SCALED DOWN DYNAMIC WIRELESS POWER TRANSFER FOR RAILROAD APPLICATIONS

by

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# ABSTRACT

EDGAR A. SALAZAR REA. Scaled down dynamic wireless power transfer for railroad applications. (Under the direction of DR. TIEFU ZHAO)

Locomotives served humanity since their early origins. There were many different types of energy sources such as gas, coal, diesel, electricity, etc. Some energy sources were more environmentally friendly than others. The research focus was to advance the knowledge of the use of electricity as an energy source. The research investigates the wireless power transfer system at low voltage levels. The system was investigated at low voltage to understand the behavior of different coil types under different scenarios. A testing prototype was developed to perform the tests. There were three main coil types which were air coils, air coils with added cores, and E-core coils. Moreover, each coil type had two subcategories; the first one was the one transmitter to one receiver, and the second one was multiple transmitters to one receiver. There were several tests which include vertical separation or airgap test, horizontal separation test, and different load test. The tests were performed to observe the efficiency changes and maximum efficiency achievable. Also, simulations were performed using ANSYS Maxwell and Pspice to compare actual measurements to simulation results. The results were as expected. The simulation and measurement results were similar for most scenarios. However, there were tolerance variations because to differences between ideal components, and real-world components. Simulations showed slightly higher values than the measurements. Overall, the air coils had the lowest efficiency results, the air coils with added cores had intermediate efficiency results, and the E-core coils showed the highest efficiency results.

# ACKNOWLEDGEMENTS

I would like to express my thanks and appreciation to Dr. Tiefu Zhao for his support and availability to guide me during this research. Dr. Zhao knowledge on power electronics, and research guidelines helped me achieve many goals set for this research. I would like to express my thanks and appreciation to my thesis committee members Dr. Shen-En Chen, Dr. Madhav Manjrekar, and Dr. Kathryn Smith for their involvement, willingness to help, and constant support during this research. I would like to express my thanks and appreciation to all the Ph.D. students working on wireless power transfer research for their feedback, and support throughout my research.

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| | |
|---|---|
| R | Resistance |
| V | Volts |
| Vout | Output Voltage |
| Vin | Input Voltage |
| Pin | Input Power |
| Pout | Output Power |
| % | Percentage |
| mm | Millimeters |
| cm | Centimeters |
| p.u. | Per Unit |

# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

The need for transportation was present since ancient times. Among the mediums of transport, railroads had been used to transport materials and people. There were records of primitive guided rails used in Greece around 600 BC [1]. The railroad and locomotives technology had evolved throughout centuries. Current locomotive energy technologies involve coal, gas, fossil fuels, and electricity. A cargo locomotive is shown in Figure 1-1.

Figure 1-1 Railroad locomotive [2]

Depending on the generation source, electricity can be the most environmentally friendly energy source for locomotives, and transportation in general. The Rail Division of the North Carolina Department of Transportation (NCDOT) along with the University of North Carolina at Charlotte started a project to explore more environmentally friendly sources of energy for locomotives. Wireless power transfer for railroad applications was identified as the topic of research. The wireless power transfer intends to transmit energy from the railroads to the locomotives without contact. Wireless power transmitters were positioned between the tracks, and wireless power receivers were positioned at the bottom of the locomotive. The transmitted energy was stored in batteries and used to power the electric motors. This research focuses on the scaled-down wireless power transfer system measurements and simulation.

The wireless power transfer research comprises three research phases, and a modularized prototype. The first phase comprised the simulation and testing of an existing design proposed by Hanyu Liu [3] which, was a system based on multiple air coil transmitters and one air coil receiver. The second phase comprises comparisons between the air coil system from the first section and the same system with added ferrite cores for efficiency improvement. The third phase comprises a new experimental design inspired by the results and conclusions from the first two phases. The third phase uses an E-shape ferrite core aligned to the locomotive and railroad track axis. The coils wind around the E-shape ferrite core center part. Measurements and simulations were conducted for the second and third phases as well. All phases were tested using low voltage input (6 volts DC). The prototype was built as a modular, easy-to-move system, and was made using parts from the RAIL_WIRE2 2019 [4] senior design prototype, and new parts used to make the prototype a movable unit. This research explored different coils designs to find an efficient and reliable wireless power transfer system for railroad applications.

## 1.2 Concept of Operation

Wireless power transition occurs when the electromagnetic field from a coil induces current on another coil. The electromagnetic field is shown in Figure 1-2. The wireless power transfer system is comprised of two main components, the transmitter and the receiver.

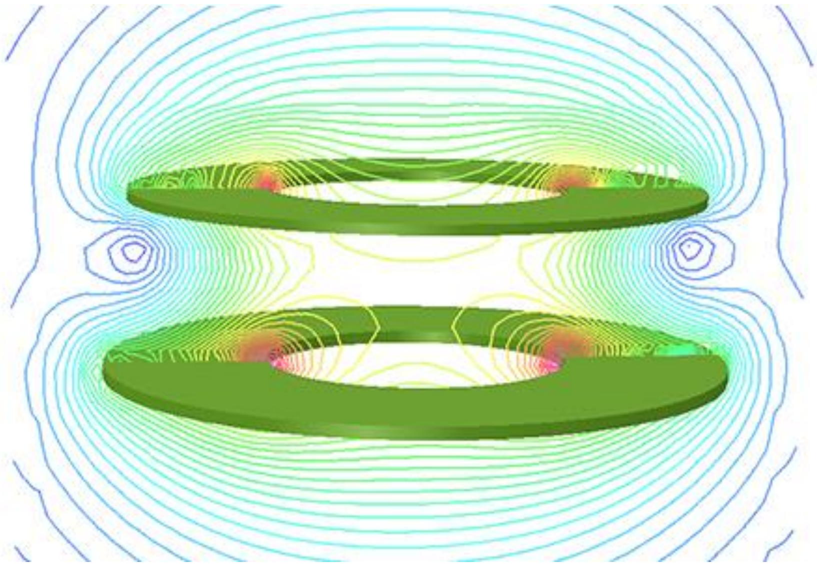


Figure 1-2 Coils Electromagnetic Field [5]

The transmitter uses a high-frequency current to generate the electromagnetic field. Currently, the system utilizes as energy source the AC power lines. The AC current is rectified to obtain DC current. The DC current is then inverted to obtain a high-frequency AC current. The high-frequency AC current is connected to a transmitter coil.

The receiver side starts with the receiver coil. The receiver coil receives the electromagnetic field from the transmitter, and high-frequency AC current is induced. The high-frequency AC current is rectified to obtain DC current. The DC current is used to charge batteries and/or power the locomotive electric systems and motors. The concept of operation block diagram is shown in figure 1-3.

An electric current is created when an electromagnetic field interacts with a conducting material. However, electromagnetic fields radiate to the environment as well; thus, makes the system less efficient. A way to improve efficiency is to insert a coupling capacitor creating an LC inductive-capacitive circuit [6]. The LC circuit operates at a resonant frequency.

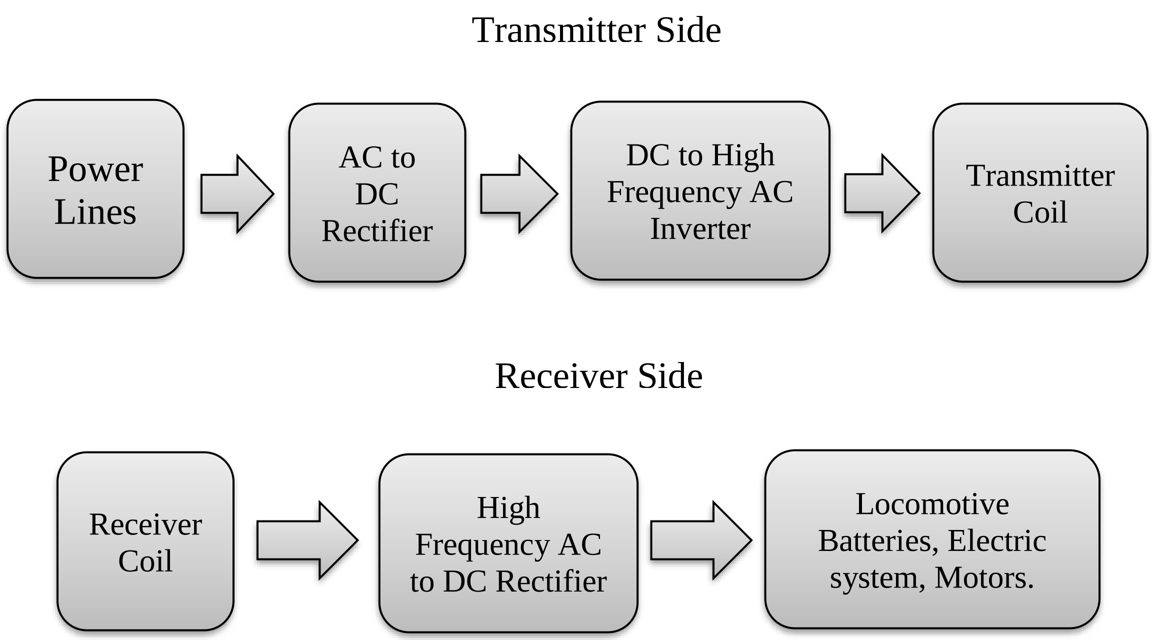



Figure 1-3 Concept of Operation Block Diagram

When the resonant frequency of the transmitter and receiver are the same, the efficiency reaches its maximum point.

The prototype comprised several parts. Some parts were premade parts, and other parts were made out of individual components. The premade parts are as follow:

a) Power Lines (Electric Outlet)

b) AC to DC Rectifier (DC Power Supply)

The individual component parts are as follow:

a) DC to High-Frequency AC Inverter (KIT8020 Half Wave Inverters, TI control/CARD R1.3)

b) High-Frequency AC to DC Rectifier (Full Wave Rectifier Chip, Rectifier Capacitor)

c) Transmitter Coil

d) Receiver Coil

e) Coupling Capacitors

The coupling capacitors were optional, but they were attached for all testing and measurements related to this research. The “DC Power Supply” is shown in Figure 1-4. The “KIT8020 Half Wave Inverters” and a “Coupling Capacitor” are shown in Figure 1-5. The TI control/CARD R1.3 is shown in Figure 1-6. The “High-Frequency AC to DC Rectifier” and a “Coupling Capacitor” is shown in Figure 1-7.


Figure 1-4 DC Power Supply

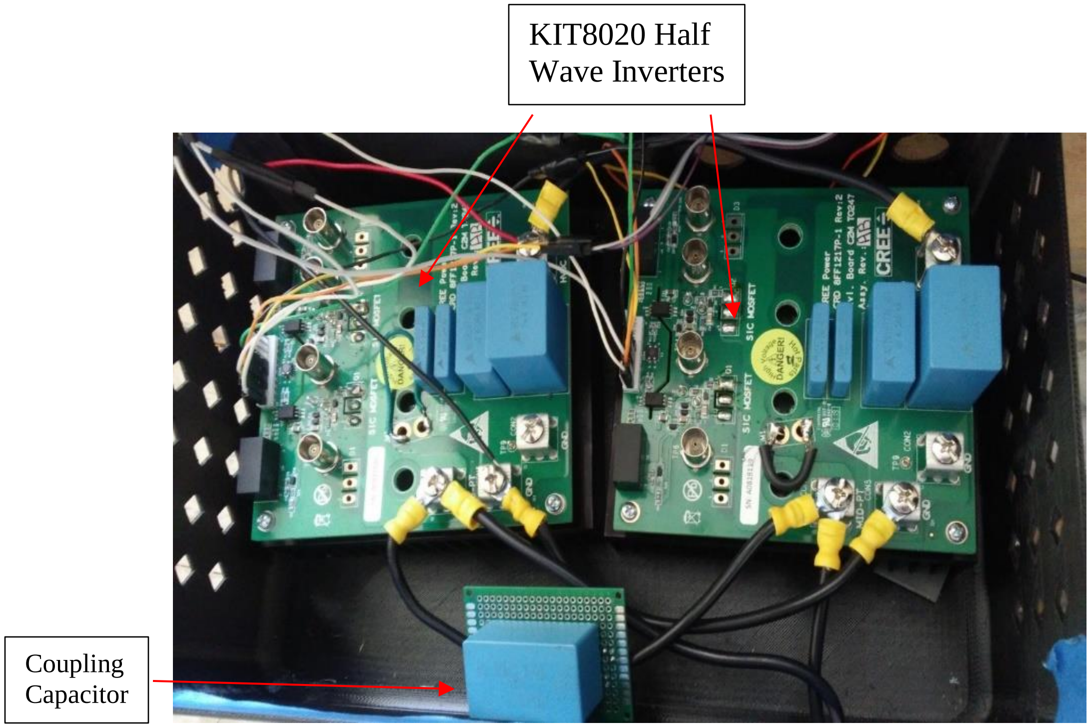



Figure 1-5 KIT8020 Half Wave Inverters and Coupling Capacitor

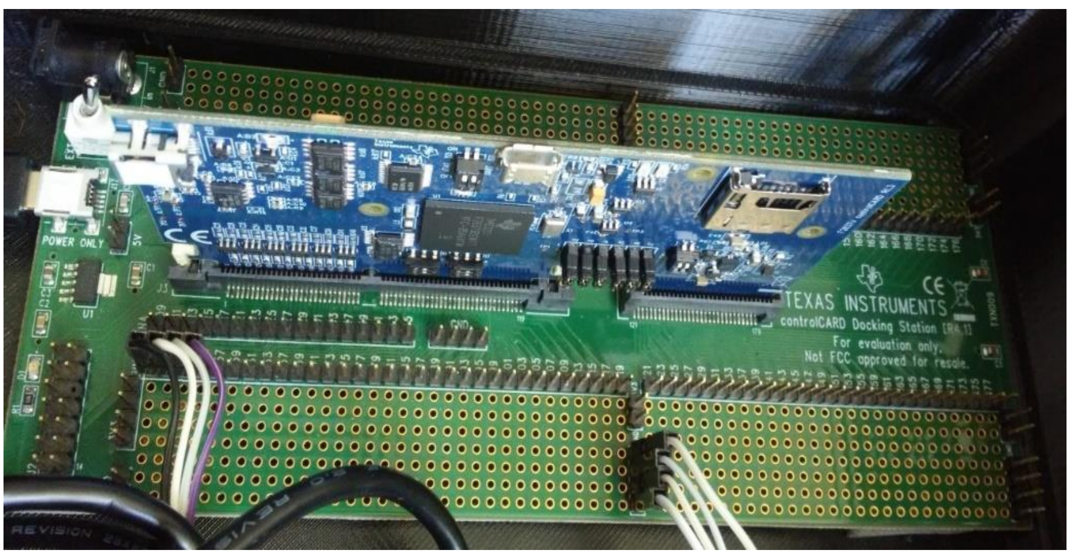



Figure 1-6 TI CONTROL/CARD R1.3

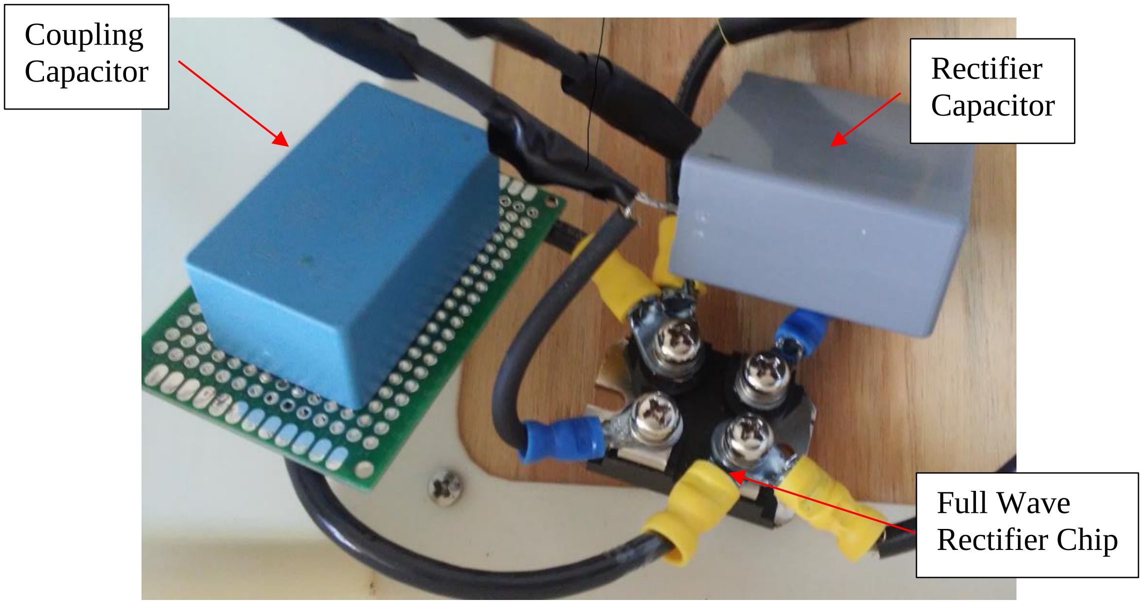



Figure 1-7 High-Frequency AC to DC Rectifier and Coupling Capacitor

The system was analyzed and represented on Pspice. The Pspice design/schematic is shown in Figure 1-8.

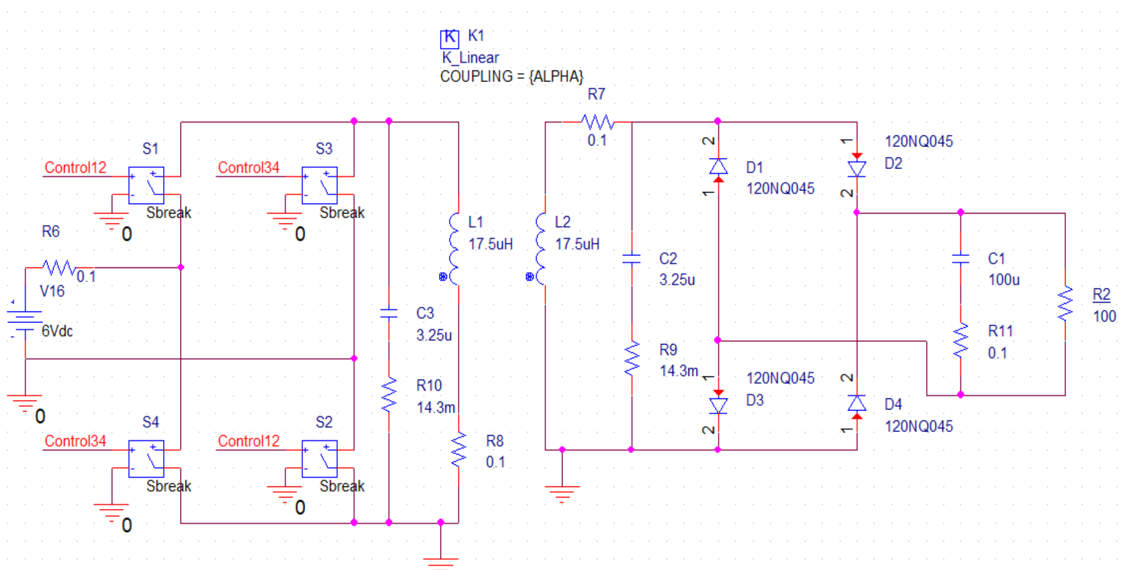



Figure 1-8 System Pspice Schematic

## 1.3 Research Objectives

The research focus was to test efficiencies for the low voltage level. This was done because lower voltages will produce lower efficiency results, and the purpose of this research was to compare different coil designs rather than to optimize a specific coil design.

The input voltage was maintained at 6 volts DC. The measured values were Pin (Input Power), Vout (Output Voltage), and Load. The measured parameters were used to calculate Pout (Power Output), and Efficiency. In addition, the research involved vertical separation or airgap where thermoplastic spacers were used to increase the vertical separation. The thermoplastic spacers are shown in Figure 1-9. The thermoplastic spacers were 1/16 of an inch thick or 1.59 mm thick. Finally, there were tests for horizontal separation. The receiver was horizontally separated every 5 mm intervals in relation to the transmitter.

Figure 1-9 Thermoplastic Spacers

The measurement tests were also simulated using the same parameters. The simulations comprised two parts. The first part used ANSYS Maxwell software to find the coupling coefficient between the transmitter and receiver coils. The ANSYS Maxwell environment is shown in Figure 1-10.

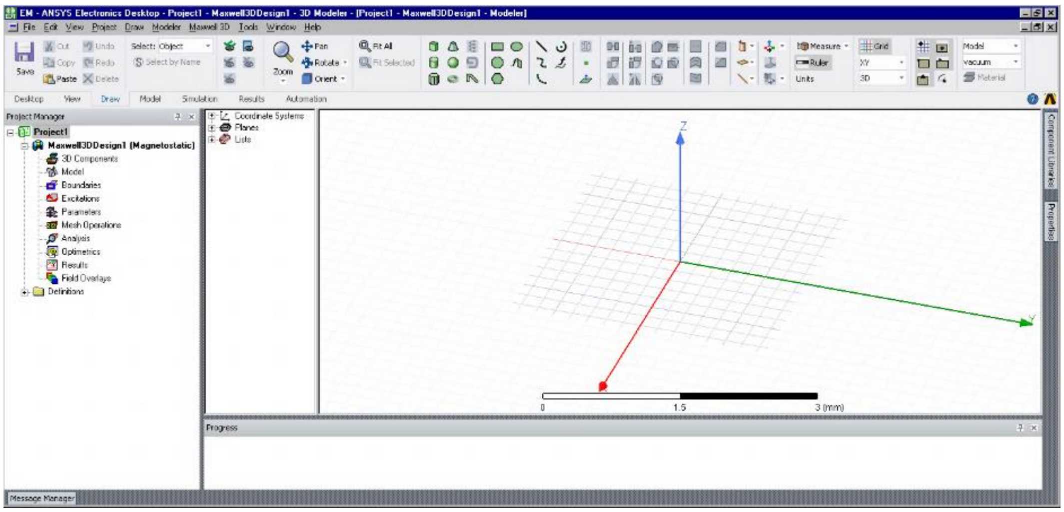



Figure 1-10 ANSYS Maxwell Environment

The second part used Pspice software. The Pspice software used the coupling coefficient as the transformer parameters. With all the parameters in place, Pspice was used to generate the system output voltage; the efficiency was calculated from the output voltage. The Pspice environment is shown in Figure 1-11.

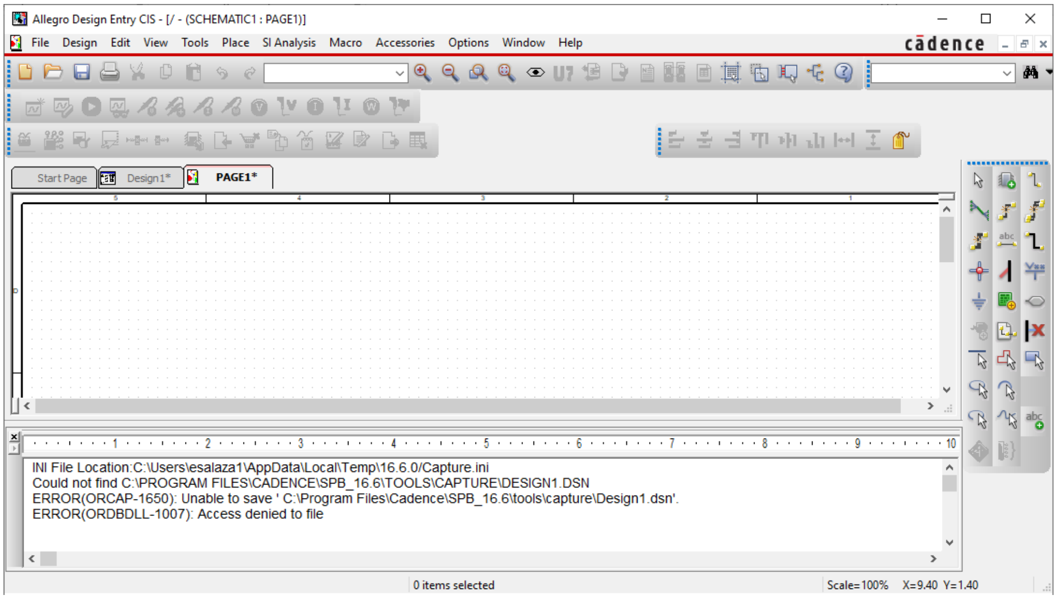



Figure 1-11 Pspice Environment

Both software allowed for parametric analysis. The analysis was performed by increasing or decreasing values.

The software simulation results and actual measurements were compared. The comparison showed how well was the simulation approximation was in comparison to the actual measurements. The results helped to predict future scenarios with higher power transfer levels.

## 1.4 Literature Review

Wireless power transfer was researched by Nikola Tesla in 1899; using the Earth as a conductor. Nikola Tesla transmitted wireless energy to light 200 lamps at a range of 40 kilometers. Through his discoveries, Nikola Tesla got founding from J. Pierpont Morgan to build his Wardenclyffe laboratory and transmission tower. In his laboratory Nikola Tesla developed a system that used his tower and the Earth's Magnetic field to transmit power around the world. Tesla's funding was stopped by Morgan; for the fear of free power without a proper way to charge the consumers [7]. The Tesla tower is shown in Figure 1-12

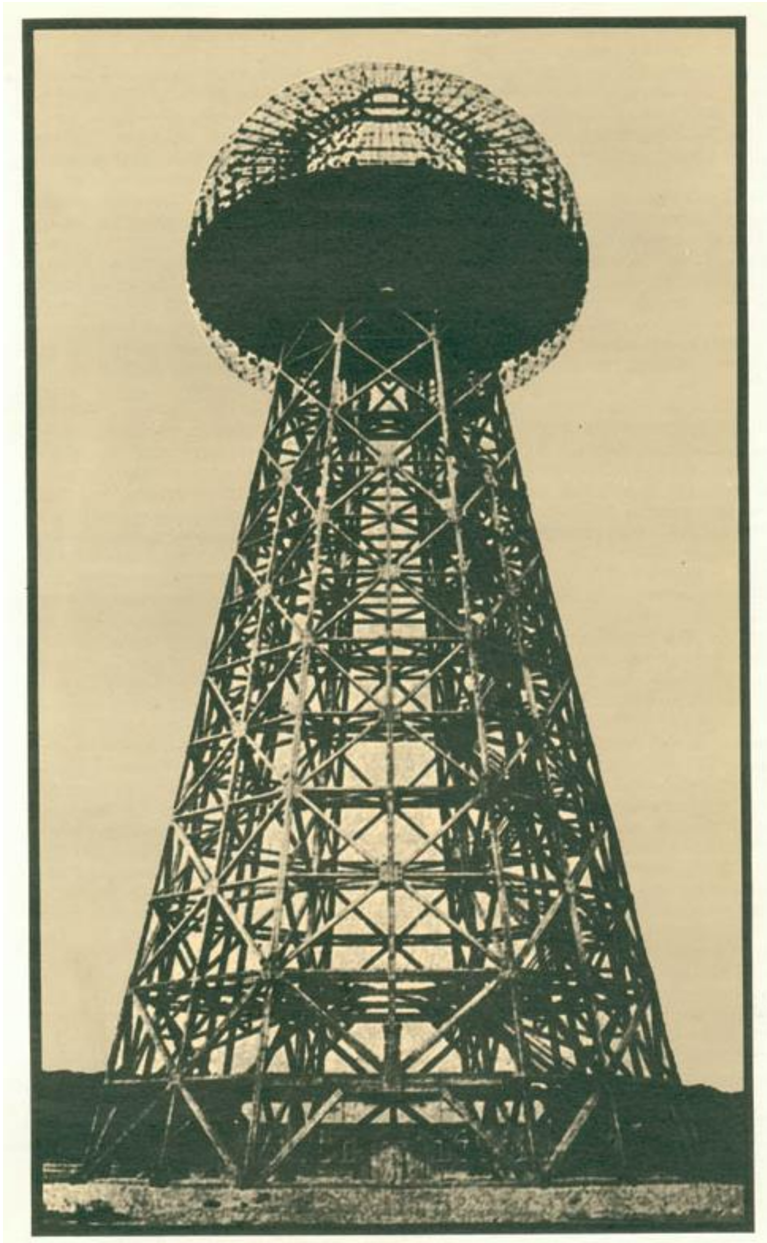


Figure 1-12 Tesla Tower [8]

One of the popular inventions that allows for wireless power transfer was the Tesla Coil. The Tesla Coil was a high voltage air transformer. It produced electric arcs, and had the capability of lighting up light bulbs wirelessly. During Nikola Tesla experiments, he was able to light a bulb up to 50 feet away [9]. A picture of the Tesla Coil is shown in Figure 1-13.

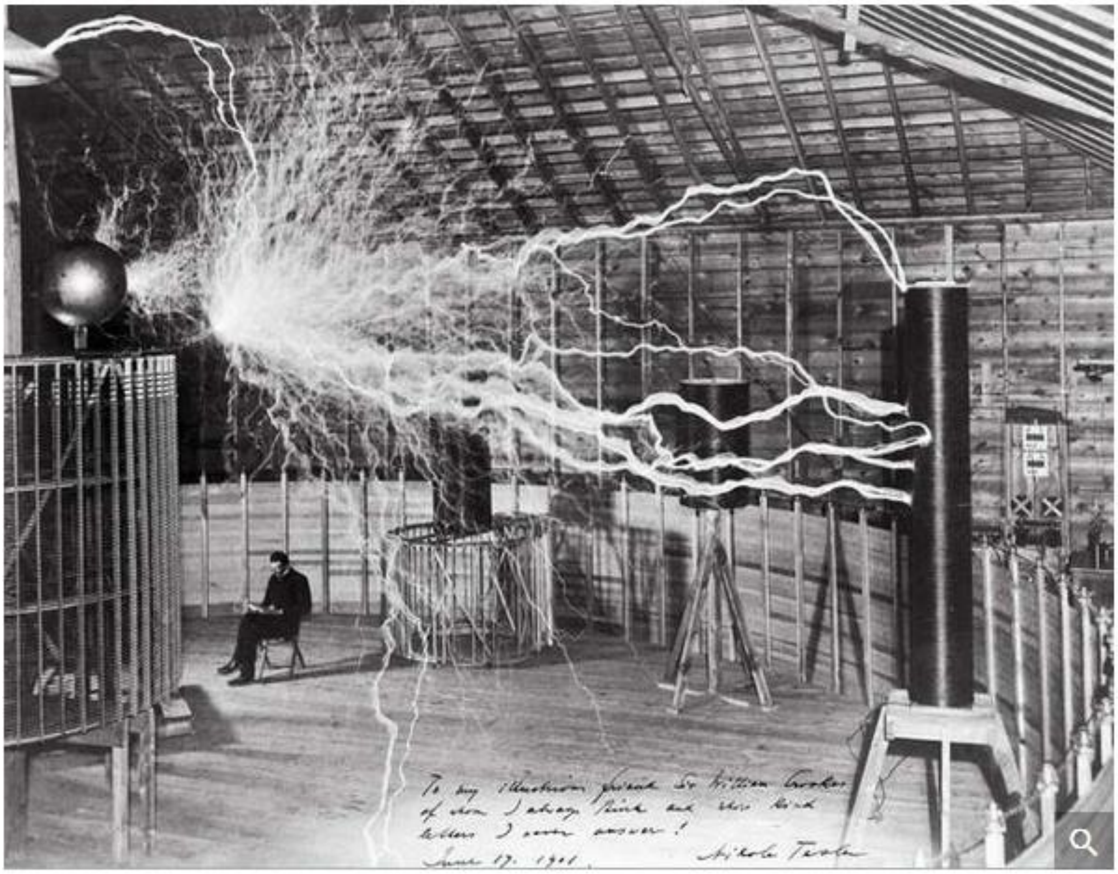


Figure 1-13 Tesla Coil [9]

After Nikola Tesla's wireless power projects founding was withdrawn, the research for wireless power transfer was stopped until recent years. The contemporary wireless power transfer research focused on point to point transmission instead of the global transmission of Tesla's model.

An article on the "Science" publication talks about the achievements of recent studies. By using highly coupled coils a group of researchers were able to transmit power at a 40% efficiency. The power transmitted was 60 watts, and the distance was 2 meters. The power was transferred using induction. The main purpose of this article was to show the capabilities of wireless transmission. Wireless transmission can be used for big and small things, and the risk is lower than with regular transmission devices [10].

The research expanded from conventional coils in some cases. An article showed the research of metamaterials utilized for wireless power transmission. The metamaterials were printed in a single layer circuit board. The specific circuit board had negative permeability. The system allowed for an efficiency increase of 4.26% at 100 centimeters, and 9.13% at 200 centimeters. The maximum efficiency obtained was 18.58% at 160 centimeters [11].

Compensating capacitors can help with the efficiency increase. However, conventional capacitors have an internal impedance that consumes power. An alternative is to use superconductive capacitors to set the resonant frequency. Research showed that the use of superconductive capacitors can increase the efficiency even more since the power dissipation in the superconductive capacitors was minimum. The capacitor diameter increased by 50 % from the conventional capacitor size. However, there was an efficiency increase of 4.25%. The system's maximum attained efficiency was 58.42% [12]. The use of superconducting capacitors can increase efficiency. However, the current low voltage, low-frequency system being analyzed requires very small compensating capacitors, and the superconductive capacitors approach cannot be implemented. The efficiency increase for the use of superconductive capacitors can be seen in Figure 1-14.

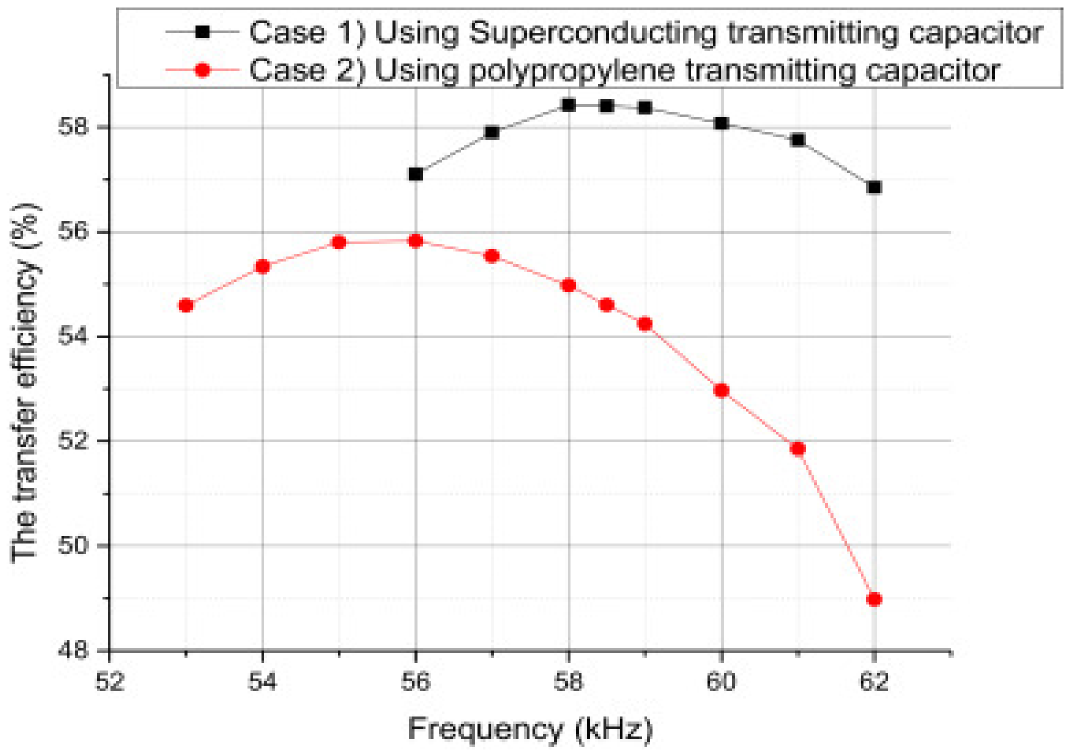



Figure 1-14 Superconducting Capacitors Efficiency Comparison [12]

# CHAPTER 2: AIR COILS

## 2.1 Introduction

The “Air Coils” design was introduced during the senior design “RAIL_WIRE2 2019” [4]. The coil design was proposed by a graduate student Hanyu Liu [3]. The design is shown in Figure 2-1.

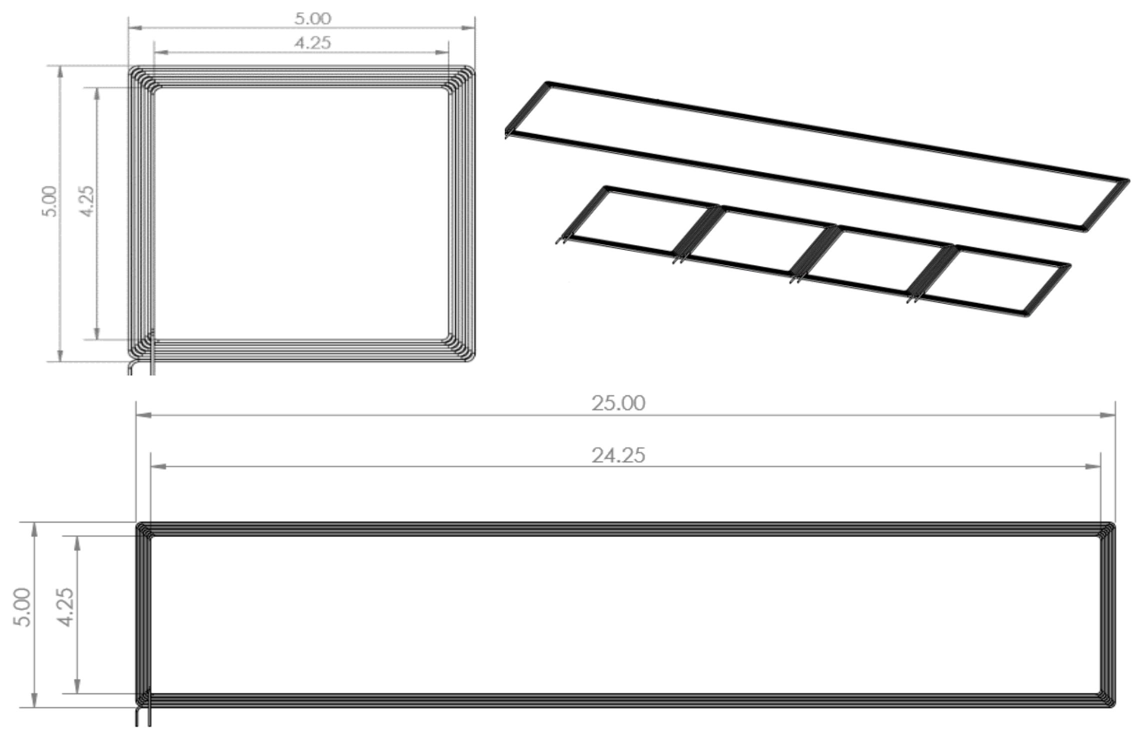



Figure 2-1 Air Coils Design [3]

The air coil transmitters had a square shape, and the long receiver had a rectangular shape. The transmitter coils were connected in series. The transmitter coils measured 5 inches by 5 inches or 127 mm by 127 mm. The receiver coil measures 25 inches by 5 inches or 635 mm by 127 mm. The coil transfer capabilities were simulated and measured considering two scenarios. The first scenario examined the behavior of one transmitter to one receiver. A square coil was used as the transmitter and a square coil was used as the receiver. The second scenario examined the behavior of four-square coils connected in series working as the transmitter and one rectangular long coil working as the receiver. For all scenarios the target values were the “Vout” and “Efficiency”.

2.2 Air Coils One-to-One

The coils were tested in a one-to-one scenario. A square coil was used as a transmitter and a square coil was used as a receiver. The air coils one-to-one from the prototype is shown in Figure 2-2.

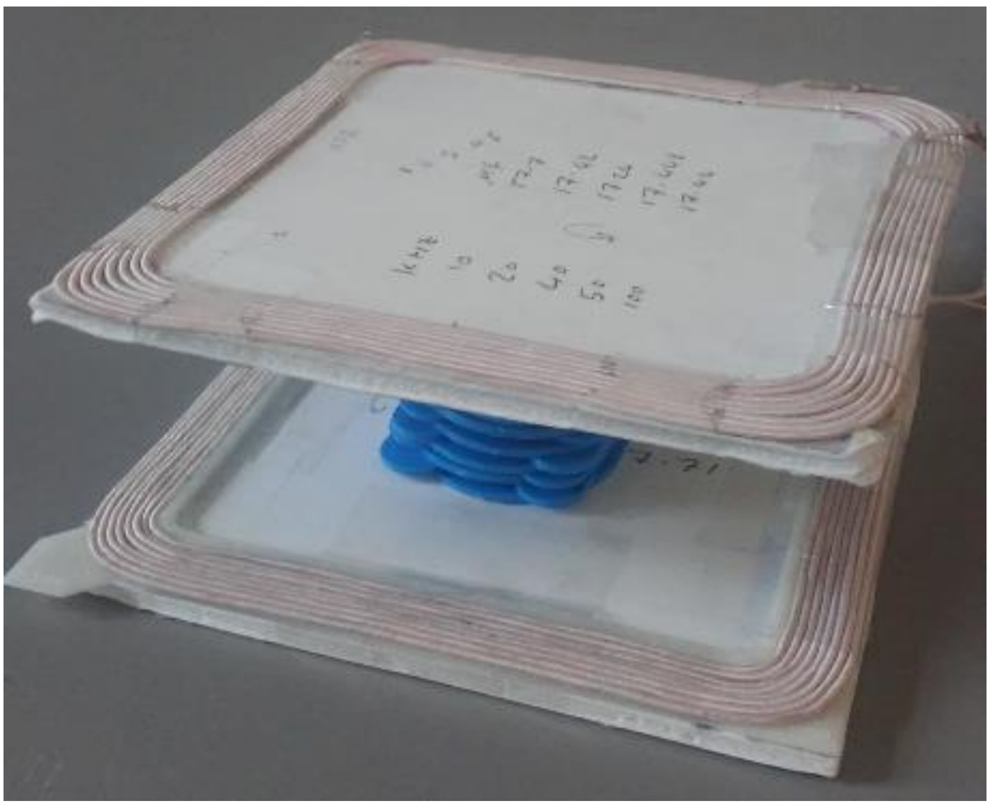


Figure 2-2 Prototype Air Coils One-to-One

The ANSYS Maxwell design for the one-to-one coil is shown in Figure 2-3.

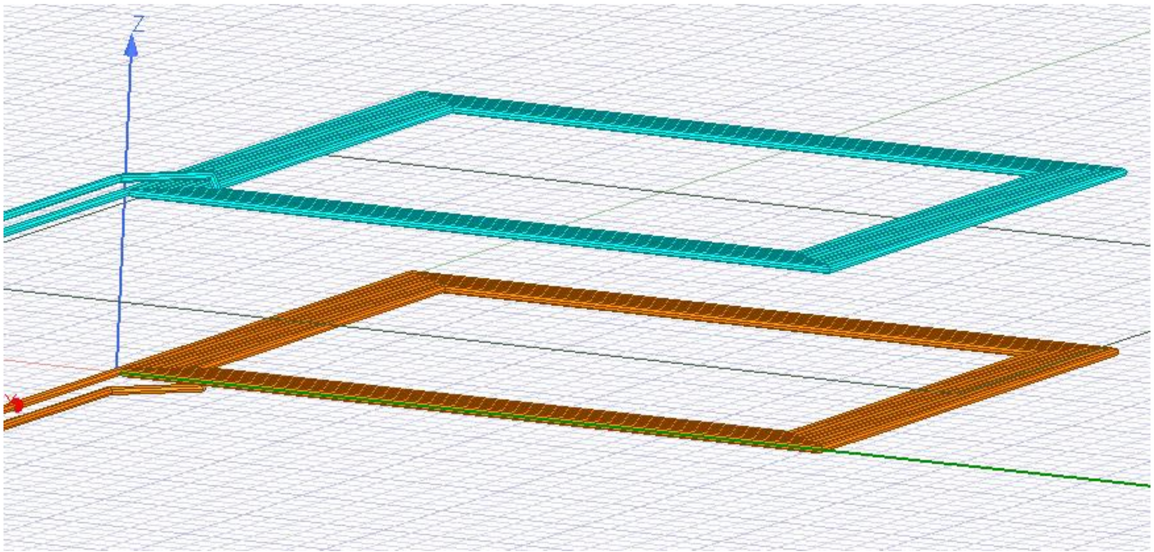



Figure 2-3 ANSYS Maxwell Air Coils One-to-One

The magnetic fields are shown in Figure 2-4.

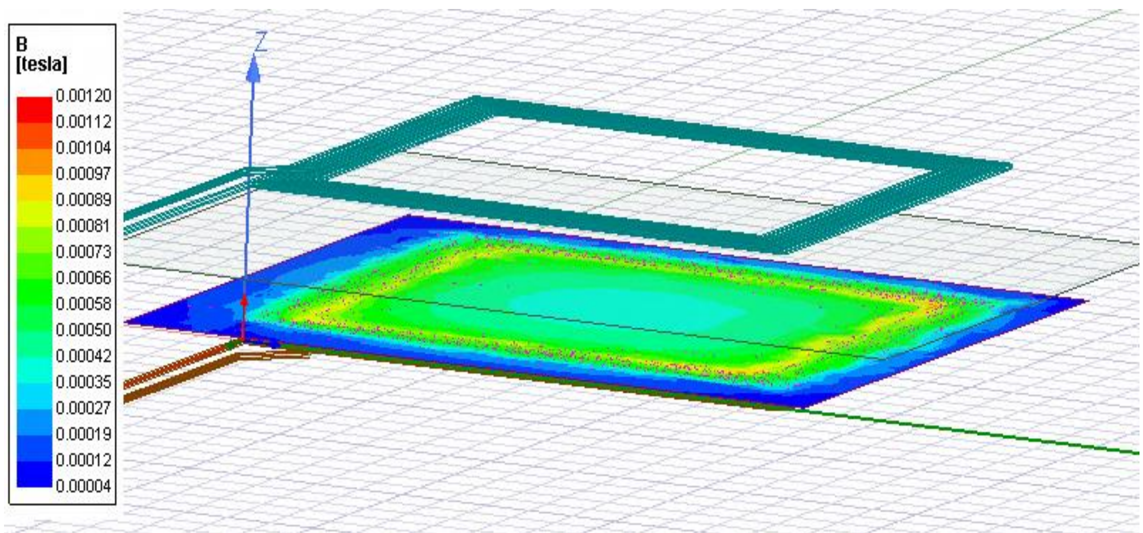



Figure 2-4 Air Coils One-to-One Magnetic Fields

The efficiency comparisons were made using actual measurements and simulations data. The simulations started with the ANSYS Maxwell coupling coefficient results. The first test was the vertical separation test. The ANSYS Maxwell coupling coefficient results for vertical separation are shown in Figure 2-5.

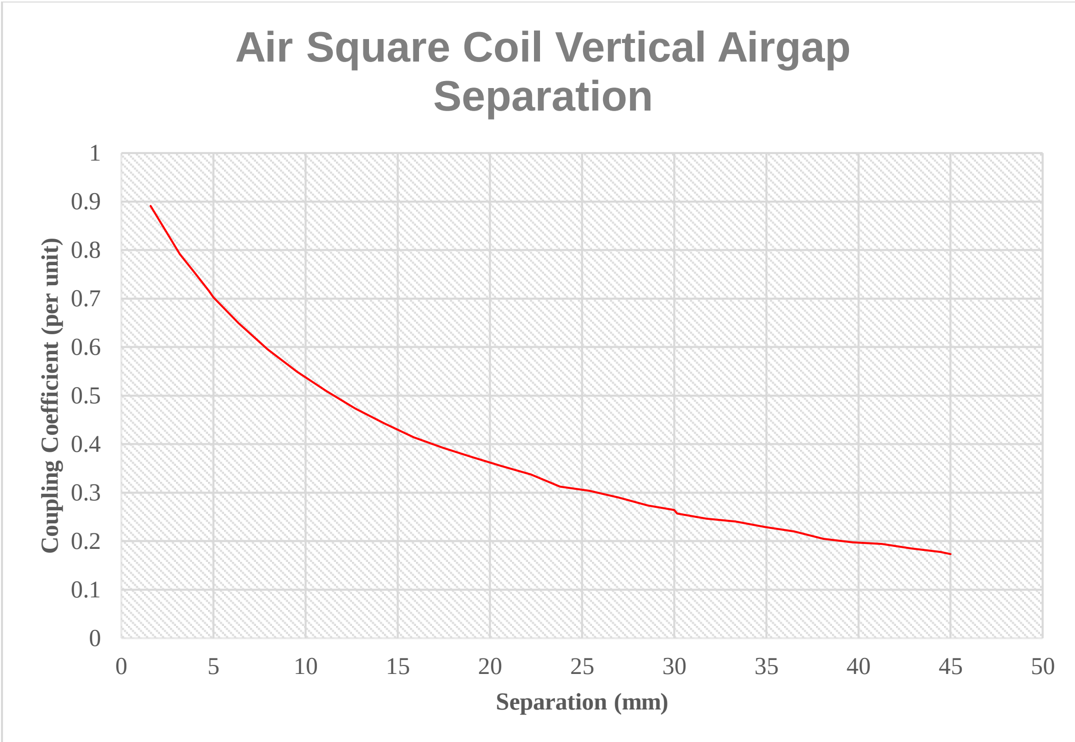



Figure 2-5 Air Coils One-to-One Vertical Separation vs Coupling Coefficient

The coupling coefficient decreased in an inverse exponential manner. The maximum coupling coefficient was 0.89 p.u. and decreased below 0.2 p.u. at 45 mm separation. The numeric data can be found in APPENDIX A. The vertical separation vs voltage graph is found in Figure 2-6.

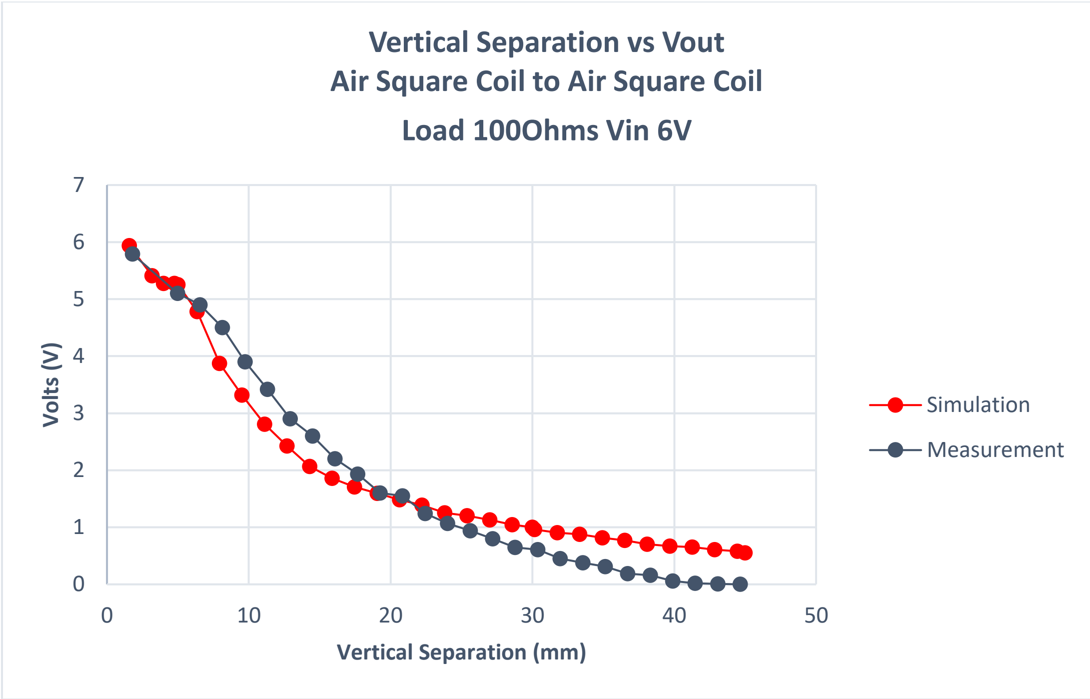



Figure 2-6 Air Coils One-to-One Vertical Separation vs Vout

The measured and simulated values were similar. The graphs were uneven. The maximum values were 5.94 volts for the simulated value, and 5.79 volts for the measured value. The numerical values can be found in APPENDIX B. The vertical separation vs efficiency graph is shown in Figure 2-7.

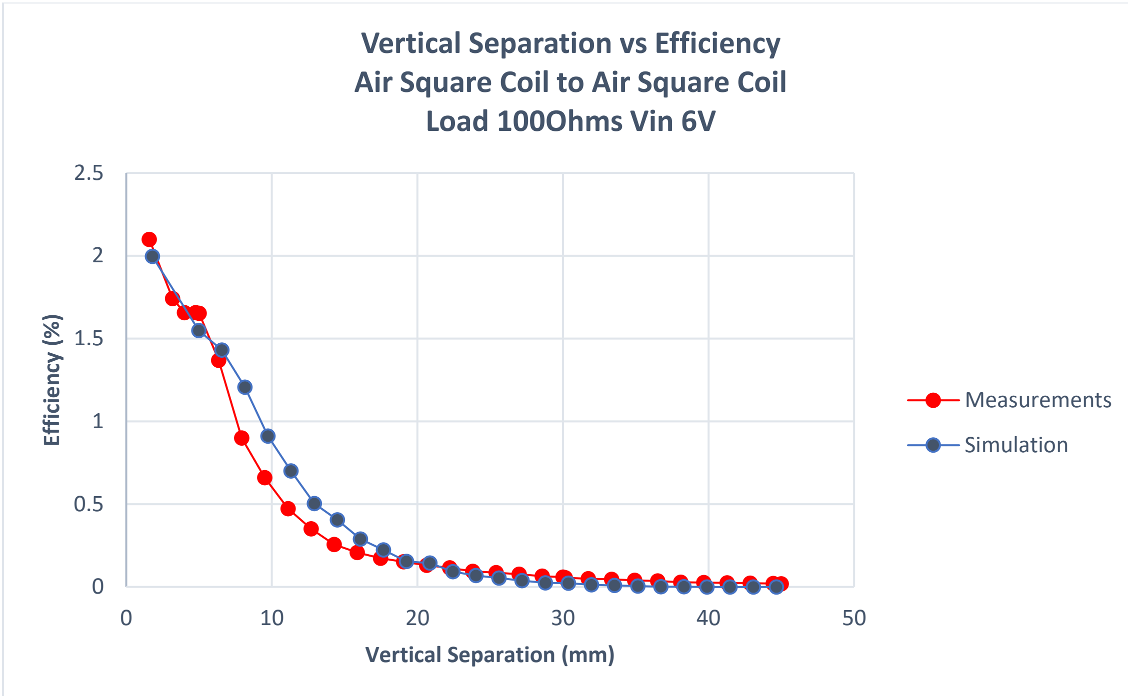



Figure 2-7 Air Coils One-to-One Vertical Separation vs Efficiency

The measurements and simulations had similar values except for some minor differences. The efficiency decrease was uneven until 15 mm separation, and it approached, and became zero from thereon. The numeric data can be found in APPENDIX B. The tests continued with the horizontal separation. The ANASYS Maxwell simulation for horizontal separation is shown in Figure 2-8.

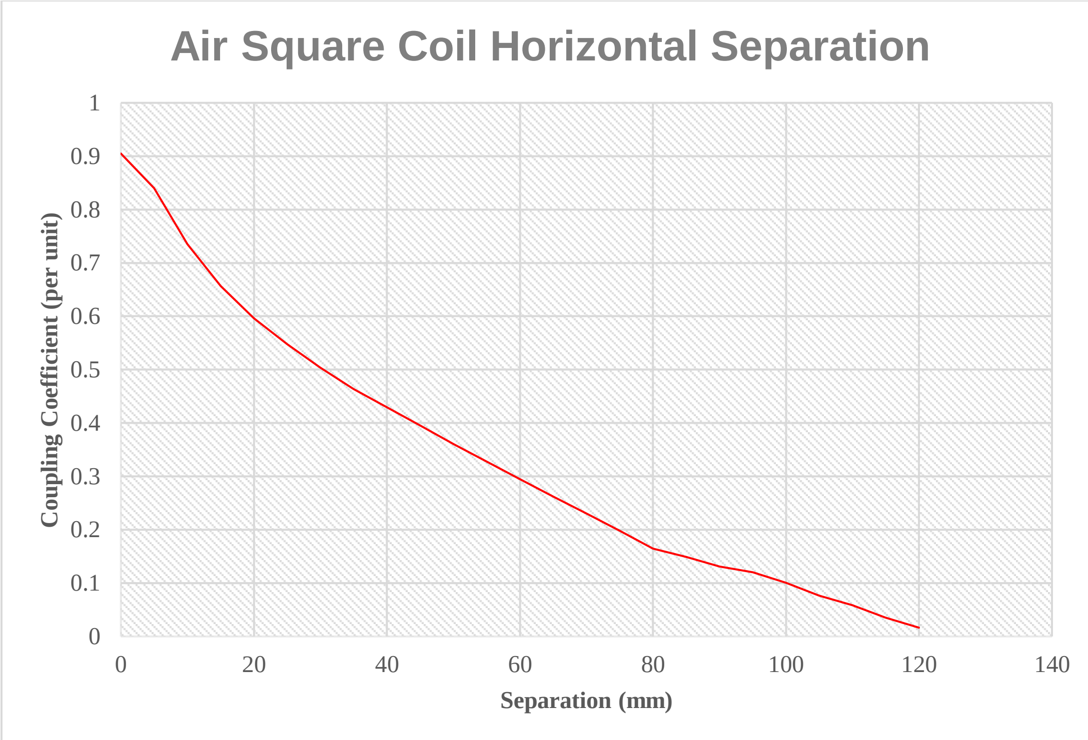



Figure 2-8 Air Coils One-to-One Horizontal Separation Coupling Coefficient

The horizontal separation graph showed a maximum coupling coefficient of 0.9 p.u. at 0 cm separation. The coupling coefficient dropped in an uneven way to close to zero at 120 cm separation.

The horizontal separation coupling coefficient was used for the voltage and efficiency simulations. Also, actual measurements were taken. The horizontal separation vs voltage graph is shown in Figure 2-9.

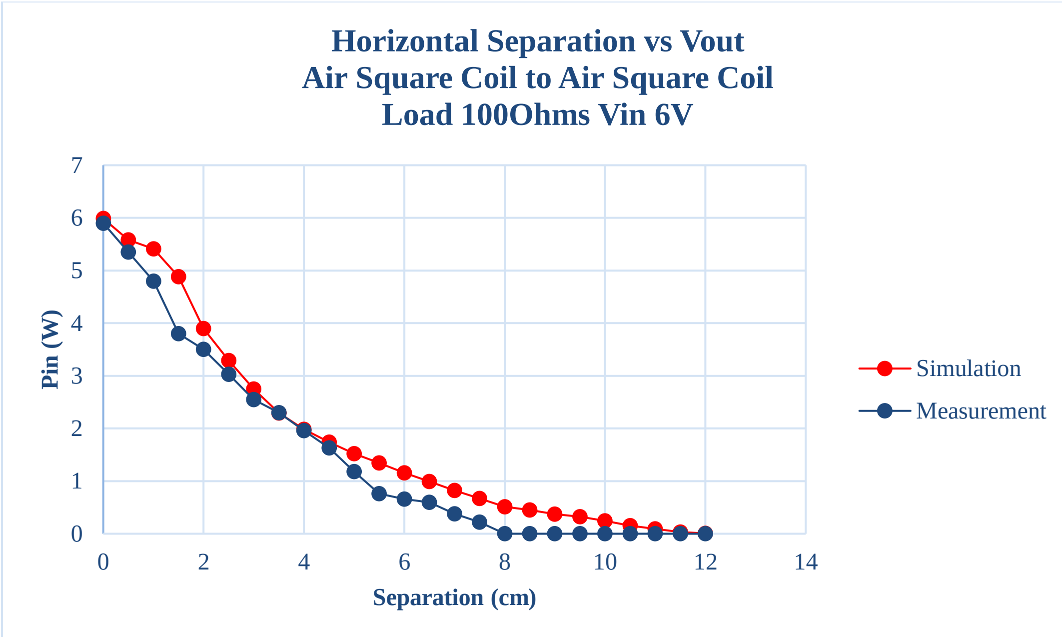



Figure 2-9 Air Coils One-to-One Horizontal Separation vs Vout

The graphs were uneven. The maximum values were 5.9 volts for actual measurements and 5.9 volts for the simulations. The numerical data is shown in APPENDIX C. The horizontal separation vs efficiency graph is shown in Figure 2-10.

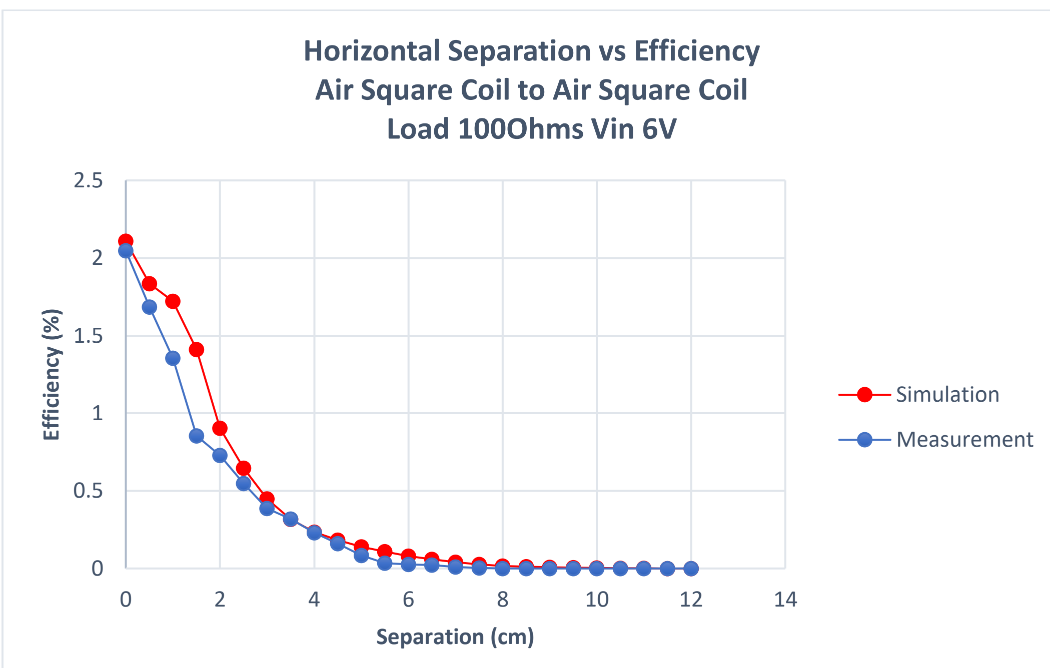



Figure 2-10 Air Coils One-to-One Horizontal Separation vs Efficiency

The graphs were similar in value; they had a semi linear decrease until 3cm of horizontal separation. After 3 cm the values approached and reached zero until 12 cm separation. The maximum values achieved were 2.05 % for actual measurements and 2.12 % for the simulations.

At zero horizontal distance and zero vertical separation the behavior was tested as well. However, the changing parameter was the load. The load vs voltage graph is shown in Figure 2-11.

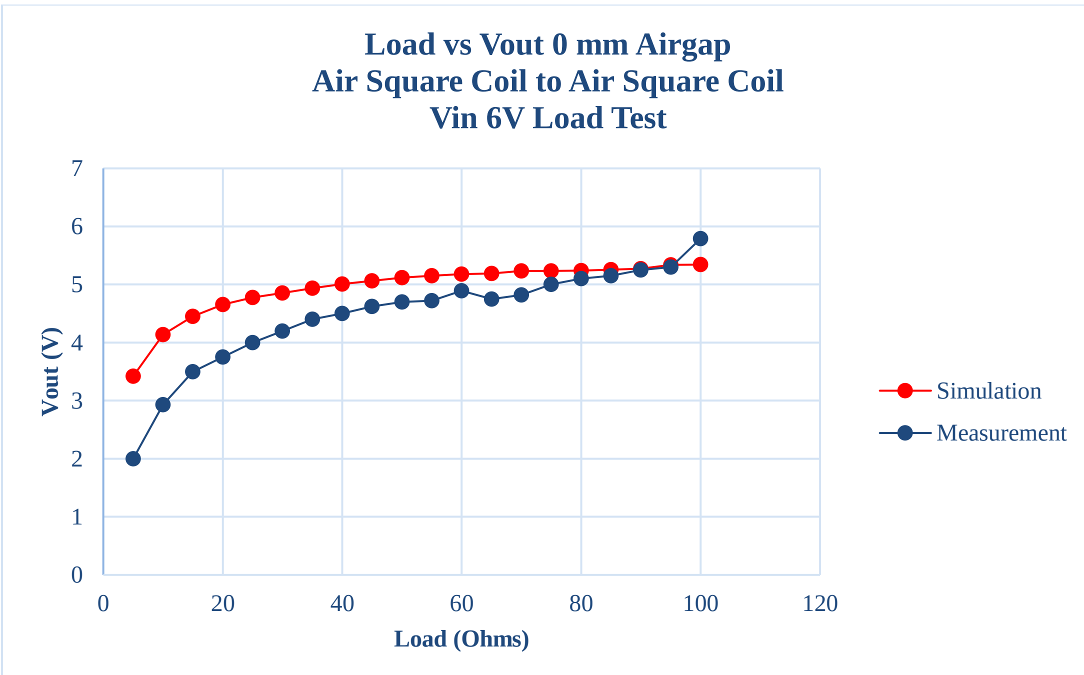



Figure 2-11 Air Coils One-to-One Load vs Voltage

The measured and simulated graphs were similar in value. There was an inverse exponential increase in voltage as the load increased. The numeric data can be found in APPENDIX D. The maximum values achieved were 5.79 volts for actual measurements and 5.34 volts for the simulation. The load vs efficiency graph is shown in Figure 2-12.

