Andrews University

Design of an Induction – Based Plug for Car Engine Block Heater Application

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SOLIDWORKS

EMWORKS

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[1] Appendix A contains an expansion of the simulation results that section **6.1.6** details.

1. Introduction

1.1 Background Motivation

A car engine block heater—often known simply as a block heater – is a device installed in a car engine for the purpose of warming the engine, thus increasing the likelihood that the engine will start while also decreasing the time it takes to warm the vehicle up in cold weather. A secondary benefit of block heating is it increases fuel economy. [5] A block heater operates through an alternating current (AC) flowing through a high wattage resistive element replacing a core plug bolt or the oil dip stick. When plugged in the block heater warms the resistive element which in turn heats the engine oil, decreasing oil viscosity. Block heaters are often used in northern latitudes such as in the northern USA, Canada, Russia, and the Scandinavian region. A block heater system consists of three primary components: an extension cord from plug in to the car's grille, a plug-in connector to a second cord going from the grille to underneath the engine block, and the resistive element which typically threads into a bolt hole in the engine block. Block heaters typically operate off of 350 to 1800 watts and are usually powered by the local power grid wall socket plug in, which for the USA is 120 volts (V) at 15-20 amps (A). [13]

Figure 1: *Engine block heater [11]*

Figure 2: *Engine block heater resistive element (copper-colored unit), extension cord to grille, and extension cord prongs cover [10]*

1.2 Problem Statement

When using a conventional block heater, the user must plug in the power cord into a power source—typically another power cord—and when done being used the block heater power cord must be unplugged. This constitutes a total of two mechanical operations of plugging and unplugging per warming period. A plug system operating off of two small parallel plates that attach via a mechanical latch would allow the user not to have to insert the plug into the socket. Instead, the user would simply need to align the two plates and the attaching mechanism would secure them in parallel to each other. Such a parallel plate plug design increases ergonomics of plug as conventional socket plugs can fill with snow or other debris whereas a parallel plate design would not.

1.3 Objective: Summary

A plug system will be designed such that the plug is comprised of two units—a transmitter (on the power cord side) and a receiver (on the car side) —parallel to each other. The transmitter and receiver may or may not be separated by a small distance, either way allowing a wireless power transfer through magnetic flux. Power transfer will occur through metal cores in the transmitter and the receiver with induction as the means of power transfer. In application, the proposed plug system will then replace the plug in a pre—existing block heating unit to be specified. This project consists of the design of the transmitter and receiver components *and does not account for any peripheral mechanical fasteners* or similar units for aligning the two plug halves. This is a proof—of—concept design, therefore, the goal of this project is to quantify the viability of such an induction-based plug and design a prototype which will demonstrate the simulated viability.

1.4 Objective: Details

The following bullet point lists give a comparison between the common friction-based plug and the induction-based plug considered in this project.

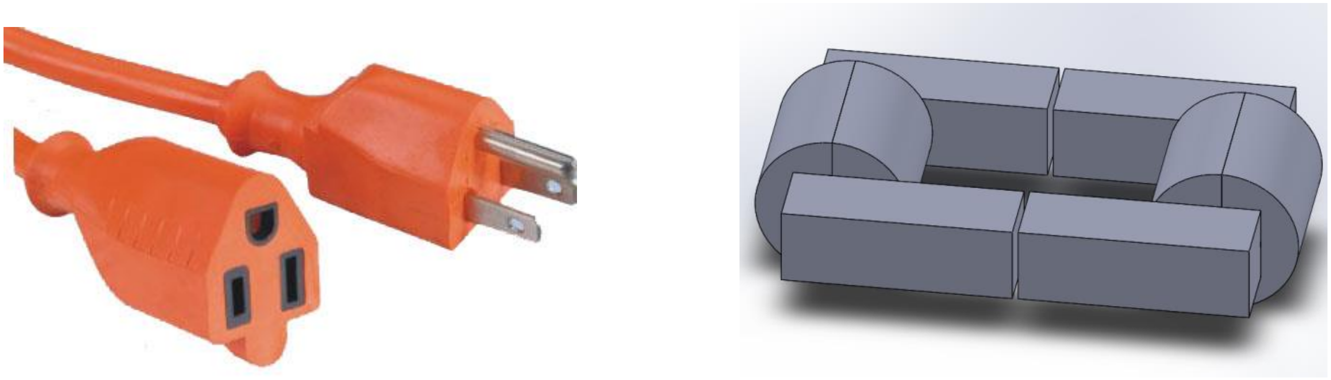
Friction-based plug:

- Most commonly used type of electrical connector
- Requires user to plug and unplug connection
- Effectively 100% power transfer

Induction-based plug:

- Does not exist on market currently
- Possible increased plugging and unplugging ergonomics due to simply aligning two parallel cores
- Efficiency: unknown

Figure 3. On the left is the conventional friction-based plug while on the right is an early-model of a possible induction-based plug.



2. Design Specifications

- Input AC signal frequency of 60 Hz
- Input AC voltage of 120 V
- Output AC voltage of 120 V
- output power: 350 watts
- Coil wire gauge: safety factor of 1.5 for input power
- Power output efficiency: 50% of input power (Input power therefore must be 700 [W])
- Electrical prototype will be 2 metal half transformers
- Compatible with National Electrical Code (NEC) power grid frequency and power specifications (60 Hz, 120 V)

3. Design Constraints

- Time: Design must be completed by December 2018
- Budget: $620: ($120) allotted for this project by Andrews University ECS Department and ($500) Robert Zdor education funding
- Safety:
  - No hanging wires
- Size: Entire system should have reasonable dimensions:
  - Weight < 10 pounds
  - Displacement < 1 cubic foot
- Power handling capacity scalable according to scaling of unit's size

4. Theoretical Framework

4.1 Conceptual Theory

A transformer is an AC device that operates under the principles of Faraday's law that is used to transform between voltages and currents. [1] A single-phase transformer consists of a series of continuous coils—the primary winding— wrapped around a square core with a second set of coils—the secondary winding—on the opposite side of the primary winding. The core is typically made of a ferromagnetic material—usually a type of iron—in order to provide a low magnetic reluctance path. Additionally, the core of the transformer is typically made up of layers of laminated steel cross-sections coated so as to reduce electrical conductivity between the laminations.

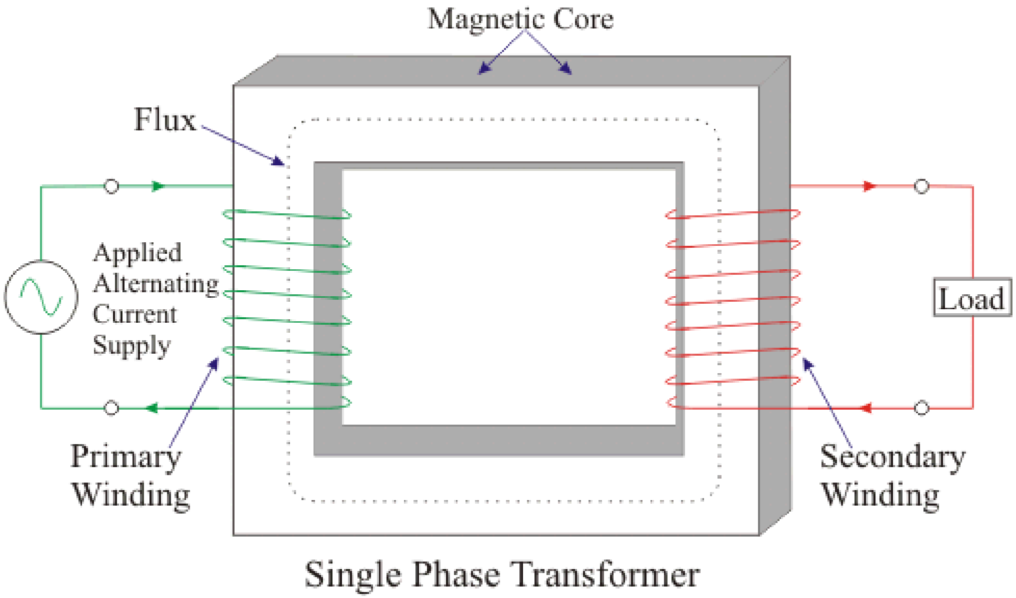
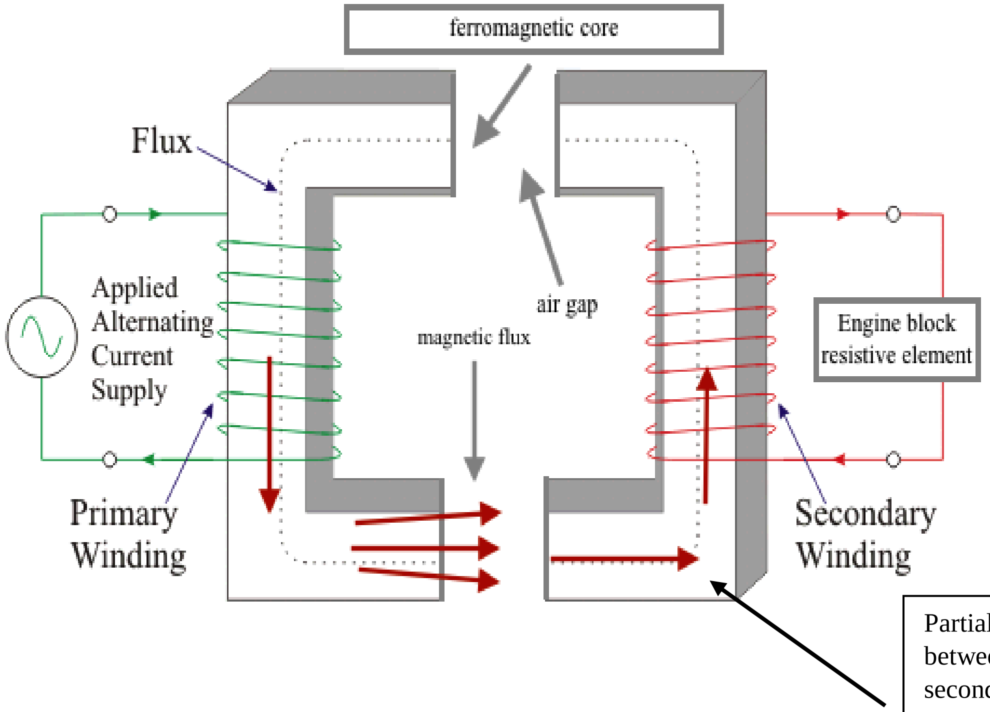


Figure 4: *Schematic of single-phase transformer [7]*

A transformer operates through an AC current creating a changing magnetic field in its core. Changes in the magnetic field in the core induces an alternating voltage in the secondary coil, which in turn induces an AC current in the secondary coil, creating a magnetic field to opposite the change in the magnetic field due to the primary coil. Since the transformer core is made of a material with a non—zero magnetic reluctance (low permeability), there are energy losses in the magnetic circuit of the transformer. Another source of energy loss is flux leakage out of the core. When the core is separated by an air gap, only a fraction of the flux from the primary coil links the second coil. This design project proposes a plug based off of a single-phase transformer where there exist two air gaps in the core, separating the primary and secondary coil, as Figure 4. Illustrates. For the engine block heater unit, the applied AC current will be supplied from a conventional 120 V 15 A wall outlet. The left half of the plug is the transmitter transmitting changing magnetic flux to the right half of the plug, the receiver side. This unit will then replace the conventional socket—based plug that connects the power cord to the cord extending out of the car's grille.



Partial flux linkage between primary and secondary coils due to flux loss at air gap and due to finite permeability of core material

Figure 5: *Schematic of proposed induction—based plug*

Since this *project does not include the creation of a mechanical fastener to align the two half transformers*, clamps will be used to clamp the halves in a fixed proximity to each other. In order to achieve an output power efficiency of 50%, the distance between the transmitter and the receiver must be minimized to ensure sufficient magnetic flux linkage—if following a gap—based design. Another feature to maximize is the receiving half transformer's cross—sectional area that is receiving the magnetic flux; increasing this surface area determines in part how much flux the receiver's core captures. The magnetic reluctance of the core also affects efficiency, therefore choosing a core material to decrease magnetic "resistance" is key. Lastly, wire gauges must be selected capable of handling 2.92 A at 120 V, thus 350 watts.

