting the operating frequency and bandwidth of electronic components and circuits.

2.3 Factors affecting inductance

2.3.1 Numbers of turns and the spacing between them

The self-inductance (L) is proportional to the square of the number of turns (N), making it the most determining factor for both the solenoid and the toroid. The number of turns per unit length ($n = N/l$) affects the leakage flux, where a tighter spacing between the turns reduces stray magnetic fields. For large air-gapped inductors, spatially non-uniform magnetic flux and the resulting fringing flux around air gaps must be accounted for, as uniform-flux assumptions underestimate both core losses and additional winding losses beyond conventional copper-loss calculations [9].

2.3.2 Core material

2.3.2.1 Permeability

Magnetic permeability is a measure of how much a material can be magnetized, i.e. how easily a magnetic field can penetrate and be supported within a given material. The permeability of free space or vacuum is $\mu_0 = 4\pi \cdot 10^{-7} [N/A^2]$ and it relates to the absolute permeability μ of a generic material in terms of multiples according to the relation

$$\mu = \mu_r \mu_0 \quad (14)$$

Where μ_r is the relative permeability. The relative permeability for different core materials are shown in Table 1. The listed constants represent typical average values at low frequency and room temperature. It should be noted that the constitutive parameters of several materials are dependent on both frequency and temperature.

Table 1: Typical relative permeability values for common magnetic materials [7, p.676].

Material	Relative permeability μ_r
Air	1
Ferrite	1 000
Iron (pure)	4 000
Transformer steel	20 000
Mu-metal	100 000

In air, the magnetic permeability is constant, resulting in a linear B-H relationship (Eq. (2)). In ferromagnetic materials such as iron, the permeability depends on the magnetic field due to domain alignment and saturation effects, leading to a nonlinear B-H characteristic.

2.3.2.2 Magnetic materials

Materials can be classified according to how they respond in the presence of magnetic fields [7, p.257].

Diamagnetism arises mainly from the orbital motion of the electrons within an atom and is present in all materials [7, p.258]. In most materials it is too weak to be of any practical importance. Diamagnetic materials such as air, copper and water exhibit no permanent magnetism independent of temperature [7, p.258], and the induced magnetic moment disappears as soon as the applied magnetic field is withdrawn.

Paramagnetic materials such as aluminium, magnesium and titanium on the other hand become temporarily magnetized when subjected to an applied magnetic field. As soon as the applied field is withdrawn the material returns to its former non-magnetized state. Paramagnetism arises when the alignment forces, acting upon molecular dipoles by the applied field, are counteracted by the deranging effects of thermal agitation [7, p.258]. Unlike diamagnetism, the paramagnetic effect is temperature dependent, being stronger at lower temperatures where there is less thermal collision.

Ferromagnetic materials such as iron and ferrites become permanently magnetized compared to paramagnetic materials even after the applied field is withdrawn. Ferromagnetism can be explained in terms of magnetized domains, which contain magnetic moments that are randomly oriented before an external field is applied. When an external field is applied, the walls of those domains having magnetic moments aligned with the applied field move in such a way as to make the volumes of those domains grow at the expense of other domains [7, p.259]. As a result, magnetic flux density (B) is increased. Moreover, ferromagnetic materials can be many orders of magnitude larger than that of paramagnetic substances, explaining why they are usually used in transformers and conventional inductors.

2.3.2.3 Hysteresis

The phenomenon of where a ferromagnetic material's magnetization lag behind the magnetic field producing it, making its current magnetic state depend on its history is called hysteresis, which is derived from a Greek word meaning "to lag" [7, p.259].

Prior to being subjected to an external magnetic field, an unmagnetized ferromagnetic material exhibits zero net magnetization due to the random orientation of the magnetic moments inside its domains. As the applied magnetic field intensity (H) is increased by applying current to the coil, the magnetic fields of the domains tend to align with the applied field. At first (point O to P1 in Figure 4) this is a reversible process, so that if the applied field is reduced to zero, the domains return to their original random orientations. However, for greater applied field intensities, the domains align with the applied field such that they tend to maintain their alignment even if the applied field is reduced to zero (point O to P2). Eventually, for sufficiently high fields, all of the domains are aligned with the applied field and the material is saturated (at point P3). At saturation the slope of the B - H curve approaches 0. For typical iron core materials, saturation occurs when the magnetic flux density (B) is in the range of 1 to 2 T [6, p.738].

If the applied field is now reduced to zero (from point P3), a residual flux density B remains in the core because the magnetic domains continue to point in the direction imposed earlier by the applied field. If the applied field is increased in the reverse direction, B at first is reduced to zero and then eventually saturates in the reverse direction (point P3'). If an AC current is applied to the coil, a hysteresis loop is traced in the B - H plane.

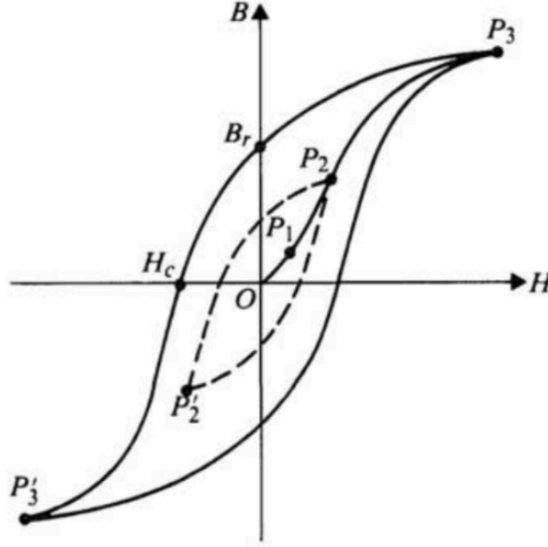


Figure 4: Hysteresis loop in the B-H plane for ferromagnetic material.

2.3.3 Geometry

The geometry of an inductor is mainly composed of its cross-sectional area (A) and length (L) in the case of a solenoid or height (h) in the case of a toroid. From the expressions of self-inductance it can be observed that a larger cross-sectional area yields a larger self-inductance.

The expressions of self-inductance for an ideal inductor are, as any scientific model based upon assumptions and thus have limitations. An important limitation of the expression for the self-inductance of an ideal solenoid is that it assumes that the length of the solenoid is much greater than its cross-sectional radius, i.e., $l \gg r$. If this condition is not fulfilled the answers the formula provides might not be accurate, which is important to consider when analyzing different inductor geometries.

2.3.4 Frequency of operation

The frequency of operation can give rise to certain phenomena that affect the inductance. In low-frequency (DC) scenarios the earlier mentioned parasitic effects of a real inductor are mostly mitigated. In high-frequency scenarios on the other hand, effects such as skin and proximity naturally arise.

2.3.4.1 Current density

Current density is a fundamental concept in electromagnetics that describes how electric current is distributed within a conductor. It is defined as the current per unit cross-sectional area and is expressed as:

$$J = \frac{I}{A} \quad (15)$$

where J is the current density (A/m^2), I is the total current, and A is the cross-sectional area of

the conductor (m^2). This relation indicates that, for a given current, increasing the conductor area reduces the current density, while decreasing the area increases it. Consequently, conductors with larger cross-sectional areas experience lower current density and therefore reduced thermal stress.

Under direct current (DC) conditions, where the current remains constant in magnitude and direction, the current density is uniformly distributed across the entire cross-section of the conductor. In this case, the electrical resistance is determined by the material properties and geometry according to:

$$R = \rho \frac{L}{A} \quad (16)$$

where ρ is the resistivity of the material and L is the length of the conductor. Since the entire cross-section contributes to conduction, the resistance remains constant. However, under alternating current (AC) conditions, the situation changes significantly.

Current density is particularly important from a practical design perspective, since high currents are required in the inductor windings. A lower current density requires a larger conductor cross-section, which increases the mechanical difficulty of the winding process. This effect is especially pronounced in inductor geometries, where limited access and tight bending radii make thick conductors difficult to wind uniformly. Therefore, a trade-off arises between electrical performance, thermal limitations, and manufacturability of the winding.

2.3.4.2 Skin effect

A time-varying current produces a time-varying magnetic field, which according to Faraday's Law of induction induces internal electric fields within the conductor. These fields generate circulating currents, known as eddy currents, which unevenly alter the distribution of the main current. As a result, the current density becomes non-uniform and tends to concentrate near the surface of the conductor, a phenomenon known as the skin effect. The current density decreases exponentially from the surface toward the center of the conductor, and this behaviour can be described by:

$$J(r) = J_0 \cdot e^{-(R-r)/\delta} \quad (17)$$

where r is the radial position, R is the conductor radius, J_0 is the surface current density, and δ is the skin depth. The skin depth defines how deeply the current penetrates into the conductor and is given by:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \quad (18)$$

where f is the frequency and μ is the magnetic permeability. As the frequency increases, the skin depth decreases, confining the current to a thinner region near the surface. In the extreme case the current may essentially concentrate in the "skin" of the conductor as a surface current (making the effective cross-sectional area zero), and the self-inductance is reduced to zero [7, p.272]). Using Eq. (18) the skin depth for copper can be approximated for different frequencies, see Table 2.

Table 2: Skin depth for copper.

Frequency [kHz]	Skin depth δ [mm]
5	0.922
25	0.412
100	0.206

This non-uniform current distribution has important practical consequences. Since the effective area available for current flow is reduced, the effective resistance of the conductor increases at higher frequencies. For a cylindrical conductor where the skin depth is much smaller than the radius, the effective conducting area can be approximated as:

$$A_{eff} \approx 2\pi R\delta \quad (19)$$

This leads to a significant increase in AC resistance compared to DC resistance. The increase in resistance directly impacts power losses, which are given by:

$$P = I^2 R \quad (20)$$

Thus, higher resistance at high frequencies results in increased power dissipation in the form of heat. This effect is particularly important in inductors and high-frequency systems, where losses can reduce efficiency and lead to thermal challenges.

To mitigate these effects, various design strategies are employed, such as using litz wire, which distributes current more evenly, or optimizing conductor geometry to maximize the effective surface area. These approaches aim to reduce AC resistance and improve overall performance.

2.3.4.3 Proximity effect

The magnetic field produced when current flows through a conductor plays a central role in the proximity effect. When two conductors are placed in close proximity and carry alternating current, the magnetic field generated by each conductor penetrates the other. This external magnetic field induces eddy currents within the neighbouring conductor, which redistribute the main current and confine it to a smaller portion of the cross-sectional area. As a result, the effective conducting area is reduced and the resistance increases accordingly.

The direction in which the current concentrates depends on the relative current directions in the two conductors. When the conductors carry currents in opposite directions, as is the case on the forward and return paths of a solenoid winding, the magnetic fields between the conductors add together and the current density concentrates on the inner facing surfaces. When the conductors carry currents in the same direction, the fields partially cancel between them and the current instead concentrates on the outer surfaces.

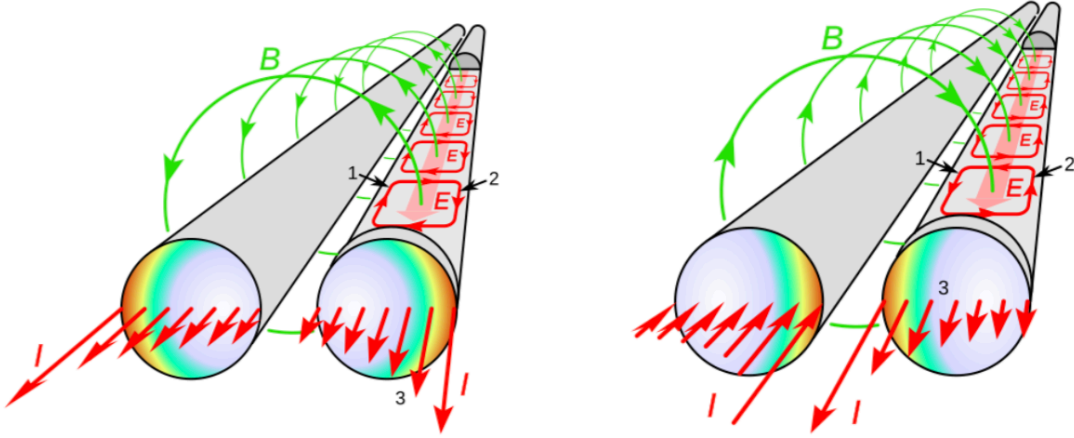


Figure 5: Proximity effect.

The severity of the proximity effect is strongly dependent on frequency. At higher frequencies, the induced eddy currents become stronger, causing a more pronounced redistribution of current and a further reduction in the effective conducting area. This leads to a significant increase in AC resistance compared to DC resistance, and consequently higher power dissipation according to Eq. (20). At high operating frequencies, copper losses are dominated by skin and proximity effects, and these losses can be greatly reduced through proper geometric optimisation [10].

2.3.4.4 Core losses

When an AC current is applied to a coil having an iron core, more energy is put into the coil on each cycle than is returned to the circuit. This is because part of the energy is converted to heat in reversing the directions of the magnetic domains. The volumetric energy converted to heat per cycle is equal to the area of the hysteresis loop and is called core loss [6, p.739]. Since a fixed amount of energy is converted to heat for each cycle, the power loss due to hysteresis is proportional to frequency. By choosing certain alloys that have a smaller hysteresis loop (area), core losses can be reduced. Core losses can be described using the Steinmetz equation (Eq. (21)), which relates the losses to the frequency and the peak magnetic flux density in the core [12]. The equation is given by

$$P_{core} = kf^{\alpha}B_{max}^{\beta} \quad (21)$$

where P_{core} is the core loss per unit volume (W/m^3), f is the excitation frequency (Hz), and B_{max} is the maximum magnetic flux density (T). The parameters k , α , and β are material-dependent constants determined experimentally.

The equation shows that core losses increase with both increasing frequency and increasing flux density. This is due to the fact that higher frequency leads to more rapid magnetization reversals, while higher flux density increases the energy required to drive the magnetic material through each hysteresis cycle.

2.3.4.5 Eddy-current losses

As the magnetic fields vary periodically with the applied AC current, voltages are induced in the core, causing eddy currents to circulate in the core material, as shown in Figure 6.

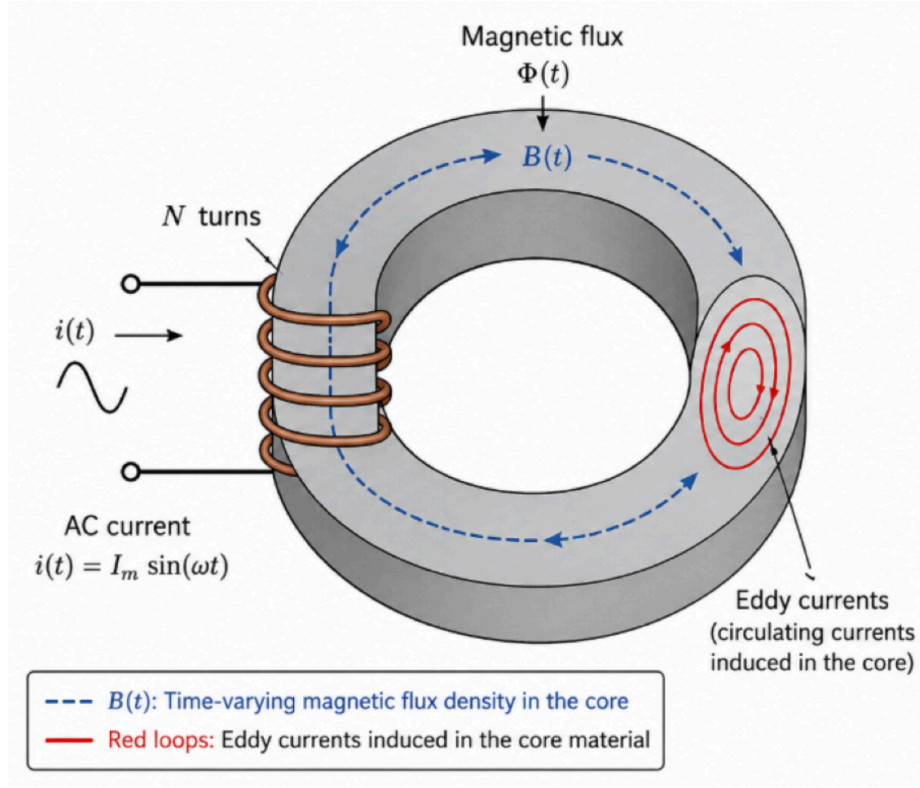


Figure 6: Induced eddy currents in a magnetic core caused by a time-varying magnetic flux density.

As a result, power is dissipated in the core according to:

$$P = \frac{V^2}{R} \quad (22)$$

Here, P is the power loss (in watts), V is the induced voltage driving the eddy currents in the core, and R is the effective electrical resistance of the current paths within the material. The expression shows that the dissipated power increases with the square of the induced voltage, while increasing resistance reduces the losses.

Eddy-current losses are usually mitigated by laminating the core with thin sheets of iron that are electrically insulated from one another such that they interrupt the flow of current. Thus the resistance becomes higher for eddy currents, and the loss is greatly reduced. For operation with a given peak flux density, the voltages induced in the core are proportional to frequency (due to Faraday's Law), making power loss due to eddy currents proportional to the square of frequency according to Eq. (22) above.

2.3.5 Temperature

When an electric current flows through a conductor, electrical energy is partly converted into heat due to the resistance of the material according to Eq. (20). This means that even a small increase in current can lead to a significant increase in heat generation. In practical applications, such as inductors carrying high currents, this effect becomes highly important, as excessive heating can affect both performance and safety.

As the temperature of the conductor increases, its electrical resistance also changes. For most conductive materials, such as copper and aluminium, the resistance increases with temperature. This relationship can be expressed as

$$R = R_0(1 + \alpha \Delta T) \quad (23)$$

where R_0 is the initial resistance, α is the temperature coefficient, and ΔT is the temperature change. This means that as a conductor heats up, its resistance becomes higher.

Current density affects resistive heating in a conductor and can lead to an increase in temperature. A high current density corresponds to a larger current per unit cross-sectional area, which results in increased resistive losses and a higher temperature. This, in turn, increases the resistance of the conductor and leads to even greater losses.

When current flows, heat is generated due to resistive losses. As the temperature rises, the resistance increases, which further enhances the power dissipation. This creates a positive feedback effect, which can lead to a continuous temperature rise if the system is not properly designed.

Thermal measurements are therefore essential in evaluating the performance of electrical components. By measuring the temperature rise under load conditions, it is possible to assess whether a conductor can safely handle a given current. In this project, thermal measurements are used to analyze how different conductor sizes affect temperature rise and overall efficiency. Additionally, at high temperatures a core material if it is present can lose its permeability. An inductor's performance depends theoretically on the above mentioned factors making accurate measurement essential for reliable circuit design.

2.4 Inductors role in power electronics

The hardware used to convert electric energy to and from other energy forms is called power electronics and is constituted in various forms of silicon-based components like diodes, transistors and thyristors [13, p.8]. Power electronics are also equipped with a control process in order to enhance the performance or to facilitate the conversion at all. One such common control technique is called Pulse Width Modulation (PWM) that regulates voltage and power by rapidly switching transistors on and off. PWM changes the width of pulses in a switching signal by adjusting how long the signal stays on or off (the duty cycle) and thus controlling the average output voltage.

The most trivial power electronic converter (PEC) is the Buck (step down) converter whose purpose is to convert the DC voltage applied between the input terminals to an average output voltage that is

lower or equal to the input voltage [13, p.9]. Its counterpart, the Boost (step up) converter similarly outputs a voltage that is always higher than or equal to the input voltage. In both these PECs inductors serve the function of smoothing out the current and storing energy during switching cycles. Inductors also play a crucial role in active dynamic filters (ADFs) which are PECs that are used in electrical power systems to improve power quality. Inductors suppress high-frequency current ripple generated in switching and ensure stable DC output. ADFs work by sensing, in real-time, the waveforms and injecting current to immediately cancel out the electrical disturbances.

ADFs consist of a three-phase LCL filter, a passive filter commonly used in grid-connected converters to attenuate switching harmonics before current is injected into the grid. The single-phase equivalent circuit of an LCL filter is shown in Figure 7. An LCL filter consists of three main components, a converter-side inductor (L) that smooths current from the inverter, a shunt capacitor (C) that provides a low-impedance path for harmonics and a grid-side inductor (L_g) that is smaller than L and further filters the current before it enters the grid. LCL filters offer superior performance compared to simple L filters, enabling the use of smaller inductors and thus a more compact overall design while achieving better harmonic attenuation. Among their drawbacks is the resonance that can occur by the interaction of its constituent components.

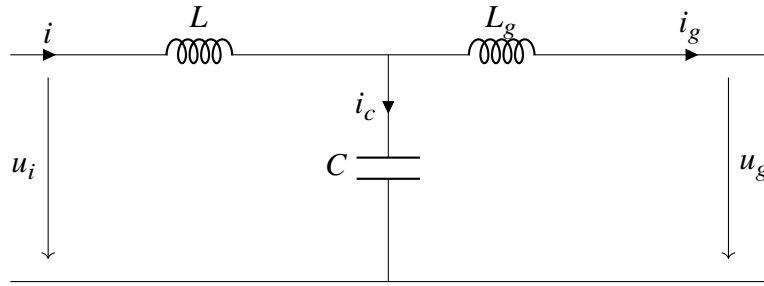


Figure 7: Single-phase equivalent circuit of an LCL filter.

Power quality can be defined as the ability of the electrical grid to provide a reliable power supply. Good power quality means that the voltage, current, and frequency remain close to their ideal values, and that the waveform is nearly a pure sinusoid. In practice, power quality issues occur when the electricity supplied to equipment is distorted, unstable, or interrupted. Electrical disturbances can be categorized into several categories, namely harmonics, reactive power, network unbalance, voltage variations, oscillations, flicker and transients [14]. These disturbances are mainly caused by nonlinear electrical loads such as variable frequency drives (VFDs). A nonlinear load draws current in pulses rather than smoothly, which distorts the waveform.