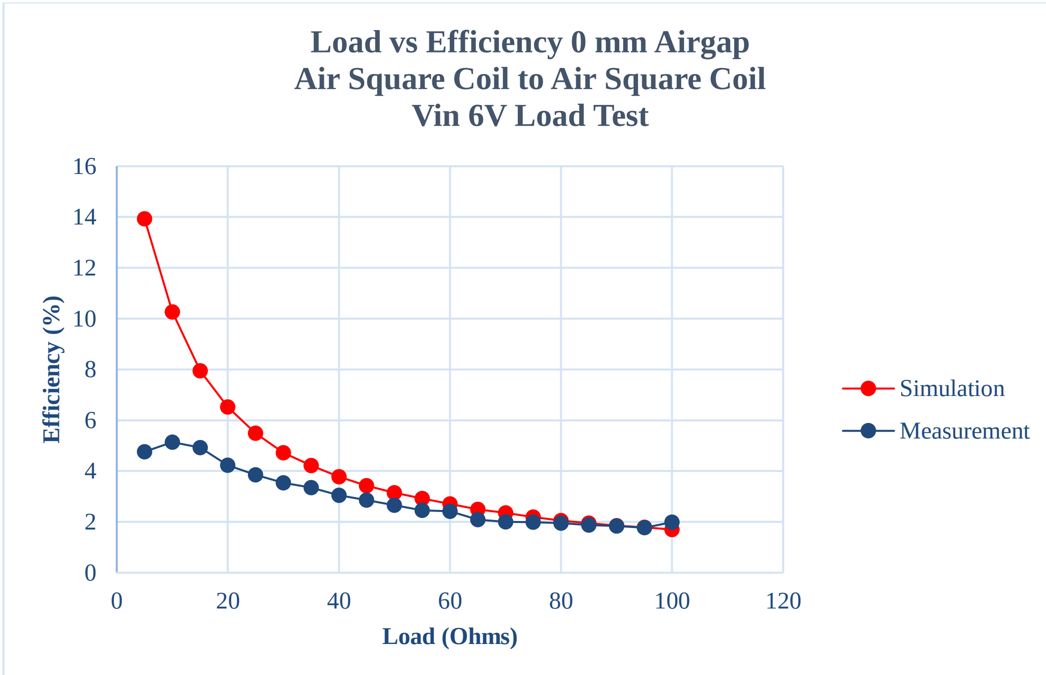



Figure 2-12 Air Coils One-to-One Load vs Efficiency

The graphs were similar in value from 25 Ohms to 100 Ohms. However, the simulation results showed larger deviation initially from 5 Ohms to 20 Ohms, and the deviation reduced gradually. The power supply used in the experiment had an internal resistance. However, in the simulation this internal resistance was not considered; thus, there was an unrealistic increase in efficiency in the simulation. The maximum values achieved were 2 % for actual measurements and 1.7 % for the simulation. The numeric data can be found in APPENDIX D. Also, the load test was performed at 12.91 mm for comparison purposes with other systems. The load vs voltage at 12.91 mm graph is shown in Figure 2-13.

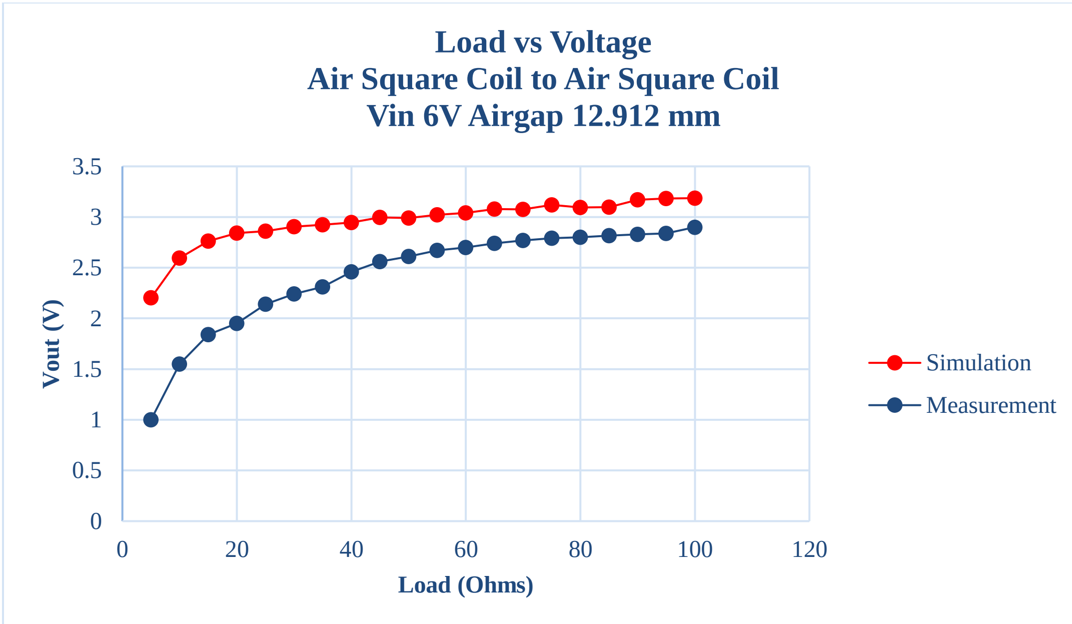



Figure 2-13 Air Coils One-to-One Load vs Voltage at 12.912 mm

The curves were similar from 45 Ohms to 100 Ohms. From 5 Ohms to 45 Ohms with consistent deviation, the simulation showed higher values. The graphs increased unevenly. The numerical values can be found in APPENDIX E. The load vs efficiency at 12.912 mm graph is shown in Figure 2-14.

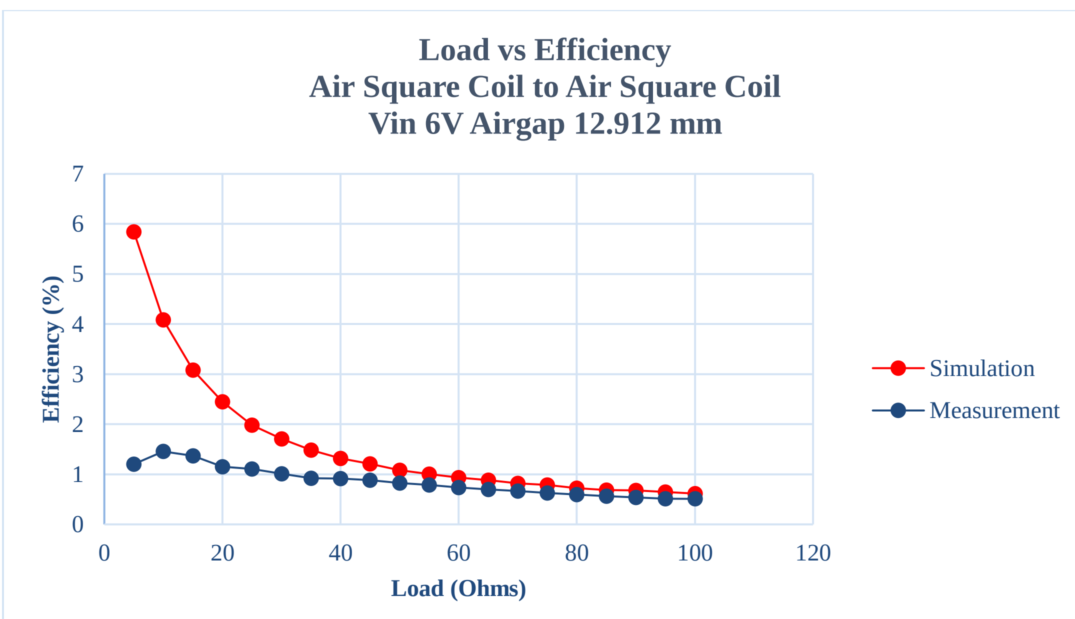



Figure 2-14 Air Coils One-to-One Load vs Efficiency at 12.912 mm

The curves were similar from 25 Ohms to 100 Ohms. From 5 Ohms to 25 Ohms the simulation was higher. The big increase in the simulation was due to an unrealistic ideal source. The numerical data can be found in APPENDIX E

## 2.3 Air Coils Four-to-One

The system was also tested with a configuration of four transmitted coils and one receiver coil. The tests were divided into vertical, horizontal, and load test. The four-to-one test differs from the one-to-one test because it had two main positions for vertical tests. There was a “Peak” position in which there was a maximum power transfer. This happens when the receiver edge and transmitter outermost edge were aligned. There was another main position which was considered the “Steady” position. The steady position happens during a range in which the transmitters were inside the receiver longitudinal axis. During this state the power transfer was constant even though there was horizontal separation. The four transmitter air coils prototype is shown in Figure 2-15.

Figure 2-15 Prototype Four Square Coils

The receiver coil is shown in Figure 2-16.

Figure 2-16 Prototype Receiver Coil

The ANSYS Maxwell air coils four-to-one peak position design is shown in Figure 2-17.

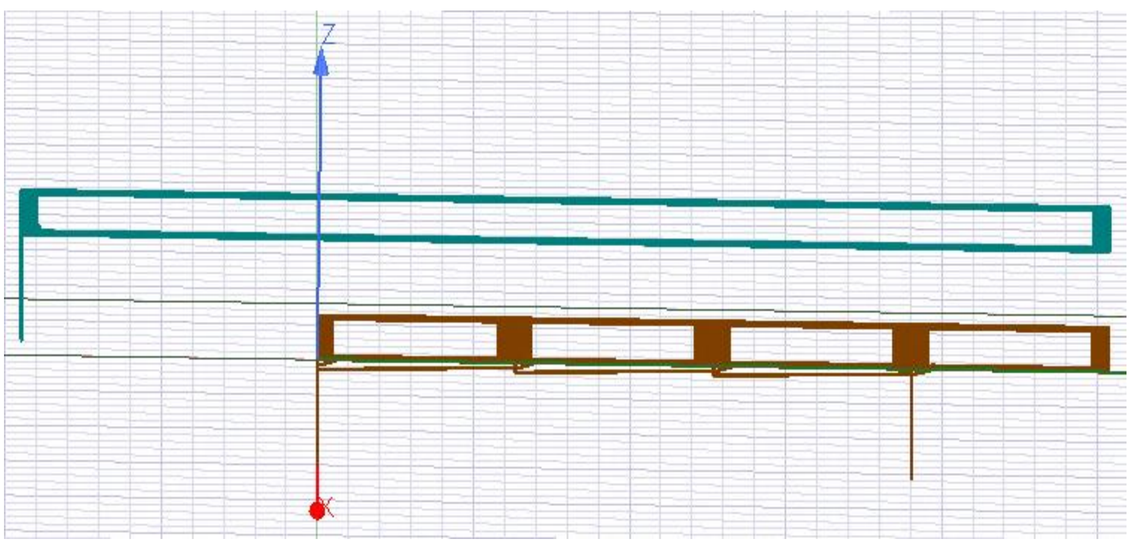



Figure 2-17 ANSYS Maxwell Air Coils Four-to-One Design Peak Position

The air coils four-to-one peak position magnetic fields is shown in Figure 2-18.

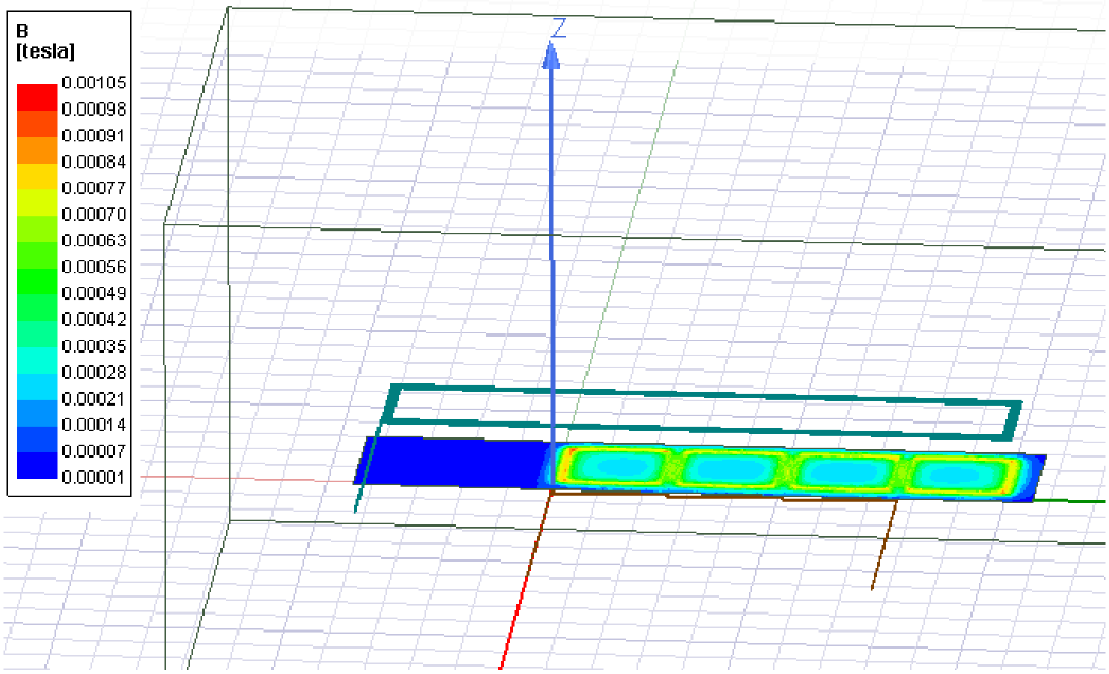



Figure 2-18 ANSYS Maxwell Air Coils Four-to-One Design Peak Position

The ANSYS Maxwell air coils four-to-one steady position design is shown in Figure 2-19.

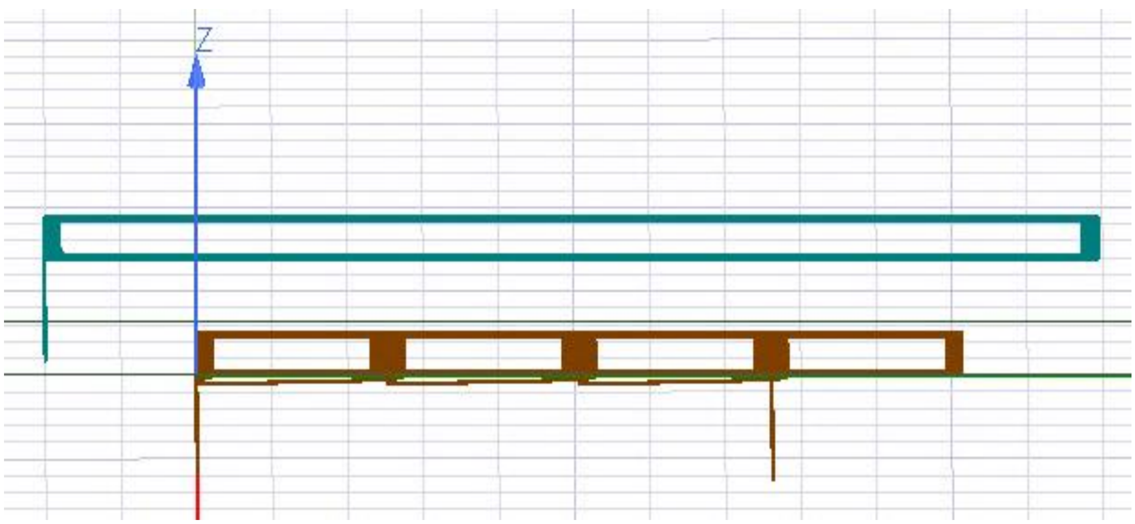



Figure 2-19 ANSYS Maxwell Air Coils Four-to-One Design Steady Position

The air coils four-to-one steady position magnetic fields are shown in Figure 2-20.

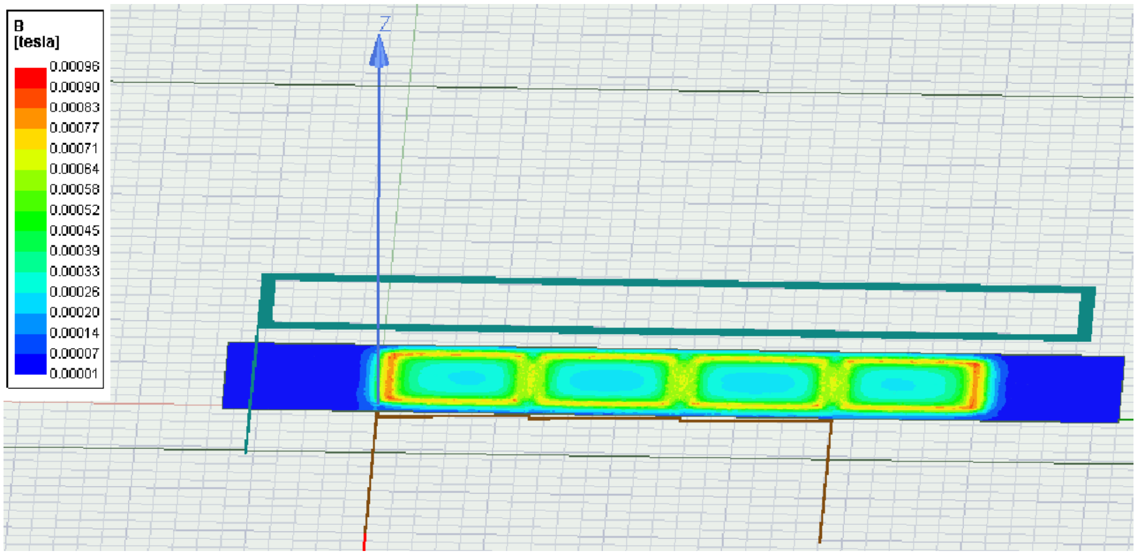



Figure 2-20 ANSYS Maxwell Air Coils Four-to-One Design Steady Position

The ANSYS Maxwell simulation for air coils four-to-one horizontal separation is shown in Figure 2-21.

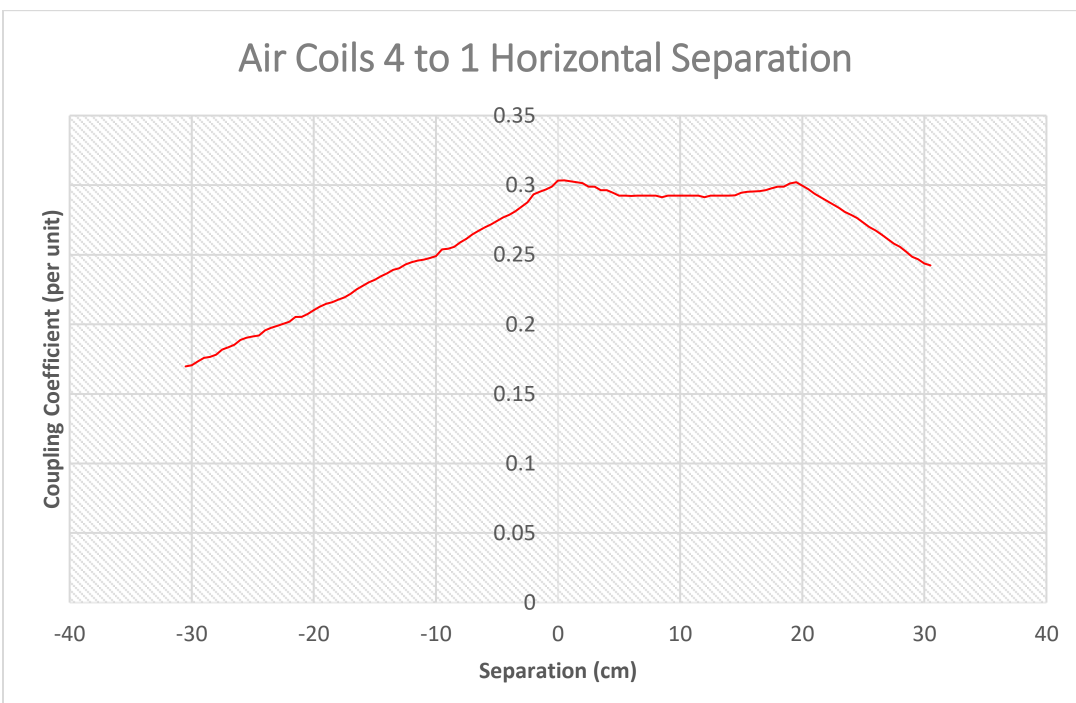



Figure 2-21 ANSYS Maxwell Simulation Air Coils Four-to-One Horizontal Separation

The zero-centimeter position determined the “Peak” position. The negative values indicate that the receiver separation was to the left. The positive values indicate the receive separation to the right. The graph showed two peak positions one when the receiver right edge was aligned with the right-most transmitter edge, and the other was when the receiver left edge was aligned with the left most transmitter edge. There was the Steady position also from 5 mm to 15 mm horizontal separation. The horizontal separation vs voltage is shown in Figure 2-22.

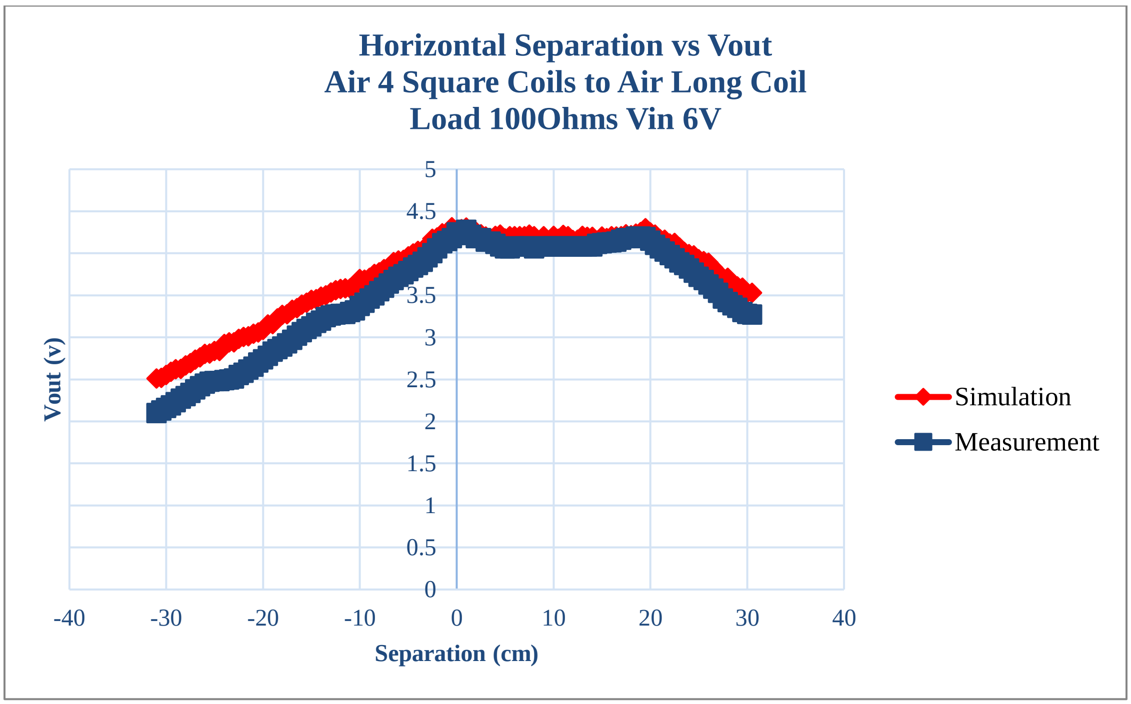



Figure 2-22 Air Coils Four-to-One Horizontal Separation vs Voltage

The simulation and measurement values were similar. The voltage graph showed the two peak positions at 4.25 volts and 4.2 volts for actual measurements. The voltage graph showed the two peak positions at 4.31 volts and 4.299 volts for simulation. The steady values were around 4.08 volts for actual measurements and 4.21 volts for the simulation. The simulation values were a little higher than real values. The numerical values are shown in APPENDIX F. The horizontal separation vs efficiency is shown in Figure 2-23.

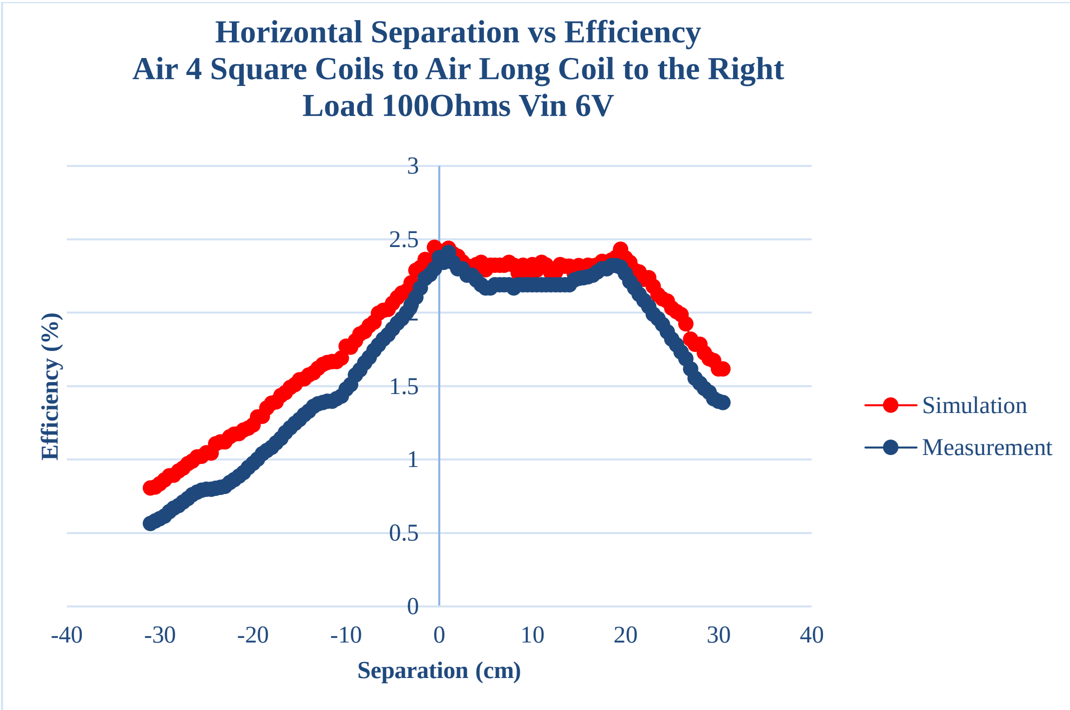



Figure 2-23 Air Coils Four-to-One Horizontal Separation vs Efficiency

The simulation and real values were similar. The simulation values were slightly higher than the real measurement values. The efficiency also showed two peak values at 2.38 % and 2.32 % for actual measurements. Also, two peaks at 2.44 % and 2.43 % for the simulation. The steady values were around 2.19 % for real measurement and 2.33 % for simulation. The numeric data is shown in APPENDIX F. The ANSYS Maxwell simulation for the air coils four-to-one vertical separation peak position is shown in Figure 2-24.

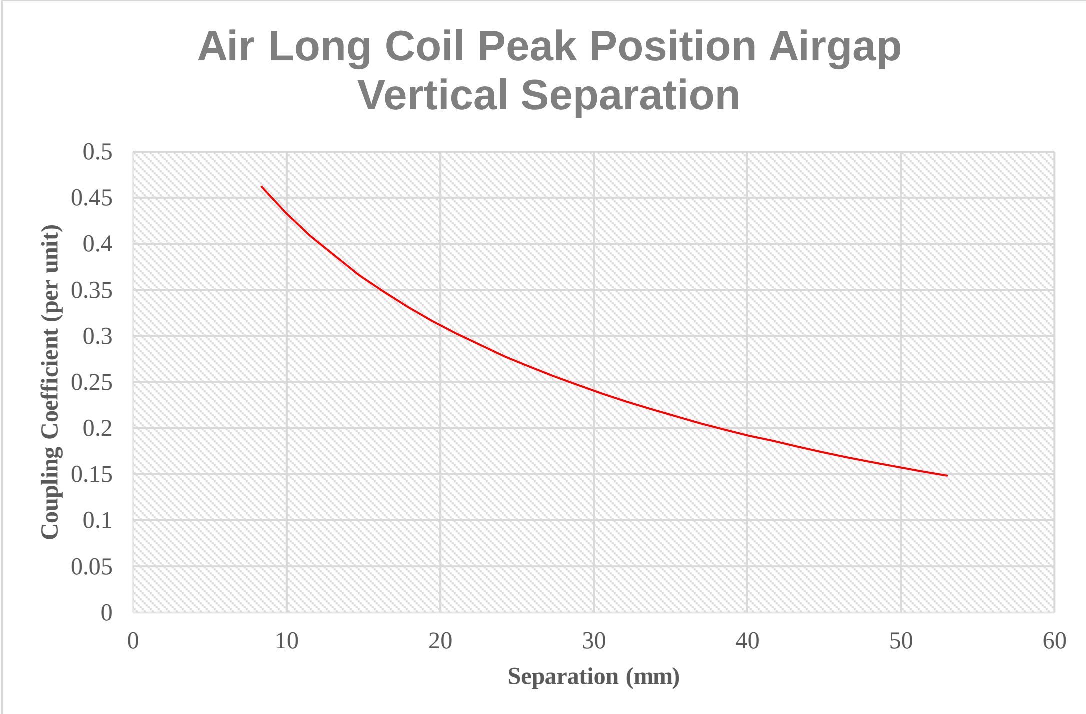



Figure 2-24 Air Coils Four-to-One Vertical Separation Peak Position

The graph showed a semi inverse exponential decrease. The maximum value was at 0.46 p.u. The numerical data is shown in APPENDIX G. The vertical separation at the peak position vs voltage is shown in Figure 2-25.

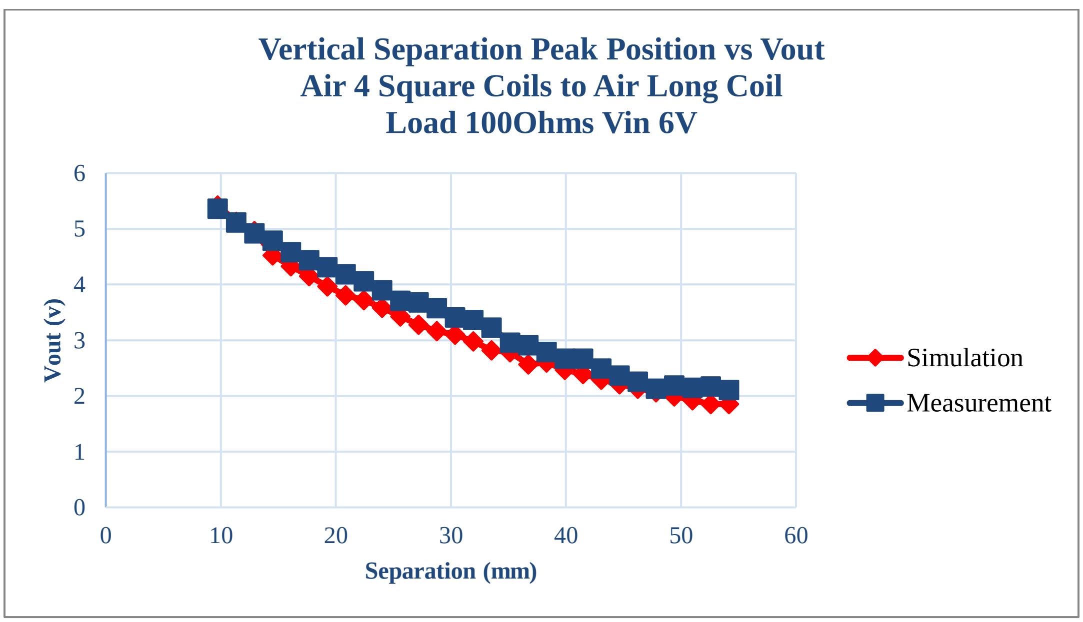



Figure 2-25 Air Coils Four-to-One Vertical Separation Peak Position vs Voltage

The simulation and the actual measurements were similar. The graph was very linear for both values. The maximum values were 5.36 volts for actual measurements and 5.42 volts for simulations. The numerical data is shown in APPENDIX H. The vertical separation at the peak position vs efficiency is shown in Figure 2-26.

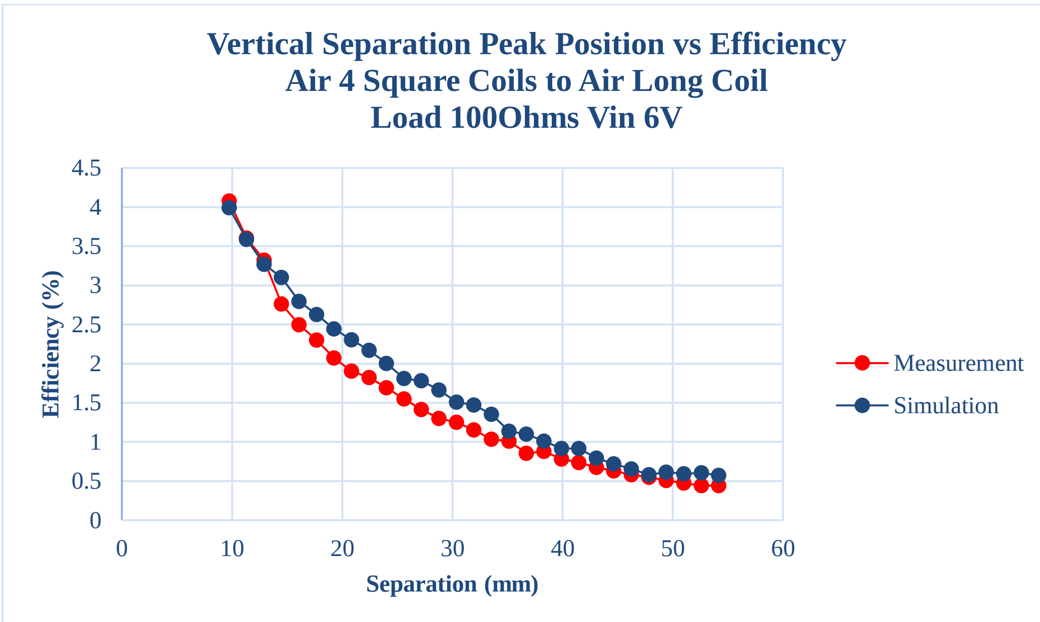



Figure 2-26 Air Coils Four-to-One Vertical Separation Peak Position vs Efficiency

The measured and simulated values were similar. Both graphs showed a semi inverse exponential decrease. The maximum values were 3.99 % for the actual measurements and 4.08 % for simulations. The numeric values are shown in APPENDIX H. The ANSYS Maxwell simulation for the vertical separation at the steady position. The air coils four-to-one vertical separation at the steady position graph is shown in Figure 2-27.

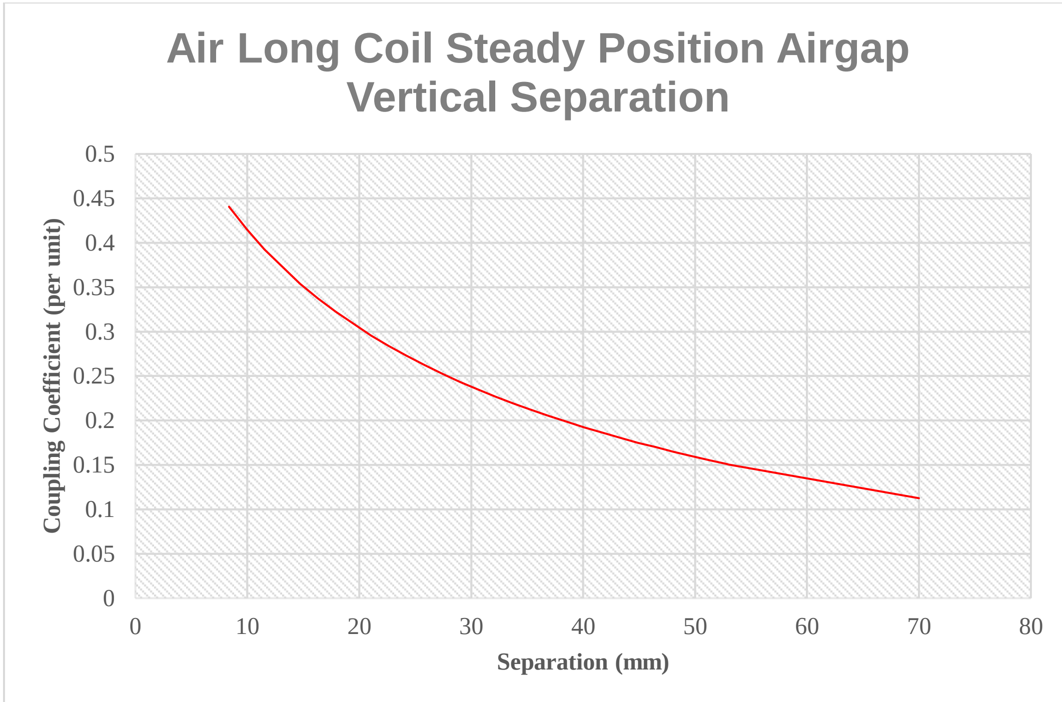



Figure 2-27 Air Coils Four-to-One Vertical Separation at the Steady Position

The graph had an inverse exponential decrease. The maximum value was 0.44. The numerical data was in APPENDIX I. The vertical separation at the steady position vs voltage is shown in Figure 2-28.

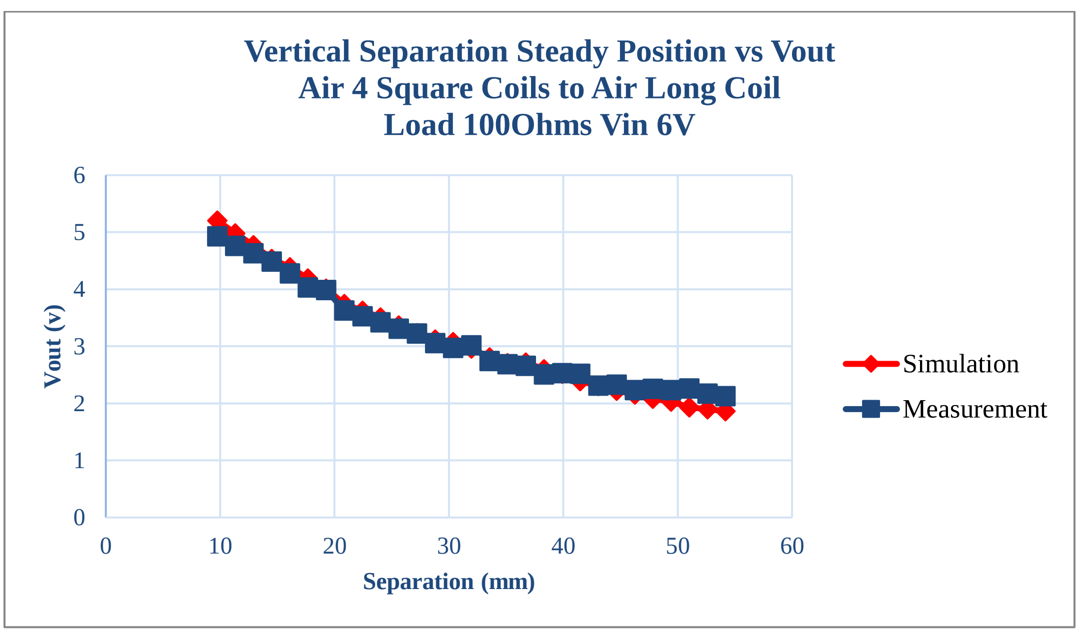



Figure 2-28 Air Coils Four-to-One Vertical Separation vs Voltage at Steady Position

The measurements and simulations were similar. The graphs were semi inverse exponential. The maximum values were 4.93 volts for actual measurements and 5.21 volts for simulations. The numeric data is shown in APPENDIX J. The vertical separation at the steady position vs efficiency graph is shown in Figure 2-29.

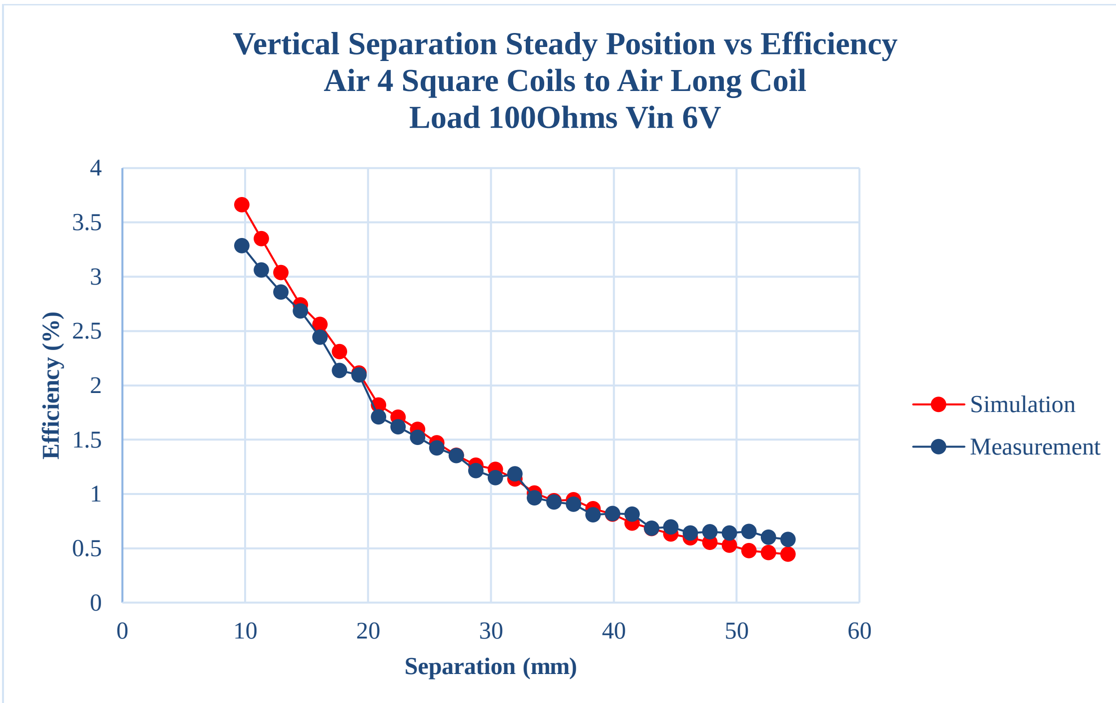



Figure 2-29 Air Coils Four-to-One Vertical Separation vs Efficiency at Steady Position

The simulation and the measured values were similar. The graphs were semi exponential decreasing. The maximum values were 3.28 % for actual measurements and 3.66 % for simulations. The numerical data is shown in APPENDIX J. The four-to-one peak position load vs voltage graph is shown in Figure 2-30.

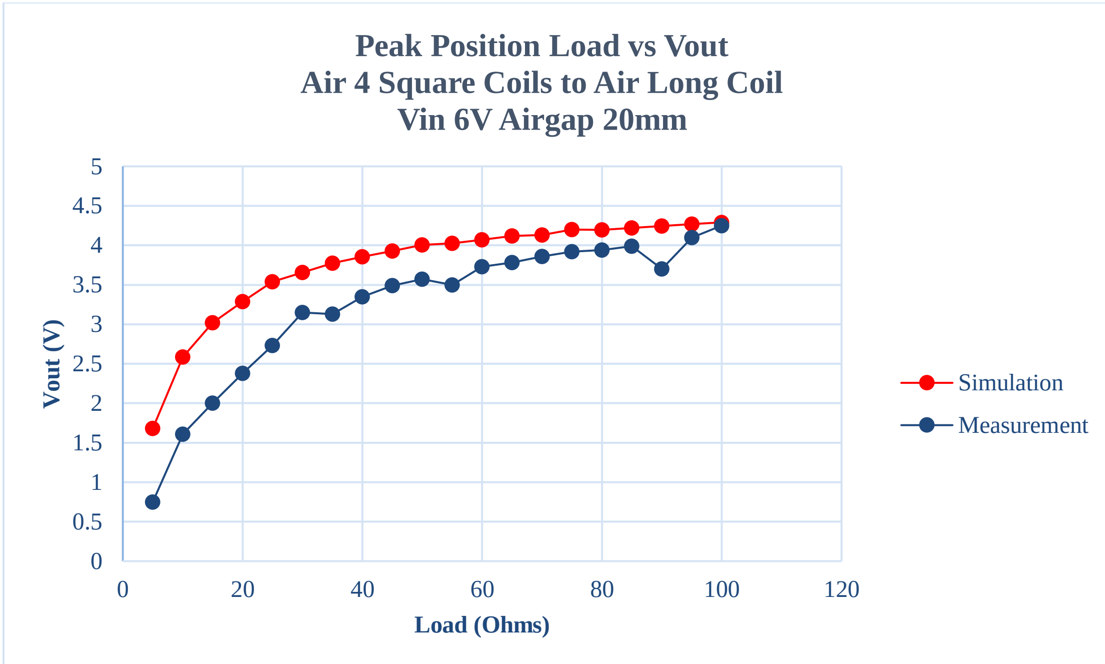



Figure 2-30 Four-to-One Peak Position Load vs Voltage Airgap 20mm

The vertical separation for this test was 20 mm. The real measurement and the simulations were similar. The graphs had an inverse exponential increase. The maximum values were 4.25 volts for the actual measurements and 4.29 volts for the simulations. The numerical data was in APPENDIX K. The air coils four-to-one peak position load vs efficiency graph is shown in Figure 2-31.

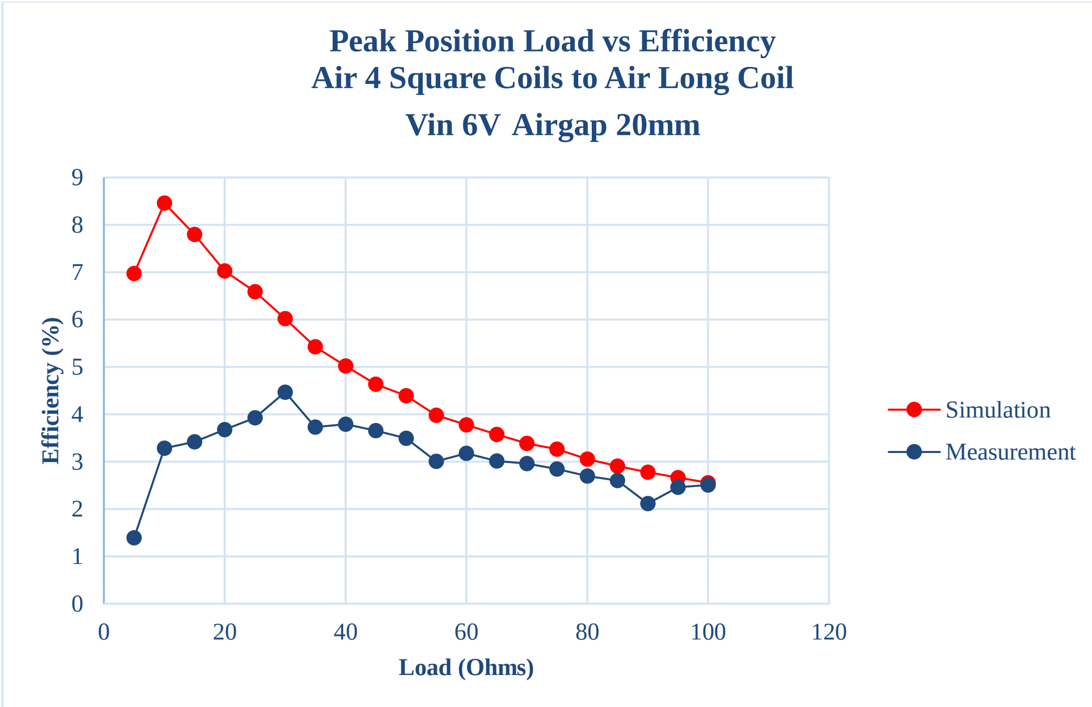



Figure 2-31 Four-to-One Peak Position Load vs Efficiency Airgap 20mm

The vertical separation for this test was 20 mm. The actual measurements and simulation were similar from 35 Ohms to 100 Ohms. There was a difference from 35 Ohms to 5 Ohms; at that range the simulation showed an increase of values. The increase happens because of the lack of a realistic source of internal resistance. The maximum values were 3.92 % for the actual measurements and 8.46 % for the simulation. The numerical data is shown in APPENDIX K. The air coils four-to-one load vs voltage steady position is shown in Figure 2-32.

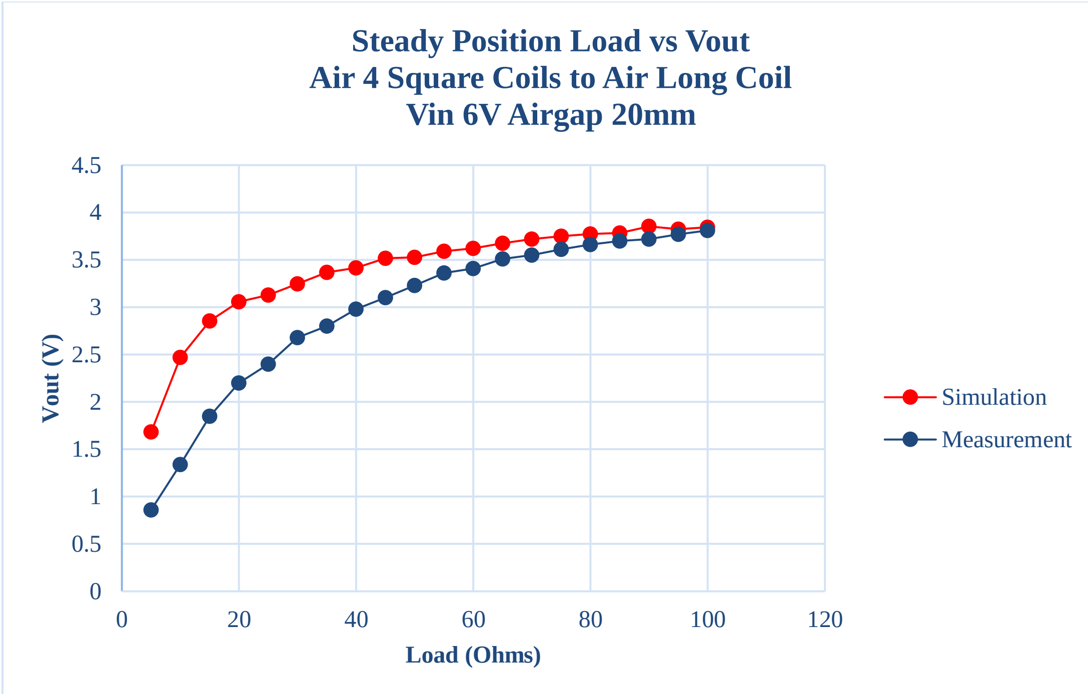



Figure 2-32 Air Coils Four-to-One Load vs Voltage Steady Position Airgap 20mm

The vertical separation for this test was 20 mm. The real measurement and simulation values were similar except for the 10 Ohms to 25 Ohms range; the Simulation showed higher values in those areas. The maximum values were 3.81 volts for actual measurements and 3.84 volts for simulation. The numerical data is shown in APPENDIX L. The air coils four-to-one load vs efficiency at steady position is shown in Figure 2-33.

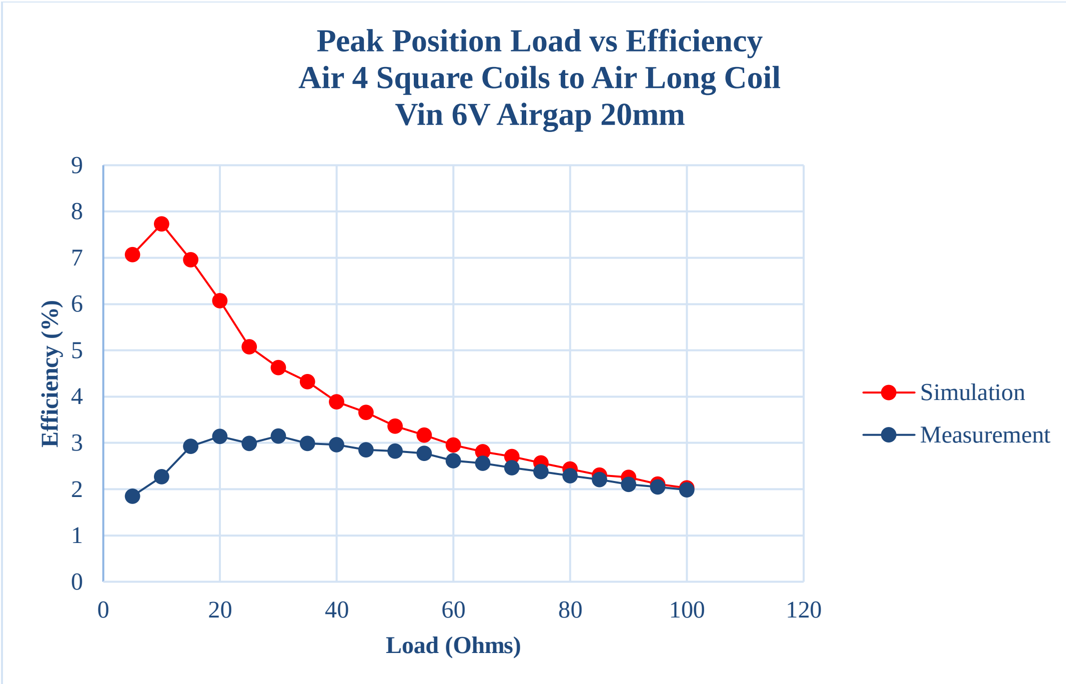



Figure 2-33 Air Coils Four-to-One Load vs Efficiency Steady Position Airgap 20mm

The vertical separation for this test was 20 mm. The curves were similar from 40 Ohms to 100 Ohms. The graphs differ from 5 Ohms to 40 Ohms; at this range the simulation showed higher values due to an unrealistic almost ideal voltage source. The maximum values were 3.15 % for the actual measurements and 7.73 % for the simulation. The numerical data is in APPENDIX L. There were also simulations with a distance separation higher at 27.2 mm. The air coils four-to-one peak position vs voltage graph is shown in Figure 2-34.

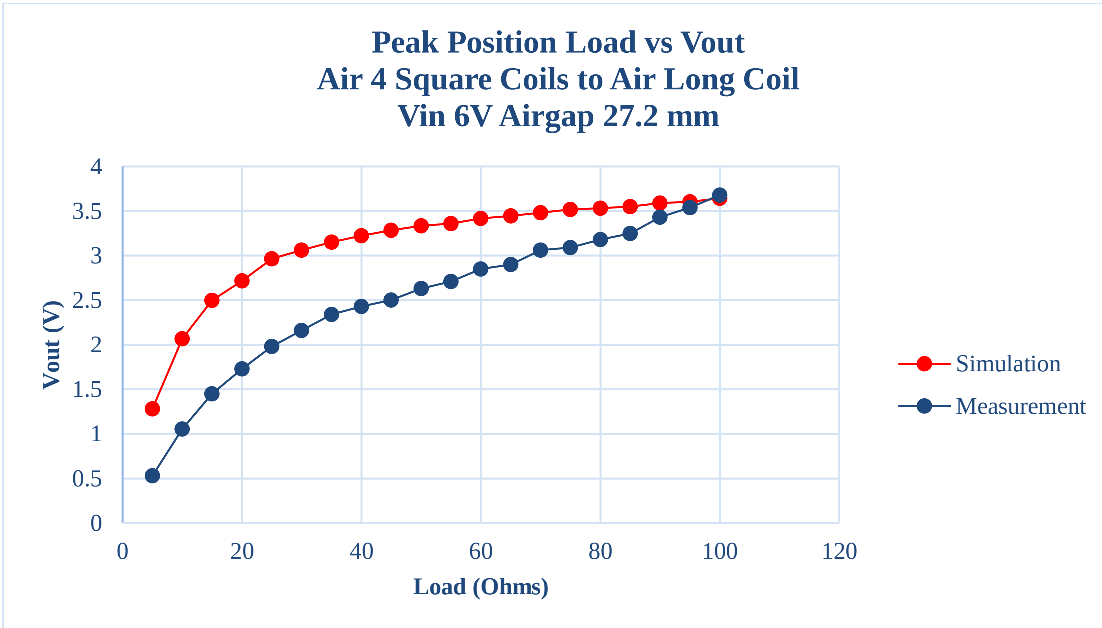



Figure 2-34 Air Coils Four-to-One Load vs Voltage Peak Position Airgap 27.2 mm

The vertical separation for this test was 27.2 mm. The graph was similar from 100 Ohms to 70 Ohms, and closes up at 5 Ohms. However, for the rest of the range it was different; the simulation showed higher values. The maximum values were 3.68 volts for the actual measurements and 3.64 volts for the simulation. The data can be found in APPENDIX M. The air coils four-to-one peak position vs efficiency graph is shown in Figure 2-35.

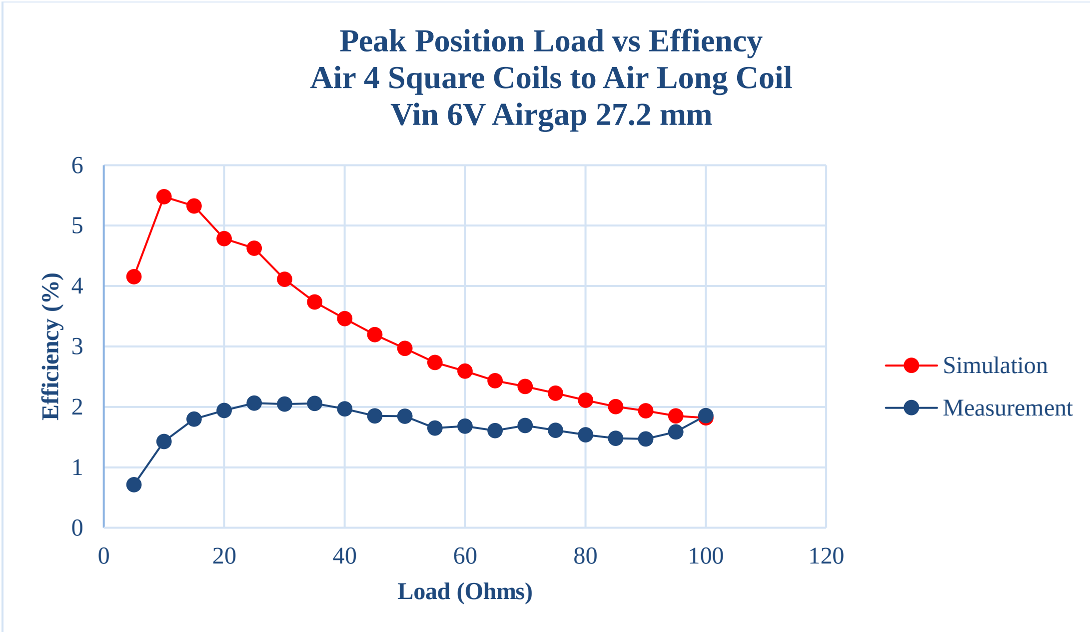



Figure 2-35 Air Coils Four-to-One Load vs Efficiency Peak Position Airgap 27.2 mm

The vertical separation for this test was 27.2 mm. The graphs were similar from 75 Ohms to 100 Ohms. For the rest of the range the graphs were similar. The simulation showed higher values than the actual measurements. The highest values were 2.06 % for the real values and 5.33 % for simulation values. The numerical data is shown in APPENDIX M. The air coils four-to-one steady position vs voltage graph is shown in Figure 2-36.

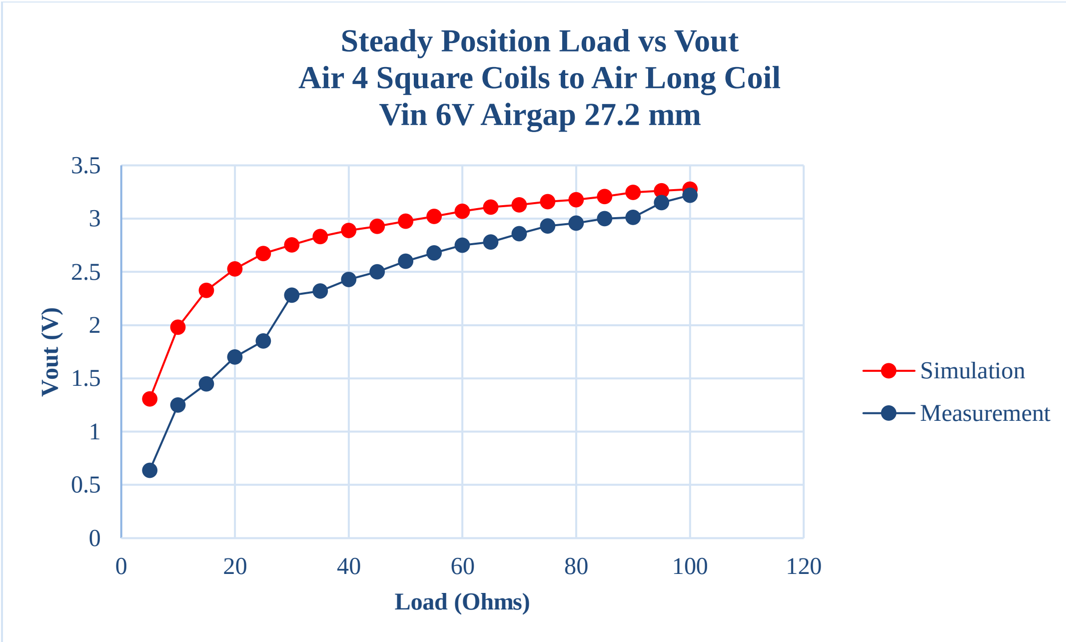



Figure 2-36 Air Coils Four-to-One Load vs Voltage Steady Position Airgap 27.2 mm

The vertical separation for this test was 27.2 mm. The graph values were similar. The actual measurements were irregularly increasing and the simulations were semi inverse exponential increasing. The maximum values were 3.22 volts for actual measurements and 3.28 volts for simulation. The numerical data is shown in APPENDIX N. The air coils four-to-one steady position vs efficiency graph is shown in Figure 2-37.

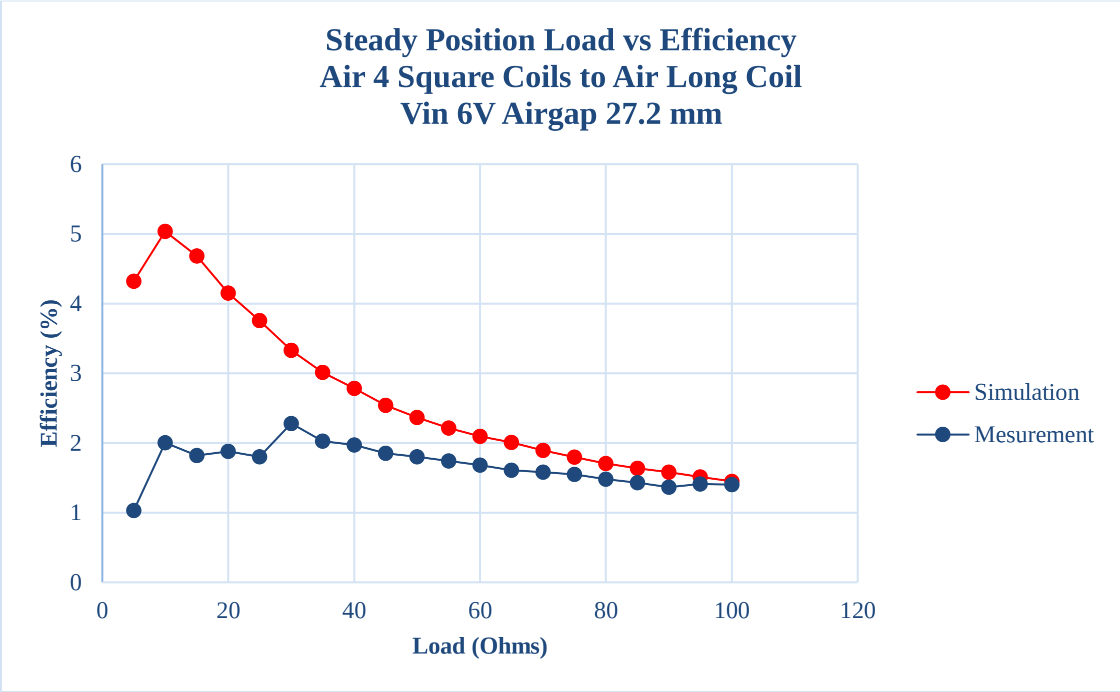



Figure 2-37 Air Coils Four-to-One Load vs Efficiency Steady Position Airgap 27.2 mm

The vertical separation for this test was 27.2 mm. The graphs were similar from 100 Ohms to 30 Ohms. From 30 Ohms to 5 Ohms, the graphs differ; the simulation values were higher. The values were higher because of the unrealistic almost ideal power source. The maximum values were 2.28 % for real measurement and 5.03 % for simulation. The numerical data can be found in APPENDIX N.

