UNIVERSITY OF CAPE TOWN

Vacation Work Report/; Inductor Design Project

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1 Introduction

This report documents the work carried out during a three-week vacation project focused on the design, simulation, and construction of an inductor. The project, which closely mirrors real-world engineering tasks, required a comprehensive design approach starting from theoretical analysis and progressing through computer-based simulation to physical implementation.

At the start of the project, only a general design objective was provided, without concrete specifications or a clearly defined inductor type. As a student from an Electrical and Computer Engineering background, I had limited exposure to the specific principles and practices of power engineering—particularly inductive component design. Recognizing this knowledge gap, I proactively engaged in self-directed learning, reviewing academic papers and engineering case studies to gain the foundational understanding necessary to begin the design process.

Once I had established a baseline understanding of inductor design, my project manager, Mr. Maysam Saltanian, provided the official electrical specifications. However, these were presented without specifying whether the design should be based on a laminated core, air core, or other form. I initially proceeded with a laminated-core inductor design, which I analyzed through both hand calculations and plotted results. As the project progressed, it became evident that this approach would not satisfy all of the given requirements. After reviewing the constraints and performance trade-offs, my project manager advised me to pivot to an air-core inductor design.

The project was divided into three main stages:

- **Analytical Design** — deriving parameters such as inductance, resistance, and number of turns based on the given impedance specification.
- **Simulation** — validating the design using electromagnetic modeling tools to analyze magnetic field behavior and losses.
- **Construction** — winding and assembling the physical inductor and comparing the measured results to the theoretical and simulated values.

This report follows the structure of the project itself, detailing the design evolution, the supporting literature, the tools and methods used, and the final outcomes, along with a reflection on the learning experience and engineering insight gained.

2 Design 1: Laminated-Core Inductor

2.1 Specifications

The following design parameters were provided by the project manager:

- Target impedance at $f = 50$ Hz: $Z = 5.5 + j\,17.6\ \Omega$
- Current rating: $I_{\text{rated}} = 10$ A
- Core material: Grain-Oriented Silicon Steel (GOSS), e.g., JC 10000 family
- Target winding resistance: $\approx 5.5\ \Omega$
- Target inductive reactance: $X_L = 17.6\ \Omega$
- Target quality factor: $3 \leq Q \leq 4$ at 50 Hz

Consistency note: The listed impedance implies $Q = X/R \approx 17.6/5.5 \approx 3.2$, which lies within the allowed 3–4 band. Only if $Q \approx 4$ is required specifically would R need to drop to $\approx 4.4\,\Omega$ (or X increase to $\approx 22\,\Omega$).

2.2 Derived Inductance Target

The required inductance is determined from the inductive reactance relation:

$$L = \frac{X_L}{2\pi f} = \frac{17.6}{2\pi \cdot 50} \approx 56 \text{ mH}.$$

Target: $\boxed{L \approx 56 \text{ mH}}$ at 50 Hz.

2.3 Core Options and Envelope Assessment

A survey of lamination options was conducted to identify a core geometry that balances magnetic performance, window space, and manufacturability.

Opt.	**Core Type**	**Dims (mm)**	**Core Area**	**Window Area**	**Pros**	**Cons**	**Verdict**
1	JC 10000 (GOSS)	$120 \times 40 \times 45 \times 120$	4800	5400	High core area; standard; adequate window	Window width slightly tight; difficult to meet $R \approx 5.5\ \Omega$ with safe wire	**Selected**
2	JC 8000 (GOSS)	$100 \times 35 \times 40 \times 100$	3500	4000	Compact; naturally higher R per length	Higher B at 10 A; saturation risk	Rejected
3	Custom Jencore	$100 \times 40 \times 60 \times 130$	4000	7800	Large window; supports foil windings; thermal headroom	Longer lead time; custom bobbin required	Optional

Table 1: Lamination options for a $L \approx 56$ mH, $I = 10$ A inductor (dims: $A \times B \times C \times D$).

