DESIGN OF LINEAR GENERATOR

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By

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FINAL PROJECT REPORT

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CERTIFICATION OF APPROVAL

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Approved by:

……………………………………

Assoc. Prof Dr Mohd Noh Karsiti

Project Supervisor

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained here have not been undertaken or done by unspecified sources or persons.

………………………………………………

Nik Mohd Kamil B Nik Lah @ Nik Abdullah

ACKNOWLEDGEMENT

Firstly I would like the express my token of appreciation to my Supervisor, AP Dr Mohd Noh for the ideas and guides that he has contributed throughout the project. I would also like to thank all the technicians involved either directly and indirectly in this project for their assistants with the lab equipment and materials. Lastly, I would like to thanks the University for the Facilities provided in the labs which the most important part in making my project possible.

ABSTRACT

Linear Generator is one of the alternatives to the commonly used rotary generator. For motion-based generator, the rotary type is widely used compared to linear type because the momentum built up in a rotary motion is continuous. While in linear motion, the momentum breaks at the end of the stroke. However, there are some situations where linear generators can perform better than rotary generators such as when the source of the motion itself is linear. If rotary type generator is to be coupled to a linear motion, there will be a translation loss in the gearing mechanism. Thus, the potential of Linear Generator must be further studied in order to extract more output out of the available sources. This project is mainly about analysing the known factors that affect the efficiency of a Linear Generator thus come up with the best design for the generator. In general, there are many factors that need to be taken into account in designing a Linear Generator. They can be grouped as Material, Dimension and Components Configuration. The project will cover the study on the Components Configuration on the efficiency of the generator. The Components Configuration can be further broken into 3 smaller factors; Mover-Stator Configuration, Magnet's Configuration and Winding Configuration. Each of these factors will be analyse in this project. For each sub-factors, a few designs has been built and tested. The outputs (Voltage and Current) obtained from each design are used to make comparison in order to get the best configuration for each category. From the best design of each category, they will be combined to produce the best design for the Linear Generator.

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Chapter 1

INTRODUCTION

1.1 Project Background

Since the early years of electricity discovery, researchers constantly improve the technology of electrical generator in order to come up with the most efficient generator which can produce the most electrical power out of a given source. However, converting mechanical energy to electrical is energy is still the main practice in the industry. Most electric generator still uses the concept of inducing current from a moving conductor in a magnetic field.

Linear Generator is a less popular type of generator compared to the widely used rotary type generator. Currently, Linear Generator is commercially used to generate electricity from tidal waves. However, there are more situations where Linear Generator can perform well or maybe even better than a rotary type generator. For example, a car engine, the combustion of fuel in the cylinder pushes the piston upward producing a linear motion which is later translated to rotary motions by means of shafts and gears. A car dynamo which generates electricity for the car is mounted on the rotary part. Let say, a linear generator is coupled directly to the piston; the electricity generated will be free of mechanical losses from the translation process.

Currently, there are many good designs available for a Linear Generator, but it does not mean that it is the end for its development. The design can be improved from time to time and that is the objective of the project.

1.2 Problem Statement

In general, there are many factors that need to be taken into account in designing a Linear Generator. They can be grouped as Material, Dimension and Components Configuration. The project will cover the study on the Components Configuration on the efficiency of the generator.

1.3 Objective

- To analyse the effects of various component configuration on the efficiency of the Linear Generator
- To come up with the best design by the combination of the best configurations obtained from the analysis.

1.4 Scope of Study

The Components Configuration can be further broken into 3 smaller factors;

- Mover-Stator Configuration
- Magnet's Configuration
- Winding Configuration.

Each of these sub-factors will be analyse in this project by testing various designs for each sub-factor.

Chapter 2

LITERATURE REVIEW

Analysis of Tubular Linear Generator for Free-Piston Engine

Uses coil-wounded stator and permanent magnet mover. The magnet can be radial magnet or in Halbach array. For a simple analysis, a ring shaped magnets are used. Magnets are arranged with opposite poles facing each other with a spacer. The stator coils also spaced with the same measurement. Advantage of tubular design is that it is symmetric, has smaller leakage and less coils needed[5].

Permanent Magnet Linear Alternator, Part II : Design Guidelines

Permanent magnet excited tubular three phase linear alternator[6],

Stroke length $$l_{\text{stroke}} = \frac{u}{2f_e}$$ where Sn = rated power

Electromagnetic thrust $$F_{xr} = \frac{S_n}{u\eta_r}$$ u = rated speed

Stator no-load volatage $$V_0 = \frac{\omega_1}{\sqrt{2}} W_1 \frac{2}{\pi} B_{gr}\tau\pi D$$ fe = electric frequency

Permanent Magnet Linear Generator for Renewable Energy Applications: Tubular vs Four-sided Structure

Analysis between tubular design and four-sided structure, keeping the volume of the magnet constant. Maximum magnetic flux in tubular design is slightly higher than the four-sided design but the average magnetic flux are the same. Air gap length is longer for four-sided structure. Four-sided structure has longer coils resulting in higher loss[7].

Novel Permanent Magnet Linear Generator for Wave Energy Converter

Permanent magnet mover with spacer made of iron core of the same thickness of the magnet. Coil on stator spaced by iron core-teeth with the same thickness as the spacer in the mover. Second design, air-cored stator and ironless spacer with the same dimension as the first design. First design; better output, second design; simpler and less cost. [8]

2.1 ELECTROMAGNETIC THEORY

It is best to start the designing stage by understanding the magnetic field line of a permanent magnet. For a normal bar-typed magnet, the field line is as shown in the figure.