# CHAPTER 3: AIR COILS WITH ADDED CORES

## 3.1 Introduction

The previous chapter researched the “Air Coils” design. In this chapter there will be comparisons between the air coils and air coils with added ferrite cores.

The ferrite cores were added in different positions and configurations. There were tests done for the one-to-one configuration and the four-to-one configuration. The ferrite cores blocks were 90.5 mm by 80.2 mm by 15 mm. The core blocks were made of three smaller ferrite cores. The ferrite core block is shown in Figure 3-1.


Figure 3-1 Ferrite Core Block

The same ferrite cores were used for the transmitter and receivers. The systems were measured and also simulated. The systems were tested to find the “Vout” and “Efficiency”. The tests were performed for the one-to-one configuration and the four-to-one configuration.

3.2 Air Coils with Added Cores One-to-One

The system tested different scenarios for the one-to-one test. The scenarios included different ferrite core positions, and different number of ferrite cores. The tests were performed by maintaining the input voltage and position while changing the load. The one-to-one air coils with a core are shown in Figure 3-2.

Figure 3-2 One-to-One Air Coils with a Core

The one-to-one air coils with a core ANSYS Maxwell design is shown in Figure 3-3.

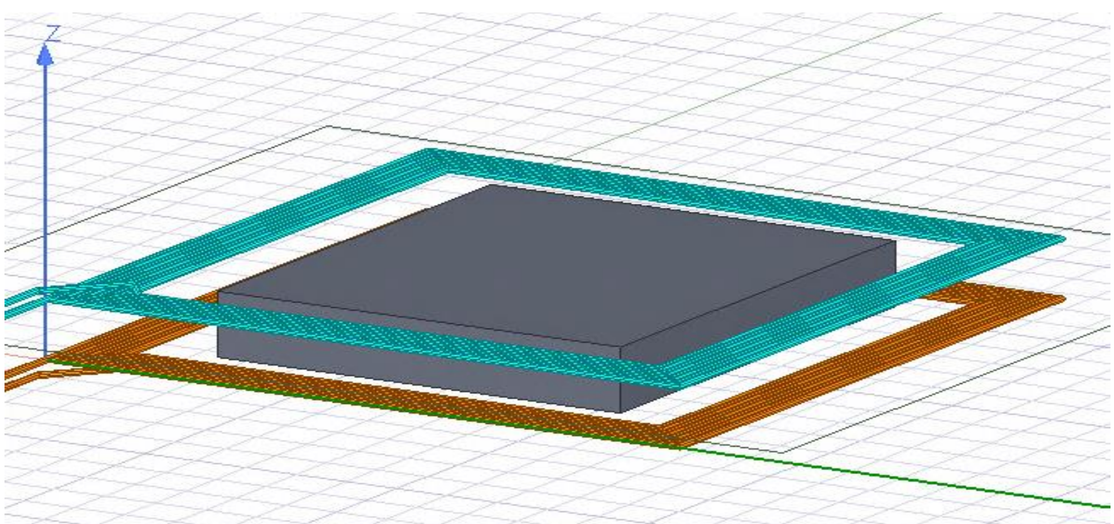



Figure 3-3 One-to-One Air Coils with a Core ANSYS Maxwell Design

The one-to-one air coils with a core ANSYS Maxwell magnetic field is shown in Figure 3-4.

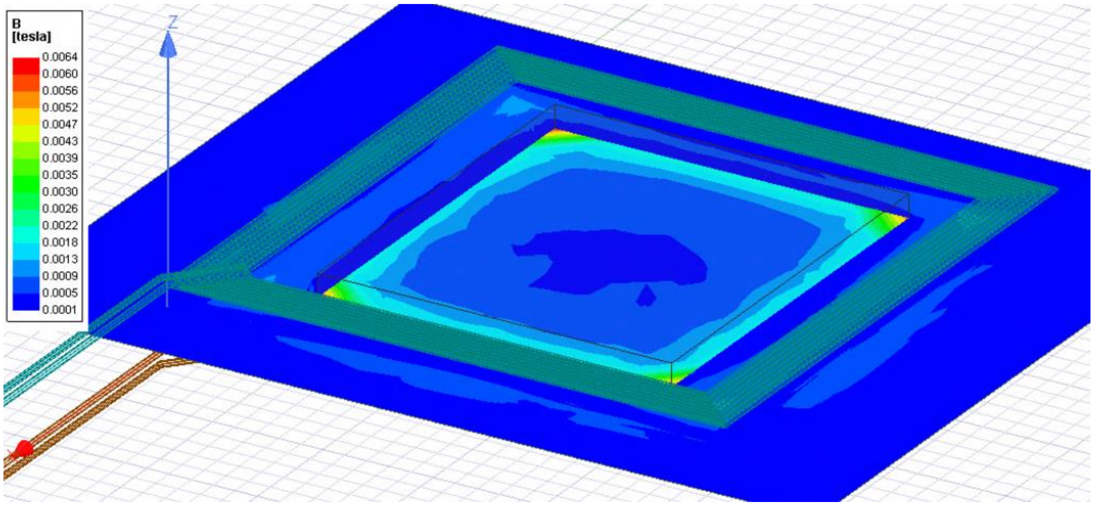



Figure 3-4 One-to-One Air Coils with a Core ANSYS Maxwell Magnetic Field

The one-to-one air coils with a core ANSYS Maxwell coupling coefficient simulation data is shown in Appendix O. The one-to-one air coils with a core load vs voltage graph is shown in Figure 3-5.

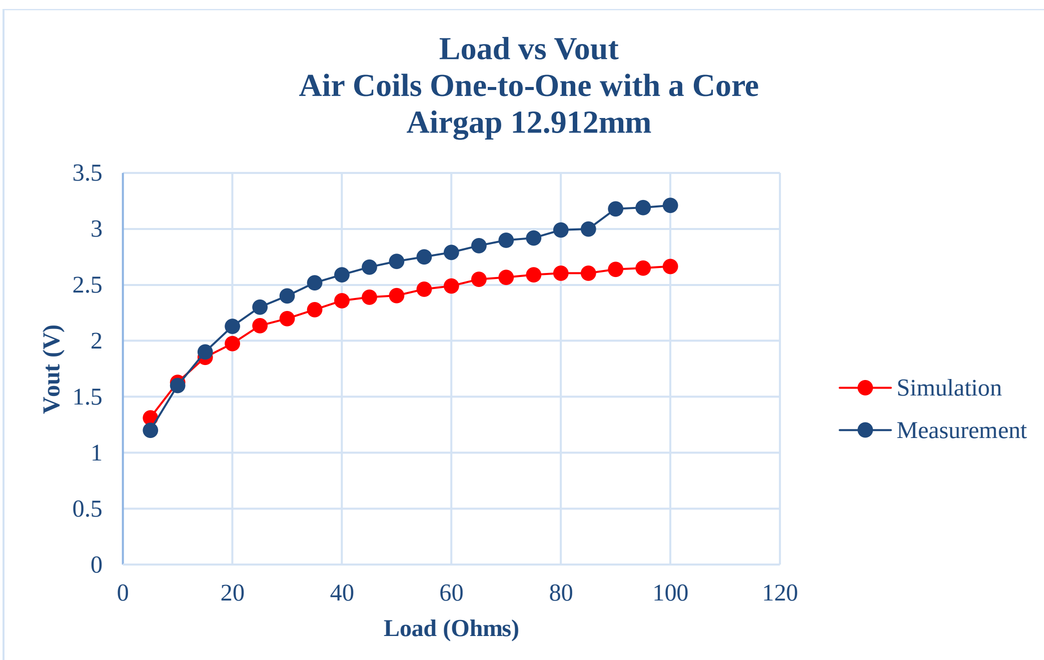



Figure 3-5 One-to-One Air Coils with a Core Load vs Voltage

The graphs were similarly increasing in a semi exponential way. The measurements show higher values than the simulation from 40 Ohms to 100 Ohms. The maximum values were 3.21 volts for the real values and 2.67 volts for the simulation. The numerical data is shown in APPENDIX P. The one-to-one air coils with a core load vs efficiency graph is shown in Figure 3-6.

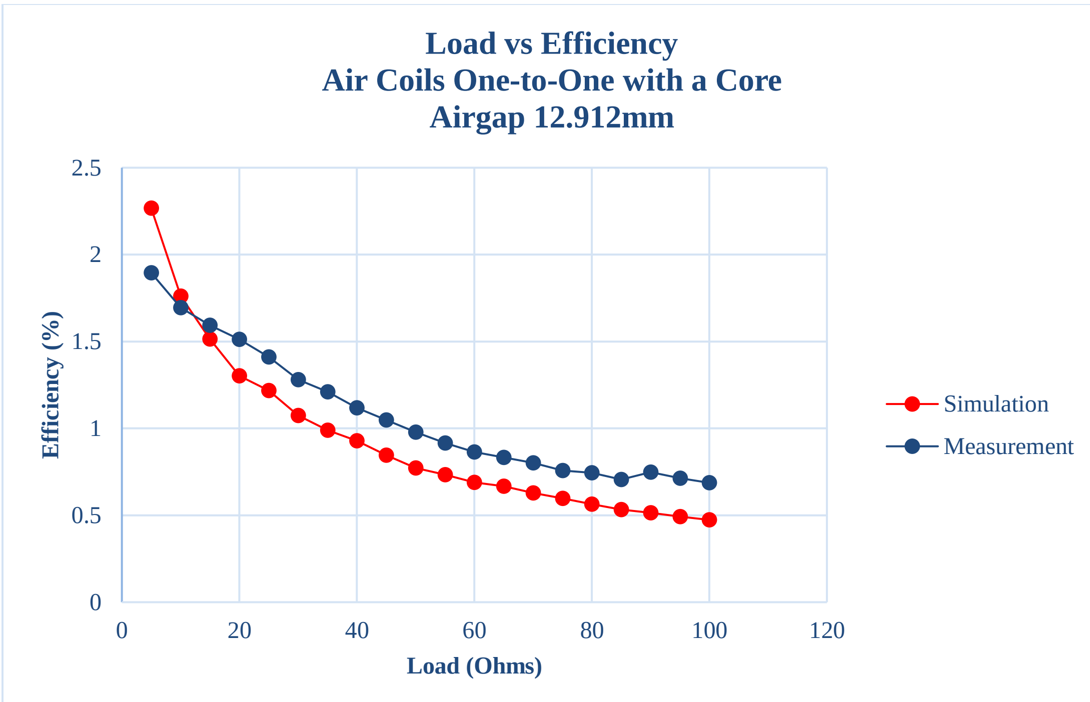



Figure 3-6 One-to-One Air Coils with a Core Load vs Efficiency

The graphs were similar. However, the simulation showed higher values from 5 Ohms to 10 Ohms, and the measurement values were higher than the simulation values from 10 Ohms to 100 Ohms. The maximum values were 1.894 % for the measurements and 2.266 % for the simulation. The numerical data is shown in APPENDIX P. The one-to-one air coils with two cores is shown in Figure 3-7.

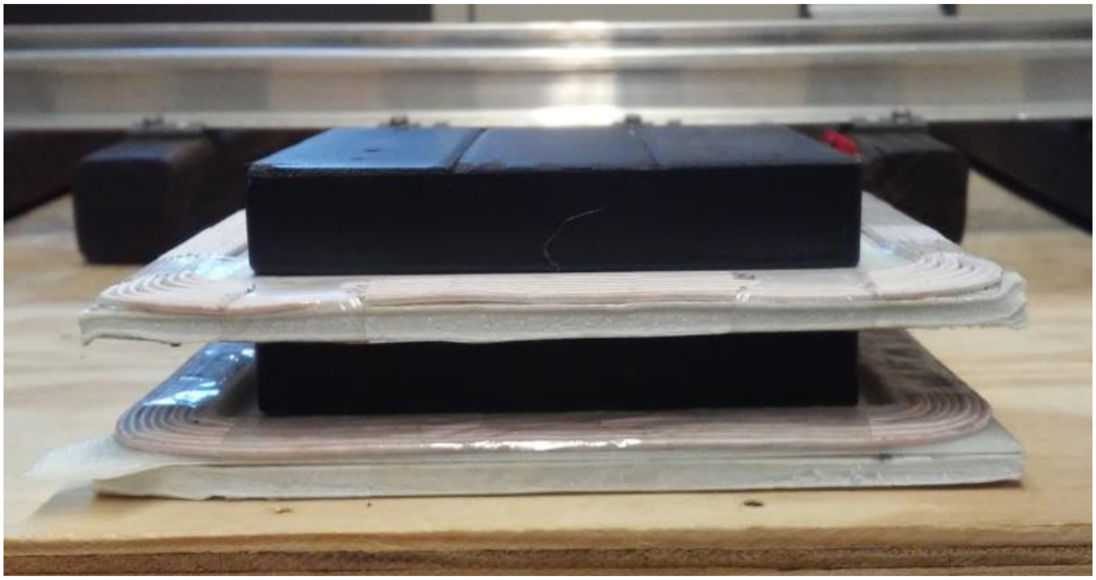


Figure 3-7 One-to-One Air Coils with Two Cores

The one-to-one air coils with two cores ANSYS Maxwell design is shown in Figure 3-8.

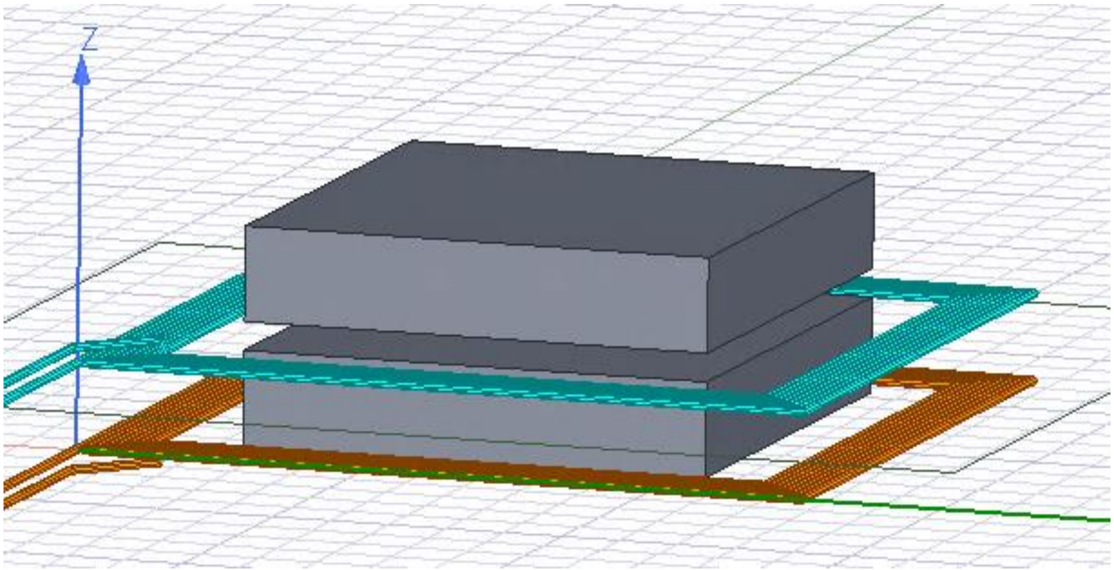



Figure 3-8 One-to-One Air Coils with Two Cores ANSYS Maxwell Design

The one-to-one air coils with two core ANSYS Maxwell magnetic field is shown in Figure 3-9.

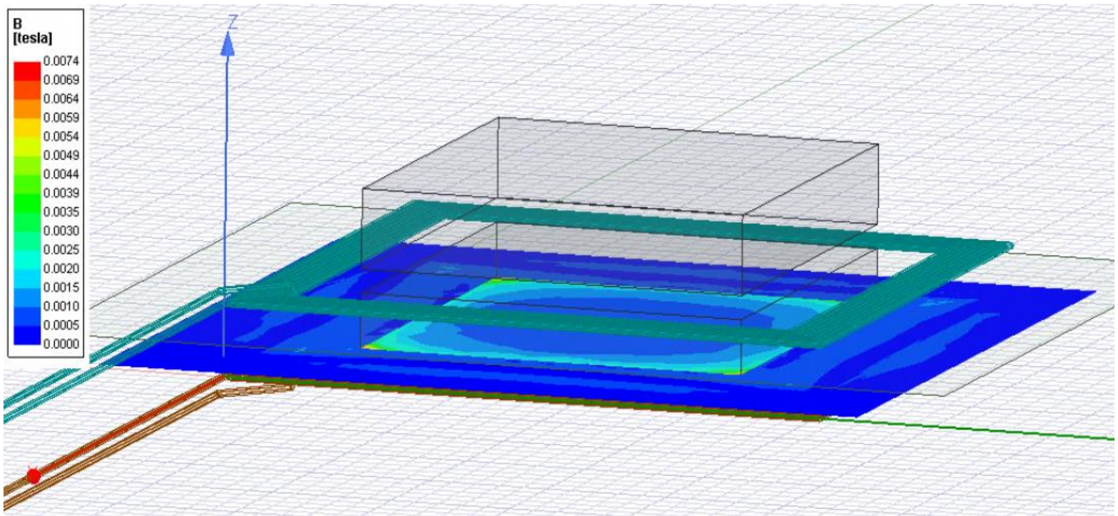



Figure 3-9 One-to-One Air Coils with Two Cores ANSYS Maxwell Magnetic Field

The one-to-one air coils with two cores ANSYS Maxwell coupling coefficient simulation data is shown in Appendix O. The one-to-one air coils with two cores load vs voltage graph is shown in Figure 3-10.

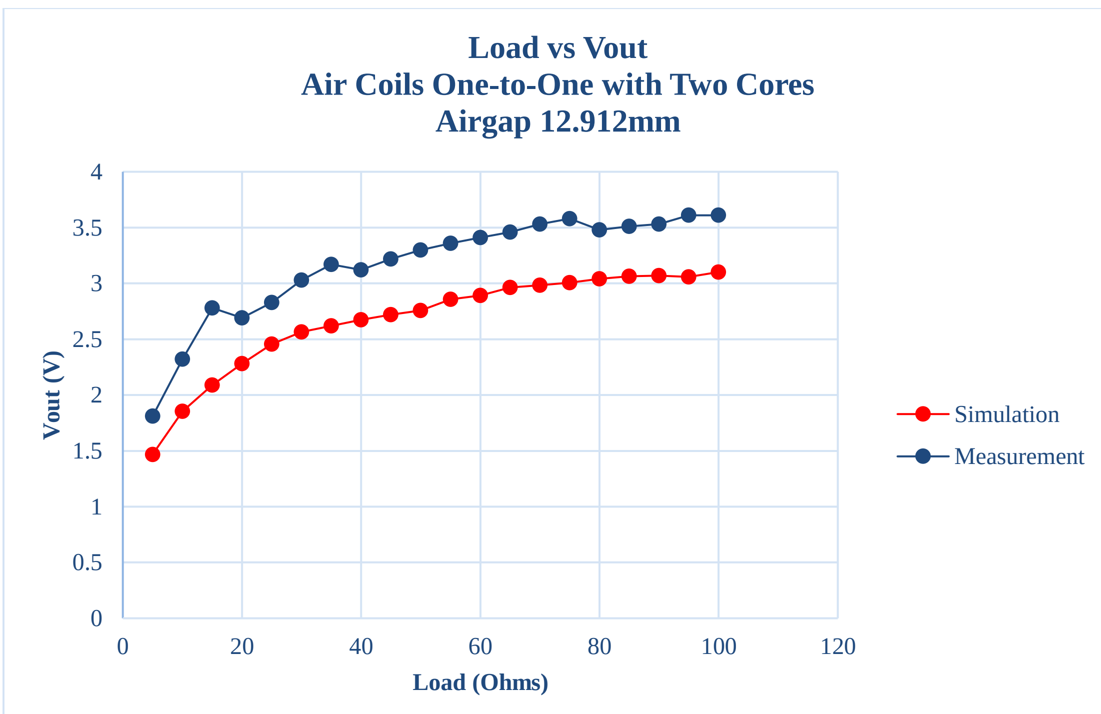



Figure 3-10 One-to-One Air Coils with Two Cores Load vs Voltage

The simulation and measurement graphs were similar. However, the measurements show higher values. The maximum values were 3.61 volts for actual measurements and 3.1 volts for the simulation. The numerical data is shown in APPENDIX Q. The one-to-one air coils with two cores load vs efficiency graph is shown in Figure 3-11.

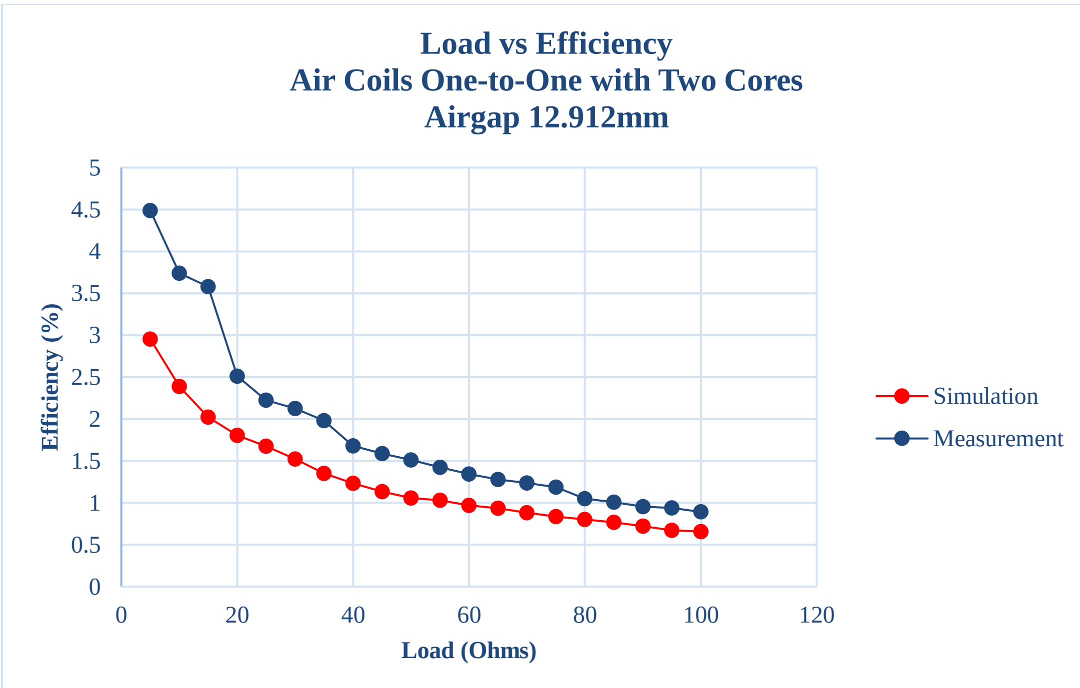



Figure 3-11 One-to-One Air Coils with Two Cores Load vs Efficiency

The graphs were similar. However, the measurement values were higher than the simulation values. The maximum values were 4.49 % for measurements and 2.95 % for simulation. The numerical data can be found in APPENDIX Q.

## 3.3 Air Coils with Added Cores Four-to-One

The four-to-one configuration was also tested. The four-to-one configuration had two main positions the peak position and the steady position. Load tests were conducted for the peak position and steady position at different airgap distances. The number of cores also varied. The four-to-one air coils with a core at 20 mm is shown in Figure 3-12.

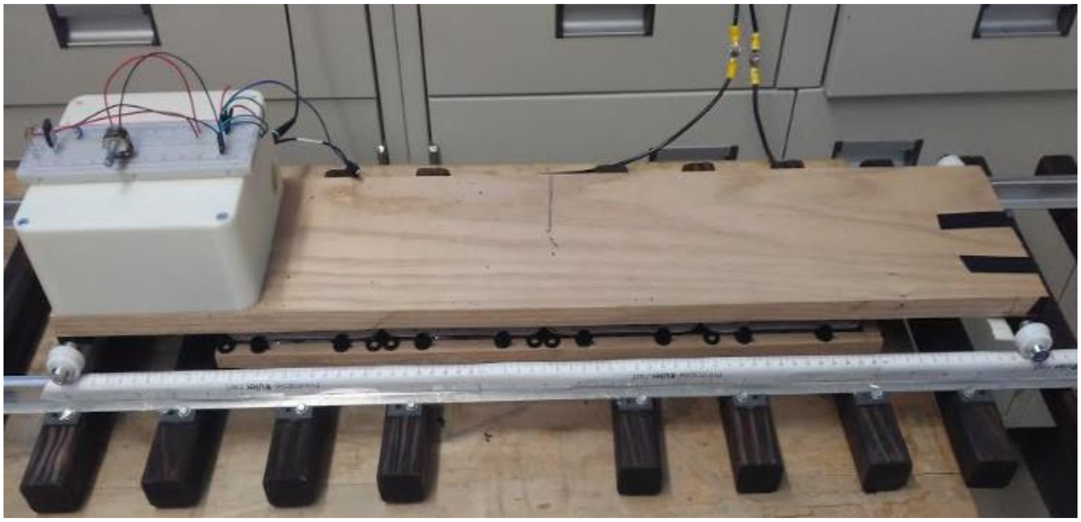


Figure 3-12 Four-to-One Air Coils with a Core at 20 mm

The cores were positioned on top of the four transmitter coils. The set up is shown in Figure 3-13

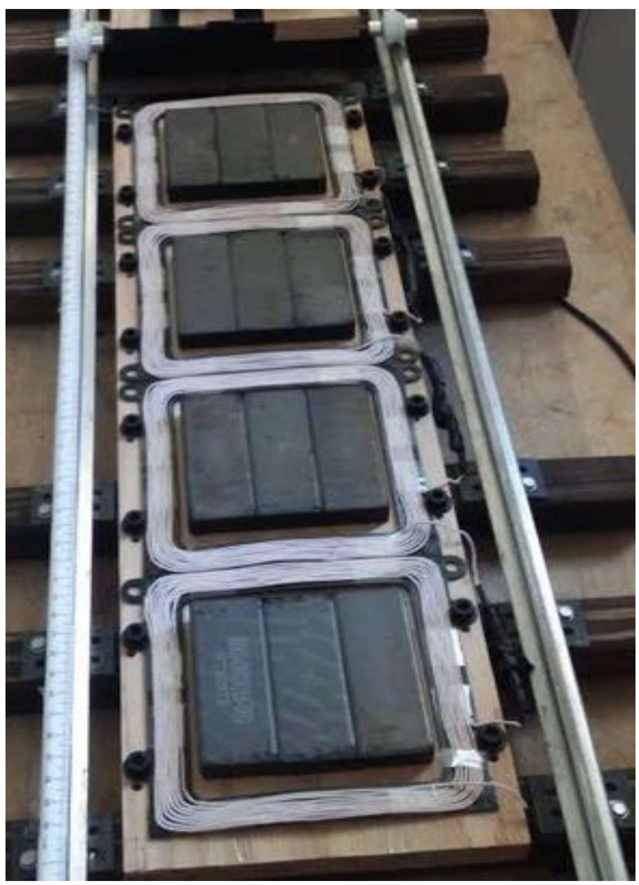


Figure 3-13 Cores Positioned on Transmitter Coils

The four-to-one air coils with a core peak position at 20 mm height ANSYS Maxwell design is shown in Figure 3-14.

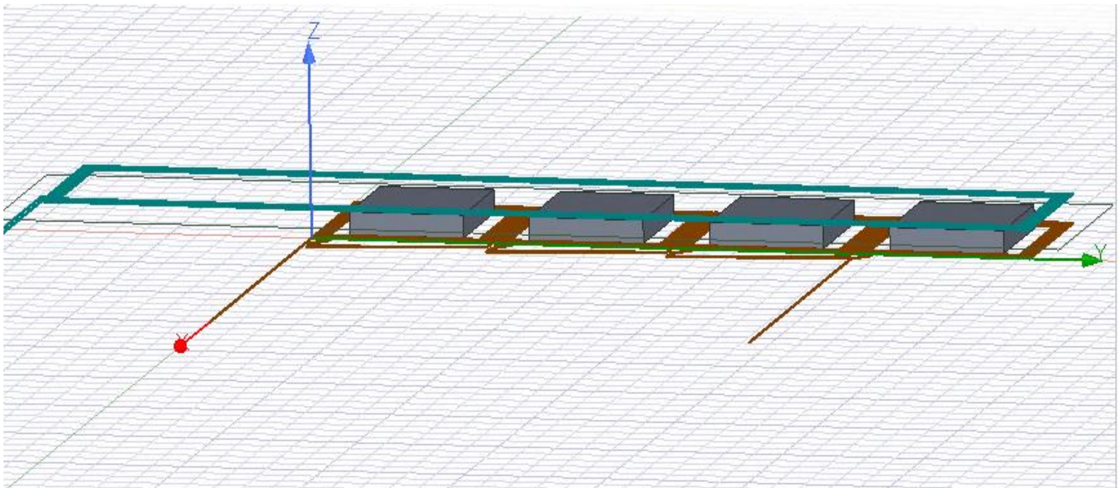



Figure 3-14 Four-to-One Air Coils with a Core Peak Position at 20 mm Height ANSYS Maxwell Design

The four-to-one air coils with a core peak position at 20 mm height ANSYS Maxwell electromagnetic simulation is shown in Figure 3-15.

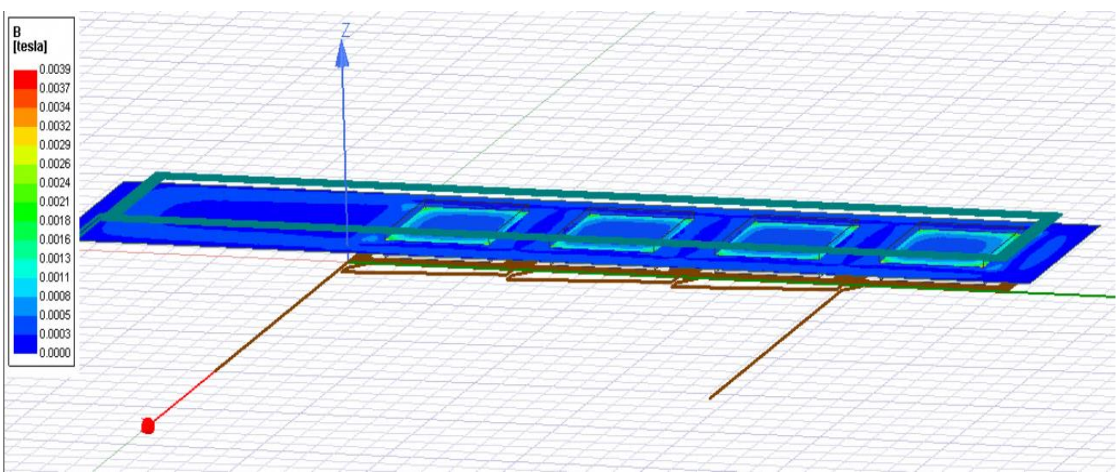



Figure 3-15 Four-to-One Air Coils with a Core Peak Position at 20 mm Height ANSYS Maxwell Electromagnetic Simulation

The coupling coefficient data for the peak position 20 mm airgap one core is shown in APPENDIX R.

The four-to-one air coils with a core at 20 mm load vs voltage graph is shown in Figure 3-16.

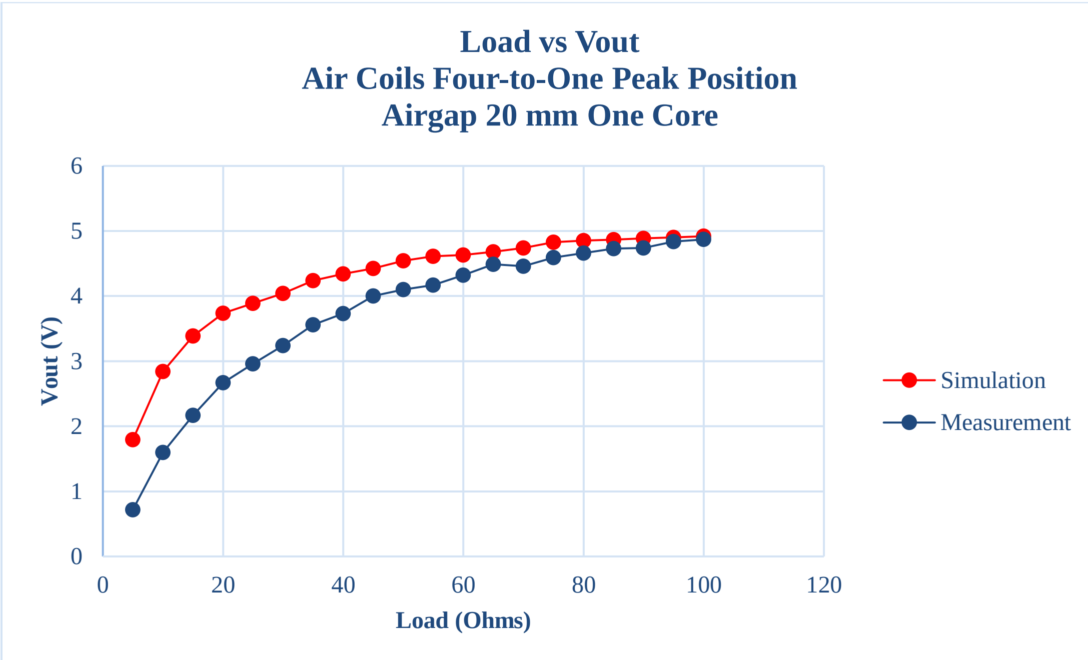



Figure 3-16 Four-to-One Air Coils with a Core at 20 mm Load vs Voltage

The test was done at 20 mm vertical separation. The graphs were similar from 100 Ohms to 45 Ohms. However, the simulation was higher than the measurement from 45 Ohms to 5 Ohms. The maximum vales were 4.87 volts for the measurements and 4.92 volts for the simulation. The numerical data can be found in APPENDIX S. The four-to-one air coils with a core at 20 mm load vs efficiency graph is shown in Figure 3-17.

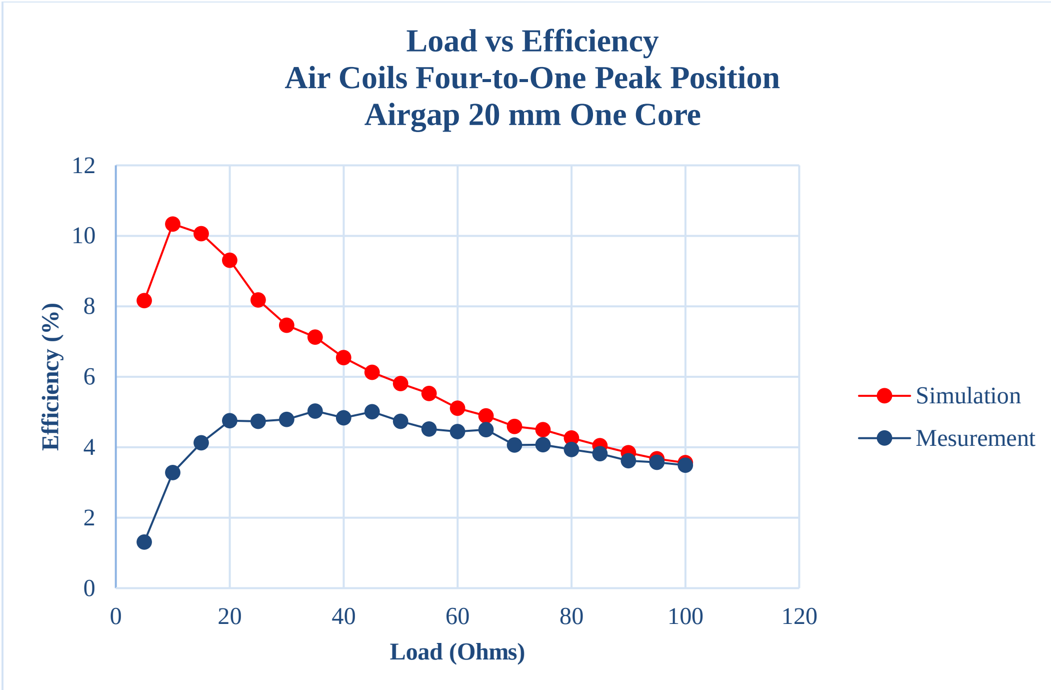



Figure 3-17 four-to-one air coils with a core at 20 mm load vs efficiency

The test was done at 20 mm vertical separation. The graphs were measurement and simulation graphs were similar from 100 Ohms to 50 Ohms. However, the simulation showed higher values from 50 Ohms to 5 Ohms. The maximum values were 5.03 % for the measurement and 10.34 % for the simulation. The numerical data is shown in APPENDIX S. The system was tested with two core levels as well; one core level on the transmitter coils and one on the receiver coil. The four-to-one air coils four-to-one with two core levels are shown in Figure 3-18.

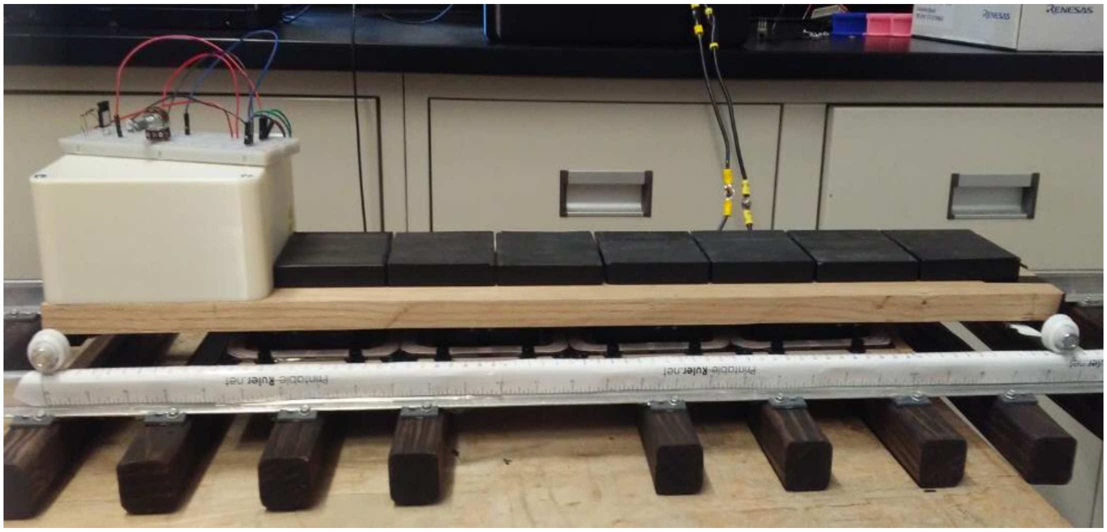


Figure 3-18 Four-to-One Air Coils with Two Core

The core positions are shown better in Figure 3-19

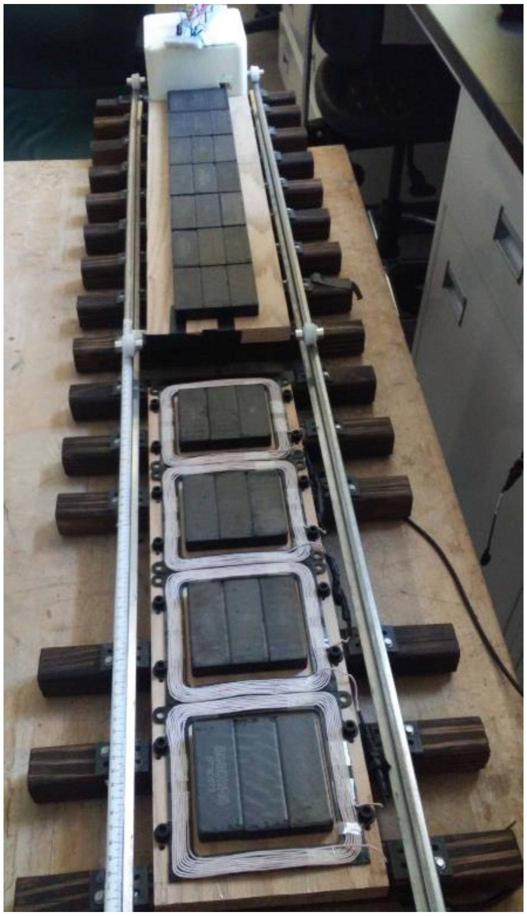


Figure 3-19 Core Positions for Air Coils Four-to-One with Two Levels

The four-to-one air coils with two cores peak position at 20 mm height ANSYS Maxwell design is shown in Figure 3-20.

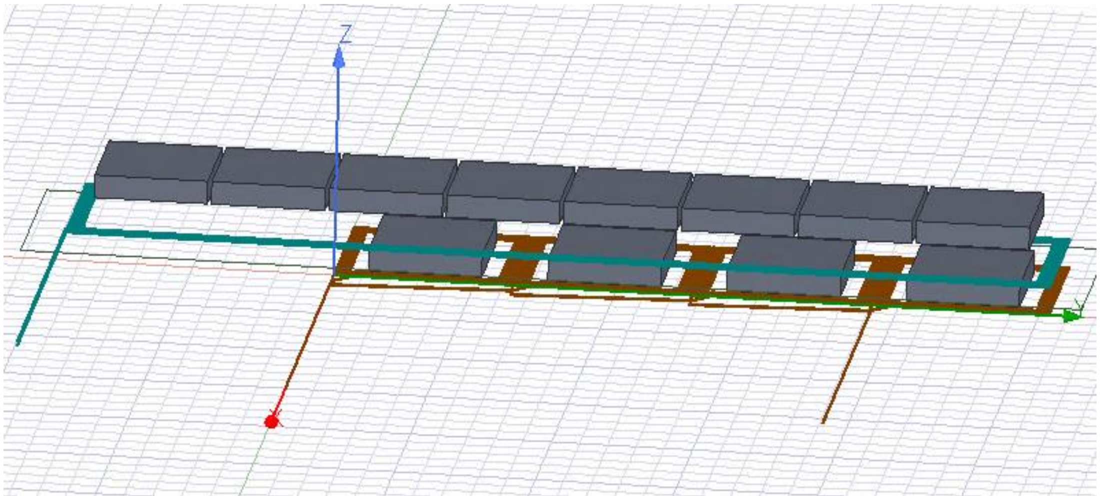



Figure 3-20 Four-to-One Air Coils with Two Cores Peak Position at 20 mm Height ANSYS Maxwell Design

The four-to-one air coils with two cores peak position at 20 mm height ANSYS Maxwell electromagnetic simulation is shown in Figure 3-21.

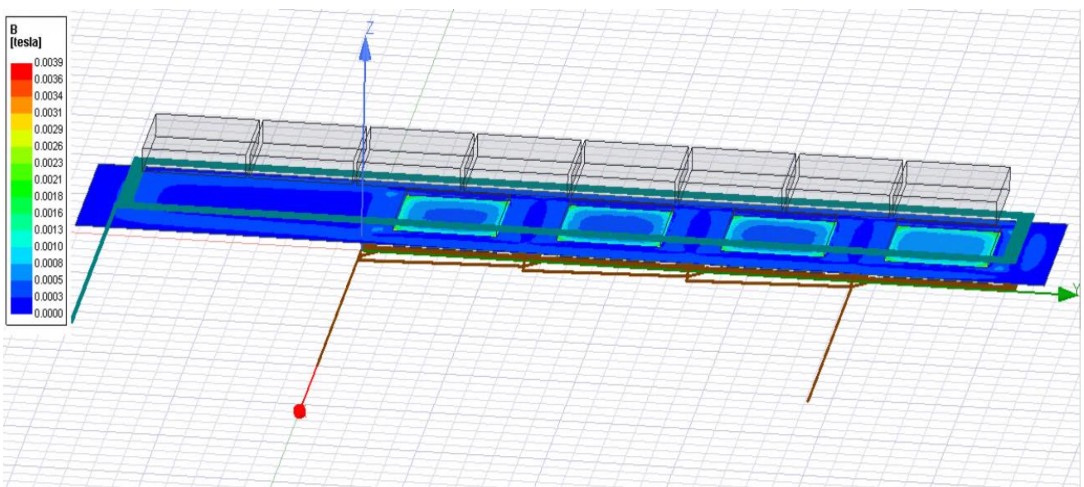



Figure 3-21 Four-to-One Air Coils with Two Cores Peak Position at 20 mm Height ANSYS Maxwell Electromagnetic Simulation

The simulation numerical data is shown in APPENDIX R. The four-to-one air coils with two cores peak position at 20 mm height load vs voltage graph is shown in Figure 3-22.

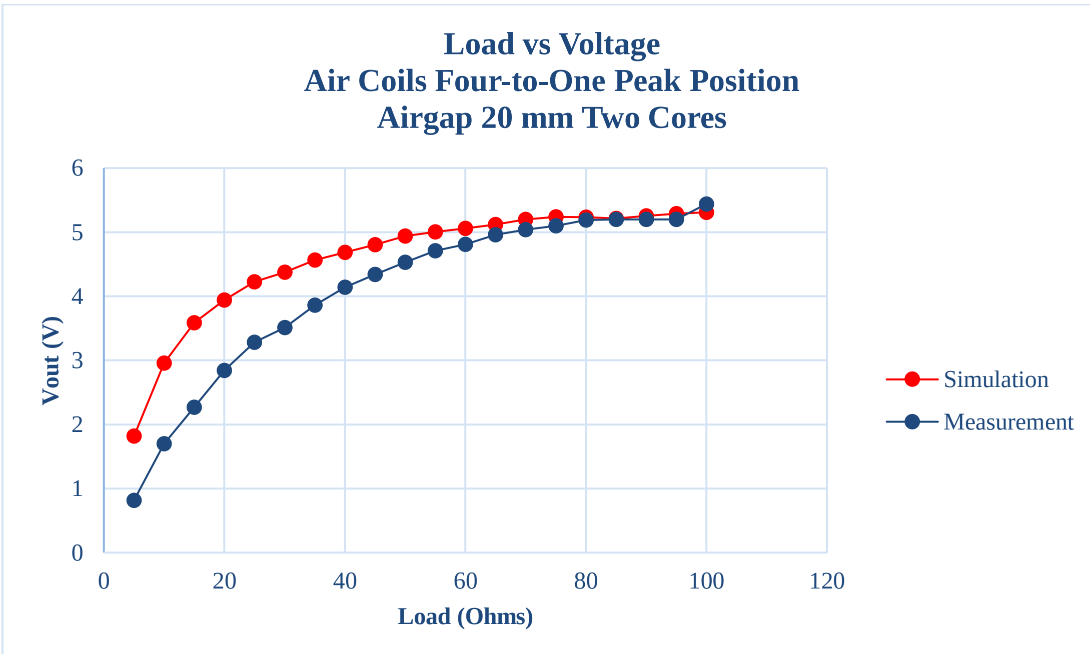



Figure 3-22 Four-to-One Air Coils with Two Cores Peak Position at 20 mm Height Load vs Voltage

The test was done at 20 mm vertical separation. The graphs were similar. Both had inverse exponential increasing curves. The simulation showed higher values than the measurements from 5 Ohms to 35 Ohms. The maximum values were 5.44 volts for the measurement and 5.31 volts for the simulation. The four-to-one air coils with two cores peak position at 20 mm height Load vs efficiency graph is shown in Figure 3-23. The numerical data is shown in APPENDIX T.

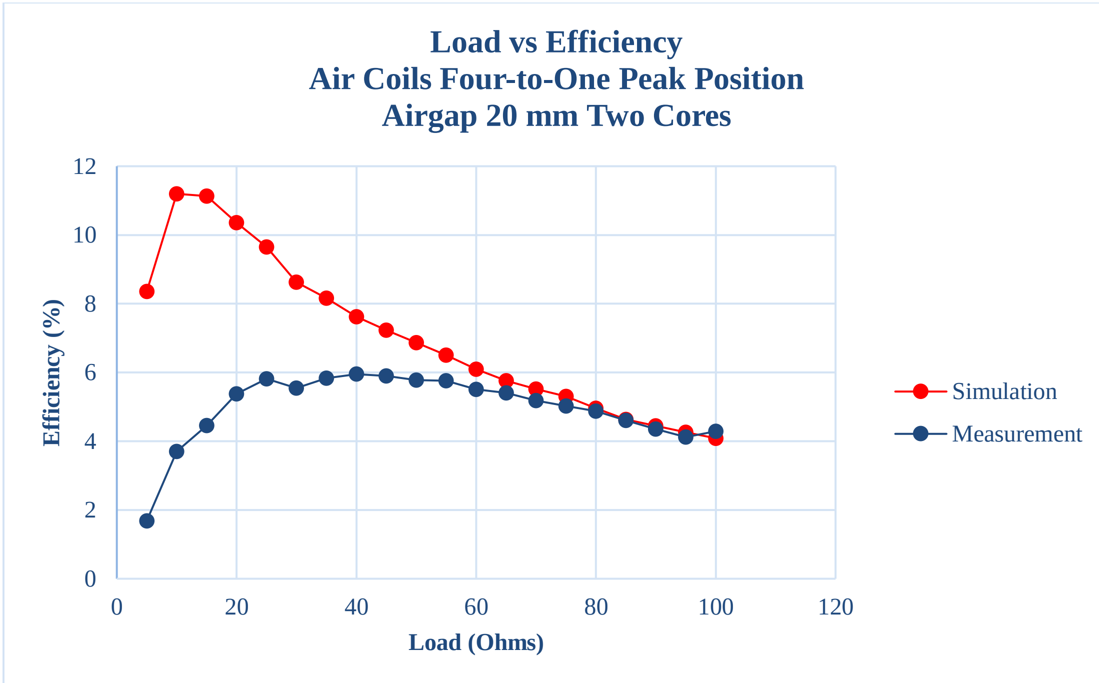



Figure 3-23 Four-to-One Air Coils with Two Cores Peak Position at 20 mm Height Load vs Efficiency

The test was done at 20 mm vertical separation. The graphs were similar from 100 Ohms to 50 Ohms. However, the simulation showed higher values from 50 Ohms to 5 Ohms. The simulation showed an increased efficiency due to an unrealistic voltage source. The maximum values were 11.19 % for the simulation and 5.9 % for the measurements. The numerical data is shown in APPENDIX T. The Load tests were done for the steady position as well. The four-to-one air coils with a core steady position at 20 mm height ANSYS Maxwell design is shown in Figure 3-24.

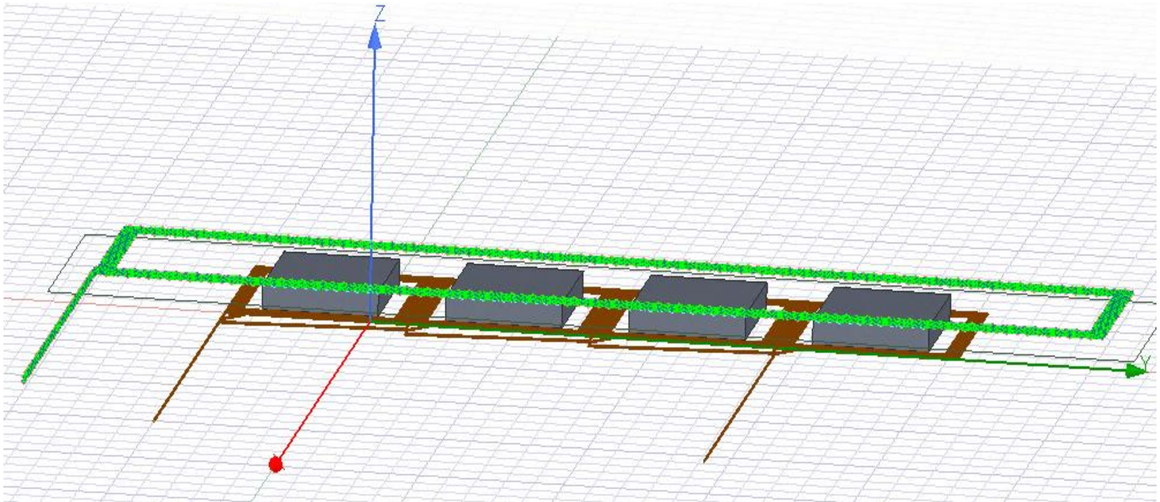



Figure 3-24 Four-to-One Air Coils with a Core Steady Position at 20 mm Height ANSYS Maxwell Design

The four-to-one air coils with a core steady position at 20 mm height ANSYS Maxwell electromagnetic simulation is shown in Figure 3-25.

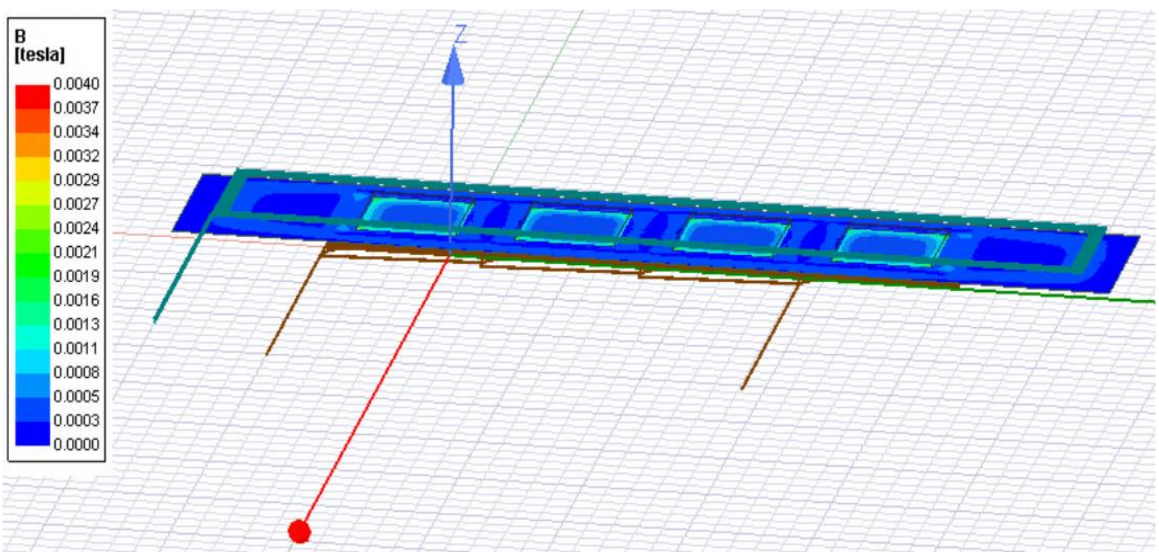



Figure 3-25 Four-to-One Air Coils with a Core Steady Position at 20 mm Height ANSYS Maxwell Electromagnetic Simulation

The four-to-one air coils with a core steady position at 20 mm height load vs voltage graph is shown in Figure 3-26.

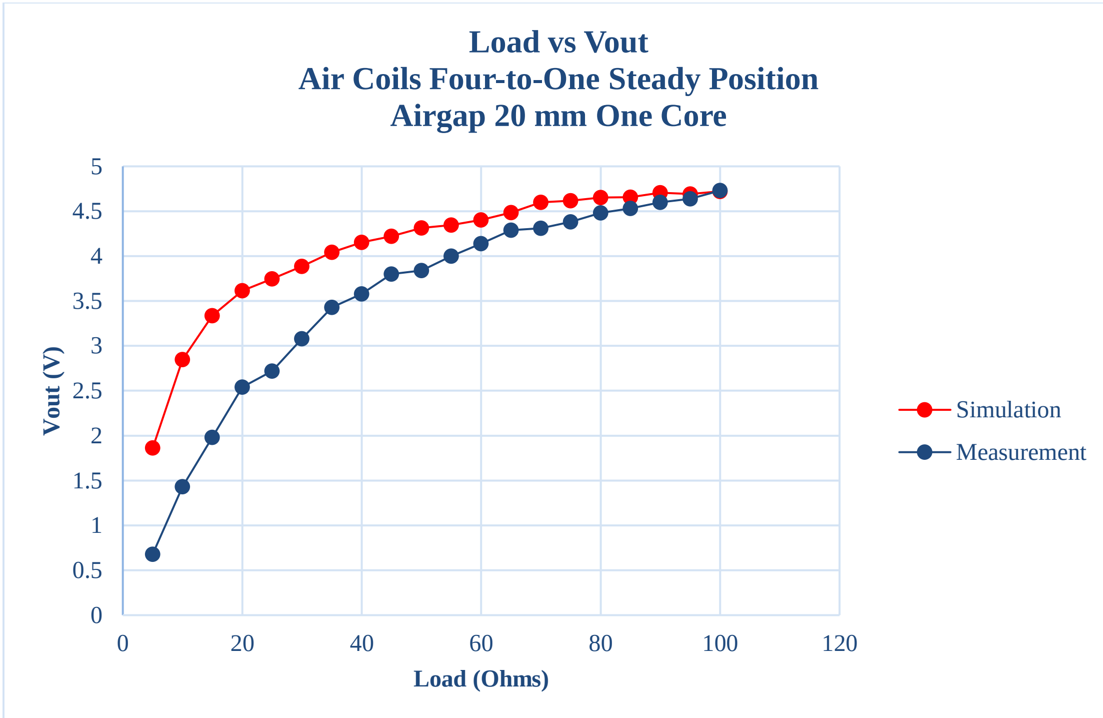



Figure 3-26 Four-to-One Air Coils with a Core Steady Position at 20 mm Height Load vs Voltage

The test was done at 20 mm vertical separation. The graphs were similar from 100 Ohms to 45 Ohms. The Simulation showed higher values from 45 Ohms to 5 Ohms. The maximum values were 4.73 volts for the measurements and 4.72 volts for the simulation. The numerical data is shown in APPENDIX U. The four-to-one air coils with a core steady position at 20 mm height load vs efficiency graph is shown in Figure 3-27.

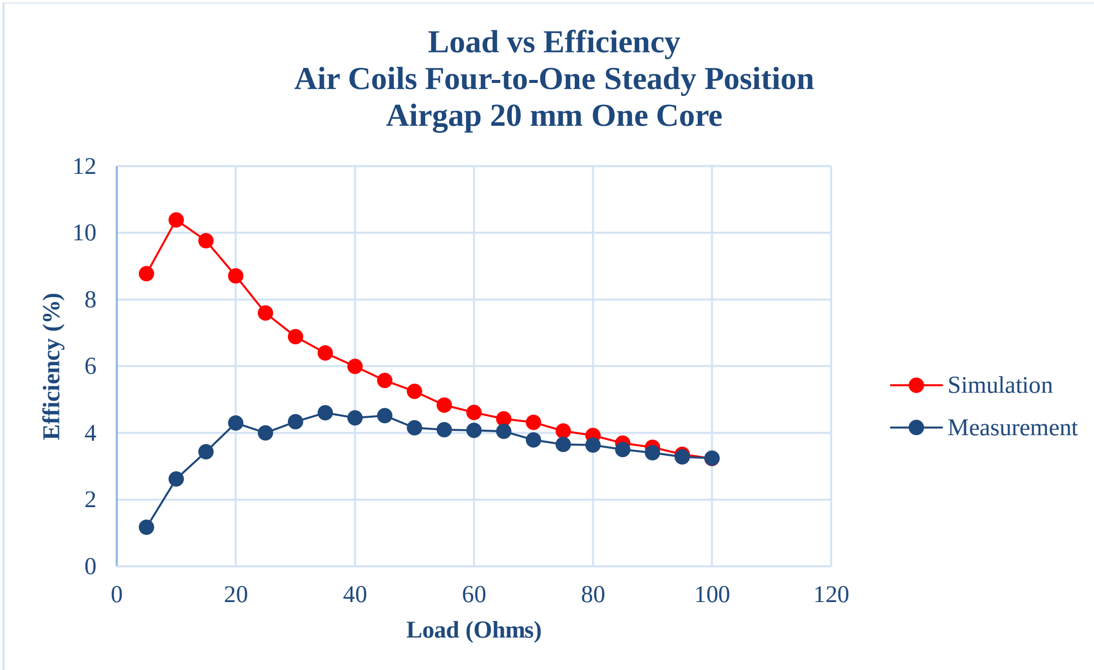



Figure 3-27 Four-to-One Air Coils with a Core Steady Position at 20 mm Height Load vs Efficiency

The test was done at 20 mm vertical separation. The graphs were similar from 100 Ohms to 45 Ohms. The simulation was higher from45 Ohms to 5 Ohms. The simulation large increase was due to an unrealistic almost ideal source. The maximum values were 4.6 % for the measurements and 10.39 % for the simulation. The numerical data is shown in APPENDIX U. The four-to-one air coils with two cores steady position at 20 mm height ANSYS Maxwell design is shown in Figure 3-28.

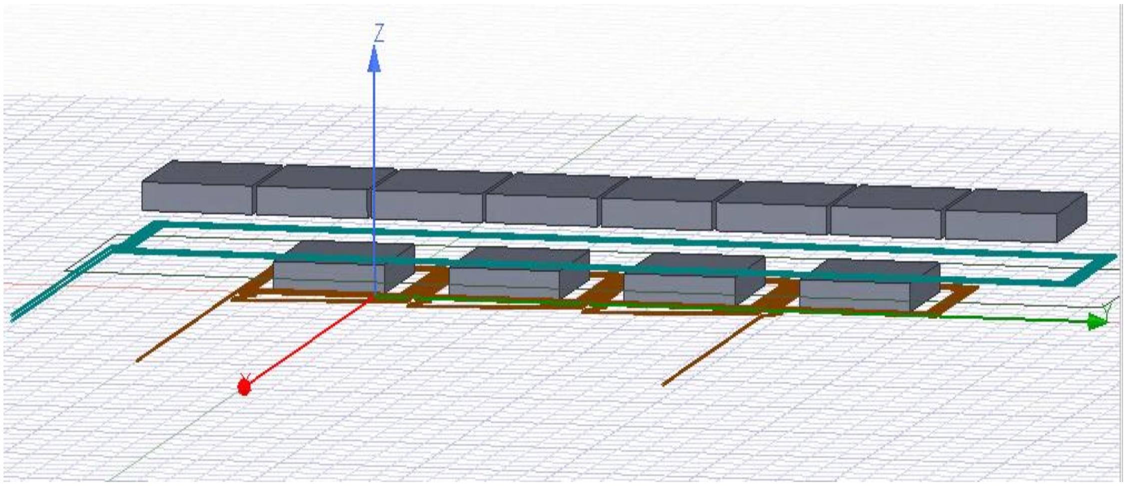



Figure 3-28 Four-to-One Air Coils with Two Cores Steady Position at 20 mm Height ANSYS Maxwell Design

The four-to-one air coils with two cores steady position at 20 mm height ANSYS Maxwell electromagnetic simulation is shown in Figure 3-29.

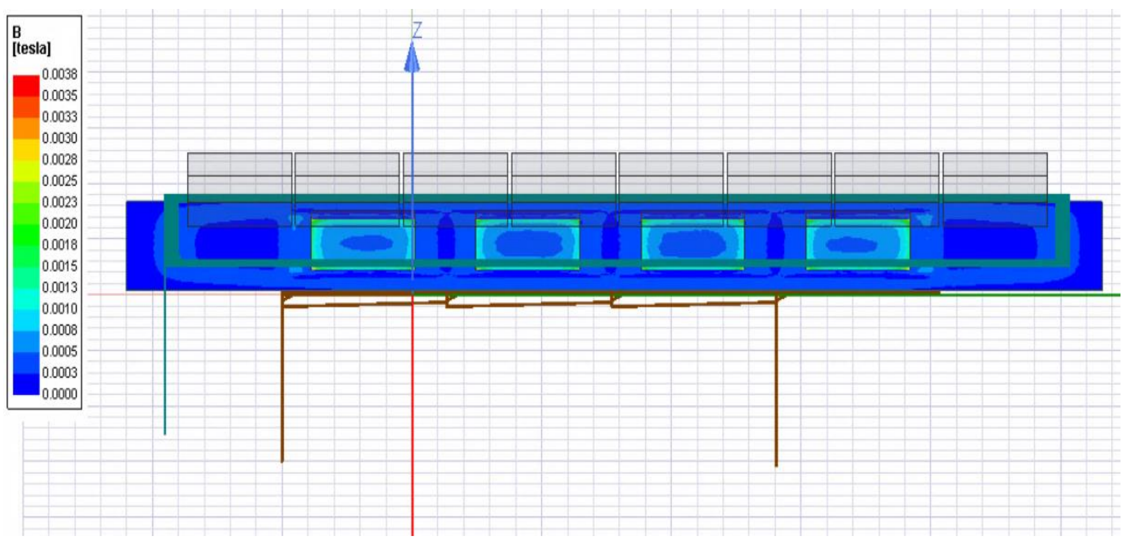



Figure 3-29 Four-to-One Air Coils with Two Cores Steady Position at 20 mm Height ANSYS Maxwell Electromagnetic Simulation

The four-to-one air coils with two cores steady position at 20 mm height load vs voltage graph is shown in Figure 3-30.