4.2 Quantitative Theory

Faraday's law in words states that time-varying electric fields (such as from an AC current source) produce time-varying magnetic fields and vice versa. As explained earlier, this is the mechanism for energy transfer for the proposed plug unit. Specifically, Faraday's states:

$$\varepsilon \text{ (induced emf)} = - N \frac{\Delta \Phi s}{\Delta t} \quad \text{[V]}$$

Where emf is the electromotive force induced in the secondary coil and N is the number of turns of wire present in the considered coil. $\frac{\Delta \Phi s}{\Delta t}$ is the change in magnetic flux as a function of time. In order to generate transformer equations, in an ideal situation with infinity magnetic permeability and 100% flux linkage, the flux in the core is calculated as follows where I is current, *R* is magnetic reluctance, and the *1* and *2* indicate primary and secondary cores, respectively:

$$\Phi = \frac{(N1)(I1) - (N2)(I2)}{\Re}$$

- $\Re$ = reluctance = $\frac{L}{\mu S}$ = 0
- ($\mu \longrightarrow$ infinity), [ideal case]
- All flux links coils (closed path)

In the ideal case the above three points hold true, allowing for the rearrangement of the flux equation into the following transformer equation relationships:

$$\text{Constant} = \frac{emf\ 1}{emf\ 2} = \frac{I2}{I1} = \frac{V1}{V2} = \frac{N1}{N2}$$

Table 1. Shows various materials often encountered in transformers and their respective relative magnetic permeabilities μr.

Material	**Permeability ($\mu r = \frac{\mu medium}{\mu 0}$)**
Air	1.000000037
Copper wire	0.9999991
Pure iron (0.05%)	200,000
Wood	1.000000043
Silicon iron (3% Si)	55,000

As **Table 1.** above shows, *R* the magnetic reluctance is non-infinite in the real-world non-ideal case, $\mathfrak{R}$ = reluctance = $\frac{L}{\mu S} \neq 0$. Additionally, the copper coils have resistance, resulting in joule losses, induced eddy current in the magnetic core also result in heating and joule losses, partial flux linkage due to imperfect core alignment, and losses due to hysteresis (losses due to changes in the magnetization vector) – all these factors must be accounted for in the non-ideal scenario of this project. The following equations allow for a quantification of these losses; however, knowing the fraction of flux coupling between cores is not calculatable exactly. *K* the flux linkage coefficient must be calculated via numerical simulation based off of the geometry of the considered transformer setup.

- Losses in coils: = $P_{loss} = \frac{V^2}{R}$, R = resistance of coils, V = applied voltage, [W]
- Hysteresis loss $= n * B(max)^\wedge(n) * f * Volume$ [W]
    - *n = Steinmetz hysteresis coefficient (J/m^3)*
    - *B(max) = maximum flux density*
    - *f = frequency*
    - *Volume = volume of core*
- *Emf1* = $L11\frac{dI1}{dt} - K\sqrt{L11 * L22}\frac{dI2}{dt}$ [V]
- *Emf2* = $K\sqrt{L11 * L22}\frac{dI1}{dt} - L22\frac{dI2}{dt}$ [V]
    - *K = fraction of flux coupling coils*
    - *L11 = self inductance of primary* = $\frac{u\,S}{l}N1^2$ [H]
    - *L22 = self inductance of secondary* = $\frac{u\,S}{l}N2^2$ [H]

The importance in calculating *K* the flux linkage coefficient is so that the output current may corresponding be calculated, which then allows for calculating the efficiency of the transformer setup, which in turn allows for assessing the viability of the proposed project. Instead of calculating *K* explicitly, an AC magnetic modeling program was used to calculate the output current as a function of the input current, allowing then for a direct calculation of efficiency, where efficiency *E* is defined as:

$$E = (100)\left(\frac{current\ in\ secondary\ coil}{applied\ current\ in\ primary\ coil}\right) \quad [\%]$$

5. Review of Relevant Literature

In in order to ensure an induction-based plug unit did not exist on the market already, a literature review of similar existing products was performed. Andrew Freeman, invented and patented the head bolt heater, a bolt that replaced one of the engine cylinder head bolts with a hollow resistive heating element. [8] This patent does not mention any use of an induction—based plug for the power cord to grille cord connection. Since then Will Topping and Arash Janfada designed and patented an "apparatus for electrically connecting a power source to an electrical device." Their device—named the Magno plug—replaced the conventional socket plug connection for engine block heaters. However, it is noted that their plug operates off of two "ferromagnetic plates." Additionally, in their patent it explicitly states the following:

> "The first component has a substantially planar contoured first face comprising a ferromagnetic plate, a first set of contacts electrically connectable to a power source, two power switches and a magnetically actuated sensor controlling the switches. The second component has a substantially planar contoured second face complementary to the first face comprising a magnet and a second set of electrically conductive contacts electrically connectable to a device." [12]

Figure 6. Shows Topping and Janfada's magnetically activated plug unit; which operates off of a friction plug setup (solely electric field), and not an electric field, to magnetic field, and back to electric field power transfer method.

While Topping and Janfadas' design is that of a type of plug, their patent is of a magnetically activated power transfer circuit wherein a continuous wire connection lies. In this literature search, no design was found that utilizes an induction based—half transformer design where wireless power transfer via magnetic flux is the mode of energy transfer.

6. Design Process

6.0 Simulation Software for Predicting Efficiency:

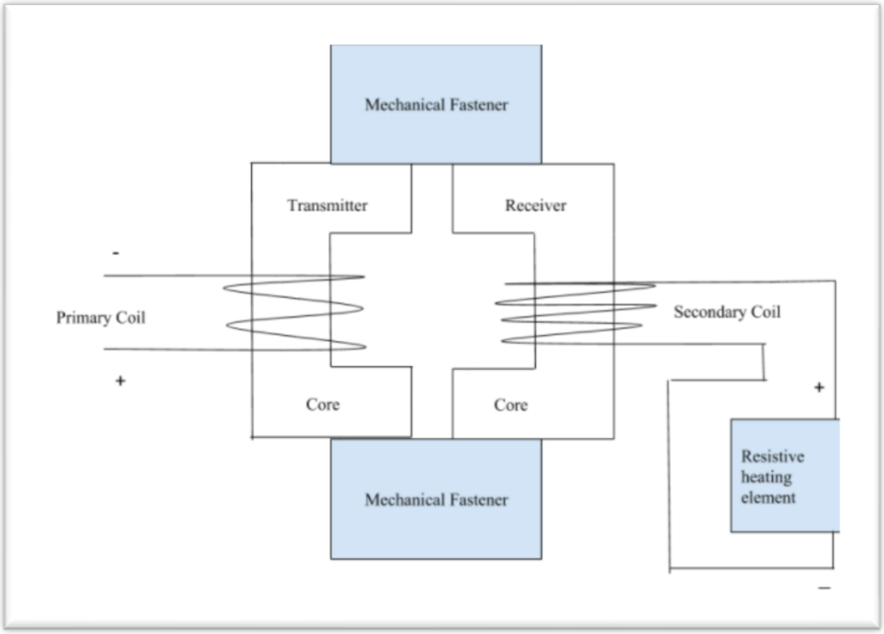
In order to predict the output current in the secondary coil, spring semester 2018 was largely spent exploring resources offered by COMSOL Multiphysics and MATLAB for transformer modeling. However, both of these programs do not allow for uploading of a preexisting CAD model (for example for Solidworks) into the simulation. Therefore, EMWorks, an optional toolbox of Solidworks, was chosen as the simulation tool, since it specifically allows for uploading a CAD model into a simulation. Moreover, the AC Magnetic module in EMWorks allows for calculating magnetic field, flux, current density, voltage, and current at all points in a given CAD model, with input parameters such as AC current or voltage, frequency, CAD model geometer, coil type (AWG wire thickness, wire packing efficiency) and more.

Therefore, April 2018 a 2-seat educational 2018 EMWorks license from sales engineer Mike Curcic from procured for free, a license valued at approximately $1,000. This license was used for the duration of this project and expired December 1st, 2018.

6.1 Design Iterations

The design consisted of two cores, the primary and secondary cores, and the corresponding wire coils wrapped around each coil. Design iterations started with preliminary calculations for CAD model dimensions, Solidworks CAD model generation, EMWorks simulations, and simulated efficiency calculations.

Figure 7. illustrates a preliminary sketch used in the design phase of this project. Note, the mechanical fasteners pictured refer to the clamps used for aligning the two half transformers. Additionally, recognize this project was designing just the plug component, and did not consist of installing the designed plug unit in a car and attaching to an engine block heater. An engine block heater plug is application of this design, and future work could include implementing this design in an engine block heater.



6.1.1 Design Iteration: Core Material Choice Theory (Spring 2018)

The core of the transmitter and receiver was made of a ferromagnetic material M36 0.36 mm grade electrical steel with a high magnetic permeability so as to trap and then guide the magnetic field.[2] The high permeability of the core relative to the surrounding air concentrates magnetic flux in the core. Changing magnetic fields in the core induce eddy currents perpendicular to the field line direction which in turn heat up the core due to core's resistance. Due to this, one solid core was used; rather a series of laminated stacked steel plates comprised the core. The laminations decrease the surface area of the path of the eddy currents, therefore increasing resistance, and thus causing smaller eddy currents. Figure 6 illustrates these stacked plates.

Hysteresis losses are the result of when a material that is sensitive to magnetization is slightly magnetized due to an external alternating magnetic field so when the magnetic field switches direction, extra work (energy loss) must be exerted by the magnetic field to neutralize the slight traces of permanent magnetism left in the material. Therefore, selecting a core material with low hysteresis losses is important, which is why in this design M36 grade electrical steel was used.

***Figure 8**: (Left) basic CAD model of core; (Right) stacked laminated layers to reduce eddy currents*

6.1.2 Design Iteration: Primary and Secondary Coil Materials and Wire Gauge Calculation (Spring 2018)

Enamel insulated copper was used for the primary and secondary coil wiring. The same number of turns was used for the primary as for the secondary coils, as the plug is transferring power only and is not acting to transform voltages or currents. Another key consideration was the wire gauge—the coil wires and the wires leads

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[2] See section 6.1.5 for explanation of why M36 0.36 mm electrical steel was chosen as the core material.

connecting to the coil wires must be able to handle at least 700 watts. The design constraint of a safety factor of 1.5 for the wire gauge power—handling capacity means wire must be able to handle 1050 watts.

For the coil wire material, magnet wire—a wire coated with a very thin coating of polymer insulation—was used. The gauge or diameter of the coil wire was calculated as follows:

Maximum amperage in primary wire = 1050 watts / 120 V = 8.75 A

700 circular mils / 1 A [reference 9]

(8.75 A) x (700 circular mils / 1 A) = 6125 circular mils[3]*; diameter of circle =* $(6125)^{0.5}$ *= 78.3 mils*

78.3 mils = 0.0783 inches in diameter

From American Wire Gauge (AWG) Table: [reference 9] 0.0783 inches in diameter = ***AWG gauge of 12***[4]

Repeating for the secondary coil with a power output of 525 watts, gives a secondary coil wire ***AWG gauge of 15****.*

6.1.3 Design Iteration: Primary and Secondary Coils Number of Turns (Spring 2018)

The N number of turns in the primary N1 and secondary coils N2 were set equal, since this transformer was for power transfer and not voltage or current transforming.

$$N1 = N2$$

With this relationship established, the voltage per turn ratio was calculated using the following method:

☐ F = frequency = 60 hertz

☐ A = cross sectional area of core = estimated at = 3.15 cm x 3.15 cm = 0.99225E-3 m^2

☐ V = Input voltage = 120 V

☐ B = Maximum magnetic field = 1 T

☐ $[\frac{input\ voltage}{coil\ turn} = \frac{2\,\pi\, f * A * B}{\sqrt{2}}]$ [reference 5]

- $N\ turns = [120V] \,/\, [\frac{input\ voltage}{coil\ turn}] = [120\ V] / \left[\frac{2\,\pi\,(60\ Hz)\,(0.99225E{-3}\ m2)\,(1\ T)}{\sqrt{2}}\right] = \mathbf{450}$

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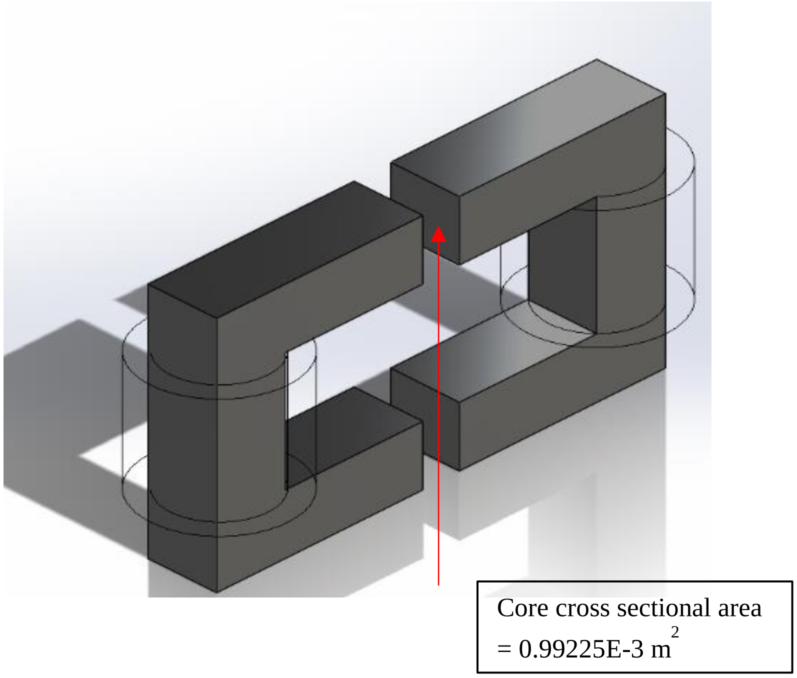
[3] Circular mil is a unit of area equal to the area of a circle with a diameter of one—thousandth of an inch

[4] Light blue highlighted numbers were values used in the design of the Solidworks CAD models.