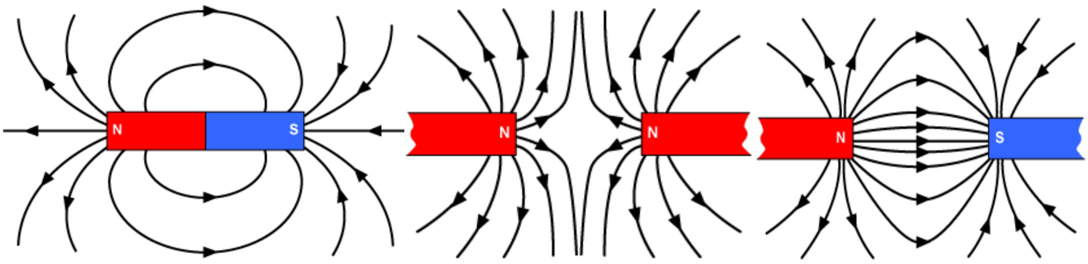


Figure 2.1 Magnetic field lines

The direction of the magnetic field line is from the North Pole to the South Pole. It same for all types of magnet except for the shape of the line might varies depending on the shape of the magnet.[1]

Magnetic Field Intensity

Current flowing through a conductor produces a magnetic field around the conductor. The magnitude of the magnetic field on a given area is known as the Magnetic Field Intensity, H.

$$H = \frac{1}{4\pi} \tau I \int \frac{dl\ x\ r}{r^2}$$

Magnetic Induction

Magnetic induction is the force exerted on the current carrying conductor,B.

$$B = \mu H$$

Where μ is the permeability of the medium. The unit for *B* is Tesla.

Magnetic Flux

Magnetic flux Φ is the magnetic induction passing through a surface. The magnetic flux for a given surface S is:

$$\Phi = \int_S B.da$$

Induced Emf,

Induced electromotive e force in a closed circuit is equal to the negative time derivative of the total flux bound by the circuit.

$$e = -\frac{d\Phi}{dt}$$

Flux linkage

If the closed circuit is consist N turns close together, each intercepts the same magnetic flux, the emf will add up in multiple of N. NΦ is called the flux linkage Λ.

$$e = -\frac{dN\Phi}{dt} = -\frac{d\Lambda}{dt}$$

2.2 PRINCIPLE OF INDUCTION GENERATOR

An induction generator consists of 2 major components: stator and rotor. Stator is the non-moving part of the generator while rotor comes from the rotating part of a rotary generator. In this case, rotor will be called as mover. Other elements connected to the stator and mover are the source of magnetic field (can either be a permanent magnet or and induced magnetic field from current carrying conductor) and coils where the current will be induced. Both the source and the coils can be either on the mover or stator based on the respective design. In between the stator and the mover, it is necessary to provide an air gap as to ensure a smooth movement of the mover. It is also necessary to design the air gap to be as small as possible. Smaller air gap makes the mover closer to the stator which results in stronger magnetic field in contact with the coils. [3]

2.3 MOVER-STATOR CONFIGURATION

1. Moving Magnet

   Coils will be wrapped around a structure (cage) and the mover (magnet) will inside the cage and connected to a shaft which is connected to an external moving force. [2]

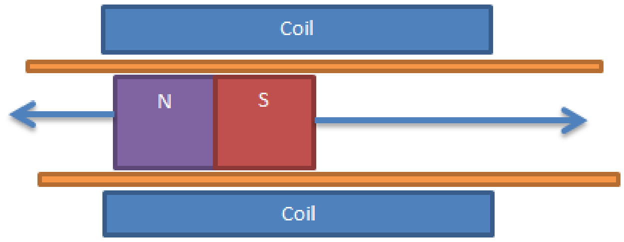
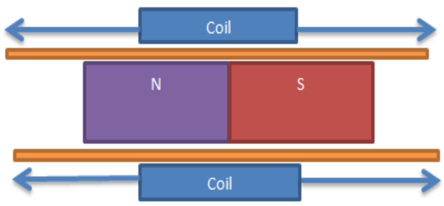


Figure 2.2 Moving Magnet

2. Moving Coils.

   Coils are connected to the external moving force while the magnet will be mounted to a fixed position.



or

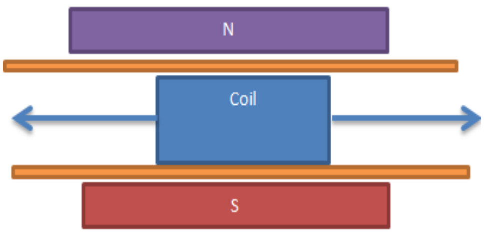


Figure 2.3 Moving Coil (external)   Figure 2.4 Moving Coil (internal)

3. Moving Iron Core

   Magnet on the outside will magnetize the iron core in the cage to make it a temporary magnet. The temporary magnet will have its magnetic field cutting across the coil.