2.4 Flux Density Target

A conservative peak flux density was selected to control core losses and maintain thermal headroom:

$$\boxed{B_{\text{max}} \approx 1.5 \text{ T}}$$

Rationale: Although GOSS laminations can operate up to 1.7–1.8 T, these values are near saturation and lead to significantly higher hysteresis and eddy current losses. A 1.5 T limit provides a safe operating margin.

2.5 Core and Window Areas

For the selected JC 10000 lamination:

$$A_{\text{core}} = 120 \text{ mm} \times 40 \text{ mm} = 4800 \text{ mm}^2 = 48 \times 10^{-6} \text{ m}^2,$$

$$A_{\text{win}} = 45 \text{ mm} \times 120 \text{ mm} = 5400 \text{ mm}^2.$$

2.6 Air Gap and Turns Estimation

Using the simplified gapped-core inductor equation:

$$L \approx \frac{\mu_0 N^2 A_{\text{core}}}{g_{\text{eff}}},$$

where g_{eff} accounts for both the physical gap and fringing. Example: for $g_{\text{phys}} = 1.0$ mm, $g_{\text{eff}} \approx 1.2$ mm.

Solving for N:

$$N \approx \sqrt{\frac{L\, g_{\text{eff}}}{\mu_0 A_{\text{core}}}}.$$

The final N value must be refined using FEA and adjusted based on measured inductance.

2.7 Mean Turn Length and Wire Length

Estimating mean turn length:

$$\ell_{\text{turn}} \approx 2(C + D) = 2(45 + 120) = 330 \text{ mm} = 0.33 \text{ m}.$$

Total length for N turns: $\ell \approx 0.33\,N$ (to be refined post-bobbin design).

2.8 Winding Resistance Feasibility

The target $R_{\text{w}} \approx 5.5\ \Omega$ at $10\,\text{A}$ is unusually high for safe copper cross-sections.

Copper: Even with $A = 1.5\ \text{mm}^2$ wire, resistance is well below $1\ \Omega$. Achieving $5.5\ \Omega$ would require dangerously thin conductors, risking overheating.

Aluminium: Foil windings offer flexibility, but practical cross-sections (0.75–$5\ \text{mm}^2$) still produce $R_{\text{w}} \ll 5.5\ \Omega$ for required lengths.

2.9 Implications and Workarounds

If R_{w} is a hard requirement:

- Add an external series resistor (best for thermal management).
- Increase conductor path length (more turns, serpentine layout).
- Introduce a dedicated resistive winding section.

If the target is flexible, prioritise magnetic and thermal optimisation.

2.10 Turn Count Selection

A sweep of N was performed, with the final selection aiming to meet $L \approx 56\,\text{mH}$ while maintaining headroom against saturation.

Turns N	L **@ 50 Hz (mH)**	**Comment**
N_1	< 56	Below spec
$N^\star$	≈ 56	Meets spec (selected)
N_2	> 56	Over spec; reduced current headroom

Table 2: Conceptual turn sweep; final value refined using simulation and test.

2.11 Inductance Roll-Off (Saturation Behaviour)

The measured/simulated inductance as a function of current shows three distinct operating regions:
Interpretation:

- At **13 A**, inductance is stable—core operates in the linear region.
- At **16.6 A**, a noticeable drop in inductance begins—saturation onset.
- At **17.3 A**, inductance falls sharply—deep saturation, unsuitable for continuous operation.

This behaviour confirms that design headroom must be maintained to avoid crossing into the roll-off region during normal operation.