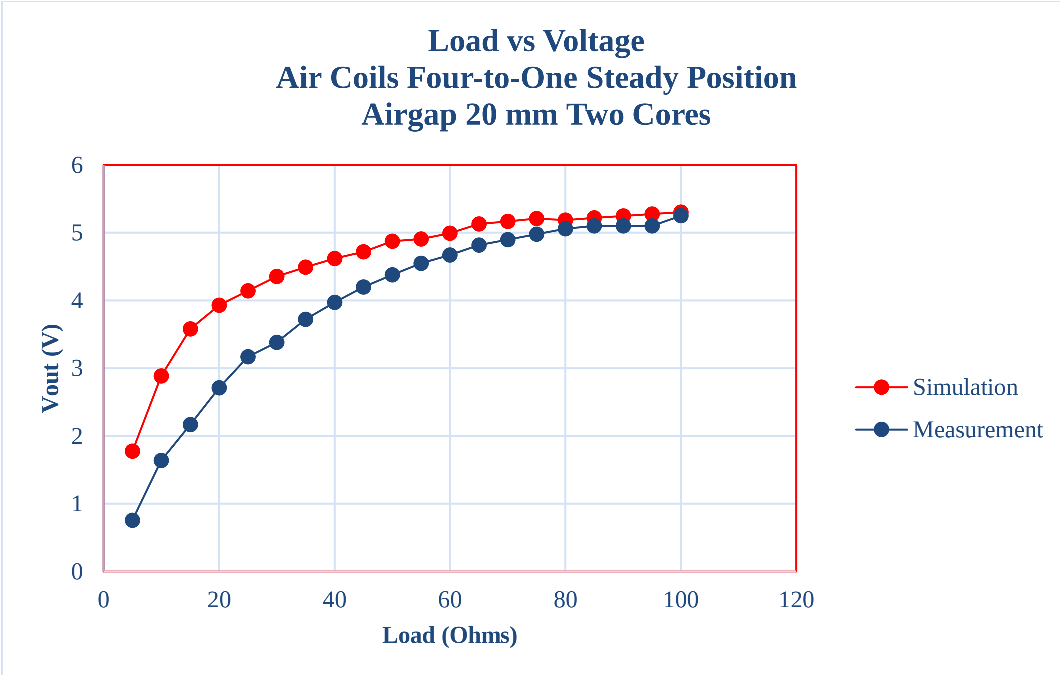



Figure 3-30 Four-to-One Air Coils with Two Cores Steady Position at 20 mm Height Load vs Voltage

The test was done at 20 mm vertical separation. The graphs were similar both had a semi exponential increase. The values were similar from 100 Ohms to 40 Ohms; the simulation was higher from 40 Ohms to 5 Ohms. The maximum values were 5.25 volts for the measurements and 5.3 volts for the simulation. The numerical data is shown in APPENDIX V. The four-to-one air coils with two cores steady position at 20 mm height load vs efficiency graph is shown in Figure 3-31.

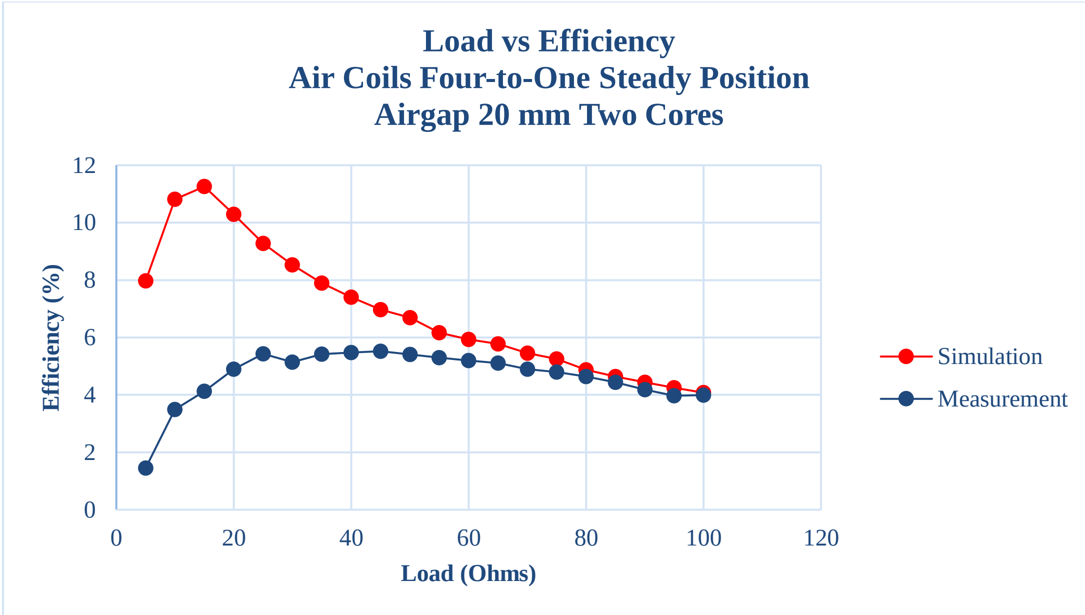



Figure 3-31 Four-to-One Air Coils with Two Cores Steady Position at 20 mm Height Load vs Efficiency

The test was done at 20 mm vertical separation. The graphs were similar from 100 Ohms to 45 Ohms. The simulation values increased from 45 Ohms to 5 Ohms. The simulation values increase was due to an unrealistic source. The maximum values were 5.52 % for measurements and 11.26 % for simulation. The numerical data is shown in APPENDIX V. the system was tested with a different ferrite core setting where the cores were positioned on top of the other. As a result, the airgap increased to 27.2 mm. The four-to-one air coils with two cores at 27.2 mm height is shown in Figure 3-32.

Figure 3-32 Four-to-One Air Coils with Two Cores at 27.2 mm Height

For this configuration the transmitter coils had a ferrite block on top as in previous tests, and the receiver had a core at the bottom. The receiver ferrite cores configuration is shown in Figure 3-33.

Figure 3-33 Receiver Ferrite Cores Configuration

The four-to-one air coils with two cores peak position at 27.2 mm height ANSYS Maxwell design is shown in Figure 3-34.

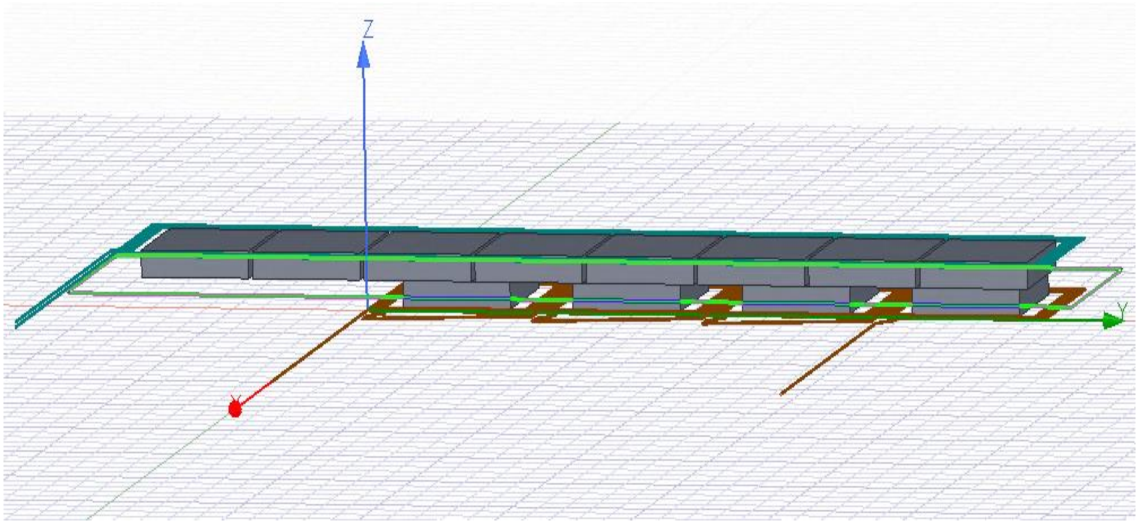



Figure 3-34 Four-to-One Air Coils with Two Cores Peak Position at 27.2 mm Height ANSYS Maxwell Design

The four-to-one air coils with two cores peak position at 27.2 mm height ANSYS Maxwell electromagnetic simulation is shown in Figure 3-35.

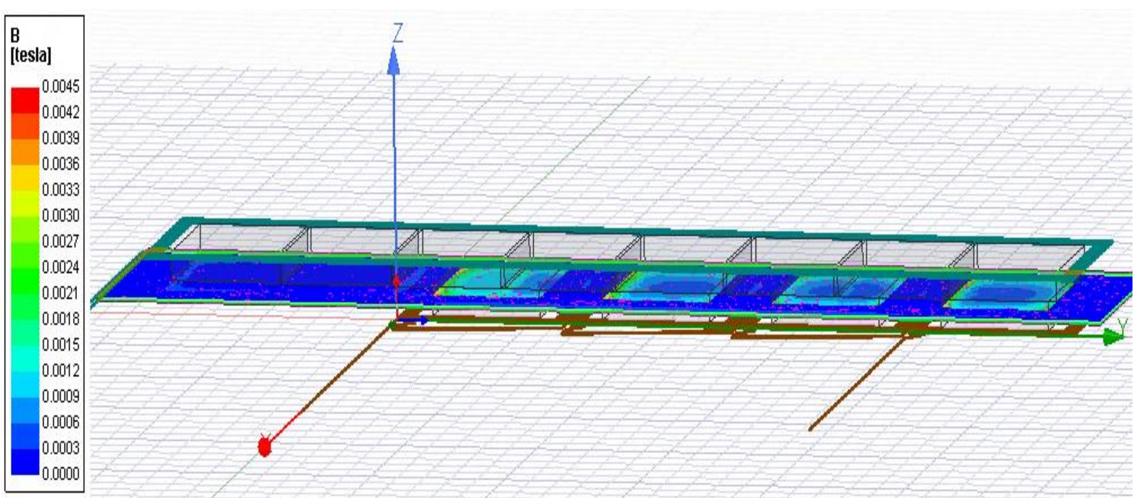



Figure 3-35 Four-to-One Air Coils with Two Cores Peak Position at 27.2 mm Height ANSYS Maxwell Electromagnetic Simulation

The four-to-one air coils with two cores peak position at 27.2 mm height load vs voltage graph is shown in Figure 3-36.

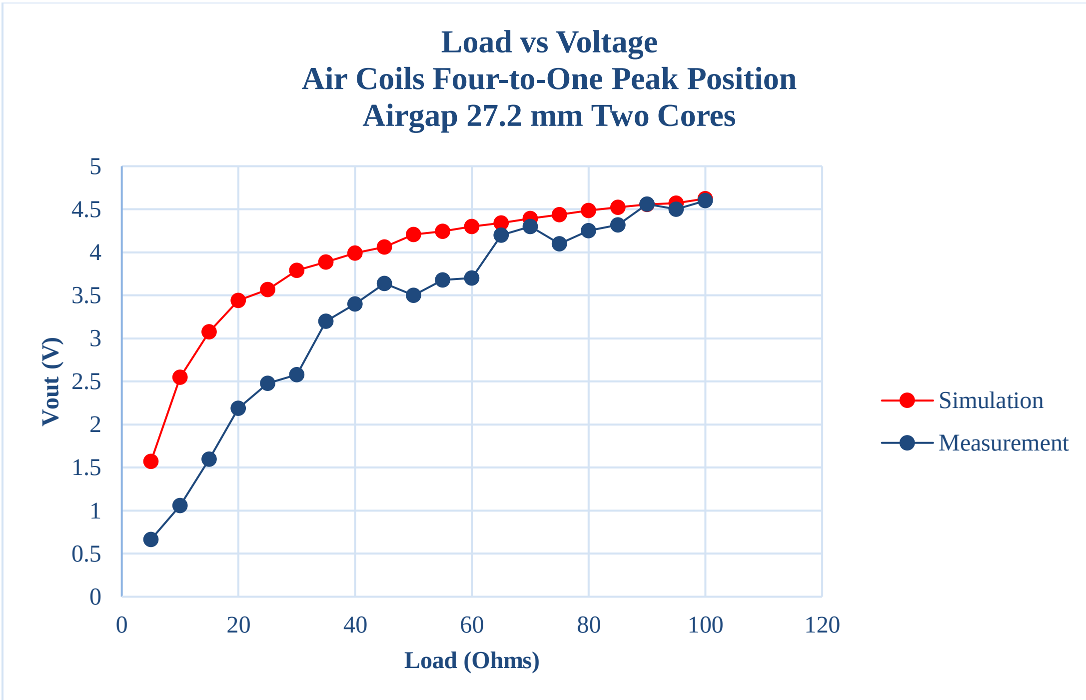



Figure 3-36 Four-to-One Air Coils with Two Cores Peak Position at 27.2 mm Height Load vs Voltage

The test was done at 27.2 mm vertical separation. The graphs were similar both show a semi exponential increase. The simulation graph was uniform, and the measurement graph was uneven. The maximum values were 4.6 volts for the measurements and 4.62 volts for the simulation. The numerical data is shown in APPENDIX W. The four-to-one air coils with two cores peak position at 27.2 mm height load vs efficiency graph is shown in Figure 3-37.

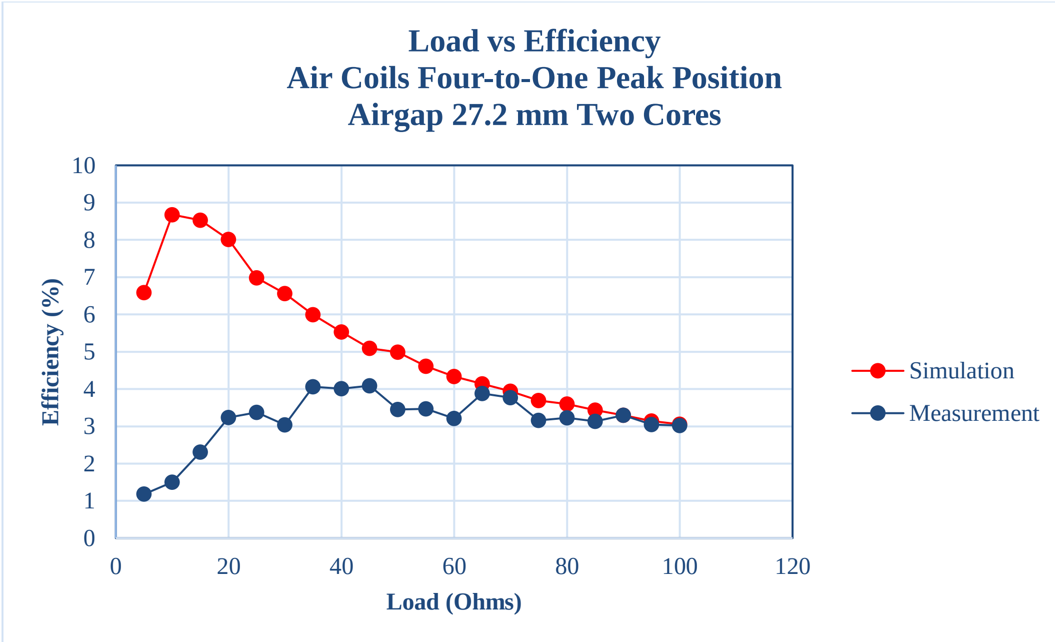



Figure 3-37 Four-to-One Air Coils with Two Cores Peak Position at 27.2 mm Height Load vs Efficiency

The test was done at 27.2 mm vertical separation. The graphs were similar from 40 Ohms to 100 Ohms. The simulation showed higher values from 5 Ohms to 40 Ohms. The simulation showed an increase because of an unrealistic source. The maximum values 4.09 % for the measurements and 8.68 % for the simulation. The numerical data is shown in APPENDIX W. The four-to-one air coils with two cores steady position at 27.2 mm height ANSYS Maxwell design is shown in Figure 3-38.

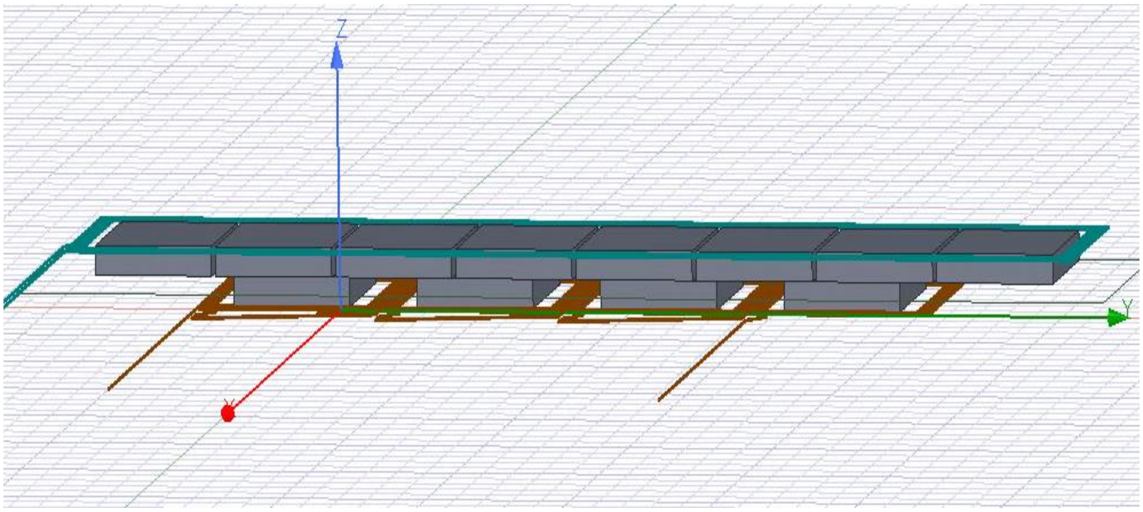


Figure 3-38 Four-to-One Air Coils with Two Cores Steady Position at 27.2 mm Height ANSYS Maxwell Design

The four-to-one air coils with two cores steady position at 27.2 mm height ANSYS Maxwell electromagnetic simulation is shown in Figure 3-39.

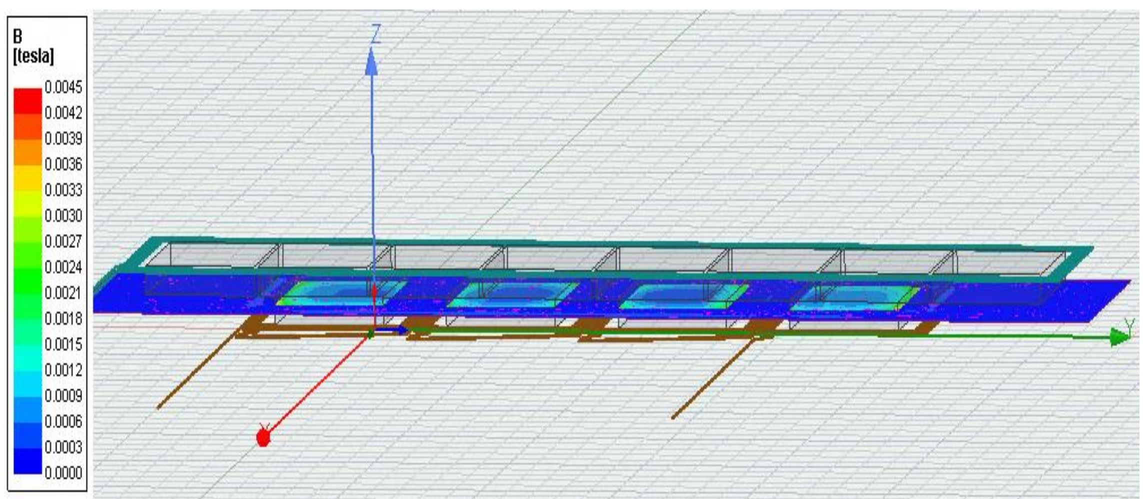



Figure 3-39 Four-to-One Air Coils with Two Cores Steady Position at 27.2 mm Height ANSYS Maxwell Electromagnetic Simulation

The four-to-one air coils with two cores steady position at 27.2 mm height load vs voltage graph is shown in Figure 3-40.

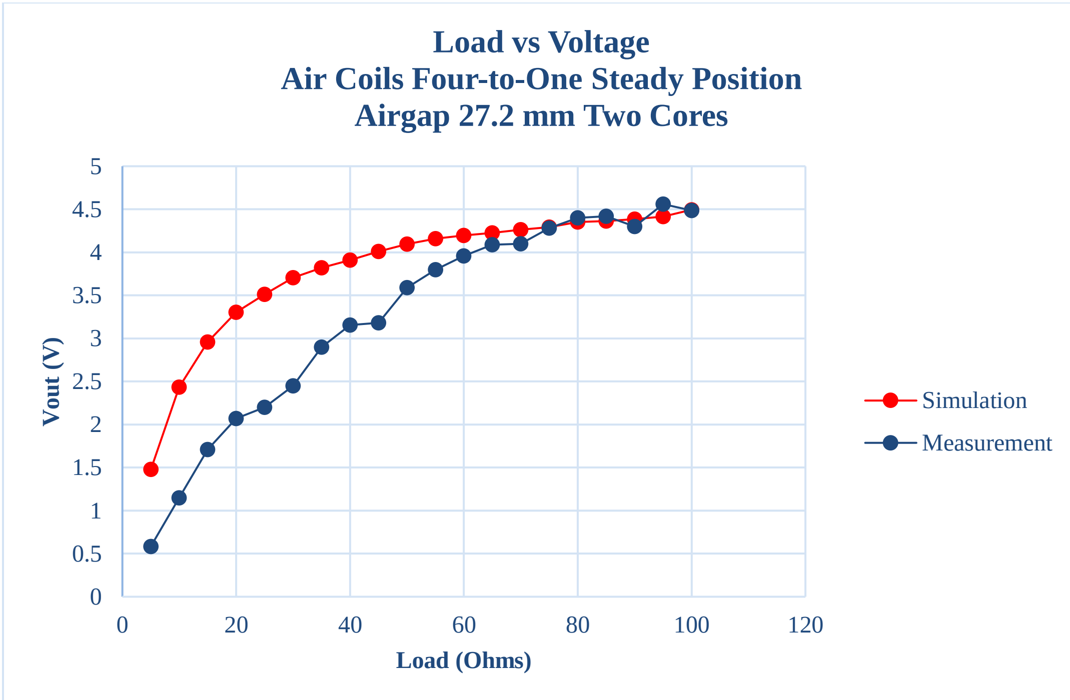



Figure 3-40 Four-to-One Air Coils with Two Cores Steady Position at 27.2 mm Height Load vs Voltage

The test was done at 27.2 mm vertical separation. The graphs were similar from 100 Ohms to 45 Ohms. The simulation showed higher values from 5 Ohms to 45 Ohms. Both graphs show a semi exponential increase. The maximum values were 4.49 volts for the measurements and 4.49 volts for the simulation. The numerical data is shown in APPENDIX X. The four-to-one air coils with two cores steady position at 27.2 mm height load vs efficiency graph is shown in Figure 3-41.

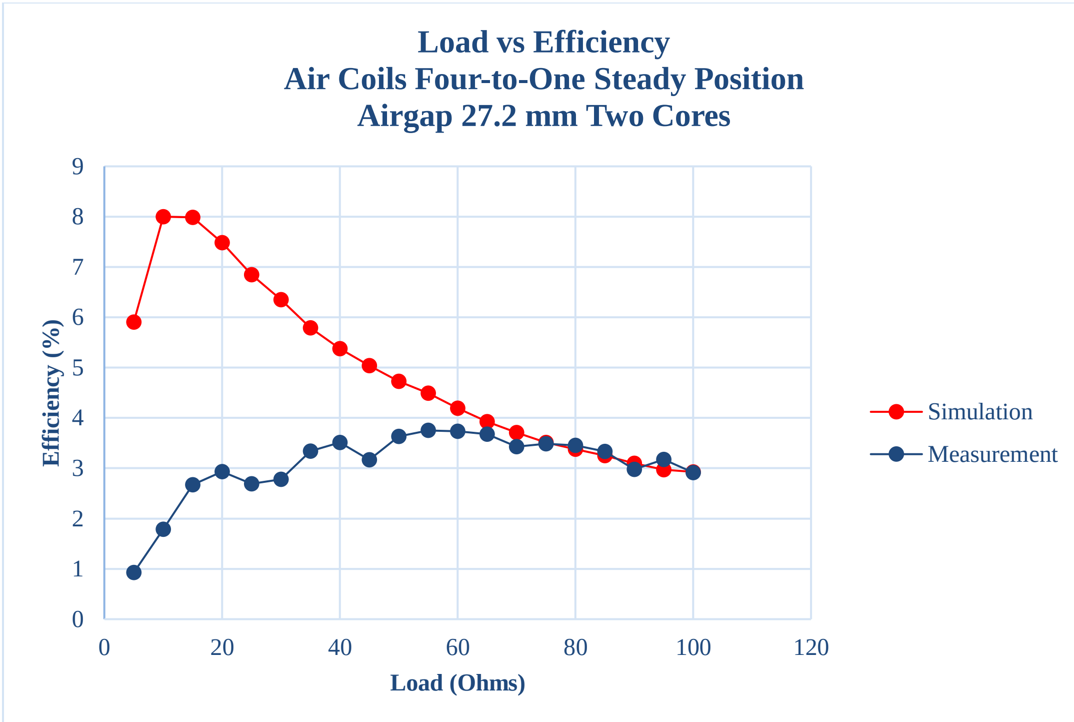



Figure 3-41 Four-to-One Air Coils with Two Cores Steady Position at 27.2 mm Height Load vs Efficiency

The test was done at 27.2 mm vertical separation. The graphs were similar from 55 Ohms to 100 Ohms. The simulation showed higher values from 5 Ohms to 55 Ohms. The simulation values increase was due to an unrealistic source. The maximum values were 3.49 % for the measurements and 8 % for the simulation. The numerical data is shown in APPENDIX X.

# CHAPTER 4: E-CORE COILS

## 4.1 Introduction

Based on the information gathered from the air coils and the air coils with added cores, a new design was introduced. Somethings learned from previous tests show that adding a ferrite core, increases efficiency. Another thing was the efficiency was higher when the transmitter and receiver were closer. The ferrite block design did improve efficiency, but it also increased the airgap leading to not optimum efficiency. The selected core was an E-shaped core material that allows the wire to rest inside its channels. This design resembles similar to the E-core of a traditional transformer. The E-shaped ferrite core is shown in Figure 4-1.

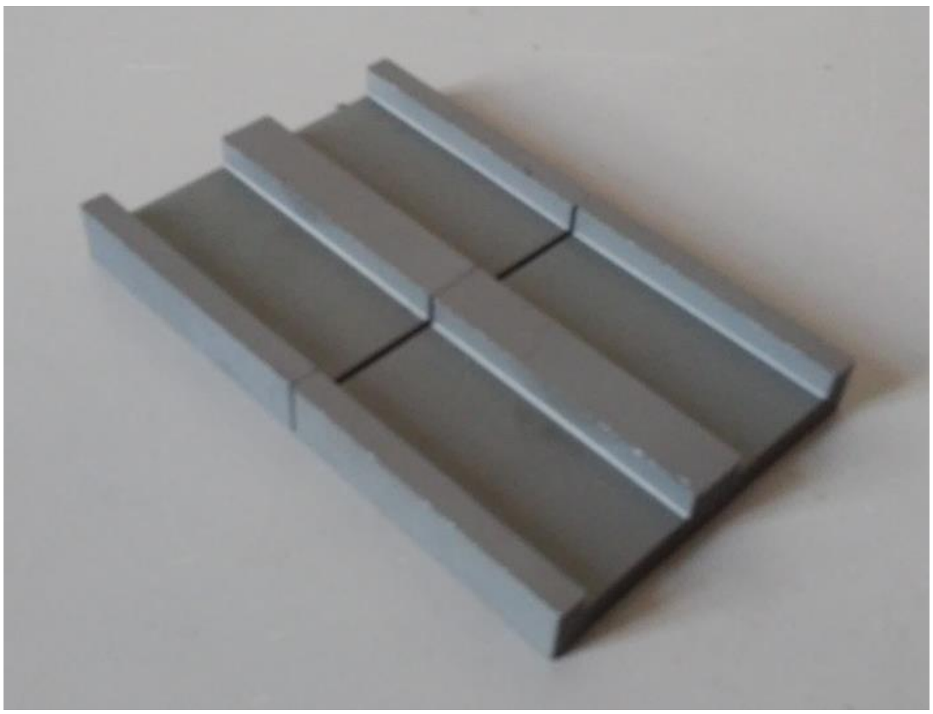
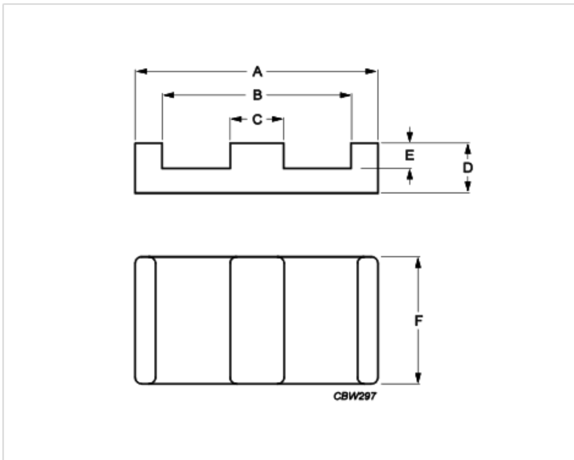


Figure 4-1 E-shaped Ferrite Core

The core was formed out of two small E-cores. The small E-core dimensions were 64 mm wide, 50.8 mm long, 10.2 mm of height, the side blocks were 5.1 mm wide, and the center block was 10.2 mm wide. The center and side blocks were 5.1 mm of height. Similar to previous tests the E-core coils were divided into two main groups. The specs for the E-shaped ferrite core is shown in Figure 4-2.




| Effective parameters | | | |
|---|---|---|---|
| | Parameter | Value | Unit |
| Σ(I/A) | *core factor (C1)* | 0.156 | $mm^{-1}$ |
| Ve | *effective volume* | 40700 | $mm^3$ |
| Le | *effective length* | 79.9 | mm |
| Ae | *effective area* | 519 | $mm^2$ |
| Amin | *minimum area* | 519 | $mm^2$ |
| m | *E64/10/50* | ≈ 100 | g/pcs |

| Dimensions for product: E64/10/50 | | | | | | |
|---|---|---|---|---|---|---|
| | Nom | Tol + | Tol - | Max | Min | Unit |
| A | 64.00 | 1.30 | 1.30 | 65.30 | 62.70 | mm |
| B | 53.80 | 1.10 | 1.10 | 54.90 | 52.70 | mm |
| C | 10.20 | 0.20 | 0.20 | 10.40 | 10.00 | mm |
| D | 10.20 | 0.13 | 0.13 | 10.33 | 10.07 | mm |
| E | 5.10 | 0.13 | 0.13 | 5.23 | 4.97 | mm |
| F | 50.80 | 1.00 | 1.00 | 51.80 | 49.80 | mm |

Figure 4-2 E-shaped Ferrite Core Specs [13]

The tests were divided on individual or one-to-one test and multiple transmitters to one long receiver. The second group divides into two other subgroups; the subgroups were seven transmitters to one long receiver considered for dynamic charging, and three transmitters to one long receiver considered for static charging.  Each transmitter coil comprises two E-cores, and two coil layers. Each layer had eight wire loops. The wire was tightly packed around the core center block. The individual transmitter E-core coil is shown in Figure 4-3.

Figure 4-3 Individual E-core Coil

The receiver had the same configuration as the transmitters, with the exception of utilizing eight E-shaped ferrite cores together instead of two cores. The E-core long receiver is shown in Figure 4-4.

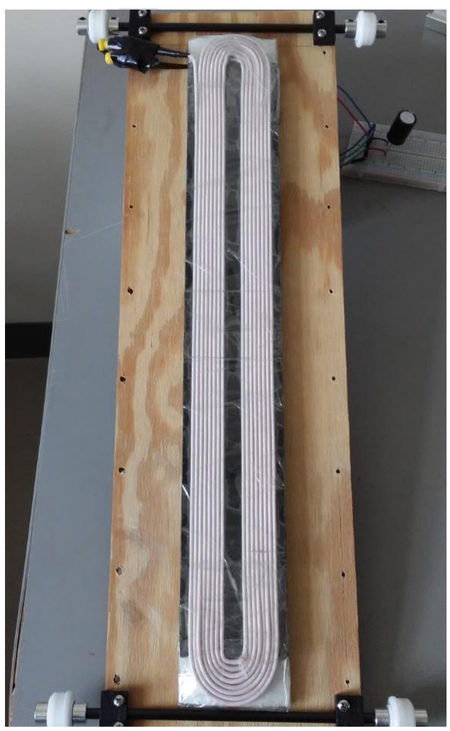


Figure 4-4 E-core Long Receiver

4.2 E-Core Coils One-to-One

The one-to-one test uses one transmitter and one receiver. Among the testes were vertical separation or airgap, horizontal separation, and different load test. The E-core one-to-one is shown in Figure 4-5.

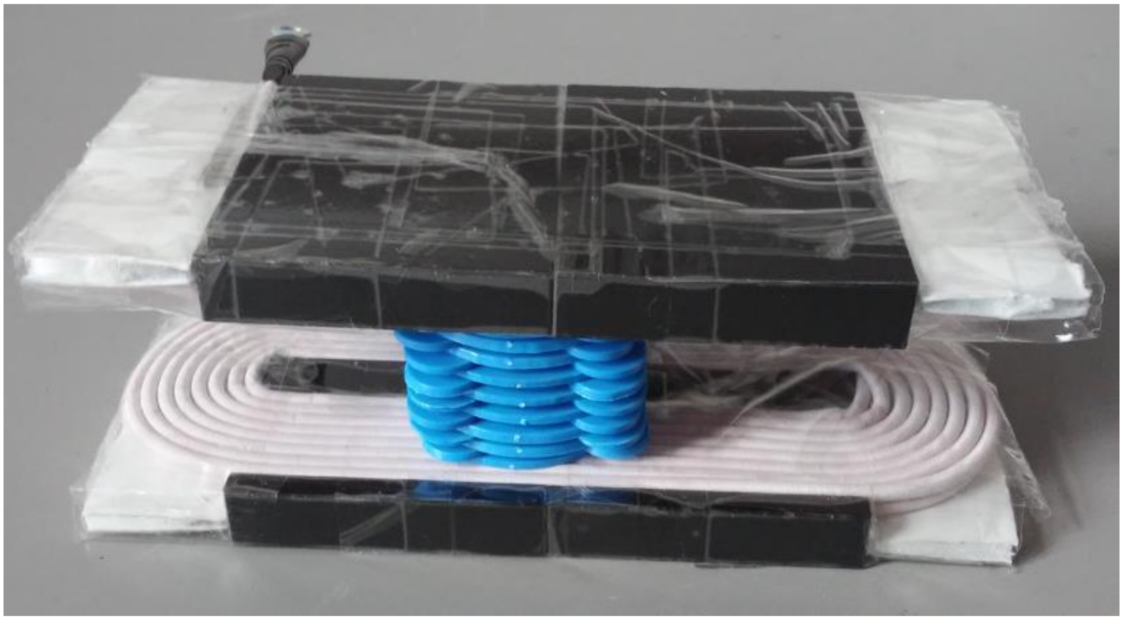


Figure 4-5 E-core One-to-One Vertical Separation Test

The individual one-to-one ANSYS Maxwell design is shown in Figure 4-6.

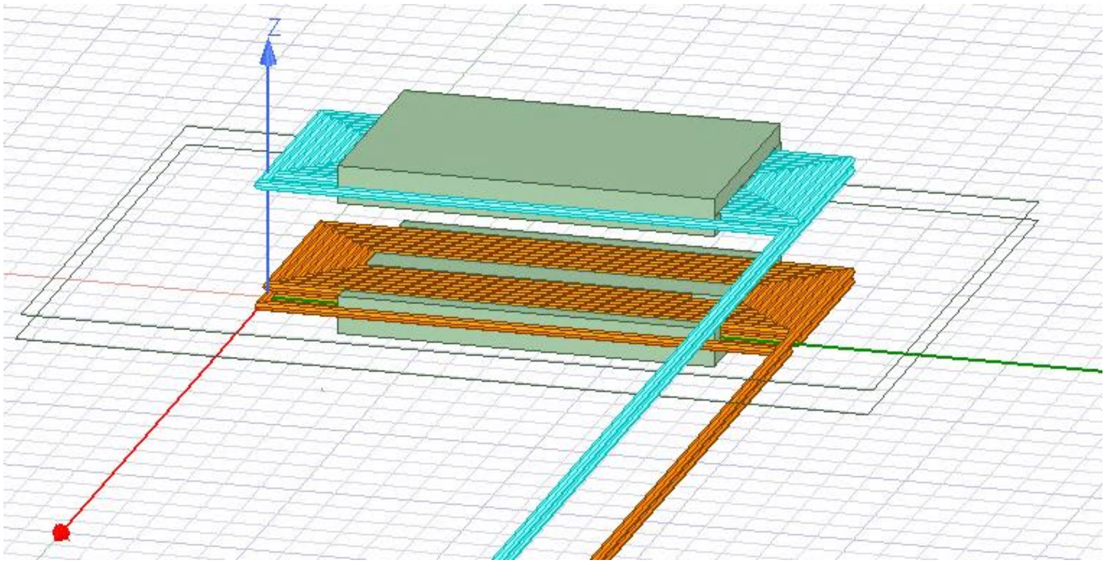


Figure 4-6 Individual One-to-One ANSYS Maxwell Design

The individual one-to-one ANSYS Maxwell electromagnetic simulation is shown in Figure 4-7.

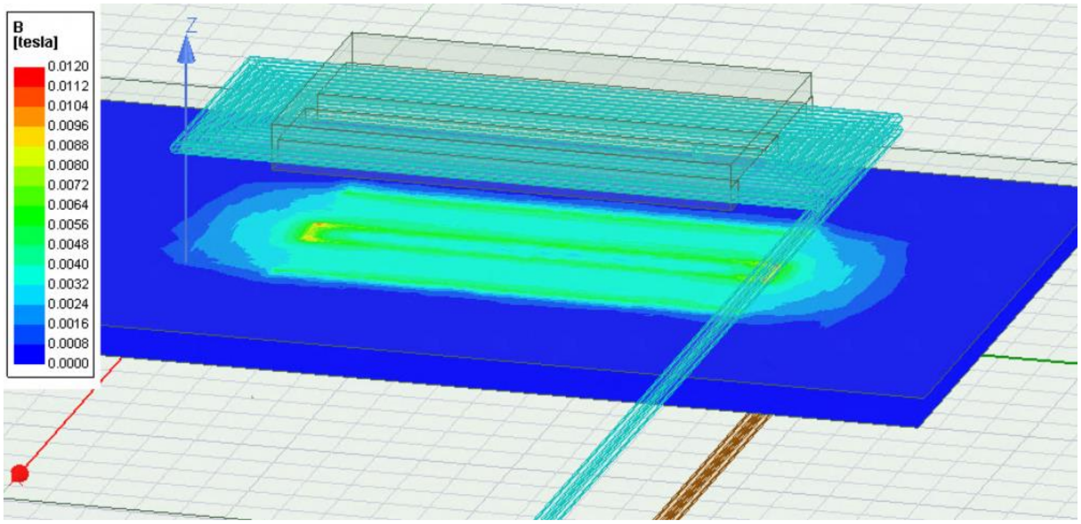



Figure 4-7 Individual One-to-One ANSYS Maxwell Electromagnetic Simulation

The individual tests started with the vertical separation. The individual one-to-one ANSYS Maxwell coupling coefficient simulation is shown in Figure 4-8.

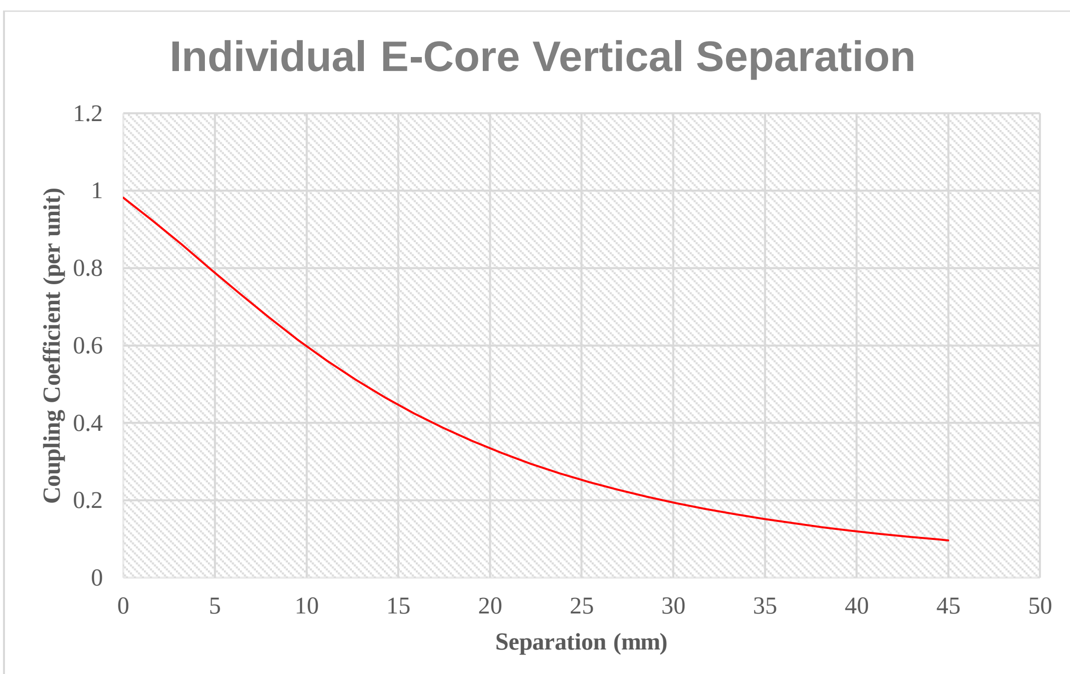



Figure 4-8 Individual One-to-One ANSYS Maxwell Coupling Coefficient Simulation

The individual one-to-one coupling coefficient numerical data can be found on APPENDIX Y. The individual one-to-one vertical separation vs voltage test is shown in Figure 4-9.

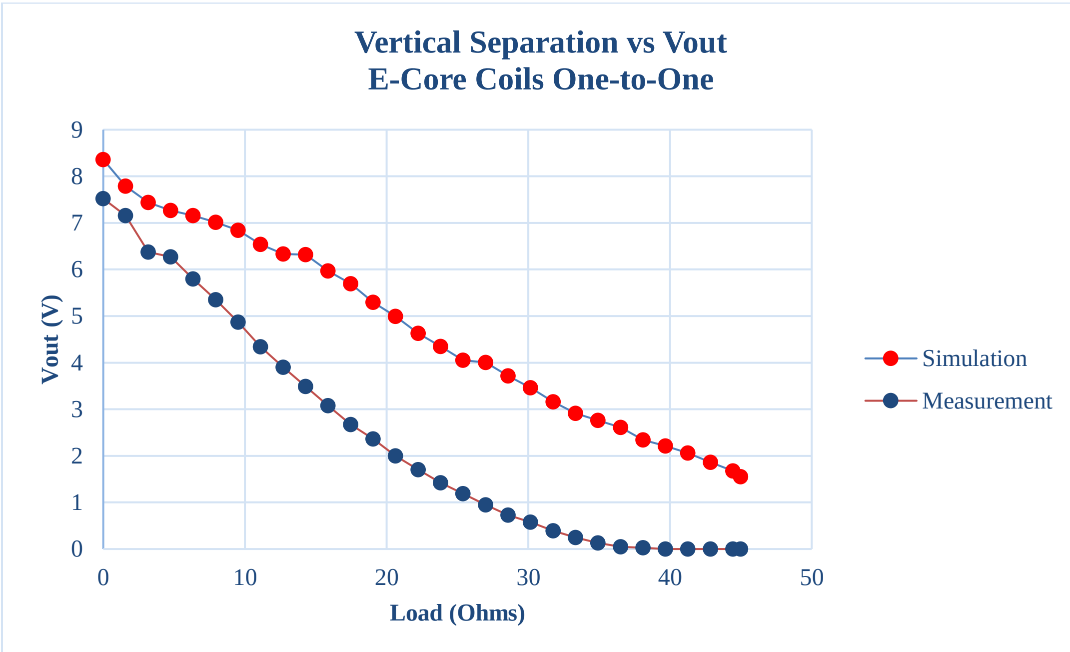



Figure 4-9 E-core Coils Individual One-to-One Vertical Separation vs Vout Test

Both graphs show a decreasing pattern. The simulation was more linear than the measured results. The simulation showed higher values from around 4 mm to around 45 mm. the maximum values were 7.52 volts for the measurements and 8.36 volts for the simulation. The numerical data can be found in APPENDIX Z. The individual one-to-one vertical separation vs efficiency test is shown in Figure 4-10.

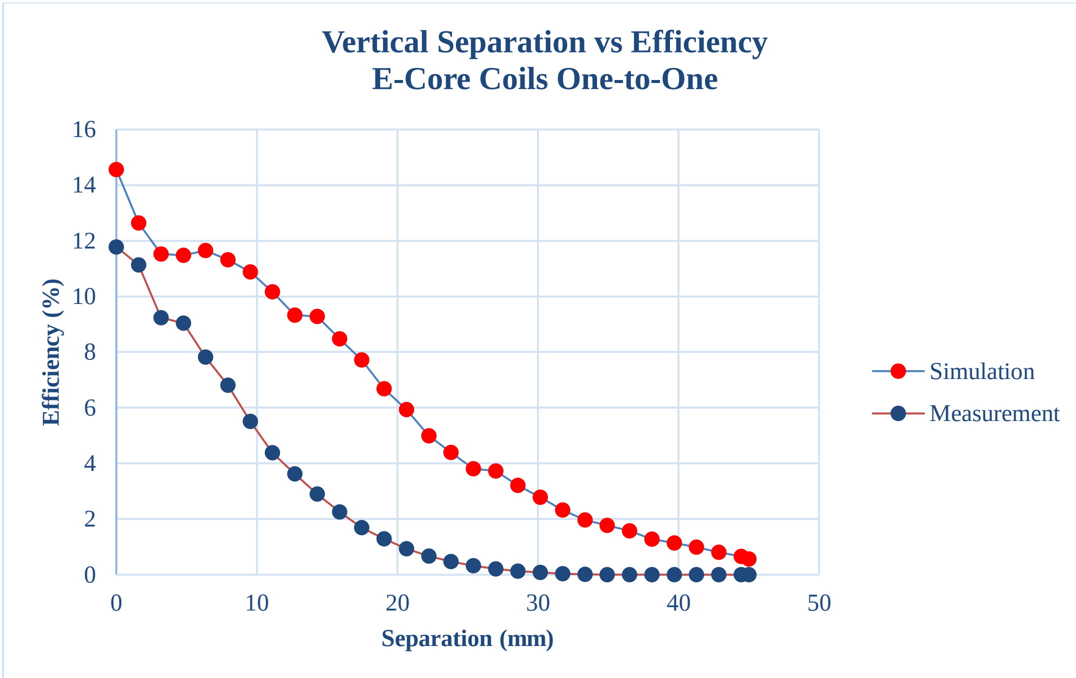



Figure 4-10 Individual One-to-One Vertical Separation vs Efficiency

The graphs were unevenly decreasing. The simulation showed higher values from around 4mm to around 35 mm. The maximum values were 11.78 % for the measurement and 14.56 % for the simulation. The numerical data is shown in APPENDIX Z. The E-core coils individual one-to-one horizontal separation ANSYS Maxwell coupling coefficient simulation is shown in Figure 4-11.

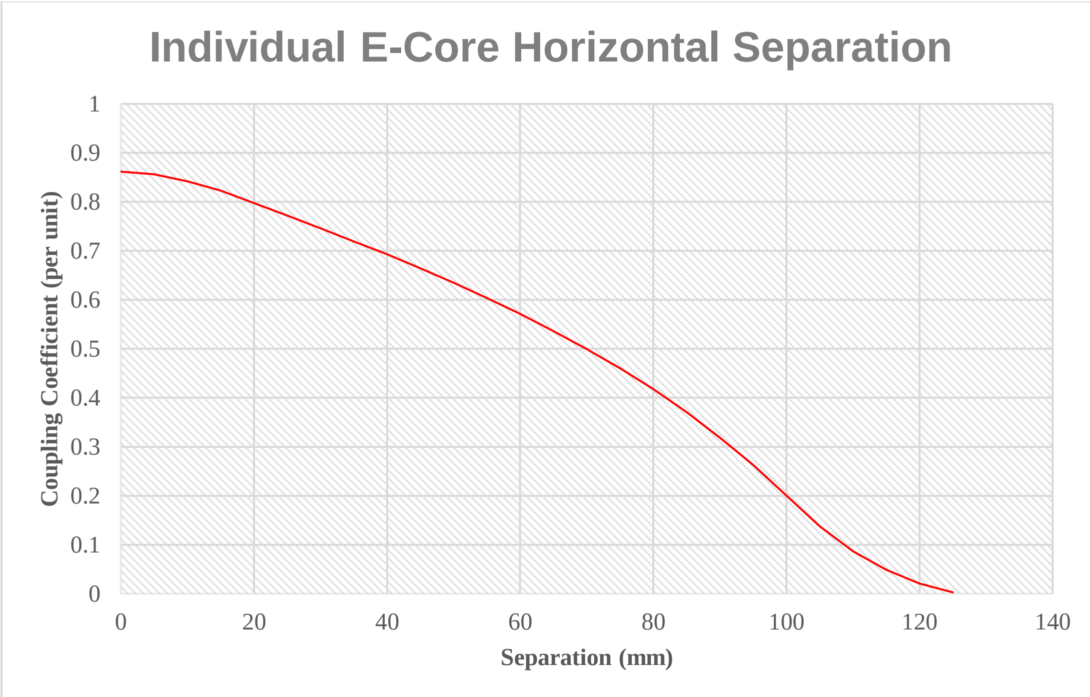



Figure 4-11 E-core Coils Individual One-to-One Horizontal Separation ANSYS Maxwell Coupling Coefficient Simulation

The ANSYS Maxwell simulation showed a semi exponential decrease for the most part with some irregularities closer to 110 mm separation. The maximum coupling coefficient value was 0.86 p.u. The numerical data is shown in APPENDIX A2. The E-core coils individual one-to-one horizontal separation vs voltage test is shown in Figure 4-12.

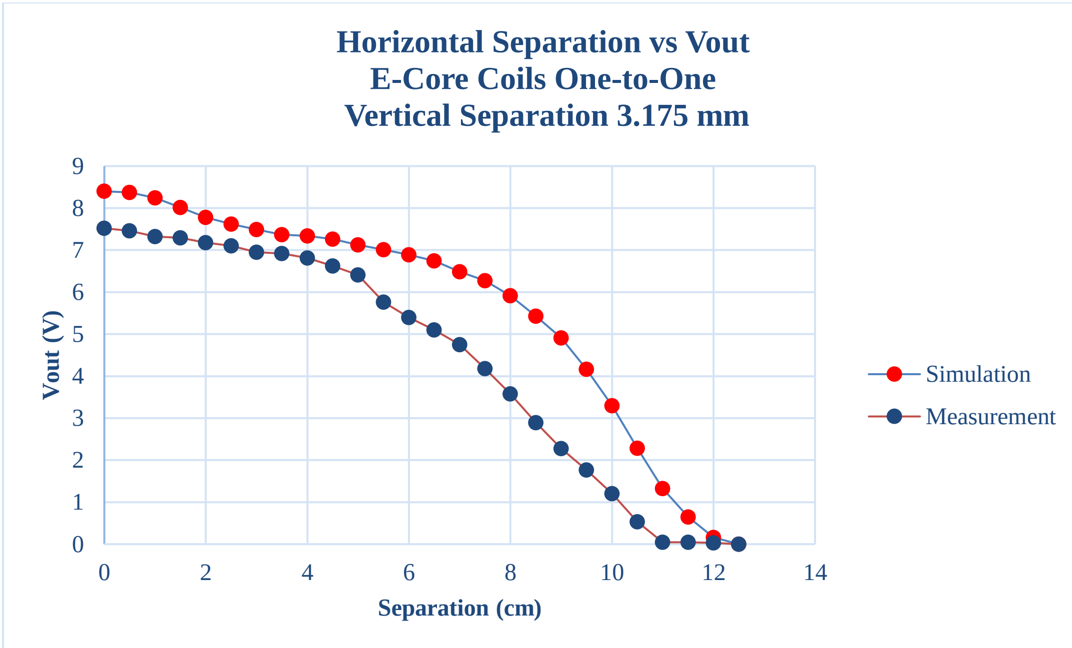



Figure 4-12 E-core coils Individual One-to-One Horizontal Separation vs Voltage

The graph showed a bi-linear trend for both curves. The maximum values were 7.52 volts for the measurements and 8.4 for the simulation. The numerical data is shown in APPENDIX B2. The E-core coils individual one-to-one horizontal separation vs efficiency test is shown in Figure 4-13.

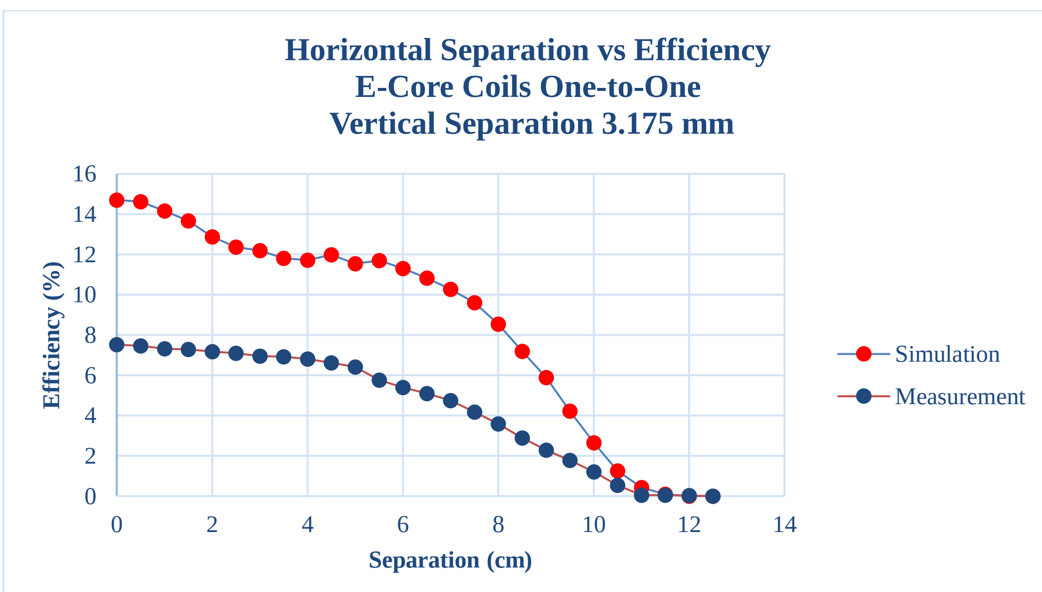



Figure 4-13 E-core Coils Individual One-to-One Horizontal Separation vs Efficiency

The graphs were decreasing. However, the simulation showed higher values than the measurements from 0 cm to 10 cm. The maximum values were 11.78 % for the measurements and 14.7 % for the simulation. The numerical data is shown in APPENDIX B2. The E-core coils individual one-to-one load vs voltage test is shown in Figure 4-14.

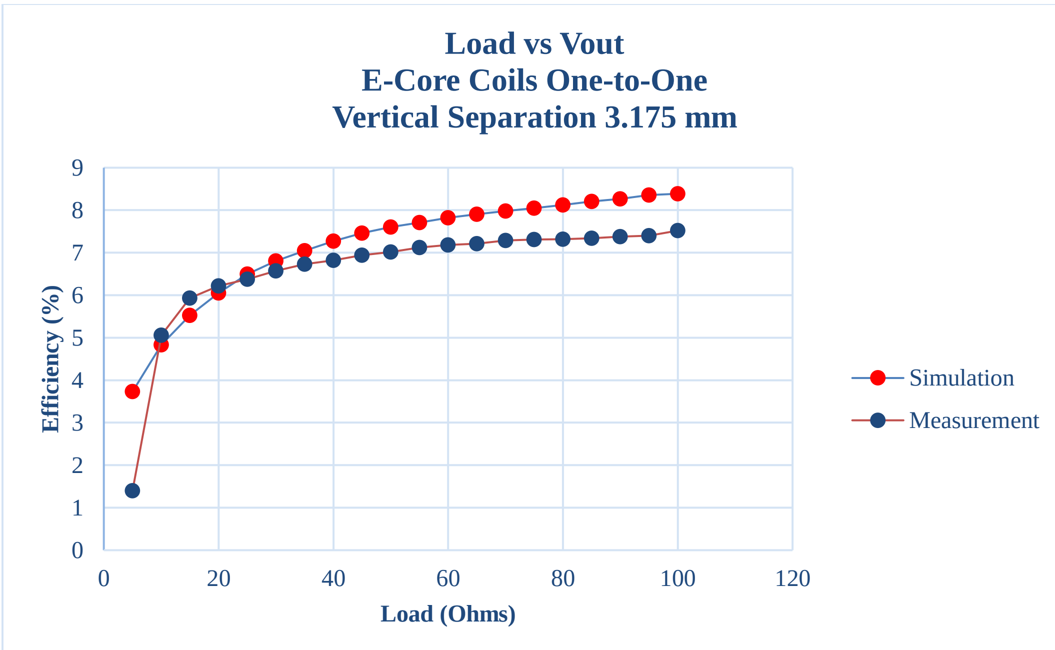



Figure 4-14 E-core Coils Individual One-to-One Load vs Voltage

The graphs show a semi exponential increase. The graphs had similar values except for the test at 5 Ohms; the simulation showed higher values at 5 Ohms. The maximum values were 7.52 volts for the measurement and 8.386 volts for the simulations. The numerical data is shown in APPENDIX C2. The E-core coils individual one-to-one load vs efficiency test is shown in Figure 4-15.

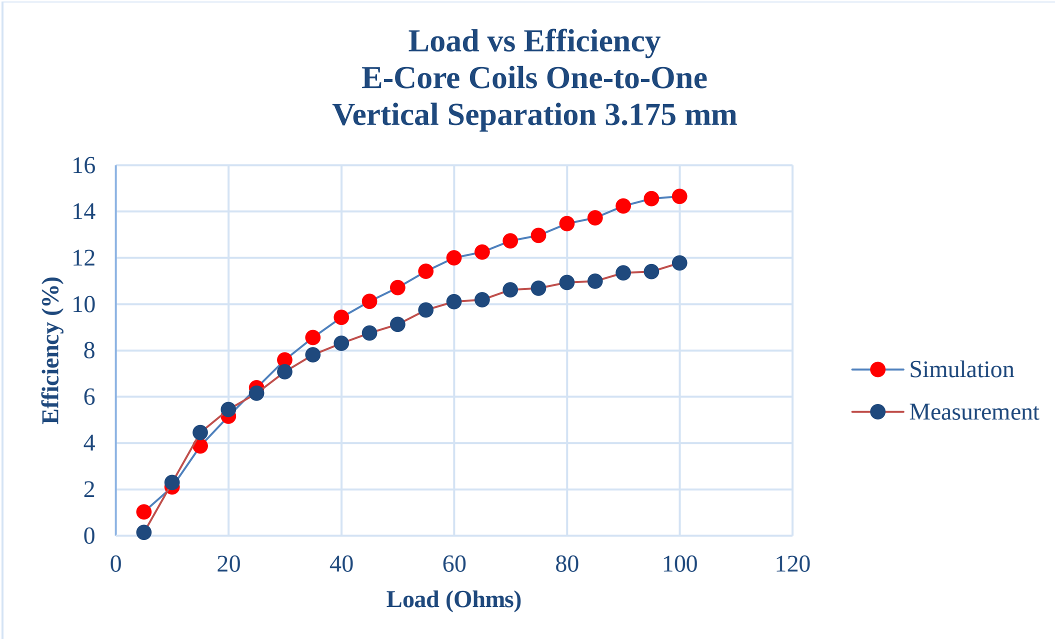



Figure 4-15 E-core Coils Individual One-to-One Load vs Efficiency

The graphs were similar. The graphs show a semi exponential increase. The simulation showed higher values from 50 Ohms to 100 Ohms. The numerical data is shown in APPENDIX C2.

4.3 E-Core Coils Seven-to-One

The dynamic movement design in railroad applications requires a pre and post power transfer. This means that transmitter coils will be energized in front and at the back of the receiver in addition to the coils directly under the receiver. Hence the power transfer was sufficient to power the locomotive. The configuration used seven transmitters and one receiver. The transmitters were connected in parallel for higher voltage and lower current transfer. Two main positions had been selected. The peak position was when there was the maximum power transfer; this occurs when the receiver was properly aligned with the three transmitters underneath. There was also a low position which occurs when the receiver had moved forward half the distance of one transmitter. The E-core coils transmitters picture is shown in Figure 4-16.

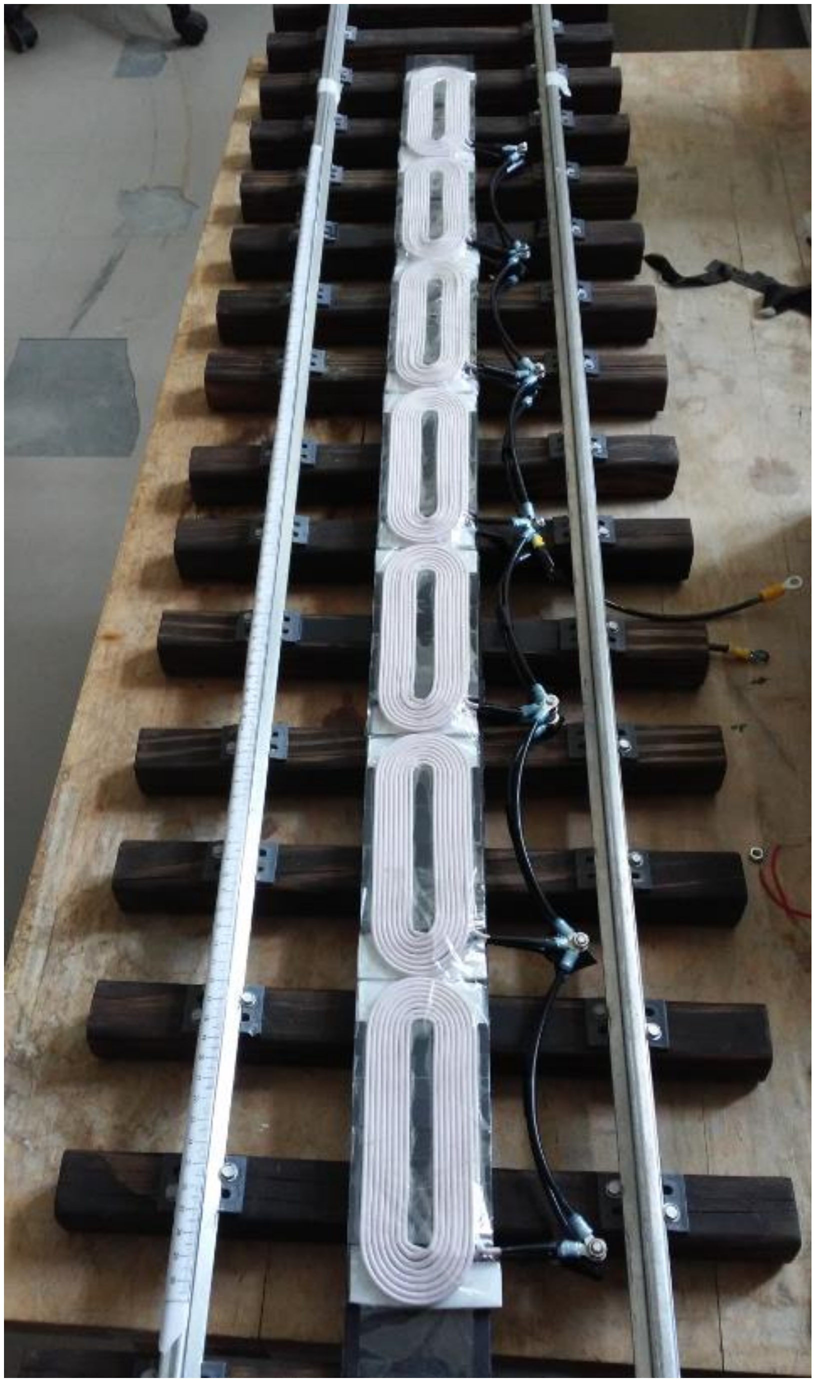


Figure 4-16 E-core Coils Transmitters

The E-core coils seven-to-one configuration is shown in Figure 4-17.