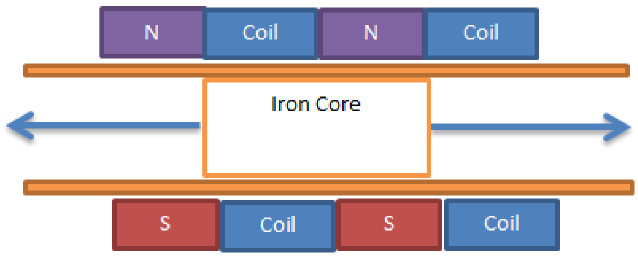
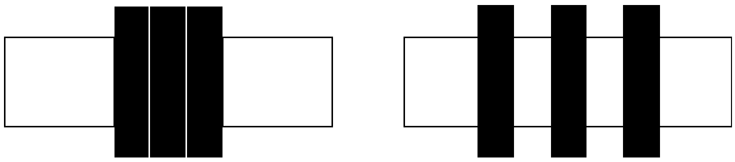


Figure 2.5 Moving Iron Core

2.4 MOVER’S MAGNET CONFIGURATION



(a) Magnets without spacer (b) Magnets with spacer

Figure 2.6 Mover’s Magnet Configuration

Based on the designs from the literature review, most of the design uses a configuration (a). Configuration (b) is an alternative where both will be compared later on.

In design (a), the magnets are attached to each other where the magnetic flux of each piece of magnet combines to produce 1 loop of magnetic flux coming out from the north pole of the end-most magnet to the south pole of the magnet on the other end.

In design (b), the magnets are separated by a certain distance far enough not to let the flux to come across each other thus each magnet will have their own flux line loop.