Harmonic distortion occurs when the current or voltage waveform in an electrical system is no longer a pure sinusoidal wave. Instead, the waveform contains additional frequencies that are multiples of the fundamental frequency which distorts the original sine wave. A distorted waveform can be understood as the sum of multiple sinusoidal waves. The current or voltage can be expressed as:

$$v(t) = V_1 \sin(\omega t) + V_2 \sin(2\omega t) + V_3 \sin(3\omega t) + \dots \quad (24)$$

Where V_1 is the fundamental component while the remaining terms ($V_2, V_3, \dots$) are the harmonic components. The DC component is excluded while the remaining values are RMS values. A common measure of distortion is Total Harmonic Distortion (THD) which is usually expressed as a percentage where a lower value indicates a purer waveform.

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots}}{V_1} \quad (25)$$

As nonlinear loads are increasing in modern grids due to the proliferation of PEC devices such as EV chargers, PVs and BESS, so does the concern of ensuring good enough power quality. This is because poor power quality can lead to overheating transformers, increased losses, reduced equipment lifetime and equipment malfunction.

2.5 Testing inductance

An LCR meter is an electronic test instrument used to measure the fundamental electrical properties of components, namely inductance (L), capacitance (C) and resistance (R). The LCR meter used in this study is illustrated in Figure 8. They can also measure the quality factor (Q -factor) which serves as a measurement of the reactance purity. The Q -factor is generally associated with inductors and the dissipation factor (D) with capacitors. The Q -factor can be defined as the ratio of the stored energy (reactance) and the dissipated energy (resistance) [5].

$$Q = \frac{1}{D} = \frac{|X_L|}{R} = \frac{\omega L}{R} = \frac{2\pi f L}{R} \quad (26)$$

LCR meters work by applying an AC voltage to the device under test and measuring the resulting voltage and current. From these measurements, the LCR meter calculates impedance and phase angle, which are then used to determine the component's L , C , and R values. In this study mainly small inductance values, around microhenries, are measured and thus the series circuit measurement model in the LCR meter is used to measure inductance.



Figure 8: B&K Precision 891 Bench LCR Meter.

The test frequency can greatly affect the results of measurement reading, especially when measuring inductance and capacitance as resistance is independent of frequency. The LCR meter used in the

study has a frequency range of 20 Hz - 300 kHz and according to its manual, frequencies above 1 kHz should be used to accurately measure inductance values below 2 mH.

2.6 DM- & CM-inductance

Inductors behave differently depending on how currents run through them. When the currents are flowing in the same direction through an inductor they see what is called the common mode (CM) inductance but when they are flowing in the opposite direction they see the differential mode (DM) inductance [15, p.1]. These two characteristics are manifested in the electrical component called Common mode choke (CMC) which acts as an electrical filter. It is a special type of inductor that consists of two or more windings wound on the same magnetic core, see Figure 9.

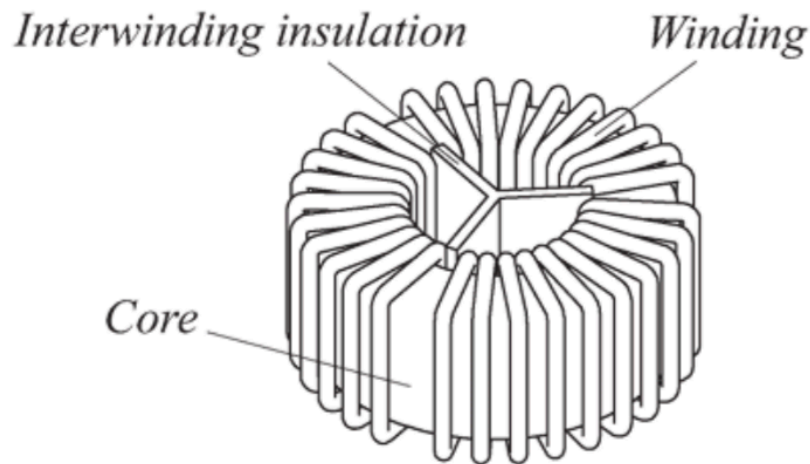


Figure 9: Three-phase Common mode choke (CMC).

When a differential signal (the desired signal) passes through, currents flow in opposite directions in the windings generating magnetic fluxes that ideally cancel each other entirely, resulting in no inductance. Non-idealities and leakage flux do introduce a certain amount of differential-mode inductance. When common mode (noise) currents pass through they instead generate magnetic fluxes that add up resulting in a large inductance that opposes the (common mode) noise.

3 Method

This chapter describes the methodology used in this study.

3.1 Hands-on calculations

The work was initiated by doing a literature review of the theory thought relevant in order to carry out the project. Given from the specifications of the thesis project the target value of inductance was 50 μH for one inductor. This value was used as a reference value throughout the entire project. As a grid-connected line filter is three-phase based it was necessary to construct three such inductors. The three 50 μH inductors are the converter-side inductors (which are the larger ones) of an LCL filter. The three grid-side inductors of the LCL filter were not considered in this thesis work. The solenoid topology was first investigated followed by the toroid topology due to it being more simple and familiar.

In order to get an initial feeling and understanding of the variables affecting the self-inductance of a solenoid and toroid, the ideal basic formulas for self-inductance (Eq. (11) and Eq. (12)) were used. By testing different combinations of values for the variables in Eq. (11) and Eq. (12) respectively, several inductance values of 50 μH were yielded. Only the value combinations that fit inside the volume (28 cm x 21 cm x 22 cm) that is occupied by the currently installed iron core LCL filter in the ADF P100 model from Comsys were considered. The results are shown in Table 5 under the results section.

In addition to the inductance calculations, manual calculations using Eq. (27)-(35) are performed in an Excel sheet to determine the conductor length, winding volume, total inductor volume, conductor mass, and DC resistance for each candidate design. The conductor length was estimated from the geometry of the winding arrangement (Eq. (30)), while the conductor mass was calculated from the conductor volume and the material density of copper (Eq. (33) and Eq. (34)). The DC resistance was determined using the conductor length, cross-sectional area, and the electrical resistivity of copper (Eq. (35)).

$$A_{cs} = \pi r^2 \quad (27)$$

$$C_{cs} = 2\pi r \quad (28)$$

$$C_{cs} = (D - d) + 2h \quad (29)$$

$$L_{Cu} = C_{Cu}N \quad (30)$$

$$A_{Cu} = \pi r_{Cu}^2 \quad (31)$$

$$V_{Cu} = A_{Cu}L_{Cu} \quad (32)$$

$$m_{solenoid} = \rho_{Cu} V_{solenoid} \quad (33)$$

$$m_{toroid} = \rho_{Cu} V_{Cu} \quad (34)$$

$$R_{DC} = \rho_{Cu} \frac{L_{Cu}}{A_{Cu}} \quad (35)$$

This approach ensured that the designed air-core inductors could be integrated into an existing system without modifying the overall layout. This avoids the need for a completely new system design and helps reduce development effort and resource consumption.

3.2 Simulations

3.2.1 LCL Filter Simulation in MATLAB/Simulink

To evaluate the performance of the designed inductors in a realistic application, simulations were also carried out using a pre-existing MATLAB/Simulink model of a grid-connected LCL filter. The simulation model was based on the course material provided in EIEN90 [16], specifically the simulation model provided in Lecture 5.

The purpose of these simulations was to investigate the behavior of the converter when using the designed coreless inductors as the converter-side inductors of the LCL filter. The complete system consisted of a converter-side inductance of $L_1 = 50 \mu\text{H}$, a filter capacitance of $C_f = 50 \mu\text{F}$, and a grid-side inductance of $L_2 = 20 \mu\text{H}$.

The simulations were used to study the current and voltage waveforms as well as the filtering performance of the LCL filter. The obtained results are compared with the design requirements to verify that the selected inductance value is suitable for the intended application. Representative simulation results are presented in Figure 22 under the Results section.

3.2.2 Inductor Simulation in COMSOL

The simulations in this study were conducted using COMSOL Multiphysics to investigate the electromagnetic behavior of the inductors. They complemented the analytical calculations by providing further insight into the magnetic flux density distribution, current density, inductance, and resistance of the investigated designs. In addition, the simulations contributed to a deeper theoretical understanding of the studied phenomena and served as a valuable preliminary step prior to experimental testing.

Initially, simple solenoid models were developed to familiarize the authors with the simulation environment and validate the modeling procedure. Various geometries and operating conditions were examined, with particular focus on the magnetic flux density distribution and current density within the conductors.

The simulations were performed using the *Magnetic Fields* physics interface in the AC/DC module of COMSOL Multiphysics. Frequency-domain studies were mainly used in order to analyze the inductors under AC operating conditions and to investigate the frequency dependence of the resistance and current density distribution. Stationary studies were also used in selected cases to examine the magnetic field distribution at DC conditions.

Copper was assigned as the conductor material, while the surrounding domain was defined as air. The excitation current was applied through multi-turn coil domains with specified RMS current values depending on the investigated operating condition. Magnetic insulation boundary conditions were applied at the outer boundaries of the surrounding air domain in order to approximate an open boundary environment.

A physics-controlled mesh with additional mesh refinement around the conductor regions was used to improve the accuracy of the current density distribution, particularly at higher frequencies where skin and proximity effects become more pronounced.

The inductance was extracted using the built-in coil parameter evaluation available in COMSOL, while the AC resistance was determined from the simulated voltage and current relations for different operating frequencies. The obtained simulation results are compared with analytical calculations and experimental measurements.

Due to the rotational symmetry of the solenoid geometry, a 2D axisymmetric model was employed, reducing computational effort while maintaining high accuracy. Inductance and AC resistance were evaluated for different frequencies and geometries using the same dimensions and operating conditions as in the analytical calculations, enabling direct comparison between theoretical and simulated results.

A similar methodology was applied to the toroidal inductors. Owing to their more complex geometry, full 3D models were required, resulting in larger meshes and higher computational demands. The magnetic flux density distribution was analyzed using surface plots and Cut Line 3D evaluations, with both vertical and horizontal cut lines used to examine the field distribution throughout the toroid. Furthermore, the inductance and AC resistance obtained from the simulations were compared with the corresponding analytical results.

3.3 Experiments

3.3.1 Experimental objective

The purpose of the experimental work was to validate the analytical calculations and COMSOL simulations while evaluating the feasibility of air-core inductors for use as converter-side inductors in the Comsys Active Dynamic Filter (ADF P100). The experiments were designed to characterize the electrical and thermal performance of different air-core inductor geometries and to assess their practical suitability with respect to manufacturability, cooling, and system integration.

Both solenoid and toroidal air-core inductors were investigated experimentally. Several prototype geometries and conductor cross-sections were evaluated in order to determine how these design

parameters influence inductance, electrical resistance, and temperature rise during operation. The experimental results were subsequently compared with the corresponding analytical calculations and numerical simulations.

3.3.2 Test objects

The experimental investigation comprised both solenoid and toroidal air-core inductors manufactured specifically for this study. All prototypes, except for the initial manually constructed solenoid, were designed in Rhinoceros (Rhino) and manufactured using PLA by means of 3D printing. This approach enabled accurate control of the inductor geometry while providing mechanically robust structures suitable for repeated winding and testing.

3.3.2.1 Solenoid prototypes

Two solenoid prototypes were investigated. The first consisted of a manually constructed prototype using a duct tape roll as the winding support. This prototype served as a preliminary reference design for verifying the measurement procedure and gaining practical experience with winding air-core inductors. It was wound using a 16 mm² copper conductor and consisted of ten turns, see Figure 10.



Figure 10: Duct tape solenoid.

The second (pink) solenoid prototype was manufactured using 3D printing and maintained the same geometry throughout the investigation while being successively wound using 16 mm², 10 mm², and 6 mm² copper conductors, see Figure 11. This allowed the influence of conductor cross-section on both electrical and thermal performance to be evaluated. All inductors in this study were wound using commercially available copper conductors with a maximum continuous operating temperature of 100°C. These conductors were selected primarily based on their availability rather than their

suitability for the intended application. The investigated solenoid geometries are summarized in Table 3.

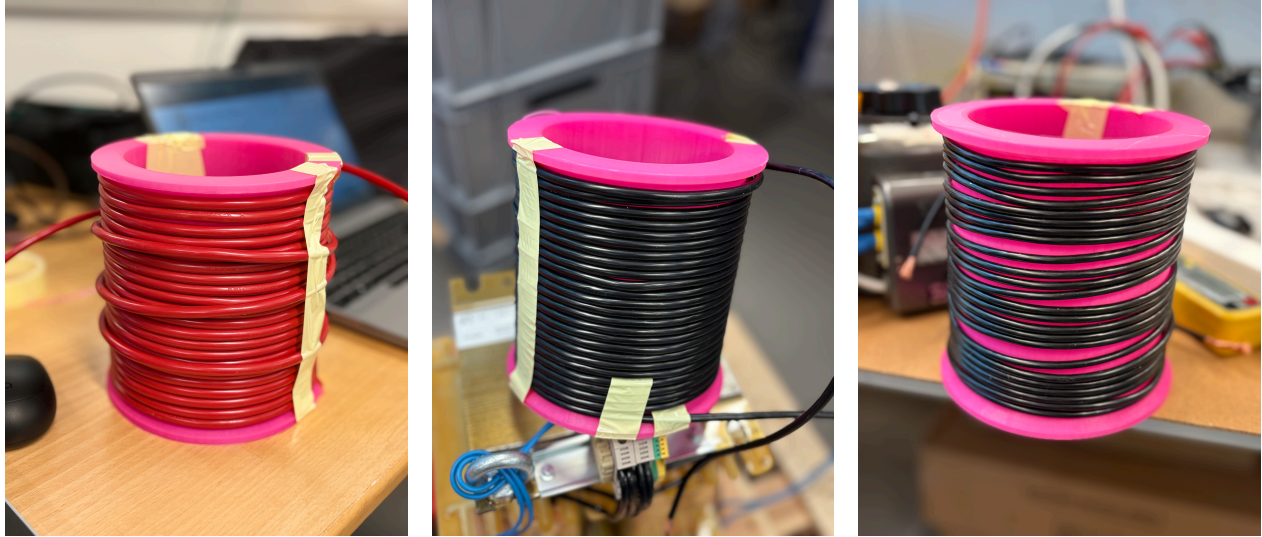


Figure 11: Pink solenoid wound with 16 mm² (left), 10 mm² (middle) and 6 mm² (right).

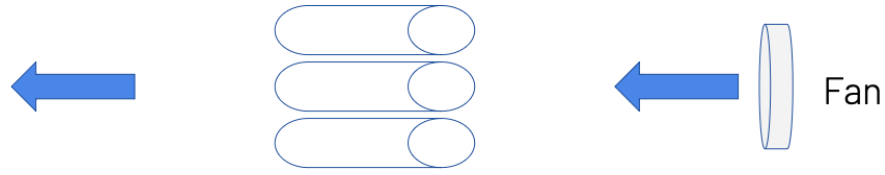
Table 3: Summary of the manufactured solenoids used in the experimental investigation.

Prototype	Length (l) [cm]	Inner radius (r) [cm]	Turns (N)	Weight [g]
Duck tape solenoid	5	5	10	850
Pink solenoid	15	6	24	282 (without windings)

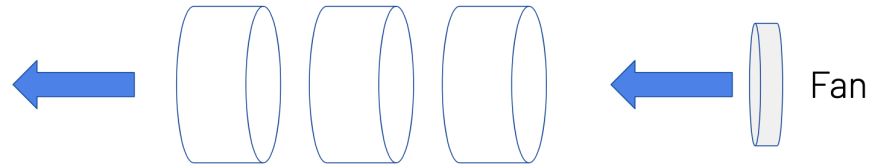
Only one solenoid was 3D printed was in order to save time and resources because it was already expected from the theory that a toroid would probably be the final choice due to it naturally confining the magnetic field within the structure.

3.3.2.2 Toroidal prototypes

Two main toroid configurations were investigated in more detail. Both designs satisfied the dimensional constraints imposed by the available installation volume within the Comsys cabinet. One configuration consisted of three long and thin toroids arranged in parallel, while the other consisted of three short and thick toroids connected in series, see Figure 12.



(a) Three long and thin toroids in parallel.



(b) Three short and thick toroids in series.

Figure 12: Toroid configurations.

One prototype from each configuration was manufactured using 3D printing and are illustrated in Figure 13.



(a) Long and thin (black) toroid.



(b) Short and thick (yellow-white) toroid.

Figure 13: One toroid prototype from each configuration.

The black toroid was wound using a 6 mm^2 copper conductor, while the yellow-white toroid was initially wound using a 10 mm^2 conductor before later being rewound using a 6 mm^2 conductor to

investigate the influence of conductor size and winding quality.

Based on the experimental results, a final toroidal design (the white toroid) was developed from the short and thick configuration. As can be seen in Figure 14, additional ventilation openings were incorporated into the end caps to improve airflow during operation.

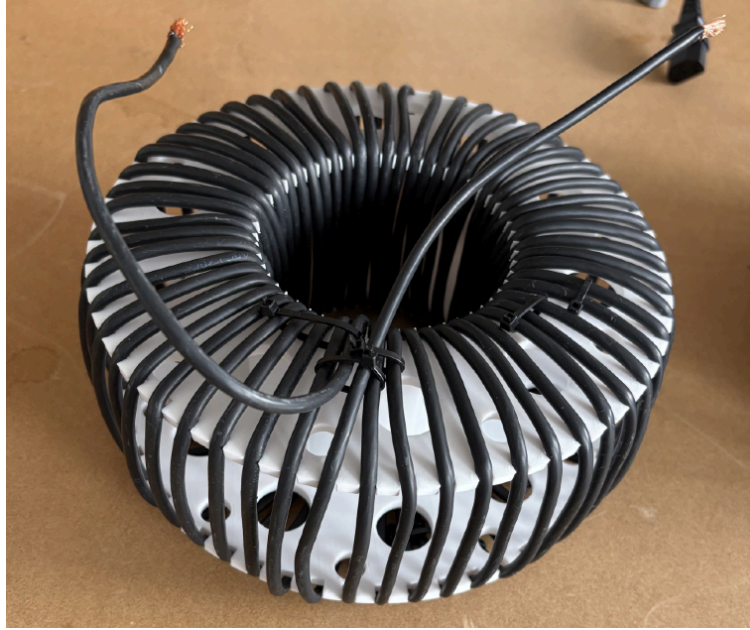


Figure 14: Final design of (white) toroid.

Two identical toroidal inductors (yellow and blue toroids) were subsequently manufactured to represent the three phases of the converter-side inductors. All the three final toroids are shown in Figure 15.

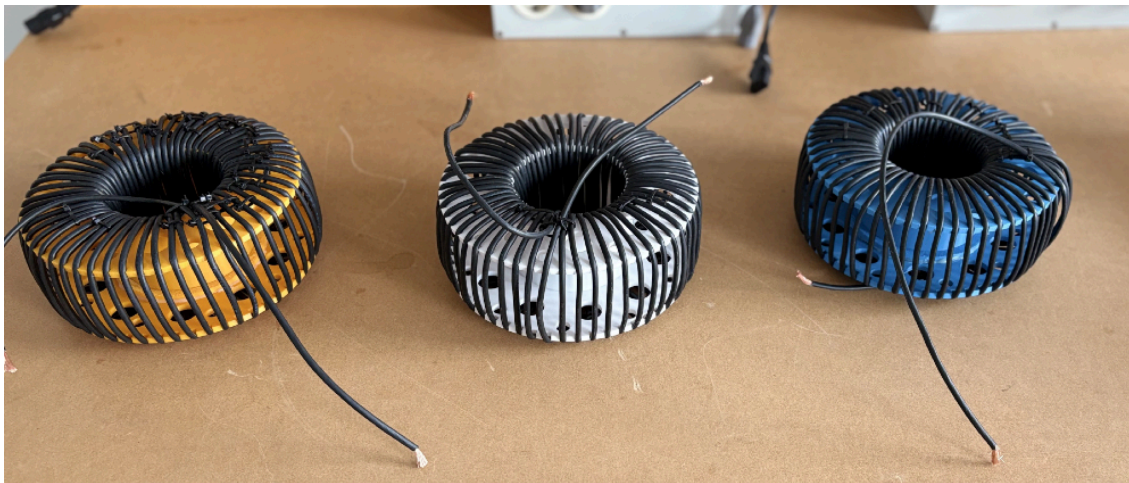


Figure 15: Final design of the coreless inductors.

The investigated toroidal geometries are summarized in Table 4.

Table 4: Summary of the manufactured toroids used in the experimental investigation.

Prototype	Inner diameter d [cm]	Outer diameter D [cm]	Height h [cm]	Turns N	Weight [g]
Black toroid	6	10	25	31	757
Yellow-white toroid	10	20	8	50	1176
White/yellow/blue toroid	10	20	8	50	1377

3.3.3 Measurement setup

The inductance and series resistance were measured with the LCR meter over multiple excitation frequencies using the series measurement mode, which is suitable for low-inductance components. The LCR meter was connected with Kelvin cables which are specialized cables used to accurately measure electrical parameters by eliminating the voltage drop caused by wire and contact resistance.

Thermal measurements were performed using an infrared temperature gun. During the thermal tests, the inductors were energized from an AC supply through a variable transformer connected to a single-phase transformer, allowing the current to be continuously regulated to the desired test level (by adjusting the wheel on the variable transformer). Current transformers (CTs) were installed on both the low-voltage and high-voltage sides of the single-phase transformer to continuously monitor the current throughout the experiments.

Forced-air cooling was investigated using both a conventional desk fan and the cooling fan employed in the Comsys ADF P100 cabinet. Additional experiments were conducted using two fans simultaneously to evaluate the influence of increased airflow on the thermal behaviour of the inductors. The laboratory setups (including the equipment used) are shown in Figures 16 and 18, while the corresponding electrical connections are illustrated in Figures 17 and 19.