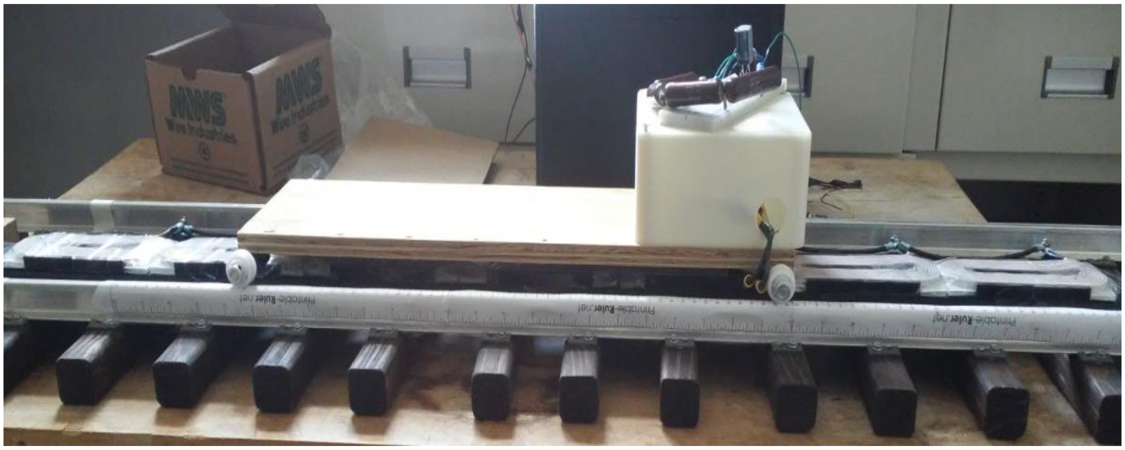



Figure 4-17 E-core Coils Seven-to-One

The E-core seven-to-one vertical separation peak position ANSYS Maxwell design is shown in Figure 4-18.

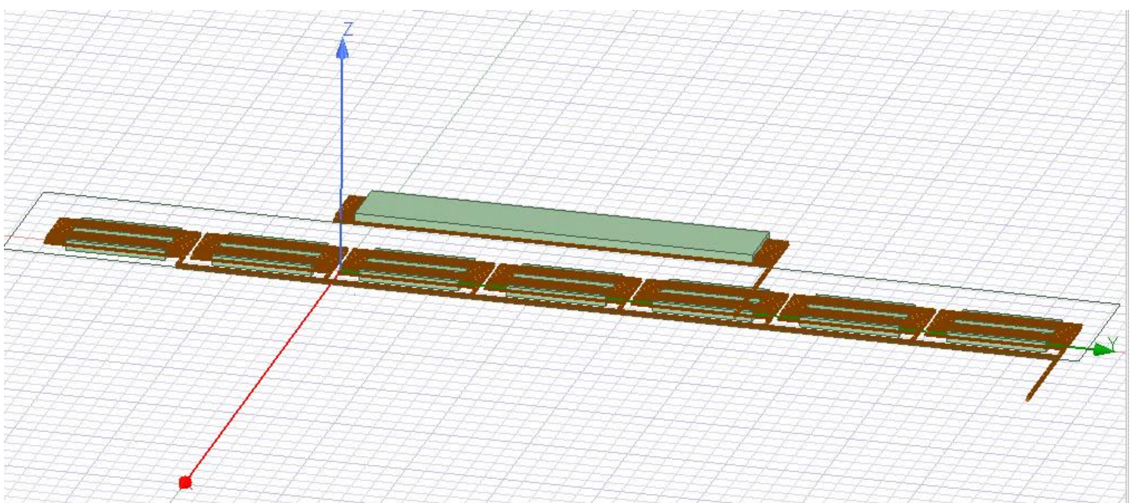



Figure 4-18 E-core Seven-to-One Vertical Separation Peak Position ANSYS Maxwell Design

The E-core seven-to-one vertical separation peak position ANSYS Maxwell electromagnetic simulation is shown in Figure 4-19.

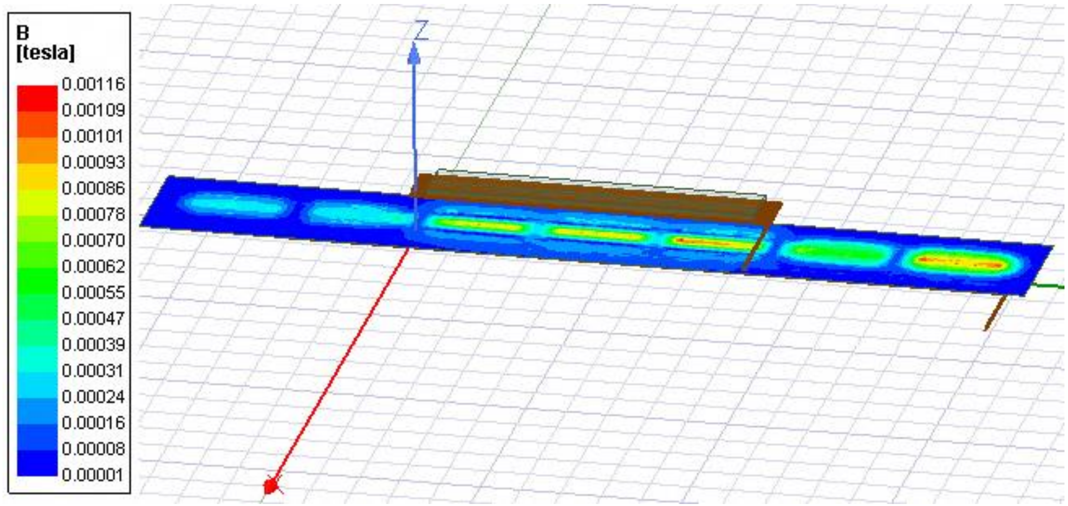



Figure 4-19 E-core Seven-to-One Vertical Separation Peak Position ANSYS Maxwell Electromagnetic Simulation

The E-core seven-to-one vertical separation peak position ANSYS Maxwell coupling coefficient is shown in Figure 4-20.

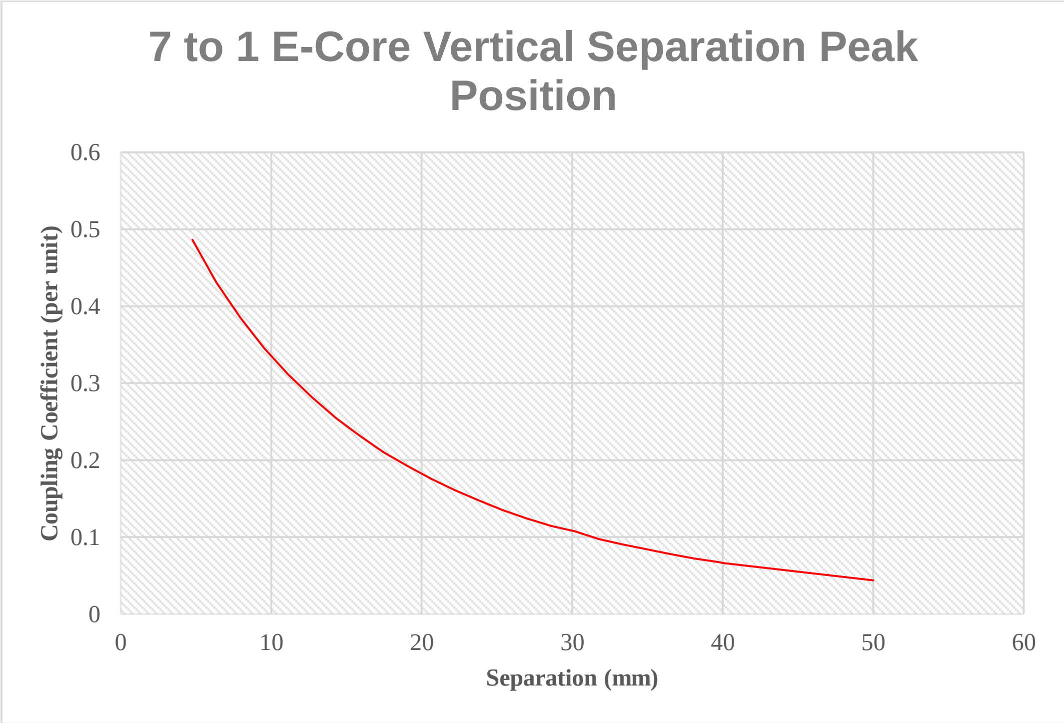



Figure 4-20 E-core Coils Seven-to-One Vertical Separation Peak Position ANSYS Maxwell Coupling Coefficient

The graph decreases in a semi inverse exponential manner. The coupling coefficient maximum value was 0.486. The numerical data is shown in APPENDIX D2. The E-core seven-to-one vertical separation vs voltage peak position test shown in Figure 4-21.

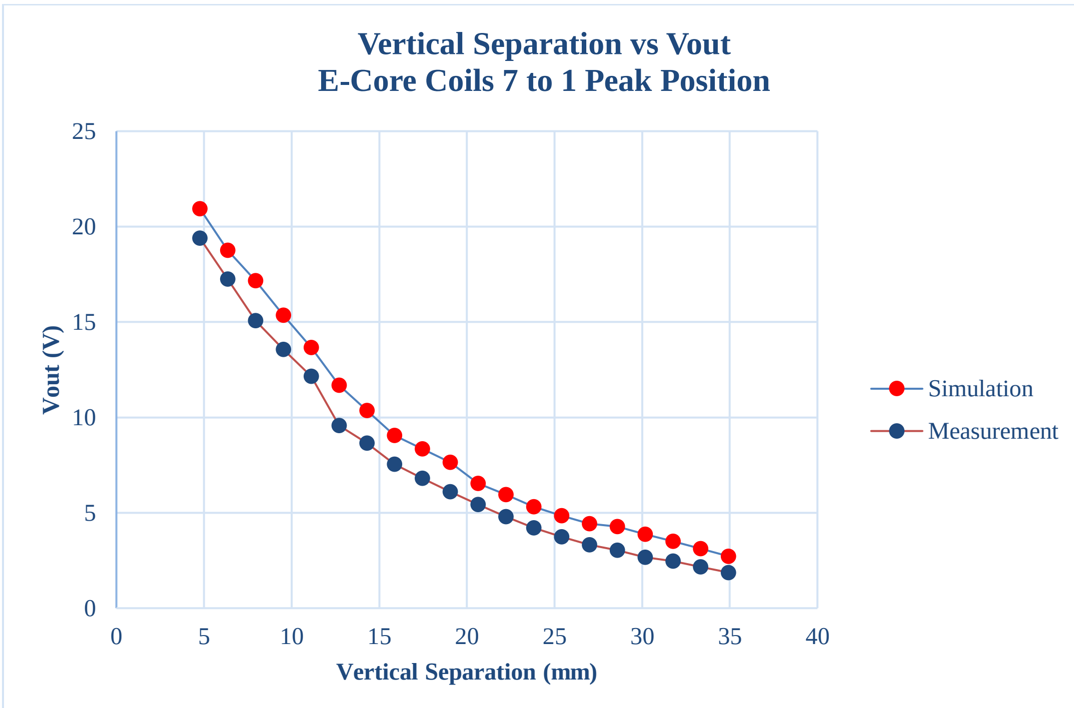



Figure 4-21 E-core Seven-to-One Vertical Separation vs Voltage Peak Position

The graphs were decreasing in a bi-linear manner. The simulation and measurement values were very similar throughout the vertical separation. The simulation showed an even small percentage increase from the measurements. The maximum values were 19.4 volts for the measurements and 20.94 volts for the simulations. The numerical data can be found in APPENDIX E2. The E-core seven-to-one vertical separation vs efficiency peak position test is shown in Figure 4-22.

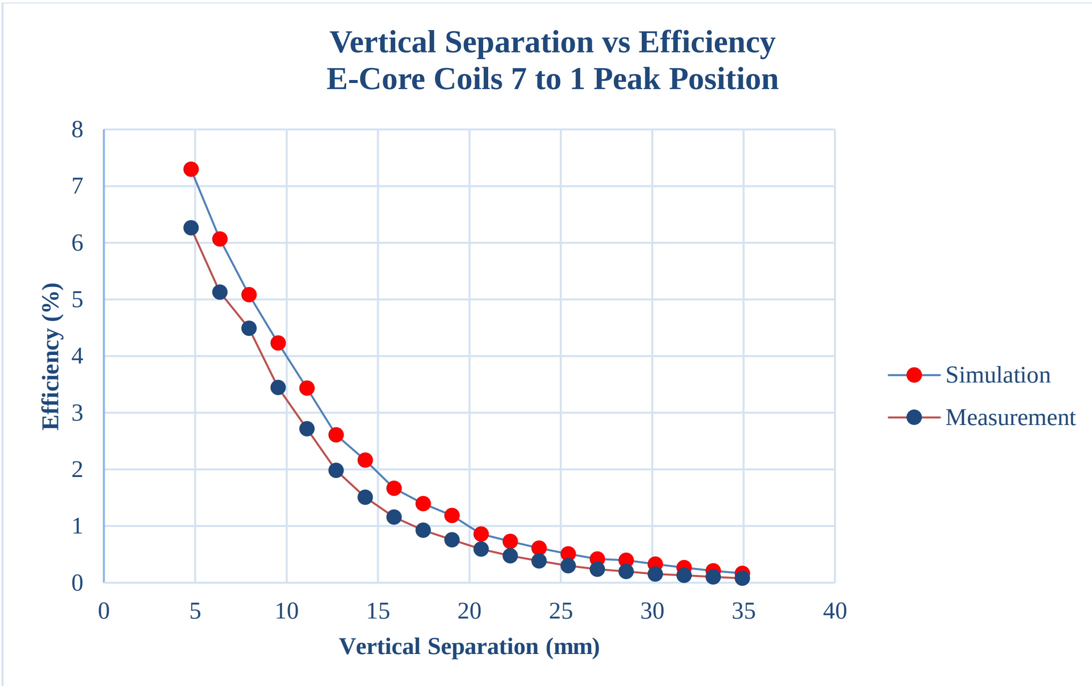



Figure 4-22 E-core Seven-to-One Vertical Separation vs Efficiency Peak Position

The graphs decrease in an exponential manner. The graphs were similar closer to 35 mm separation and the simulation showed higher values from 5 mm to 20 mm separation. The maximum values were 6.26 % for the measurements and 7.3 % for the simulation.  The numerical data is shown in APPENDIX E2. The test was performed for the low position as well. The E-core seven-to-one low position ANSYS Maxwell design is shown in Figure 4-23.

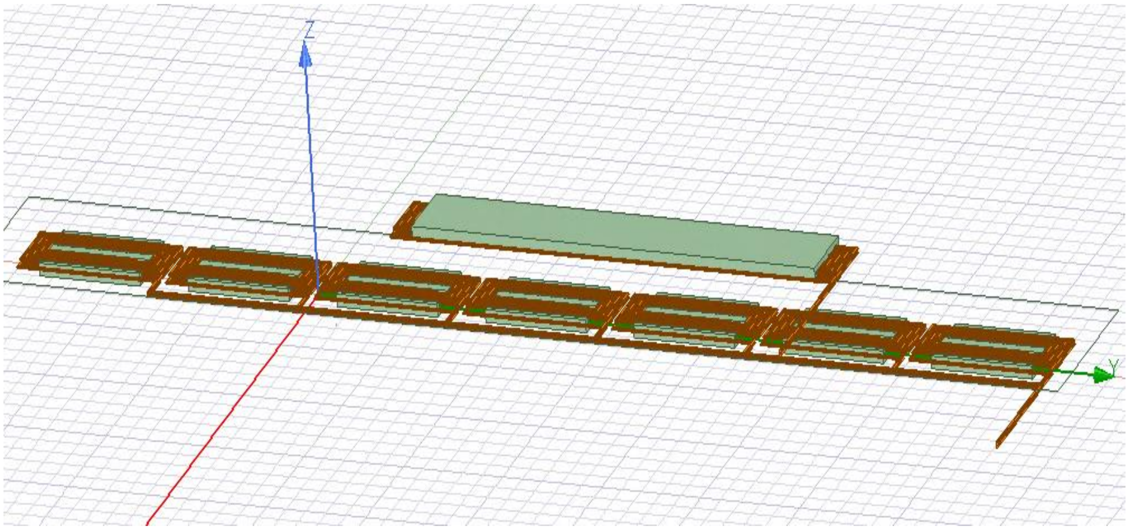


Figure 4-23 E-core Seven-to-One Low Position ANSYS Maxwell Design

The E-core seven-to-one low position ANSYS Maxwell electromagnetic simulation is shown in Figure 4-24.

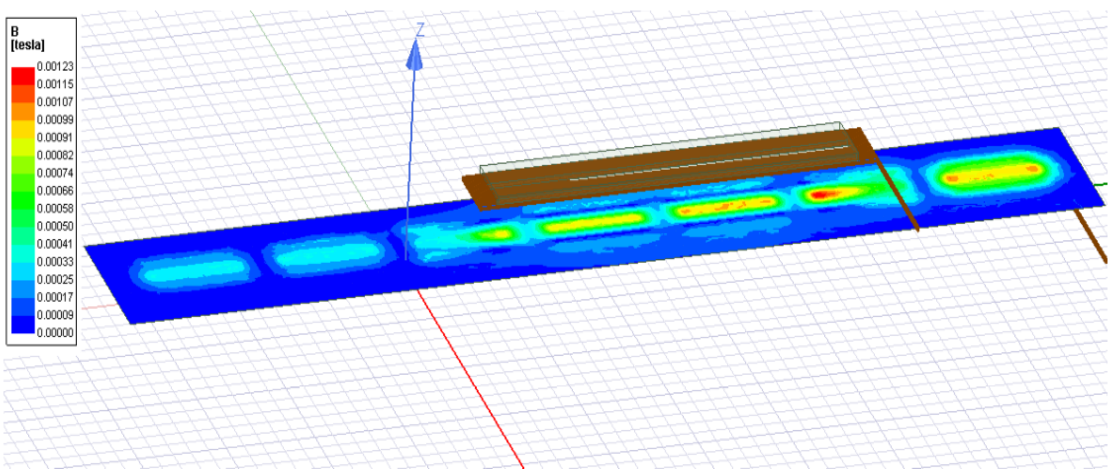



Figure 4-24 E-core Seven-to-One Low Position ANSYS Maxwell Electromagnetic Simulation

The E-core seven-to-one low position vertical separation ANSYS Maxwell coupling coefficient simulation is shown in Figure 4-25.

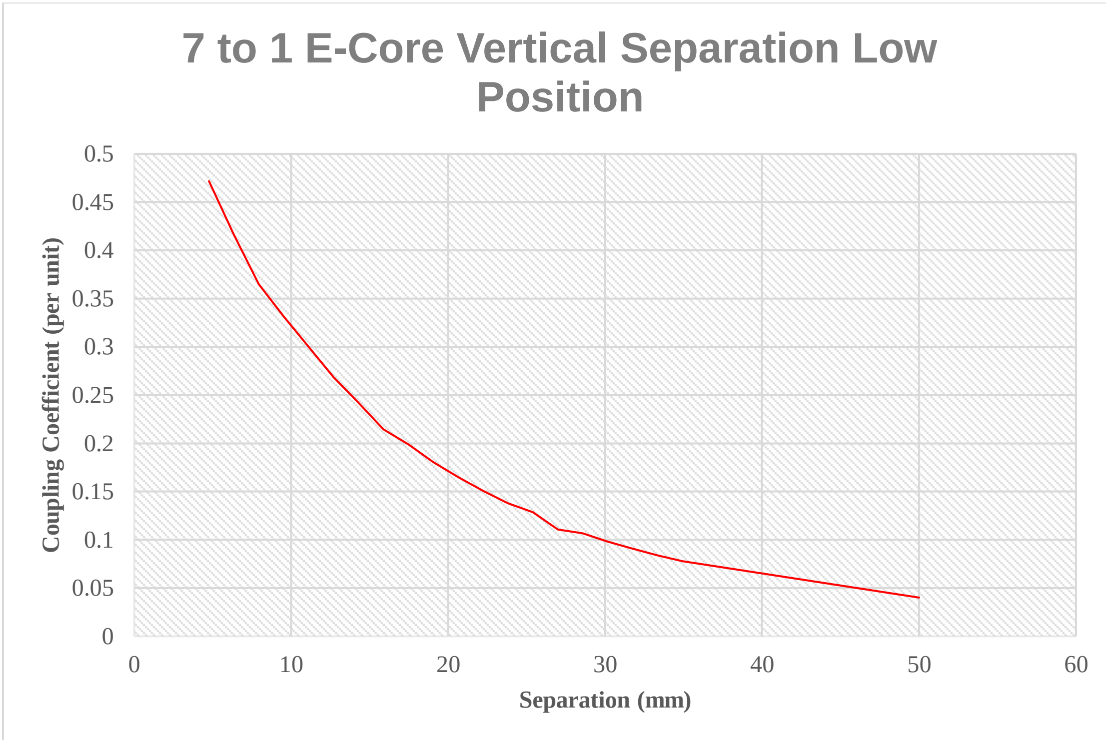



Figure 4-25 E-core Seven-to-One Low Position Vertical Separation ANSYS Maxwell Coupling Coefficient Simulation

The graph was decreasing in a semi exponential manner. The maximum value was 0.47. the numerical data is shown in APPENDIX F2. The E-core seven-to-one low position vertical separation vs voltage is shown in Figure 4-26.

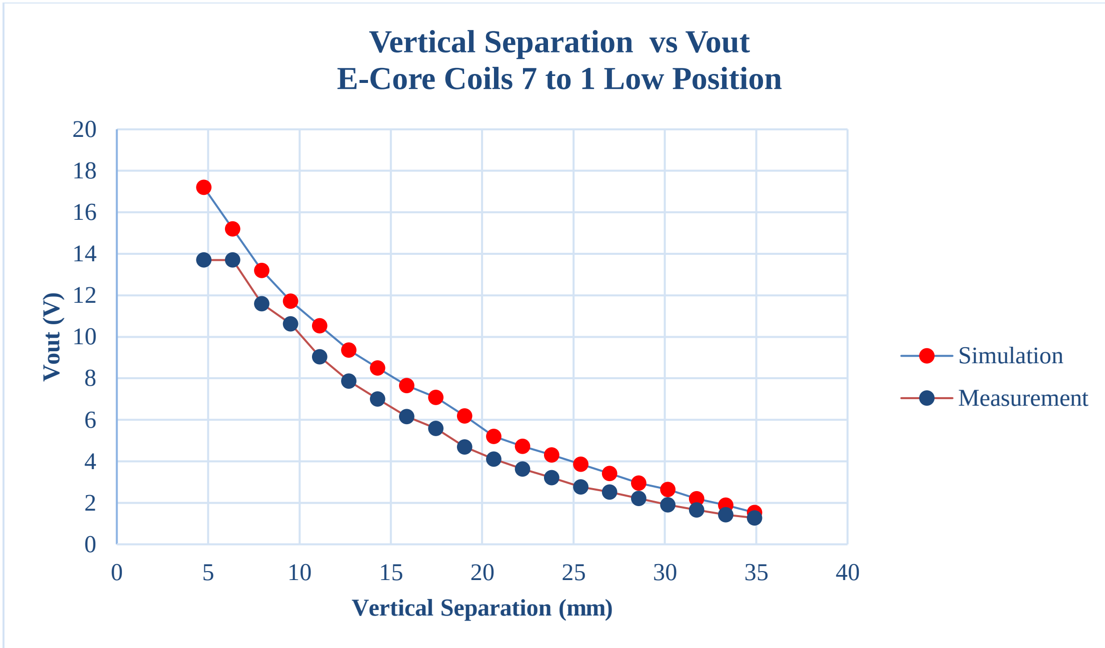



Figure 4-26 E-core Seven-to-One Low Position Vertical Separation vs Voltage

The graphs were almost linearly decreasing. Both graphs were similar, but they had some differences. The simulation decreases continuously, but the measurements show a non-changing voltage for the first two tests around 4.76 mm and 6.35 mm. The maximum values were 13.7 volts for the measurements and 17.2 volts for the simulation. The numerical data is shown in APPENDIX G2. The E-core seven-to-one low position vertical separation vs efficiency is shown in Figure 4-27.

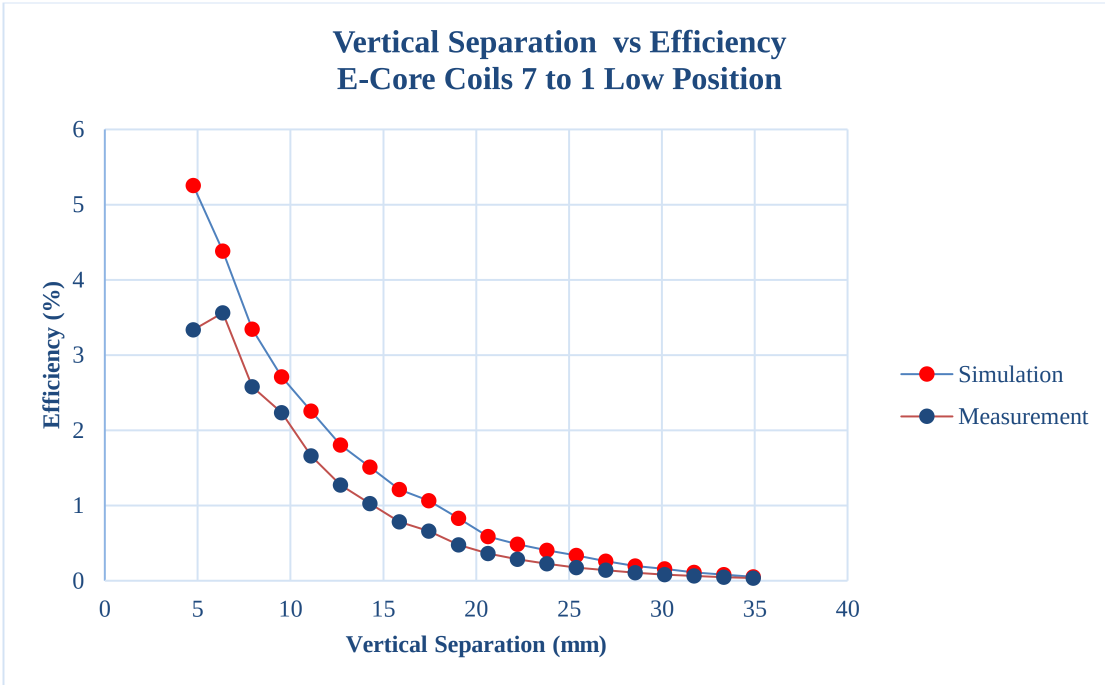



Figure 4-27 E-core Seven-to-One Low Position Vertical Separation vs Efficiency

The graphs were similar and they decrease for the most part. The decrease was semi exponential. The simulation decreased mostly continuously, but the measurements increased at first and then decreased. The maximum values were 3.56 % for the measurements and 5.25 % for the simulations. The numerical data is shown in APPENDIX G2. There were load tests perform as well for the peak and low positions. The E-core seven-to-one peak position load vs voltage is shown in Figure 4-28.

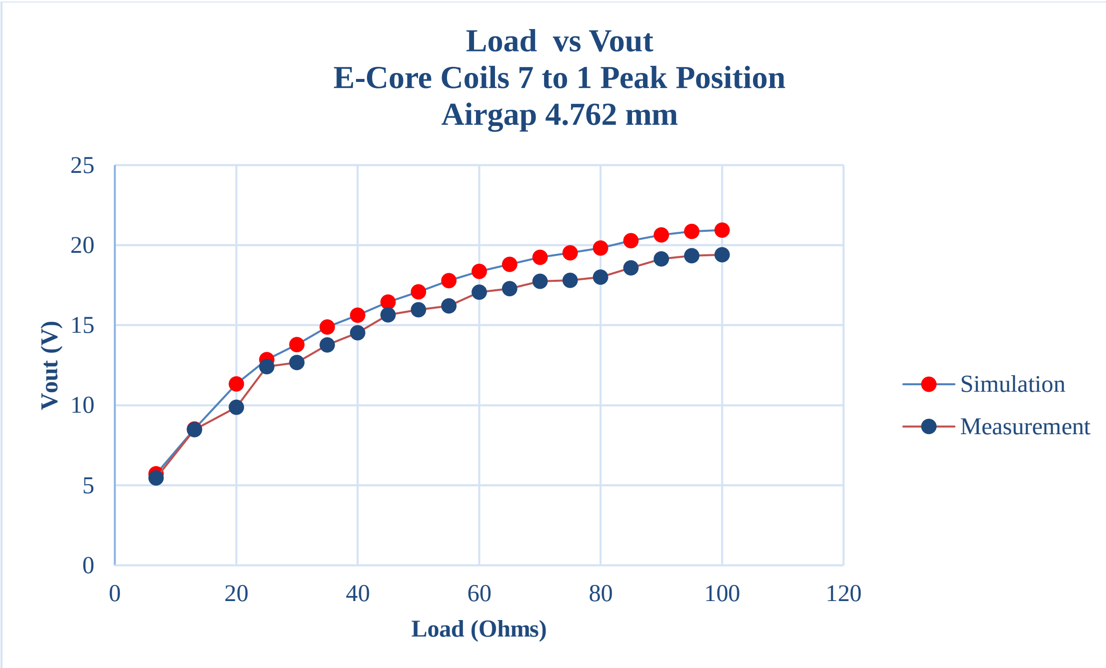



Figure 4-28 E-core Seven-to-One Peak Position Load vs Voltage

The test was performed at 4.76 mm vertical separation. The graphs were similar. The simulation showed a smooth increase. The measurements showed an uneven increase. The graphs were similar from 5 Ohms to 45 Ohms. The simulation showed higher values from 45 Ohms to 100 Ohms. The maximum values were 19.4 volts for the measurements and 20.94 volts for the simulation. The numerical data is shown in APPENDIX H2. The E-core seven-to-one peak position load vs efficiency is shown in Figure 4-29.

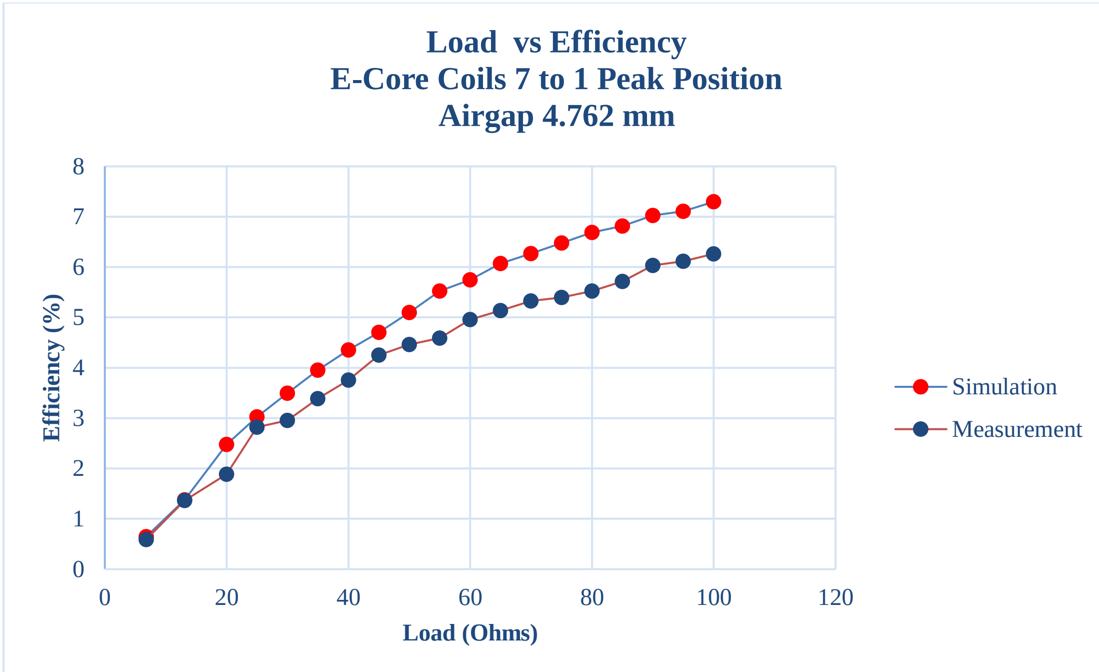



Figure 4-29 E-core Seven-to-One Peak Position Load vs Efficiency

The test was performed at 4.76 mm vertical separation. The graphs were increasing in a semi exponential manner. The graphs were similar from 5 Ohms to 45 Ohms. The simulation showed higher values from 45 Ohms to 100 Ohms. The maximum values were 6.26 % for the measurements and 7.3 % for the simulations. The numerical data is shown in APPENDIX H2. The numerical data is shown in APPENDIX H2. The E-core seven-to-one low position load vs voltage is shown in Figure 4-30.

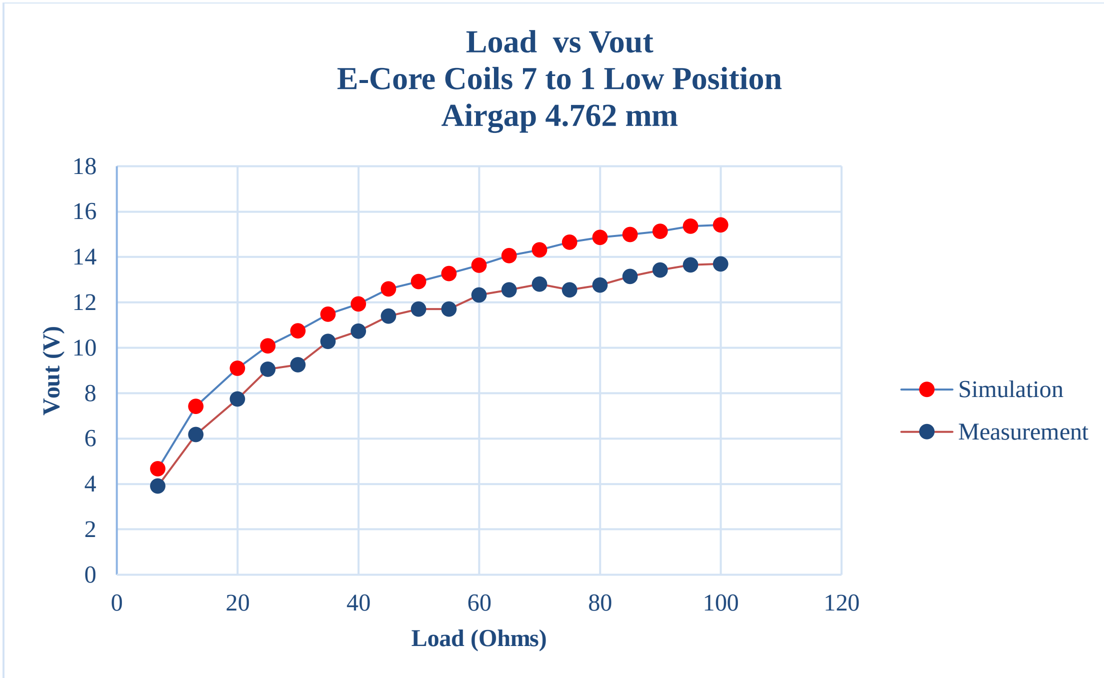



Figure 4-30 E-core Seven-to-One Low Position Load vs Voltage

The graphs were similar. The values were almost the same for both graphs although the simulation showed slightly higher values than the measurements. The simulation showed higher values from 60 Ohms to 100 Ohms. The maximum values were 13.7 volts for the measurements and 15.41 volts for the simulations. The numerical values are shown in APPENDIX I2. The E-core seven-to-one low position load vs efficiency is shown in Figure 4-31.

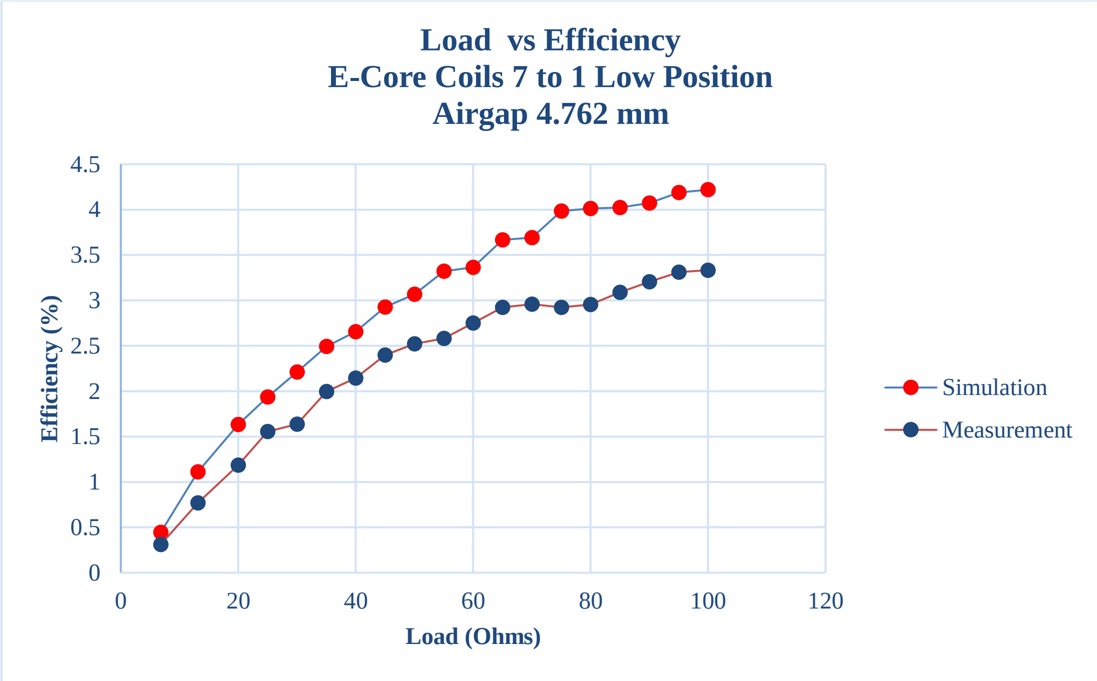



Figure 4-31 E-core Seven-to-One Low Position Load vs Efficiency

The graphs were similar. Both graphs showed a slightly uneven increase. The simulation showed higher values from 65 Ohms to 100 Ohms. The maximum values were 3.33 % for the measurements and 4.22 % for the simulations. The numerical values are shown in APPENDIX I2. The tests were completed with a horizontal separation test. The E-core coils horizontal separation ANSYS Maxwell coupling coefficient simulations graph is shown in Figure 4-32.

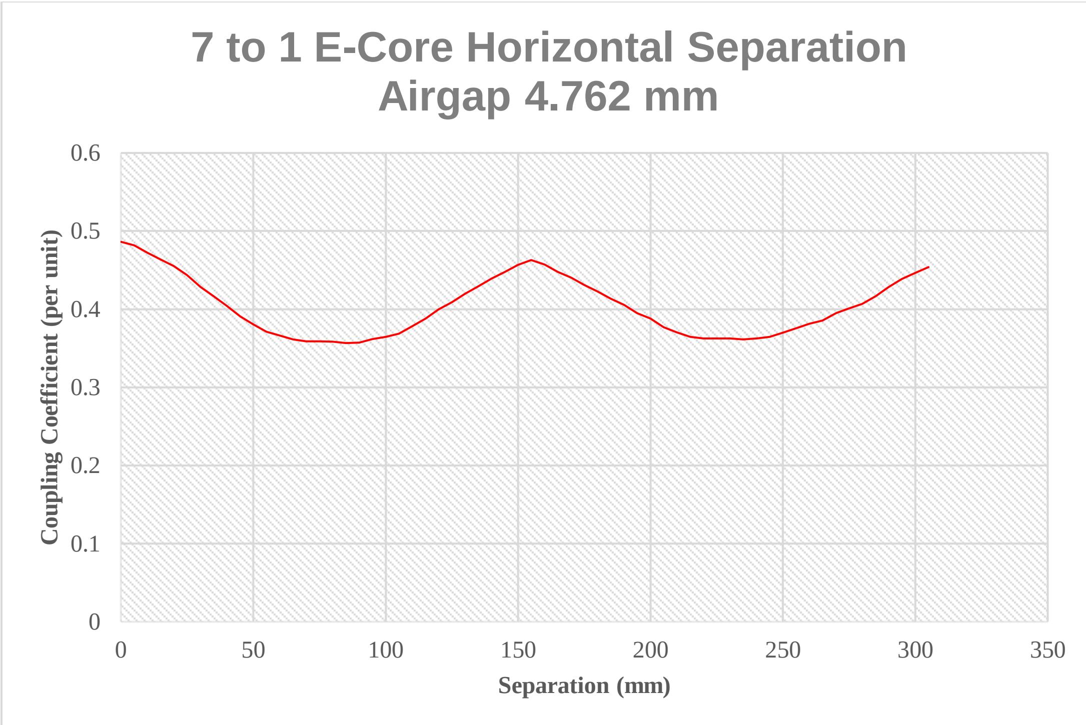



Figure 4-32 E-core Coils Horizontal Separation ANSYS Maxwell Coupling Coefficient Simulation

The test started at the peak position at 0 mm, then the receiver was moved forward in 5 mm increments. The first low point showed the Low Position at around 75 mm. The peak position value was 0.49 p.u. and the low position value was 0.36 p.u. The numerical data is shown in APPENDIX J2. The E-core seven-to-one horizontal separation vs voltage is shown in Figure 4-33.

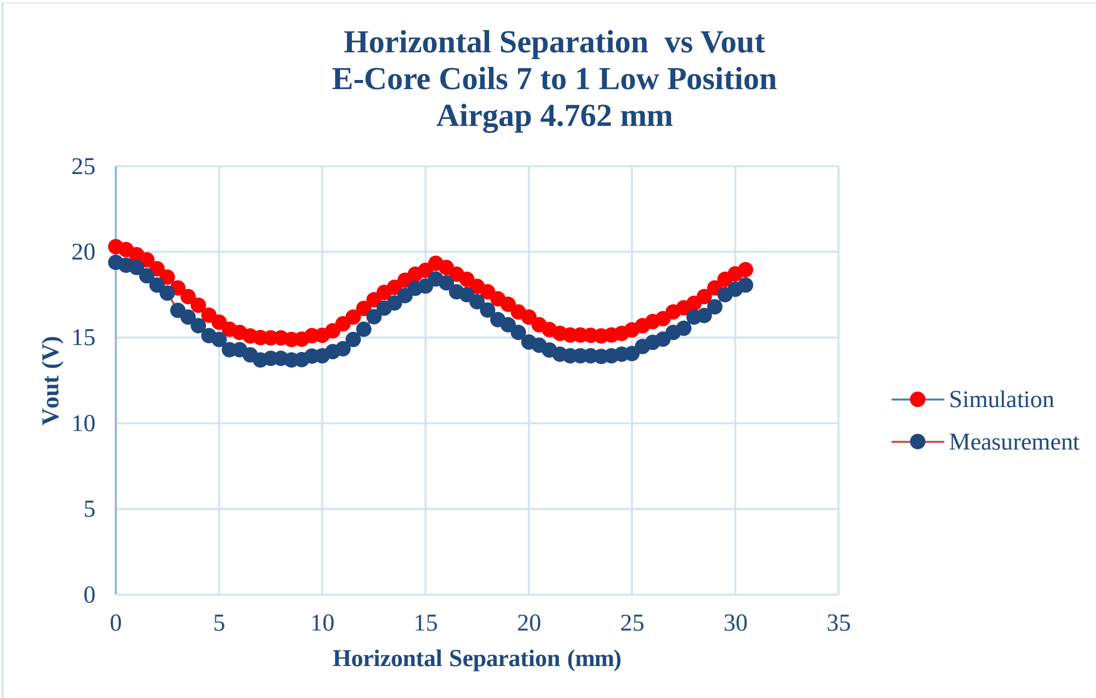



Figure 4-33 E-core Seven to One Horizontal Separation vs Voltage

The test was performed at 4.76 mm. The simulations and measurements show similar values. However, the simulations showed slightly higher values overall. The peak position values were 19.4 volts for the measurements and 20.32 volts for the simulations. The low position values were 13.79 for the measurements and 14.99 for the simulations. The numerical data is shown in APPENDIX K2. The E-core seven-to-one horizontal separation vs efficiency is shown in Figure 4-34.

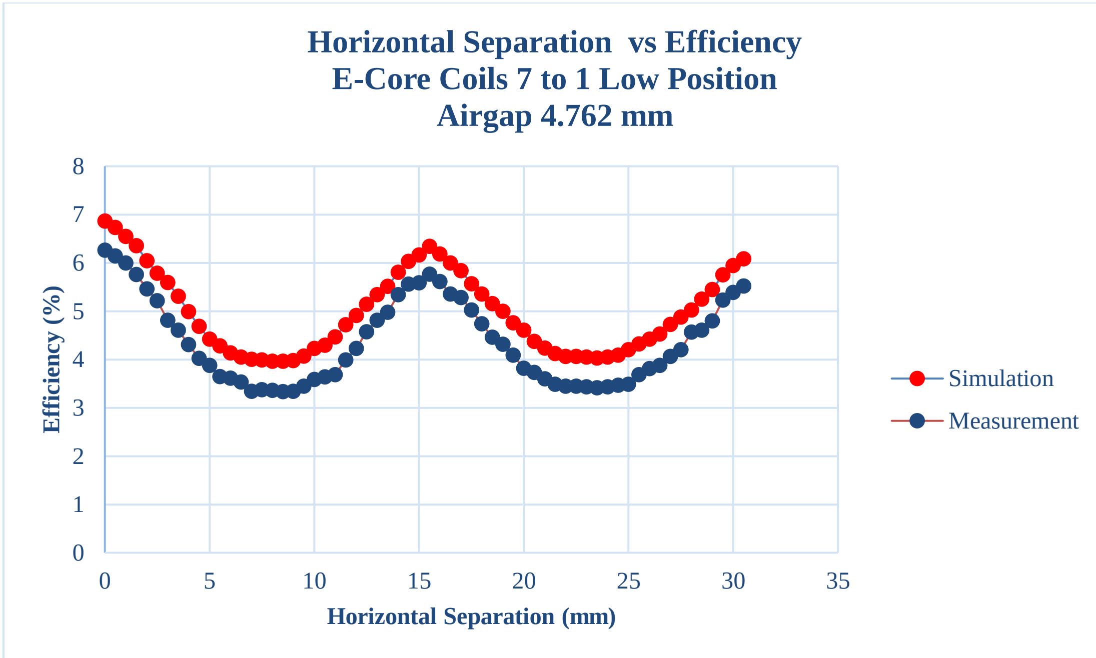



Figure 4-34 E-core Seven-to-One Horizontal Separation vs Efficiency

The test was performed at 4.76 mm. The graphs showed similar values. The efficiency showed overall higher values. The peak values were 6.26 % for the measurements and 6.87 % for the simulation. The low values were 3.38 % for the measurements and 3.99 % for the simulation. The numerical data is shown in APPENDIX K2.

## 4.4 E-core Coils Three-to-One

The tests also included a static efficient test with proper alignment. This test simulates the scenario of static charging when the locomotive was at rest. For this test, the locomotive was assumed to be properly aligned with the transmitter coils. Based on the seven-to-one results, the peak position provided the highest efficiency. Therefore, the two transmitters in front and the two transmitters behind the receiver were excluded. The E-core coils three-to-one transmitter coils picture is shown in Figure 4-35.

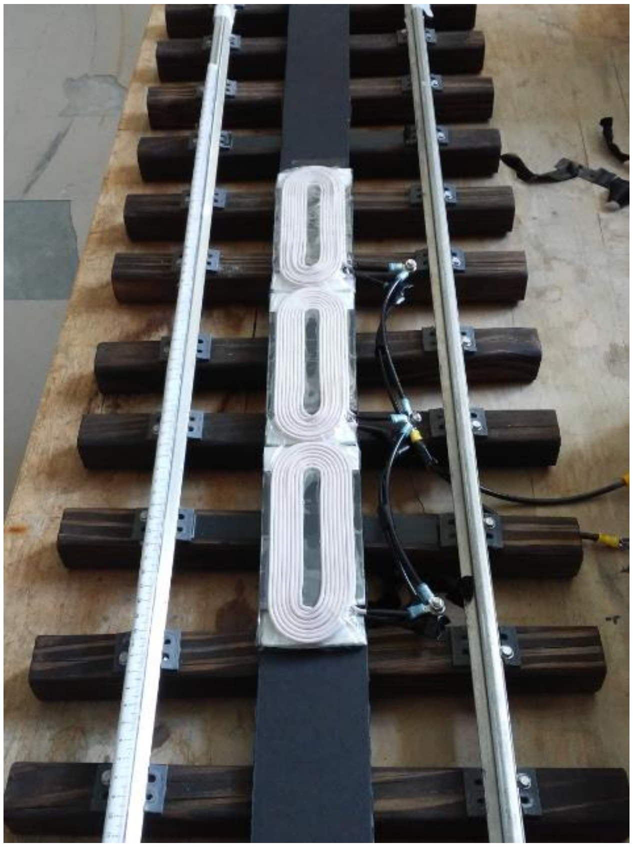


Figure 4-35 E-core Coils Transmitter Coils

The E-core coils three-to-one picture is shown in Figure 4-36.

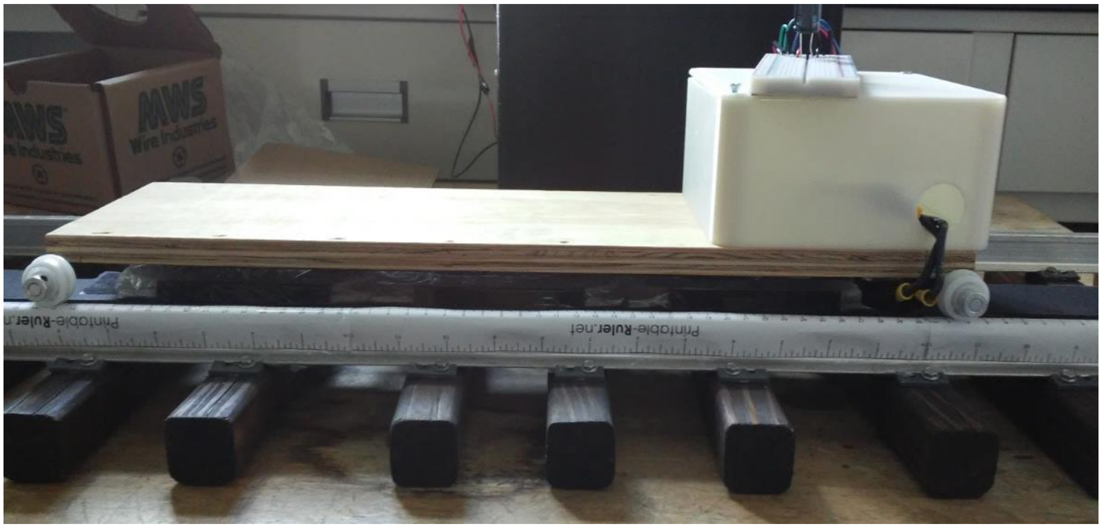



Figure 4-36 E-core Coils Three-to-One

The E-core coils three-to-one ANSYS Maxwell design is shown in Figure 4-37.

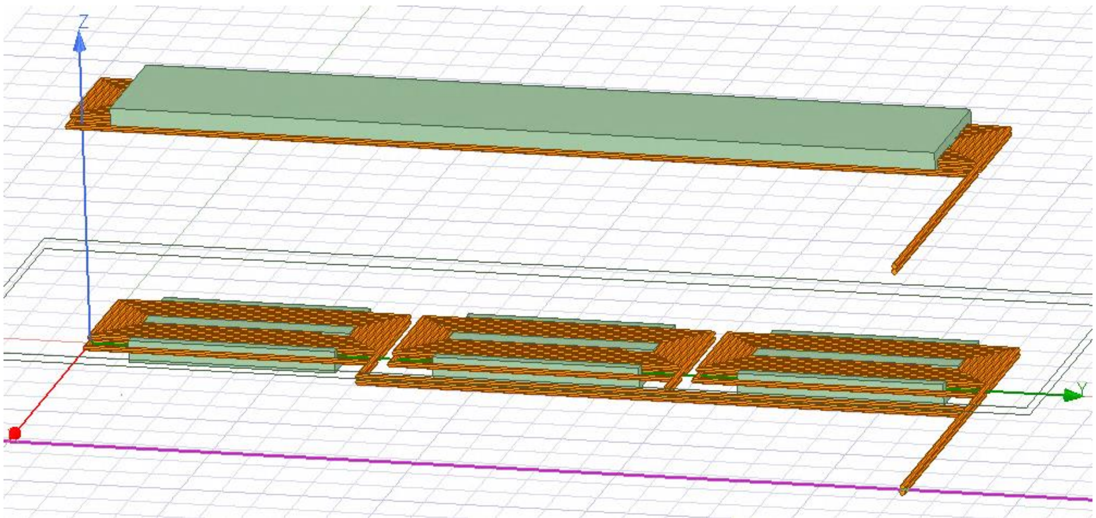


Figure 4-37 E-core Coils Three-to-One ANSYS Maxwell Design

The E-core coils three-to-one ANSYS Maxwell electromagnetic simulation is shown in Figure 4-38.

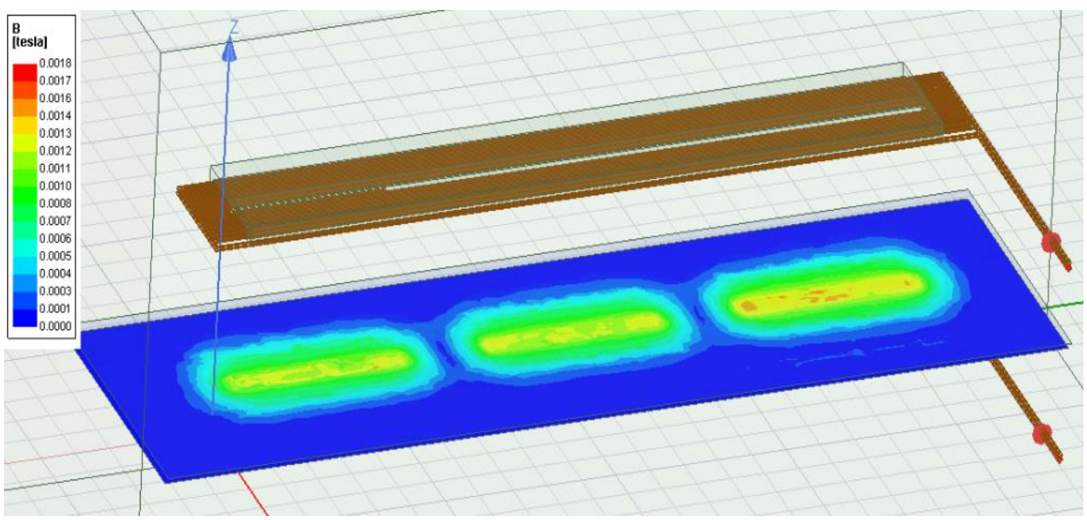



Figure 4-38 E-core Coils Three-to-One ANSYS Maxwell Electromagnetic Simulation

The E-core coils three-to-one vertical separation ANSYS Maxwell coupling coefficient simulations graph is shown in Figure 4-39.

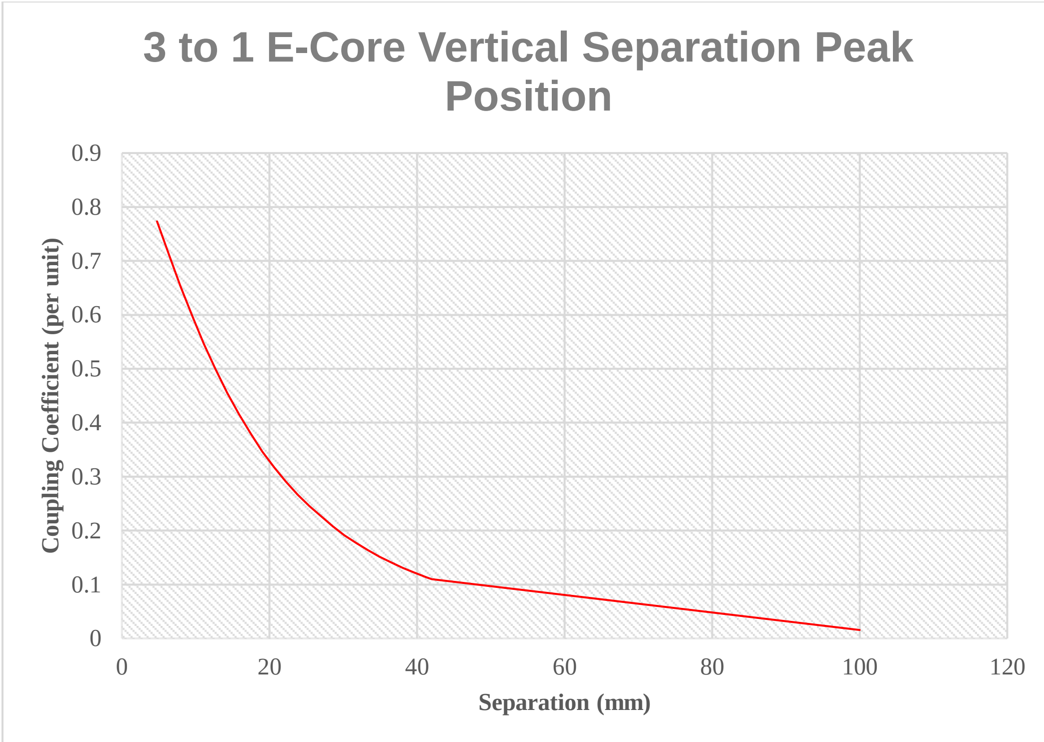



Figure 4-39 E-core Coils Three-to-One Vertical Separation ANSYS Maxwell Coupling Coefficient Simulation

The simulation showed a semi inverse exponential decrease from around 5 mm to 40 mm and then a linear decrease until it reaches 100 mm. The maximum value was 0.77 p.u. at 4.762 mm. the numerical data is shown in APPENDIX L2. The E-core coils three-to-one vertical separation vs voltage test is shown in Figure 4-40.

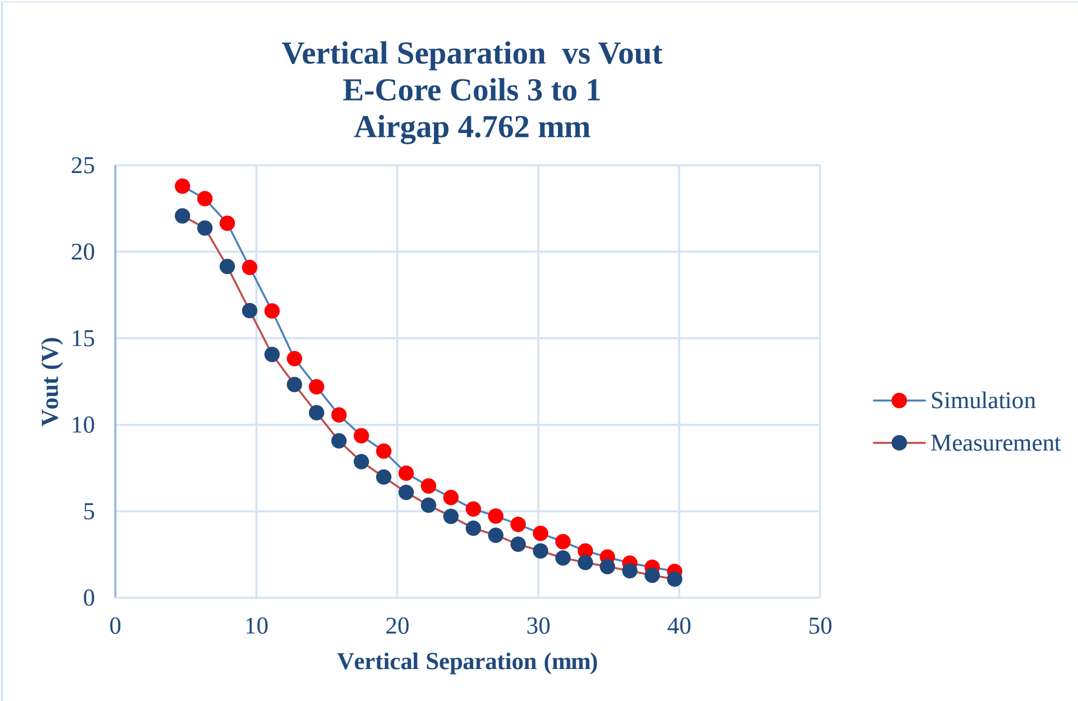



Figure 4-40 E-core Coils Three-to-One Vertical Separation vs Voltage

The graphs decreased in a similar manner. The values were similar from around 35 mm to around 40 mm. However, the simulation showed higher values overall, specially from around 5 mm to around 35 mm. The maximum values were 22.08 volts for the measurements and 23.78 volts for the simulation. The numerical data is shown in APPENDIX M2. The E-core coils three-to-one vertical separation vs efficiency test is shown in Figure 4-41.

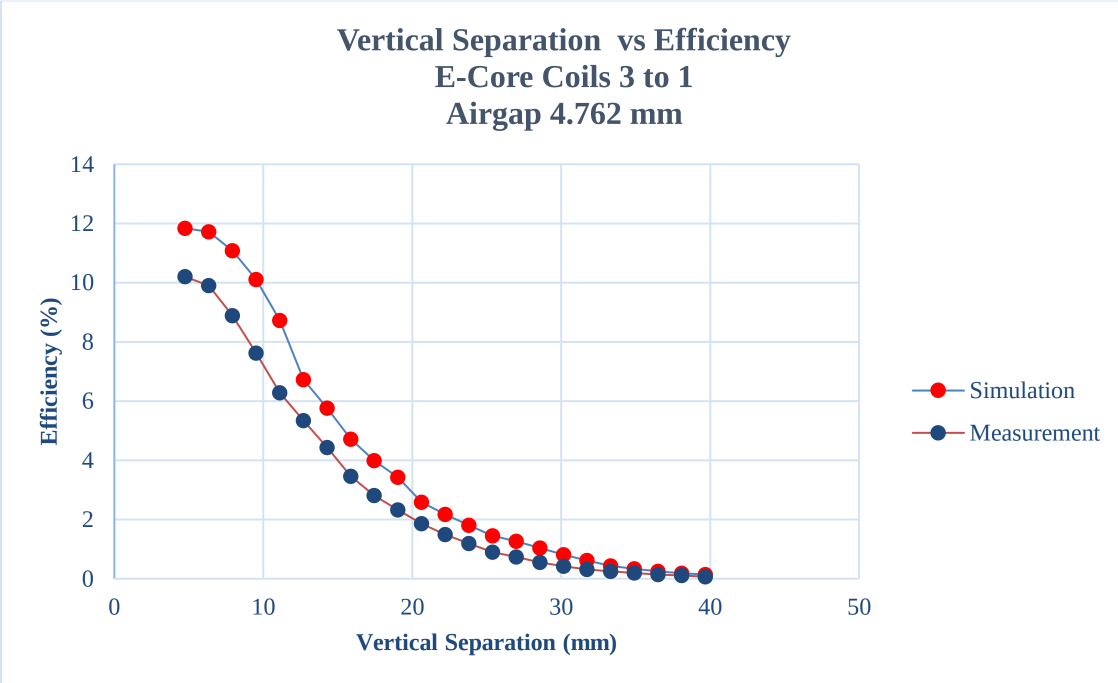



Figure 4-41 E-core Coils Three-to-One Vertical Separation vs Efficiency

The graphs decreased in a similar manner. The values were similar from around 20 mm to around 40 mm. the simulation showed higher values from around 5 mm to around 20 mm. The maximum values were 10.2 % for the measurements and 11.83 % for the simulations. The numerical data is shown in APPENDIX M2. The E-core coils three-to-one load vs voltage test is shown in Figure 4-42.