2.5 STATOR WINDING CONFIGURATION

1. Vertically Coiled Winding

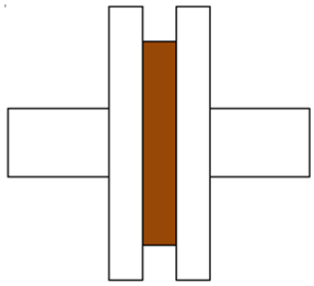


Figure 2.7

2. Horizontally Coiled Winding with Spacer

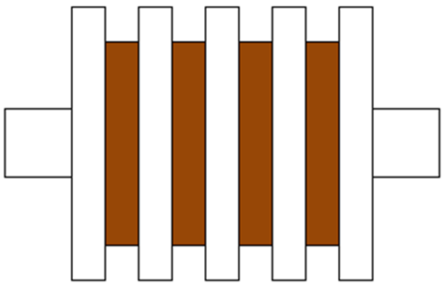


Figure 2.8

3. Horizontally Coiled Winding without Spacer (Single Layer)

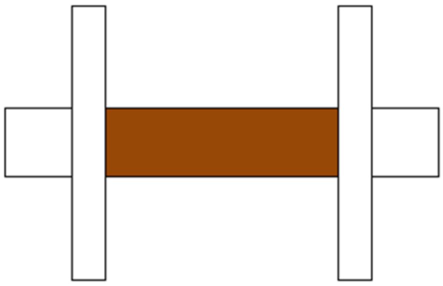


Figure 2.9

4. Horizontally Coiled Winding without Spacer (Multiple Layers)

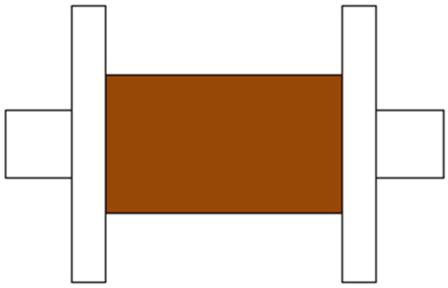


Figure 2.10

5. Horizontally Coiled Winding (Twisted)

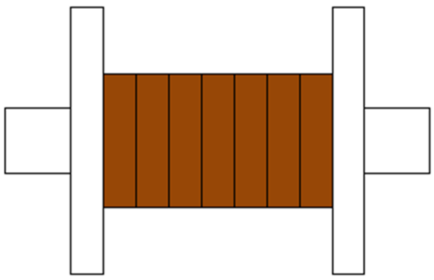


Figure 2.11

Chapter 3

METHODOLOGIES

3.1 PROJECT FLOWCHART

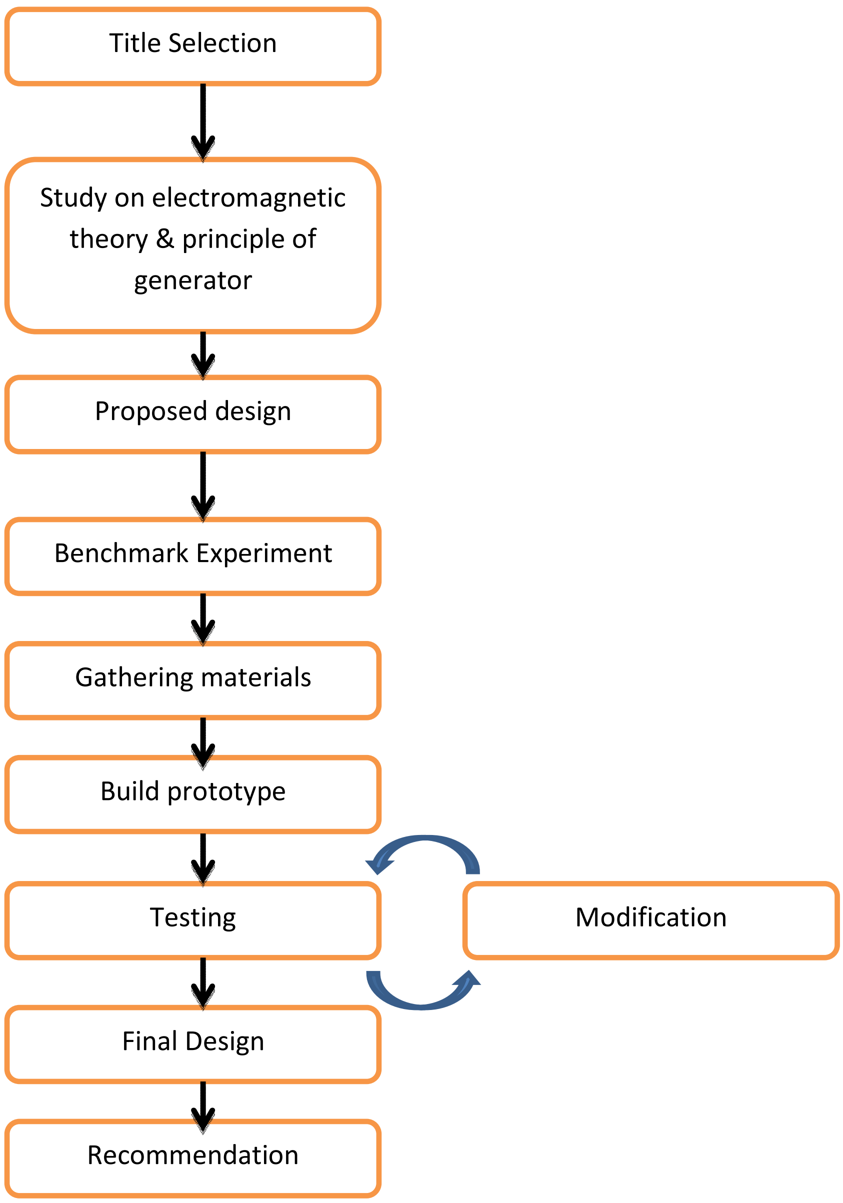


Figure 3.1

3.2 PROJECT ACTIVITIES

3.2.1 Determining the Magnets' Configuration

By using Finite Element software, some simulations are done to observe the flux line of the magnet based on different configuration. The results obtained are as follows:

1. The North pole meets the South Pole

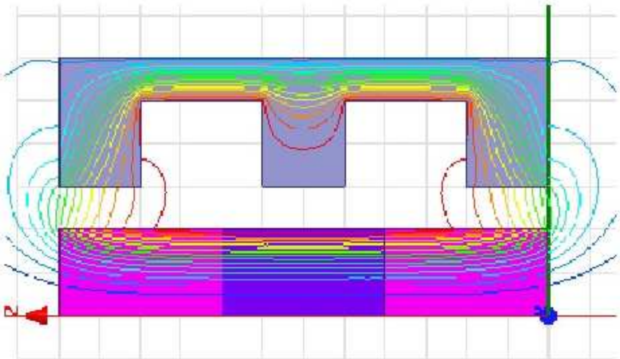


Figure 3.2

From the figure shown, when the end meets the opposite end, the magnets act like 1 magnet where the flux came out from the North pole of the outest magnet to the South pole of the outest magnet on the other end.

2. Same Poles face the same direction

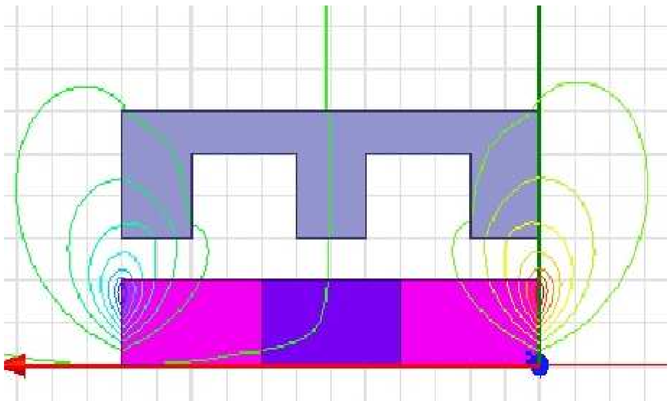


Figure 3.3

From the figure, when all the North pole of the magnets face upwards, theflux line of the magnet in the middle goes straight upward as it has no path to return while the other magnets' flux line behave normally.

3. Poles arranged alternately

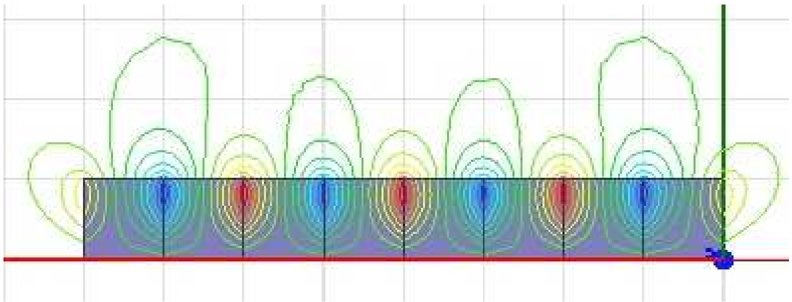


Figure 3.4

From this configuration, the flux lines have a complete path. However, since the opposite pole is close to each other. The flux line is short and there might be no flux crossing the conductor.