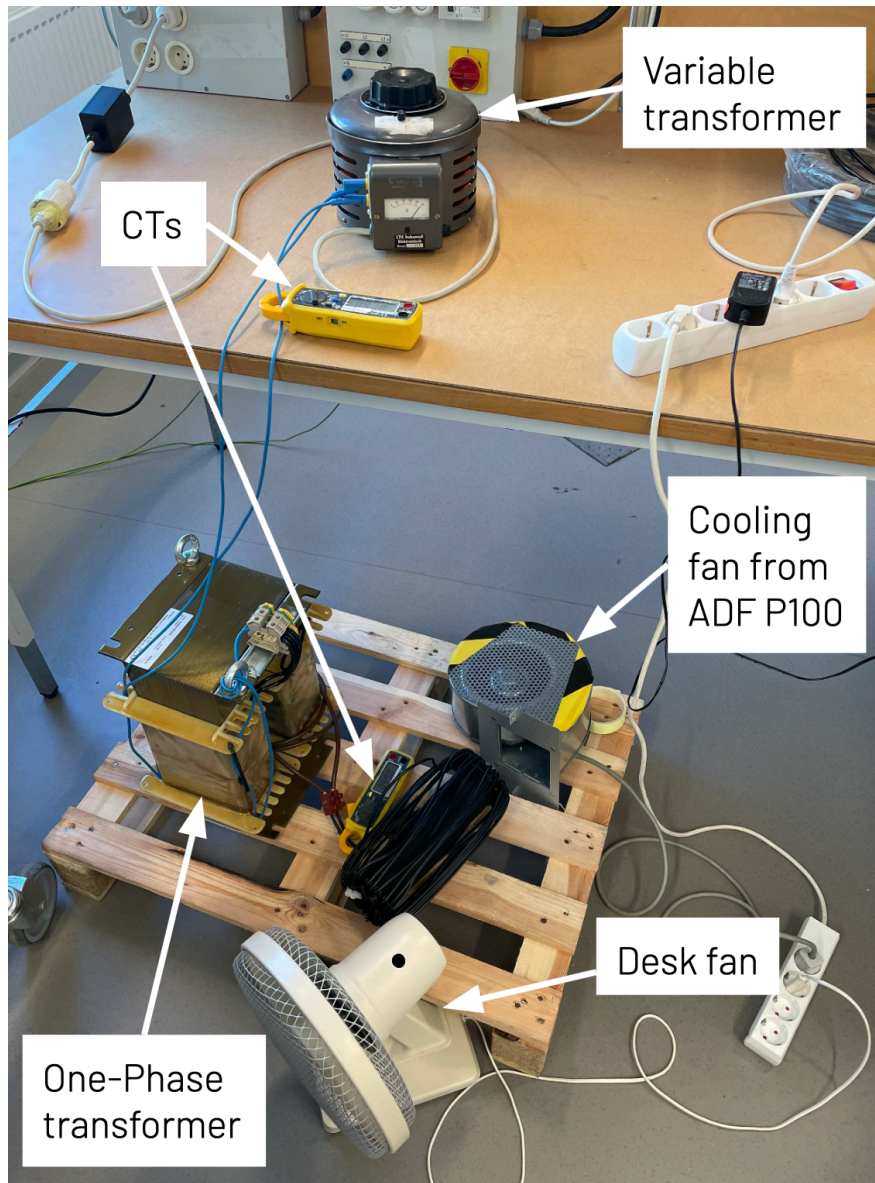


Figure 16: Lab setup.

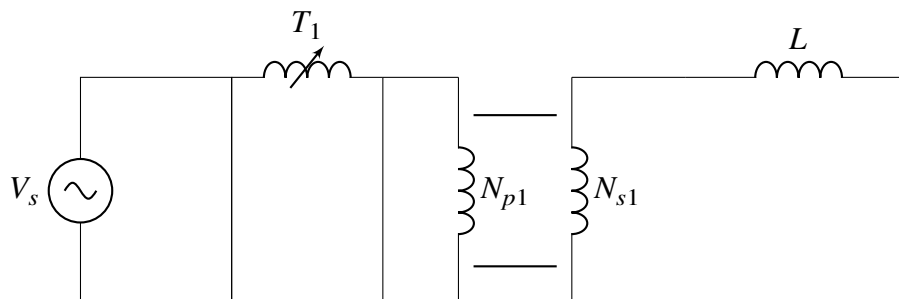


Figure 17: Circuit diagram corresponding to the laboratory setup.

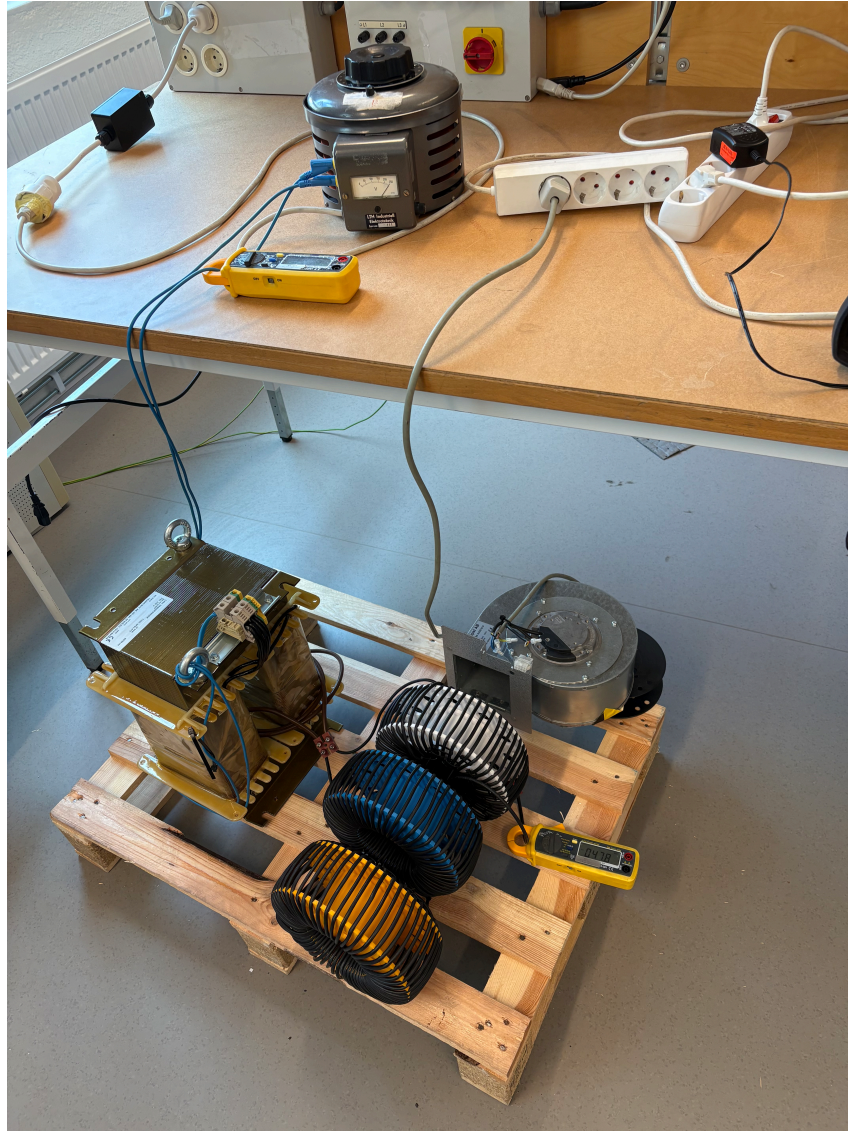


Figure 18: Lab setup with the three inductors connected in series.

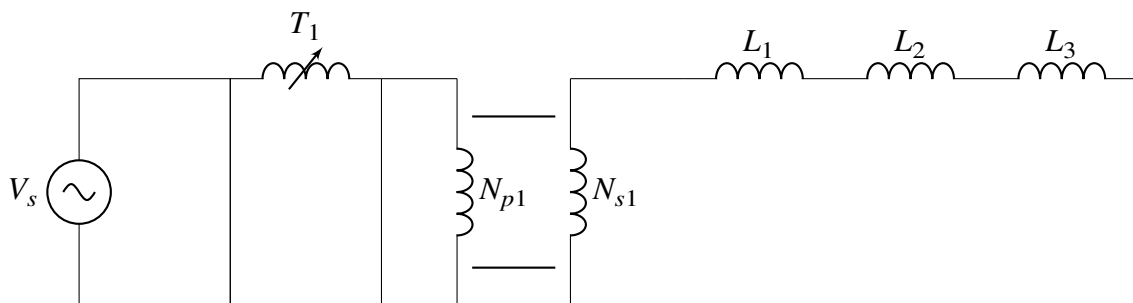


Figure 19: Circuit diagram corresponding to the laboratory setup of the three inductors connected in series.

3.3.4 Measurement procedure

The experimental investigation consisted of electrical characterization, thermal characterization, and final system validation.

The electrical characterization consisted of measuring the inductance and series resistance of each prototype over a range of excitation frequencies using the LCR meter. The measured values were later compared with the corresponding analytical calculations and COMSOL simulations to evaluate the accuracy of the theoretical models.

Thermal performance was evaluated by operating each prototype at a constant current of $100 A_{rms}$ for 15 minutes. A current exceeding the rated operating current of $80 A_{rms}$ was selected to provide additional thermal margin during the evaluation of the prototype designs.

Several cooling conditions were also investigated. Measurements were performed without forced cooling as well as with forced-air cooling using a desk fan and the Comsys cooling fan. For the toroidal prototypes, additional measurements were conducted by varying both the orientation of the prototype and the fan position to evaluate the influence of airflow distribution on the cooling performance.

After the preferred toroidal geometry had been identified, the final design was evaluated individually before being connected in series with the other two identical inductors (Figure 18) to represent the converter-side inductors of the three-phase LCL filter. The complete three-phase arrangement was then thermally tested at the rated operating current of $80 A_{rms}$ under different cooling conditions.

3.3.5 Measurement uncertainty

The experimental uncertainty originates primarily from the measurement instruments, manufacturing tolerances, and environmental conditions.

The electrical measurements are influenced by the accuracy of the LCR meter and the repeatability of the electrical connections during testing. Variations in winding geometry, conductor placement, and turn spacing introduced during manual winding may also affect the measured inductance and resistance.

The thermal measurements are affected by the accuracy and positioning of the infrared thermometer, uncertainties associated with the surface emissivity of the conductors, and variations in ambient temperature and airflow. Since the prototypes were wound manually, small differences in winding tension and conductor positioning may also influence both the thermal behaviour and cooling performance. These uncertainties were minimized by performing all measurements using identical laboratory equipment and consistent experimental procedures.

3.3.6 Evaluation criteria

The investigated prototypes were evaluated using both electrical and practical performance criteria. The primary electrical criterion was achieving an inductance close to the design target of $50 \mu H$

while maintaining low electrical resistance and acceptable thermal performance during continuous operation.

In addition to the measured electrical performance, the prototypes were evaluated with respect to manufacturability, ease of winding, effectiveness of forced-air cooling, compatibility with the available installation volume within the Comsys cabinet, and overall suitability for implementation as the converter-side inductors of the three-phase LCL filter.

3.3.7 Integration in the Comsys Cabinet

As a final validation step, the three air-core inductors were mounted and tested inside a Comsys grid filter cabinet (ADF P100). The purpose of this step was to verify that the proposed toroidal design could be physically integrated into the available cabinet space and operate under realistic system conditions.

The test setup consisted of a three-phase inverter connected to the fabricated toroidal inductors and the LCL filter arrangement. The inverter used in the experiments was a SKiiP 513 GB 172 CT module manufactured by Semikron Danfoss [17]. The current was measured using a PAC17 current probe manufactured by Chauvin Arnoux [18].

The complete laboratory setup is shown in Figures 20 and 21. Figure 20 shows the cabinet with the cover removed, illustrating the placement of the toroidal inductors and associated components. Figure 21 shows the fully assembled cabinet used during the final validation tests. The installation was evaluated with respect to mechanical fit, integration feasibility, and practical implementation aspects.

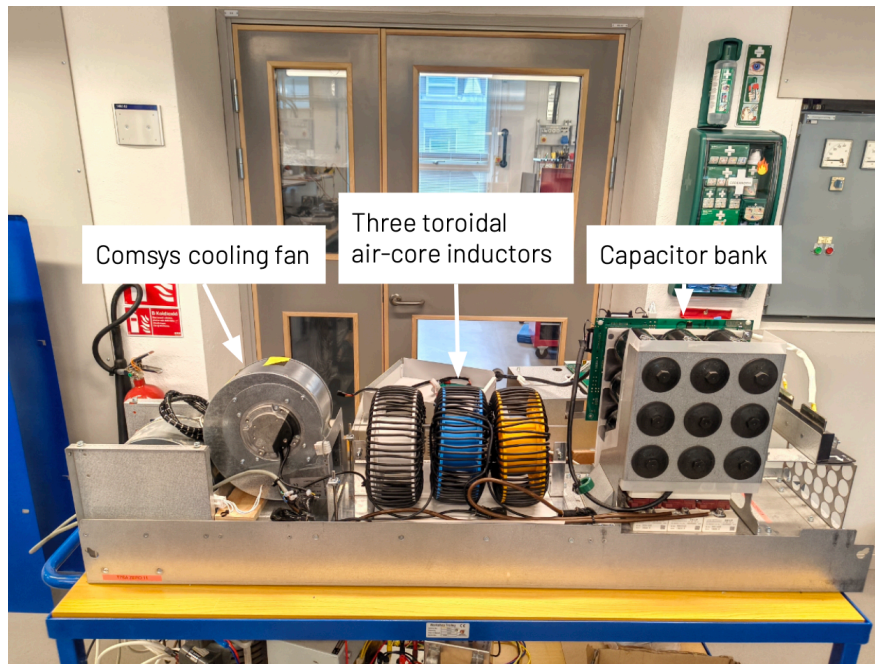


Figure 20: Comsys cabinet with the enclosure removed, showing the installation of the three toroidal air-core inductors.



Figure 21: Final Comsys cabinet assembly used during the validation tests.

4 Results

4.1 LCL Filter Simulations in MATLAB/Simulink

Figure 22 shows the MATLAB/Simulink results of the LCL filter under full-load operation. The converter current represents the current through the inductors, while the grid current corresponds to the filtered current injected into the grid. The results indicate that the grid current is intentionally controlled to be approximately 90° phase-shifted relative to the grid voltage, corresponding to reactive power operation. The total harmonic distortion (THD) is around 5%, which is within acceptable limits.

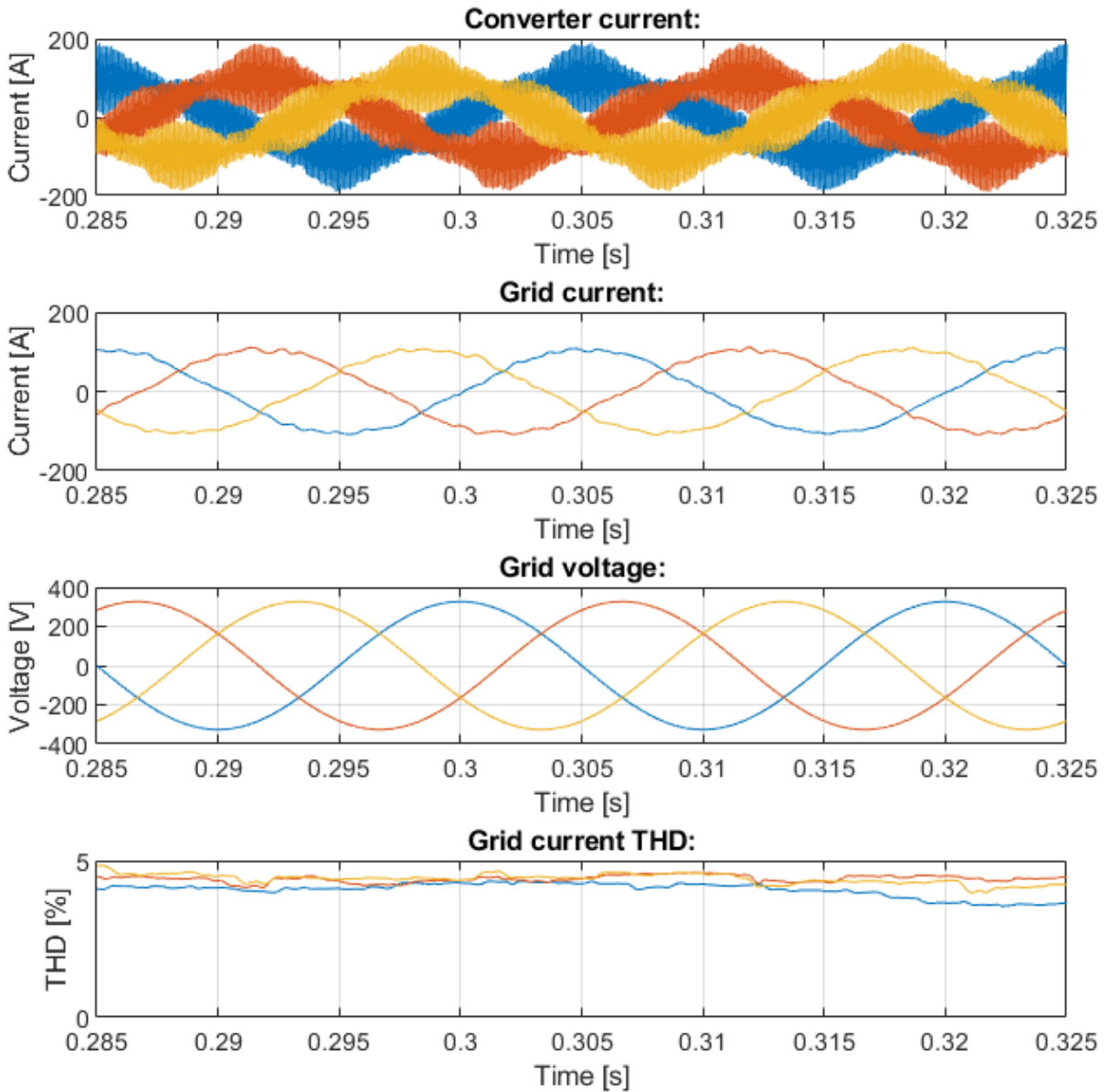


Figure 22: Simulated currents in the LCL filter under full-load operation.

4.2 Solenoid

4.2.1 Theoretical calculation results

The solenoid values derived from both analytical calculations and steady-state simulations are presented in Table 5, whereas the corresponding geometric parameters are given in Table 6.

Table 5: Solenoid inductance parameter values.

Prototype	r [cm]	l [cm]	N	L_{theory} [μ H]	L_{sim} [μ H]	L_{sim}/L_{theory} [%]	l/r	N/l
-	6	5	20	113	56.8	49.9%	0.83	4
Pink solenoid	6	15	24	54	45.9	84%	2.5	1.6
-	6	20	28	55	51.16	91.8%	3.33	1.4
Duct tape solenoid	5	5	10	19.7	9.96	50.4%	1	2

Table 6: Solenoid geometry parameter values.

A_{cs} [m^2]	C_{Cu} [m]	L_{Cu} [m]	r_{Cu} [m]	A_{Cu} [m^2]	$V_{solenoid}$ [m^3]	$m_{solenoid}$ [kg]	ϱ_{Cu} [Ωm]	R_{DC} [m Ω]
0.0113	0.377	7.53	0.006	0.000113	0.00085	7.61	1.67×10^{-8}	1.11
0.0113	0.377	9.04	0.006	0.000113	0.00102	9.13	1.67×10^{-8}	1.33
0.0113	0.377	10.55	0.006	0.000113	0.00119	10.65	1.67×10^{-8}	1.55
0.0078	0.314	3.14	0.006	0.000113	0.00035	3.17	1.67×10^{-8}	0.46

The comparison between theoretical and simulated inductance shows that the agreement depends strongly on the solenoid geometry.

Good agreement is observed for solenoids with a high length-to-radius ratio ($l \gg r$), since the analytical model is based on ideal assumptions such as uniform current distribution and negligible edge effects.

For shorter and thicker solenoids, larger deviations are observed. This is because the analytical model does not fully capture real electromagnetic effects, while the 2D axisymmetric COMSOL model includes more realistic field distribution effects such as magnetic flux fringing and non-uniform current density within the coil cross-section.

Overall, the results confirm that the analytical model is valid for long and thin solenoids, while numerical simulations provide more accurate results for compact geometries.

4.2.2 Simulation results

Table 7: Simulated inductance and resistance values of the duct tape solenoid.

Frequency [Hz]	Inductance [μ H]	AC Resistance [$m\Omega$]
50	10.17	3.76
500	10.16	3.82
1 000	10.15	4.01
5 000	10.07	6.92
10 000	10.01	10.37
20 000	9.96	15.00
50 000	9.91	23.83
100 000	9.89	33.83
200 000	9.88	47.97
300 000	9.87	58.81

Table 8: Simulated inductance and resistance values of the pink solenoid (16 mm²).

Frequency [Hz]	Inductance [μ H]	(AC) Resistance [$m\Omega$]
50	36.28	3.32
500	35.45	7.11
1 000	34.69	11.78
5 000	33.34	35.47
10 000	32.93	59.27
20 000	32.59	102.51
50 000	32.19	230.85
100 000	31.89	457.66
200 000	31.56	921.04
300 000	31.36	1363.00

Figures 23, 24 and 25 illustrate the magnetic flux density from different viewing angles while Figure 26 illustrates the current density distribution inside a conductor making up a solenoid.