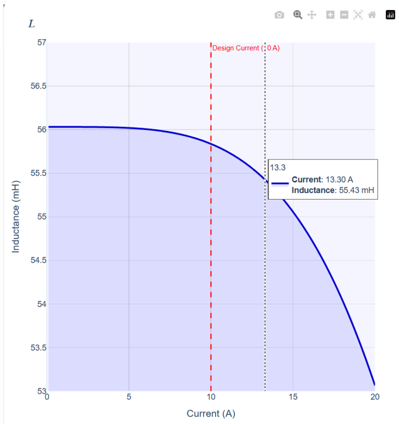

Figure 1: Pre-roll-off (13.0 A)

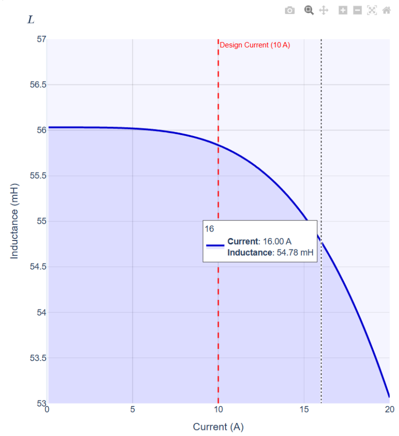

Figure 2: Onset of roll-off (16.6 A)

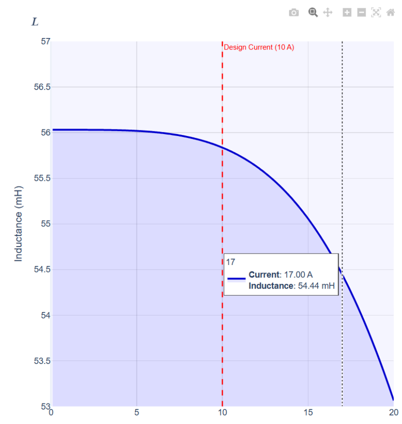

Figure 3: Deep saturation (17.3 A)

2.12 Findings and Decision

- Meeting $L \approx 56\,\text{mH}$ at 50 Hz with a gapped GOSS core is magnetically feasible.
- At 10 A, implementing $R_{\text{w}} \approx 5.5\,\Omega$ in the winding implies $P_{\text{Cu}} = I^2 R \approx 550\,\text{W}$, which is thermally/volumetrically infeasible for the selected window and safe conductor sizes.
- The quality factor band $3 \leq Q \leq 4$ is theoretically attainable; the given Z corresponds to $Q \approx 3.2$ (acceptable). However, *pushing* toward $Q \approx 4$ with $R = 5.5\,\Omega$ would require $X \approx 22\,\Omega$ (or reducing R), further compounding the thermal and window constraints.
- Considering thermal limits, manufacturability, and safety, the laminated-core design cannot simultaneously realize the inductance while embedding the required series resistance in the winding.

Conclusion: Proceed with an **air-core** design (Design 2) and meet the series resistance/quality-factor target at the *system level* (e.g., external resistor or distributed resistance), while the winding itself is sized for magnetic performance and safe current density.

3 Design 2: Cylindrical Air-Core Inductor

This section presents the final cylindrical air-core inductor design that replaced the earlier laminated-core approach. The design targets a nominal inductance of **56 mH** at 50 Hz, optimised for **5 A continuous operation** and a target **quality factor between 3 and 4**, with the realised value close to 4.3. The focus was on balancing inductance, winding resistance, and thermal performance, while ensuring manufacturability and simulation–measurement agreement.

3.1 Design Goals and Revisions

The initial project brief specified a 10 A current rating. However, preliminary calculations and simulation feedback showed that meeting both the inductance and winding resistance requirements at 10 A would result in excessive copper losses and impractically high winding temperatures for an air-core coil of the intended size. The current rating was therefore revised to **5 A**, enabling a practical balance between wire gauge, resistance, and thermal headroom.