Figure 9. below shows the estimated core cross-sectional area, an estimate based off of the available transformer lamination dimensions.



Core cross sectional area = 0.99225E-3 m^2

6.1.4 Design Iteration: Calculation of Wire Coil Cross-Sectional Areas (Spring 2018)

With the number of turns and wire types for respective coils known, the last calculation needed to generate a Solidworks CAD model of the two half transformers was that of the total wire cross-sectional areas. The following steps show how the wire cross sectional areas were calculated.

Calculation of primary and secondary cross—sectional areas:

***Primary coil**: 12 AWG gauge wire @ radius = 1.03 mm [reference 4]*

Area / 12 AWG gauge wire = 3.32 mm^2

For 450 wires = 450 x 3.32 = 1494 mm^2 *= total cross-sectional area of primary coil*

Circular wire packing efficiency of 85% [reference 6]

Effective cross—sectional area considering packing efficiency = ***1758 mm***^{2}

***Secondary coil**: 15 AWG gauge wire @ radius = 0.730 mm [reference 4]*

Area / 15 AWG gauge wire = 1.66 mm^2

For 450 wires = 450 x 1.66 = 747 mm^2 *= total cross-sectional area of primary coil*

Circular wire packing efficiency of 85% [reference 6]

Effective cross-sectional area considering packing efficiency = ***879 mm***^{2}

6.1.5 Design Iteration: Solidworks CAD Model (Fall 2018)

Introduction:

The preliminary calculations, dimension estimates, preliminary CAD illustrations, and procuring access to EMWorks were design iterations accomplished Spring and Summer 2018. Fall 2018 started the Solidworks CAD modeling phase. It was during the beginning of the CAD modeling phase that a fundamental factor determining this project's end goal was discovered.

Infinite CAD Models Versus Research-Oriented Prototypable CAD Model Method:

The goal of the Solidworks modeling was to generate a CAD model that would achieve the design specifications and constraints for this project. Most important of these specifications is plug efficiency—a parameter that is a function of a large number of parameters including but limited to the following:

1. Plate alignment cross-sectional areas
2. Core material
3. Sharpness of corners and bends (sharper bends results in greater magnetic flux loss)
4. Core geometry (circular section versus square or rectangular cross sectional)

This large number of parameters to consider when designing the ideal, most efficient transformer model meant that effectively, this project could take two directions: spent most of the project time optimizing an ideal CAD model, *or* take a more research-oriented approach and limit the CAD model by the materials available for prototyping. Since the infinite CAD model option was largely a mechanical problem and also since it had no definite end, the second option was chosen.

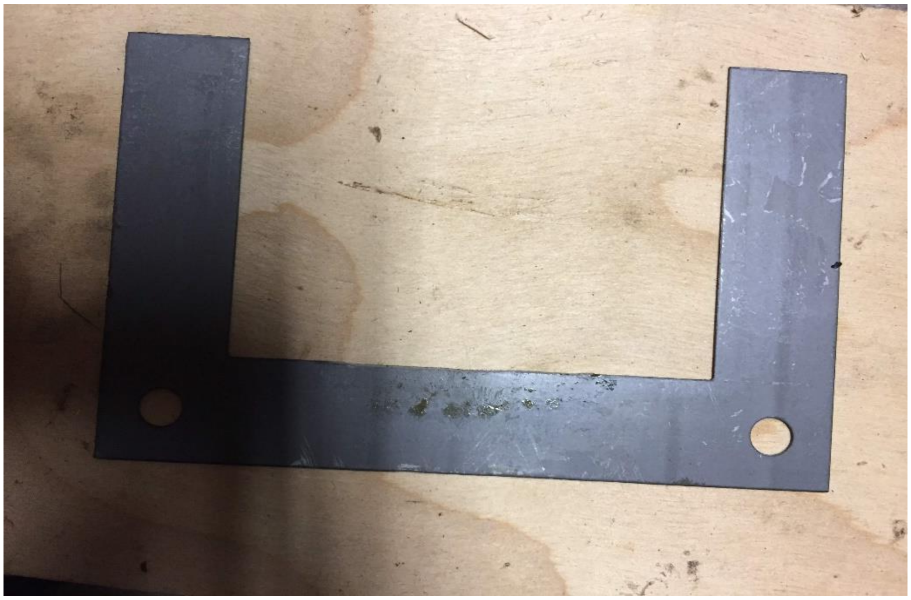
Why the Research-Oriented Prototypable CAD Model Method:

Another reason contributing to taking a research and defined-end approach to the modeling was due to prototype limitations. Specifically, if an ideal most efficient CAD model were generated, such a model would invariably require custom molding or laminations at the least. The two major electrical steel lamination producers in the USA were therefore contacted to see price options at low quantity (less than 1000 laminations). The results of this investigation included:

- **Custom lamination option:**
  - Tempel Steel Inc. [1-ton minimum]
  - Thomas and Skinner Steel [2-ton minimum]
- **Alternate option:**
  - Take apart existing transformer (microwave transformer)
  - M36 Grade Silicon Steel (Electrical Steel) at 0.368 mm = ~ 0.36 mm
  - Free

Since Tempel Steel and Thomas and Skinner did not offer custom laminations in small quantities, the alternative option of using existing laminations was chosen. Specifically, a microwave transformer's laminations (see following specifications of laminations) were used for the CAD modeling and prototyping, allowing for a clear comparison between simulation results and prototype results.

Figure 10. Shows the microwave transformer lamination upon which the CAD modeling was based on.

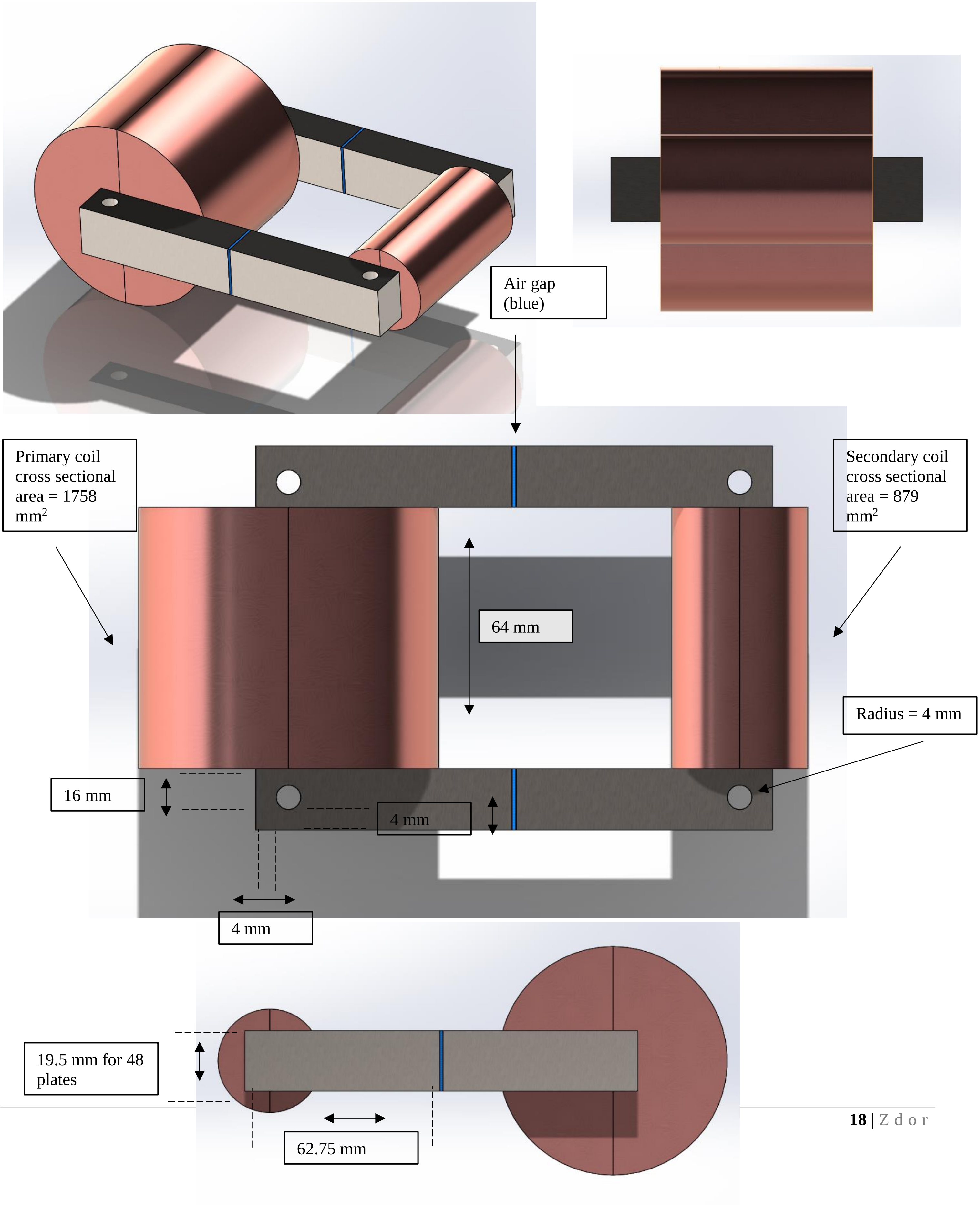


Solidworks CAD Model:

The dimensions of the CAD model were determined by the laminations, as the following list outlines. Dimensions were measured with digital calipers from Dr. Boon Chai, where the precision of the calipers went to 1E-6 meters.

- **Geometry**
  - Based on dimensions and number of (48 laminations available per core) of available transformer laminations (for prototype)
  - Measured lamination thickness = 0.368 mm (rounded to 0.36 mm)
  - Wire-cross sectional area calculation: (see section **6.1.4** for calculation of values below)
    - Primary coil cross-sectional area = 1758 mm^2
    - Secondary coil cross-sectional area = 879 mm^2

Figure 11. Shows the isometric, top, side, and overhead views of the designed CAD model, with its dimensions as well.



6.1.6 Design Iteration: EMWorks Simulation Parameters

Simulation parameters were chosen to fit the stated **Specifications** and **Constraints.** The following list outlines the simulation procedure utilized. Note that the core material M36 .36 mm electrical steel with losses built-in accounts for the finite permeability and also for the eddy currents present at a thickness of 0.36 mm. **Appendix A** expands on the physical properties of the materials used and tabulates the inputs used in EMWorks.

- ☐ **Choose AC Magnetic Module in EMWorks**
    - Frequency = F = 60 Hz
- **Assign materials to CAD model parts**
    - Core (laminated M36 steel at 0.36 mm) with losses built in
    - Air gap (air) [not shown]
    - Air box (air)
    - Coils (copper)
- **Apply electromagnetic input:**
    - Wound coil 1: primary
        - 12 AWG wire
        - Input current = 6 [A]
        - Wiring packing efficiency = 85% [reference 6]
    - Wound coil 2: secondary
        - 15 AWG wire
        - Input current = 0 [A]
        - Wiring packing efficiency = 85% [reference 6]

Figure 12. Shows the mesh results that EMWorks uses as a part of the Finite Element Method (FEM) to solve Faraday's law for the inputted geometry and current inputs.