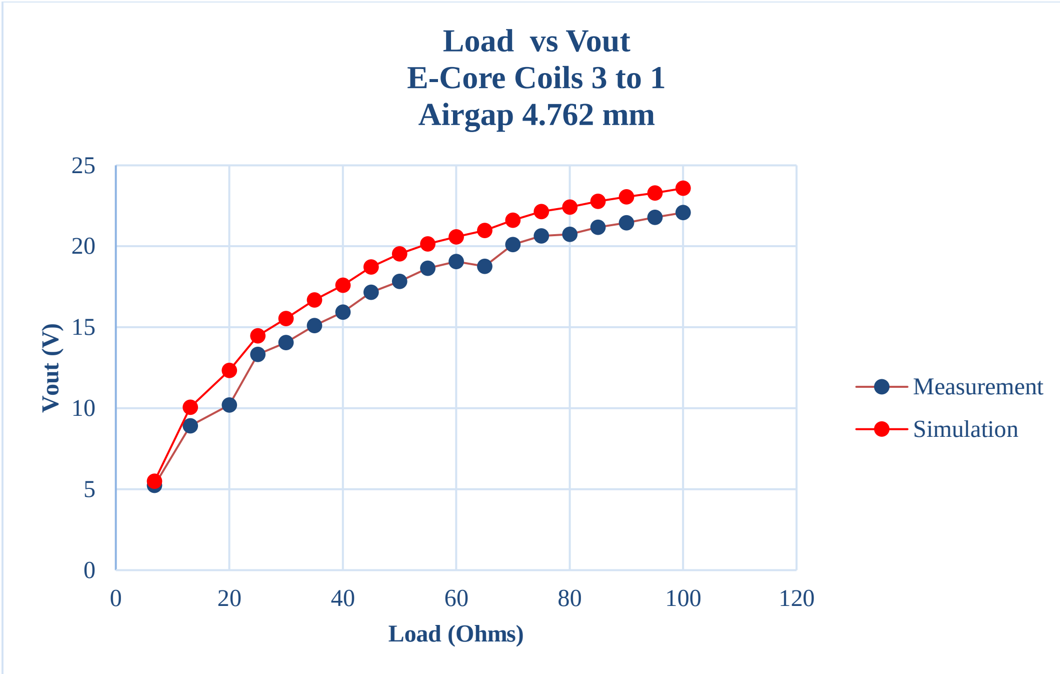



Figure 4-42 E-core Coils Three-to-One Load vs Voltage

The test was performed at 4.77 mm vertical separation. The graphs increased in a similar manner. The values were similar. However, the simulation values were higher from 35 Ohms to 100 Ohms. The maximum values were 22.08 volts for the measurements and 23.58 volts for the simulations. The numerical data is shown in APPENDIX N2. The E-core coils three-to-one load vs efficiency test is shown in Figure 4-43.

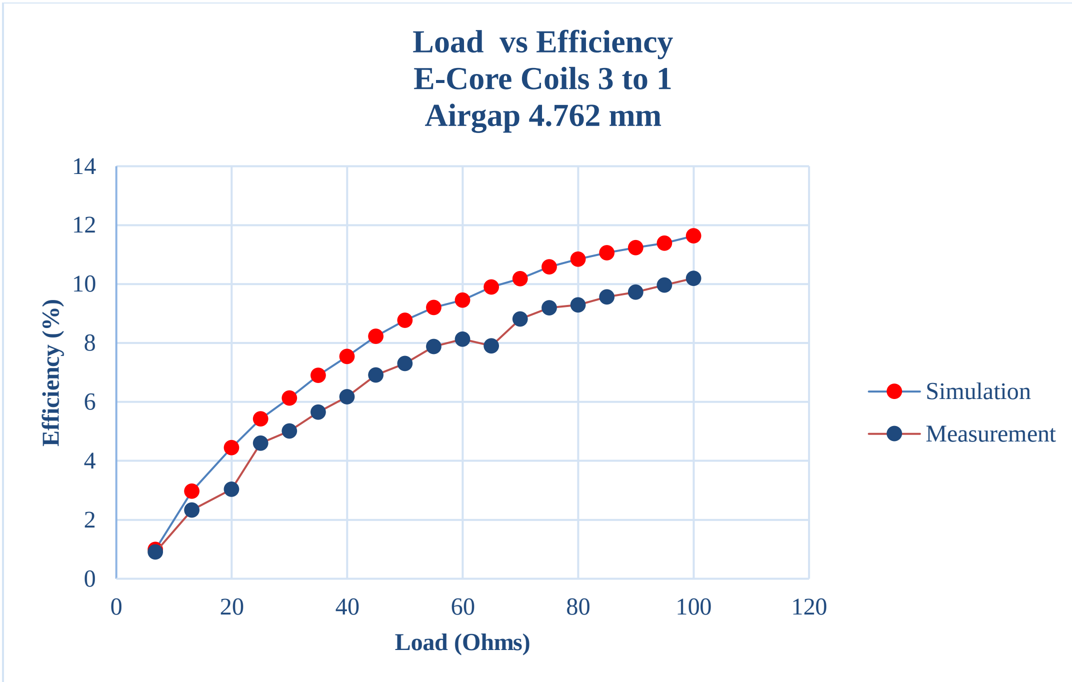



Figure 4-43 E-core Coils Three-to-One Load vs Efficiency

The test was performed at 4.77 mm vertical separation. The graphs increase in a similar manner. The simulation showed higher values from 10 Ohms to 100 Ohms. The maximum values were 10.2 % for the measurements and 11.63 % for the simulation. The numerical data is shown in APPENDIX N2.

# CHAPTER 5: COIL TYPES EFFICIENCY COMPARISONS

## 5.1 Introduction

The previous chapters 2 to 4 showed the experiment and simulation results for air coils, air coils with added cores, and E-core coils. The different coil types were tested for vertical separation, horizontal separation, and different loads. The tests took place to understand the voltage and efficiency behavior under different circumstances. This chapter focuses on the comparison of the different coil types to determine the appropriate coil type for future railroad applications research. Voltage is an important parameter when considering scenarios such as charging batteries, the efficiency comparisons overwrite the output voltage comparison. However, additional power electronics converters can be added to adjust the output voltage as required. Therefore, this research focuses on efficiency comparisons. In addition, simulations help understand the behavior of the configurations, but based on the results of previous chapters, there was usually a tolerance in comparison to the actual measurements. Moreover, simulations introduce these tolerances because of ideal scenario assumptions that do not occur very often in real life. This being the case, the comparisons will use the actual measurements data to ensure real-life expectations and capabilities.

## 5.2 One Transmitter to One Receiver Coil Comparisons

The comparisons start with the one transmitter to one receiver coil comparisons. For the one-to-one, the transmitter coils were arranged in a transmitter and receiver configuration having one transmitter and one receiver. The comparisons started with the efficiency comparisons at the same vertical separation considering 100 Ohms as the load. The vertical separation comparisons are shown in Table 5-1.

| Table 5-1 Vertical Separation Comparisons One-to-One | | | | |
|---|---|---|---|---|
| Efficiency Comparison, Vin 6 Volts | | | | |
| Load 100 Ohms, Horizontal separation 0 mm | | | | |
| Vertical Separation (mm) | Air Coils Efficiency (%) | Air Coils with One Core Efficiency (%) | Air Coils with Two Cores Efficiency (%) | E-core Coils Efficiency (%) |
| 12.912 | **0.213** | 0.686 | 0.893 | **3.525** |
| 27.2 | **0.0115** | | 0.112 | **0.196** |

The comparisons for table 5-1 had two types of sources the first type was direct measurement data and the second was data calculated using linear interpolation. The Linear interpolation data is shown in Table 5-2. The Vertical separation comparisons show the increase of efficiency from left to right. The Air coils show the lowest efficiency for 12.91 mm and 27.7 mm airgap. The air coil with one core was higher than air coils. The air coils with one core had only data for the 12.91 mm because that’s the test condition set for the coil’s airgap. The air coils with two cores show higher efficiencies than the air coils, and air coils with one core. The E-core coils had the highest efficiencies for the 12.91 mm and 27.2 mm airgap.

| Table 5-2 Linear Interpolation One-to-One | | | | | | |
|---|---|---|---|---|---|---|
| Coil Type | Dist (X) | X0 | X1 | Y0 | Y1 | Efficiency |
| E-Core 12.9125 mm | 12.9125 | 12.7 | 14.2875 | 3.621429 | 2.90002381 | **3.524863** |
| Air Coils 12.912 mm | 12.9125 | 12.7 | 14.2875 | 0.2230479 | 0.15329341 | **0.213711** |
| Air Coils 27.2 mm | 27.2 | 26.9875 | 28.575 | 0.01198225 | 0.00854438 | **0.011522** |
| E-core Coils 27.2 mm | 27.2 | 26.9875 | 28.575 | 0.20768023 | 0.12393023 | **0.19647** |

Table 5-2 showed the linear interpolation data from Excel. The parameters used to calculate the efficiency were vertical separation determined by X0 and X1, and efficiencies determined by Y0 and Y1. The target distance variable was "Dist (x)", which was the distance at which the efficiency should be calculated. The efficiency percentage differences were calculated as well. The vertical separation comparisons percentage are shown in Table 5-3.

| Table 5-3 Vertical Separation Comparisons Percentage One-to-One | | | | |
|---|---|---|---|---|
| Vertical Separation (mm) | Air Coils | Air Coils with One Core | Air Coils with Two Cores | E-core Coils |
| 12.912 | 6.042553 | 19.46099 | 25.33333 | 100 |
| 27.2 | 5.867347 | | 57.14286 | 100 |

In order to calculate the percentages, the highest value was set to 100 % for the 12.91 mm airgap, and separately for the 27.2 mm airgap. Therefore, the percentages were in relation to the highest efficiency achieved for the given airgap. The efficiency percentages increase from left to right as expected. Also, comparisons for the highest efficiency were performed. The comparisons took into consideration different airgaps, and different loads. The load comparisons values are shown in Table 5-4.

| Table 5-4 Load Comparisons One-to-One | | | | | |
|---|---|---|---|---|---|
| Highest Efficiency Comparison, Vin 6 Volts | | | | | |
| Horizontal separation 0 mm | | | | | |
| Load (Ohms) | Air Coils Airgap 1.375 mm Efficiency (%) | Air Coils with One Core Airgap 12.912 mm Efficiency (%) | Air Coils with Two Cores Airgap 12.912 mm Efficiency (%) | Air Coils with Two Cores Airgap 27.2 mm Efficiency (%) | E-core Coils Airgap 3.175 mm Efficiency (%) |
| 100 | | | | | 11.781 |
| 10 | 5.141 | | | | |
| 7 | | | | 0.277 | |
| 5 | | | 4.488 | | |
| 5 | | 1.895 | | | |

.

The load comparisons showed the maximum efficiency achieved for the different coil types during the measurements. The maximum efficiencies don’t have a set pattern since the airgap and load were different for each coil type. The highest efficiency was found for the E-core coils, the efficiency was 11.78 % at 3.18 mm airgap. The efficiency was very good for 6 volts input voltage. The second highest efficiency comes from the air coils; This happens because the airgap was close to 0 mm, which facilitates high efficiency. The third highest was air coils with two cores at 12.91 mm. The fourth efficiency was air coils with one core at 12.91 mm. the lowest efficiency was for air coils with two cores at 27.2 mm. The low efficiency was due to the high airgap. A percentage comparison for the load test was also performed. The load comparison percentage results are shown in Table 5-5.

| Table 5-5 Load Comparisons Percentage One-to-One | | | | | |
|---|---|---|---|---|---|
| Load (Ohms) | Air Coils | Air Coils with One Core Airgap 12.912 mm | Air Coils with Two Cores Airgap 12.912 mm | Air Coils with Two Cores Airgap 27.2 mm | E-core Coils Airgap 3.175 mm |
| 100 | | | | | 100 |
| 10 | 43.63806 | | | | |
| 7 | | | | 2.3512435 | |
| 5 | | | 38.09524 | | |
| 5 | | 16.08522 | | | |

The percentages were made relative to the highest efficiency. The highest efficiency was found for the E-core coils, and it was determined to be 100 %. All other efficiencies were compared to this efficiency. The percentages were as expected proportional to the measured percentages.

5.3 Multiple transmitter Coils to One Receiver Coil Comparisons

The measurement across coil types were mainly dedicated to multiple transmitters to one receiver since that was the closest configuration to a real-life scenario. The tests were conducted to test the wireless power transmission dynamic behavior. However, the behaviors directly apply to static transfer as well. There was a combination dedicated for the static charging scenario, the E-core coils three transmitters to one receiver. The multiple-to-one comparisons were more complex since there were several categories for comparison. Similar to the ono to one there was a universal comparison across the coil types. In addition, there were more specific comparisons that take place across two coil types or even one coil type. The specific comparisons had two categories. The first category were comparisons between air coils and air coils with added cores. The second category compares the E-cores 7 to 1 and E-cores 3 to 1. The load vs efficiency comparison graph for air coils and air coils with added load at peak position at 20 mm airgap is shown in Figure 5-1.

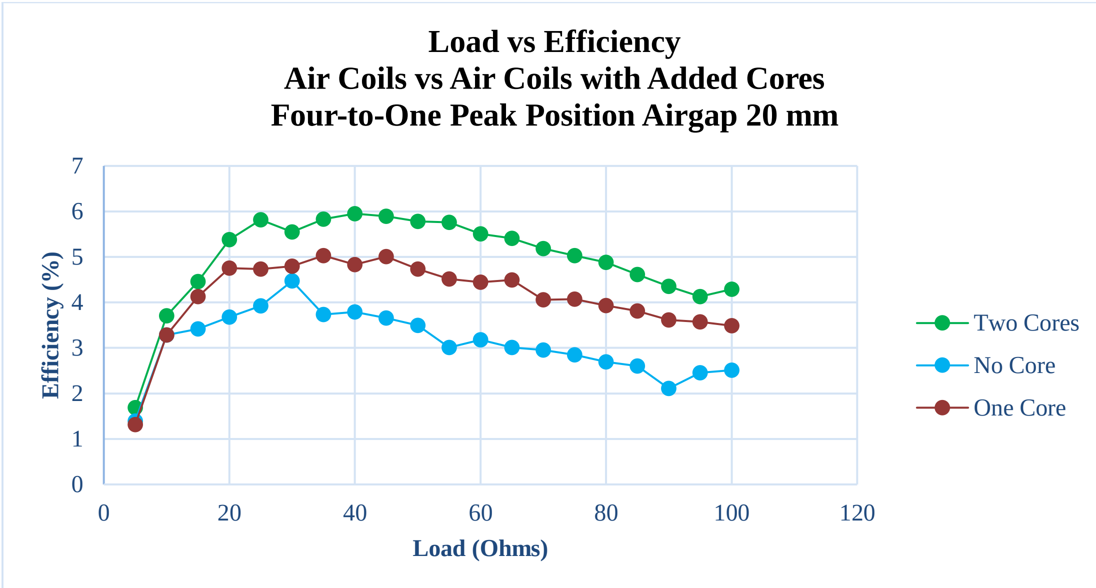



Figure 5-1 Air Coils vs Air Coils with Added Cores Load vs Efficiency Peak Position at 20 mm Airgap

The comparisons were performed at 20 mm vertical separation and 0 mm horizontal separation. The graphs show the differences between air coils and air coils with added cores. The lower efficiency was shown by air coils with no core. The air coils with one core show higher efficiencies and have intermediate values. The air coils with two cores show the highest efficiency across different loads. The maximum values for the graphs were 4.47 % for no core at 30 Ohms, 5.03 % for one core at 35 Ohms, and 5.95 % at 40 Ohms. The load vs efficiency comparison graph for air coils and air coils with added load at steady position at 20 mm airgap is shown in Figure 5-2.

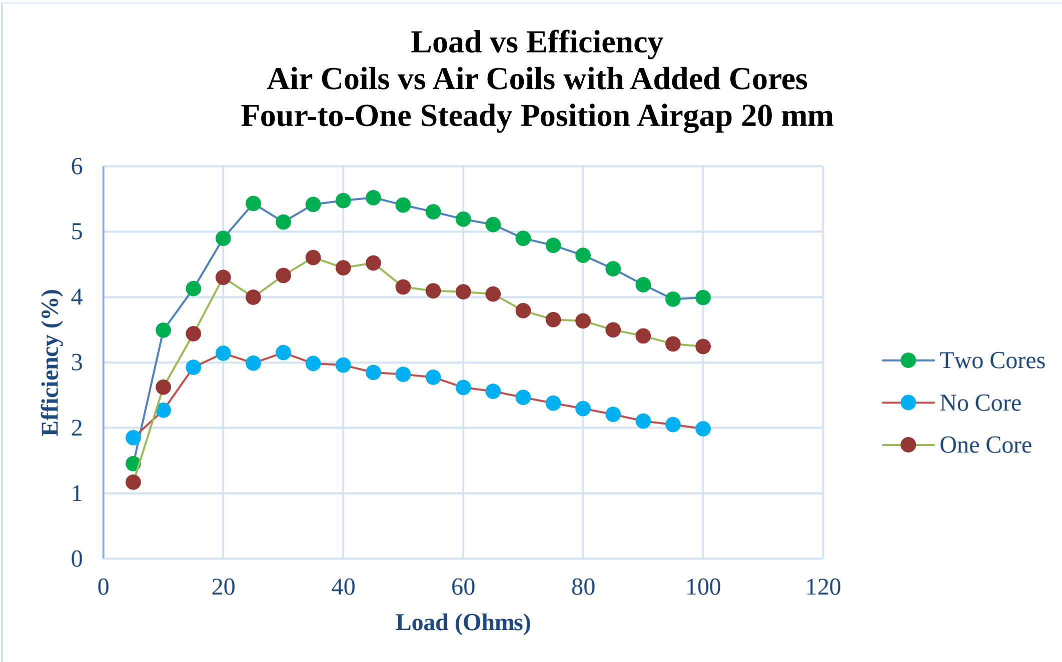



Figure 5-2 Air Coils vs Air Coils with Added Cores Load vs Efficiency Steady Position at 20 mm Airgap

The comparisons were performed at 20 mm vertical separation and 100 mm horizontal separation. The difference in efficiencies was higher between the graphs in the steady position. Similar to the peak position, the graphs increase in efficiency with the number of cores. The air coils with no core were the least efficient. The air coils with one core were intermediate efficient. The air coils with two cores were the ones with the highest efficiency. The maximum values for the graphs were 3.15 % for no core at 30 Ohms, 4.61 % for one core at 35 Ohms, and 5.52 % for two cores at 45 Ohms. The load vs efficiency comparison graph for air coils and air coils with added load at peak position at 27.2 mm airgap is shown in Figure 5-3.

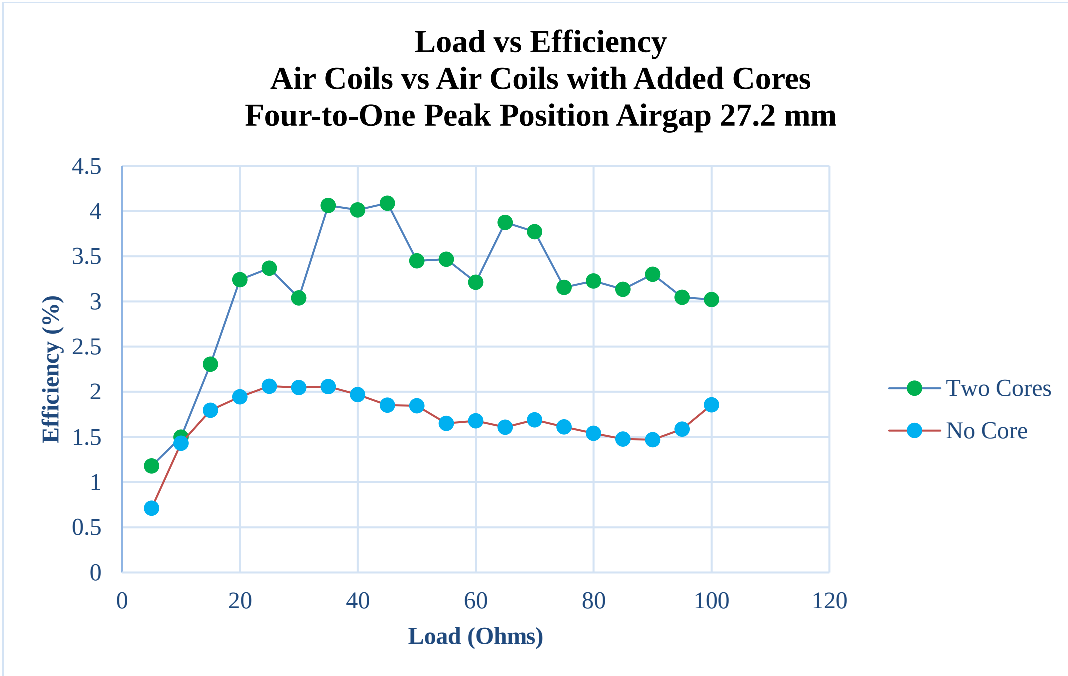



Figure 5-3 Air Coils vs Air Coils with Added Cores Load vs Efficiency Peak Position at 27.2 mm Airgap

The comparisons were performed at 27.2 mm vertical separation and 0 mm horizontal separation. The graphs show a big gap. The air coils with no core had the lowest efficiency. The air coils with two cores had the highest frequency. The maximum values were 2.06 % for no core at 35 Ohms, and 4.09 % for two cores at 45 Ohms. The load vs efficiency comparison graph for air coils and air coils with added load at steady position at 27.2 mm airgap is shown in Figure 5-3.

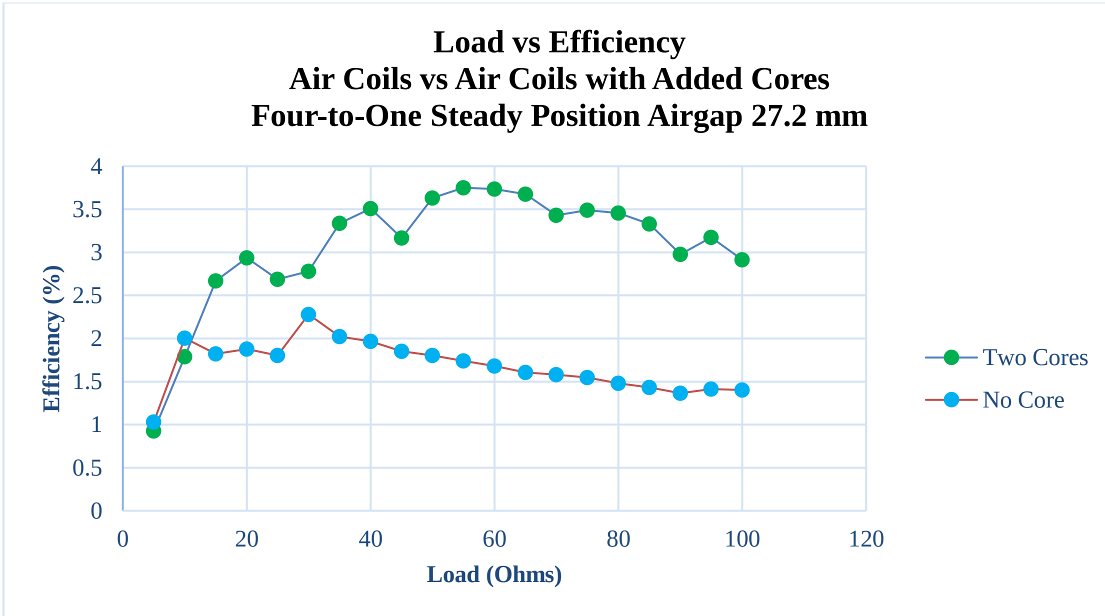



Figure 5-4 Air Coils vs Air Coils with Added Cores Load vs Efficiency Steady Position at 27.2 mm Airgap

The comparisons were performed at 27.2 mm vertical separation and 100 mm horizontal separation. The graphs showed a big difference in efficiencies. The air coils with no core showed the lowest efficiency. The air coils with two cores showed the highest efficiency. The maximum values were 2.28 % for no core at 30 Ohms and 3.75 % for two cores at 55 Ohms. The second specific comparisons focus on E-core coils. The load vs efficiency comparison graph for E-core coils 7 to 1 and E-core coils 3 to 1 load at peak position at 4.76 mm airgap is shown in Figure 5-5.

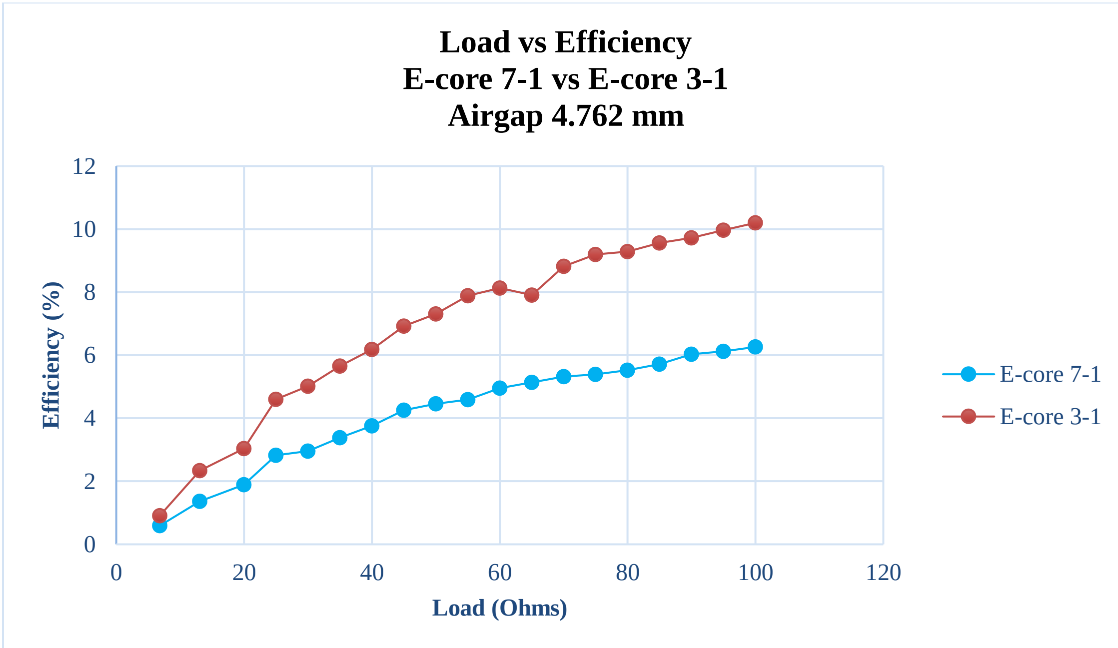



Figure 5-5 E-core 7-1 vs E-core 3-1 Load vs Efficiency Peak Position at 4.762 mm Airgap

The comparisons were performed at 27.2 mm vertical separation and 0 mm horizontal separation. The graphs were similar at lower resistance values. Both graphs show an uneven efficiency increase as the resistance increases. The E-core 7-1 graph showed the lowest efficiency values, and the E-core 3-1 showed the highest efficiency values. The maximum values were 10.2 % for E-core 3-1 at 100 Ohms, and 6.26 % for E-core 7-1 at 100 Ohms. Similar to the one-to-one comparison, there were comparisons comprising all the tested coil types. The vertical separation comparison across coil types multiple transmitter to one receiver is shown in Table 5-6.

| Table 5-6 Vertical Separation Comparisons Multiple Transmitter to One Receiver | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Efficiency Comparison, Vin 6 Volts | | | | | | | | | |
| Load 100 Ohms | | | | | | | | | |
| Vertical Separation (mm) | Air Coils 4 to 1 Peak Position Efficiency (%) | Air Coils 4 to 1 Steady Position Efficiency (%) | Air Coils 4 to 1 with One Core Peak Position Efficiency (%) | Air Coils 4 to 1 with One Core Steady Position Efficiency (%) | Air Coils 4 to 1 with Two Cores Peak Position Efficiency (%) | Air Coils 4 to 1 with Two Cores Steady Position Efficiency (%) | E-core Coils 7 to 1 Peak Position Efficiency (%) | E-core Coils 7 to 1 Low Position Efficiency (%) | E-core Coils 3 to 1 Peak Position Efficiency (%) |
| 20 | 2.509 | 1.989 | 3.488 | 3.242 | 4.288 | 3.995 | **0.659** | **0.408** | **2.041** |
| 27.2 | 1.855 | 1.401 | | | 3.023 | 2.915 | **0.232** | **0.137** | **0.715** |

The efficiencies were higher at peak positions for every group. The test airgaps were 20 mm and 27.2 mm since these were the physical boundary limitations given by the ferrite blocks size, for air coils with added cores. Unlike the one-to-one comparisons, the E-core coil efficiencies were very low at the given airgaps. The air coils and air coils with added cores had values increase as the number of cores increases. The lowest efficiency was given by E-core 3 to 1 peak position at 20 mm airgap, and E-core 7 to 1 low position at 27.2 mm. The highest efficiencies were given by air coils with two cores peak position at 20 mm and 27.2 mm.  The bolded values were calculated using linear interpolation to had a proper parallel comparison across the coil types. The linear interpolation values and calculations are shown in Table 5-7.

| Table 5-7 Linear Interpolation Multiple Transmitter to One Receiver | | | | | | |
|---|---|---|---|---|---|---|
| Coil Type | Dist (X) | X0 | X1 | Y0 | Y1 | Efficiency |
| E-core Coils 7 to 1 Peak Position 20 mm | 20 | 19.05 | 20.637 | 0.756 | 0.595 | **0.65962319** |
| E-core Coils 7 to 1 Low Position 20 mm | 20 | 19.05 | 20.637 | 0.476 | 0.364 | **0.40895526** |
| E-core Coils 7 to 1 Peak Position 27.2 mm | 27.2 | 26.9875 | 28.575 | 0.237041 | 0.1991724 | **0.23197186** |
| E-core Coils 7 to 1 Low Position 27.2 mm | 27.2 | 26.9875 | 28.575 | 0.14112 | 0.1085356 | **0.1367583** |
| E-core Coils 3 to 1 Peak Position 20 mm | 20 | 19.05 | 20.637 | 2.320019 | 1.854405 | **2.04129608** |
| E-core Coils 3 to 1 Peak Position 27.2 mm | 27.2 | 26.9875 | 28.575 | 0.740362 | 0.5522989 | **0.71518783** |

The linear interpolations show the higher values, lower values, and the setpoint for the calculation. The X0 and X1 were for the lower and higher distances consecutively. The Y0 and Y1 were for the higher and lower efficiencies consecutively. The set distance was shown under “Dist (X)” for all the calculations. The “Efficiency” showed the new calculated efficiency. The table was made using Excel. The comparison percentages were also calculated, and are shown in Table 5-8.

Table 5-8 Vertical Separation Comparisons Percentage Multiple Transmitter to One Receiver

| Vertical Separation (mm) | Air Coils 4 to 1 Peak Position | Air Coils 4 to 1 Steady Position | Air Coils 4 to 1 with One Core Peak Position | Air Coils 4 to 1 with One Core Steady Position | Air Coils 4 to 1 with Two Cores Peak Position | Air Coils 4 to 1 with Two Cores Steady Position | E-core Coils 7 to 1 Peak Position | E-core Coils 7 to 1 Low Position | E-core Coils 3 to 1 Peak Position |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 58.512 | 46.385 | 81.343 | 75.606 | 100 | 93.167 | 15.368 | 9.514 | 47.598 |
| 27.2 | 61.362 | 46.344 | | | 100 | 96.427 | 7.674 | 4.531 | 23.652 |

The vertical separation comparison percentage table showed the efficiency percentages in relation to the highest efficiency achieved. The table was as expected. The table was made using Excel. The vertical separation comparisons show the efficiencies at relatively high vertical separations. However, practical applications will happen at the highest efficiency vertical separation. Also, for practical applications, the most efficient load will be taken into consideration. The load comparisons for multiple transmitters to one receiver are shown in Table 5-9.

Table 5-9 Load Comparisons Multiple Transmitter to One Receiver

Highest Efficiency Comparison, Vin 6 Volts

| Load (Ohms) | Air Coils 4 to 1 Peak Position Airgap 20 mm Efficiency (%) | Air Coils 4 to 1 Steady Position Airgap 9.738 mm Efficiency (%) | Air Coils 4 to 1 with One Core Peak Position Airgap 20 mm Efficiency (%) | Air Coils 4 to 1 with One Core Steady Position Airgap 20 mm Efficiency (%) | Air Coils 4 to 1 with Two Cores Peak Position Airgap 20 mm Efficiency (%) | Air Coils 4 to 1 with Two Cores Steady Position Airgap 20 mm Efficiency (%) | E-core Coils 7 to 1 Peak Position Airgap 4.7625 mm Efficiency (%) | E-core Coils 7 to 1 Low Position Airgap 4.7625 mm Efficiency (%) | E-core Coils 3 to 1 Peak Position Airgap 4.7625 mm Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|
| 100 | | 3.284 | | | | | 6.262 | 3.334 | 10.199 |
| 45 | | | | | | 5.521 | | | |
| 40 | | | | | 5.951 | | | | |
| 35 | | | 5.029 | 4.605 | | | | | |
| 30 | 4.47 | | | | | | | | |

The efficiency results were as expected. The coil types efficiencies increase from left to right, for the peak positions, considering that the peak position values were always higher compared to the steady position and low position values of the same group. The air coils showed the lowest efficiencies 3.28 % at 100 Ohms steady position and 9.74 mm airgap. The highest efficiency was 10.2 %for the E-core coils 3 to 1 at 100 Ohms and 4.76 mm airgap. The highest efficiency was close to the heist efficiency from the one-to-one comparisons 11.78 %. The vertical separation was slightly lower for the one-to-one comparisons though at 3.18 mm airgap. The percentage comparisons were also performed.

| Table 5-10 Load Comparisons Percentages Multiple Transmitter to One Receiver | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Highest Efficiency Comparison, Vin 6 Volts | | | | | | | | | |
| Load | Air Coils 4 to 1 Peak Position Airgap 20 mm | Air Coils 4 to 1 Steady Position Airgap 9.738 mm | Air Coils 4 to 1 with One Core Peak Position Airgap 20 mm | Air Coils 4 to 1 with One Core Steady Position Airgap 20 mm | Air Coils 4 to 1 with Two Cores Peak Position Airgap 20 mm | Air Coils 4 to 1 with Two Cores Steady Position Airgap 20 mm | E-core Coils 7 to 1 Peak Position Airgap 4.7625 mm | E-core Coils 7 to 1 Low Position Airgap 4.7625 mm | E-core Coils 3 to 1 Peak Position Airgap 4.7625 mm |
| 100 | | 32.199 | | | | | 61.398 | 32.689 | 100 |
| 45 | | | | | | 54.133 | | | |
| 40 | | | | | 58.349 | | | | |
| 35 | | | 49.309 | 45.151 | | | | | |
| 30 | 43.827 | | | | | | | | |

The percentage comparisons were done in relation to the highest efficiency value. The percentages were as expected directly proportional to the efficiencies. The table was made with Excel.

# CHAPTER 6: PROTOTYPE DEVELOPMENT

## 6.1 Introduction

The research started with the NCDOT's project for wireless power transfer systems. There had been a few previous researches about wireless power transfer. However, the current prototype was initially built by the senior design team RAIL_WIRE2 2019 [4]. The team made a basic system used to test the air coils. After the senior design finished the project, the initial prototype was retrieved and modified to conduct a new research. The new research was documented in this thesis. The initial prototype had the basic capabilities without the modularity aspect. During this research, the prototype was modularized to be mobile for research and demonstration/presentation purposes.

## 6.2 Prototype Modularization and Improvements

The prototype modularization was proposed and performed during this research. The improvements and modifications required the addition of power electronics components. Also, some aspects were improved such as voltage ripple for the output voltage, and a digital display for the output voltage. A list of the utilized materials is shown in Table 6-1.

| Table 6-1 Materials List | | | |
|---|---|---|---|
| **Part Name** | **Vendor** | **Quantity** | **Item Number** |
| Power Supply | Digikey | 2 | 285-1825-ND |
| Rectifying Capacitor | Digikey | 2 | 493-14604-1-ND |
| Potentiometer | Digikey | 2 | CT2155-ND |
| ACtoDC 5V Converter | Digikey | 2 | 945-3190-ND |
| USB Adaptor | Digikey | 3 | 1568-1300-ND |
| Perforated Board | Digikey | 2 | 1568-1129-ND |
| LCD Display Voltmeter | Digikey | 4 | 1528-1141-ND |
| Power Switch | Digikey | 1 | 360-1927-ND |
| Power Cord | Digikey | 1 | Q110-ND |
| Tape | Digikey | 2 | 3M9848-ND |
| Terminals | Digikey | 50 | A1072CT-ND |

The materials are shown in Figure 6-1 and Figure 6-2.

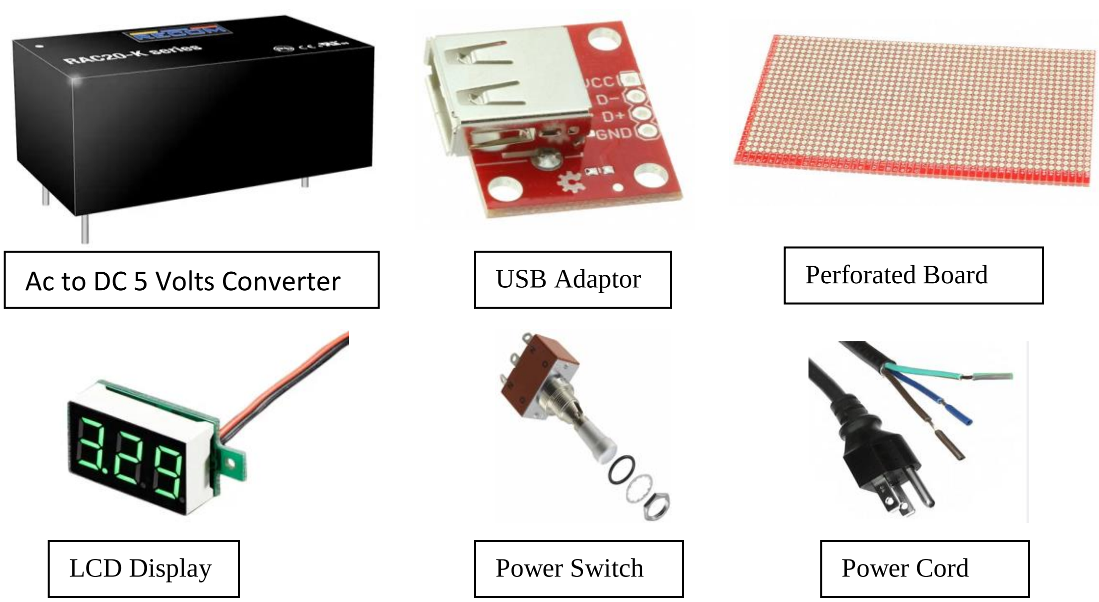



Figure 6-1 Prototype Materials

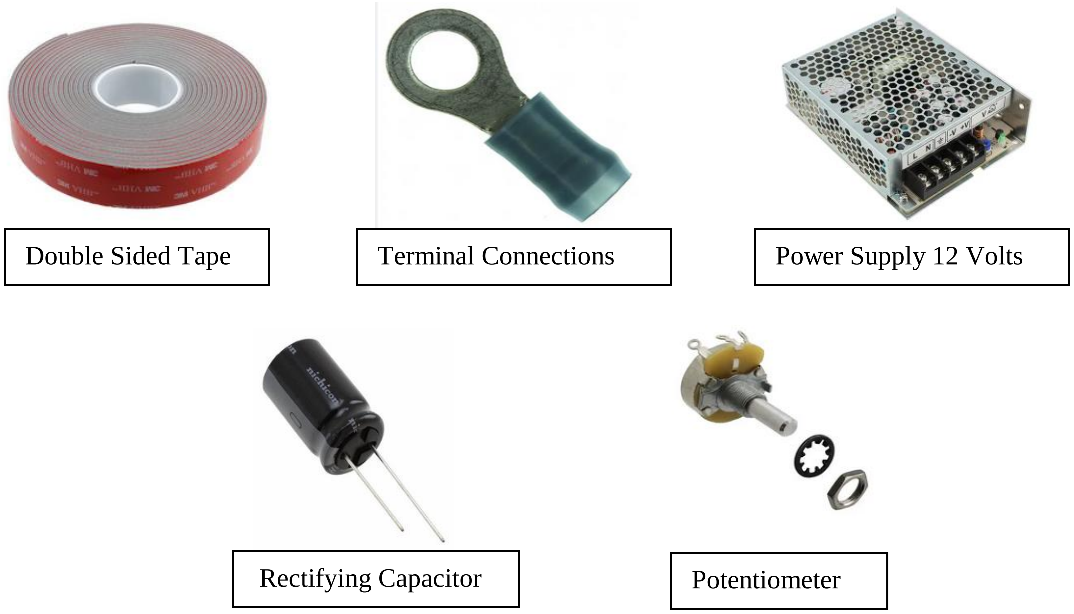



Figure 6-2 Prototype Materials Continuation

The power supply 12 volts was used to power the two half H-bridge inverters. The rectifying capacitor was used to mitigate the ripple from the output voltage. The potentiometer was used to test different loads. The AC to DC 5V converter was used to power the TI control/CARD R1.3 that controls the inverters. The UBS adaptors connect to the TI control/CARD R1.3 and the AC to DC 5V converter. The perforated board was used to host the AC to DC 5V converter and the UBS adaptors. The LCD display voltmeter was used to display the output voltage. The Power switch connecter the power supply 12 volts and the AC to DC 5V converter to the power cord allowing for electronics independent power. The power cord connects to the power switch and the power outlet. The tape was double-sided tape used to hold power electronics in place and to attach the plastic railways to the new platform. The terminals were used to connect the inverter outputs to the transmitter coils; it was also used to connect the transmitter and receiver coils. The system connections controller block diagram is shown in Figure 6-3.

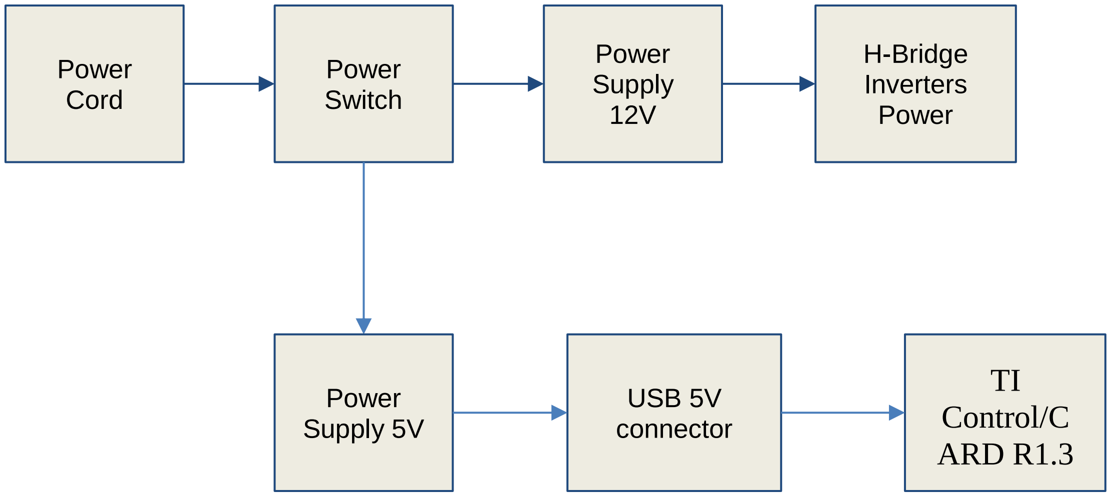



Figure 6-3 Connections Controller Block Diagram

The initial prototype used power supplies connected to the H-bridge inverters and the TI control/CARD R1.3 boards. This new modular prototype comprises the power supply and power converter inside the same enclosing. The connections power transmission block diagram is shown in Figure 6-4.

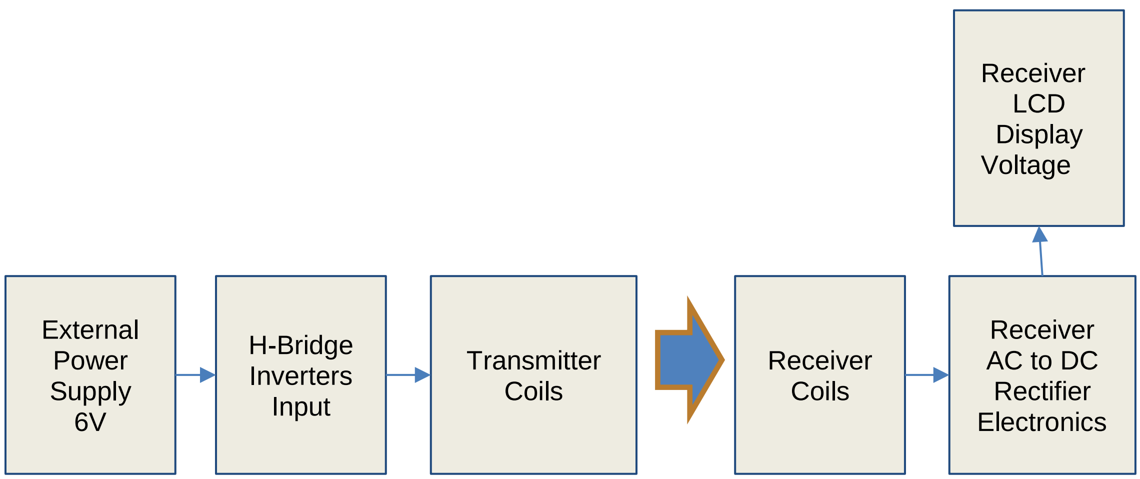



Figure 6-4 Connections Power Transmission Block Diagram

The connections power transmission block diagram showed the system transmission. The power transmitted works separately from the power electronic power, and it was provided by an external power supply. The power supply was connected to the H-Bridge inverter input; the inverter converted the DC signal into high-frequency AC signal. The H-bridge output was connected to the transmitter coils powering them with the high-frequency AC. The power was transferred wirelessly to the receiver coils. The receiver coils powered the AC to DC rectifier. The rectifier was connected to a load, in this diagram the LCD display voltage was connected. The electronics box module comprised the H-bridge inverter, the TI Control/CARD R1.3, and the power electronics components to make the prototype modular. The electronics box module is shown in Figure 6-5.


Figure 6-5 Electronics Box Module

The terminal connections are shown in Figure 6-6.

Figure 6-6 Terminal Connections

The Additional components added to the electronics module are shown in Figure 6-7. The additional components included the 12 volts power supply, the converter assembly with the USB adaptors, and the power cord and power switch connections.

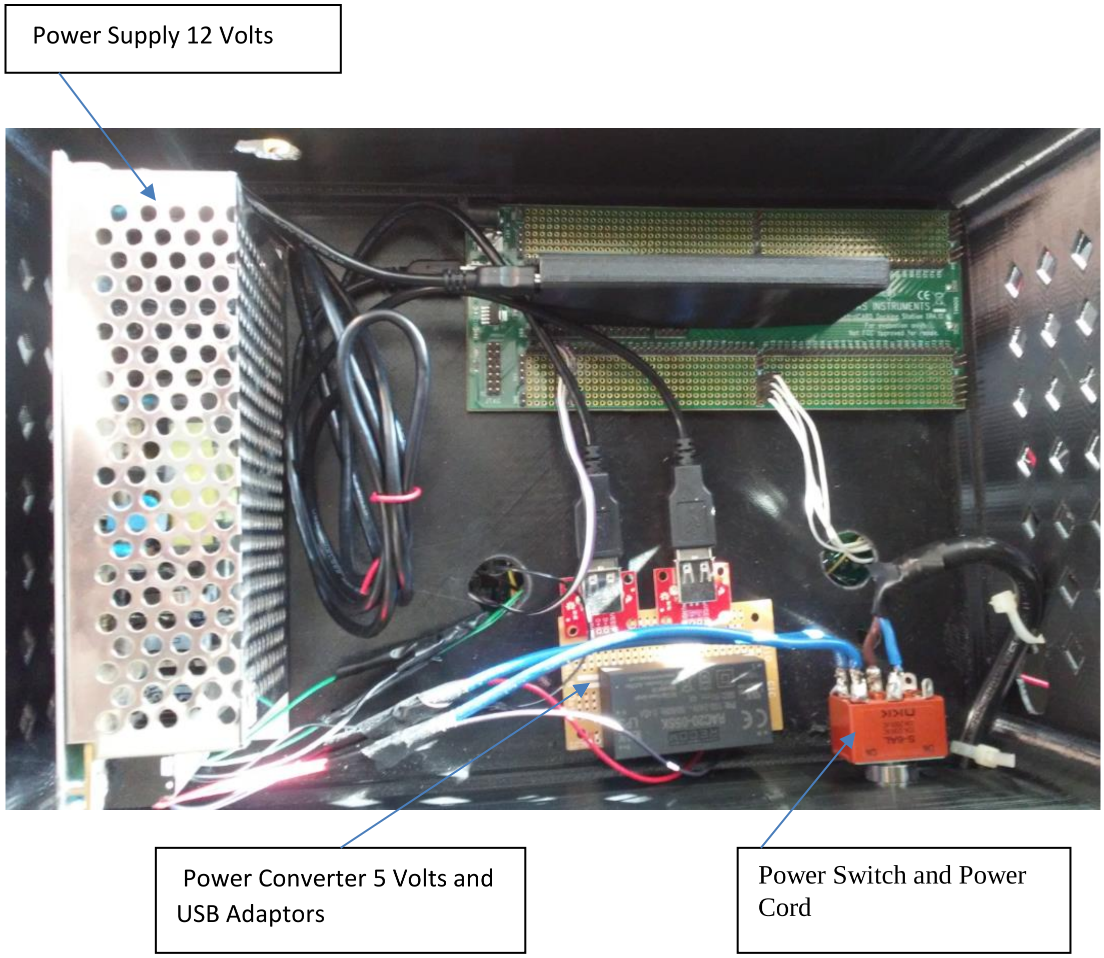



Figure 6-7 Additional Components for Modularity

The LCD display voltmeter was positioned on the receiver side electronics housing. The receiver LCD display voltmeter is shown in Figure 6-8.

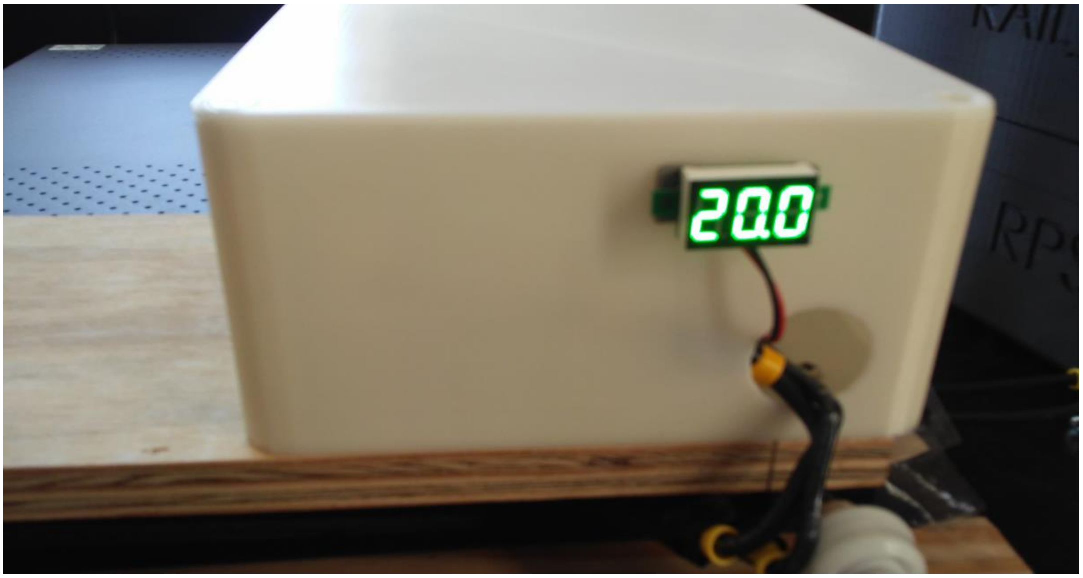



Figure 6-8 LCD Display Voltmeter

There were plastic rails also used for the transmitter base. The rails were 3D printed. The transmitter base was replaced with a wooden base with engraved channels. The channels run longitudinal and horizontally; they were meant to house metal bars for testing different scenarios. The testing will show how different base support materials will affect the system efficiency. The wooden base with plastic rail tracks is shown in Figure 6-9.

Figure 6-9 Wooden Base with Plastic Rails

The wooden base longitudinal engravings are shown in Figure 6-10

Figure 6-10 Wooden Base Longitudinal Engraving

The wooden base horizontal engraving is shown in Figure 6-11

Figure 6-11 Wooden base Horizontal Engraving

The improvements made the prototype modular for presentations, and easy to use for testing. The engravings in the wooden base were for different reinforcement and material testing considering the creation of a base for the transmitter coils. The base materials testing was part of another parallel research conducted by other researchers.

# CHAPTER 7: CONCLUSIONS AND FUTURE WORK

## 7.1 Conclusions

This research involved the testing and simulation of scaled-down wireless power transfer systems. The tests were divided into three main categories and two main subcategories. The three main categories were air coils, air coils with added cores, and E-core coils. The two main subcategories were the one transmitter to one receiver and the multiple transmitters to one receiver. Most of the results were as expected with some exceptions that can help us understand more the behavior of wireless power transfer using different core types. There were very consistent results for common behaviors across all coils types. Such behaviors were higher efficiency at lower vertical separation, and higher efficiency at proper horizontal separation, namely, “peak position”.

An interesting pattern for the results was the increase of efficiency for air coils and air coils with added cores at lower loads; the loads were in the range from 30 Ohms to 45 Ohms. On the other hand, the E-cores showed higher values at the highest load-tested value of 100 Ohms. The one transmitter to one receiver maximum efficiency value was very close to the maximum efficiency for the multiple transmitters to one receiver. The small difference seems to be associated with a difference in vertical separation (3.18 mm for the one transmitter to one receiver, and 4.76 mm for multiple transmitters to one receiver). Since the vertical separation for the one transmitter to one receive was smaller, its efficiency was slightly higher. This demonstrates a good scalability factor going from a small configuration with only one transmitter and one receiver to a larger configuration of multiple transmitters and one receiver. The utilization of ferrite cores increased the efficiency of the overall system.

For the air coil and air coils with added cores. Another pattern showed that the more core material utilized, the higher the resulting efficiency within one design. This does not apply to the E-core coils, since the amount of core material was less than the amount utilized by air coils with cores; yet the E-core coils show much higher capable efficiency.

The E-core coils were designed in a way that the E-core surrounded the Litz wire directing and shielding the magnetic flux at the same time. The E-core design also reduced the width and increased the length of the coils; this helped to reduce directional flux cancellation due to the modularization of transmitter coils. The air coils design had a 127 mm width and the E-core had a 64 mm width; this makes the E-core coils it 50.4 % shorter than the air coils with added cores. Another aid was the oval shape like the winding of the E-core making the flux cancellation with the next transmitter even smaller.

An interesting result for the multiple transmitter coils and one receiver coil was the different behavior for different coil shapes; while the air coils and air coils with added cores showed higher efficiencies at relatively high vertical separations of 20 mm and 27.2 mm, the E-core coils showed higher efficiencies at relatively low vertical separations. Even though the E-core coils efficiency was lower at 20 mm and 27.2 mm, its highest efficiency achieved was much higher than the other coil types at 10.2 %. The one transmitter to one receiver comparison showed higher efficiencies as the number of cores increase for air coils and air coils with added cores; the E-core coils showed the highest efficiency for all test comparisons in this subcategory. The highest efficiency achieved by the one transmitter to one receiver E-core was 11.78 %. Even though, the achieved efficiencies were not high enough to be considered practical, the efficiency will increase once the input voltage was increased. This occurs due to higher voltages require lower current to transmit the same amount of power. The current was what creates heat on components from dissipated energy.; this was lost energy dropping the overall efficiency.

The research had shown valuable input in several parameters that previously might have been not considered in the same way. The main parameters influencing the efficiency of an inductive system were vertical separation, horizontal separation, and load resistance. These three parameters will directly influence the output voltage and efficiency. Since actual components and materials have tolerances, such as internal resistances and component values, efficiencies have some tolerance. This tolerance can be accounted for in actual designs. The research was successful by investigating and comparing results for all the tested coil types. Also, the simulations tend to produce smoother graphs than actual measurements. For most of the cases, the simulations showed higher values than the actual measurements, but there were a few exceptions when the actual measurements showed higher values than the simulations. The simulations were good reference sources. However, there are many variables in the real world which, interfere and alter the final obtained efficiency. Simulations will not consider all real-life factors making then good for reference, but not ideal for final engineering decisions. Design decisions should be based on actual measurements performed under real-life circumstances. Finally, the construction of a modular demonstration and test prototype was a successful. Furthermore, the prototype makes it easier to transport, operate, and test, for future studies.

## 7.2 Future Work

Since the behavior of different coil types was explored in this research, many other questions and test scales were raised: The E-core coil showed the grate potential for enhancing wireless power transfer performance. However, improvements should be made to achieve even higher efficiency at low voltage (6 volts). The one possible improvement was to extend the E-core to cover all the Litz wire to shield the magnetic field. Another improvement would be to make individual electronics for the transmitters or a selective system that will power the coils independently instead of powering all the coils from the same electronics. This will allow for more real-life scenarios since when powering long miles of transmitter coils will require multiple electronic sets located along the railroads. The current system can handle higher input voltages.

More research regarding input voltage and efficiency re can be conducted. Since it was a small-scale system, there will be limitation, therefore the testing should be performed by small increments at a time; this should also include temperature measurements at the component level. The coils should be temperature-controlled to avoid damaging the Litz wire coating, therefore maintaining good efficiency at high frequencies.

There is another set of testing that should take place for the system; the transmitters base construction depends on how different reinforcement material will affect the system efficiency, hence, should be further investigated. There were several tests to take place especially with the wooden base; the different tests will give better guidance showing how the system reacts to different materials and metals used as a base. Another improvement will be the implementation of a closed-loop system, since the current prototype operates as an open-loop system. The closed-loop system can be implemented by using pulse width modulation.  The closed-loop system can prevent overheating of the transmitter and receiver coils. The mentioned improvements will help with further testing and research. However, the small-scale system can only provide so much data. Scaling up the system would be needed to attain even more realistic data. The next scaling-up scenarios involve a 5 Kw system that will be conducted by other members of the NCDOT wireless power transfer research at UNCC.

Finally, a full-size scale system needs to be explored. The full-scale system design will start with the load in consideration (battery pack). The power needed can be calculated by accounting for the worst-case scenario when the locomotive was operating at maximum load. The wireless power transfer system should provide continuous power to maintain full operation in a scenario where the battery was empty or not available for usage. After the worst-case scenarios were accounted for, more cost-benefits parameters should be established to obtain a full design criterion.