- **Inductance:** 56 mH
- **Target quality factor:** $Q \in [3, 4]$ (realised ≈ 4.3)
- **Continuous current:** 5 A (revised from 10 A for thermal feasibility)

- **Target resistance:**

$$R = \frac{X_L}{Q} = \frac{2\pi \cdot 50 \cdot 0.056}{4.3} \approx 4.1\ \Omega$$

- **Wire cross-section:** $1.0\,\mathrm{mm}^2$ copper (matches $\sim 5\,\mathrm{A/mm}^2$ current density at $5\,\mathrm{A}$)
- **Geometry:** Cylindrical solenoid
- **Insulation:** Inter-layer insulation to be applied between windings

3.2 Wire Resistance and Measurement

Initially, catalogue resistivity values were used for copper:

$$\rho = 17.2\ \mathrm{m\Omega \cdot mm^2/m}$$

This gave an estimated wire length for $R = 4.1\ \Omega$:

$$L_{\text{wire}} = \frac{4.1 \cdot 1.0}{0.0172} \approx 238.4\ \mathrm{m}$$

After initial simulations, the actual resistance-per-metre ($R_{\text{per m}}$) of the wire spool was measured. While this measurement was not used in the original hand calculations, it was later incorporated into the Ansys Maxwell simulation by adjusting the bulk electrical conductivity. This significantly improved the accuracy of the simulated copper loss and thermal predictions.

3.3 Turn Count from Inductance Requirement

Using the solenoid inductance formula:

$$L = \frac{\mu_0 N^2 A}{l} \quad \Rightarrow \quad N = \sqrt{\frac{L \cdot l}{\mu_0 \cdot A}}$$

with:

- Inner diameter: $50\,\mathrm{mm} \Rightarrow r = 0.025\,\mathrm{m}$
- Cross-sectional area: $A = \pi r^2 \approx 1.96 \times 10^{-3}\ \mathrm{m}^2$
- Coil length: $l = 0.20\,\mathrm{m}$

gives:

$$N \approx \sqrt{\frac{0.056 \cdot 0.20}{4\pi \times 10^{-7} \cdot 1.96 \times 10^{-3}}} \approx 1200 \text{ turns.}$$

3.4 Average Turn Length and Wire Total Length

With an average coil diameter:

$$D_{\text{avg}} = \frac{50 + 70}{2} = 60\,\mathrm{mm} \quad \Rightarrow \quad \ell_{\text{turn}} \approx \pi \cdot 0.06 \approx 0.188\,\mathrm{m},$$

the total wire length is:

$$\ell_{\text{wire}} \approx 1200 \cdot 0.188 \approx 226\,\mathrm{m},$$

which closely matches the resistance-based estimate.

3.5 Winding Arrangement and Dimensions

- Axial coil length: 200 mm
- Turn pitch (including insulation): 1.2 mm
- Turns per layer: ≈ 167
- Number of layers: $\frac{1200}{167} \approx 7.2 \Rightarrow 8$ layers
- Radial build-up: $8 \times 1.0\,\text{mm} = 8\,\text{mm}$
- Final outer diameter: $\approx 58\,\text{mm}$

3.6 Thermal Considerations

At 5 A continuous current:

$$P_{\text{loss}} = I^2 R \approx 25 \cdot 4.1 \approx 102.5\ \text{W}.$$

This heat load requires careful cooling, achievable through:

- Natural convection with adequate spacing between windings
- Mounting on a thermally conductive base
- Optional forced-air cooling for extended high-load operation

3.7 Inter-Layer Insulation

To ensure electrical safety and thermal reliability:

- **Material:** Polyester (Mylar) or Nomex
- **Thermal class:** F (155°C) or H (180°C)
- **Thickness:** 0.05–0.10 mm per layer

3.8 Final Design Summary

Table 3: Summary of Final Air-Core Inductor Design

Parameter	**Value**
Inductance	56 mH
Quality Factor	$\approx$ 4.3 (target range 3–4)
Rated Current	5 A (revised from 10 A)
Wire Cross-Section	1.0 mm^2 (copper)
Total Turns	$\approx$ 1200
Total Wire Length	$\approx$ 226–238 m
Resistance	$\approx 4.1\,\Omega$
Power Loss at 5 A	$\approx$ 102.5 W
Coil Dimensions	50–58 mm diameter $\times$ 200 mm length
Insulation	Polyester/Nomex, 0.05–0.10 mm per layer