4. Hallbach Configuration

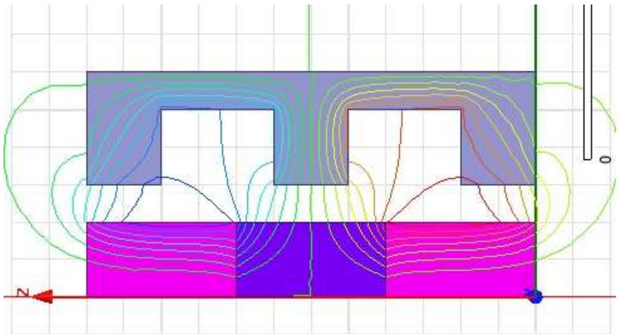


Figure 3.5

This configuration improves the first configuration in terms on the locations of the flux crossing the conductor. From 3 magnets, 2 loops of flux lines are formed compared to the first once which only 1 loop is formed.

Based on the simulation, the Hallbach configuration is selected. The magnetic field of the magnets are directed to the centre magnet where it releases the flux to the conductor. This method provides a better path for the flux line going out from the North Pole to the South Pole of the magnet. The flux produced is much denser which later will contribute to higher EMF produced when the conductor cut the flux lines.

3.2.2 Benchmarking Experiments

Experiment 1

Objective: to obtain a rough estimation of the output that will be produced by a small size linear generator.

Apparatus and material:

- Winding (300 turns, 0.8mm copper wire, borrowed from the lab)
- Permanent magnet
- Multi-meter

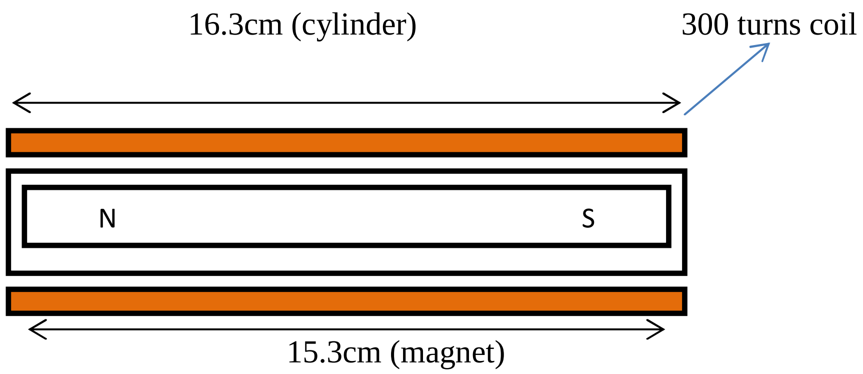


Figure 3.6

Procedure

1. Ends of winding are connected to multi meter.
2. To obtain a constant speed for all runs, the magnet is set at a constant height of 5cm above the winding. Then it is released in the winding with gravitational acceleration.
3. Maximum voltage is recorded.
4. Steps 1 to 3 are repeated for 3 runs.
5. Steps 1 to 4 are repeated for current measurement.

Results

Table 1 Result for Experiment 1

Run	Voltage (V)	Current (A)
1	0.30	0.30
2	0.30	0.30
3	0.28	0.30

Experiment 2

Objective: to test the self-made winding.

Apparatus and material:

- Winding (100 turns, 0.8mm copper wire, self-made)
- Permanent magnet
- Multi-meter

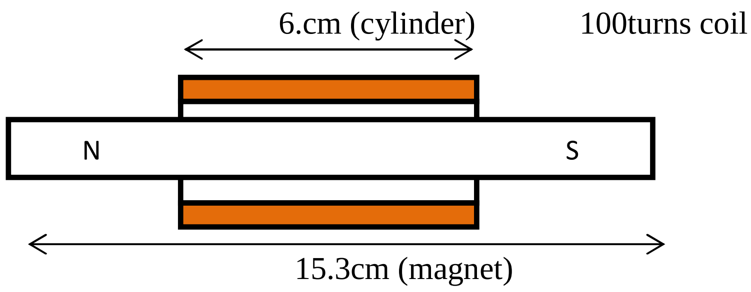


Figure 3.7

Procedure

1. Ends of winding are connected to multi meter.
2. To obtain a constant speed for all runs, the magnet is set at a constant height of 5cm above the winding. Then it is released in the winding with gravitational acceleration.
3. Maximum voltage is recorded.
4. Steps 1 to 3 are repeated for 3 runs.
5. Steps 1 to 4 are repeated for current measurement.