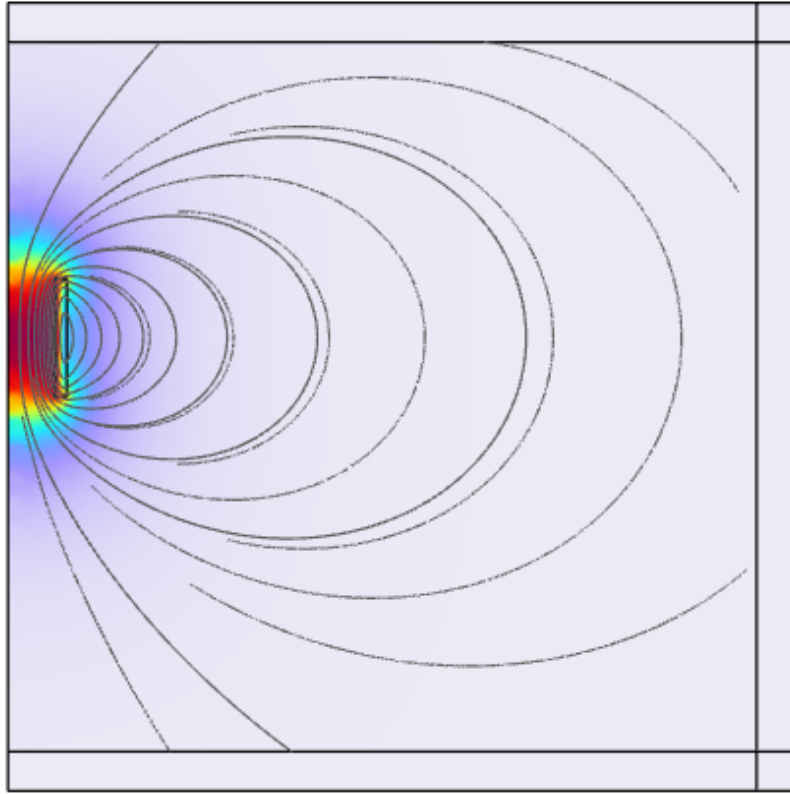


Figure 23: Spread of magnetic flux density (2D-Axisymmetric view).

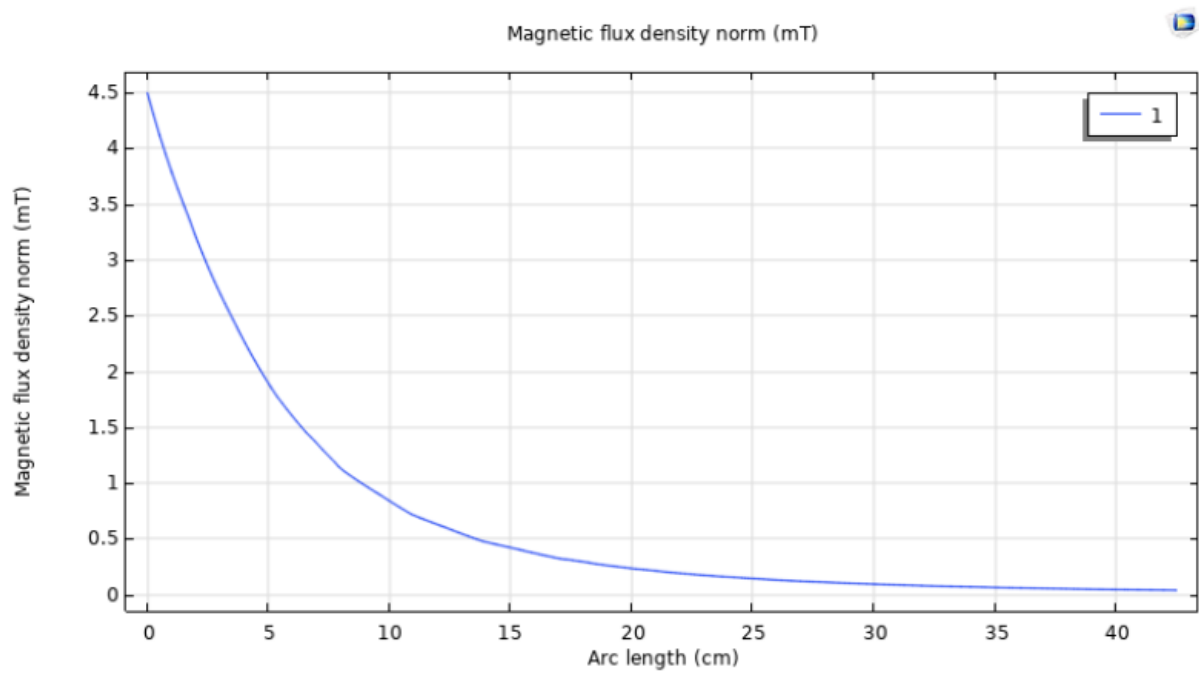


Figure 24: Horizontal spread of magnetic flux density from the side of a solenoid.

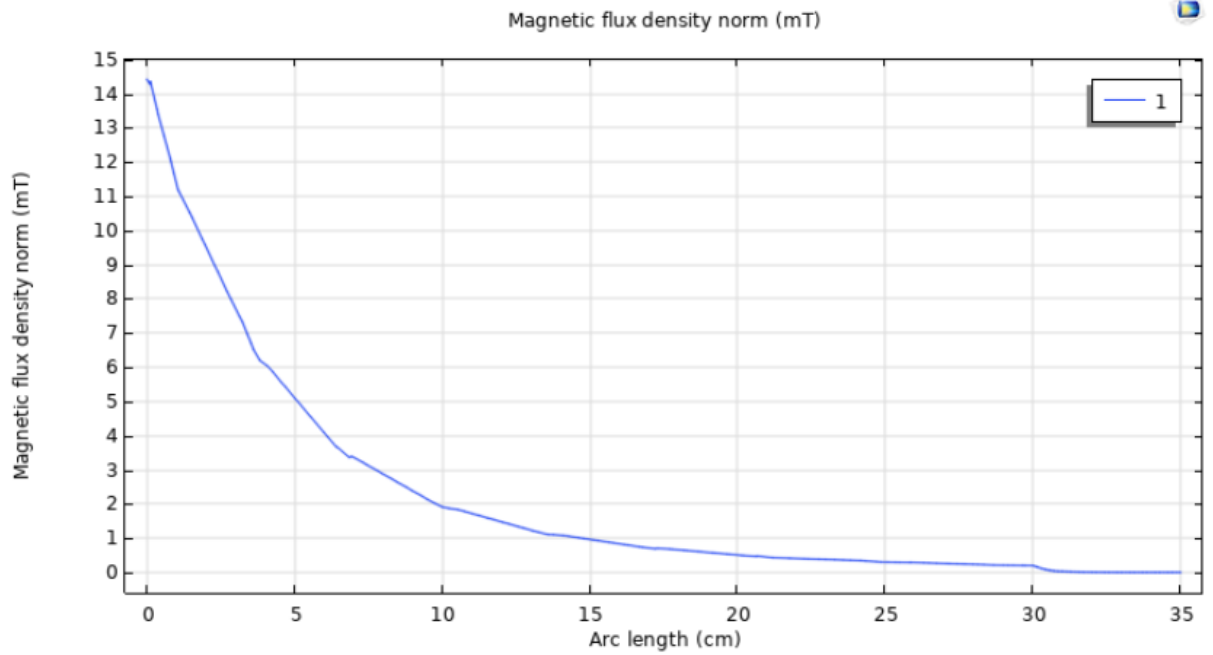


Figure 25: Vertical spread of magnetic flux density from the top of a solenoid.

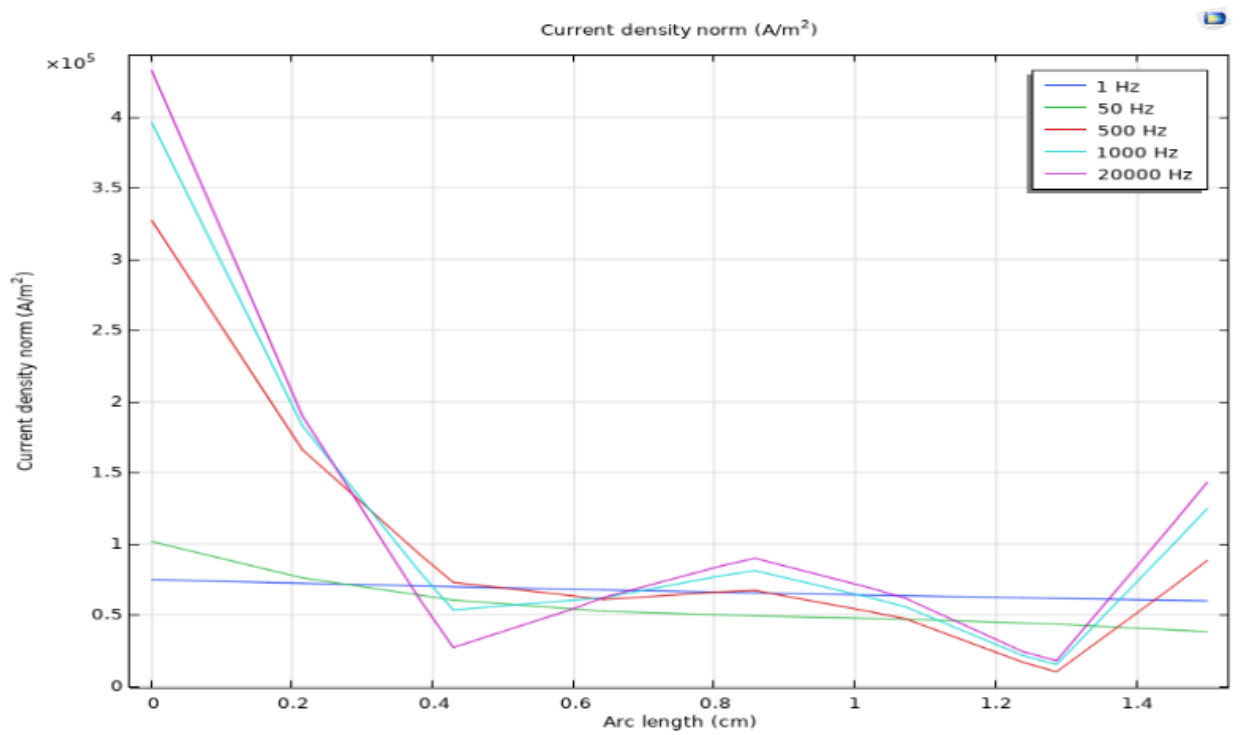


Figure 26: Current density distribution at different frequencies inside a conductor making up a solenoid.

4.2.3 Experimental results

The measured (from LCR meter) inductance and resistance values of the solenoids over different frequencies are shown in Tables 9 and 10.

Table 9: Measured inductance and resistance values of the duct tape solenoid.

Frequency [Hz]	Inductance [μ H]	Equivalent resistance [$m\Omega$]
50	22.44	5.20
500	18.29	5.53
1 000	17.70	6.00
5 000	17.20	11.50
10 000	17.06	18.52
20 000	16.97	30.80
50 000	16.81	106.20
100 000	16.60	277.30
200 000	16.38	620.00
300 000	16.25	825.00

Table 10: Measured inductance and resistance values of the pink solenoid.

Frequency [Hz]	Inductance [μ H]	Equivalent resistance [$m\Omega$]
	16 mm ² 10 mm ² 6 mm ²	16 mm ² 10 mm ² 6 mm ²
50	65.60 60.00 60.00	14.2 21.0 31.8
500	62.30 59.60 56.50	14.0 22.8 33.1
1 000	61.90 59.10 55.86	14.2 23.1 33.9
5 000	61.38 58.50 55.10	22.0 29.5 43.4
10 000	61.20 58.40 54.90	37.5 49.4 57.3
20 000	61.00 58.21 54.66	69.6 59.1 78.9
50 000	60.56 57.90 54.30	237.0 140.2 176.3
100 000	60.25 57.80 54.25	580.0 327.0 276.0
200 000	59.90 57.50 54.08	1100.0 638.0 473.8
300 000	59.84 57.30 54.96	1450.0 840.0 650.0

The thermal results of duct tape inductor were discussed live during testing and were thus not noted. The thermal results of the pink solenoid on the other hand are illustrated in Figures 27 - 29.

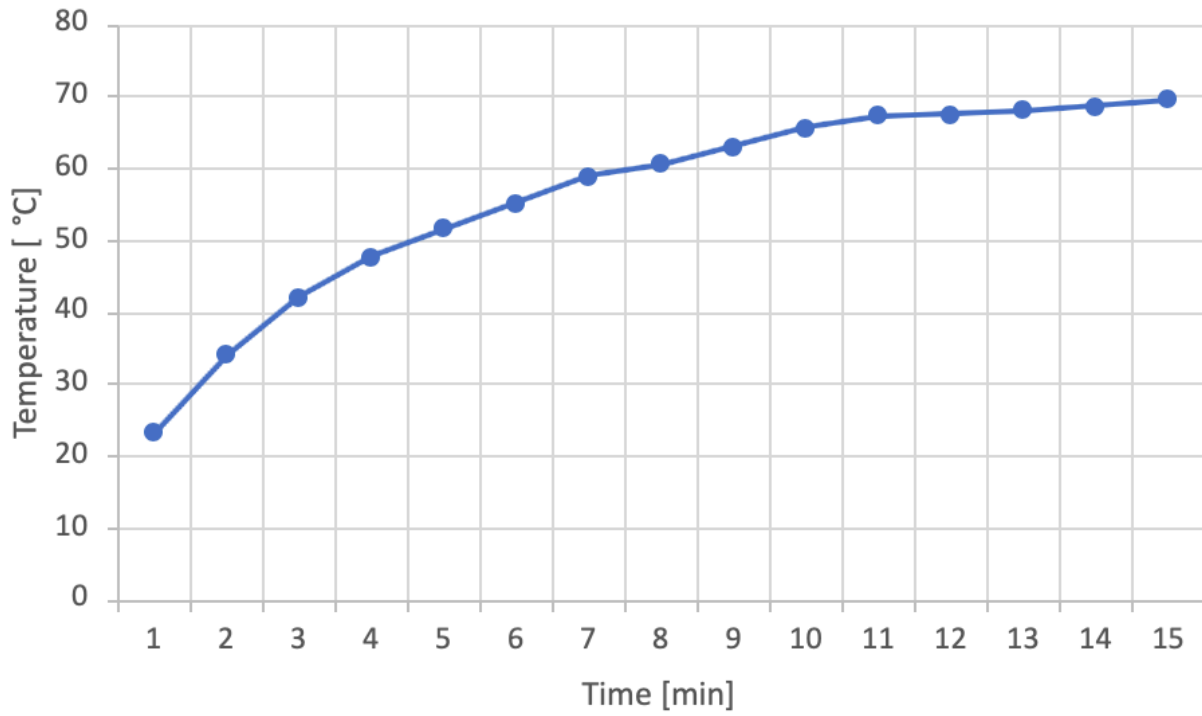


Figure 27: $I = 80 A_{rms}$, 10 mm^2 and desk fan.

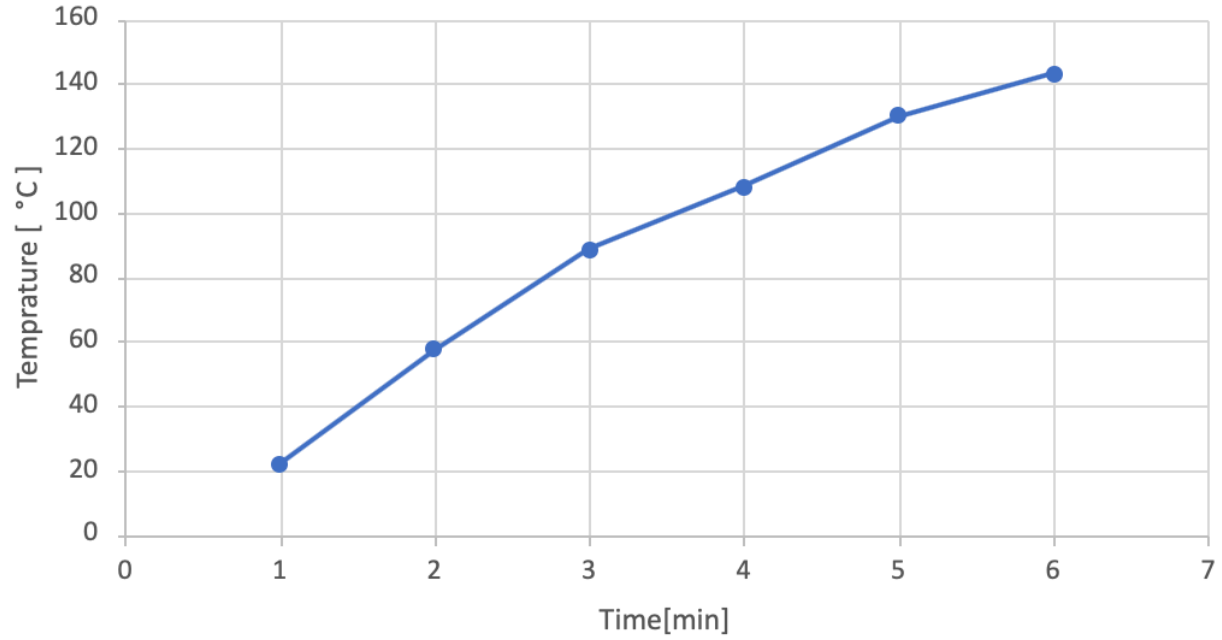


Figure 28: $I = 100 A_{rms}$, 6 mm^2 and desk fan.

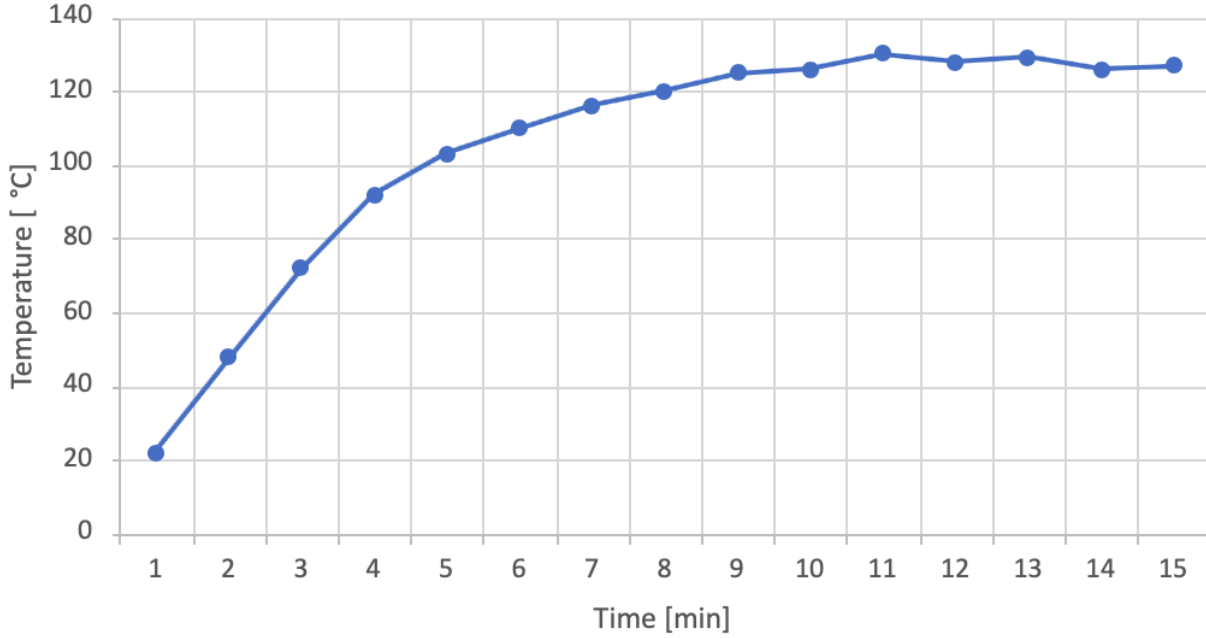


Figure 29: $I = 100 A_{rms}$, 6 mm^2 and Comsys fan.

4.3 Toroid

4.3.1 Theoretical calculation results

The toroid values obtained from the hand calculations and COMSOL simulations are presented in Table 11, while the corresponding geometric parameters are listed in Table 12. The values in the second and third rows of both tables served as the basis for the design of the black toroid and the yellow-white toroid, respectively.

Table 11: Toroid inductance parameter values.

Prototype	D [cm]	d [cm]	h [cm]	N	$L_{theory} [\mu\text{H}]$	$L_{sim} [\mu\text{H}]$	$L_{sim}/L_{theory} [\%]$	$C_{in} [\text{cm}]$	$N/C_{in} [\text{turns/cm}]$
-	9	5	17	50	49.96	48.01	96%	15.70	3.18
Black toroid	10	6	25	44	49.40	47.60	84%	18.84	2.33
Yellow-white toroid	20	10	8	50	27.72	27.09	104%	31.41	1.59

Table 12: Toroid geometry parameter values.

$C_{Cu} [\text{m}]$	$L_{Cu} [\text{m}]$	$A_{Cu} [\text{m}^2]$	$V_{Cu} [\text{m}^3]$	$\rho_{Cu} [\text{kg/m}^3]$	$m_{toroid} [\text{kg}]$	$\rho_{Cu} [\Omega\text{m}]$	$R_{DC} [\text{m}\Omega]$
0.38	19.00	0.000008	0.00015	8960	1.36	1.67×10^{-8}	40.0
0.54	23.76	0.00001	0.00023	8960	2.12	1.67×10^{-8}	40.0
0.26	13.00	0.00001	0.00013	8960	1.16	1.67×10^{-8}	21.8

When comparing the agreement between theoretical and simulated results for the toroid and the solenoid, a clear difference can be observed.

For the toroidal inductors, the agreement between L_{theory} and L_{sim} is generally very good, with only small deviations across all designs. This strong agreement is partly explained by the fact that the toroid was modeled using a full 3D simulation, which accurately captures the complete magnetic field distribution and winding geometry.

In contrast, the solenoid shows larger deviations between theoretical and simulated inductance values. The solenoid was modeled using a 2D axisymmetric approach, which assumes perfect rotational symmetry and a continuous current distribution. While this significantly reduces computational cost, it also introduces simplifications that do not fully capture real 3D effects such as edge fringing and discrete winding structure.