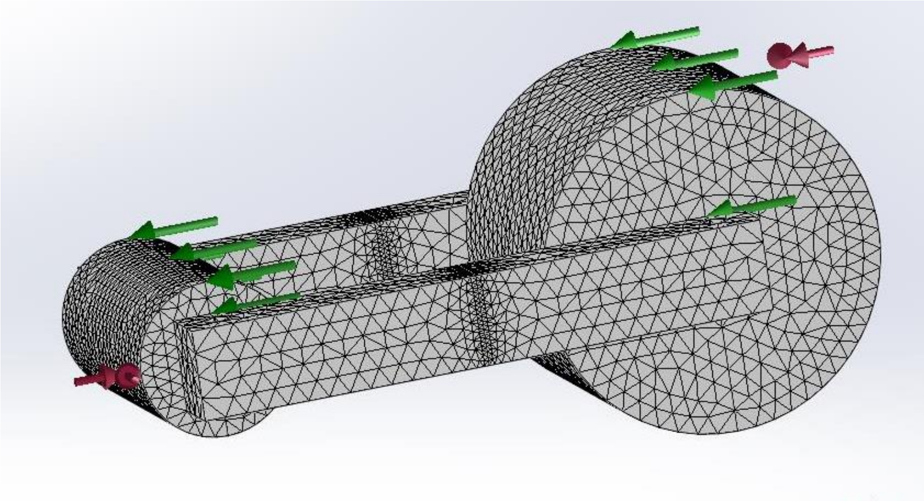
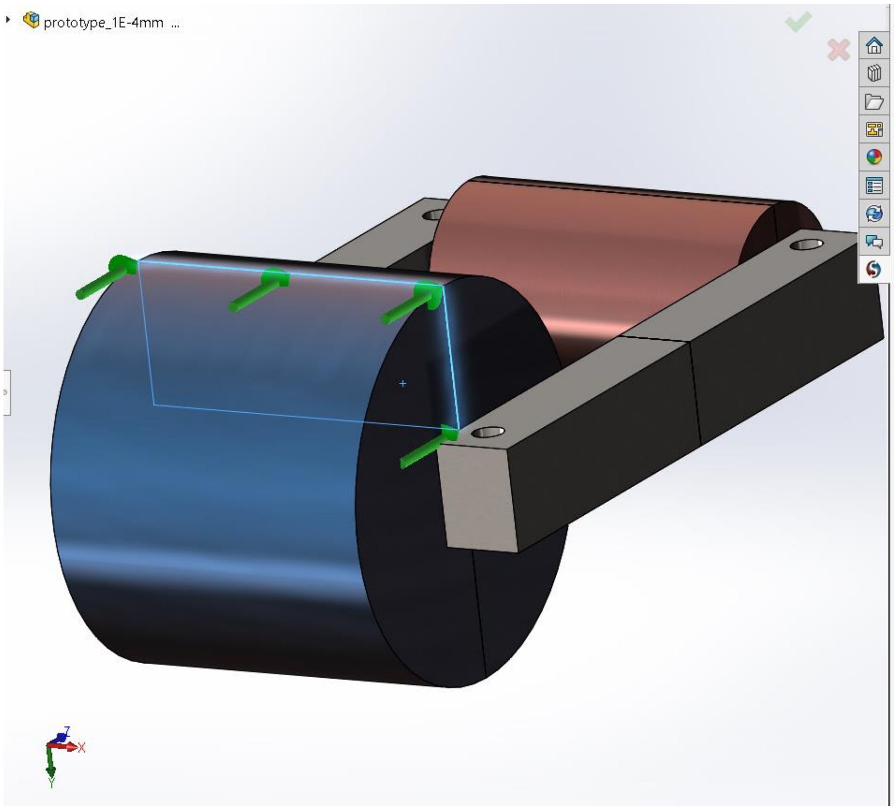
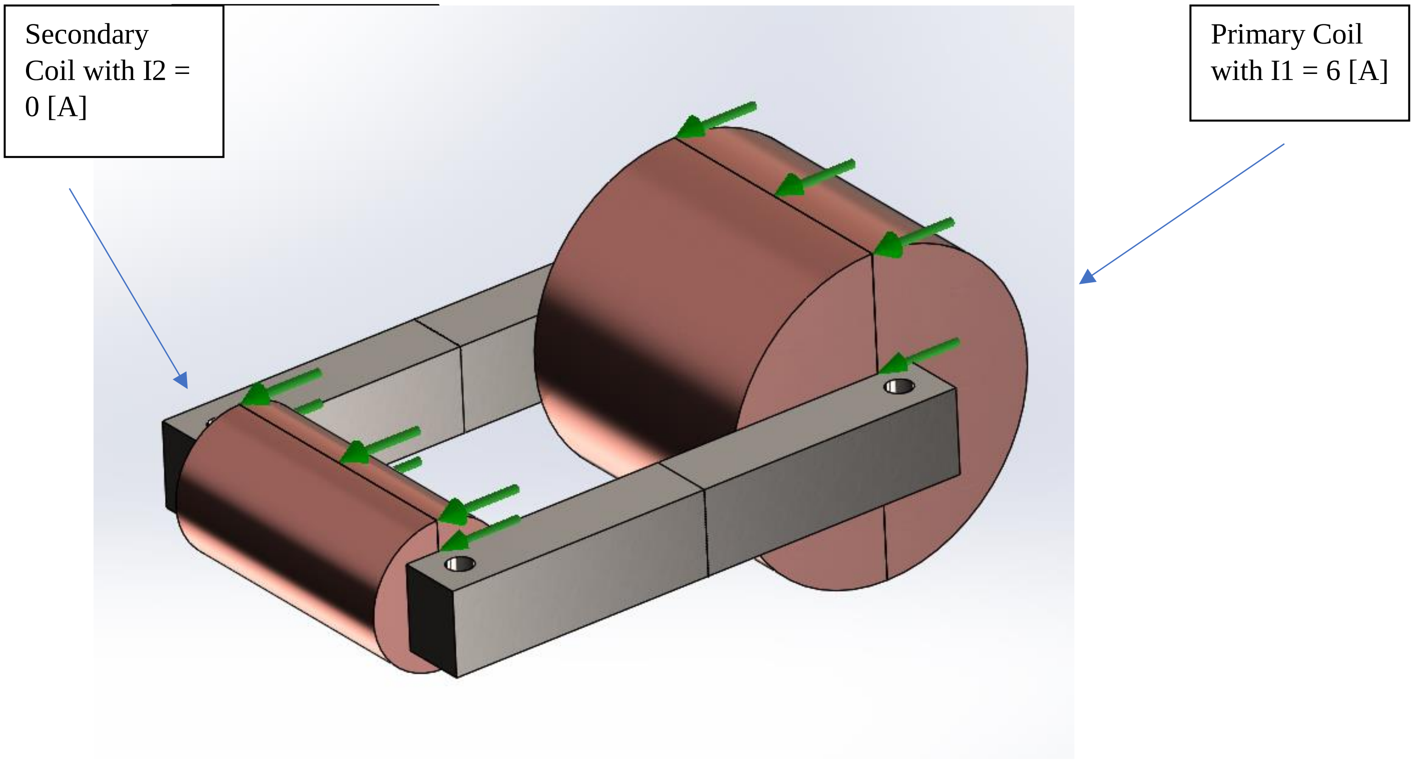


Figure 13 and 14. Illustrates in the upper figure how the cross-sectional face of the primary coil was selected as the current input. EMWorks has a built-in wound coil electromagnetic input parameter, which allows the user not to have to create individual windings in Solidworks. The second figure, **Figure 13**, shows the applied currents. (next page)

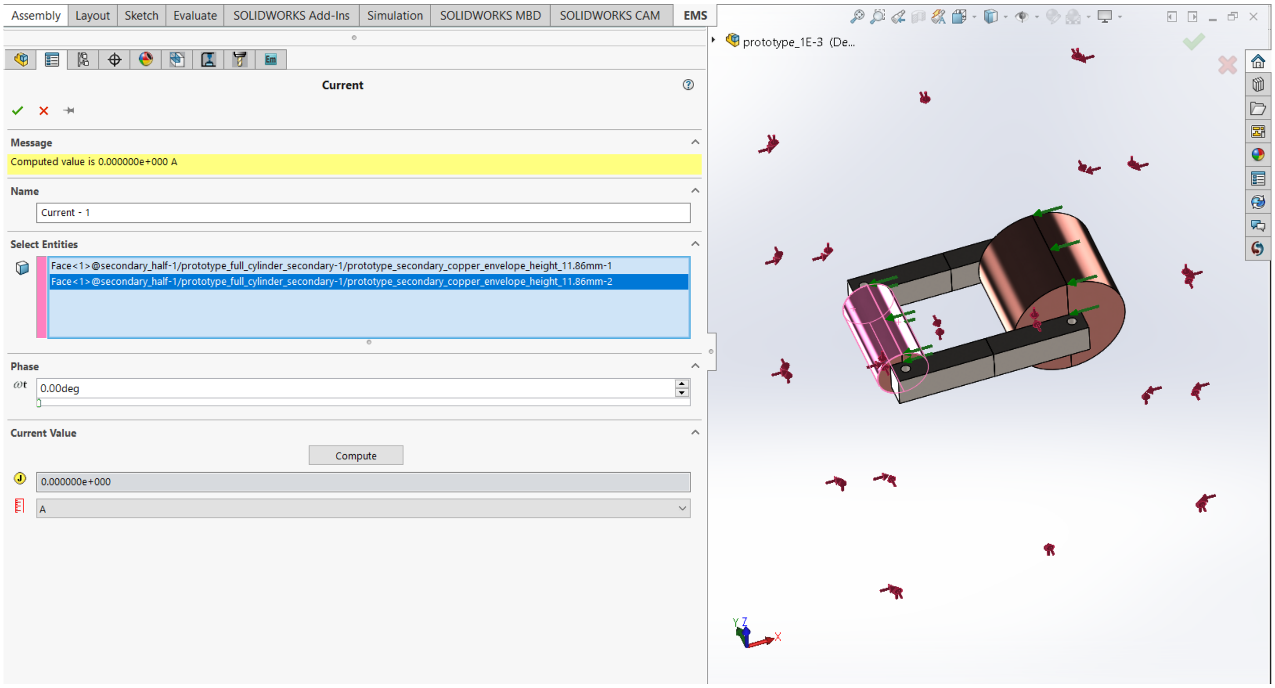




6.1.7 Design Iteration: EMWorks Simulation: Current Measurement

The AC Magnetic module in EMWorks 2018 has a built-in current measurement tool for measuring the current through a selected face or geometry. Current was measured and the resulted tabulated in Excel.

Figure 15. in the upper figure shows the selection of the secondary coil and corresponding current measurement of 0.0000000 [A] result for an air gap separation of 1E-6 meters. See **Appendix A** for more current measurement figures.



Message

Computed value is 0.000000e+000 A

Name: Current - 1

Select Entities

Face<1>@secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secondary_copper_envelope_height_11.86mm-1

Face<1>@secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secondary_copper_envelope_height_11.86mm-2

Phase

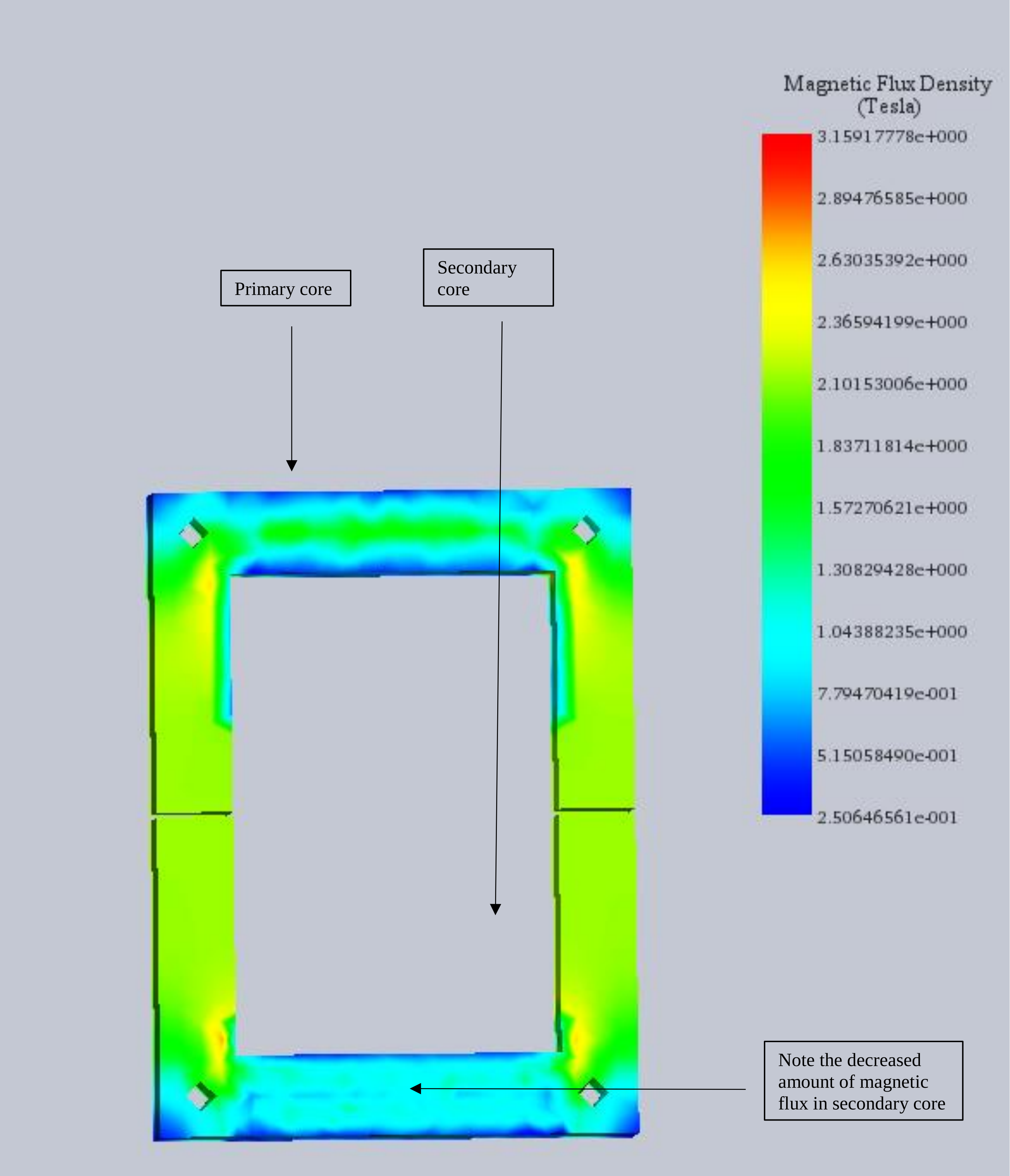
ωt 0.00deg

Current Value

0.000000e+000

A

Figure 16. Shows the magnetic flux in the primary secondary cores at an air gap of 5E-3 mm = 5E-6 m = 5000 nm.