Result: Voltage

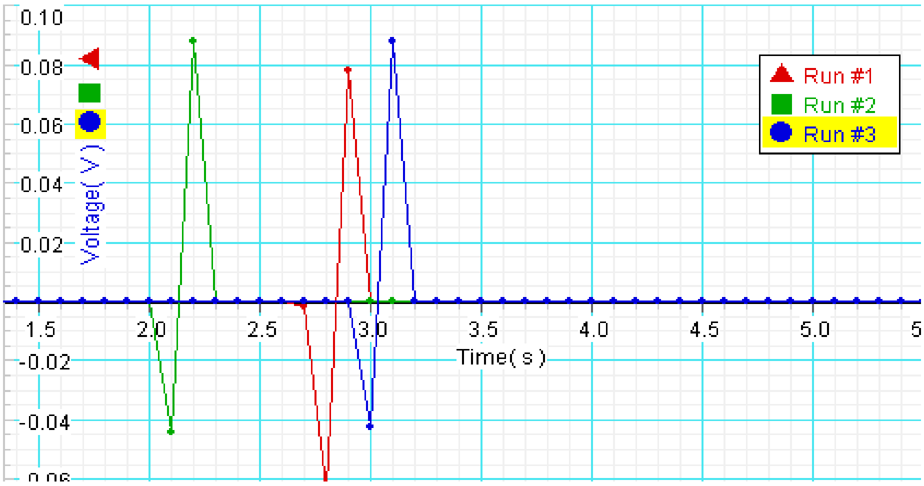


Figure 3.8

Current

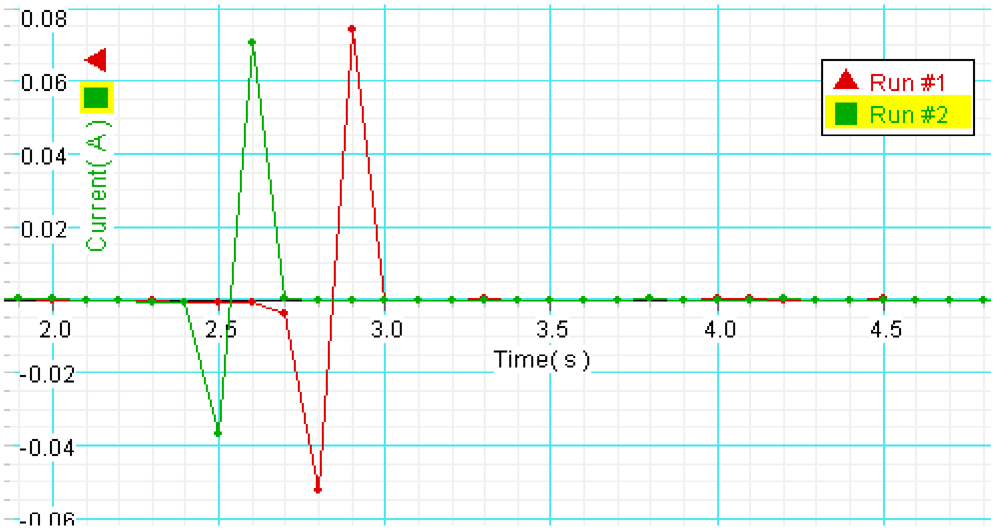


Figure 3.9

Table 2 Result for Experiment 2

Run	Voltage (V)	Current (A)
1	0.080	0.075
2	0.090	0.080
3	0.090	na

Discussion

For both experiment, a bar magnet is used instead of the magnet as per design this is due to the strength of the magnet bought. The magnets bought satisfy the requirement in terms of its shape and size. However, the strength of the magnet is too weak, thus the magnetic field could not reach the coil causing no output. For the sake of continuing the experiment, the magnet factor needs to be neglected for the time being and only the effect of windings can be experimented.

From both experiment, it shows the effect of the number of turns of the coils. In experiment 2, the no of turns is (100 turns) 1/3 of the 1^{st} experiment (300 turns). The output obtained from the 2^{nd} experiment is (0.09V & 0.08A) and also almost 1/3 of the output from the 1^{st} experiment (0.3V & 0.3A).