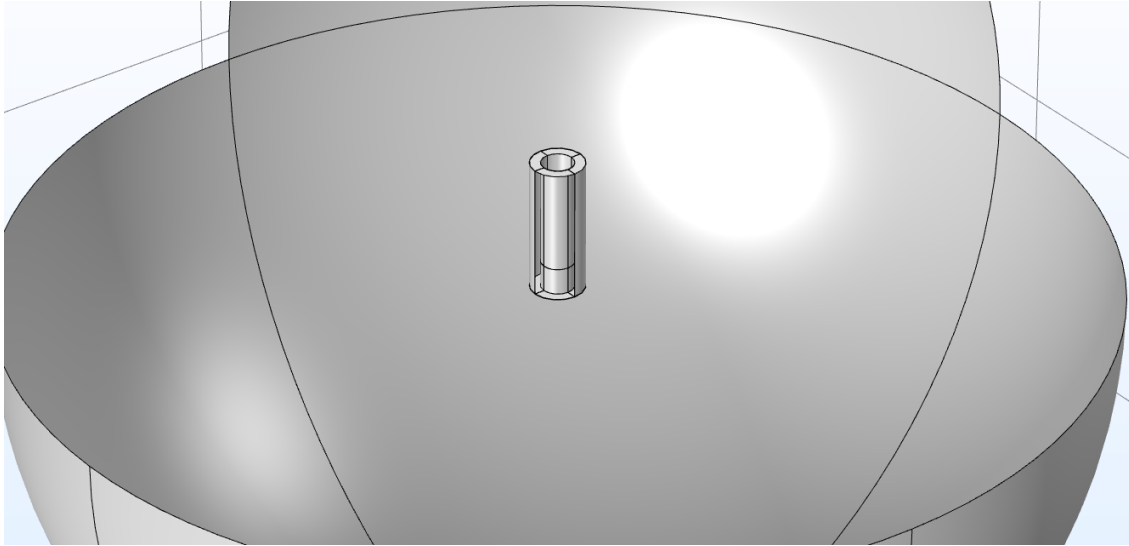
Overall, the results show that the toroidal configuration provides a better agreement between theory and simulation than the solenoid. This is due to both the more accurate physical behavior of the toroid (magnetic flux confinement) and the higher-fidelity 3D simulation model used.

4.3.2 Simulation results

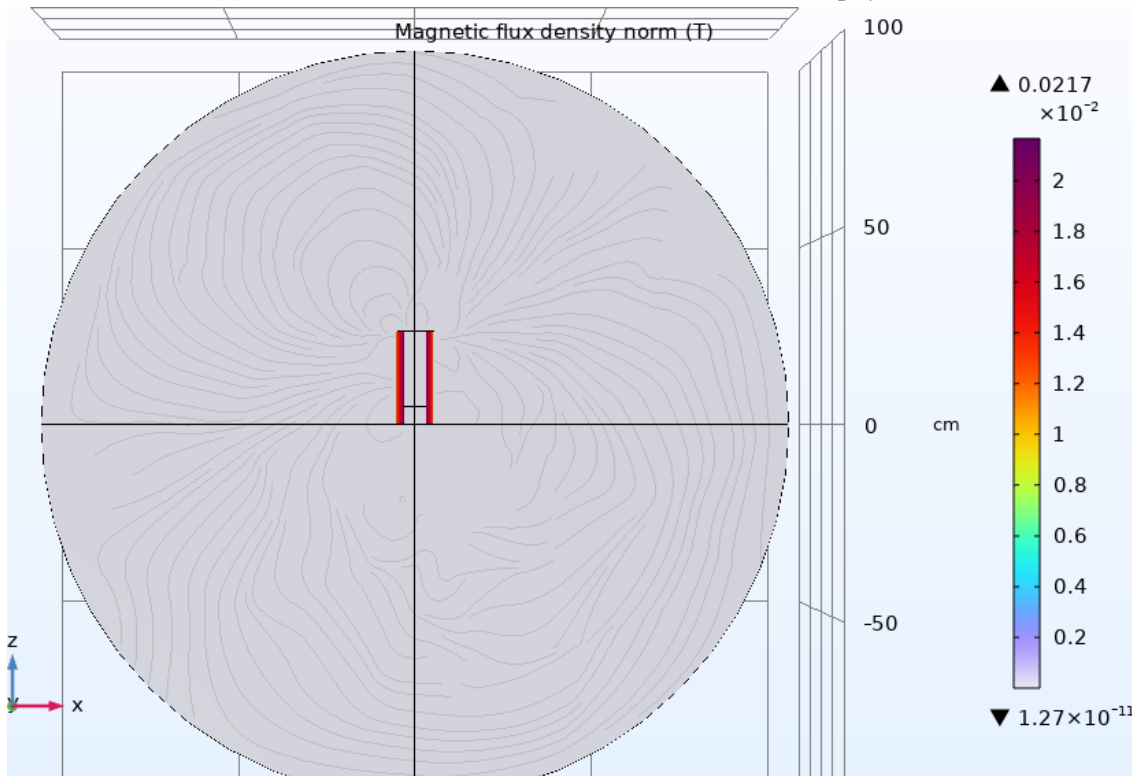
The black toroid was modeled in COMSOL Multiphysics with a length of 25 cm, an outer diameter of 10 cm, and an inner diameter of 6 cm. The simulations were performed for different numbers of turns in order to evaluate the effect on inductance and AC resistance. The results for the inductance and AC resistance are summarized in Table 13.

Table 13: Simulated inductance and AC resistance of the black toroid.

Number of turns (N)	Inductance (μH)	AC Resistance ($\text{m}\Omega$)
21	10.84	18.79
31	23.62	27.75

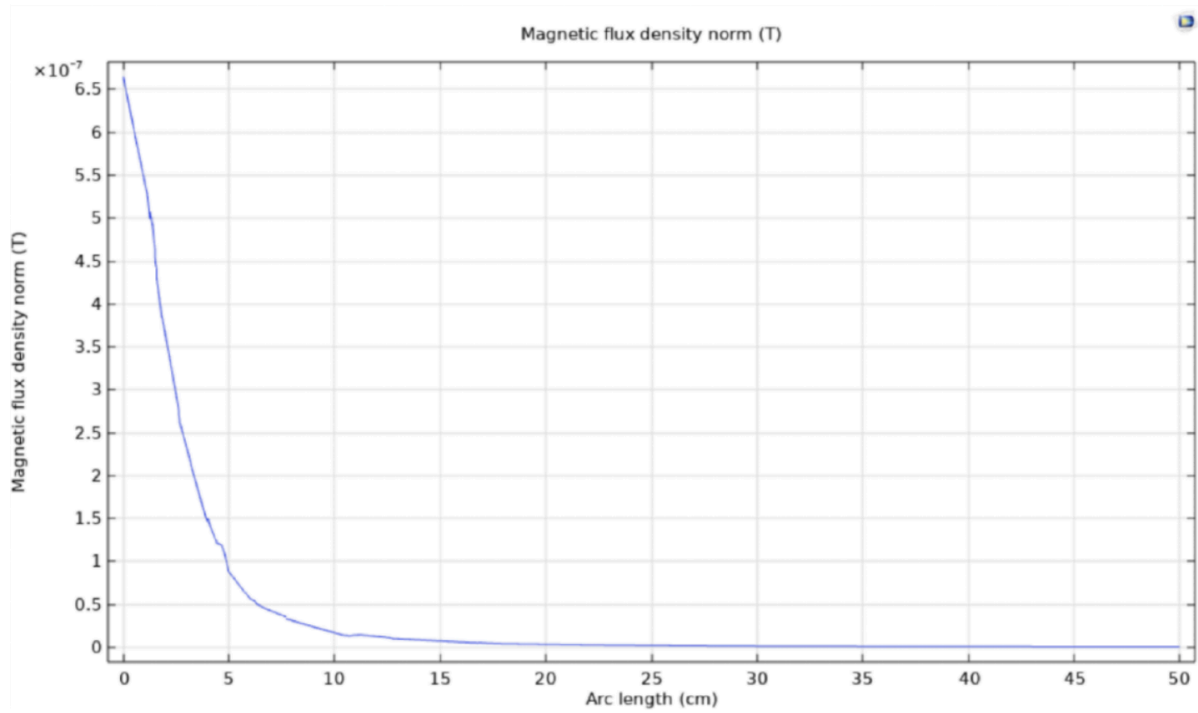


(a) 3D model of the toroid created in COMSOL Multiphysics.

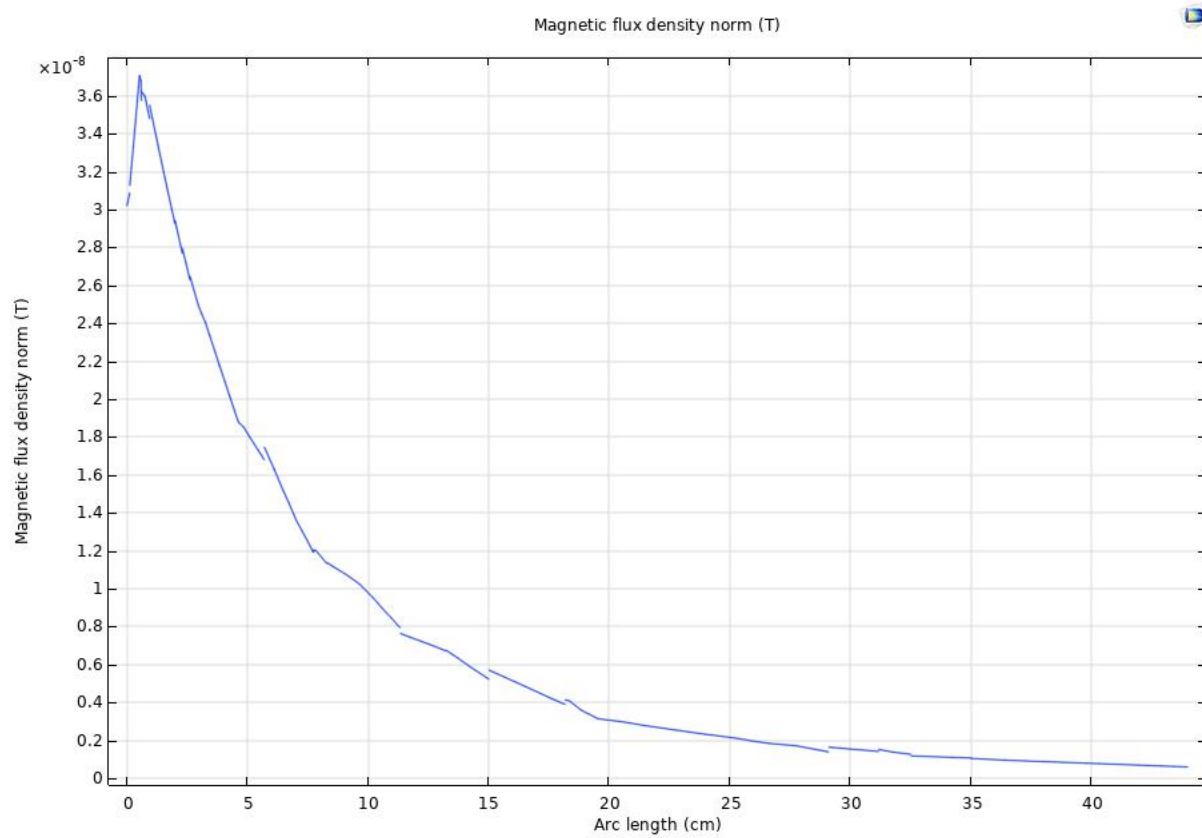


(b) Magnetic flux density distribution (B) in the toroid obtained from COMSOL Multiphysics simulations.

Figure 30: Black toroid ($N = 31$, $I = 100$ A): geometry and magnetic flux density distribution.



(a) Magnetic flux density (B) along the vertical axis.



(b) Magnetic flux density (B) along the horizontal axis.

Figure 31: Magnetic field distribution in the black toroid measured along vertical and horizontal axes.

The second toroid was modeled in COMSOL Multiphysics with a height of 8 cm, an outer diameter of 20 cm, and an inner diameter of 10 cm. The number of turns was set to $N = 50$ in order to evaluate the inductance and AC resistance of the configuration. The simulation results are summarized in Table 14.

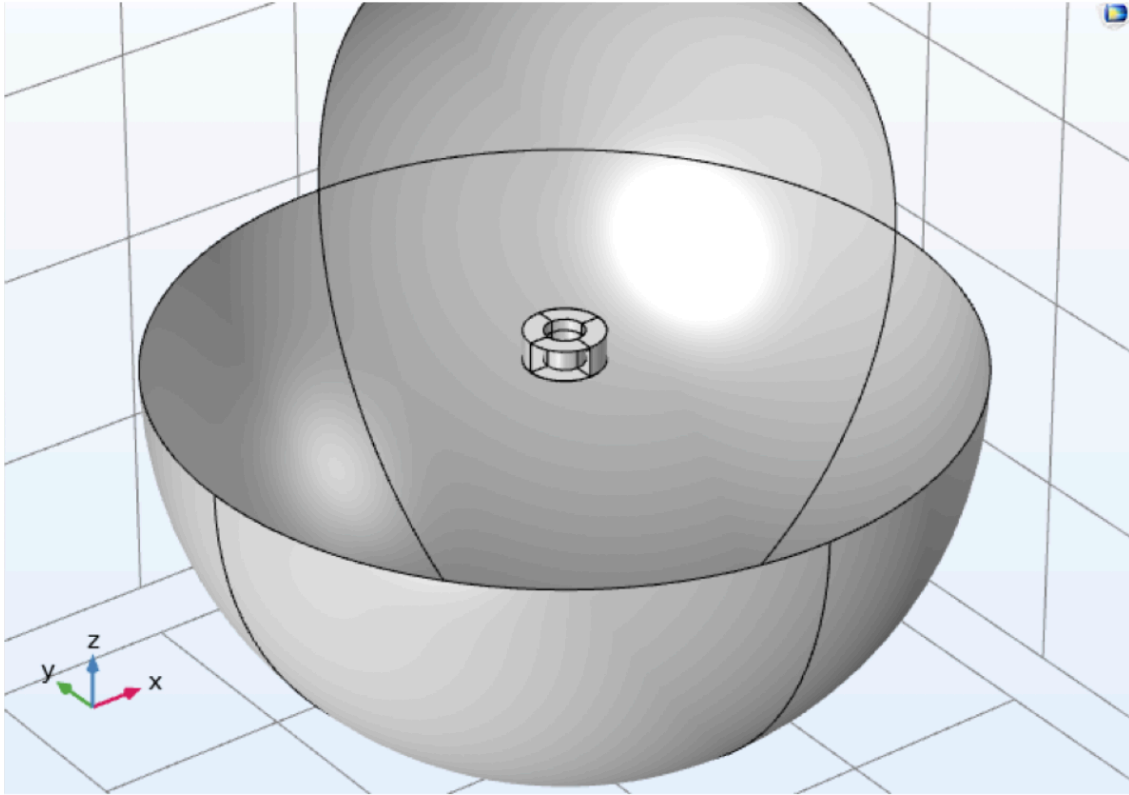
Table 14: Simulated inductance and AC resistance of the toroid with $N = 50$.

Number of turns (N)	Inductance [μH]	AC Resistance [$\text{m}\Omega$]
50	27.09	21.42

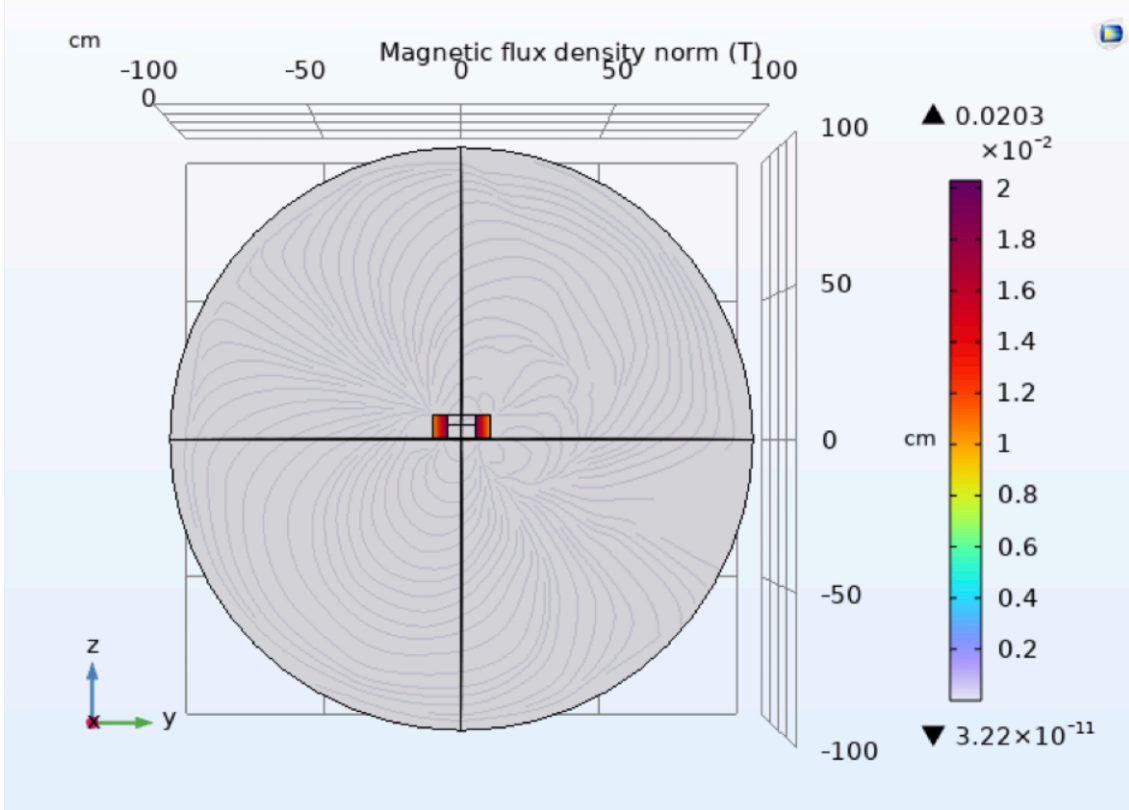
To validate the simulation results, the inductance was also compared with experimental measurements. The measured inductance of the manufactured toroid was approximately $50 \mu\text{H}$, as presented in Table 16.

A noticeable difference can be observed between the simulated value ($27.09 \mu\text{H}$) and the experimental result ($50 \mu\text{H}$). This discrepancy is mainly attributed to differences between the idealized simulation model and the physical prototype. In particular, manufacturing tolerances, winding distribution, and simplified material and boundary assumptions in COMSOL can significantly affect the accuracy of the simulated inductance.

Despite the difference in absolute values, both results confirm the same order of magnitude and validate that the toroidal design achieves the intended inductive behavior.

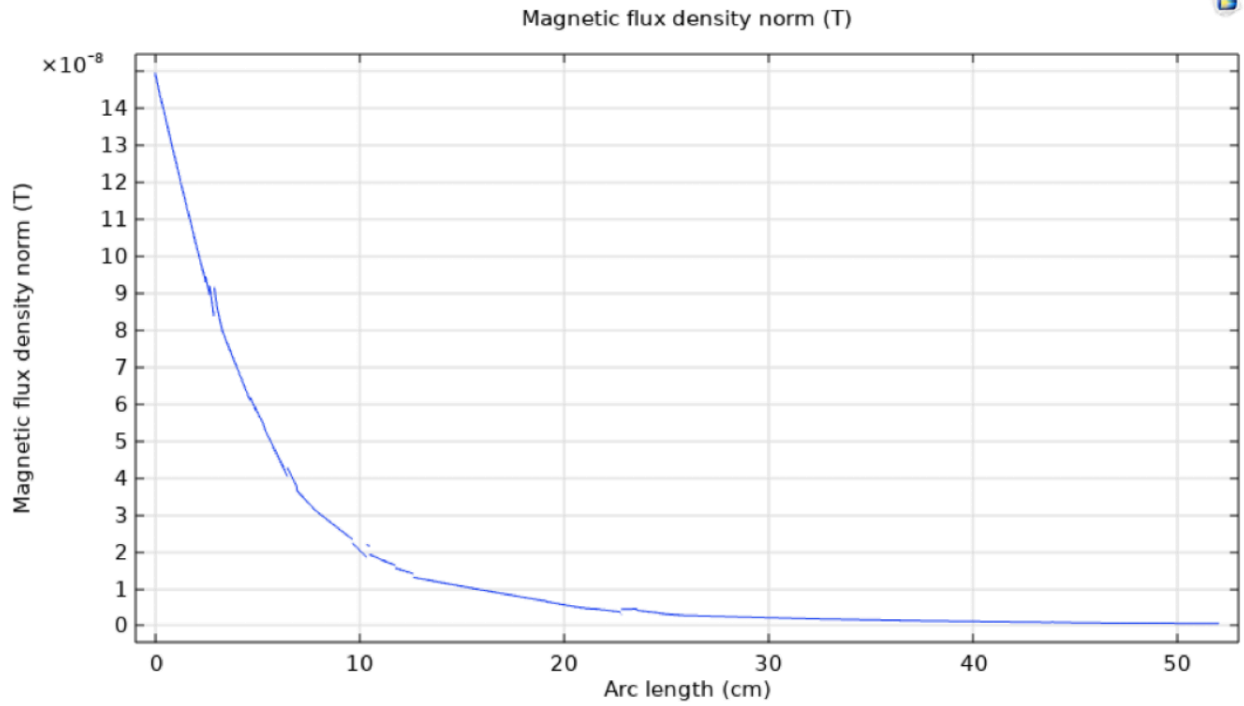


(a) 3D model of the toroid ($h = 8$ mm, $D = 20$ mm, $d = 10$ mm) created in COMSOL Multiphysics.