Note the decreased amount of magnetic flux in secondary core

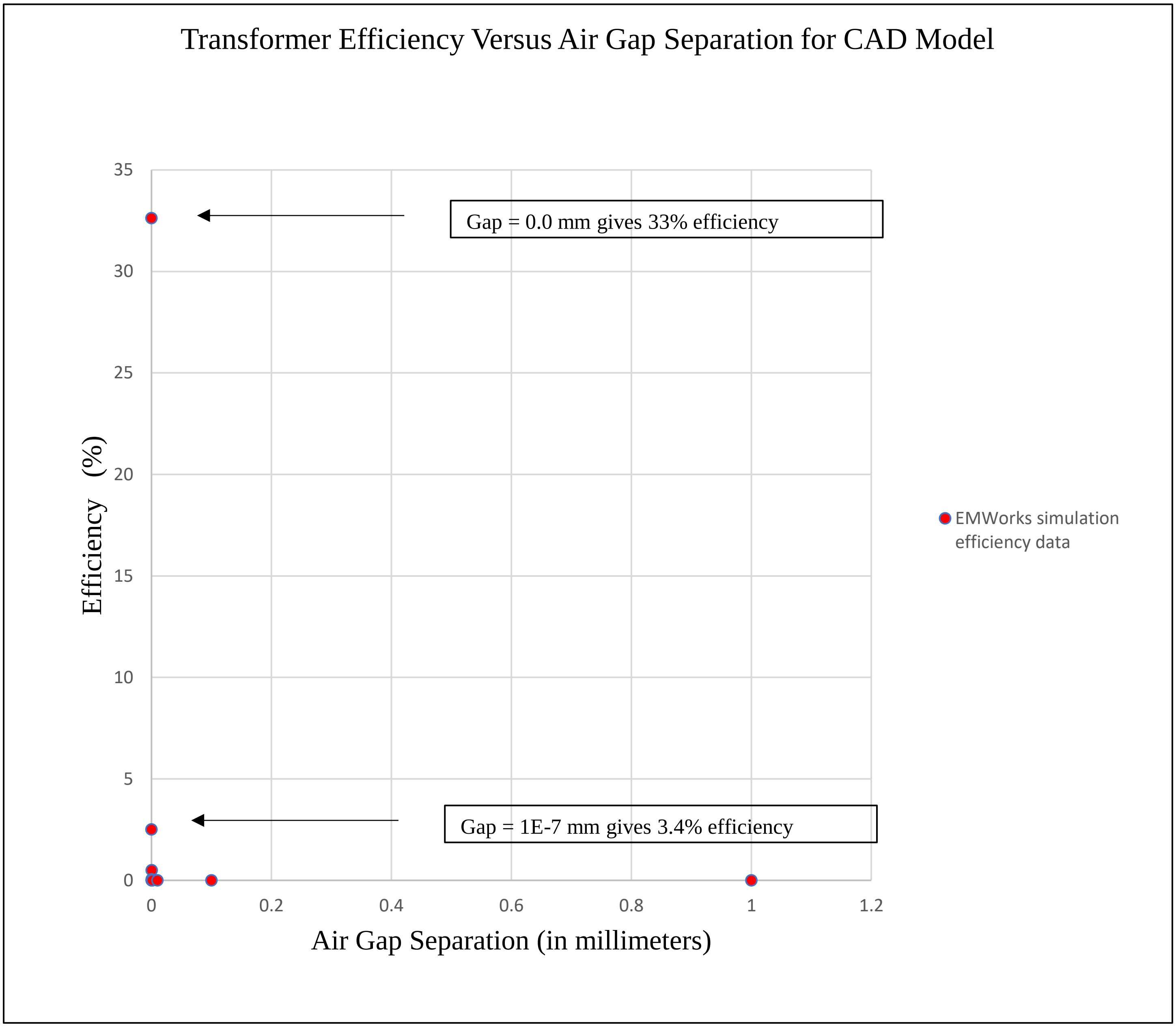
6.1.8 Design Iteration: EMWorks Simulation: Simulated Efficiency Results

Efficiency was calculated as follows:

$$\text{Efficiency} = \frac{current\ in\ secondary\ coil}{applied\ current\ in\ primary\ coil}\ x\ 100\ \%$$

and the results were plotted as a function of air gap separation. Since EMWorks and Solidworks has no method to perform the same task repetitively such as in a for loop, for each efficiency versus air gap data point, a new CAD model with a different air had to be created, resulting in a time-intensive process.

Figure 17. Shows that even at an air gap of 0.0 mm, the CAD model had only 33% efficiency. In contrast, many toroidal and E-shaped single-phase transformers have over 99% efficiency in power transfer. [reference 8]



6.1.9 Design Iteration: Prototyping Stage: Materials

Having completed the simulation of the predicted efficiencies as a function of air gap separation, the next step was to build the prototype based on this CAD model and then test it at a simulated air gap and compare the results. The first step in prototype construction was selection of materials, which included the following items:

Table 2. Shows the materials chosen and their respective costs, along with their key physical properties, such as temperature resistance.

Materials	**Description**	**Cost ($)**
M36 0.36 mm laminations (97 total)	Electrical steel laminations to create core from	0.00
Flame Retardant insulating tape 266 F	Yellow Polyester Film 3M Flame Regardant Tape 1530-F-1 72 yd. length	9.20
12 AWG Copper Magnet wire	TEMCo 12 AWG Copper Magnet Wire 5 lb. 200 C Winding wire (250 ft)	73.60
15 AWG Copper Magnet wire	TEMCo 15 AWG Copper Magnet Wire 5 lb. 200 C Winding wire (498 ft)	67.15
High Dielectric Insulating Varnish	MG Chemicals 4228-55 ml red insulating varnish (3000 V / mil)	11.05
Total Cost		$161.00

6.1.10 Design Iteration: Prototyping Stage: Getting Laminations

As stated earlier, laminations were procured from a former microwave transformer of M36 0.36 mm electrical steel. The following pictures illustrate how these laminations were secured.

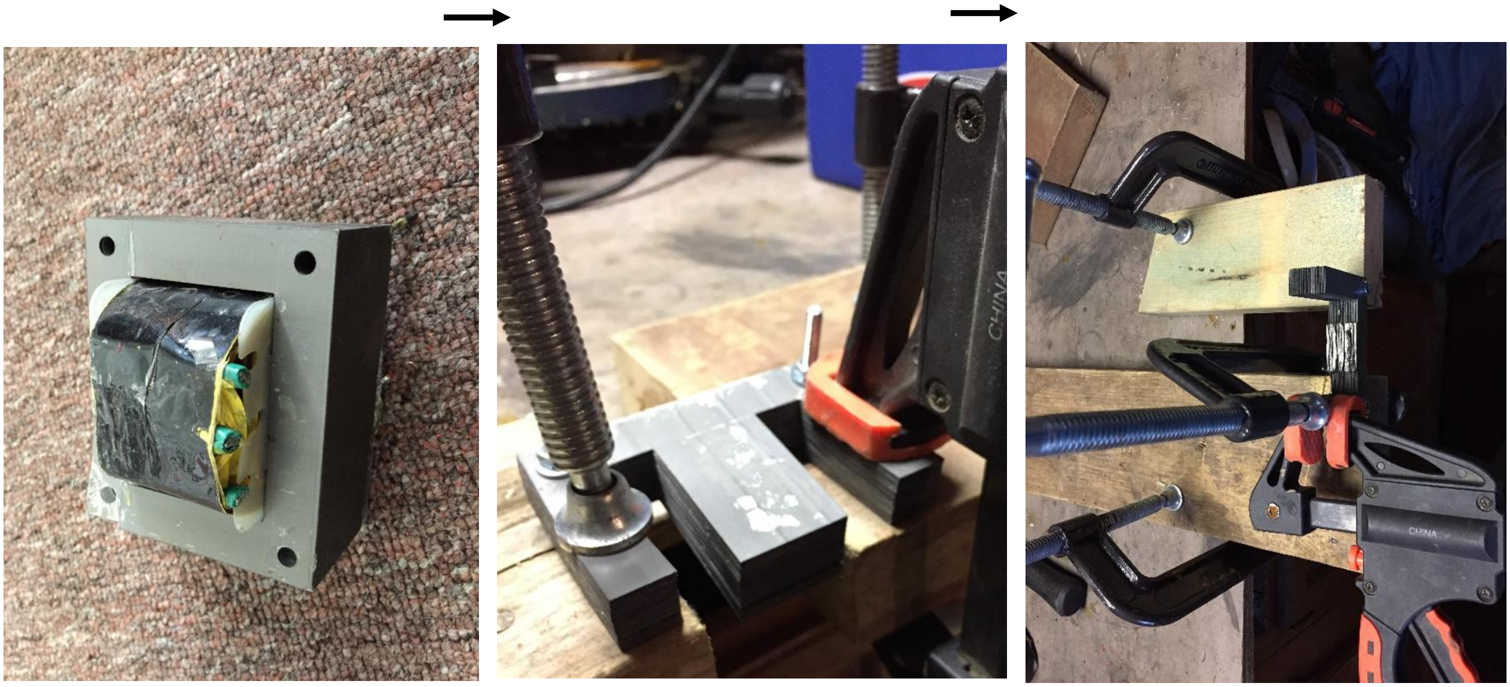


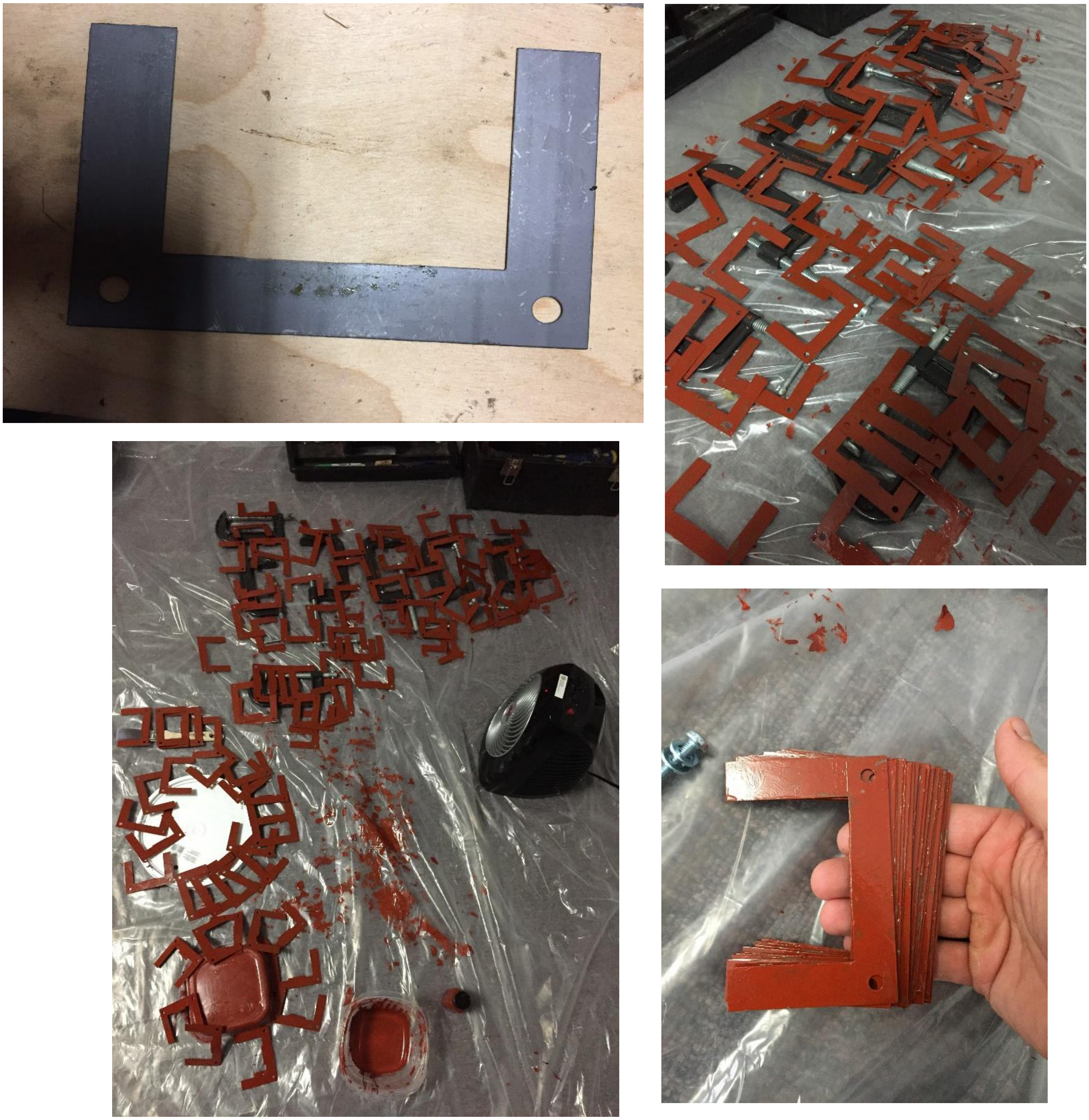
Figure 18. Shows the microwave transformer, the laminations taken out of it, and then cutting the middle E out of the laminations via a grinder, respectively.