3.3 PROTOTYPES

1. Design 1: Vertically Coiled Winding

Figure 3.10

2. Design 2: Horizontally Coiled Winding with Spacer

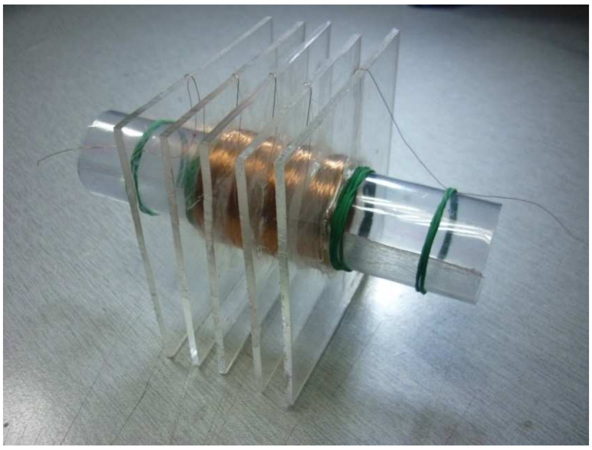


Figure3.11

3. Design 3: Horizontally Coiled Winding without Spacer (Single Layer)

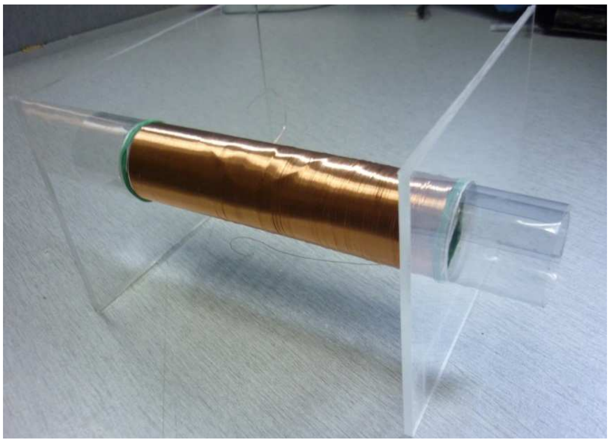


Figure 3.12

4. Design 4; Horizontally Coiled Winding without Spacer (Multiple Layers)

Figure 3.13

5. Design 5: Horizontally Coiled Winding (Twisted)

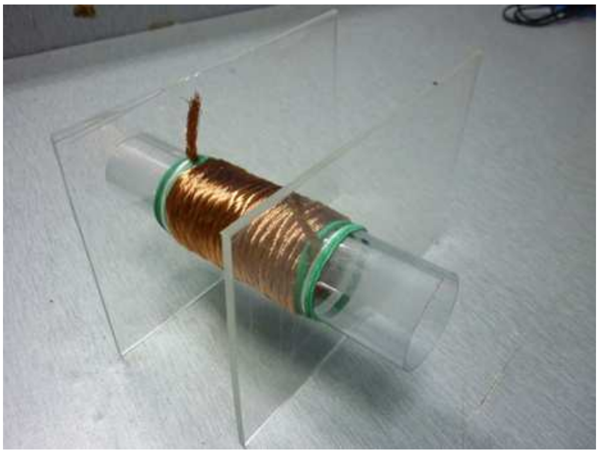


Figure 3.14

Table 3 Prototypes' Profile

Design Number	Resistance	Capacitance	Inductance
1	27kΩ	-38nF	168mH
2	53kΩ	-94nF	66mH
3	67Ω	1uF	5mH
4	672Ω	-204nF	31mH
5	300kΩ	0.6nF	9H

3.4 TESTING PROTOTYPES

Experiment 3

Objective

To measure the output current and voltage for each design.

Apparatus

Prototypes

Current Sensor

Connecting Wires

DataStudio Software

Science Workshop 750 Interface

Current Sensor (1ohm internal resistance)

Magnets

Part 1: Measuring Voltage

Procedure

1. The apparatus is set up as shown in the figure.

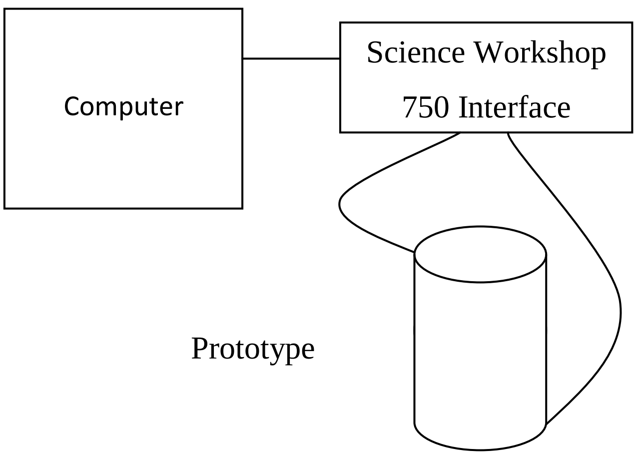


Figure 3.15 Measuring Voltage Set up

2. Wires are connected to each end of the coil. The other ends of the wires are connected to the port of Science Workshop 750 Interface.
3. Magnets are released from a height of 15cm into the coil.
4. The output recorded by the DataStudio is observed.

Part 2: Measuring Current

Procedure

1. The apparatus is set up as shown in the figure.

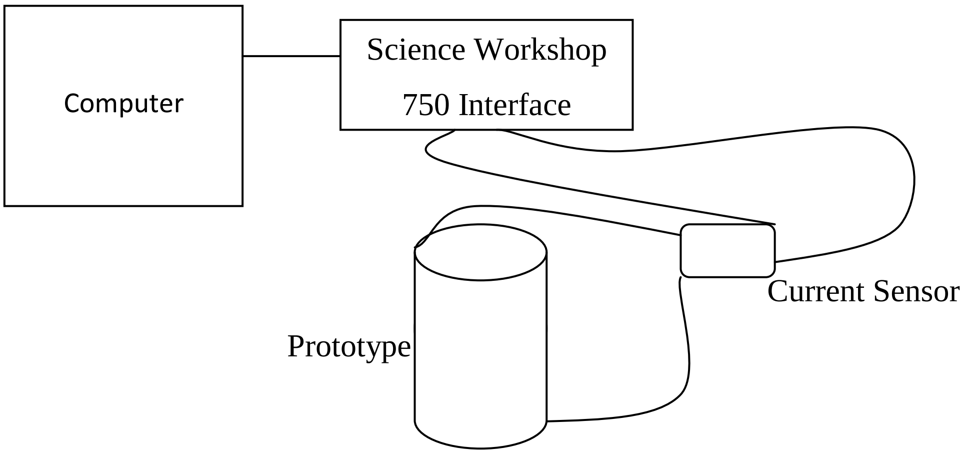


Figure 3.16 Measuring Current set up

2. Wires are connected to each end of the coil. The other ends of the wires are connected to the current sensor.
3. The current sensor is connected to the port of Science Workshop 750 Interface.
4. Magnets are released from a height of 15cm into the coil.
5. The output recorded by the DataStudio is observed.