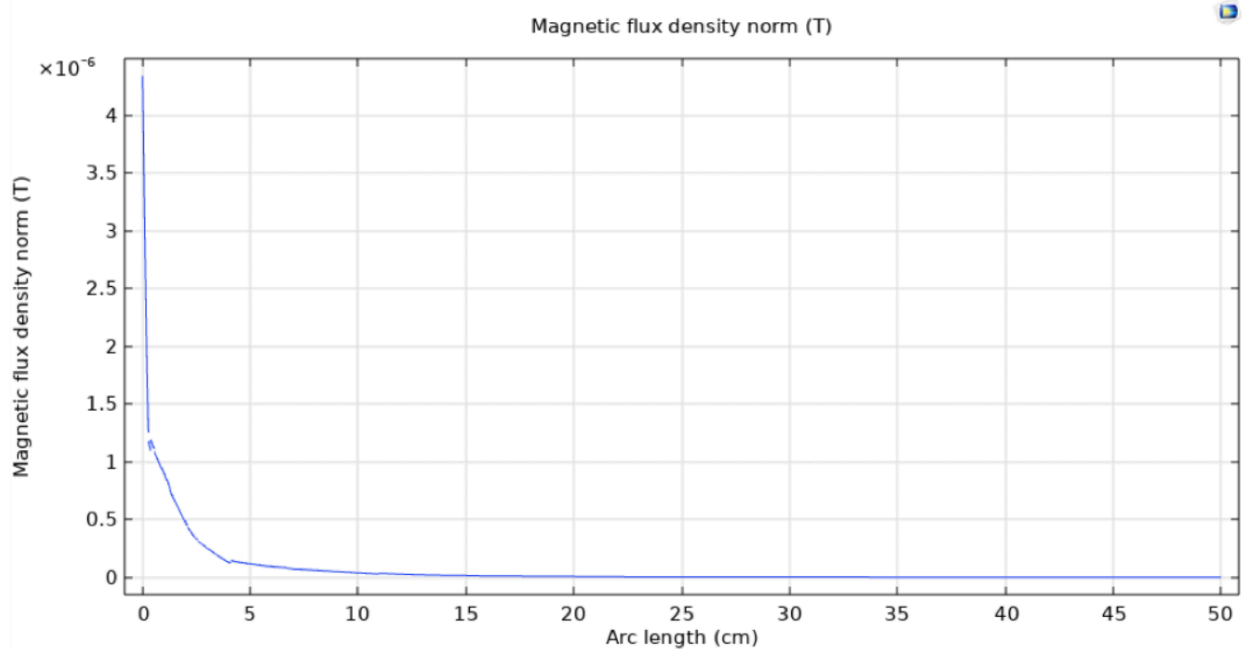


(b) Magnetic flux density distribution (B) in the toroid obtained from COMSOL simulations.

Figure 32: Toroid with $N = 50$: geometry and magnetic flux density distribution.



(a) Magnetic flux density (B) along the vertical Cut Line.



(b) Magnetic flux density (B) along the horizontal Cut Line.

Figure 33: Magnetic field distribution in the toroid ($N = 50$) measured along vertical and horizontal Cut Line profiles.

4.3.3 Experimental results

The Tables 15, 16 and 17 contain the measured inductance and resistance values of the different toroids. The thermal results of the black toroid are shown in Figures 34 - 37 while for the yellow-white toroid they are shown in Figures 38 - 43. Figure 44 contains the thermal results of the white toroid while Figure 45 contains the thermal results of the three final toroids connected in series.

Table 15: Measured inductance and resistance values of the black toroid.

Frequency [Hz]	Inductance [μ H]	Resistance [$m\Omega$]
	N = 21 N = 31	N = 21 N = 31
50	28.0 68.0	43.0 60.0
500	25.0 64.0	44.7 61.0
1 000	24.7 64.3	43.6 61.5
5 000	24.3 63.9	46.3 67.4
10 000	24.0 63.7	54.7 82.8
20 000	24.1 63.5	69.1 110.1
50 000	23.9 63.1	115.8 223.0
100 000	23.8 63.1	205.0 530.8
200 000	23.6 63.0	418.0 1330.0
300 000	23.6 63.0	572.0 2270.0

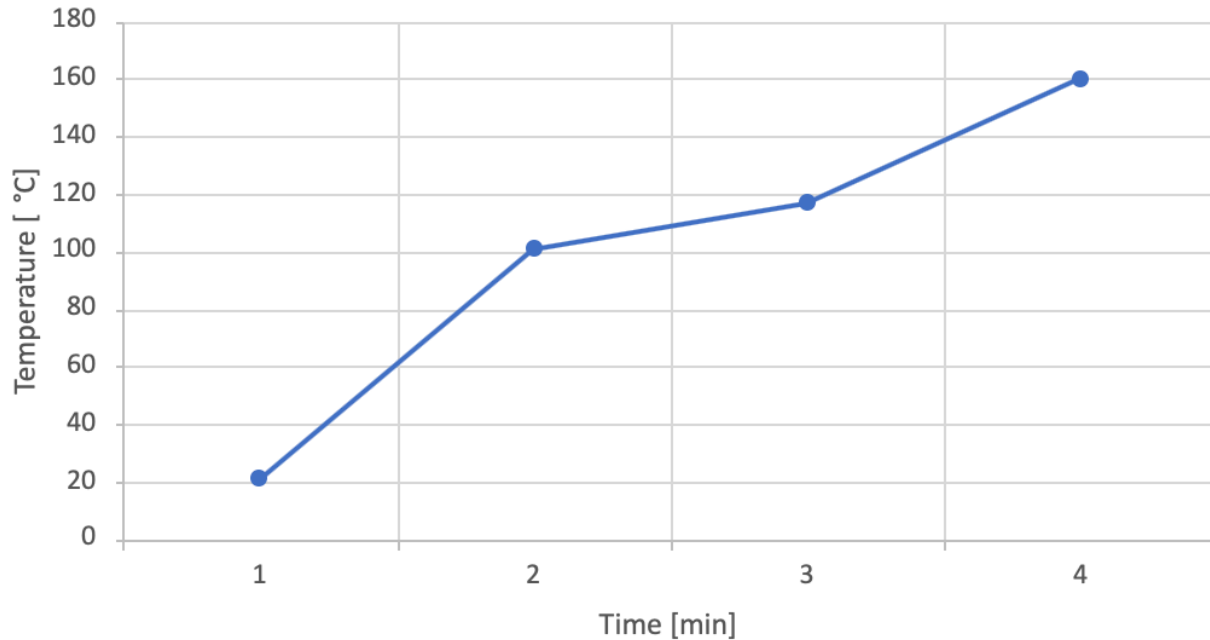


Figure 34: $I = 100 A_{rms}$, $N = 31$ and desk fan.

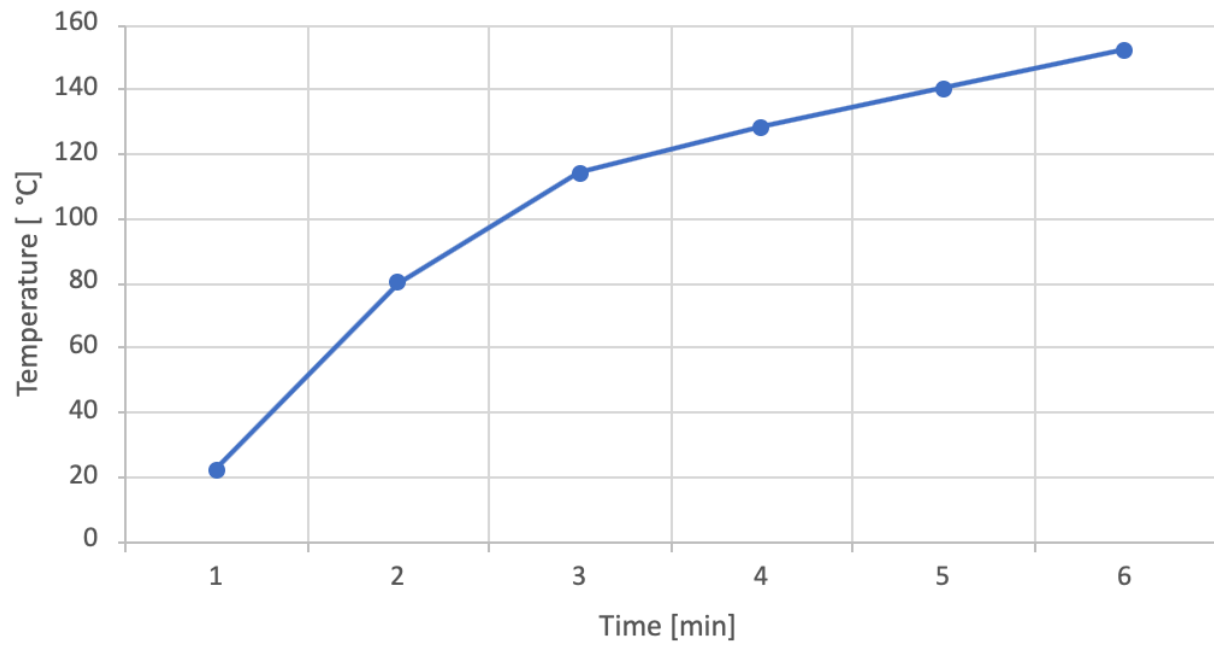


Figure 35: $I = 100 A_{rms}$, $N = 31$ and Comsys fan.

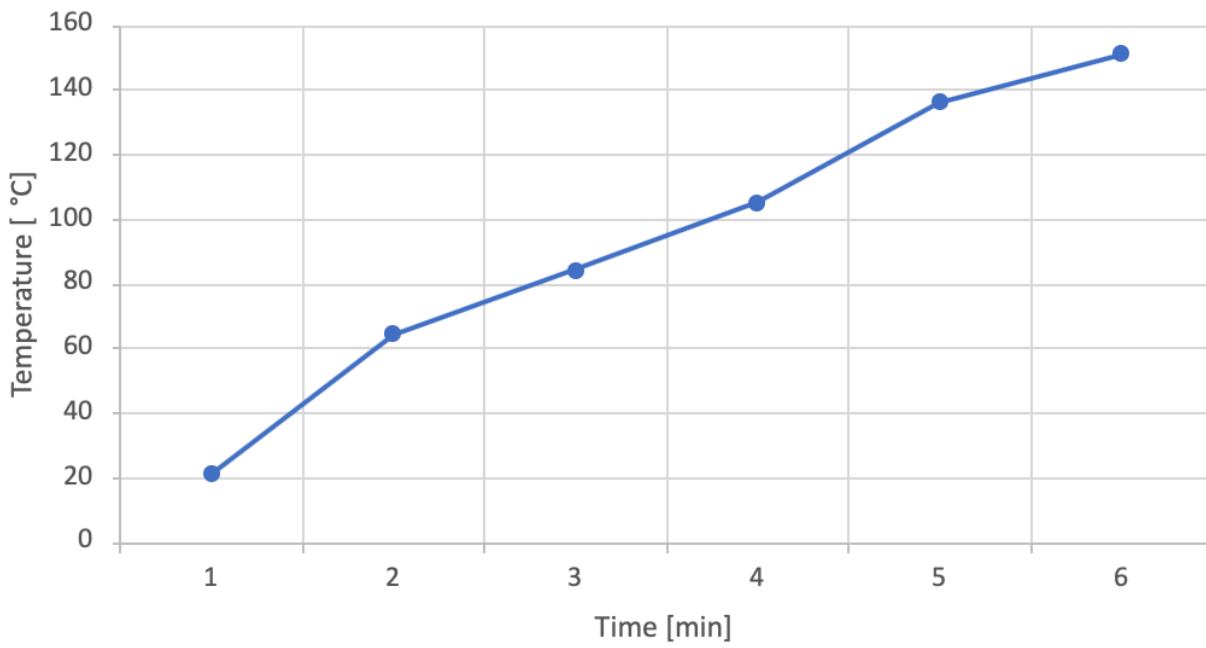


Figure 36: $I = 80 A_{rms}$, $N = 31$ and desk fan.

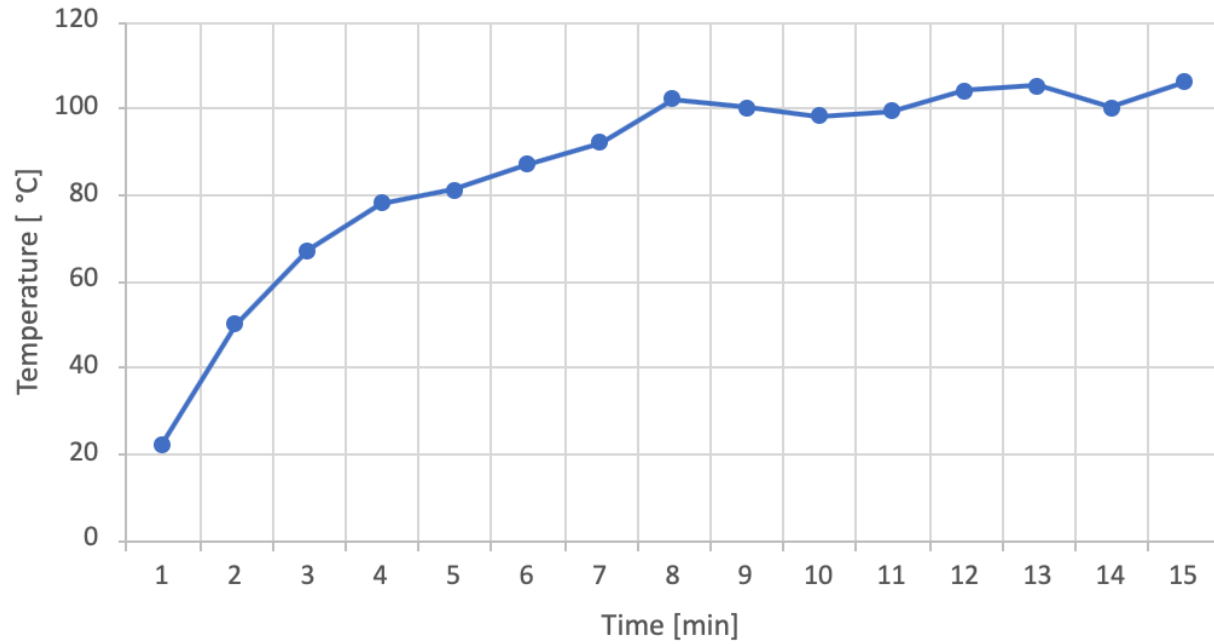


Figure 37: $I = 100 A_{rms}$, $N = 31$ and two fans.

Table 16: Measured inductance and resistance values of the yellow-white toroid.

Frequency [Hz]	Inductance [μ H] 10 mm ² 6 mm ²	Resistance [m Ω] 10 mm ² 6 mm ²
50	57.4 57.4	31.0 51.0
500	53.6 52.6	31.5 52.3
1 000	53.0 52.2	31.5 51.7
5 000	52.7 51.8	40.5 54.1
10 000	52.5 51.7	61.7 64.9
20 000	52.2 51.5	108.0 82.2
50 000	51.7 51.3	318.8 161.9
100 000	51.2 51.2	707.0 362.0
200 000	50.8 51.3	1250.0 764.0
300 000	50.9 51.4	1624.0 1180.0

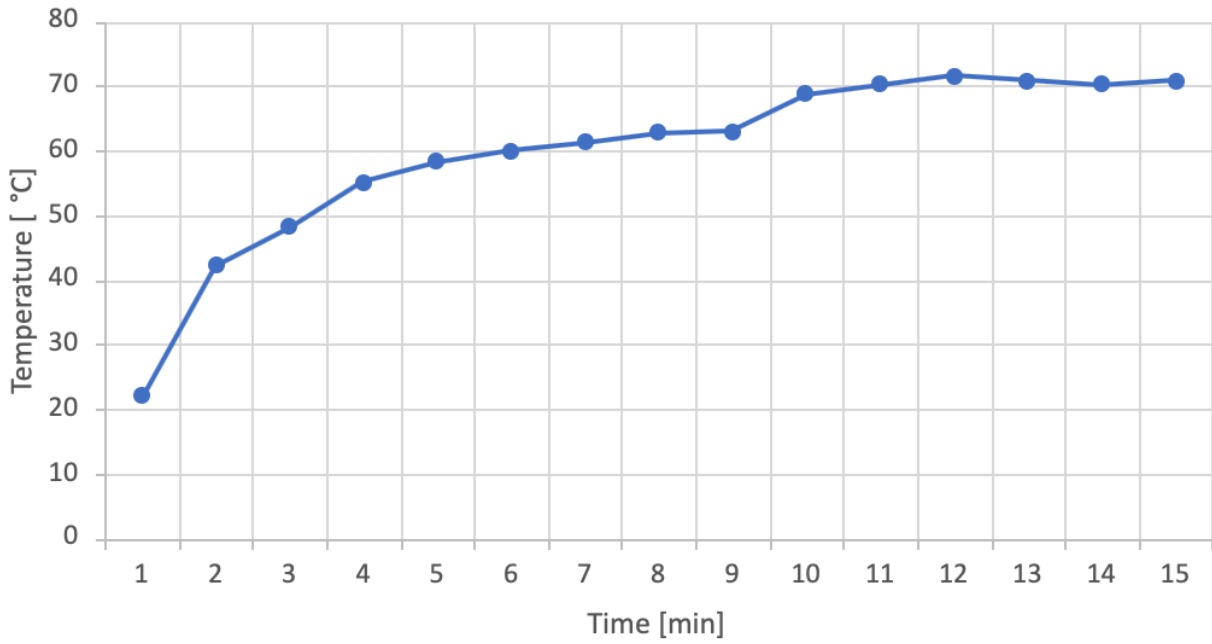


Figure 38: $I = 100 A_{rms}$, 10 mm^2 and desk fan.

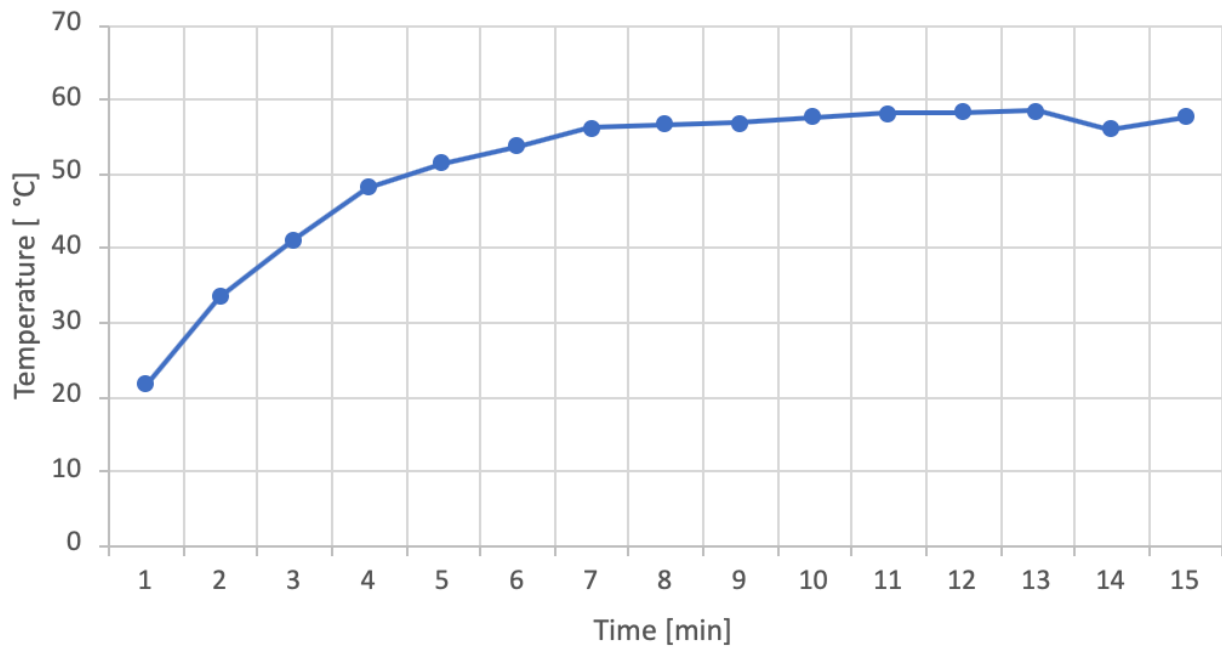


Figure 39: $I = 100 A_{rms}$, 10 mm^2 and Comsys fan.

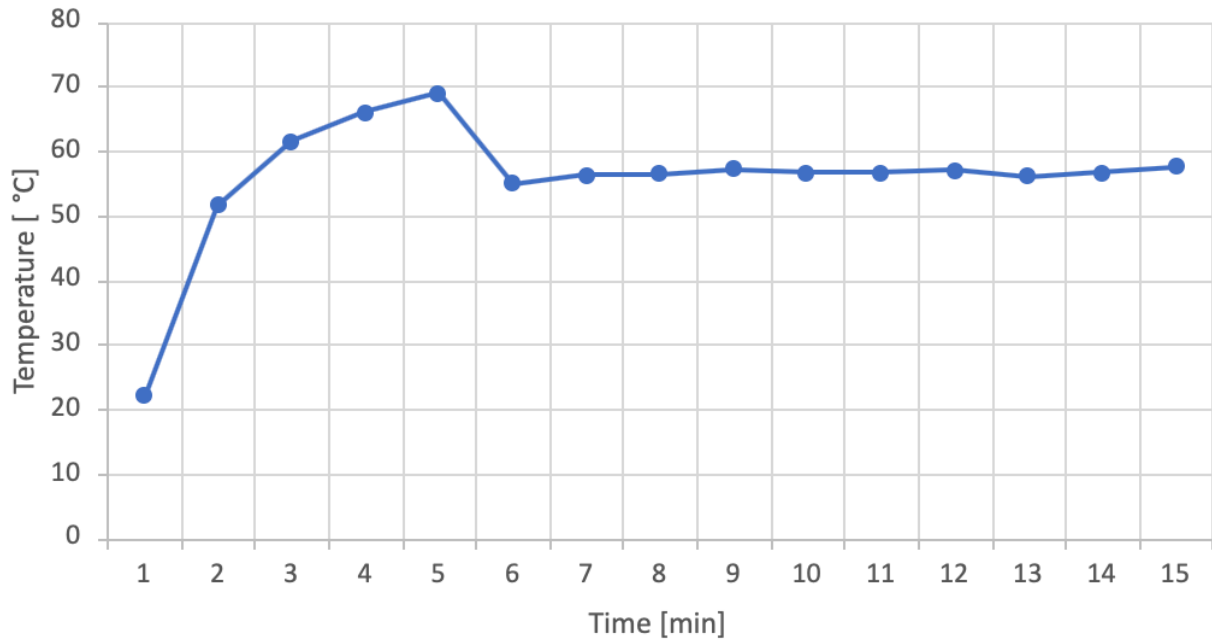


Figure 40: $I = 100 A_{rms}$, 10 mm^2 and two fans.