6.1.11 Design Iteration: Prototyping Stage: Insulating the Laminations

MG Chemicals Red Insulating Varnish # 4228 55 ML was the varnish that was used to insulate the laminations. Insulating laminations was key to reduce eddy current losses. The varnish used had a dry dielectric strength of 3000 V / mil or 3000 V / 0.0254 mm. Since the varnish was applied at approximately 1.5 mil, this provided far more than the needed insulation for the applied 120 volts.

Figure 19. Shows the lamination with the middle of the E cut out, and then varnish application process, during which each side of each of the 97 laminations were painted by hand.

→



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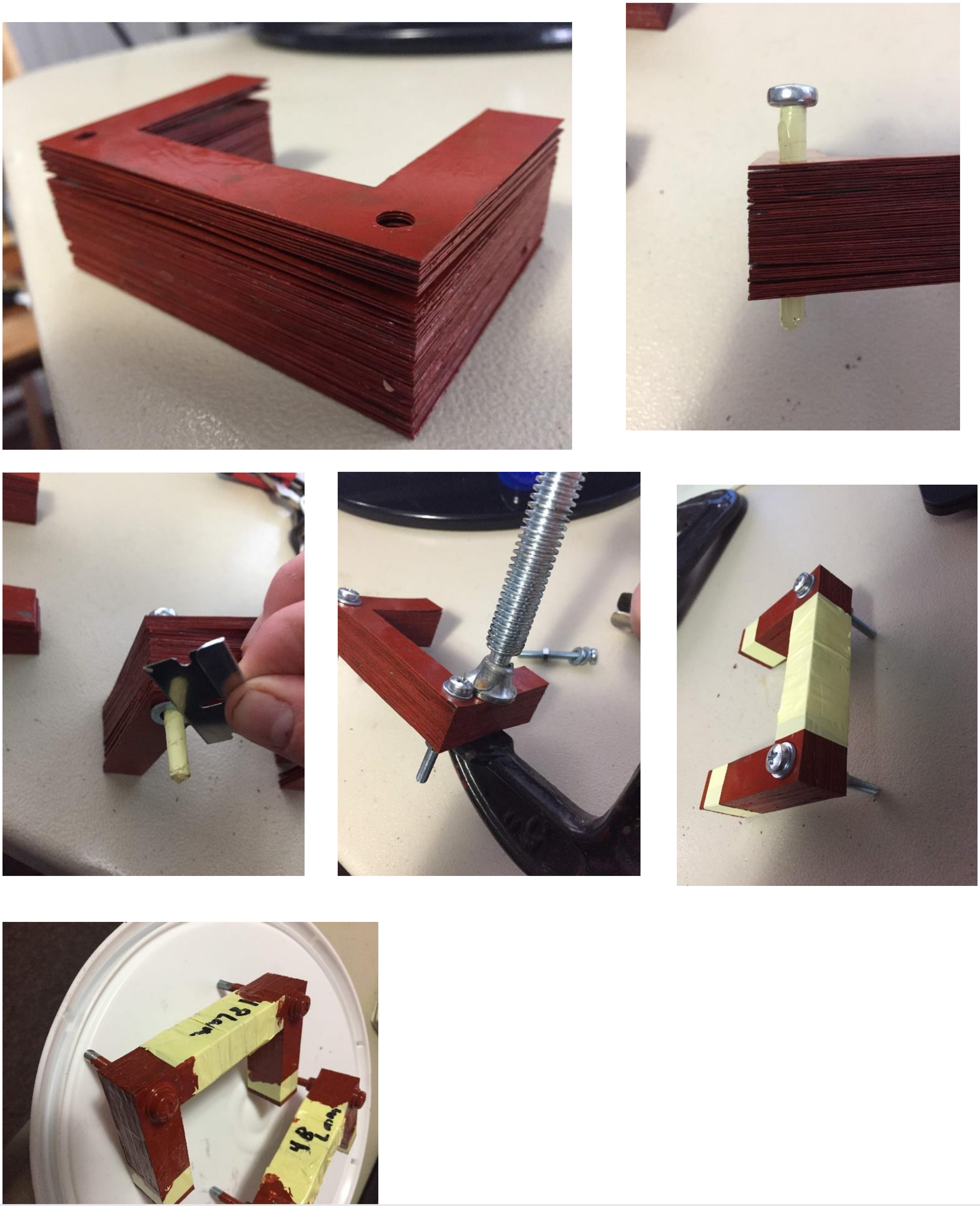
6.1.12 Design Iteration: Prototyping Stage: Stacking and Wrapping the Core

Figure 20. Shows how the bolts for holding the core together were insulated, how the core was bolted together, and then how the two have cores were wrapped with their respective coil wire types.

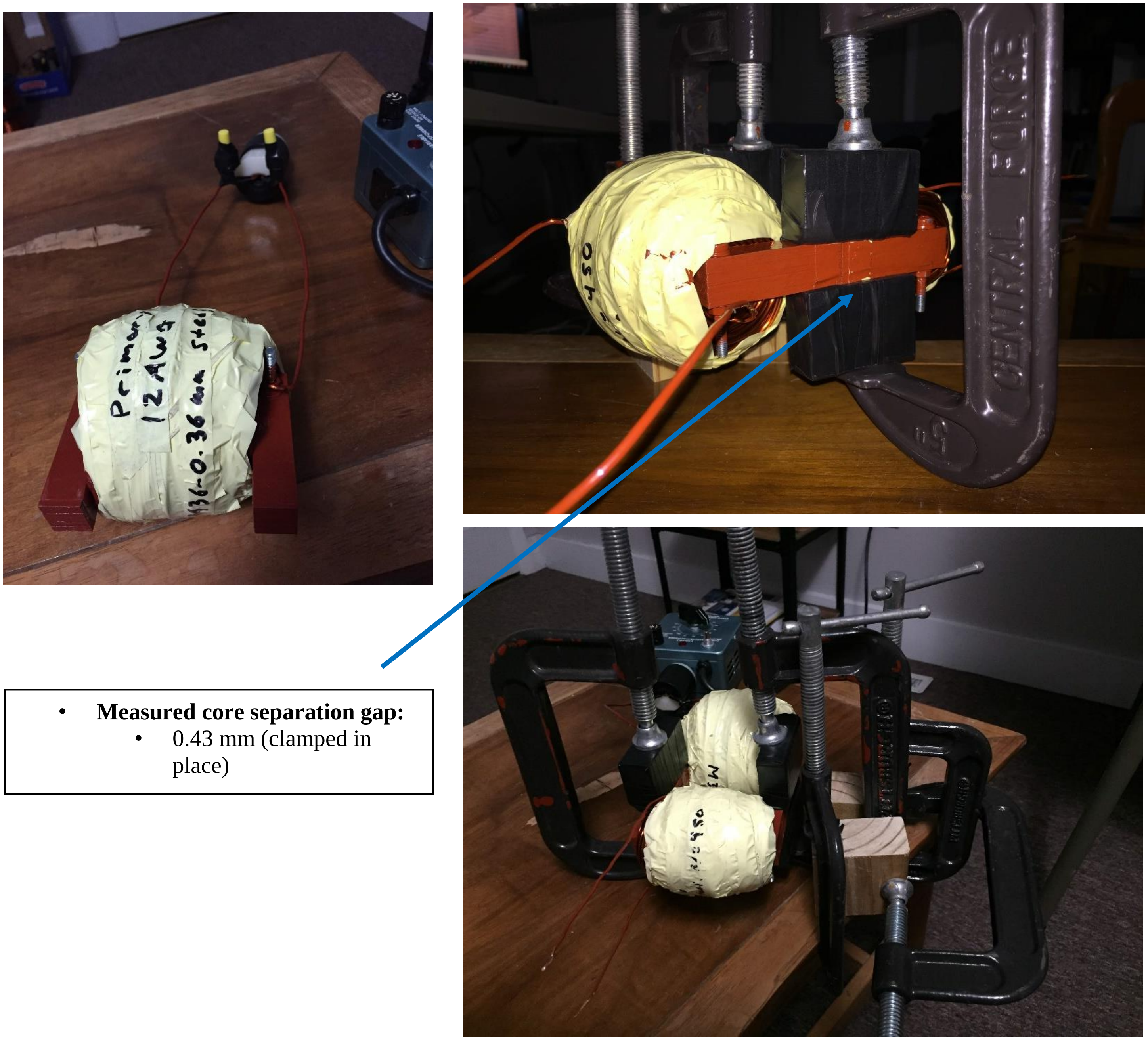


6.1.13 Design Iteration: Prototyping Stage: Wrapping the Core Continued

Figure 21. Shows the coil wrapping process; note 3M Flame Retardant Insulating Yellow Polyester Film Tape 1350F-1Y with an upper temperature rating of 266 F. was used to wrap the core edges prior wrapping the cores with the copper wire. This edge wrapping was to make the edges less sharp so as to avoid a sharp metal edge that would pierce the enamel copper wire insulation and cause a short.

6.1.14 Design Iteration: Prototyping Stage: Final Prototype

Figure 22. Shows the final prototype system in which the two transformer halves have been clamped to in alignment with each using C-clamps. Wooden spacers 2 inches thick were used to insulate the metal C-clamps from the transformer cores to avoid magnetic flux losses into the clamps. The primary half was wired to a plug unit and the junctions connected via wire nuts and then wrapped in electrical tape to ensure no loose wires.



- **Measured core separation gap:**
  - 0.43 mm (clamped in place)

6.2. Performance Evaluation

Performance for the prototype was tested by measuring the voltage across the secondary coil and the current through the secondary coil. A variable auto transformer was used to supply the 120 V at 1.75 A and a multi meter in AC mode was used to measure the secondary coil's voltage and current. Results yielded 0.000 A for current and 0.000 V for current and voltage respectively, at an air gap of 0.43 mm.

Figure 23. Shows the variable auto transformer used as the power supply, along with the multi meter used in the voltage and current tests.