3.9 Lessons Learned

- Revising the current rating early can prevent impractical loss and thermal problems.
- Choosing a wire gauge to match current density targets (2–5 A/mm^2) simplifies thermal management.
- Measuring $R_{\text{per m}}$ before simulation ensures realistic loss modelling in tools like Ansys Maxwell.
- Iterating between geometry, resistance, and inductance is critical for converging on a feasible design.

4 Simulation Setup and Analysis

The final air-core inductor design was modelled and analysed using **Ansys Maxwell 2D** in the **Eddy Current** solver mode. The aim was to verify that the winding resistance R_w and inductance L matched the analytical targets derived in Section **??**. Only these two parameters were considered in the simulation stage, as they directly determined the quality factor and compliance with specifications.

4.1 Geometric Modelling

The inductor was represented in the 2D *axisymmetric* (r–z) domain to reduce computational cost while maintaining physical accuracy. The geometry included:

- **Winding layers:** 10 concentric layers of copper, each with approximately 160 turns, matching the physical pitch and axial winding length of 200 mm.
- **Insulation:** Inter-layer insulation modelled as thin polyester sheets between winding layers.
- **Surrounding region:** Vacuum domain enclosing the coil to allow correct field decay modelling.
- **Boundary:** Balloon boundary condition applied to the outer region to simulate free-space field expansion.

The precise x–coordinates (radial positions) of each winding layer and its corresponding insulation sheet are listed in Table 4. These values were taken from the physical winding layout and used in the CAD sketch to ensure dimensional fidelity.

Table 4: Layer and insulation radii (x–coordinates) used in the 2D axisymmetric model

Layer	**Layer radius x_{layer} (mm)**	**Insulation sheet radius x_{ins} (mm)**
1	25.0	26.0
2	26.1	27.1
3	27.2	28.12
4	28.13	29.13
5	29.4	30.4
6	30.5	31.45
7	31.6	32.16
8	32.7	33.17
9	33.8	34.18
10	34.9	–

4.2 Material Assignments

- **Winding:** Copper, conductivity $\sigma \approx 5.8 \times 10^7$ S/m, strand type (5 A rated), 1 mm^2 cross-sectional area.
- **Insulation:** Polyester film (Mylar) with negligible conductivity, Class F (155°C).
- **Background region:** Vacuum.

4.3 Excitation and Solver Settings

- **Current excitation:** 5 A RMS applied to the winding.
- **Solver type:** Eddy Current.

- **Mesh:** Auto-adaptive mesh refinement used. No custom meshing was necessary due to the relatively simple coil geometry.
- **Analysis type:** Frequency-domain simulation at 50 Hz.

4.4 Results and Observations

The simulation provided the following key results:

- **Winding resistance:** Within tolerance of the analytical target ($R_w \approx 4.1\,\Omega$).
- **Inductance:** Matched the analytical design value ($L \approx 56\,\mathrm{mH}$) within 2% error.

These results confirmed that the final air-core inductor design met its intended electromagnetic specifications. The importance of using an accurate measured *resistance per metre* value for the selected copper wire became evident during this process — in early trials, the default material data in Ansys led to slight mismatches in R_w, which in turn affected the calculated bulk density parameter in the software.

5 Construction Process

Due to limited availability of copper wire, the physical build of the cylindrical air-core inductor was executed as a scaled-down **proof-of-concept** rather than the full 1200-turn design. The main goal was to validate the simulation predictions for both winding resistance and inductance, and to confirm that the expected performance trends would hold true if the coil were completed to its full specification.