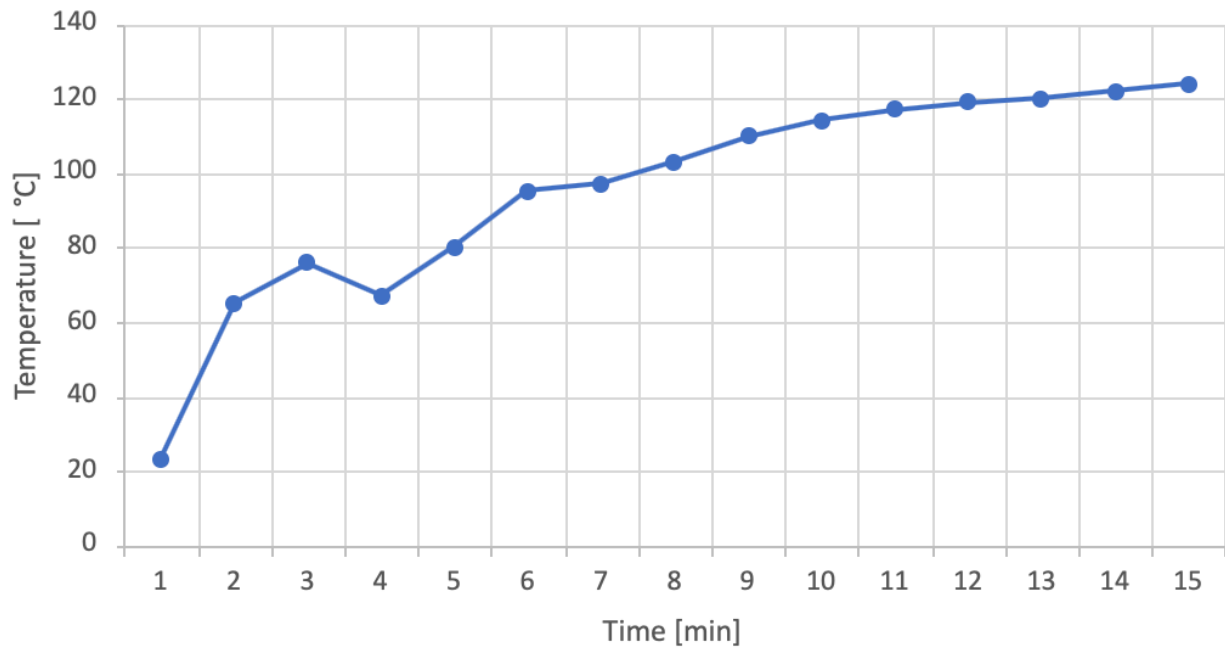


Figure 41: $I = 100 A_{rms}$, 6 mm^2 and two fans.

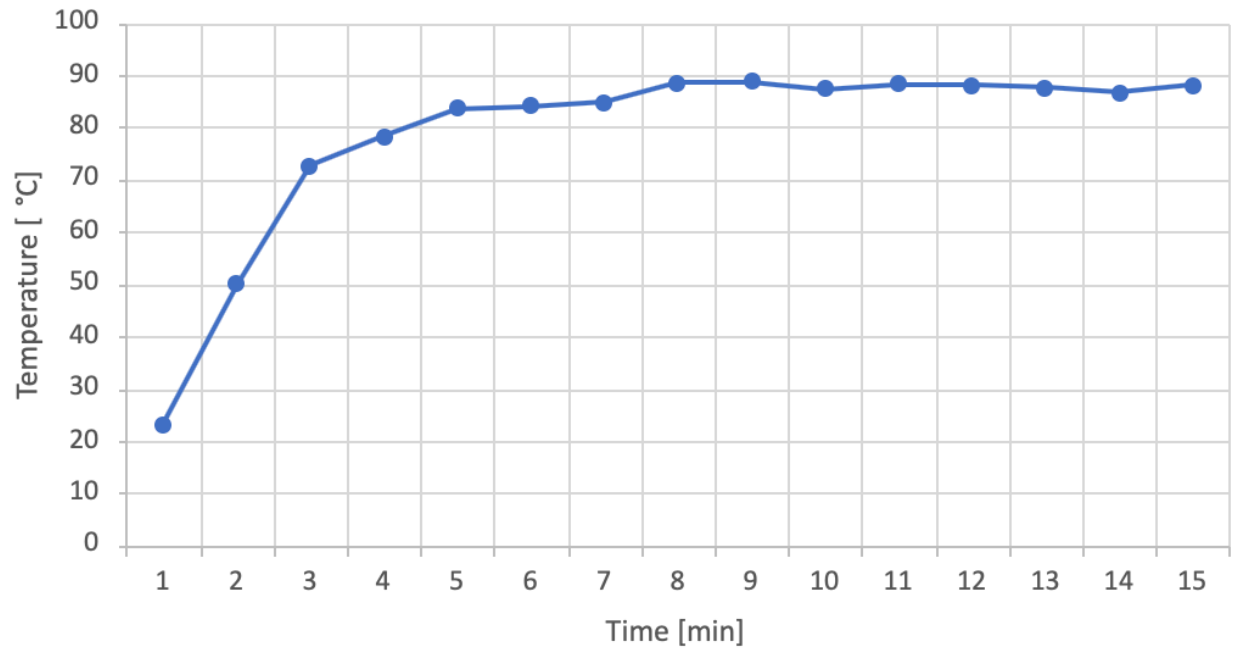


Figure 42: $I = 80 A_{rms}$, 6 mm^2 and two fans.

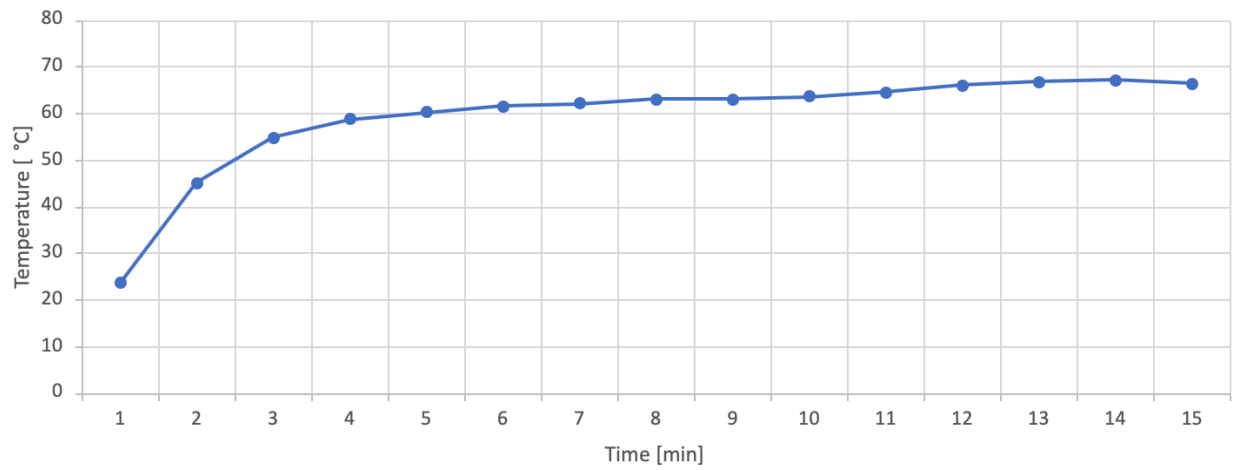


Figure 43: $I = 80 A_{rms}$, 6 mm^2 and two fans (different fan configuration).

Table 17: Measured inductance and resistance values of the three final toroids.

Frequency [Hz]	Inductance [μ H]			Equivalent resistance [m Ω]		
	White	Yellow	Blue	White	Yellow	Blue
50	53.0	55.3	55.5	51.5	51.0	52.7
500	49.5	49.9	50.5	52.8	53.1	53.9
1 000	49.1	49.4	50.0	52.1	54.6	53.2
5 000	48.7	48.9	49.5	54.0	55.4	55.9
10 000	48.6	48.8	49.4	64.1	64.7	65.7
20 000	48.4	48.7	49.3	81.0	85.8	85.7
50 000	48.1	48.4	48.9	156.0	158.0	160.0
100 000	48.1	48.3	48.8	327.0	307.0	324.0
200 000	47.8	48.1	48.6	716.0	603.0	650.0
300 000	47.6	47.9	48.5	1020.0	896.0	965.0

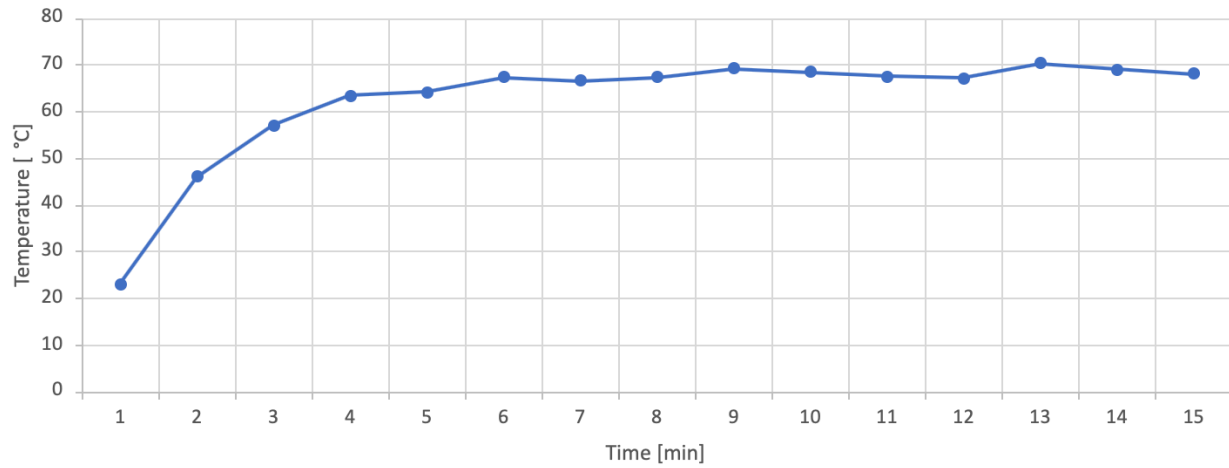
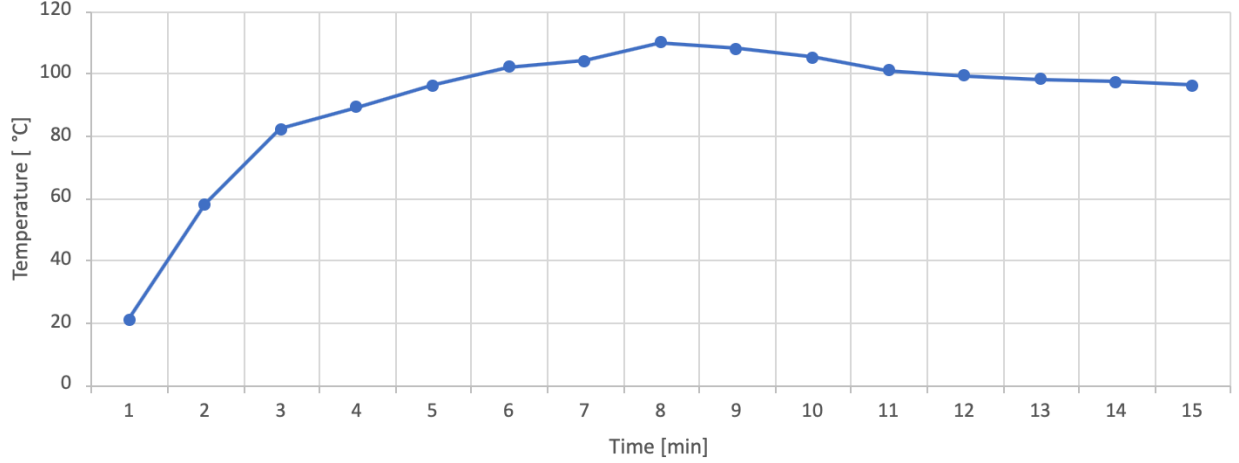
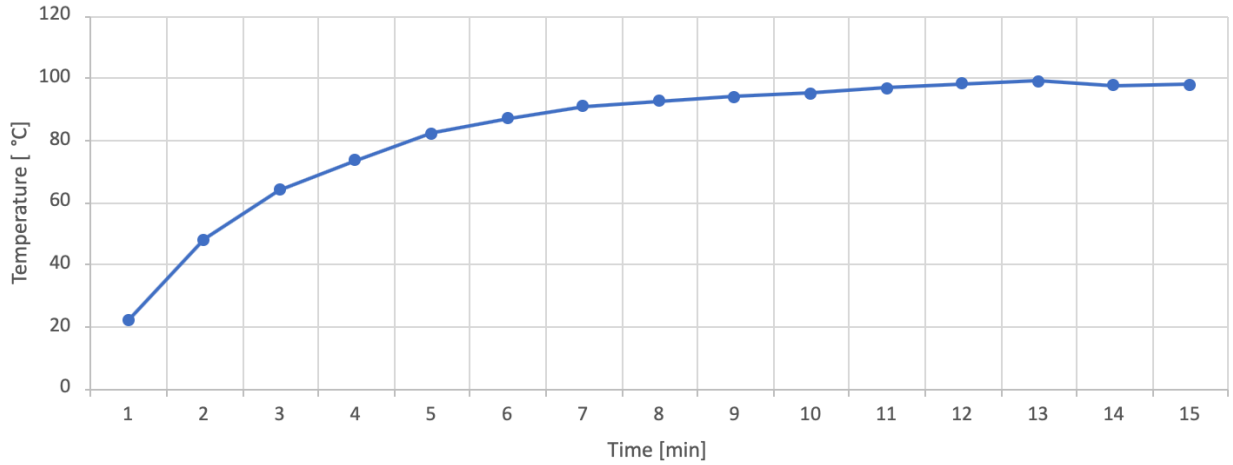


Figure 44: Thermal results of the white toroid, $I = 80 A_{rms}$ and only the Comsys fan.



(a) Comsys cooling fan not ideally positioned.



(b) Comsys cooling fan properly positioned.

Figure 45: Thermal results of the three final toroids connected in series, $I = 80 A_{rms}$ and only the Comsys fan.

4.4 Experimental Results – Hardware Implementation in Cabinet

As a final validation step, the three air-core inductors were mounted and tested inside a Comsys grid filter cabinet (ADF P100). The purpose of this step was to verify that the proposed toroidal design could be physically integrated into the available cabinet space and operate under realistic system conditions. The test case consisted of a low-voltage (31 V DC-link), low-power (≈ 1.5 kW) functional test of a three-phase inverter with the designed air-core inductors as the converter-side inductors of the LCL filter. The system was operated with reactive power injection to emulate a typical ADF operating scenario. The experimentally measured current is shown in Figure 46 while its simulation equivalent is shown in Figure 47. The DC-link power supply operating conditions are shown in Figure 48. The tests confirmed that the air-core inductors could be successfully integrated and operated within the cabinet without compromising performance or thermal stability.

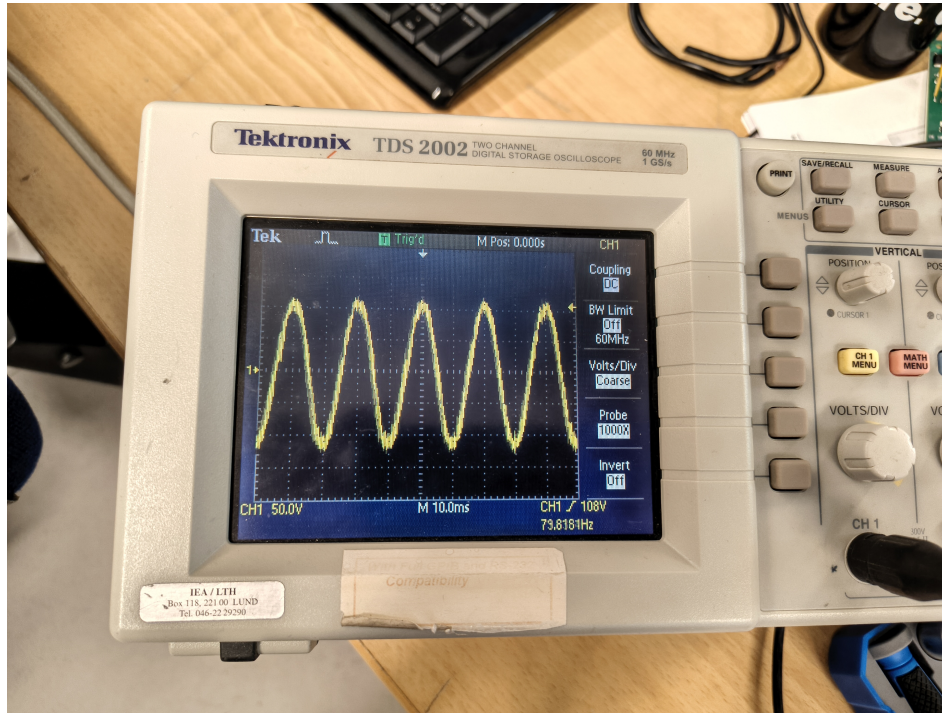


Figure 46: Experimentally measured grid current using Chauvin Arnoux PAC 17 current probe.

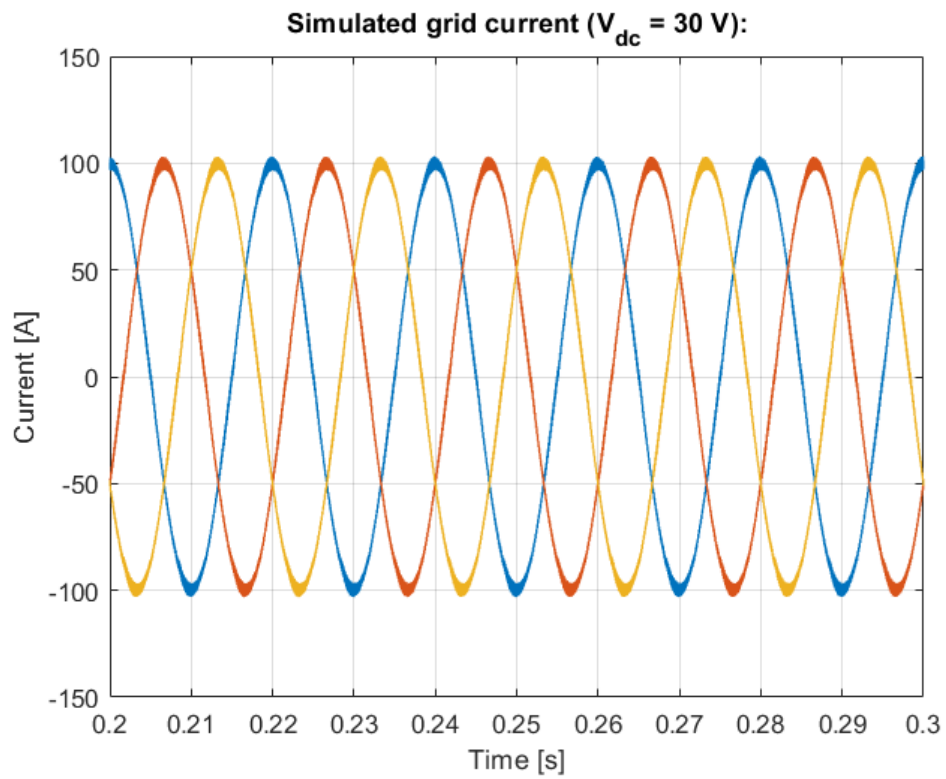


Figure 47: Simulated grid current.