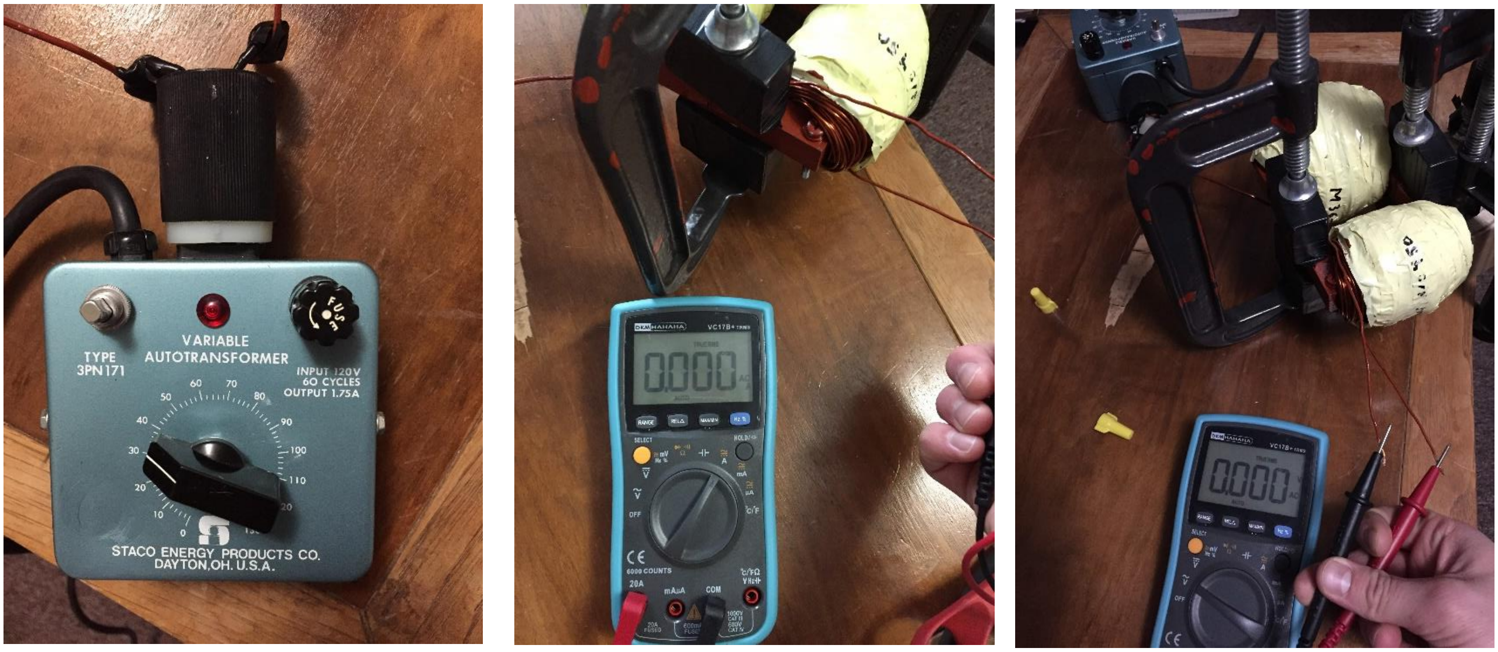
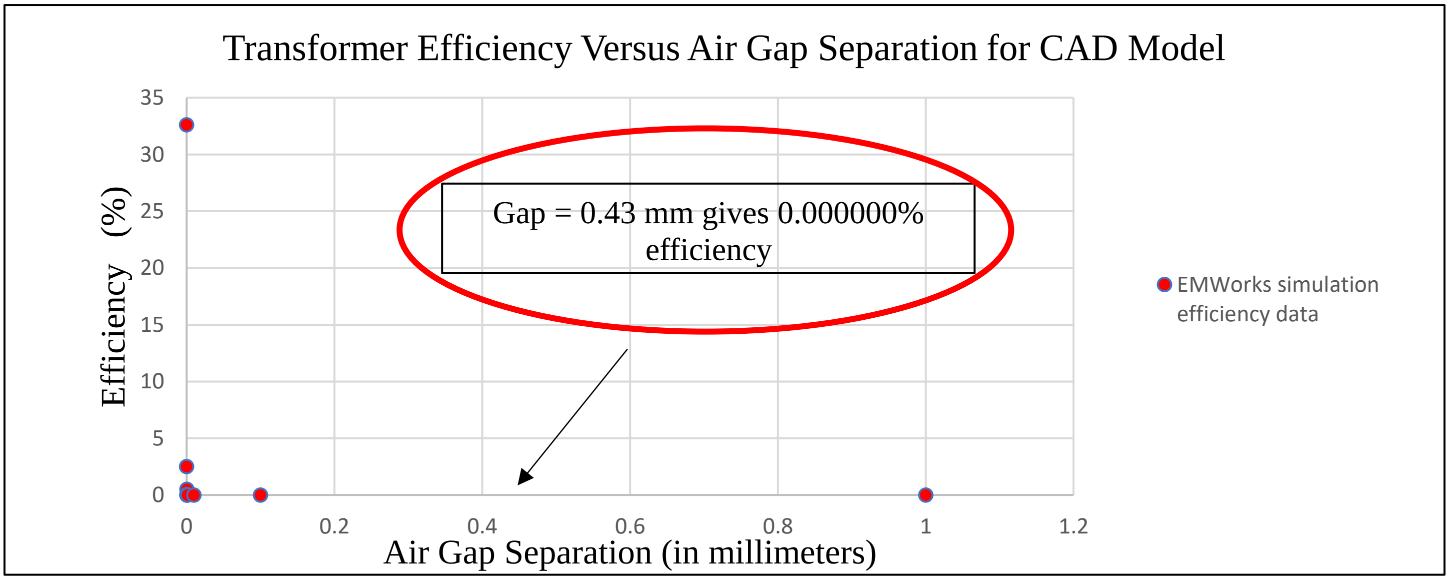


Figure 24. Shows where the prototype's actual efficiency of 0.000000% was accurately predicted by the EMWorks simulation data.



6.3 Comparison of Results with Specifications and Constraints

Table 3. Compares the specifications and constraints for this project with actual results of the actual prototype and shows where the prototype did not fit the needed specifications. The only category specifications were not met was the 50% efficiency category.

Design Specification or Constraint	**Results**	**Specification or Constraint met?**
Input frequency = 60 Hz	Simulations used 60 Hz; prototype tested at 60 Hz	Yes
Input voltage = 120 V	Simulations used 120 V; prototype tested at 120 V	Yes
Coil wire gauge safety factor of 1.5 used	Yes, simulations and prototype accounted for safety factor in AWG wire gauge	Yes
Electrical prototype will be two metal half transformers	Yes	Yes
Rust-resistant: protective varnish used	Yes, prototype is sealed with varnish	Yes
Within 620$ budget?	Yes ($161.01)	Yes
Weight < 10 lbs.	Yes (7.8 lbs. for both half transformers)	Yes
Displacement < = 1 cubic foot	Yes (0.05701906 ft^3)	Yes
Efficiency at 50% at 350 [W]	No	No

7. Conclusion

As a proof of concept project with a research-oriented CAD modeling approach, this project met all it’s needed specifications and constraints. A prototype was constructed that demonstrated the predicted output current in the secondary transformer half. Of the initial specifications outlined, having a prototype at an efficiency of 50% at 350 [W] in the secondary half was the only specification not met. The reason this specification was not met was due to the following points:

- **Prototyping constraints**
  - The prototype was constrained by the available lamination dimensions, which in turn limited the following parameters:
    - Surface area of cores aligned
    - Amount of core wrapped with coils
    - Magnetic flux loss due to outer portion of coils not fully wrapping around the core
- **Infinite CAD models not pursued**
  - Instead of pursuing a CAD model that would yield 50% efficiency, instead a CAD model that could be prototyped and tested was pursued. By maximizing alignment surface area and core geometry, 50% efficiency have been achievable via simulation. Yet such a model could have been prototyped and tested.

In conclusion, creating an induction-based plug in the style of a single-phase transformer was possible. However, the prototype built proved the point of the EMWorks simulations that such a plug has zero percent efficiency at a real-world achievable air gap (0.43 mm in this case). Therefore, further design and investigation for an induction-based plug for the application of improving car engine block plugging ergonomics is not deemed worthy of time or viable.

8. Future Considerations

Parameters not considered in this project are as follows:

- Higher frequency
- Increased surface area of adjoining ends of cores
- Geometry of core-using E core layout or a similar more efficient design

Since permeability is affected frequency such that the relative permeability increases with increasing frequency, further work could explore higher frequency applications. Moreover, changing the mechanical design such that core geometry maximized surface area for flux transfer was a parameter not varied. Investigation in varying these parameters lay outside the specifications and constraints for this project, therefore they were not pursued. However, it is acknowledged that further work does lie in these areas.

9. References

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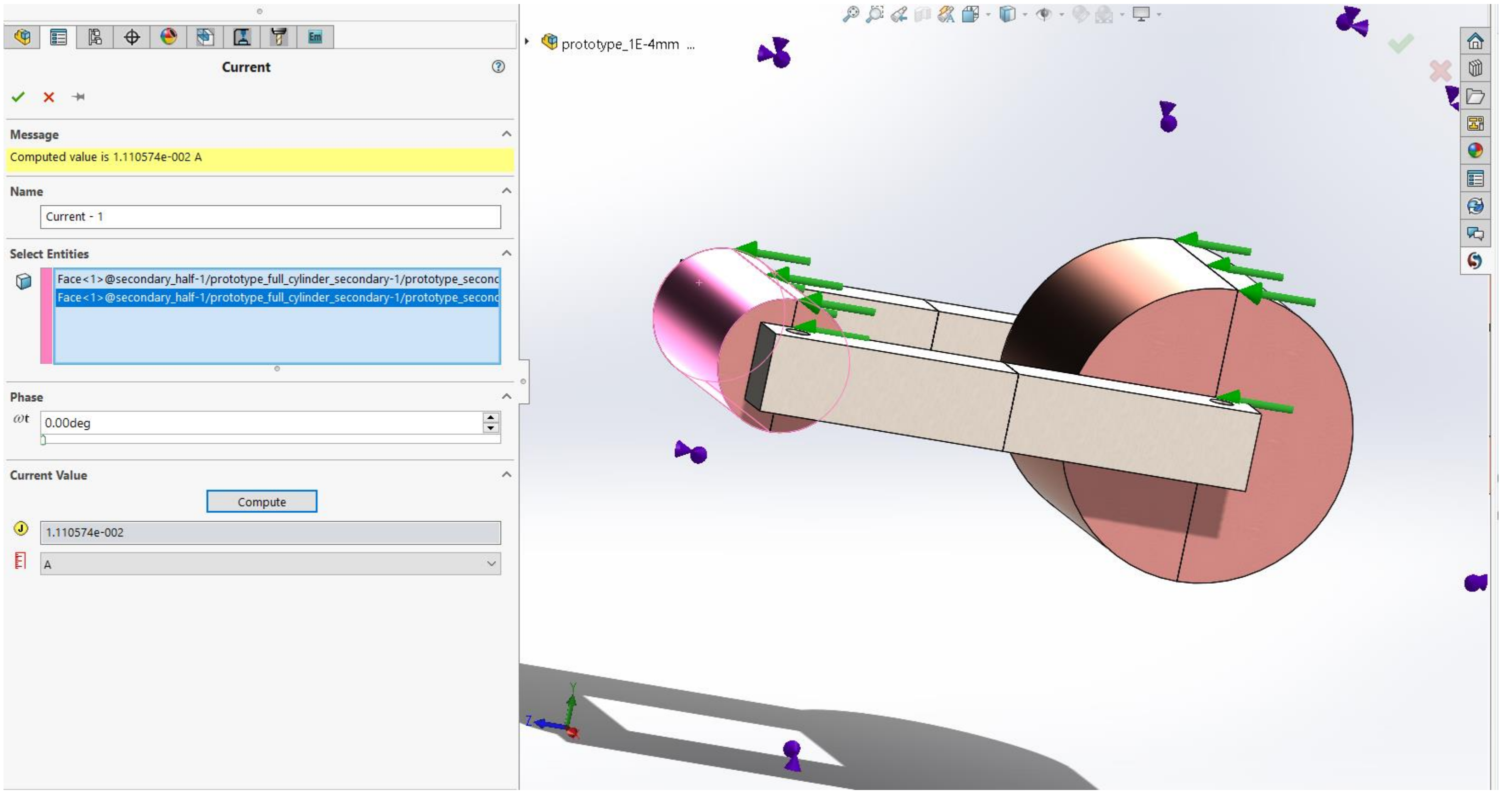
Appendix A:

Figure A.1 Shows current measurement in the secondary coil at an air gap separation of 1E-7 meters, resulting in an efficiency of 3.4%



Message

Computed value is 1.110574e-002 A

Name

Current - 1

Select Entities

Face<1>@secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secon
Face<1>@secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secon

Phase

ωt 0.00deg

Current Value

1.110574e-002

A

Table A.1 Shows the materials used in the EMWorks simulations, the respective CAD model faces and bodies they were assigned to. **Note:** R.P. stands for Relative Permeability

Number	Part Name	Material Name	Permeability Type
1	primary_half-6/prototype_full_cylinder_primary-3/prototype_primary_copper_envelope_height_23.5mm-1-Body 1 (Boss-Extrude1)	Copper	Isotropic
2	primary_half-6/prototype_full_cylinder_primary-3/prototype_primary_copper_envelope_height_23.5mm-2-Body 1 (Boss-Extrude1)	Copper	Isotropic

3	primary_half-6/prototype_single_half_core-3-Body 1 (Boss-Extrude1)	M36 @ 0.36 mm (60Hz)	Isotropic
4	prototype_air_gap_1E-4mm-1-Body 1 (Boss-Extrude1)	Air	Isotropic
5	prototype_air_gap_1E-4mm-4-Body 1 (Boss-Extrude1)	Air	Isotropic
6	secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secondary_copper_envelope_height_11.86mm-1-Body 1 (Boss-Extrude1)	Copper	Isotropic
7	secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secondary_copper_envelope_height_11.86mm-2-Body 1 (Boss-Extrude1)	Copper	Isotropic
8	secondary_half-1/prototype_single_half_core-1-Body 1 (Boss-Extrude1)	M36 @ 0.36 mm (60Hz)	Isotropic

Table A.2 Illustrates the load constraint applied, that is the current applied in the primary and secondary coils for the EMWorks simulation.