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# APPENDIX A: AIR COILS ONE-TO-ONE VERTICAL SEPARATION COUPLING COEFFICIENT

| Air Square Coil Vertical Airgap Separation | |
|---|---|
| Z_separation [mm] | CplCoef(Tx_In,Rx_In) [] - Space='1.375mm' |
| 1.5875 | 0.891008 |
| 3.175 | 0.79156 |
| 4 | 0.752028 |
| 4.7625 | 0.715484 |
| 5 | 0.702777 |
| 6.35 | 0.64963 |
| 7.9375 | 0.595684 |
| 9.525 | 0.549452 |
| 11.1125 | 0.509559 |
| 12.7 | 0.473523 |
| 14.2875 | 0.442301 |
| 15.875 | 0.414362 |
| 17.4625 | 0.392039 |
| 19.05 | 0.373225 |
| 20.6375 | 0.35435 |
| 22.225 | 0.337803 |
| 23.8125 | 0.312453 |
| 25.4 | 0.304139 |
| 26.9875 | 0.290028 |
| 28.575 | 0.273496 |
| 30 | 0.264523 |
| 30.1625 | 0.256915 |
| 31.75 | 0.246314 |
| 33.3375 | 0.240413 |
| 34.925 | 0.22915 |
| 36.5125 | 0.219672 |
| 38.1 | 0.204916 |
| 39.6875 | 0.197473 |
| 41.275 | 0.193985 |
| 42.8625 | 0.185088 |
| 44.45 | 0.177475 |
| 45 | 0.173371 |

# APPENDIX B: AIR COILS ONE-TO-ONE VERTICAL SEPARATION VS EFFICIENCY

| Small Square Air Coil 1 to 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Vertical Separation Test | | | | | | | | | |
| Vin 6V, Load 100 Ohms | | | | | | | | | |
| Sim | | | | | | | Real | | |
| Pin(W) | Coupling Coefficient | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Distance in mm | Vout | Efficiency |
| 16.8 | 0.891008 | 1.5875 | 0.0625 | 5.9364 | 0.352408 | 2.097669 | 1.8 | 5.79 | 1.995482 |
| 16.8 | 0.79156 | 3.175 | 0.125 | 5.4088 | 0.292551 | 1.741376 | 4.975 | 5.1 | 1.548214 |
| 16.8 | 0.752028 | 4 | 0.15748 | 5.2758 | 0.278341 | 1.65679 | 6.5625 | 4.9 | 1.429167 |
| 16.8 | 0.715484 | 4.7625 | 0.1875 | 5.2738 | 0.27813 | 1.655534 | 8.15 | 4.5 | 1.205357 |
| 16.7 | 0.702777 | 5 | 0.19685 | 5.2528 | 0.275919 | 1.65221 | 9.7375 | 3.9 | 0.910778 |
| 16.7 | 0.64963 | 6.35 | 0.25 | 4.7801 | 0.228494 | 1.368225 | 11.325 | 3.42 | 0.700383 |
| 16.7 | 0.595684 | 7.9375 | 0.3125 | 3.8737 | 0.150056 | 0.898536 | 12.9125 | 2.9 | 0.503593 |
| 16.7 | 0.549452 | 9.525 | 0.375 | 3.3185 | 0.110124 | 0.659428 | 14.5 | 2.6 | 0.40479 |
| 16.7 | 0.509559 | 11.1125 | 0.4375 | 2.8066 | 0.07877 | 0.471677 | 16.0875 | 2.2 | 0.28982 |
| 16.7 | 0.473523 | 12.7 | 0.5 | 2.423 | 0.058709 | 0.351553 | 17.675 | 1.93 | 0.223048 |
| 16.7 | 0.442301 | 14.2875 | 0.5625 | 2.065 | 0.042642 | 0.255343 | 19.2625 | 1.6 | 0.153293 |
| 16.7 | 0.414362 | 15.875 | 0.625 | 1.8615 | 0.034652 | 0.207496 | 20.85 | 1.55 | 0.143862 |
| 16.8 | 0.392039 | 17.4625 | 0.6875 | 1.7091 | 0.02921 | 0.17387 | 22.4375 | 1.24 | 0.091524 |
| 16.8 | 0.373225 | 19.05 | 0.75 | 1.5951 | 0.025443 | 0.151449 | 24.025 | 1.07 | 0.068149 |
| 16.8 | 0.35435 | 20.6375 | 0.8125 | 1.4846 | 0.02204 | 0.131193 | 25.6125 | 0.94 | 0.052595 |
| 16.8 | 0.337803 | 22.225 | 0.875 | 1.3901 | 0.019324 | 0.115023 | 27.2 | 0.8 | 0.038095 |
| 16.8 | 0.312453 | 23.8125 | 0.9375 | 1.2528 | 0.015695 | 0.093423 | 28.7875 | 0.65 | 0.025149 |
| 16.8 | 0.304139 | 25.4 | 1 | 1.2054 | 0.01453 | 0.086487 | 30.375 | 0.61 | 0.022149 |
| 16.9 | 0.290028 | 26.9875 | 1.0625 | 1.1304 | 0.012778 | 0.07561 | 31.9625 | 0.45 | 0.011982 |
| 16.9 | 0.273496 | 28.575 | 1.125 | 1.046 | 0.010941 | 0.064741 | 33.55 | 0.38 | 0.008544 |
| 16.9 | 0.264523 | 30 | 1.181102 | 1.0008 | 0.010016 | 0.059266 | 35.1375 | 0.31 | 0.005686 |
| 16.9 | 0.256915 | 30.1625 | 1.1875 | 0.960044 | 0.009217 | 0.054538 | 36.725 | 0.19 | 0.002136 |
| 16.9 | 0.246314 | 31.75 | 1.25 | 0.906995 | 0.008226 | 0.048677 | 38.3125 | 0.16 | 0.001515 |
| 16.9 | 0.240413 | 33.3375 | 1.3125 | 0.87716 | 0.007694 | 0.045527 | 39.9 | 0.06 | 0.000213 |
| 16.9 | 0.22915 | 34.925 | 1.375 | 0.816837 | 0.006672 | 0.039481 | 41.4875 | 0.02 | 2.37E-05 |
| 16.9 | 0.219672 | 36.5125 | 1.4375 | 0.771947 | 0.005959 | 0.03526 | 43.075 | 0.007 | 2.9E-06 |
| 16.9 | 0.204916 | 38.1 | 1.5 | 0.702763 | 0.004939 | 0.029223 | 44.6625 | 0 | 0 |
| 16.9 | 0.197473 | 39.6875 | 1.5625 | 0.668943 | 0.004475 | 0.026478 | | | |
| 16.9 | 0.193985 | 41.275 | 1.625 | 0.652482 | 0.004257 | 0.025191 | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 16.9 | 0.185088 | 42.862<br>5 | 1.6875 | 0.610195 | 0.003723 | 0.022032 | | | |
| 16.9 | 0.177475 | 44.45 | 1.75 | 0.578095 | 0.003342 | 0.019775 | | | |

# APPENDIX C: AIR COILS ONE-TO-ONE HORIZONTAL SEPARATION

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Small Square Air Coil 1 to 1 | | | | | | | |
| | Horizontal Separation Test at 1.375mm airgap | | | | | | | |
| | Vin 6V, Load 100 Ohms | | | | | | | |
| Sim | | | | | | | Real | |
| Coupling Coefficient | Pin (W) | Distance in cm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.904948 | 17 | 0 | 0 | 5.9867 | 0.358406 | 2.108269 | 5.9 | 2.047647 |
| 0.839732 | 17 | 0.5 | 0.19685 | 5.5839 | 0.311799 | 1.834114 | 5.35 | 1.683676 |
| 0.734839 | 17 | 1 | 0.393701 | 5.4088 | 0.292551 | 1.720889 | 4.8 | 1.355294 |
| 0.656878 | 16.9 | 1.5 | 0.590551 | 4.8807 | 0.238212 | 1.40954 | 3.8 | 0.854438 |
| 0.596136 | 16.8 | 2 | 0.787402 | 3.8978 | 0.151928 | 0.904336 | 3.5 | 0.729167 |
| 0.547499 | 16.8 | 2.5 | 0.984252 | 3.293 | 0.108438 | 0.645467 | 3.03 | 0.546482 |
| 0.503826 | 16.8 | 3 | 1.181102 | 2.7474 | 0.075482 | 0.449298 | 2.55 | 0.387054 |
| 0.463581 | 16.65 | 3.5 | 1.377953 | 2.2946 | 0.052652 | 0.316228 | 2.3 | 0.317718 |
| 0.429501 | 16.75 | 4 | 1.574803 | 1.9837 | 0.039351 | 0.234929 | 1.96 | 0.229349 |
| 0.395525 | 16.7 | 4.5 | 1.771654 | 1.743 | 0.03038 | 0.181919 | 1.63 | 0.159096 |
| 0.360857 | 16.7 | 5 | 1.968504 | 1.5232 | 0.023201 | 0.13893 | 1.18 | 0.083377 |
| 0.327842 | 16.75 | 5.5 | 2.165354 | 1.3467 | 0.018136 | 0.108275 | 0.76 | 0.034484 |
| 0.294676 | 16.8 | 6 | 2.362205 | 1.1566 | 0.013377 | 0.079626 | 0.66 | 0.025929 |
| 0.262474 | 16.85 | 6.5 | 2.559055 | 0.992672 | 0.009854 | 0.058481 | 0.6 | 0.021365 |
| 0.230592 | 16.9 | 7 | 2.755906 | 0.823945 | 0.006789 | 0.040171 | 0.38 | 0.008544 |
| 0.19803 | 16.9 | 7.5 | 2.952756 | 0.673331 | 0.004534 | 0.026827 | 0.22 | 0.002864 |
| 0.164666 | 16.9 | 8 | 3.149606 | 0.512919 | 0.002631 | 0.015567 | 0 | 0 |
| 0.149037 | 16.9 | 8.5 | 3.346457 | 0.448905 | 0.002015 | 0.011924 | 0 | 0 |
| 0.131268 | 16.9 | 9 | 3.543307 | 0.373074 | 0.001392 | 0.008236 | 0 | 0 |
| 0.12002 | 16.9 | 9.5 | 3.740157 | 0.321781 | 0.001035 | 0.006127 | 0 | 0 |
| 0.100684 | 16.9 | 10 | 3.937008 | 0.246497 | 0.000608 | 0.003595 | 0 | 0 |
| 0.076577 | 16.9 | 10.5 | 4.133858 | 0.154911 | 0.00024 | 0.00142 | 0 | 0 |
| 0.058517 | 16.9 | 11 | 4.330709 | 0.092715 | 8.6E-05 | 0.000509 | 0 | 0 |
| 0.035218 | 16.9 | 11.5 | 4.527559 | 0.032691 | 1.07E-05 | 6.32E-05 | 0 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.016468 | 17 | 12 | 4.724409 | 0.00661 | 4.37E-07 | 2.57E-06 | 0 | 0 |

# APPENDIX D: AIR COILS ONE-TO-ONE LOAD TEST

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Small Square Air Coil 1 to 1 | | | | | | | | |
| Different Loads Test 0 mm Airgap | | | | | | | | |
| Vin 6V | | | | | | | | |
| SIM | | | | | | | Real | |
| Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 16.8 | 100 | 1.375 | 0.054134 | 5.3423 | 0.285402 | 1.69882 | 5.79 | 1.995482 |
| 16.7 | 95 | 1.375 | 0.054134 | 5.3365 | 0.299771 | 1.795035 | 5.3 | 1.770564 |
| 16.7 | 90 | 1.375 | 0.054134 | 5.2725 | 0.308881 | 1.849585 | 5.25 | 1.833832 |
| 16.6 | 85 | 1.375 | 0.054134 | 5.256 | 0.325006 | 1.957869 | 5.15 | 1.879695 |
| 16.7 | 80 | 1.375 | 0.054134 | 5.2387 | 0.34305 | 2.05419 | 5.1 | 1.946856 |
| 16.7 | 75 | 1.375 | 0.054134 | 5.2336 | 0.365208 | 2.186872 | 5 | 1.996008 |
| 16.6 | 70 | 1.375 | 0.054134 | 5.2336 | 0.391294 | 2.357192 | 4.82 | 1.999346 |
| 16.6 | 65 | 1.375 | 0.054134 | 5.1898 | 0.41437 | 2.496202 | 4.75 | 2.091057 |
| 16.5 | 60 | 1.375 | 0.054134 | 5.1817 | 0.4475 | 2.712123 | 4.89 | 2.415364 |
| 16.5 | 55 | 1.375 | 0.054134 | 5.1533 | 0.482845 | 2.926336 | 4.72 | 2.45492 |
| 16.6 | 50 | 1.375 | 0.054134 | 5.1163 | 0.523531 | 3.153798 | 4.7 | 2.661446 |
| 16.6 | 45 | 1.375 | 0.054134 | 5.0624 | 0.569509 | 3.430776 | 4.62 | 2.857349 |
| 16.6 | 40 | 1.375 | 0.054134 | 5.0082 | 0.627052 | 3.77742 | 4.5 | 3.049699 |
| 16.5 | 35 | 1.375 | 0.054134 | 4.939 | 0.696963 | 4.224021 | 4.4 | 3.352381 |
| 16.6 | 30 | 1.375 | 0.054134 | 4.8531 | 0.785086 | 4.729434 | 4.2 | 3.542169 |
| 16.6 | 25 | 1.375 | 0.054134 | 4.775 | 0.912025 | 5.494127 | 4 | 3.855422 |
| 16.6 | 20 | 1.375 | 0.054134 | 4.6537 | 1.082846 | 6.52317 | 3.75 | 4.235693 |
| 16.6 | 15 | 1.375 | 0.054134 | 4.4495 | 1.31987 | 7.951024 | 3.5 | 4.919679 |
| 16.7 | 10 | 1.375 | 0.054134 | 4.1403 | 1.714208 | 10.26472 | 2.93 | 5.140659 |
| 16.8 | 5 | 1.375 | 0.054134 | 3.421 | 2.340648 | 13.93243 | 2 | 4.761905 |

# APPENDIX E: AIR COILS ONE-TO-ONE LOAD VS VOLTAGE AT 12.912 MM

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Small Square Air Coil 1 to 1 | | | | | | | | | |
| Different Loads Test 12.9 mm Airgap | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.469343 | 16.5 | 100 | 12.9125 | 0.508366 | 3.1864 | 0.101531 | 0.615342 | 2.9 | 0.509697 |
| 0.469343 | 16.5 | 95 | 12.9125 | 0.508366 | 3.1822 | 0.106594 | 0.646022 | 2.84 | 0.514552 |
| 0.469343 | 16.5 | 90 | 12.9125 | 0.508366 | 3.1696 | 0.111626 | 0.676523 | 2.83 | 0.53932 |
| 0.469343 | 16.5 | 85 | 12.9125 | 0.508366 | 3.0977 | 0.112891 | 0.684189 | 2.815 | 0.565007 |
| 0.469343 | 16.5 | 80 | 12.9125 | 0.508366 | 3.0957 | 0.119792 | 0.726012 | 2.8 | 0.593939 |
| 0.469343 | 16.5 | 75 | 12.9125 | 0.508366 | 3.1207 | 0.12985 | 0.786971 | 2.79 | 0.629018 |
| 0.469343 | 16.5 | 70 | 12.9125 | 0.508366 | 3.0769 | 0.135247 | 0.819681 | 2.77 | 0.66432 |
| 0.469343 | 16.5 | 65 | 12.9125 | 0.508366 | 3.079 | 0.14585 | 0.883939 | 2.74 | 0.700009 |
| 0.469343 | 16.5 | 60 | 12.9125 | 0.508366 | 3.0413 | 0.154158 | 0.934294 | 2.7 | 0.736364 |
| 0.469343 | 16.5 | 55 | 12.9125 | 0.508366 | 3.0225 | 0.1661 | 1.006667 | 2.67 | 0.785554 |
| 0.469343 | 16.5 | 50 | 12.9125 | 0.508366 | 2.9893 | 0.178718 | 1.083141 | 2.61 | 0.825709 |
| 0.469343 | 16.5 | 45 | 12.9125 | 0.508366 | 2.9953 | 0.199374 | 1.208326 | 2.56 | 0.88264 |
| 0.469343 | 16.5 | 40 | 12.9125 | 0.508366 | 2.9474 | 0.217179 | 1.316237 | 2.46 | 0.916909 |
| 0.469343 | 16.5 | 35 | 12.9125 | 0.508366 | 2.9246 | 0.24438 | 1.481088 | 2.31 | 0.924 |
| 0.469343 | 16.5 | 30 | 12.9125 | 0.508366 | 2.9053 | 0.281359 | 1.705206 | 2.24 | 1.013657 |
| 0.469343 | 16.5 | 25 | 12.9125 | 0.508366 | 2.8606 | 0.327321 | 1.983765 | 2.14 | 1.110206 |
| 0.469343 | 16.5 | 20 | 12.9125 | 0.508366 | 2.8429 | 0.404104 | 2.449115 | 1.95 | 1.152273 |
| 0.469343 | 16.5 | 15 | 12.9125 | 0.508366 | 2.7621 | 0.508613 | 3.082504 | 1.84 | 1.367919 |
| 0.469343 | 16.5 | 10 | 12.9125 | 0.508366 | 2.5955 | 0.673662 | 4.0828 | 1.55 | 1.456061 |
| 0.469343 | 16.6 | 5 | 12.9125 | 0.508366 | 2.2025 | 0.970201 | 5.844586 | 1 | 1.204819 |

# APPENDIX F: AIR COILS FOUR-TO-ONE HORIZONTAL TEST

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Air Coils 4 to 1 | | | | | | | |
| Horizontal Separation Test | | | | | | | |
| Vin 6V, Load 100 Ohms | | | | | | | |
| SIM | | | | | | Real | |
| Pin(W) | Distance in cm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 7.8 | -31 | -12.2047 | 2.5094 | 0.062971 | 0.807319 | 2.1 | 0.565385 |
| 7.8 | -30.5 | -12.0079 | 2.5191 | 0.063459 | 0.813572 | 2.13 | 0.581654 |
| 7.8 | -30 | -11.811 | 2.5521 | 0.065132 | 0.835027 | 2.16 | 0.598154 |
| 7.8 | -29.5 | -11.6142 | 2.5904 | 0.067102 | 0.860278 | 2.19 | 0.614885 |
| 7.7 | -29 | -11.4173 | 2.6183 | 0.068555 | 0.890324 | 2.23 | 0.645831 |
| 7.7 | -28.5 | -11.2205 | 2.625 | 0.068906 | 0.894886 | 2.27 | 0.669208 |
| 7.7 | -28 | -11.0236 | 2.6642 | 0.07098 | 0.921813 | 2.3 | 0.687013 |
| 7.7 | -27.5 | -10.8268 | 2.6926 | 0.072501 | 0.941571 | 2.34 | 0.711117 |
| 7.7 | -27 | -10.6299 | 2.7355 | 0.07483 | 0.971813 | 2.38 | 0.735636 |
| 7.7 | -26.5 | -10.4331 | 2.7616 | 0.076264 | 0.990446 | 2.42 | 0.760571 |
| 7.7 | -26 | -10.2362 | 2.8015 | 0.078484 | 1.019273 | 2.45 | 0.779545 |
| 7.7 | -25.5 | -10.0394 | 2.8065 | 0.078764 | 1.022915 | 2.47 | 0.792325 |
| 7.7 | -25 | -9.84252 | 2.8385 | 0.080571 | 1.046374 | 2.48 | 0.798753 |
| 7.7 | -24.5 | -9.64567 | 2.8369 | 0.08048 | 1.045195 | 2.48 | 0.798753 |
| 7.7 | -24 | -9.44882 | 2.9205 | 0.085293 | 1.107704 | 2.49 | 0.805208 |
| 7.7 | -23.5 | -9.25197 | 2.938 | 0.086318 | 1.121019 | 2.5 | 0.811688 |
| 7.7 | -23 | -9.05512 | 2.9382 | 0.08633 | 1.121171 | 2.51 | 0.818195 |
| 7.7 | -22.5 | -8.85827 | 2.9823 | 0.088941 | 1.15508 | 2.55 | 0.844481 |
| 7.7 | -22 | -8.66142 | 3.0055 | 0.09033 | 1.173121 | 2.58 | 0.864468 |
| 7.7 | -21.5 | -8.46457 | 3.0102 | 0.090613 | 1.176793 | 2.615 | 0.888081 |
| 7.7 | -21 | -8.26772 | 3.0412 | 0.092489 | 1.201156 | 2.65 | 0.912013 |
| 7.7 | -20.5 | -8.07087 | 3.0588 | 0.093563 | 1.215098 | 2.7 | 0.946753 |
| 7.7 | -20 | -7.87402 | 3.0863 | 0.095252 | 1.237045 | 2.74 | 0.975013 |
| 7.7 | -19.5 | -7.67717 | 3.1526 | 0.099389 | 1.290765 | 2.78 | 1.003688 |
| 7.7 | -19 | -7.48031 | 3.157 | 0.099666 | 1.29437 | 2.83 | 1.040117 |
| 7.7 | -18.5 | -7.28346 | 3.2259 | 0.104064 | 1.351485 | 2.86 | 1.062286 |
| 7.7 | -18 | -7.08661 | 3.2653 | 0.106622 | 1.384699 | 2.89 | 1.084688 |
| 7.7 | -17.5 | -6.88976 | 3.2757 | 0.107302 | 1.393534 | 2.93 | 1.114922 |
| 7.7 | -17 | -6.69291 | 3.3262 | 0.110636 | 1.436832 | 2.97 | 1.145571 |
| 7.7 | -16.5 | -6.49606 | 3.3484 | 0.112118 | 1.456076 | 3.02 | 1.184468 |
| 7.7 | -16 | -6.29921 | 3.3882 | 0.114799 | 1.490896 | 3.06 | 1.216052 |
| 7.7 | -15.5 | -6.10236 | 3.4101 | 0.116288 | 1.510231 | 3.1 | 1.248052 |
| 7.7 | -15 | -5.90551 | 3.447 | 0.118818 | 1.543092 | 3.13 | 1.272325 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7.7 | -14.5 | -5.70866 | 3.4549 | 0.119363 | 1.550173 | 3.17 | 1.305052 |
| 7.7 | -14 | -5.51181 | 3.483 | 0.121313 | 1.575492 | 3.2 | 1.32987 |
| 7.7 | -13.5 | -5.31496 | 3.5003 | 0.122521 | 1.591182 | 3.24 | 1.363325 |
| 7.7 | -13 | -5.11811 | 3.5332 | 0.124835 | 1.621234 | 3.26 | 1.380208 |
| 7.7 | -12.5 | -4.92126 | 3.5618 | 0.126864 | 1.647587 | 3.27 | 1.388688 |
| 7.7 | -12 | -4.72441 | 3.5755 | 0.127842 | 1.660286 | 3.28 | 1.397195 |
| 7.7 | -11.5 | -4.52756 | 3.5839 | 0.128443 | 1.668096 | 3.28 | 1.397195 |
| 7.7 | -11 | -4.33071 | 3.5841 | 0.128458 | 1.668282 | 3.3 | 1.414286 |
| 7.7 | -10.5 | -4.13386 | 3.6085 | 0.130213 | 1.691074 | 3.32 | 1.431481 |
| 7.7 | -10 | -3.93701 | 3.6931 | 0.13639 | 1.771297 | 3.375 | 1.479302 |
| 7.7 | -9.5 | -3.74016 | 3.6873 | 0.135962 | 1.765738 | 3.41 | 1.510143 |
| 7.6 | -9 | -3.54331 | 3.7071 | 0.137426 | 1.808236 | 3.46 | 1.575211 |
| 7.6 | -8.5 | -3.34646 | 3.7555 | 0.141038 | 1.855761 | 3.5 | 1.611842 |
| 7.6 | -8 | -3.14961 | 3.7733 | 0.142378 | 1.873394 | 3.55 | 1.658224 |
| 7.6 | -7.5 | -2.95276 | 3.8108 | 0.145222 | 1.910815 | 3.59 | 1.695803 |
| 7.6 | -7 | -2.75591 | 3.8361 | 0.147157 | 1.936271 | 3.64 | 1.743368 |
| 7.6 | -6.5 | -2.55906 | 3.896 | 0.151788 | 1.997213 | 3.68 | 1.781895 |
| 7.6 | -6 | -2.3622 | 3.9155 | 0.153311 | 2.017255 | 3.72 | 1.820842 |
| 7.6 | -5.5 | -2.16535 | 3.9204 | 0.153695 | 2.022307 | 3.75 | 1.850329 |
| 7.6 | -5 | -1.9685 | 3.9615 | 0.156935 | 2.064932 | 3.79 | 1.890013 |
| 7.6 | -4.5 | -1.77165 | 3.9974 | 0.159792 | 2.102527 | 3.83 | 1.930118 |
| 7.6 | -4 | -1.5748 | 4.0265 | 0.162127 | 2.13325 | 3.86 | 1.960474 |
| 7.6 | -3.5 | -1.37795 | 4.0407 | 0.163273 | 2.148323 | 3.9 | 2.001316 |
| 7.6 | -3 | -1.1811 | 4.0926 | 0.167494 | 2.203865 | 3.95 | 2.052961 |
| 7.6 | -2.5 | -0.98425 | 4.1707 | 0.173947 | 2.288781 | 4 | 2.105263 |
| 7.6 | -2 | -0.7874 | 4.1879 | 0.175385 | 2.307698 | 4.06 | 2.168895 |
| 7.6 | -1.5 | -0.59055 | 4.237 | 0.179522 | 2.362128 | 4.12 | 2.233474 |
| 7.6 | -1 | -0.3937 | 4.229 | 0.178844 | 2.353216 | 4.145 | 2.260661 |
| 7.6 | -0.5 | -0.19685 | 4.3105 | 0.185804 | 2.444791 | 4.18 | 2.299 |
| 7.6 | 0 | 0 | 4.2745 | 0.182714 | 2.404125 | 4.25 | 2.376645 |
| 7.6 | 0.5 | 0.19685 | 4.2883 | 0.183895 | 2.419673 | 4.22 | 2.343211 |
| 7.6 | 1 | 0.393701 | 4.3046 | 0.185296 | 2.438103 | 4.28 | 2.410316 |
| 7.6 | 1.5 | 0.590551 | 4.2732 | 0.182602 | 2.402663 | 4.22 | 2.343211 |
| 7.6 | 2 | 0.787402 | 4.2568 | 0.181203 | 2.384256 | 4.18 | 2.299 |
| 7.6 | 2.5 | 0.984252 | 4.2244 | 0.178456 | 2.348099 | 4.18 | 2.299 |
| 7.6 | 3 | 1.181102 | 4.1976 | 0.176198 | 2.318401 | 4.14 | 2.255211 |
| 7.6 | 3.5 | 1.377953 | 4.1751 | 0.174315 | 2.293613 | 4.14 | 2.255211 |
| 7.6 | 4 | 1.574803 | 4.2058 | 0.176888 | 2.327468 | 4.11 | 2.222645 |
| 7.6 | 4.5 | 1.771654 | 4.2208 | 0.178152 | 2.344099 | 4.08 | 2.190316 |
| 7.6 | 5 | 1.968504 | 4.1745 | 0.174265 | 2.292954 | 4.06 | 2.168895 |
| 7.6 | 5.5 | 2.165354 | 4.2014 | 0.176518 | 2.3226 | 4.06 | 2.168895 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7.6 | 6 | 2.362205 | 4.2014 | 0.176518 | 2.3226 | 4.08 | 2.190316 |
| 7.6 | 6.5 | 2.559055 | 4.2014 | 0.176518 | 2.3226 | 4.08 | 2.190316 |
| 7.6 | 7 | 2.755906 | 4.2015 | 0.176526 | 2.322711 | 4.08 | 2.190316 |
| 7.6 | 7.5 | 2.952756 | 4.2208 | 0.178152 | 2.344099 | 4.08 | 2.190316 |
| 7.6 | 8 | 3.149606 | 4.2015 | 0.176526 | 2.322711 | 4.06 | 2.168895 |
| 7.6 | 8.5 | 3.346457 | 4.1546 | 0.172607 | 2.271145 | 4.08 | 2.190316 |
| 7.6 | 9 | 3.543307 | 4.2022 | 0.176585 | 2.323485 | 4.08 | 2.190316 |
| 7.6 | 9.5 | 3.740157 | 4.1508 | 0.172291 | 2.266992 | 4.08 | 2.190316 |
| 7.6 | 10 | 3.937008 | 4.2062 | 0.176921 | 2.32791 | 4.08 | 2.190316 |
| 7.6 | 10.5 | 4.133858 | 4.1718 | 0.174039 | 2.289989 | 4.08 | 2.190316 |
| 7.6 | 11 | 4.330709 | 4.2192 | 0.178016 | 2.342322 | 4.08 | 2.190316 |
| 7.6 | 11.5 | 4.527559 | 4.2044 | 0.17677 | 2.325918 | 4.08 | 2.190316 |
| 7.6 | 12 | 4.724409 | 4.1568 | 0.17279 | 2.273551 | 4.08 | 2.190316 |
| 7.6 | 12.5 | 4.92126 | 4.1606 | 0.173106 | 2.27771 | 4.08 | 2.190316 |
| 7.6 | 13 | 5.11811 | 4.2071 | 0.176997 | 2.328907 | 4.08 | 2.190316 |
| 7.6 | 13.5 | 5.314961 | 4.1961 | 0.176073 | 2.316744 | 4.08 | 2.190316 |
| 7.6 | 14 | 5.511811 | 4.1961 | 0.176073 | 2.316744 | 4.08 | 2.190316 |
| 7.6 | 14.5 | 5.708661 | 4.1514 | 0.172341 | 2.267648 | 4.11 | 2.222645 |
| 7.6 | 15 | 5.905512 | 4.1999 | 0.176392 | 2.320942 | 4.12 | 2.233474 |
| 7.6 | 15.5 | 6.102362 | 4.1796 | 0.174691 | 2.29856 | 4.125 | 2.238898 |
| 7.6 | 16 | 6.299213 | 4.2031 | 0.17666 | 2.32448 | 4.13 | 2.244329 |
| 7.6 | 16.5 | 6.496063 | 4.1983 | 0.176257 | 2.319174 | 4.14 | 2.255211 |
| 7.6 | 17 | 6.692913 | 4.2041 | 0.176745 | 2.325586 | 4.16 | 2.277053 |
| 7.6 | 17.5 | 6.889764 | 4.2268 | 0.178658 | 2.350768 | 4.18 | 2.299 |
| 7.6 | 18 | 7.086614 | 4.2131 | 0.177502 | 2.335554 | 4.18 | 2.299 |
| 7.6 | 18.5 | 7.283465 | 4.2336 | 0.179234 | 2.358338 | 4.2 | 2.321053 |
| 7.6 | 19 | 7.480315 | 4.2518 | 0.180778 | 2.378658 | 4.2 | 2.321053 |
| 7.6 | 19.5 | 7.677165 | 4.299 | 0.184814 | 2.431763 | 4.19 | 2.310013 |
| 7.6 | 20 | 7.874016 | 4.2479 | 0.180447 | 2.374297 | 4.15 | 2.266118 |
| 7.6 | 20.5 | 8.070866 | 4.2204 | 0.178118 | 2.343655 | 4.1 | 2.211842 |
| 7.6 | 21 | 8.267717 | 4.1697 | 0.173864 | 2.287684 | 4.06 | 2.168895 |
| 7.6 | 21.5 | 8.464567 | 4.1612 | 0.173156 | 2.278367 | 4.02 | 2.126368 |
| 7.6 | 22 | 8.661417 | 4.115 | 0.169332 | 2.228056 | 3.98 | 2.084263 |
| 7.6 | 22.5 | 8.858268 | 4.1241 | 0.170082 | 2.237921 | 3.94 | 2.042579 |
| 7.6 | 23 | 9.055118 | 4.0693 | 0.165592 | 2.178842 | 3.89 | 1.991066 |
| 7.6 | 23.5 | 9.251969 | 4.0174 | 0.161395 | 2.123619 | 3.86 | 1.960474 |
| 7.6 | 24 | 9.448819 | 3.9897 | 0.159177 | 2.094435 | 3.82 | 1.920053 |
| 7.6 | 24.5 | 9.645669 | 3.9762 | 0.158102 | 2.080285 | 3.77 | 1.870118 |
| 7.6 | 25 | 9.84252 | 3.9303 | 0.154473 | 2.032534 | 3.72 | 1.820842 |
| 7.6 | 25.5 | 10.03937 | 3.9051 | 0.152498 | 2.006553 | 3.68 | 1.781895 |
| 7.6 | 26 | 10.23622 | 3.8869 | 0.15108 | 1.987894 | 3.63 | 1.733803 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7.6 | 26.5 | 10.43307 | 3.8256 | 0.146352 | 1.925686 | 3.58 | 1.686368 |
| 7.7 | 27 | 10.62992 | 3.7442 | 0.14019 | 1.820654 | 3.53 | 1.618299 |
| 7.7 | 27.5 | 10.82677 | 3.7071 | 0.137426 | 1.784752 | 3.46 | 1.554753 |
| 7.7 | 28 | 11.02362 | 3.7067 | 0.137396 | 1.784367 | 3.42 | 1.519013 |
| 7.7 | 28.5 | 11.22047 | 3.6457 | 0.132911 | 1.726121 | 3.38 | 1.483688 |
| 7.7 | 29 | 11.41732 | 3.6044 | 0.129917 | 1.687234 | 3.35 | 1.457468 |
| 7.7 | 29.5 | 11.61417 | 3.5899 | 0.128874 | 1.673686 | 3.3 | 1.414286 |
| 7.7 | 30 | 11.81102 | 3.5296 | 0.124581 | 1.617932 | 3.28 | 1.397195 |
| 7.7 | 30.5 | 12.00787 | 3.5284 | 0.124496 | 1.616832 | 3.27 | 1.388688 |

# APPENDIX G: AIR COILS FOUR-TO-ONE VERTICAL SEPARATION PEAK POSITION

| **Air Long Coil Peak Position Airgap Vertical Separation** | |
|---|---|
| Z_separation [mm] | CplCoef(Tx_In,Rx_In) [] |
| 8.3625 | 0.462101 |
| 9.95 | 0.433885 |
| 11.5375 | 0.408457 |
| 14.7125 | 0.366131 |
| 16.3 | 0.348539 |
| 17.8875 | 0.331539 |
| 19.475 | 0.316516 |
| 21.0625 | 0.302411 |
| 22.65 | 0.290061 |
| 24.2375 | 0.277663 |
| 25.825 | 0.266804 |
| 27.4125 | 0.256254 |
| 29 | 0.24669 |
| 30.5875 | 0.237234 |
| 32.175 | 0.228708 |
| 33.7625 | 0.220524 |
| 35.35 | 0.212867 |
| 36.9375 | 0.205346 |
| 38.525 | 0.198503 |
| 40.1125 | 0.191889 |
| 41.7 | 0.186114 |
| 43.2875 | 0.179807 |
| 44.875 | 0.174106 |
| 46.4625 | 0.168589 |
| 48.05 | 0.163316 |
| 49.6375 | 0.15844 |
| 51.225 | 0.153648 |
| 52.8125 | 0.149004 |
| 53 | 0.148571 |

# APPENDIX H: AIR COILS FOUR-TO-ONE VERTICAL SEPARATION PEAK POSITION

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Large Air Coil 4 to 1 | | | | | | | | |
| Vertical Separation Test Peak Position | | | | | | | | |
| Vin 6V, Load 100 Ohms | | | | | | | | |
| SIM | | | | | | | Real | |
| Pin(W) | Spacers | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 7.2 | 7 | 9.7375 | 0.383366 | 5.4175 | 0.293493 | 4.076293 | 5.36 | 3.990222 |
| 7.3 | 8 | 11.325 | 0.445866 | 5.1276 | 0.262923 | 3.601682 | 5.118 | 3.588209 |
| 7.4 | 9 | 12.9125 | 0.508366 | 4.9581 | 0.245828 | 3.321994 | 4.918 | 3.268476 |
| 7.4 | 10 | 14.5 | 0.570866 | 4.5219 | 0.204476 | 2.763186 | 4.79 | 3.100554 |
| 7.5 | 11 | 16.0875 | 0.633366 | 4.3277 | 0.18729 | 2.497198 | 4.58 | 2.796853 |
| 7.5 | 12 | 17.675 | 0.695866 | 4.1531 | 0.172482 | 2.299765 | 4.44 | 2.62848 |
| 7.6 | 13 | 19.2625 | 0.758366 | 3.9696 | 0.157577 | 2.073385 | 4.31 | 2.444224 |
| 7.6 | 14 | 20.85 | 0.820866 | 3.8053 | 0.144803 | 1.905304 | 4.187 | 2.306706 |
| 7.6 | 15 | 22.4375 | 0.883366 | 3.7226 | 0.138578 | 1.823388 | 4.06 | 2.168895 |
| 7.6 | 16 | 24.025 | 0.945866 | 3.585 | 0.128522 | 1.691082 | 3.9 | 2.001316 |
| 7.6 | 17 | 25.6125 | 1.008366 | 3.4307 | 0.117697 | 1.548645 | 3.71 | 1.811066 |
| 7.6 | 18 | 27.2 | 1.070866 | 3.2774 | 0.107414 | 1.413336 | 3.68 | 1.781895 |
| 7.7 | 19 | 28.7875 | 1.133366 | 3.1618 | 0.09997 | 1.298309 | 3.58 | 1.664468 |
| 7.7 | 20 | 30.375 | 1.195866 | 3.1019 | 0.096218 | 1.249582 | 3.41 | 1.510143 |
| 7.7 | 21 | 31.9625 | 1.258366 | 2.9797 | 0.088786 | 1.153067 | 3.367 | 1.472297 |
| 7.7 | 22 | 33.55 | 1.320866 | 2.8204 | 0.079547 | 1.033072 | 3.229 | 1.354083 |
| 7.7 | 23 | 35.1375 | 1.383366 | 2.7865 | 0.077646 | 1.008387 | 2.96 | 1.13787 |
| 7.7 | 24 | 36.725 | 1.445866 | 2.5675 | 0.065921 | 0.856111 | 2.91 | 1.099753 |
| 7.7 | 25 | 38.3125 | 1.508366 | 2.6004 | 0.067621 | 0.878192 | 2.79 | 1.010922 |
| 7.8 | 26 | 39.9 | 1.570866 | 2.4693 | 0.060974 | 0.781723 | 2.67 | 0.913962 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7.8 | 27 | 41.4875 | 1.633366 | 2.3978 | 0.057494 | 0.737108 | 2.67 | 0.913962 |
| 7.8 | 28 | 43.075 | 1.695866 | 2.2944 | 0.052643 | 0.674907 | 2.49 | 0.794885 |
| 7.8 | 29 | 44.6625 | 1.758366 | 2.2137 | 0.049005 | 0.628265 | 2.368 | 0.718901 |
| 7.8 | 30 | 46.25 | 1.820866 | 2.1296 | 0.045352 | 0.581435 | 2.26 | 0.654821 |
| 7.8 | 31 | 47.8375 | 1.883366 | 2.0683 | 0.042779 | 0.548444 | 2.13 | 0.581654 |
| 7.8 | 32 | 49.425 | 1.945866 | 1.9916 | 0.039665 | 0.508522 | 2.19 | 0.614885 |
| 7.8 | 33 | 51.0125 | 2.008366 | 1.9229 | 0.036975 | 0.474044 | 2.15 | 0.592628 |
| 7.8 | 34 | 52.6 | 2.070866 | 1.8543 | 0.034384 | 0.440824 | 2.17 | 0.603705 |
| 7.8 | 35 | 54.1875 | 2.133366 | 1.8559 | 0.034444 | 0.441585 | 2.11 | 0.570782 |

# APPENDIX I: AIR COILS FOUR-TO-ONE STEADY POSITION VERTICAL SEPARATION

| **Air Long Coil Steady Position Airgap Vertical Separation** | |
|---|---|
| Z_separation [mm] | CplCoef(Tx_In,Rx_In) [] |
| 8.3625 | 0.440624 |
| 9.95 | 0.415029 |
| 11.5375 | 0.392368 |
| 13.125 | 0.373047 |
| 14.7125 | 0.353964 |
| 16.3 | 0.337496 |
| 17.8875 | 0.32241 |
| 21.0625 | 0.295374 |
| 22.65 | 0.283621 |
| 24.2375 | 0.272703 |
| 25.825 | 0.26237 |
| 27.4125 | 0.252514 |
| 29 | 0.243481 |
| 30.5875 | 0.235042 |
| 32.175 | 0.226784 |
| 33.7625 | 0.219245 |
| 35.35 | 0.211823 |
| 36.9375 | 0.205011 |
| 38.525 | 0.19881 |
| 40.1125 | 0.192296 |
| 41.7 | 0.186389 |
| 43.2875 | 0.180592 |
| 44.875 | 0.175015 |
| 46.4625 | 0.170127 |
| 48.05 | 0.164932 |
| 49.6375 | 0.1601 |
| 51.225 | 0.155474 |
| 52.8125 | 0.151124 |
| 53 | 0.150546 |
| 70 | 0.112548 |

# APPENDIX J: AIR COILS FOUR-TO-ONE VERTICAL SEPARATION VS VOLTAGE

| Large Air Coil 4 to 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Vertical Separation Test Steady Transfer Position | | | | | | | | |
| Vin 6V, Load 100 Ohms | | | | | | | | |
| SIM | | | | | | | Real | |
| Pin(W) | Spacers | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 7.4 | 7 | 9.7375 | 0.383366 | 5.2065 | 0.271076 | 3.663195 | 4.93 | 3.284446 |
| 7.4 | 8 | 11.325 | 0.445866 | 4.9803 | 0.248034 | 3.351809 | 4.76 | 3.061838 |
| 7.5 | 9 | 12.9125 | 0.508366 | 4.7744 | 0.227949 | 3.039319 | 4.63 | 2.858253 |
| 7.5 | 10 | 14.5 | 0.570866 | 4.5328 | 0.205463 | 2.739503 | 4.488 | 2.685619 |
| 7.5 | 11 | 16.0875 | 0.633366 | 4.384 | 0.192195 | 2.562594 | 4.28 | 2.442453 |
| 7.6 | 12 | 17.675 | 0.695866 | 4.1905 | 0.175603 | 2.310565 | 4.03 | 2.136961 |
| 7.6 | 13 | 19.2625 | 0.758366 | 4.0088 | 0.160705 | 2.114537 | 3.99 | 2.09475 |
| 7.7 | 14 | 20.85 | 0.820866 | 3.743 | 0.1401 | 1.819487 | 3.63 | 1.711286 |
| 7.7 | 15 | 22.4375 | 0.883366 | 3.6257 | 0.131457 | 1.707234 | 3.53 | 1.618299 |
| 7.7 | 16 | 24.025 | 0.945866 | 3.5059 | 0.122913 | 1.596277 | 3.424 | 1.522568 |
| 7.7 | 17 | 25.6125 | 1.008366 | 3.3657 | 0.113279 | 1.471161 | 3.31 | 1.42287 |
| 7.7 | 18 | 27.2 | 1.070866 | 3.2325 | 0.104491 | 1.35702 | 3.228 | 1.353245 |
| 7.7 | 19 | 28.7875 | 1.133366 | 3.1213 | 0.097425 | 1.265262 | 3.06 | 1.216052 |
| 7.7 | 20 | 30.375 | 1.195866 | 3.073 | 0.094433 | 1.226406 | 2.975 | 1.149432 |
| 7.7 | 21 | 31.9625 | 1.258366 | 2.9615 | 0.087705 | 1.139024 | 3.02 | 1.184468 |
| 7.8 | 22 | 33.55 | 1.320866 | 2.804 | 0.078624 | 1.008002 | 2.743 | 0.964622 |
| 7.8 | 23 | 35.1375 | 1.383366 | 2.7045 | 0.073143 | 0.937733 | 2.686 | 0.924948 |
| 7.8 | 24 | 36.725 | 1.445866 | 2.7176 | 0.073853 | 0.94684 | 2.66 | 0.907128 |
| 7.8 | 25 | 38.3125 | 1.508366 | 2.5969 | 0.067439 | 0.864601 | 2.51 | 0.807705 |
| 7.8 | 26 | 39.9 | 1.570866 | 2.5192 | 0.063464 | 0.813637 | 2.53 | 0.820628 |
| 7.8 | 27 | 41.4875 | 1.633366 | 2.3903 | 0.057135 | 0.732504 | 2.52 | 0.814154 |
| 7.8 | 28 | 43.075 | 1.695866 | 2.3073 | 0.053236 | 0.682517 | 2.31 | 0.684115 |
| 7.8 | 29 | 44.6625 | 1.758366 | 2.2213 | 0.049342 | 0.632586 | 2.33 | 0.696013 |
| 7.8 | 30 | 46.25 | 1.820866 | 2.1573 | 0.046539 | 0.596659 | 2.236 | 0.640987 |
| 7.8 | 31 | 47.8375 | 1.883366 | 2.0804 | 0.043281 | 0.55488 | 2.254 | 0.651348 |
| 7.8 | 32 | 49.425 | 1.945866 | 2.0303 | 0.041221 | 0.528477 | 2.234 | 0.639841 |
| 7.8 | 33 | 51.0125 | 2.008366 | 1.9318 | 0.037319 | 0.478442 | 2.26 | 0.654821 |
| 7.8 | 34 | 52.6 | 2.070866 | 1.8984 | 0.036039 | 0.462041 | 2.17 | 0.603705 |
| 7.8 | 35 | 54.1875 | 2.133366 | 1.8642 | 0.034752 | 0.445544 | 2.13 | 0.581654 |
| 7.8 | 36 | 55.775 | 2.195866 | 1.339 | 0.017929 | 0.229862 | | |

# APPENDIX K: AIR COILS FOUR-TO-ONE PEAK POSITION LOAD VS VOUT AIRGAP 20 MM

| Large Air Coils 4 to 1 Peak Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Different Loads Test | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.32456 | 7.2 | 100 | 20 | 0.787402 | 4.2908 | 0.18411 | 2.557078 | 4.25 | 2.508681 |
| 0.32456 | 7.2 | 95 | 20 | 0.787402 | 4.2673 | 0.191683 | 2.662259 | 4.1 | 2.457602 |
| 0.32456 | 7.2 | 90 | 20 | 0.787402 | 4.2423 | 0.199968 | 2.777332 | 3.7 | 2.112654 |
| 0.32456 | 7.2 | 85 | 20 | 0.787402 | 4.219 | 0.209411 | 2.90849 | 3.99 | 2.601324 |
| 0.32456 | 7.2 | 80 | 20 | 0.787402 | 4.1937 | 0.219839 | 3.053319 | 3.94 | 2.695069 |
| 0.32456 | 7.2 | 75 | 20 | 0.787402 | 4.199 | 0.235088 | 3.265111 | 3.92 | 2.84563 |
| 0.32456 | 7.2 | 70 | 20 | 0.787402 | 4.1294 | 0.243599 | 3.383322 | 3.86 | 2.95627 |
| 0.32456 | 7.3 | 65 | 20 | 0.787402 | 4.118 | 0.260891 | 3.573851 | 3.78 | 3.011254 |
| 0.32456 | 7.3 | 60 | 20 | 0.787402 | 4.069 | 0.275946 | 3.780082 | 3.73 | 3.176461 |
| 0.32456 | 7.4 | 55 | 20 | 0.787402 | 4.0243 | 0.294454 | 3.979113 | 3.5 | 3.009828 |
| 0.32456 | 7.3 | 50 | 20 | 0.787402 | 4.0051 | 0.320817 | 4.394747 | 3.57 | 3.491753 |
| 0.32456 | 7.4 | 45 | 20 | 0.787402 | 3.929 | 0.343045 | 4.635748 | 3.49 | 3.657688 |
| 0.32456 | 7.4 | 40 | 20 | 0.787402 | 3.8559 | 0.371699 | 5.022961 | 3.35 | 3.791385 |
| 0.32456 | 7.5 | 35 | 20 | 0.787402 | 3.7728 | 0.406686 | 5.422484 | 3.13 | 3.732152 |
| 0.32456 | 7.4 | 30 | 20 | 0.787402 | 3.6567 | 0.445715 | 6.023178 | 3.15 | 4.469595 |
| 0.32456 | 7.6 | 25 | 20 | 0.787402 | 3.5374 | 0.500528 | 6.585894 | 2.73 | 3.922579 |
| 0.32456 | 7.7 | 20 | 20 | 0.787402 | 3.2892 | 0.540942 | 7.025219 | 2.38 | 3.678182 |
| 0.32456 | 7.8 | 15 | 20 | 0.787402 | 3.021 | 0.608429 | 7.800377 | 2 | 3.418803 |
| 0.32456 | 7.9 | 10 | 20 | 0.787402 | 2.5847 | 0.668067 | 8.456549 | 1.61 | 3.281139 |
| 0.32456 | 8.1 | 5 | 20 | 0.787402 | 1.6809 | 0.565085 | 6.976358 | 0.75 | 1.388889 |

# APPENDIX L: AIR COILS FOUR-TO-ONE STEADY POSITION LOAD VS VOUT AIRGAP 20 MM

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Large Air Coil 4 to 1 Steady Position | | | | | | | | |
| | Different Loads Test | | | | | | | | |
| | Vin 6V | | | | | | | | |
| | | | | | | | | | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.31613 | 7.3 | 100 | 20 | 0.787402 | 3.8446 | 0.147809 | 2.024788 | 3.81 | 1.988507 |
| 0.31613 | 7.3 | 95 | 20 | 0.787402 | 3.8244 | 0.153958 | 2.109017 | 3.77 | 2.049445 |
| 0.31613 | 7.3 | 90 | 20 | 0.787402 | 3.8527 | 0.164926 | 2.259254 | 3.72 | 2.106301 |
| 0.31613 | 7.3 | 85 | 20 | 0.787402 | 3.7834 | 0.168401 | 2.306868 | 3.7 | 2.206285 |
| 0.31613 | 7.3 | 80 | 20 | 0.787402 | 3.7722 | 0.177869 | 2.436557 | 3.66 | 2.293767 |
| 0.31613 | 7.3 | 75 | 20 | 0.787402 | 3.7501 | 0.18751 | 2.56863 | 3.61 | 2.380292 |
| 0.31613 | 7.3 | 70 | 20 | 0.787402 | 3.7205 | 0.197745 | 2.70883 | 3.55 | 2.466243 |
| 0.31613 | 7.4 | 65 | 20 | 0.787402 | 3.6738 | 0.207643 | 2.805989 | 3.51 | 2.561351 |
| 0.31613 | 7.4 | 60 | 20 | 0.787402 | 3.6205 | 0.218467 | 2.952257 | 3.41 | 2.618941 |
| 0.31613 | 7.4 | 55 | 20 | 0.787402 | 3.5922 | 0.234616 | 3.170492 | 3.36 | 2.773857 |
| 0.31613 | 7.4 | 50 | 20 | 0.787402 | 3.5277 | 0.248893 | 3.363424 | 3.23 | 2.819703 |
| 0.31613 | 7.5 | 45 | 20 | 0.787402 | 3.5159 | 0.274701 | 3.662682 | 3.1 | 2.847407 |
| 0.31613 | 7.5 | 40 | 20 | 0.787402 | 3.4139 | 0.291368 | 3.884904 | 2.98 | 2.960133 |
| 0.31613 | 7.5 | 35 | 20 | 0.787402 | 3.369 | 0.32429 | 4.323871 | 2.8 | 2.986667 |
| 0.31613 | 7.6 | 30 | 20 | 0.787402 | 3.2472 | 0.351477 | 4.624696 | 2.68 | 3.150175 |
| 0.31613 | 7.7 | 25 | 20 | 0.787402 | 3.1271 | 0.39115 | 5.079872 | 2.4 | 2.992208 |
| 0.31613 | 7.7 | 20 | 20 | 0.787402 | 3.0573 | 0.467354 | 6.069535 | 2.2 | 3.142857 |
| 0.31613 | 7.8 | 15 | 20 | 0.787402 | 2.8535 | 0.542831 | 6.959369 | 1.85 | 2.925214 |
| 0.31613 | 7.9 | 10 | 20 | 0.787402 | 2.4713 | 0.610732 | 7.730789 | 1.34 | 2.272911 |
| 0.31613 | 8 | 5 | 20 | 0.787402 | 1.6815 | 0.565488 | 7.068606 | 0.86 | 1.849 |

# APPENDIX M: AIR COILS FOUR-TO-ONE LOAD VS VOLTAQGE PEAK POSITION AIRGAP 27.2 MM

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Large Air Coil 4 to 1 Peak Position | | | | | | | | | |
| Different Loads Test | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.248949 | 7.3 | 100 | 27.2 | 1.070866 | 3.6433 | 0.132736 | 1.818306 | 3.68 | 1.855123 |
| 0.248949 | 7.4 | 95 | 27.2 | 1.070866 | 3.6052 | 0.136815 | 1.848857 | 3.54 | 1.586856 |
| 0.248949 | 7.4 | 90 | 27.2 | 1.070866 | 3.5895 | 0.143161 | 1.934611 | 3.43 | 1.471006 |
| 0.248949 | 7.4 | 85 | 27.2 | 1.070866 | 3.5509 | 0.14834 | 2.004593 | 3.25 | 1.478935 |
| 0.248949 | 7.4 | 80 | 27.2 | 1.070866 | 3.5327 | 0.156 | 2.108103 | 3.18 | 1.540608 |
| 0.248949 | 7.4 | 75 | 27.2 | 1.070866 | 3.5172 | 0.164943 | 2.228954 | 3.09 | 1.610829 |
| 0.248949 | 7.4 | 70 | 27.2 | 1.070866 | 3.4805 | 0.173055 | 2.338587 | 3.06 | 1.691429 |
| 0.248949 | 7.5 | 65 | 27.2 | 1.070866 | 3.4455 | 0.182638 | 2.435173 | 2.9 | 1.608205 |
| 0.248949 | 7.5 | 60 | 27.2 | 1.070866 | 3.4168 | 0.194575 | 2.594338 | 2.85 | 1.680556 |
| 0.248949 | 7.5 | 55 | 27.2 | 1.070866 | 3.3605 | 0.205327 | 2.737687 | 2.71 | 1.651418 |
| 0.248949 | 7.5 | 50 | 27.2 | 1.070866 | 3.3358 | 0.222551 | 2.96735 | 2.63 | 1.844507 |
| 0.248949 | 7.5 | 45 | 27.2 | 1.070866 | 3.2833 | 0.239557 | 3.194092 | 2.5 | 1.851852 |
| 0.248949 | 7.5 | 40 | 27.2 | 1.070866 | 3.2236 | 0.25979 | 3.463866 | 2.43 | 1.9683 |
| 0.248949 | 7.6 | 35 | 27.2 | 1.070866 | 3.153 | 0.28404 | 3.737372 | 2.34 | 2.058496 |
| 0.248949 | 7.6 | 30 | 27.2 | 1.070866 | 3.062 | 0.312528 | 4.112212 | 2.16 | 2.046316 |
| 0.248949 | 7.6 | 25 | 27.2 | 1.070866 | 2.9641 | 0.351436 | 4.624152 | 1.98 | 2.063368 |
| 0.248949 | 7.7 | 20 | 27.2 | 1.070866 | 2.7153 | 0.368643 | 4.787568 | 1.73 | 1.943442 |
| 0.248949 | 7.8 | 15 | 27.2 | 1.070866 | 2.4964 | 0.415468 | 5.326507 | 1.45 | 1.797009 |
| 0.248949 | 7.8 | 10 | 27.2 | 1.070866 | 2.0672 | 0.427332 | 5.47861 | 1.056 | 1.429662 |
| 0.248949 | 7.9 | 5 | 27.2 | 1.070866 | 1.2815 | 0.328448 | 4.157575 | 0.53 | 0.711139 |

# APPENDIX N: AIR COILS FOUR-TO-ONE LOAD VS VOLTAGE STEADY POSITION AIRGAP 27.2 MM

| Large Air Coil 4 to 1 Steady Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Different Loads Test | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.245615 | 7.4 | 100 | 27.2 | 1.070866 | 3.2754 | 0.107282 | 1.449763 | 3.22 | 1.401135 |
| 0.245615 | 7.4 | 95 | 27.2 | 1.070866 | 3.2608 | 0.111924 | 1.512492 | 3.15 | 1.411451 |
| 0.245615 | 7.4 | 90 | 27.2 | 1.070866 | 3.2463 | 0.117094 | 1.582352 | 3.013 | 1.363088 |
| 0.245615 | 7.4 | 85 | 27.2 | 1.070866 | 3.207 | 0.120998 | 1.635111 | 3 | 1.430843 |
| 0.245615 | 7.4 | 80 | 27.2 | 1.070866 | 3.1781 | 0.126254 | 1.706135 | 2.958 | 1.478001 |
| 0.245615 | 7.4 | 75 | 27.2 | 1.070866 | 3.1578 | 0.132956 | 1.796703 | 2.93 | 1.546829 |
| 0.245615 | 7.4 | 70 | 27.2 | 1.070866 | 3.1304 | 0.139991 | 1.891777 | 2.86 | 1.579073 |
| 0.245615 | 7.4 | 65 | 27.2 | 1.070866 | 3.1073 | 0.148543 | 2.007342 | 2.78 | 1.606736 |
| 0.245615 | 7.5 | 60 | 27.2 | 1.070866 | 3.0688 | 0.156959 | 2.092785 | 2.75 | 1.680556 |
| 0.245615 | 7.5 | 55 | 27.2 | 1.070866 | 3.022 | 0.166045 | 2.213936 | 2.679 | 1.739889 |
| 0.245615 | 7.5 | 50 | 27.2 | 1.070866 | 2.9768 | 0.177227 | 2.363024 | 2.6 | 1.802667 |
| 0.245615 | 7.5 | 45 | 27.2 | 1.070866 | 2.9283 | 0.190554 | 2.540723 | 2.5 | 1.851852 |
| 0.245615 | 7.5 | 40 | 27.2 | 1.070866 | 2.8887 | 0.208615 | 2.781529 | 2.43 | 1.9683 |
| 0.245615 | 7.6 | 35 | 27.2 | 1.070866 | 2.8309 | 0.228971 | 3.01278 | 2.32 | 2.023459 |
| 0.245615 | 7.6 | 30 | 27.2 | 1.070866 | 2.754 | 0.252817 | 3.326542 | 2.28 | 2.28 |
| 0.245615 | 7.6 | 25 | 27.2 | 1.070866 | 2.6707 | 0.285306 | 3.75402 | 1.85 | 1.801316 |
| 0.245615 | 7.7 | 20 | 27.2 | 1.070866 | 2.5275 | 0.319413 | 4.148218 | 1.7 | 1.876623 |
| 0.245615 | 7.7 | 15 | 27.2 | 1.070866 | 2.3251 | 0.360406 | 4.680597 | 1.45 | 1.820346 |
| 0.245615 | 7.8 | 10 | 27.2 | 1.070866 | 1.9817 | 0.392713 | 5.034788 | 1.25 | 2.003205 |
| 0.245615 | 7.9 | 5 | 27.2 | 1.070866 | 1.306 | 0.341127 | 4.318066 | 0.638 | 1.030491 |

# APPENDIX O: ONE-TO-ONE AIR COILS WITH ADDED CORES

| Square coils with **one core** 12.91 mm separation | | | | | | Square coils with **No core** 12.91 mm separation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Separation | ClpCoef | | | | | Separation | ClpCoef | | | |
| 13.625 | 0.495559 | | | | | 13.625 | 0.455331 | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| Square coils with **two cores** 12.91 mm separation | | | | | | | | | | |
| Separation | ClpCoef | | | | | | | | | |
| 13.625 | 0.531777 | | | | | | | | | |

# APPENDIX P: ONE-TO-ONE AIR COILS WITH A CORE

| Small Square Air Coil 1 to 1 **With ONE Core** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Different Loads Test | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.495559 | 15 | 100 | 12.9125 | 0.508366 | 2.6655 | 0.071049 | 0.473659 | 3.21 | 0.68694 |
| 0.495559 | 15 | 95 | 12.9125 | 0.508366 | 2.6511 | 0.073982 | 0.493216 | 3.19 | 0.714112 |
| 0.495559 | 15 | 90 | 12.9125 | 0.508366 | 2.6376 | 0.077299 | 0.515328 | 3.18 | 0.749067 |
| 0.495559 | 15 | 85 | 12.9125 | 0.508366 | 2.6055 | 0.079866 | 0.532442 | 3 | 0.705882 |
| 0.495559 | 15 | 80 | 12.9125 | 0.508366 | 2.6038 | 0.084747 | 0.564981 | 2.99 | 0.745008 |
| 0.495559 | 15 | 75 | 12.9125 | 0.508366 | 2.5908 | 0.089497 | 0.596644 | 2.92 | 0.757902 |
| 0.495559 | 15 | 70 | 12.9125 | 0.508366 | 2.5675 | 0.094172 | 0.627815 | 2.9 | 0.800952 |
| 0.495559 | 15 | 65 | 12.9125 | 0.508366 | 2.551 | 0.100117 | 0.667446 | 2.85 | 0.833077 |
| 0.495559 | 15 | 60 | 12.9125 | 0.508366 | 2.4902 | 0.103352 | 0.689011 | 2.79 | 0.8649 |
| 0.495559 | 15 | 55 | 12.9125 | 0.508366 | 2.4615 | 0.110163 | 0.734422 | 2.75 | 0.916667 |
| 0.495559 | 15 | 50 | 12.9125 | 0.508366 | 2.4054 | 0.115719 | 0.77146 | 2.71 | 0.979213 |
| 0.495559 | 15 | 45 | 12.9125 | 0.508366 | 2.3895 | 0.126882 | 0.845883 | 2.66 | 1.048237 |
| 0.495559 | 15 | 40 | 12.9125 | 0.508366 | 2.3597 | 0.139205 | 0.928031 | 2.59 | 1.118017 |
| 0.495559 | 15 | 35 | 12.9125 | 0.508366 | 2.2786 | 0.148343 | 0.988956 | 2.52 | 1.2096 |
| 0.495559 | 15 | 30 | 12.9125 | 0.508366 | 2.1986 | 0.161128 | 1.074187 | 2.4 | 1.28 |
| 0.495559 | 15 | 25 | 12.9125 | 0.508366 | 2.1365 | 0.182585 | 1.217235 | 2.3 | 1.410667 |
| 0.495559 | 15 | 20 | 12.9125 | 0.508366 | 1.9761 | 0.195249 | 1.301657 | 2.13 | 1.5123 |
| 0.495559 | 15.1 | 15 | 12.9125 | 0.508366 | 1.8514 | 0.228512 | 1.513325 | 1.9 | 1.593819 |
| 0.495559 | 15.1 | 10 | 12.9125 | 0.508366 | 1.6304 | 0.26582 | 1.7604 | 1.6 | 1.695364 |
| 0.495559 | 15.2 | 5 | 12.9125 | 0.508366 | 1.3125 | 0.344531 | 2.266653 | 1.2 | 1.894737 |

# APPENDIX Q: ONE-TO-ONE AIR COILS WITH TWO CORES

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Small Square Air Coil 1 to 1 | | | | | | | | | |
| Different Loads Test **with Two Cores** | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.531777 | 14.6 | 100 | 12.9125 | 0.508366 | 3.1018 | 0.096212 | 0.658984 | 3.61 | 0.89261 |
| 0.531777 | 14.6 | 95 | 12.9125 | 0.508366 | 3.0588 | 0.098487 | 0.674568 | 3.61 | 0.939589 |
| 0.531777 | 14.5 | 90 | 12.9125 | 0.508366 | 3.0685 | 0.104619 | 0.721509 | 3.53 | 0.954858 |
| 0.531777 | 14.4 | 85 | 12.9125 | 0.508366 | 3.0641 | 0.110455 | 0.767051 | 3.51 | 1.006544 |
| 0.531777 | 14.4 | 80 | 12.9125 | 0.508366 | 3.0417 | 0.115649 | 0.80312 | 3.48 | 1.05125 |
| 0.531777 | 14.4 | 75 | 12.9125 | 0.508366 | 3.0074 | 0.120593 | 0.83745 | 3.58 | 1.186704 |
| 0.531777 | 14.4 | 70 | 12.9125 | 0.508366 | 2.9837 | 0.127178 | 0.883181 | 3.53 | 1.2362 |
| 0.531777 | 14.4 | 65 | 12.9125 | 0.508366 | 2.9623 | 0.135003 | 0.937524 | 3.46 | 1.279017 |
| 0.531777 | 14.4 | 60 | 12.9125 | 0.508366 | 2.8931 | 0.1395 | 0.968753 | 3.41 | 1.345845 |
| 0.531777 | 14.4 | 55 | 12.9125 | 0.508366 | 2.8583 | 0.148543 | 1.03155 | 3.36 | 1.425455 |
| 0.531777 | 14.4 | 50 | 12.9125 | 0.508366 | 2.7583 | 0.152164 | 1.056697 | 3.3 | 1.5125 |
| 0.531777 | 14.5 | 45 | 12.9125 | 0.508366 | 2.7209 | 0.164518 | 1.134605 | 3.22 | 1.589027 |
| 0.531777 | 14.5 | 40 | 12.9125 | 0.508366 | 2.6736 | 0.178703 | 1.232437 | 3.12 | 1.678345 |
| 0.531777 | 14.5 | 35 | 12.9125 | 0.508366 | 2.6185 | 0.195901 | 1.351043 | 3.17 | 1.980079 |
| 0.531777 | 14.4 | 30 | 12.9125 | 0.508366 | 2.5661 | 0.219496 | 1.524275 | 3.03 | 2.125208 |
| 0.531777 | 14.4 | 25 | 12.9125 | 0.508366 | 2.4574 | 0.241553 | 1.677449 | 2.83 | 2.224694 |
| 0.531777 | 14.4 | 20 | 12.9125 | 0.508366 | 2.2807 | 0.26008 | 1.806109 | 2.69 | 2.512535 |
| 0.531777 | 14.4 | 15 | 12.9125 | 0.508366 | 2.0898 | 0.291151 | 2.021882 | 2.78 | 3.577963 |
| 0.531777 | 14.4 | 10 | 12.9125 | 0.508366 | 1.8547 | 0.343991 | 2.388828 | 2.32 | 3.737778 |
| 0.531777 | 14.6 | 5 | 12.9125 | 0.508366 | 1.4684 | 0.43124 | 2.953697 | 1.81 | 4.487808 |

# APPENDIX R: FOUR-TO-ONE AIR COILS WITH CORES

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Peak | Long Coil with One Core 20mm airgap Peak | | | | | | Long Coil with **No Core** 20mm airgap Peak | | | | |
| | Separation | ClpCoef | | | | | Separation | ClpCoef | | | |
| | 18.625 | 0.348191 | | | | | 18.625 | 0.32456 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Long Coil with Two Core 20mm airgap Peak | | | | | | | | | | |
| | Separation | ClpCoef | | | | | | | | | |
| | 18.625 | 0.361506 | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Long Coil with Two Core 27.2mm airgap Peak | | | | | | Long Coil with No Core 27.2mm airgap Peak | | | | |
| | Separation | ClpCoef | | | | | Separation | ClpCoef | | | |
| | 28.625 | 0.292638 | | | | | 28.625 | 0.248949 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| Stead<br>y | | | | | | | | | | | |
| | Long Coil with Two Core 27.2mm airgap Steady | | | | | | | | | | |
| | Separation | ClpCoef | | | | | | | | | |
| | 28.625 | 0.282895 | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Long Coil with Two Core 20mm airgap Steady | | | | | | Long Coil with **No Core** 20mm airgap Steady | | | | |
| | Separation | ClpCoef | | | | | Separation | ClpCoef | | | |
| | 18.625 | 0.353374 | | | | | 18.625 | 0.31613 | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Long Coil with One Core 20mm airgap Steady | | | | | | Long Coil with No Core 27.2mm airgap Steady | | | | |
| | Separation | ClpCoef | | | | | Separation | ClpCoef | | | |
| | 18.625 | 0.33901 | | | | | 28.625 | 0.245615 | | | |

# APPENDIX S: FOUR-TO-ONE AIR COILS WITH A CORE AT 20 MM PEAK POSITION

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Large Air Coil 4 to 1 Peak Position **One Core** | | | | | | | | | |
| Different Loads Test | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.348191 | 6.8 | 100 | 20 | 0.787402 | 4.9195 | 0.242015 | 3.559041 | 4.87 | 3.487779 |
| 0.348191 | 6.9 | 95 | 20 | 0.787402 | 4.9039 | 0.253139 | 3.668686 | 4.84 | 3.573699 |
| 0.348191 | 6.9 | 90 | 20 | 0.787402 | 4.8855 | 0.265201 | 3.843496 | 4.74 | 3.617971 |
| 0.348191 | 6.9 | 85 | 20 | 0.787402 | 4.8688 | 0.278885 | 4.04181 | 4.73 | 3.814646 |
| 0.348191 | 6.9 | 80 | 20 | 0.787402 | 4.8524 | 0.294322 | 4.265541 | 4.66 | 3.933986 |
| 0.348191 | 6.9 | 75 | 20 | 0.787402 | 4.8266 | 0.310614 | 4.501656 | 4.59 | 4.07113 |
| 0.348191 | 7 | 70 | 20 | 0.787402 | 4.7419 | 0.321223 | 4.588901 | 4.46 | 4.05951 |
| 0.348191 | 6.9 | 65 | 20 | 0.787402 | 4.6819 | 0.337234 | 4.887444 | 4.49 | 4.495006 |
| 0.348191 | 7 | 60 | 20 | 0.787402 | 4.6327 | 0.357698 | 5.109978 | 4.32 | 4.443429 |
| 0.348191 | 7 | 55 | 20 | 0.787402 | 4.6141 | 0.387089 | 5.529849 | 4.17 | 4.516597 |
| 0.348191 | 7.1 | 50 | 20 | 0.787402 | 4.5415 | 0.412504 | 5.809922 | 4.1 | 4.735211 |
| 0.348191 | 7.1 | 45 | 20 | 0.787402 | 4.4238 | 0.434889 | 6.125198 | 4 | 5.007825 |
| 0.348191 | 7.2 | 40 | 20 | 0.787402 | 4.342 | 0.471324 | 6.546168 | 3.73 | 4.830868 |
| 0.348191 | 7.2 | 35 | 20 | 0.787402 | 4.2369 | 0.512895 | 7.12354 | 3.56 | 5.029206 |
| 0.348191 | 7.3 | 30 | 20 | 0.787402 | 4.0417 | 0.544511 | 7.459059 | 3.24 | 4.793425 |
| 0.348191 | 7.4 | 25 | 20 | 0.787402 | 3.8906 | 0.605471 | 8.182037 | 2.96 | 4.736 |
| 0.348191 | 7.5 | 20 | 20 | 0.787402 | 3.7372 | 0.698333 | 9.311109 | 2.67 | 4.7526 |
| 0.348191 | 7.6 | 15 | 20 | 0.787402 | 3.3869 | 0.764739 | 10.06236 | 2.17 | 4.130614 |
| 0.348191 | 7.8 | 10 | 20 | 0.787402 | 2.8394 | 0.806219 | 10.33614 | 1.6 | 3.282051 |
| 0.348191 | 7.9 | 5 | 20 | 0.787402 | 1.7956 | 0.644836 | 8.162479 | 0.72 | 1.312405 |