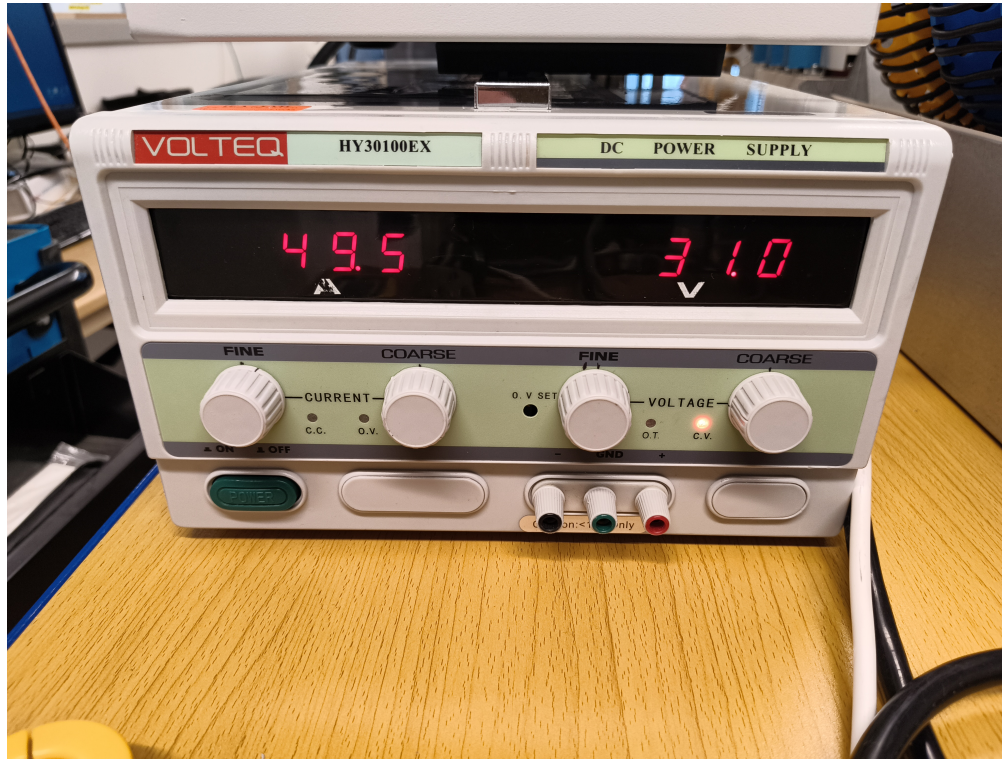


Figure 48: DC-link power supply (VOLTEQ HY30100EX) operating during testing.

5 Discussion

5.1 Solenoid

By comparing the theoretical and simulated inductance values in Table 5, it is evident that a discrepancy exists between the two methods. This can primarily be explained by the underlying assumptions in the ideal solenoid inductance expression in Eq. (11). The formula assumes the length of the solenoid is significantly greater than its radius ($l \gg r$). This assumption ensures the magnetic field is strictly uniform inside the coil and zero outside.

The l/r ratio presented in Table 5 therefore provides an indication of the validity of the analytical model. Designs with higher l/r ratios show better agreement between theory and simulation, which is reflected by the corresponding L_{sim}/L_{theory} values. The third design (row in Table 5) exhibits the highest agreement, whereas the first design shows the largest deviation. The N/l ratio also provides practical design insight, where lower values usually entail a simpler winding process, a reduced likelihood of multilayer windings, and mitigated proximity-effect losses.

Another discrepancy arises from the simulation model itself. In COMSOL, the winding is represented as a continuous block of copper where the individual windings are not modeled and, in the 2D axisymmetric model, the current density was assumed to be uniform at low frequencies. In reality, the winding consists of individual conductors separated by small air gaps, which are not fully represented in the simulation model.

Comparison of the simulated and measured results for the duct tape solenoid (Tables 7 and 9) shows that inductance decreases slightly with increasing frequency, while resistance increases significantly. The reduction in inductance happens due to the parasitic interwinding capacitance present in practical inductors. As frequency increases, the capacitive reactance decreases, allowing part of the current to bypass the inductive path. The increase in resistance is caused by the growing influence of skin and proximity effects, which reduce the effective conducting area of the conductor. By perfecting the winding and choosing conductors with larger cross-sections the skin and proximity effects can be reduced. The measured values are consistently higher than the simulated values, likely due to factors not included in the simulations, such as contact resistance, winding imperfections, stray inductance, and material impurities.

The geometric parameters presented in Table 6 were further used to estimate cable length, volume, mass, and DC resistance. The DC resistance is the resistance the solenoid sees in DC conditions and is the lowest resistance it can have. As frequency increases the solenoid's resistance start to increase from this value onward, which can be observed in Table 7.

A similar trend can be observed for the pink solenoid (Tables 8 and 10). The inductance remains relatively constant across the three conductor sizes because the overall geometry changes only slightly between the different winding configurations. The resistance, however, is strongly influenced by both conductor size and winding arrangement. At low frequencies, the thinner conductors exhibit higher resistance, consistent with Eq. (16). At higher frequencies, the trend partially reverses because the 16 mm² conductor is wound in two tightly packed layers, increasing the influence of skin

and proximity effects compared with the more loosely wound 10 mm² and 6 mm² configurations.

The thermal measurements shown in Figures 27, 28 and 29 demonstrate that current has the largest influence on temperature rise, since power dissipation (heat) is proportional to the square of the current according to Eq. (20). With a current of 80 A_{rms} , a 10 mm² cable, and a desk fan, the temperature rose continuously until it settled as expected at a certain temperature, at approximately 70°C in this case (Figure 27). Increasing the current to 100 A_{rms} while using a 6 mm² cable caused the temperature to exceed 140°C within six minutes (Figure 28), surpassing the acceptable operating limit of the cable insulation. Replacing the desk fan with the stronger Comsys cooling fan significantly improved thermal performance, keeping the temperature below 140°C throughout the measurement period of 15 minutes (Figure 29). These results highlight the importance of both conductor sizing and effective cooling when designing air-core solenoids for high-current applications.

5.2 Toroid

The theoretical and simulated inductance values in Table 11 show good agreement, indicating that the analytical model provides an accurate representation of the toroidal geometry. The use of full 3D simulations further improves accuracy compared with the 2D axisymmetric approach used for the solenoid. However, noticeable differences remain between simulated and measured values for both the black (Tables 13 and 15) and yellow-white toroid (Tables 14 and 16), mainly due to factors that are difficult to model accurately, such as winding imperfections, contact resistance, and parasitic effects.

The magnetic field distributions shown in Figures 31 and 33 confirm that the magnetic flux is largely confined within the toroid. This behavior agrees with electromagnetic theory and results in significantly lower magnetic flux leakage than for the solenoid. Reduced leakage decreases electromagnetic interference (EMI) and minimizes magnetic coupling to nearby components, making the toroidal geometry particularly attractive for power-electronic filter applications.

The measured results in Tables 15 and 16 show that inductance remains relatively constant with frequency, whereas resistance increases substantially. This increase is caused by skin and proximity effects. At low frequencies, the 6 mm² cable exhibits higher resistance due to its smaller cross-sectional area. However, above approximately 20 kHz, the 10 mm² cable becomes more resistive because its tighter winding arrangement increases the proximity-effect losses, as evident from the resistance values in Table 16.

The thermal measurements of the black toroid revealed poor thermal performance. At a current of 100 A_{rms} , the temperature increased rapidly, reaching approximately 160 °C after only 4 minutes when cooled by a desk fan (Figure 34). Replacing the desk fan with the powerful cooling fan reduced the temperature slightly, resulting in approximately 150 °C after 6 minutes (Figure 35). However, the operating temperature still exceeded the allowable limit of the cable insulation. Additional tests using two fans simultaneously or reducing the current to 80 A_{rms} provided only marginal improvements, as shown in Figures 36 and 37. The high temperatures are primarily attributed to the toroid geometry. Its long structure and relatively small inner radius create a densely packed winding arrangement with limited spacing between adjacent turns. This restricts airflow through the center

of the toroid, reducing the effective cooling. Furthermore, the close spacing between windings increases the influence of the proximity effect, leading to higher AC resistance and increased Joule losses. As a result, the generated heat cannot be dissipated efficiently, causing a rapid temperature rise during operation. Based on these observations, the thermal performance of the black toroid was deemed insufficient for the intended application. Consequently, a redesigned toroidal geometry with a shorter structure and a larger inner diameter (i.e. the yellow-white toroid) was developed.

The aim of the new design was to improve airflow through the structure and make the winding process easier while maintaining the required inductance. The thermal data presented in Figures 38 - 43 demonstrate a significant improvement in performance compared with the black toroid. For a 10 mm^2 cable and a current of $100 A_{rms}$, the temperature stabilized at approximately 70°C after 15 minutes when cooled by a desk fan (Figure 38). Using the powerful cooling fan reduced the temperature to below 60°C under the same operating conditions (Figure 39), while the addition of a second fan provided a further reduction in steady-state temperature (Figure 40). Figures 41, 42 and 43, corresponding to the 6 mm^2 cable, illustrate the effect of current on thermal performance. Reducing the current from $100 A_{rms}$ to $80 A_{rms}$ lowered the operating temperature from approximately 120°C to 90°C after 15 minutes (Figure 42), reflecting the reduction in power losses and heat generation at lower currents. This result illustrates that the current is among the factors that mostly sets the thermal margin. 90°C is acceptable for the 6 mm^2 cable. A notable difference can also be observed between Figures 42 and 43, where variations in winding quality and airflow conditions influenced the results. Poor alignment of the winding relative to the cooling fan reduced the cooling, whereas improved positioning resulted in significantly lower temperatures. These observations highlight the importance of proper winding practices and effective airflow management. Maintaining adequate spacing between adjacent conductors reduces the proximity effect, thereby lowering AC resistance, minimizing power losses, and improving thermal performance.

As shown in Table 17, the inductance values of the three individual toroids are not exactly identical due to slight variations in their winding configurations. These minor differences in winding also influence the corresponding resistance values, despite the conductors having the same length and cross-sectional area.

The white toroid reached a maximum temperature of 70°C when subjected to a current of 80 A (Figure 44), which is considered acceptable for a single inductor. When the three inductors were connected in series and exposed to the same current, the maximum temperature varied depending on the positioning of the cooling fan. With the fan not ideally positioned, the inductors reached a maximum temperature of approximately 110°C (Figure 45a). In contrast, when the fan was properly positioned, the maximum temperature remained just below 100°C (Figure 45b), representing a reduction of approximately 10°C . This result highlights the significant influence of cooling airflow on the thermal performance of the inductors and demonstrates the importance of proper fan placement. Furthermore, the maximum measured winding temperature remained slightly below the continuous operating temperature rating of the conductors (100°C). Although the conductors used in this study were selected primarily because they were readily available, conductors specifically designed for this application would likely provide a greater thermal margin and be more appropriate in a practical implementation.

Comparison of Figure 26 with Figures 31 and 33 shows that the toroidal geometry exhibits significantly lower magnetic flux leakage than the solenoid. While the solenoid's magnetic field extends into the surrounding region, the toroid confines most of the magnetic flux within its cross-section. This improved flux confinement reduces electromagnetic interference (EMI), stray magnetic fields, and associated losses, resulting in higher electromagnetic efficiency. Furthermore, the toroidal geometry provided superior thermal performance, as its structure enabled more effective heat dissipation and cooling during operation compared with the solenoid.

The integration of the designed toroidal air-core inductors in the Comsys cabinet is shown in Figures 20 and 21. The results confirm that the inductors fit within the existing P100 form factor. Although each air-core inductor occupies approximately the same volume as the existing three-phase iron-core inductor (Figure 54) in the ADF P100, the three air-core inductors could still be integrated into the available space in the Comsys cabinet. Each air-core inductor weighs approximately 1.4 kg, about one-tenth the weight of the 14 kg iron-core block. Consequently, the combined weight of the three air-core inductors is reduced by a factor of approximately 3–4 compared with the iron-core inductor, resulting in a significant reduction in mass and improving overall cabinet portability. However, since the system was implemented within an existing layout, the cooling arrangement occupies a relatively large portion of the available space. In a dedicated design, a more integrated cooling solution could reduce space requirements and improve layout efficiency. This would also free space for additional components such as the filter capacitor (C_f) and grid-side inductance (L_2). The individual weight distribution of the air-core inductors also allows for more flexible placement, potentially balancing the cabinet's center of gravity more effectively than the heavier monolithic iron-core design.

The experimental measurements indicate a total input power of approximately 1.5 kW during operation, based on the measured DC-link voltage and current (31 V and 49.5 A). This value represents a conservative estimate of the total system losses, as it includes losses from both the designed air-core inductors and other converter components, such as the transistors. To estimate the efficiency at the intended operating point, the measured losses are assumed to be representative of nominal operation because the laboratory tests were conducted at a comparable RMS current, where the dominant winding losses are expected to remain of similar magnitude. Scaling the transmitted power to the nominal three-phase rating of approximately ($\sqrt{3} \cdot 400 \cdot 100 \approx 70$ kW) gives an estimated overall efficiency of around 98%. This result should be interpreted as an approximation rather than a direct measurement, with the estimate being conservative due to the inclusion of converter losses in the measured value.

Despite this limitation, the result indicates that the system operates with high efficiency under the tested conditions, suggesting that the designed air-core inductors do not introduce excessive additional losses compared to the overall converter system.

6 Conclusion

Based on theoretical calculations, COMSOL simulations, and experimental investigations, the toroidal topology was identified as the most suitable solution for the intended application. Compared to the solenoid configuration, the toroidal design exhibited lower magnetic flux leakage, improved thermal performance, and a more compact geometry suitable for installation within the available cabinet volume.

The final proposed design consists of three toroidal inductors, each with an outer diameter of 20 cm, an inner diameter of 10 cm, a height of 8 cm, and 55 turns. Each of the three final toroids has a mass of approximately 1.4 kg, giving a combined mass of approximately 4.2 kg. This represents a mass reduction by a factor of approximately 3–4 compared with the 14 kg three-phase iron-core inductor. Additional ventilation openings were incorporated into each inductor structure to enhance airflow and improve cooling performance. The experimental results demonstrated that the toroidal geometry can operate at high current levels while maintaining acceptable temperatures when adequate cooling is provided.

Based on the obtained results, the proposed toroidal design is considered suitable for integration into the Comsys grid filter cabinet and meets the specified current requirement of $80 A_{rms}$, while also providing the required inductance and thermal performance.

6.1 Future research

This study has evaluated the feasibility of using coreless inductors as replacements for conventional iron-core inductors in existing line filter applications. To further advance the development of coreless inductors for high-power and high-frequency systems, future research should primarily focus on the optimization of toroidal inductor designs.

The manufacturing process of the inductor bodies also warrants further investigation. In this study, the structures were produced cost-effectively using the 3D-printing resources available at the university campus. Alternative manufacturing methods, materials, and mechanical designs could be evaluated to improve durability, thermal performance, manufacturability, and suitability for industrial-scale production. Furthermore, investigations into conductor selection, including material quality, could be conducted while also considering the feasibility of the winding process. Total filter losses and cooling costs could also be explored.

The results of this study demonstrate that it is possible to integrate coreless inductors into existing line filter designs without compromising performance. These findings may provide valuable insights not only for Comsys but also for other companies and researchers working with high-power electronic systems. Finally, the potential application of coreless inductors in other areas of power electronics and electrical engineering could be explored, potentially revealing additional advantages and use cases for this technology.

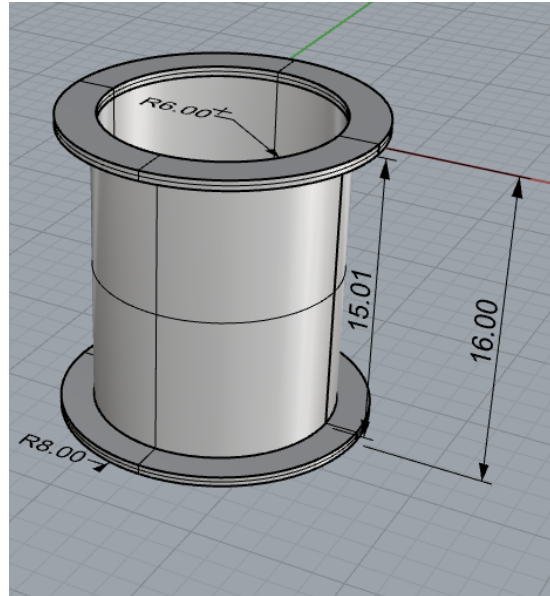
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Appendix

A Additional Figures

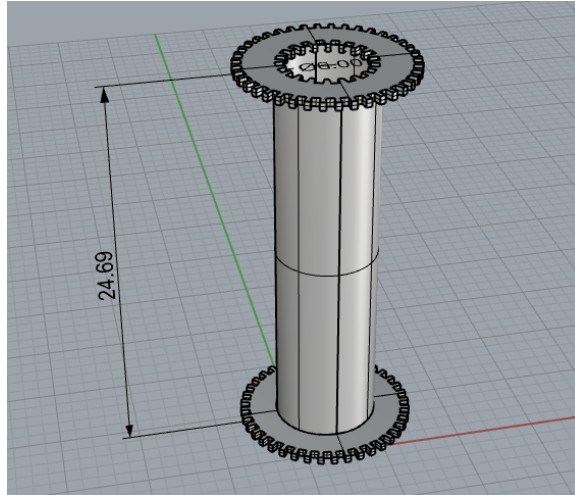


(a) 3D CAD model of the solenoid.

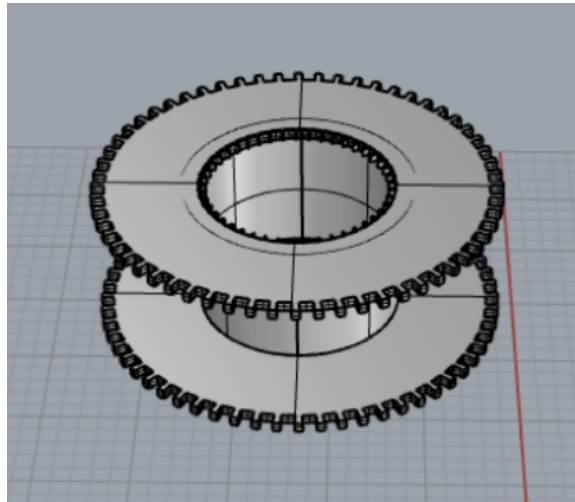


(b) Manufactured 3D-printed solenoid.

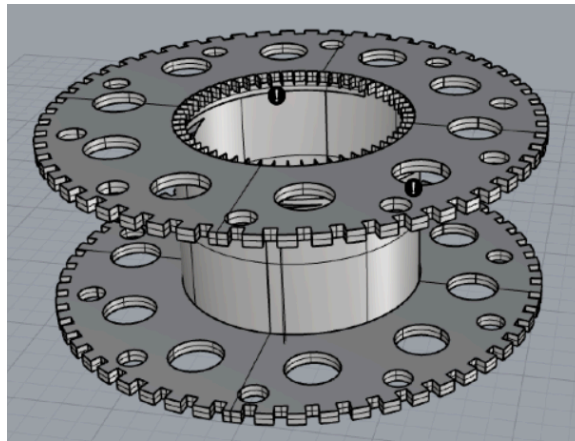
Figure 49: 3D design and manufactured prototype of the solenoid.



(a) 3D model of the long and thin toroid.



(b) 3D model of the short and thick toroid.



(c) 3D model of the short and thick toroid with cooling holes.

Figure 50: CAD models of the toroidal inductor designs used in this study.



(a) 3D-printed long and thin toroid.



(b) 3D-printed short and thick toroid without cooling holes.



(c) First 3D-printed toroid with cooling holes.

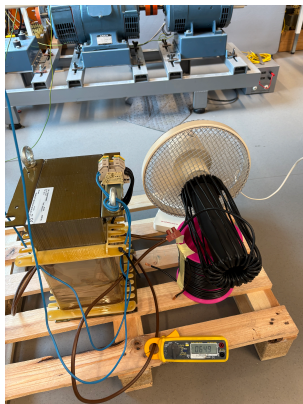


(d) Second 3D-printed toroid with cooling holes.

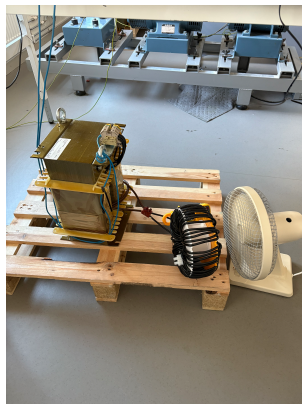


(e) Third 3D-printed toroid with cooling holes.

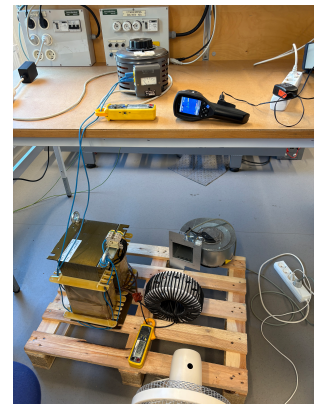
Figure 51: Manufactured 3D-printed toroidal structures used in this study.



(a) Black toroid.



(b) Yellow-white toroid.



(c) White toroid.

Figure 52: Experimental thermal testing setups for different toroid and cooling fan orientations.



(a) Desk fan.



(b) Comsys cooling fan.

Figure 53: Cooling fans used in the experimental setup.

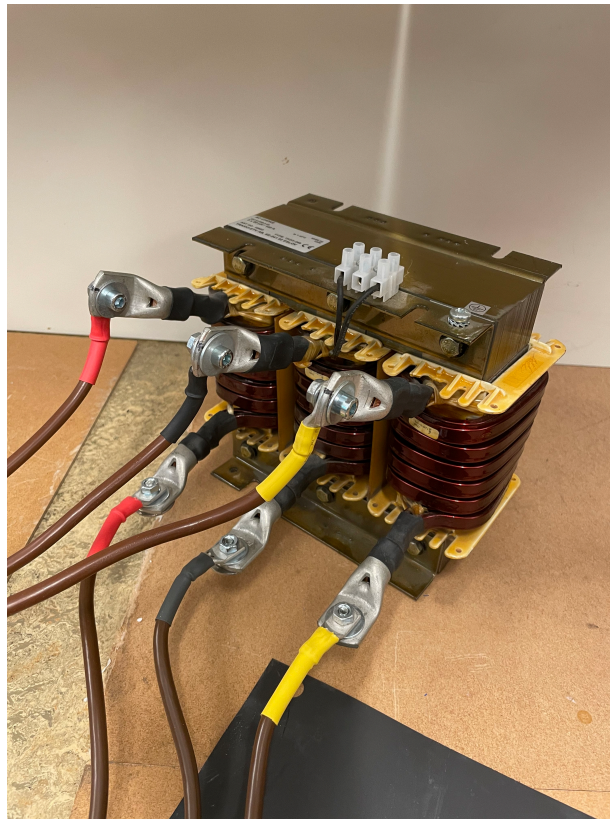


Figure 54: Three-phase iron-core inductor currently used in the ADF P100 from Comsys.