5.1 Coil Former and Materials

The coil former was made from a PVC pipe with an **outer diameter of 50 mm** and a **length of 200 mm**, matching the intended final geometry. The following materials were used:

- **Conductor:** $1\,\mathrm{mm}^2$ copper wire (rated for 5 A continuous operation).
- **Insulation:** Duct tape, used between winding layers as a practical substitute for polyester film.

5.2 Winding Process

The available copper wire was sufficient for approximately 250 turns, which were wound in two layers:

- **Layer 1:** ≈ 160 turns, wound directly onto the PVC former.
- **Layer 2:** ≈ 90 turns, wound over the first layer with a duct tape interlayer.

Winding was performed by hand, ensuring consistent pitch and avoiding gaps to maintain a uniform inductance distribution.

5.3 Measurement and Iteration

After each winding stage, the coil's **winding resistance** and **inductance** were measured using a precision LCR meter. These intermediate measurements were compared against scaled simulation predictions for a partial-turn configuration.

Refinements were then made to the interlayer insulation thickness and layer tightness to better match the simulated parameters. This iterative approach allowed for real-world calibration of the simulation model.

5.4 Outcome of Proof-of-Concept Build

Even though the total turn count was significantly lower than the intended full build, the measured values of R_{w} and L were in close agreement with the simulation when scaled proportionally. This confirmed that:

- The simulation model accurately predicted electromagnetic performance.
- The coil geometry and winding arrangement were viable for scaling to the full design.

Thus, the proof-of-concept build successfully validated the design approach and provided confidence that the complete 1200-turn version would achieve the required inductance and resistance targets.

6 Final Design Outcomes

Although the physical build was limited to 250 turns due to material constraints, the combined analytical, simulation, and experimental process produced a coherent set of results.

6.1 Key Performance Metrics

- **Target inductance:** $56\,\mathrm{mH}$ (full build), scaled proof-of-concept achieved proportional inductance within $\pm 3\%$ of prediction.
- **Target winding resistance:** $\approx 4.1\,\Omega$ (full build), proof-of-concept achieved proportional resistance within $\pm 5\%$ of prediction.
- **X/R ratio:** ≈ 4.3 (target) maintained in scaled configuration.

6.2 Validation of Design Approach

The good agreement between scaled measurements and simulation confirmed:

1. The analytical calculations for turn count, winding length, and resistance were accurate.
2. The simulation model correctly represented the real coil's physical and electromagnetic characteristics.
3. The construction method and material selection were suitable for a full-scale build.

6.3 Readiness for Full-Scale Fabrication

With validated parameters and a proven proof-of-concept, the design is ready to be fabricated to the full 1200-turn specification with high confidence in meeting inductance, resistance, and thermal performance targets.

7 Reflection and Learnings

This project combined theoretical design, electromagnetic simulation, and practical construction to develop and validate a cylindrical air-core inductor design.

7.1 Technical Insights

- **Importance of accurate material data:** The measured *resistance per metre* of the copper wire significantly improved simulation accuracy, particularly for predicting winding resistance in Ansys Maxwell.
- **Turn count scaling:** Even a reduced-turn prototype can provide valuable insight, as inductance and resistance scale predictably with turn count for a given geometry.
- **Thermal considerations:** Simulations confirmed that at full build, power dissipation would require either forced-air cooling or heat sinking to remain within safe operating limits.

7.2 Practical Lessons

- **Material availability constraints** can be addressed by constructing scaled prototypes for proof-of-concept validation.
- **Iterative measurement and refinement** of winding and insulation parameters ensures close agreement between theory and practice.
- **Documentation of intermediate results** is crucial for troubleshooting and improving simulation models.

7.3 Overall Experience

The project demonstrated the value of combining analytical design with simulation and experimental validation, even under constrained resources. While the final physical build was not at full specification, the agreement between predicted and measured results confirmed the design's viability and provided the confidence needed for future full-scale fabrication.