# APPENDIX T: FOUR-TO-ONE COILS WITH TWO CORES AT 20 MM PEAK POSITION

| Large Air Coil 4 to 1 Peak Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Different Loads Test **with Two Cores** | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.361506 | 6.9 | 100 | 20 | 0.787402 | 5.3102 | 0.281982 | 4.086699 | 5.44 | 4.288928 |
| 0.361506 | 6.9 | 95 | 20 | 0.787402 | 5.2865 | 0.29418 | 4.263476 | 5.2 | 4.125095 |
| 0.361506 | 6.9 | 90 | 20 | 0.787402 | 5.2544 | 0.306764 | 4.445849 | 5.2 | 4.354267 |
| 0.361506 | 6.9 | 85 | 20 | 0.787402 | 5.2117 | 0.319551 | 4.631171 | 5.2 | 4.610401 |
| 0.361506 | 6.9 | 80 | 20 | 0.787402 | 5.233 | 0.342304 | 4.960922 | 5.19 | 4.879728 |
| 0.361506 | 6.9 | 75 | 20 | 0.787402 | 5.2402 | 0.366129 | 5.306221 | 5.1 | 5.026087 |
| 0.361506 | 7 | 70 | 20 | 0.787402 | 5.2007 | 0.38639 | 5.519853 | 5.04 | 5.184 |
| 0.361506 | 7 | 65 | 20 | 0.787402 | 5.1213 | 0.403503 | 5.764333 | 4.96 | 5.406945 |
| 0.361506 | 7 | 60 | 20 | 0.787402 | 5.0584 | 0.426457 | 6.092241 | 4.81 | 5.508595 |
| 0.361506 | 7 | 55 | 20 | 0.787402 | 5.0037 | 0.455218 | 6.50312 | 4.71 | 5.762104 |
| 0.361506 | 7.1 | 50 | 20 | 0.787402 | 4.938 | 0.487677 | 6.868688 | 4.53 | 5.780535 |
| 0.361506 | 7.1 | 45 | 20 | 0.787402 | 4.8066 | 0.513409 | 7.231112 | 4.34 | 5.895336 |
| 0.361506 | 7.2 | 40 | 20 | 0.787402 | 4.6861 | 0.548988 | 7.624838 | 4.14 | 5.95125 |
| 0.361506 | 7.3 | 35 | 20 | 0.787402 | 4.5657 | 0.595589 | 8.158754 | 3.86 | 5.831546 |
| 0.361506 | 7.4 | 30 | 20 | 0.787402 | 4.377 | 0.638604 | 8.629788 | 3.51 | 5.549595 |
| 0.361506 | 7.4 | 25 | 20 | 0.787402 | 4.2263 | 0.714464 | 9.654925 | 3.28 | 5.815351 |
| 0.361506 | 7.5 | 20 | 20 | 0.787402 | 3.9416 | 0.776811 | 10.35747 | 2.84 | 5.377067 |
| 0.361506 | 7.7 | 15 | 20 | 0.787402 | 3.5858 | 0.857197 | 11.13243 | 2.27 | 4.461385 |
| 0.361506 | 7.8 | 10 | 20 | 0.787402 | 2.9554 | 0.873439 | 11.19793 | 1.7 | 3.705128 |
| 0.361506 | 7.9 | 5 | 20 | 0.787402 | 1.8164 | 0.659862 | 8.352681 | 0.816 | 1.685711 |

# APPENDIX U: FOUR-TO-ONE AIR COILS WITH ONE CORE AT 20 MM STEADY POSITION

| Large Air Coil 4 to 1 Steady Position **One Core** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Different Loads Test | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.33901 | 6.9 | 100 | 20 | 0.787402 | 4.7217 | 0.222945 | 3.23108 | 4.73 | 3.242449 |
| 0.33901 | 6.9 | 95 | 20 | 0.787402 | 4.6933 | 0.231864 | 3.360346 | 4.64 | 3.284455 |
| 0.33901 | 6.9 | 90 | 20 | 0.787402 | 4.7051 | 0.245977 | 3.56489 | 4.6 | 3.407407 |
| 0.33901 | 6.9 | 85 | 20 | 0.787402 | 4.6563 | 0.255072 | 3.696697 | 4.53 | 3.498875 |
| 0.33901 | 6.9 | 80 | 20 | 0.787402 | 4.6542 | 0.27077 | 3.924199 | 4.48 | 3.635942 |
| 0.33901 | 7 | 75 | 20 | 0.787402 | 4.6165 | 0.284161 | 4.059442 | 4.38 | 3.654171 |
| 0.33901 | 7 | 70 | 20 | 0.787402 | 4.5987 | 0.302115 | 4.315927 | 4.31 | 3.791041 |
| 0.33901 | 7 | 65 | 20 | 0.787402 | 4.4856 | 0.309548 | 4.422112 | 4.29 | 4.044857 |
| 0.33901 | 7 | 60 | 20 | 0.787402 | 4.4019 | 0.322945 | 4.613506 | 4.14 | 4.080857 |
| 0.33901 | 7.1 | 55 | 20 | 0.787402 | 4.3449 | 0.343239 | 4.834355 | 4 | 4.097311 |
| 0.33901 | 7.1 | 50 | 20 | 0.787402 | 4.3156 | 0.372488 | 5.246311 | 3.84 | 4.15369 |
| 0.33901 | 7.1 | 45 | 20 | 0.787402 | 4.221 | 0.39593 | 5.576476 | 3.8 | 4.519562 |
| 0.33901 | 7.2 | 40 | 20 | 0.787402 | 4.1542 | 0.431434 | 5.992145 | 3.58 | 4.450139 |
| 0.33901 | 7.3 | 35 | 20 | 0.787402 | 4.0418 | 0.466747 | 6.393795 | 3.43 | 4.604658 |
| 0.33901 | 7.3 | 30 | 20 | 0.787402 | 3.8846 | 0.503004 | 6.890464 | 3.08 | 4.331689 |
| 0.33901 | 7.4 | 25 | 20 | 0.787402 | 3.7479 | 0.56187 | 7.59284 | 2.72 | 3.999135 |
| 0.33901 | 7.5 | 20 | 20 | 0.787402 | 3.6143 | 0.653158 | 8.708776 | 2.54 | 4.301067 |
| 0.33901 | 7.6 | 15 | 20 | 0.787402 | 3.3353 | 0.741615 | 9.758093 | 1.98 | 3.438947 |
| 0.33901 | 7.8 | 10 | 20 | 0.787402 | 2.8467 | 0.81037 | 10.38936 | 1.43 | 2.621667 |
| 0.33901 | 7.9 | 5 | 20 | 0.787402 | 1.8617 | 0.693185 | 8.774498 | 0.68 | 1.170633 |

# APPENDIX V: FOUR-TO-ONE AIR COILS WITH TWO CORES AT 20 MM STEADY POSITION

| Large Air Coil 4 to 1 Steady Position | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Different Loads Test **with Two Cores** | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.353374 | 6.9 | 100 | 20 | 0.787402 | 5.3041 | 0.281335 | 4.077315 | 5.25 | 3.994565 |
| 0.353374 | 6.9 | 95 | 20 | 0.787402 | 5.2769 | 0.293112 | 4.248005 | 5.1 | 3.967963 |
| 0.353374 | 6.9 | 90 | 20 | 0.787402 | 5.2494 | 0.30618 | 4.437391 | 5.1 | 4.188406 |
| 0.353374 | 6.9 | 85 | 20 | 0.787402 | 5.2195 | 0.320508 | 4.645044 | 5.1 | 4.434783 |
| 0.353374 | 6.9 | 80 | 20 | 0.787402 | 5.1865 | 0.336247 | 4.873149 | 5.06 | 4.638333 |
| 0.353374 | 6.9 | 75 | 20 | 0.787402 | 5.2114 | 0.362116 | 5.248056 | 4.98 | 4.792348 |
| 0.353374 | 7 | 70 | 20 | 0.787402 | 5.1672 | 0.381428 | 5.448971 | 4.9 | 4.9 |
| 0.353374 | 7 | 65 | 20 | 0.787402 | 5.1292 | 0.404749 | 5.78213 | 4.82 | 5.106022 |
| 0.353374 | 7 | 60 | 20 | 0.787402 | 4.992 | 0.415334 | 5.933349 | 4.67 | 5.192595 |
| 0.353374 | 7.1 | 55 | 20 | 0.787402 | 4.909 | 0.438151 | 6.171135 | 4.55 | 5.301536 |
| 0.353374 | 7.1 | 50 | 20 | 0.787402 | 4.874 | 0.475118 | 6.691796 | 4.38 | 5.404056 |
| 0.353374 | 7.1 | 45 | 20 | 0.787402 | 4.7175 | 0.494551 | 6.965511 | 4.2 | 5.521127 |
| 0.353374 | 7.2 | 40 | 20 | 0.787402 | 4.6172 | 0.532963 | 7.402269 | 3.97 | 5.472535 |
| 0.353374 | 7.3 | 35 | 20 | 0.787402 | 4.4909 | 0.576234 | 7.893614 | 3.72 | 5.416204 |
| 0.353374 | 7.4 | 30 | 20 | 0.787402 | 4.3527 | 0.631533 | 8.534233 | 3.38 | 5.146126 |
| 0.353374 | 7.4 | 25 | 20 | 0.787402 | 4.1439 | 0.686876 | 9.282112 | 3.17 | 5.431838 |
| 0.353374 | 7.5 | 20 | 20 | 0.787402 | 3.9284 | 0.771616 | 10.28822 | 2.71 | 4.896067 |
| 0.353374 | 7.6 | 15 | 20 | 0.787402 | 3.5821 | 0.855429 | 11.25565 | 2.17 | 4.130614 |
| 0.353374 | 7.7 | 10 | 20 | 0.787402 | 2.8863 | 0.833073 | 10.81913 | 1.64 | 3.492987 |
| 0.353374 | 7.9 | 5 | 20 | 0.787402 | 1.7744 | 0.629699 | 7.970874 | 0.758 | 1.454592 |

# APPENDIX W: FOUR-TO-ONE AIR COILS WITH TWO CORES AT 27.2 MM PEAK POSITION

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Large Air Coil 4 to 1 Peak Position | | | | | | | | | |
| Different Loads Test **with Two Cores** | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.292638 | 7 | 100 | 27.2 | 1.070866 | 4.6241 | 0.213823 | 3.054614 | 4.6 | 3.022857 |
| 0.292638 | 7 | 95 | 27.2 | 1.070866 | 4.5731 | 0.220139 | 3.144849 | 4.5 | 3.045113 |
| 0.292638 | 7 | 90 | 27.2 | 1.070866 | 4.5571 | 0.230746 | 3.296375 | 4.56 | 3.300571 |
| 0.292638 | 7 | 85 | 27.2 | 1.070866 | 4.5231 | 0.240687 | 3.438392 | 4.32 | 3.136538 |
| 0.292638 | 7 | 80 | 27.2 | 1.070866 | 4.4872 | 0.251687 | 3.595529 | 4.25 | 3.225446 |
| 0.292638 | 7.1 | 75 | 27.2 | 1.070866 | 4.4361 | 0.262386 | 3.695584 | 4.1 | 3.156808 |
| 0.292638 | 7 | 70 | 27.2 | 1.070866 | 4.3945 | 0.27588 | 3.941149 | 4.3 | 3.773469 |
| 0.292638 | 7 | 65 | 27.2 | 1.070866 | 4.3416 | 0.289992 | 4.142745 | 4.2 | 3.876923 |
| 0.292638 | 7.1 | 60 | 27.2 | 1.070866 | 4.2995 | 0.308095 | 4.339366 | 3.7 | 3.213615 |
| 0.292638 | 7.1 | 55 | 27.2 | 1.070866 | 4.2433 | 0.327374 | 4.610908 | 3.68 | 3.467964 |
| 0.292638 | 7.1 | 50 | 27.2 | 1.070866 | 4.2089 | 0.354297 | 4.990096 | 3.5 | 3.450704 |
| 0.292638 | 7.2 | 45 | 27.2 | 1.070866 | 4.0634 | 0.366916 | 5.096055 | 3.64 | 4.089383 |
| 0.292638 | 7.2 | 40 | 27.2 | 1.070866 | 3.9898 | 0.397963 | 5.527258 | 3.4 | 4.013889 |
| 0.292638 | 7.2 | 35 | 27.2 | 1.070866 | 3.8874 | 0.431768 | 5.996777 | 3.2 | 4.063492 |
| 0.292638 | 7.3 | 30 | 27.2 | 1.070866 | 3.7916 | 0.479208 | 6.564489 | 2.58 | 3.039452 |
| 0.292638 | 7.3 | 25 | 27.2 | 1.070866 | 3.5695 | 0.509653 | 6.981551 | 2.48 | 3.370082 |
| 0.292638 | 7.4 | 20 | 27.2 | 1.070866 | 3.4434 | 0.59285 | 8.011489 | 2.19 | 3.240608 |
| 0.292638 | 7.4 | 15 | 27.2 | 1.070866 | 3.0764 | 0.630949 | 8.52634 | 1.6 | 2.306306 |
| 0.292638 | 7.5 | 10 | 27.2 | 1.070866 | 2.5511 | 0.650811 | 8.677482 | 1.06 | 1.498133 |
| 0.292638 | 7.5 | 5 | 27.2 | 1.070866 | 1.5716 | 0.493985 | 6.586471 | 0.665 | 1.179267 |

# APPENDIX X: FOUR-TO-ONE AIR COILS WITH TWO CORES AT 27.2 MM STEADY POSITION

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Large Air Coil 4 to 1 Steady Position | | | | | | | | | |
| Different Loads Test **with Two Cores** | | | | | | | | | |
| Vin 6V | | | | | | | | | |
| SIM | | | | | | | | Real | |
| ClpCoef | Pin(W) | Load | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.282895 | 6.9 | 100 | 27.2 | 1.070866 | 4.4948 | 0.202032 | 2.928004 | 4.485 | 2.91525 |
| 0.282895 | 6.9 | 95 | 27.2 | 1.070866 | 4.4151 | 0.205191 | 2.973777 | 4.56 | 3.172174 |
| 0.282895 | 6.9 | 90 | 27.2 | 1.070866 | 4.3866 | 0.213803 | 3.098593 | 4.3 | 2.977456 |
| 0.282895 | 6.9 | 85 | 27.2 | 1.070866 | 4.3645 | 0.224104 | 3.247888 | 4.42 | 3.331014 |
| 0.282895 | 7 | 80 | 27.2 | 1.070866 | 4.3503 | 0.236564 | 3.379484 | 4.4 | 3.457143 |
| 0.282895 | 7 | 75 | 27.2 | 1.070866 | 4.2943 | 0.24588 | 3.512574 | 4.28 | 3.489219 |
| 0.282895 | 7 | 70 | 27.2 | 1.070866 | 4.2615 | 0.259434 | 3.7062 | 4.1 | 3.430612 |
| 0.282895 | 7 | 65 | 27.2 | 1.070866 | 4.2257 | 0.274716 | 3.924514 | 4.09 | 3.676505 |
| 0.282895 | 7 | 60 | 27.2 | 1.070866 | 4.1958 | 0.293412 | 4.191604 | 3.96 | 3.733714 |
| 0.282895 | 7 | 55 | 27.2 | 1.070866 | 4.1591 | 0.314511 | 4.493016 | 3.8 | 3.750649 |
| 0.282895 | 7.1 | 50 | 27.2 | 1.070866 | 4.0959 | 0.335528 | 4.725746 | 3.59 | 3.630451 |
| 0.282895 | 7.1 | 45 | 27.2 | 1.070866 | 4.0118 | 0.357656 | 5.037414 | 3.18 | 3.16507 |
| 0.282895 | 7.1 | 40 | 27.2 | 1.070866 | 3.9086 | 0.381929 | 5.37928 | 3.157 | 3.509383 |
| 0.282895 | 7.2 | 35 | 27.2 | 1.070866 | 3.8204 | 0.417013 | 5.791848 | 2.9 | 3.337302 |
| 0.282895 | 7.2 | 30 | 27.2 | 1.070866 | 3.7044 | 0.457419 | 6.353046 | 2.45 | 2.778935 |
| 0.282895 | 7.2 | 25 | 27.2 | 1.070866 | 3.5113 | 0.493169 | 6.849571 | 2.2 | 2.688889 |
| 0.282895 | 7.3 | 20 | 27.2 | 1.070866 | 3.3058 | 0.546416 | 7.485146 | 2.07 | 2.934863 |
| 0.282895 | 7.3 | 15 | 27.2 | 1.070866 | 2.9566 | 0.582766 | 7.98309 | 1.71 | 2.670411 |
| 0.282895 | 7.4 | 10 | 27.2 | 1.070866 | 2.4331 | 0.591998 | 7.999967 | 1.15 | 1.787162 |
| 0.282895 | 7.4 | 5 | 27.2 | 1.070866 | 1.4777 | 0.436719 | 5.901614 | 0.585 | 0.924932 |

# APPENDIX Y: INDIVIDUAL ONE-TO-ONE ANSYS MAXWELL COUPLING COEFFICINET SIMULATION

| Z_separation [mm] | CplCoef(TX_in,RX_in) [] |
|---|---|
| 0 | 0.98190899 |
| 1.5875 | 0.92345649 |
| 3.175 | 0.86171661 |
| 4.7625 | 0.79727767 |
| 6.35 | 0.73422807 |
| 7.9375 | 0.67300002 |
| 9.525 | 0.61478729 |
| 11.1125 | 0.56085429 |
| 12.7 | 0.5112158 |
| 14.2875 | 0.46579855 |
| 15.875 | 0.42408464 |
| 17.4625 | 0.3867506 |
| 19.05 | 0.35286652 |
| 20.6375 | 0.3221789 |
| 22.225 | 0.29456336 |
| 23.8125 | 0.26963278 |
| 25 | 0.25267739 |
| 25.4 | 0.24725774 |
| 26.9875 | 0.22719682 |
| 28.575 | 0.20899143 |
| 30.1625 | 0.1924768 |
| 31.75 | 0.17753484 |
| 33.3375 | 0.16426218 |
| 34.925 | 0.15184159 |
| 36.5125 | 0.14094497 |
| 38.1 | 0.13064444 |
| 39.6875 | 0.12168793 |
| 41.275 | 0.11336944 |
| 42.8625 | 0.10574994 |
| 44.45 | 0.09871143 |
| 45 | 0.09633263 |

# APPENDIX Z: E-CORE COILS INDIVIDUAL ONE-TO-ONE VERTICAL SEPARATION

| E-Core Individual 1 to 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Vertical Separation Test | | | | | | | | | |
| Vin 6V, Load 100 Ohms | | | | | | | | | |
| SIM | | | | | | | | Real | |
| CplCoef | Pin(W) | Spacers | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.981909 | 4.8 | 0 | 0 | 0 | 8.3588 | 0.698695 | 14.55615 | 7.52 | 11.78133 |
| 0.923456 | 4.8 | 1 | 1.5875 | 0.0625 | 7.788 | 0.606529 | 12.63603 | 7.155 | 11.12914 |
| 0.861717 | 4.8 | 2 | 3.175 | 0.125 | 7.4369 | 0.553075 | 11.52239 | 6.3735 | 9.23216 |
| 0.797278 | 4.6 | 3 | 4.7625 | 0.1875 | 7.2662 | 0.527977 | 11.47775 | 6.27 | 9.037448 |
| 0.734228 | 4.4 | 4 | 6.35 | 0.25 | 7.1586 | 0.512456 | 11.64672 | 5.8 | 7.823256 |
| 0.673 | 4.35 | 5 | 7.9375 | 0.3125 | 7.0154 | 0.492158 | 11.31399 | 5.35 | 6.814881 |
| 0.614787 | 4.3 | 6 | 9.525 | 0.375 | 6.8403 | 0.467897 | 10.88133 | 4.87 | 5.515558 |
| 0.560854 | 4.2 | 7 | 11.1125 | 0.4375 | 6.5363 | 0.427232 | 10.17219 | 4.339 | 4.378354 |
| 0.511216 | 4.3 | 8 | 12.7 | 0.5 | 6.3334 | 0.40112 | 9.328362 | 3.9 | 3.621429 |
| 0.465799 | 4.3 | 9 | 14.2875 | 0.5625 | 6.3179 | 0.399159 | 9.282758 | 3.49 | 2.900024 |
| 0.424085 | 4.2 | 10 | 15.875 | 0.625 | 5.9652 | 0.355836 | 8.472288 | 3.08 | 2.258667 |
| 0.386751 | 4.2 | 11 | 17.4625 | 0.6875 | 5.6938 | 0.324194 | 7.718895 | 2.67 | 1.697357 |
| 0.352867 | 4.2 | 12 | 19.05 | 0.75 | 5.2984 | 0.28073 | 6.684058 | 2.36 | 1.295256 |
| 0.322179 | 4.2 | 13 | 20.6375 | 0.8125 | 4.9917 | 0.249171 | 5.932635 | 2 | 0.930233 |
| 0.294563 | 4.3 | 14 | 22.225 | 0.875 | 4.631 | 0.214462 | 4.987479 | 1.7 | 0.672093 |
| 0.269633 | 4.3 | 15 | 23.8125 | 0.9375 | 4.3499 | 0.189216 | 4.400379 | 1.42 | 0.46893 |
| 0.252677 | 4.3 | 16 | 25.4 | 1 | 4.0487 | 0.16392 | 3.812086 | 1.19 | 0.329326 |
| 0.247258 | 4.3 | 17 | 26.9875 | 1.0625 | 4.0019 | 0.160152 | 3.724466 | 0.945 | 0.20768 |
| 0.227197 | 4.3 | 18 | 28.575 | 1.125 | 3.7159 | 0.138079 | 3.211143 | 0.73 | 0.12393 |
| 0.208991 | 4.3 | 19 | 30.1625 | 1.1875 | 3.4614 | 0.119813 | 2.786347 | 0.58 | 0.078233 |
| 0.192477 | 4.3 | 20 | 31.75 | 1.25 | 3.1588 | 0.09978 | 2.320469 | 0.39 | 0.035372 |
| 0.177535 | 4.3 | 21 | 33.3375 | 1.3125 | 2.9109 | 0.084733 | 1.970544 | 0.25 | 0.014535 |
| 0.164262 | 4.3 | 22 | 34.925 | 1.375 | 2.764 | 0.076397 | 1.776673 | 0.13 | 0.00393 |
| 0.151842 | 4.3 | 23 | 36.5125 | 1.4375 | 2.6073 | 0.06798 | 1.580933 | 0.05 | 0.000581 |
| 0.140945 | 4.3 | 24 | 38.1 | 1.5 | 2.3421 | 0.054854 | 1.275682 | 0.03 | 0.000209 |
| 0.130644 | 4.3 | 25 | 39.6875 | 1.5625 | 2.2105 | 0.048863 | 1.136351 | 0 | 0 |
| 0.121688 | 4.3 | 26 | 41.275 | 1.625 | 2.0601 | 0.04244 | 0.98698 | 0 | 0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 0.113369 | 4.3 | 27 | 42.8625 | 1.6875 | 1.8612 | 0.034641 | 0.805597 | 0 | 0 |
| 0.10575 | 4.3 | 28 | 44.45 | 1.75 | 1.6781 | 0.02816 | 0.654888 | 0 | 0 |
| 0.098711 | 4.3 | 29 | 45 | 1.771654 | 1.5551 | 0.024183 | 0.562404 | 0 | 0 |

# APPENDIX A2: E-CORE COILS INDIVIDUAL ONE-TO-ONE HORIZONTAL DISPLACEMENT SIMULATION

| Z_separation [mm] | CplCoef(TX_in,RX_in) [] |
|---|---|
| 0 | 0.861715 |
| 5 | 0.856071 |
| 10 | 0.841966 |
| 15 | 0.822727 |
| 20 | 0.797767 |
| 25 | 0.771826 |
| 30 | 0.745664 |
| 35 | 0.719273 |
| 40 | 0.69277 |
| 45 | 0.66394 |
| 50 | 0.634979 |
| 55 | 0.603764 |
| 60 | 0.571202 |
| 65 | 0.536427 |
| 70 | 0.499695 |
| 75 | 0.460562 |
| 80 | 0.418067 |
| 85 | 0.370919 |
| 90 | 0.318779 |
| 95 | 0.26289 |
| 100 | 0.200187 |
| 105 | 0.137517 |
| 110 | 0.086935 |
| 115 | 0.049072 |
| 120 | 0.020894 |
| 125 | 0.002832 |

# APPENDIX B2: E-CORE COILS INDIVIDUAL ONE-TO-ONE HORIZONTAL DISPLACEMENT TEST

| E-Core Individual 1 to 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Horizontal Separation Test | | | | | | | | |
| Vin 6V, Load 100 Ohms, Vertical Separation 3.175 mm | | | | | | | | |
| SIM | | | | | | | Real | |
| ClpCoef | Pin(W) | Distance in cm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.861715 | 4.8 | 0 | 0 | 8.4008 | 0.705734 | 14.7028 | 7.52 | 11.78133 |
| 0.856071 | 4.8 | 0.5 | 0.019685 | 8.3766 | 0.701674 | 14.61821 | 7.46 | 11.59408 |
| 0.841966 | 4.8 | 1 | 0.03937 | 8.2418 | 0.679273 | 14.15151 | 7.32 | 11.163 |
| 0.822727 | 4.7 | 1.5 | 0.059055 | 8.0146 | 0.642338 | 13.66677 | 7.29 | 11.30726 |
| 0.797767 | 4.7 | 2 | 0.07874 | 7.7802 | 0.605315 | 12.87905 | 7.18 | 10.9686 |
| 0.771826 | 4.7 | 2.5 | 0.098425 | 7.6222 | 0.580979 | 12.36126 | 7.1 | 10.72553 |
| 0.745664 | 4.6 | 3 | 0.11811 | 7.4874 | 0.560612 | 12.18721 | 6.948 | 10.4945 |
| 0.719273 | 4.6 | 3.5 | 0.137795 | 7.3687 | 0.542977 | 11.80386 | 6.92 | 10.41009 |
| 0.69277 | 4.6 | 4 | 0.15748 | 7.3409 | 0.538888 | 11.71496 | 6.81 | 10.08176 |
| 0.66394 | 4.4 | 4.5 | 0.177165 | 7.2597 | 0.527032 | 11.97801 | 6.62 | 9.960091 |
| 0.634979 | 4.4 | 5 | 0.19685 | 7.127 | 0.507941 | 11.54412 | 6.41 | 9.338205 |
| 0.603764 | 4.2 | 5.5 | 0.216535 | 7.0085 | 0.491191 | 11.69502 | 5.76 | 7.899429 |
| 0.571202 | 4.2 | 6 | 0.23622 | 6.8905 | 0.47479 | 11.30452 | 5.4 | 6.942857 |
| 0.536427 | 4.2 | 6.5 | 0.255906 | 6.7454 | 0.455004 | 10.83343 | 5.1 | 6.192857 |
| 0.499695 | 4.1 | 7 | 0.275591 | 6.4874 | 0.420864 | 10.26497 | 4.75 | 5.503049 |
| 0.460562 | 4.1 | 7.5 | 0.295276 | 6.275 | 0.393756 | 9.603811 | 4.18 | 4.261561 |
| 0.418067 | 4.1 | 8 | 0.314961 | 5.9152 | 0.349896 | 8.534047 | 3.58 | 3.125951 |
| 0.370919 | 4.1 | 8.5 | 0.334646 | 5.4301 | 0.29486 | 7.191704 | 2.89 | 2.037098 |
| 0.318779 | 4.1 | 9 | 0.354331 | 4.9104 | 0.24112 | 5.880982 | 2.28 | 1.267902 |
| 0.26289 | 4.1 | 9.5 | 0.374016 | 4.1642 | 0.173406 | 4.229405 | 1.77 | 0.764122 |
| 0.200187 | 4.1 | 10 | 0.393701 | 3.2973 | 0.108722 | 2.651753 | 1.2 | 0.35122 |
| 0.137517 | 4.2 | 10.5 | 0.413386 | 2.287 | 0.052304 | 1.245326 | 0.536 | 0.068404 |
| 0.086935 | 4.2 | 11 | 0.433071 | 1.329 | 0.017662 | 0.420534 | 0.05 | 0.000595 |
| 0.049072 | 4.3 | 11.5 | 0.452756 | 0.651243 | 0.004241 | 0.098632 | 0.05 | 0.000581 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.020894 | 4.3 | 12 | 0.472441 | 0.164489 | 0.000271 | 0.006292 | 0.03 | 0.000209 |
| 0.002832 | 4.3 | 12.5 | 0.492126 | 0.001721 | 2.96E-08 | 6.89E-07 | 0 | 0 |

# APPENDIX C2: E-CORE COILS INDIVIDUAL ONE-TO-ONE LOAD TEST

| E-Core Individual 1 to 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Load Test | | | | | | | |
| Vin 6V, Vertical Separation 3.175 mm | | | | | | | |
| SIM | | | | | | Real | |
| CplCoef | Pin(W) | Load | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.861715 | 4.8 | 100 | 8.3867 | 0.703367 | 14.65349 | 7.52 | 11.78133 |
| 0.861715 | 4.8 | 95 | 8.3579 | 0.698545 | 14.55302 | 7.4 | 11.40833 |
| 0.861715 | 4.8 | 90 | 8.2659 | 0.683251 | 14.2344 | 7.38 | 11.34675 |
| 0.861715 | 4.9 | 85 | 8.2029 | 0.672876 | 13.73216 | 7.34 | 10.99502 |
| 0.861715 | 4.9 | 80 | 8.1257 | 0.66027 | 13.4749 | 7.32 | 10.93518 |
| 0.861715 | 5 | 75 | 8.0514 | 0.64825 | 12.96501 | 7.31 | 10.68722 |
| 0.861715 | 5 | 70 | 7.9784 | 0.636549 | 12.73097 | 7.285 | 10.61425 |
| 0.861715 | 5.1 | 65 | 7.9022 | 0.624448 | 12.24407 | 7.21 | 10.19296 |
| 0.861715 | 5.1 | 60 | 7.8248 | 0.612275 | 12.00539 | 7.18 | 10.10831 |
| 0.861715 | 5.2 | 55 | 7.7083 | 0.594179 | 11.42652 | 7.12 | 9.748923 |
| 0.861715 | 5.4 | 50 | 7.6058 | 0.578482 | 10.71263 | 7.02 | 9.126 |
| 0.861715 | 5.5 | 45 | 7.4599 | 0.556501 | 10.1182 | 6.94 | 8.757018 |
| 0.861715 | 5.6 | 40 | 7.2701 | 0.528544 | 9.438278 | 6.82 | 8.305786 |
| 0.861715 | 5.8 | 35 | 7.0449 | 0.496306 | 8.557003 | 6.73 | 7.809121 |
| 0.861715 | 6.1 | 30 | 6.8029 | 0.462794 | 7.586795 | 6.57 | 7.076213 |
| 0.861715 | 6.6 | 25 | 6.4964 | 0.422032 | 6.394426 | 6.375 | 6.15767 |
| 0.861715 | 7.1 | 20 | 6.0497 | 0.365989 | 5.15477 | 6.22 | 5.44907 |
| 0.861715 | 7.9 | 15 | 5.5294 | 0.305743 | 3.87016 | 5.93 | 4.451253 |
| 0.861715 | 11.1 | 10 | 4.832 | 0.233482 | 2.103444 | 5.06 | 2.306631 |
| 0.861715 | 13.5 | 5 | 3.731 | 0.139204 | 1.031138 | 1.4 | 0.145185 |

# APPENDIX D2: E-CORE COILS SEVEN-TO-ONE VERTICAL SEPARATION PEAK POSITION ANSYS MAXWELL COUPLING COEFFICIENT

| Z_separation [mm] | CplCoef(Tx_in,Rx_in) [] |
|---|---|
| 4.7625 | 0.486322 |
| 6.35 | 0.431223 |
| 7.9375 | 0.385259 |
| 9.525 | 0.345526 |
| 11.1125 | 0.311826 |
| 12.7 | 0.281883 |
| 14.2875 | 0.254832 |
| 15.875 | 0.231801 |
| 17.4625 | 0.210221 |
| 19.05 | 0.19224 |
| 20.6375 | 0.1757 |
| 22.225 | 0.160733 |
| 23.8125 | 0.147369 |
| 25.4 | 0.135126 |
| 26.9875 | 0.124275 |
| 28.575 | 0.114689 |
| 30.1625 | 0.107435 |
| 31.75 | 0.09773 |
| 33.3375 | 0.090588 |
| 34.925 | 0.084227 |
| 36.5125 | 0.077865 |
| 38.1 | 0.072403 |
| 39.6875 | 0.067445 |
| 40 | 0.066455 |
| 50 | 0.043817 |

# APPENDIX E2: E-CORE SEVEN-TO-ONE VERTICAL SEPARATION PEAK POSITION

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| E-Core Multiple 7 to 1 | | | | | | | | | |
| Vertical Separation Test | | | | | | | | | |
| Vin 6V, Load 100 Ohms, Peak Position (0 cm Horizontal Separation) | | | | | | | | | |
| SIM | | | | | | | | Real | |
| CplCoef | Pin(W) | Spacers | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.486322 | 60.1 | 3 | 4.7625 | 0.1875 | 20.9415 | 4.385464 | 7.296945 | 19.4 | 6.26223 |
| 0.431223 | 58 | 4 | 6.35 | 0.25 | 18.7565 | 3.518063 | 6.065626 | 17.25 | 5.130388 |
| 0.385259 | 58 | 5 | 7.9375 | 0.3125 | 17.1742 | 2.949531 | 5.085399 | 15.07 | 4.491216 |
| 0.345526 | 55.8 | 6 | 9.525 | 0.375 | 15.3624 | 2.360033 | 4.22945 | 13.57 | 3.447615 |
| 0.311826 | 54.3 | 7 | 11.1125 | 0.4375 | 13.6561 | 1.864891 | 3.434421 | 12.15 | 2.718646 |
| 0.281883 | 52.3 | 8 | 12.7 | 0.5 | 11.6847 | 1.365322 | 2.610559 | 9.58 | 1.981499 |
| 0.254832 | 49.5 | 9 | 14.2875 | 0.5625 | 10.3563 | 1.072529 | 2.166726 | 8.65 | 1.511566 |
| 0.231801 | 49.1 | 10 | 15.875 | 0.625 | 9.0541 | 0.819767 | 1.669587 | 7.55 | 1.160947 |
| 0.210221 | 49.9 | 11 | 17.4625 | 0.6875 | 8.3502 | 0.697258 | 1.397311 | 6.8 | 0.926653 |
| 0.19224 | 49.2 | 12 | 19.05 | 0.75 | 7.6478 | 0.584888 | 1.188798 | 6.1 | 0.756301 |
| 0.1757 | 49.7 | 13 | 20.6375 | 0.8125 | 6.5469 | 0.428619 | 0.862412 | 5.44 | 0.595445 |
| 0.160733 | 48.5 | 14 | 22.225 | 0.875 | 5.9451 | 0.353442 | 0.728747 | 4.8 | 0.475052 |
| 0.147369 | 46.1 | 15 | 23.8125 | 0.9375 | 5.3149 | 0.282482 | 0.612758 | 4.21 | 0.384471 |
| 0.135126 | 46.1 | 16 | 25.4 | 1 | 4.8478 | 0.235012 | 0.509787 | 3.74 | 0.303419 |
| 0.124275 | 46.5 | 17 | 26.9875 | 1.0625 | 4.4296 | 0.196214 | 0.421965 | 3.32 | 0.237041 |
| 0.114689 | 46.4 | 18 | 28.575 | 1.125 | 4.2823 | 0.183381 | 0.395218 | 3.04 | 0.199172 |
| 0.107435 | 45.7 | 19 | 30.1625 | 1.1875 | 3.8823 | 0.150723 | 0.329809 | 2.67 | 0.155993 |
| 0.09773 | 46.2 | 20 | 31.75 | 1.25 | 3.5123 | 0.123363 | 0.267018 | 2.47 | 0.132054 |
| 0.090588 | 46.1 | 21 | 33.3375 | 1.3125 | 3.1288 | 0.097894 | 0.212351 | 2.17 | 0.102145 |
| 0.084227 | 44.6 | 22 | 34.925 | 1.375 | 2.7232 | 0.074158 | 0.166274 | 1.87 | 0.078406 |

# APPENDIX F2: E-CORE SEVEN-TO-ONE LOW POSITION VERTICAL SEPARATION ANSYS MAXWELL COUPLING COEFFICIENCT SIMULATION

| Z_separation [mm] | CplCoef(Tx_in,Rx_in) [] |
|---|---|
| 4.7625 | 0.47167766 |
| 6.35 | 0.41622866 |
| 7.9375 | 0.36500584 |
| 9.525 | 0.33145678 |
| 12.7 | 0.26843122 |
| 14.2875 | 0.24195482 |
| 15.875 | 0.21434634 |
| 17.4625 | 0.19892679 |
| 19.05 | 0.18073717 |
| 20.6375 | 0.1651479 |
| 22.225 | 0.15065314 |
| 23.8125 | 0.1377697 |
| 25.4 | 0.12846972 |
| 26.9875 | 0.11059662 |
| 28.575 | 0.10678388 |
| 30.1625 | 0.09827074 |
| 31.75 | 0.09082868 |
| 33.3375 | 0.08391681 |
| 34.925 | 0.07782928 |
| 50 | 0.04014778 |

# APPENDIX G2: Test E-CORE SEVEN-TO-ONE LOW POSITION VERTICAL SEPARATION

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| E-Core Multiple 7 to 1 | | | | | | | | | |
| Vertical Separation Test | | | | | | | | | |
| Vin 6V, Load 100 Ohms, Low Position (8.5 cm Horizontal Separation) | | | | | | | | | |
| SIM | | | | | | | | Real | |
| CplCoef | Pin(W) | Spacers | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.471678 | 56.3 | 3 | 4.7625 | 0.1875 | 17.2 | 2.9584 | 5.254707 | 13.7 | 3.333748 |
| 0.416229 | 56.3 | 4 | 6.35 | 0.25 | 15.2 | 2.3104 | 4.384061 | 13.7 | 3.56148 |
| 0.365006 | 52.7 | 5 | 7.9375 | 0.3125 | 13.2 | 1.7424 | 3.344338 | 11.59 | 2.578274 |
| 0.331457 | 52.1 | 6 | 9.525 | 0.375 | 11.713 | 1.371944 | 2.711351 | 10.63 | 2.23314 |
| 0.268431 | 50.6 | 7 | 11.1125 | 0.4375 | 10.54 | 1.110916 | 2.253379 | 9.04 | 1.657639 |
| 0.241955 | 49.3 | 8 | 12.7 | 0.5 | 9.36 | 0.876096 | 1.802667 | 7.86 | 1.271185 |
| 0.214346 | 48.6 | 9 | 14.2875 | 0.5625 | 8.5 | 0.7225 | 1.511506 | 7 | 1.025105 |
| 0.198927 | 47.8 | 10 | 15.875 | 0.625 | 7.65 | 0.585225 | 1.21416 | 6.15 | 0.784699 |
| 0.180737 | 48.2 | 11 | 17.4625 | 0.6875 | 7.08 | 0.501264 | 1.062 | 5.58 | 0.659669 |
| 0.165148 | 47.2 | 12 | 19.05 | 0.75 | 6.19 | 0.383161 | 0.829353 | 4.69 | 0.476106 |
| 0.150653 | 46.2 | 13 | 20.6375 | 0.8125 | 5.2 | 0.2704 | 0.585281 | 4.1 | 0.363853 |
| 0.13777 | 46.1 | 14 | 22.225 | 0.875 | 4.73 | 0.223729 | 0.485312 | 3.63 | 0.285833 |
| 0.12847 | 46.1 | 15 | 23.8125 | 0.9375 | 4.31 | 0.185761 | 0.402952 | 3.21 | 0.223516 |
| 0.110597 | 44.1 | 16 | 25.4 | 1 | 3.86 | 0.148996 | 0.337859 | 2.76 | 0.172735 |
| 0.106784 | 45 | 17 | 26.9875 | 1.0625 | 3.42 | 0.116964 | 0.25992 | 2.52 | 0.14112 |
| 0.098271 | 45 | 18 | 28.575 | 1.125 | 2.9523 | 0.087161 | 0.193691 | 2.21 | 0.108536 |
| 0.090829 | 44.3 | 19 | 30.1625 | 1.1875 | 2.6423 | 0.069817 | 0.157602 | 1.9 | 0.08149 |
| 0.083917 | 43.5 | 20 | 31.75 | 1.25 | 2.1923 | 0.048062 | 0.110487 | 1.65 | 0.062586 |
| 0.077829 | 44 | 21 | 33.3375 | 1.3125 | 1.8877 | 0.035634 | 0.080987 | 1.43 | 0.046475 |
| 0.040148 | 44.7 | 22 | 34.925 | 1.375 | 1.5277 | 0.023339 | 0.052212 | 1.27 | 0.036083 |

# APPENDIX H2: E-CORE SEVEN-TO-ONE PEAK POSITION LOAD TEST

| E-Core Multiple 7 to 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Load Test | | | | | | | |
| Vin 6V, Vertical Separation 4.7625 mm, Peak Position (0 cm Horizontal Separation) | | | | | | | |
| SIM | | | | | | Real | |
| CplCoef | Pin(W) | Load | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.486322 | 60.1 | 100 | 20.9412 | 4.385339 | 7.296736 | 19.4 | 6.26223 |
| 0.486322 | 61.2 | 95 | 20.8575 | 4.350353 | 7.10842 | 19.35 | 6.118015 |
| 0.486322 | 60.7 | 90 | 20.6468 | 4.262904 | 7.022905 | 19.14 | 6.035249 |
| 0.486322 | 60.4 | 85 | 20.2863 | 4.11534 | 6.813476 | 18.58 | 5.715503 |
| 0.486322 | 58.7 | 80 | 19.8134 | 3.925708 | 6.687748 | 18.01 | 5.525726 |
| 0.486322 | 58.8 | 75 | 19.5178 | 3.809445 | 6.478648 | 17.81 | 5.394491 |
| 0.486322 | 59.1 | 70 | 19.2454 | 3.703854 | 6.267097 | 17.74 | 5.325002 |
| 0.486322 | 58.2 | 65 | 18.7921 | 3.53143 | 6.06775 | 17.29 | 5.136497 |
| 0.486322 | 58.7 | 60 | 18.3645 | 3.372549 | 5.745398 | 17.06 | 4.958153 |
| 0.486322 | 57.2 | 55 | 17.7784 | 3.160715 | 5.525726 | 16.2 | 4.588112 |
| 0.486322 | 57.2 | 50 | 17.0743 | 2.915317 | 5.096708 | 15.97 | 4.458757 |
| 0.486322 | 57.5 | 45 | 16.4443 | 2.70415 | 4.70287 | 15.64 | 4.25408 |
| 0.486322 | 56.1 | 40 | 15.6278 | 2.442281 | 4.353443 | 14.52 | 3.758118 |
| 0.486322 | 56 | 35 | 14.8774 | 2.21337 | 3.952447 | 13.77 | 3.385945 |
| 0.486322 | 54.3 | 30 | 13.7785 | 1.898471 | 3.496263 | 12.67 | 2.956333 |
| 0.486322 | 54.5 | 25 | 12.8423 | 1.649247 | 3.026141 | 12.4 | 2.821284 |
| 0.486322 | 51.7 | 20 | 11.3223 | 1.281945 | 2.479584 | 9.88 | 1.888093 |
| 0.486322 | 52.5 | 13.1 | 8.5123 | 0.724593 | 1.380176 | 8.47 | 1.366493 |
| 0.486322 | 50.4 | 6.8 | 5.7127 | 0.326349 | 0.647519 | 5.455 | 0.590417 |

# APPENDIX I2: E-CORE SEVEN-TO-ONE LOW POSITION LOAD TEST

| E-Core Multiple 7 to 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Load Test | | | | | | | |
| Vin 6V, Vertical Separation 4.7625 mm, Low Position (8.5 cm Horizontal Separation) | | | | | | | |
| SIM | | | | | | Real | |
| CplCoef | Pin(W) | Load | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.471678 | 56.3 | 100 | 15.4125 | 2.375452 | 4.219275 | 13.7 | 3.333748 |
| 0.471678 | 56.3 | 95 | 15.3548 | 2.357699 | 4.187742 | 13.65 | 3.309458 |
| 0.471678 | 56.25 | 90 | 15.1374 | 2.291409 | 4.073616 | 13.43 | 3.206487 |
| 0.471678 | 55.9 | 85 | 14.9941 | 2.24823 | 4.021879 | 13.14 | 3.088723 |
| 0.471678 | 55.1 | 80 | 14.8685 | 2.210723 | 4.012201 | 12.76 | 2.954947 |
| 0.471678 | 53.9 | 75 | 14.6545 | 2.147544 | 3.984311 | 12.55 | 2.922124 |
| 0.471678 | 55.5 | 70 | 14.3165 | 2.049622 | 3.693012 | 12.81 | 2.956686 |
| 0.471678 | 53.9 | 65 | 14.0578 | 1.976217 | 3.666452 | 12.55 | 2.922124 |
| 0.471678 | 55.3 | 60 | 13.6374 | 1.859787 | 3.363086 | 12.33 | 2.749166 |
| 0.471678 | 53 | 55 | 13.2652 | 1.759655 | 3.320104 | 11.7 | 2.58283 |
| 0.471678 | 54.4 | 50 | 12.9146 | 1.667869 | 3.065936 | 11.71 | 2.520664 |
| 0.471678 | 54.2 | 45 | 12.5954 | 1.586441 | 2.927013 | 11.4 | 2.397786 |
| 0.471678 | 53.7 | 40 | 11.9377 | 1.425087 | 2.653793 | 10.73 | 2.144002 |
| 0.471678 | 52.9 | 35 | 11.4878 | 1.319695 | 2.494698 | 10.28 | 1.997701 |
| 0.471678 | 52.3 | 30 | 10.7536 | 1.156399 | 2.211088 | 9.25 | 1.635994 |
| 0.471678 | 52.6 | 25 | 10.0923 | 1.018545 | 1.936398 | 9.05 | 1.557082 |
| 0.471678 | 50.6 | 20 | 9.0923 | 0.826699 | 1.633793 | 7.75 | 1.187006 |
| 0.471678 | 49.6 | 13.1 | 7.4223 | 0.550905 | 1.110696 | 6.18 | 0.770008 |
| 0.471678 | 49 | 6.8 | 4.6677 | 0.217874 | 0.444641 | 3.91 | 0.312002 |

# APPENDIX J2: E-CORE COILS HORIZONTAL DISPLACEMENT ANSYS MAXWELL COUPLING COEFFICIENT SIMULATION

| Z_separation [mm] | CplCoef(Tx_in,Rx_in) [] |
|---|---|
| 0 | 0.48632184 |
| 5 | 0.48194108 |
| 10 | 0.4725385 |
| 15 | 0.46379577 |
| 20 | 0.45518493 |
| 25 | 0.44368244 |
| 30 | 0.42850059 |
| 35 | 0.4165313 |
| 40 | 0.40456201 |
| 45 | 0.39067763 |
| 50 | 0.38062343 |
| 55 | 0.371048 |
| 60 | 0.36626028 |
| 65 | 0.36147257 |
| 70 | 0.35907871 |
| 75 | 0.35883932 |
| 80 | 0.35859994 |
| 85 | 0.35668485 |
| 90 | 0.35716362 |
| 95 | 0.36195134 |
| 100 | 0.36443011 |
| 105 | 0.36865414 |
| 110 | 0.37822957 |
| 115 | 0.387805 |
| 120 | 0.39977429 |
| 125 | 0.40874358 |
| 130 | 0.42003717 |
| 135 | 0.42921875 |
| 140 | 0.43927295 |
| 145 | 0.44765146 |
| 150 | 0.45691794 |
| 155 | 0.46273276 |
| 160 | 0.45722689 |
| 165 | 0.44765146 |
| 170 | 0.44046988 |
| 175 | 0.43089445 |

| | |
|---|---|
| 180 | 0.42299472 |
| 185 | 0.4131799 |
| 190 | 0.40575894 |
| 195 | 0.39498658 |
| 200 | 0.387805 |
| 205 | 0.37703264 |
| 210 | 0.37056923 |
| 215 | 0.36482397 |
| 220 | 0.36266949 |
| 225 | 0.36266949 |
| 230 | 0.36243011 |
| 235 | 0.36147257 |
| 240 | 0.36266949 |
| 245 | 0.36482397 |
| 250 | 0.36985107 |
| 255 | 0.37559633 |
| 260 | 0.38134159 |
| 265 | 0.38565053 |
| 270 | 0.39498658 |
| 275 | 0.40097122 |
| 280 | 0.40695587 |
| 285 | 0.4165313 |
| 290 | 0.42850059 |
| 295 | 0.43870927 |
| 300 | 0.44636961 |
| 305 | 0.45387549 |

# APPENDIX K2: E-CORE SEVEN-TO-ONE HORIZONTAL DISPLACEMENT TEST

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| E-Core Multiple 7 to 1 | | | | | | | | |
| Horizontal Separation Test | | | | | | | | |
| Vin 6V, Load 100 Ohms, Vertical Separation 4.7625 mm | | | | | | | | |
| SIM | | | | | | | Real | |
| CplCoef | Pin(W) | Distance in cm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.486322 | 60.1 | 0 | 0 | 20.3154 | 4.127155 | 6.867146 | 19.4 | 6.26223 |
| 0.481941 | 60.2 | 0.5 | 0.019685 | 20.1324 | 4.053135 | 6.732783 | 19.23 | 6.142739 |
| 0.474839 | 60.1 | 1 | 0.03937 | 19.8357 | 3.93455 | 6.546672 | 19.1 | 6.000164 |
| 0.467796 | 60.1 | 1.5 | 0.059055 | 19.5415 | 3.818702 | 6.353914 | 18.6 | 5.756406 |
| 0.455185 | 59.8 | 2 | 0.07874 | 19.0147 | 3.615588 | 6.046134 | 18.07 | 5.460283 |
| 0.443682 | 59.4 | 2.5 | 0.098425 | 18.5342 | 3.435166 | 5.783107 | 17.6 | 5.214815 |
| 0.428501 | 57.3 | 3 | 0.11811 | 17.9 | 3.2041 | 5.591798 | 16.6 | 4.809075 |
| 0.416531 | 57 | 3.5 | 0.137795 | 17.4 | 3.0276 | 5.311579 | 16.2 | 4.604211 |
| 0.404562 | 57.2 | 4 | 0.15748 | 16.9 | 2.8561 | 4.993182 | 15.7 | 4.309266 |
| 0.390678 | 56.8 | 4.5 | 0.177165 | 16.32 | 2.663424 | 4.689127 | 15.12 | 4.024901 |
| 0.380623 | 57.2 | 5 | 0.19685 | 15.9 | 2.5281 | 4.419755 | 14.9 | 3.881294 |
| 0.371048 | 56.1 | 5.5 | 0.216535 | 15.5 | 2.4025 | 4.282531 | 14.3 | 3.645098 |
| 0.36626 | 56.6 | 6 | 0.23622 | 15.3 | 2.3409 | 4.135866 | 14.3 | 3.612898 |
| 0.361473 | 56.3 | 6.5 | 0.255906 | 15.1 | 2.2801 | 4.049911 | 14 | 3.531261 |
| 0.359079 | 56.2 | 7 | 0.275591 | 15 | 2.25 | 4.003559 | 13.7 | 3.33968 |
| 0.358839 | 56.3 | 7.5 | 0.295276 | 14.99 | 2.247001 | 3.991121 | 13.79 | 3.377693 |
| 0.3586 | 56.6 | 8 | 0.314961 | 14.98 | 2.244004 | 3.964671 | 13.8 | 3.364664 |
| 0.356685 | 56 | 8.5 | 0.334646 | 14.9 | 2.2201 | 3.964464 | 13.7 | 3.333748 |
| 0.357164 | 56 | 9 | 0.354331 | 14.92 | 2.226064 | 3.975114 | 13.72 | 3.343488 |
| 0.361951 | 56.2 | 9.5 | 0.374016 | 15.12 | 2.286144 | 4.067872 | 13.92 | 3.447801 |
| 0.36243 | 54.2 | 10 | 0.393701 | 15.14 | 2.292196 | 4.229144 | 13.94 | 3.585306 |
| 0.368654 | 55.2 | 10.5 | 0.413386 | 15.4 | 2.3716 | 4.296377 | 14.18 | 3.642616 |
| 0.37823 | 55.9 | 11 | 0.433071 | 15.8 | 2.4964 | 4.465832 | 14.36 | 3.688902 |
| 0.387805 | 55.6 | 11.5 | 0.452756 | 16.2 | 2.6244 | 4.720144 | 14.9 | 3.992986 |
| 0.399774 | 56.8 | 12 | 0.472441 | 16.7 | 2.7889 | 4.910035 | 15.5 | 4.229754 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.411744 | 57.5 | 12.5 | 0.492126 | 17.2 | 2.9584 | 5.145043 | 16.22 | 4.57545 |
| 0.422037 | 58.2 | 13 | 0.511811 | 17.63 | 3.108169 | 5.340497 | 16.73 | 4.809156 |
| 0.429219 | 58.3 | 13.5 | 0.531496 | 17.93 | 3.214849 | 5.514321 | 17.03 | 4.97463 |
| 0.439273 | 58 | 14 | 0.551181 | 18.35 | 3.367225 | 5.80556 | 17.45 | 5.342149 |
| 0.447651 | 58 | 14.5 | 0.570866 | 18.7 | 3.4969 | 6.029138 | 17.88 | 5.559903 |
| 0.452918 | 58.1 | 15 | 0.590551 | 18.92 | 3.579664 | 6.161212 | 18.02 | 5.588991 |
| 0.462733 | 58.9 | 15.5 | 0.610236 | 19.33 | 3.736489 | 6.343784 | 18.43 | 5.766806 |
| 0.457227 | 59 | 16 | 0.629921 | 19.1 | 3.6481 | 6.18322 | 18.2 | 5.614237 |
| 0.447651 | 58.3 | 16.5 | 0.649606 | 18.7 | 3.4969 | 5.998113 | 17.67 | 5.355556 |
| 0.44047 | 58 | 17 | 0.669291 | 18.4 | 3.3856 | 5.837241 | 17.5 | 5.280172 |
| 0.430894 | 58.2 | 17.5 | 0.688976 | 18 | 3.24 | 5.56701 | 17.1 | 5.024227 |
| 0.422995 | 58.3 | 18 | 0.708661 | 17.67 | 3.122289 | 5.355556 | 16.62 | 4.737983 |
| 0.41318 | 57.8 | 18.5 | 0.728346 | 17.26 | 2.979076 | 5.154111 | 16.06 | 4.462346 |
| 0.405759 | 57.5 | 19 | 0.748031 | 16.95 | 2.873025 | 4.996565 | 15.75 | 4.31413 |
| 0.394987 | 57.2 | 19.5 | 0.767717 | 16.5 | 2.7225 | 4.759615 | 15.3 | 4.092483 |
| 0.387805 | 57 | 20 | 0.787402 | 16.2 | 2.6244 | 4.604211 | 14.75 | 3.816886 |
| 0.377033 | 56.7 | 20.5 | 0.807087 | 15.75 | 2.480625 | 4.375 | 14.55 | 3.73373 |
| 0.370569 | 56.6 | 21 | 0.826772 | 15.48 | 2.396304 | 4.233753 | 14.28 | 3.602799 |
| 0.364824 | 56.3 | 21.5 | 0.846457 | 15.24 | 2.322576 | 4.125357 | 14.04 | 3.488878 |
| 0.362669 | 56.5 | 22 | 0.866142 | 15.15 | 2.295225 | 4.062345 | 13.95 | 3.444292 |
| 0.362669 | 56.5 | 22.5 | 0.885827 | 15.15 | 2.295225 | 4.062345 | 13.95 | 3.444292 |
| 0.36243 | 56.6 | 23 | 0.905512 | 15.14 | 2.292196 | 4.049816 | 13.94 | 3.433279 |
| 0.361473 | 56.6 | 23.5 | 0.925197 | 15.1 | 2.2801 | 4.028445 | 13.9 | 3.413604 |
| 0.362669 | 56.7 | 24 | 0.944882 | 15.15 | 2.295225 | 4.048016 | 13.95 | 3.432143 |
| 0.364824 | 56.8 | 24.5 | 0.964567 | 15.24 | 2.322576 | 4.089042 | 14.04 | 3.470451 |
| 0.369851 | 56.8 | 25 | 0.984252 | 15.45 | 2.387025 | 4.202509 | 14.08 | 3.490254 |
| 0.375596 | 57 | 25.5 | 1.003937 | 15.69 | 2.461761 | 4.318879 | 14.49 | 3.683511 |
| 0.381342 | 57.4 | 26 | 1.023622 | 15.93 | 2.537649 | 4.420991 | 14.73 | 3.813232 |
| 0.385651 | 57.3 | 26.5 | 1.043307 | 16.11 | 2.595321 | 4.529356 | 14.91 | 3.879723 |
| 0.394987 | 57.6 | 27 | 1.062992 | 16.5 | 2.7225 | 4.726563 | 15.3 | 4.064063 |
| 0.400971 | 57.5 | 27.5 | 1.082677 | 16.75 | 2.805625 | 4.879348 | 15.55 | 4.205261 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0.406956 | 57.5 | 28 | 1.102362 | 17 | 2.89 | 5.026087 | 16.2 | 4.564174 |
| 0.416531 | 57.7 | 28.5 | 1.122047 | 17.4 | 3.0276 | 5.24714 | 16.3 | 4.604679 |
| 0.428501 | 58.8 | 29 | 1.141732 | 17.9 | 3.2041 | 5.44915 | 16.8 | 4.8 |
| 0.440709 | 58.9 | 29.5 | 1.161417 | 18.41 | 3.389281 | 5.754297 | 17.51 | 5.232084 |
| 0.44837 | 59 | 30 | 1.181102 | 18.73 | 3.508129 | 5.945981 | 17.83 | 5.388286 |
| 0.453875 | 59.1 | 30.5 | 1.200787 | 18.96 | 3.594816 | 6.082599 | 18.06 | 5.518843 |

# APPENDIX L2: E-CORE COILS THREE-TO-ONE VERTICAL SEPARATION ANSYS MAXWELL COUPLING COEFFICIENT SIMULATION

| Z_separation [mm] | CplCoef(Tx_in,Rx_in) [] |
|---|---|
| 4.7625 | 0.77333901 |
| 6.35 | 0.71203294 |
| 7.9375 | 0.65334026 |
| 9.525 | 0.59805194 |
| 11.1125 | 0.54660416 |
| 12.7 | 0.49900596 |
| 14.2875 | 0.45554717 |
| 15.875 | 0.41584575 |
| 17.4625 | 0.37972859 |
| 19.05 | 0.34607166 |
| 20.6375 | 0.31741529 |
| 22.225 | 0.29086575 |
| 23.8125 | 0.26679887 |
| 25.4 | 0.2450998 |
| 28.575 | 0.20765961 |
| 30.1625 | 0.191435 |
| 31.75 | 0.17690372 |
| 33.3375 | 0.1637951 |
| 34.925 | 0.15174272 |
| 36.5125 | 0.14081346 |
| 38.1 | 0.13083546 |
| 39.6875 | 0.12189839 |
| 41.275 | 0.11356398 |
| 42 | 0.1098893 |
| 100 | 0.01566804 |

# APPENDIX M2: E-CORE COILS THREE-TO-ONE VERTICAL SEPARATION TEST

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| E-Core Multiple 3 to 1 | | | | | | | | | |
| Vertical Separation Test | | | | | | | | | |
| Vin 6V, Load 100 Ohms, Peak Position (0 cm Horizontal Separation) | | | | | | | | | |
| SIM | | | | | | | | Real | |
| CplCoef | Pin(W) | Spacers | Distance in mm | Distance in in | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.773339 | 47.8 | 3 | 4.7625 | 0.1875 | 23.7874 | 5.658404 | 11.83767 | 22.08 | 10.1993 |
| 0.712033 | 45.4 | 4 | 6.35 | 0.25 | 23.0645 | 5.319712 | 11.71743 | 21.36 | 9.896954 |
| 0.65334 | 42.3 | 5 | 7.9375 | 0.3125 | 21.6501 | 4.687268 | 11.08101 | 19.15 | 8.879479 |
| 0.598052 | 36.1 | 6 | 9.525 | 0.375 | 19.0972 | 3.64703 | 10.10258 | 16.59 | 7.624047 |
| 0.546604 | 31.5 | 7 | 11.1125 | 0.4375 | 16.5735 | 2.746809 | 8.720029 | 14.07 | 6.2846 |
| 0.499006 | 28.4 | 8 | 12.7 | 0.5 | 13.8214 | 1.910311 | 6.726447 | 12.32 | 5.344451 |
| 0.455547 | 25.8 | 9 | 14.2875 | 0.5625 | 12.1944 | 1.487034 | 5.763697 | 10.69 | 4.429306 |
| 0.415846 | 23.7 | 10 | 15.875 | 0.625 | 10.5674 | 1.116699 | 4.711812 | 9.06 | 3.463443 |
| 0.379729 | 22 | 11 | 17.4625 | 0.6875 | 9.3614 | 0.876358 | 3.983446 | 7.86 | 2.808164 |
| 0.346072 | 21 | 12 | 19.05 | 0.75 | 8.4836 | 0.719715 | 3.427213 | 6.98 | 2.320019 |
| 0.317415 | 20 | 13 | 20.6375 | 0.8125 | 7.1941 | 0.517551 | 2.587754 | 6.09 | 1.854405 |
| 0.290866 | 19.2 | 14 | 22.225 | 0.875 | 6.4564 | 0.416851 | 2.171099 | 5.356 | 1.494101 |
| 0.266799 | 18.6 | 15 | 23.8125 | 0.9375 | 5.8014 | 0.336562 | 1.809475 | 4.7 | 1.187634 |
| 0.2451 | 18.1 | 16 | 25.4 | 1 | 5.1284 | 0.263005 | 1.453066 | 4.02 | 0.89284 |
| 0.20766 | 17.7 | 17 | 26.9875 | 1.0625 | 4.7236 | 0.223124 | 1.260587 | 3.62 | 0.740362 |
| 0.191435 | 17.4 | 18 | 28.575 | 1.125 | 4.2423 | 0.179971 | 1.034317 | 3.1 | 0.552299 |
| 0.176904 | 17.1 | 19 | 30.1625 | 1.1875 | 3.7142 | 0.137953 | 0.806742 | 2.7 | 0.426316 |
| 0.163795 | 17 | 20 | 31.75 | 1.25 | 3.2423 | 0.105125 | 0.618383 | 2.3 | 0.311176 |
| 0.151743 | 16.8 | 21 | 33.3375 | 1.3125 | 2.6977 | 0.072776 | 0.43319 | 2.04 | 0.247714 |
| 0.140813 | 16.6 | 22 | 34.925 | 1.375 | 2.3577 | 0.055587 | 0.334864 | 1.8 | 0.195181 |
| 0.130835 | 16.5 | 23 | 36.5125 | 1.4375 | 2.0077 | 0.040309 | 0.244295 | 1.55 | 0.145606 |
| 0.121898 | 16.4 | 24 | 38.1 | 1.5 | 1.7577 | 0.030895 | 0.188385 | 1.3 | 0.103049 |
| 0.113564 | 16.3 | 25 | 39.6875 | 1.5625 | 1.5297 | 0.0234 | 0.143557 | 1.072 | 0.070502 |

# APPENDIX N2: E-CORE COILS THREE-TO-ONE LOAD TEST

| E-Core Multiple 3 to 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Load Test | | | | | | | |
| Vin 6V, Vertical Separation 4.7625 mm, Peak Position (0 cm Horizontal Separation) | | | | | | | |
| | | | | | | | |
| CplCoef | Pin(W) | Load | Vout | Pout(W) | Efficiency | Vout | Efficiency |
| 0.773339 | 47.8 | 100 | 23.5825 | 5.561343 | 11.63461 | 22.08 | 10.1993 |
| 0.773339 | 47.65 | 95 | 23.2984 | 5.428154 | 11.39172 | 21.798 | 9.971727 |
| 0.773339 | 47.3 | 90 | 23.0573 | 5.316391 | 11.23973 | 21.45 | 9.727326 |
| 0.773339 | 46.9 | 85 | 22.7815 | 5.189967 | 11.06603 | 21.18 | 9.56487 |
| 0.773339 | 46.35 | 80 | 22.4254 | 5.028986 | 10.85002 | 20.75 | 9.289374 |
| 0.773339 | 46.3 | 75 | 22.1447 | 4.903877 | 10.59153 | 20.64 | 9.201071 |
| 0.773339 | 45.8 | 70 | 21.6024 | 4.666637 | 10.18916 | 20.1 | 8.821179 |
| 0.773339 | 44.5 | 65 | 20.9882 | 4.405045 | 9.898978 | 18.76 | 7.90871 |
| 0.773339 | 44.75 | 60 | 20.5775 | 4.234335 | 9.462201 | 19.07 | 8.12659 |
| 0.773339 | 44.1 | 55 | 20.1546 | 4.062079 | 9.211064 | 18.65 | 7.887132 |
| 0.773339 | 43.5 | 50 | 19.5378 | 3.817256 | 8.775302 | 17.83 | 7.308251 |
| 0.773339 | 42.6 | 45 | 18.7274 | 3.507155 | 8.232758 | 17.17 | 6.920397 |
| 0.773339 | 41.1 | 40 | 17.6048 | 3.09929 | 7.540851 | 15.94 | 6.182083 |
| 0.773339 | 40.3 | 35 | 16.6821 | 2.782925 | 6.90552 | 15.1 | 5.657816 |
| 0.773339 | 39.4 | 30 | 15.5416 | 2.415413 | 6.130491 | 14.06 | 5.01735 |
| 0.773339 | 38.6 | 25 | 14.4723 | 2.094475 | 5.4261 | 13.33 | 4.603339 |
| 0.773339 | 34.2 | 20 | 12.3423 | 1.523324 | 4.454163 | 10.2 | 3.042105 |
| 0.773339 | 34 | 13.1 | 10.0523 | 1.010487 | 2.972022 | 8.91 | 2.334944 |
| 0.773339 | 30.1 | 6.8 | 5.48574 | 0.300933 | 0.999779 | 5.228 | 0.908039 |