#	Name	Coil Type	N turns	RMS Current	RMS Voltage	Phase	Components & Bodies
1	Wound Coil - 1	Current driven coil	385	1.750000e+000	-	0.0000e+000 degree	primary_half-6/prototype_full_cylinder_primary-3/prototype_primary_copper_envelope_height_23.5mm-1primary_half-6/prototype_full_cylinder_primary-3/prototype_primary_copper_envelope_height_23.5mm-2
2	Wound Coil - 2	Current driven coil	385	0.000000e+000	-	0.0000e+000 degree	secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secondary_copper_envelope_height_11.86mm-2secondary_half-1/prototype_full_cylinder_secondary-1/prototype_secondary_copper_envelope_height_11.86mm-1

Table A.3 Shows the FEM analysis properties used in simulation.

- **Mesh Information**

Nbr. Of Nodes	Nbr. Of Elements	Element Size (mm)	Tolerance (mm)
14264	73429	8.081133	0.008081

- **Solver information**

Solver Type	Multi-Core Iterative Solver
Solver Accuracy	Normal Accuracy
Frequency (Hz)	6.000000e+001
Split Core Loss	Yes
Thermal Analysis	No
Motion Analysis	No

Figure A.2 Shows the magnetic flux density for an air gap of 100 nanometers.

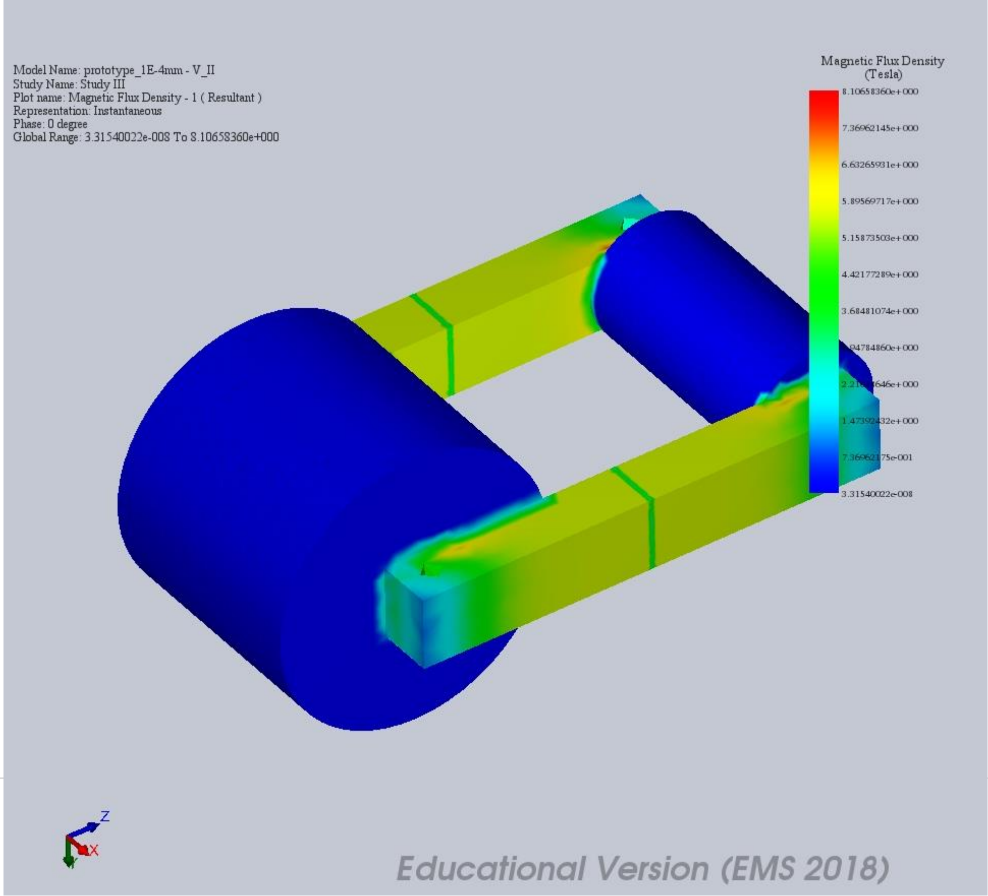
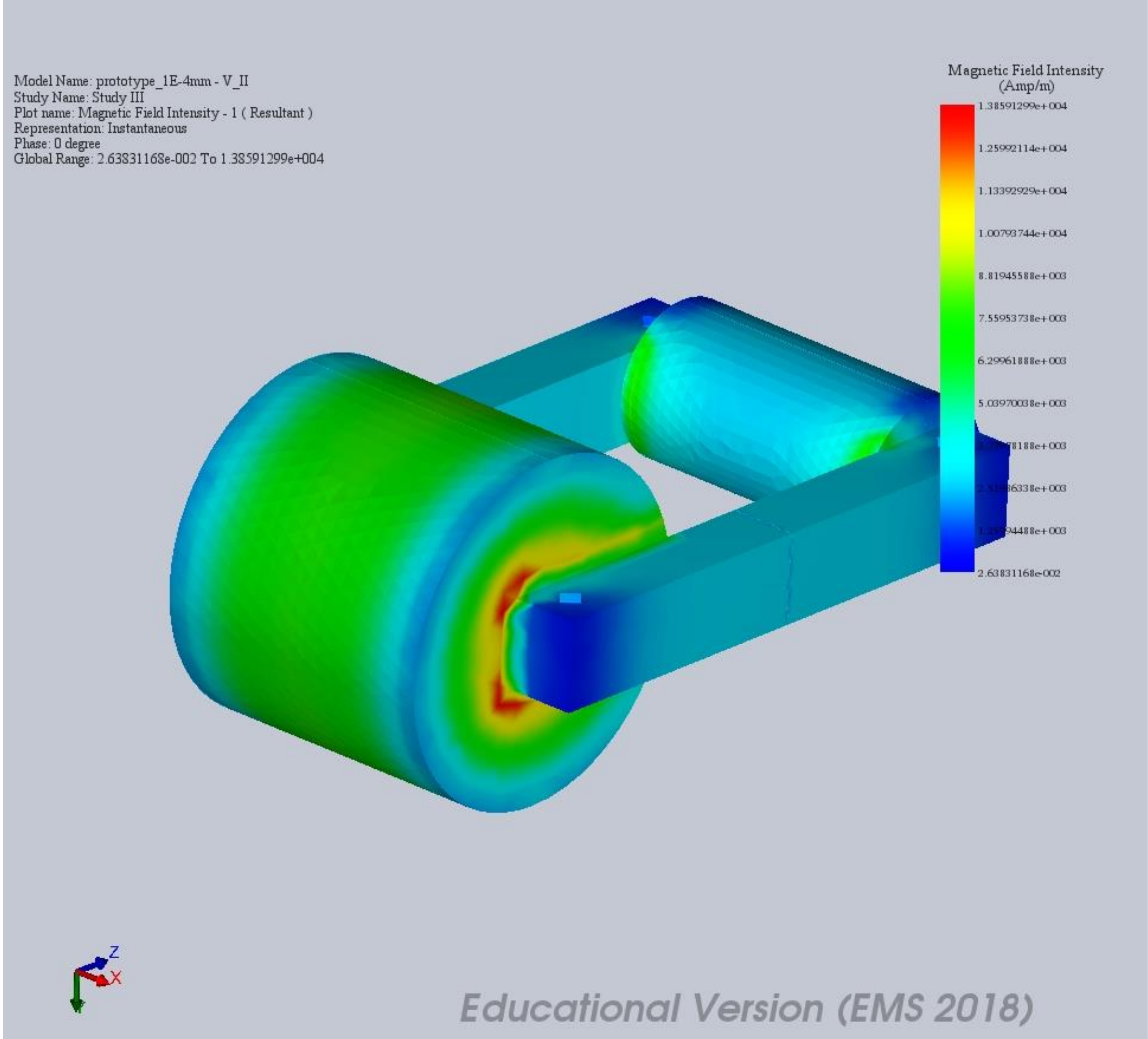
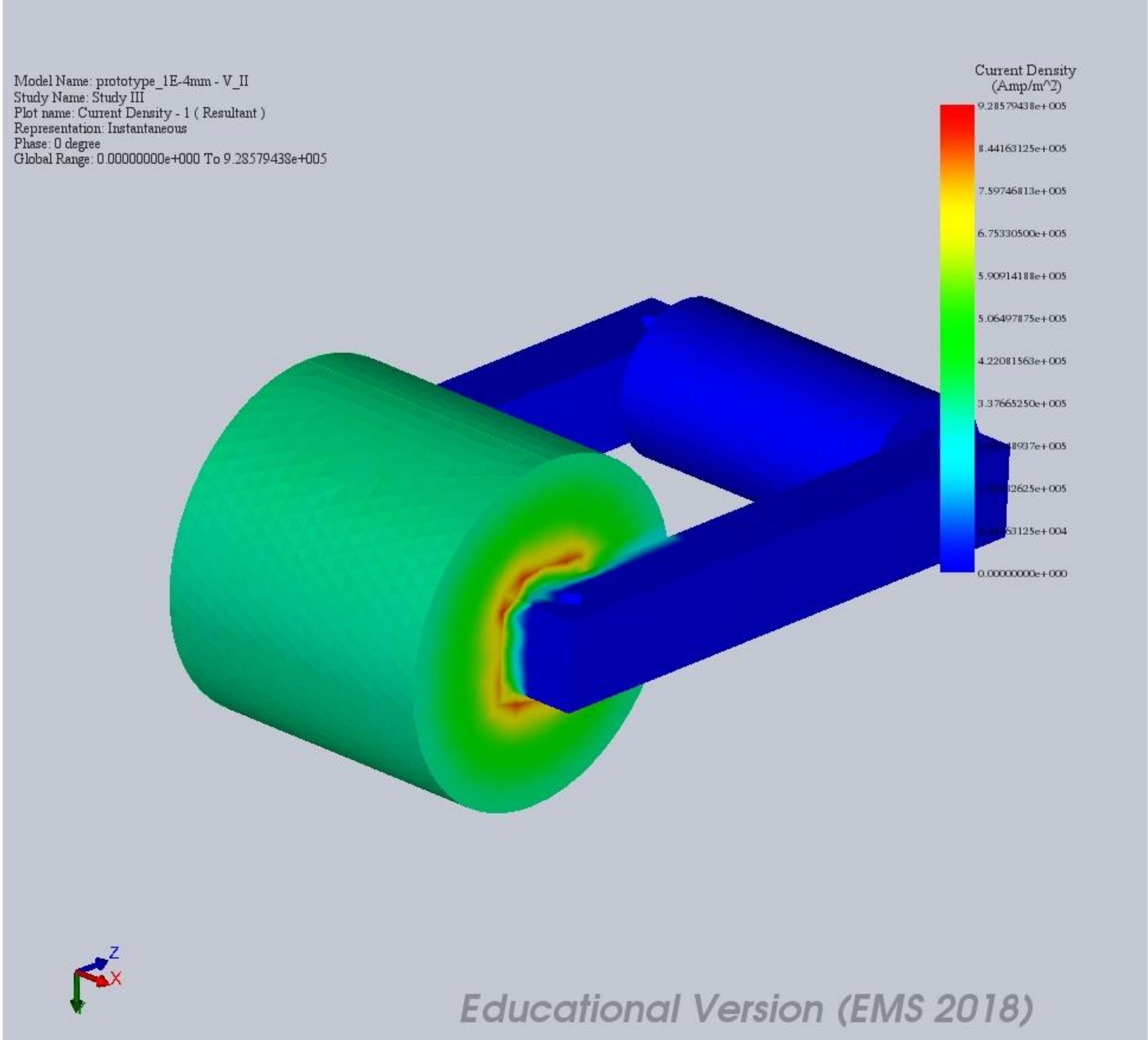


Figure A.3 Shows the resultant magnetic field intensity [A/m] for an air gap of 100 nanometers.



Model Name: prototype_1E-4mm - V_II
Study Name: Study III
Plot name: Magnetic Field Intensity - 1 (Resultant)
Representation: Instantaneous
Phase: 0 degree
Global Range: 2.63831168e-002 To 1.38591299e+004

Figure A.4 Shows the applied current density for the primary coil.



List A.1 Outlines the relevant physical properties of the three main materials used in the EMWorks simulations.

Material Name: Copper

Permeability Type: Isotropic

Note: R.P. stands for Relative Permeability

R.P.	Conductivity(S/m)	Permanent Magnet	Thermal Conductivity(W/m.K)
1.000e+000	5.700e+007	No	3.850e+002

Material Name: M36 @ 0.36 mm (60Hz)

Permeability Type: Isotropic

Note: R.P. stands for Relative Permeability

R.P.	Conductivity(S/m)	Permanent Magnet	Thermal Conductivity(W/m.K)
0.000e+000	2.326e+006	No	4.300e+001

Material Name: Air

Permeability Type: Isotropic

Note: R.P. stands for Relative Permeability

R.P.	Conductivity(S/m)	Permanent Magnet	Thermal Conductivity(W/m.K)
1.000e+000	0.000e+000	No	2.400e-002