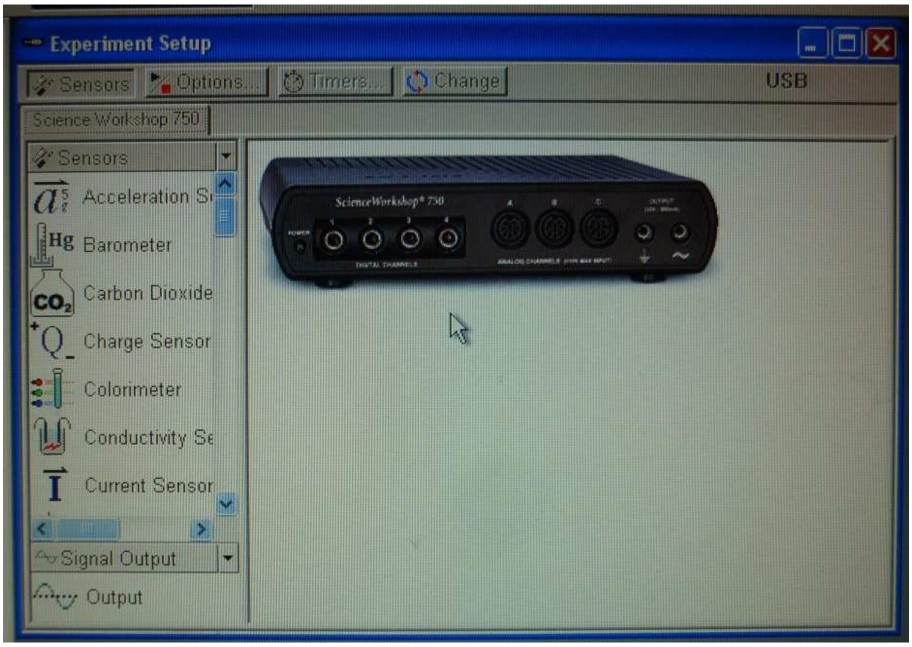


Figure 3.17 DataStudio Software

Figure 3.18 ScienceWorkshop 570 Interface

Figure 3.19 Current Sensor

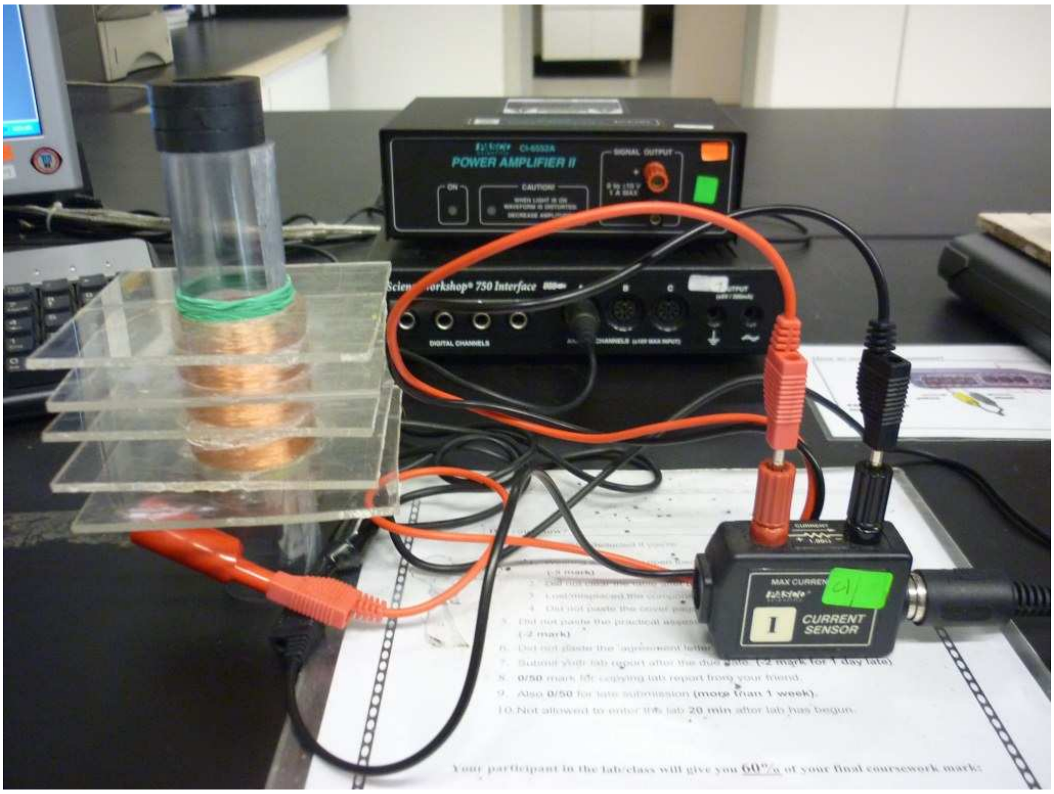


Figure 3.20 Experiment Set Up

CHAPTER 4
RESULTS & DISCUSSIONS

4.1 MOVER-STATOR CONFIGURATION

Through discussions with the project supervisor, the outcomes of the discussion are presented in the table below

Table 3 Advantages and Disadvantages of Designs

Design	Advantage	Disadvantage
Moving Magnet	High flux density in contact with the coil Easy to establish connection for the coil	Magnet exposed to physical contact, might demagnetize by time
Moving Coil	High flux density in contact with the coil	Complicated to establish connection since the coils is not stationary
Moving Iron Core	Magnet safe from physical contact Easy to establish connection for the coil Iron core will not demagnetize as long as source magnet is available	Less flux density

4.2 MAGNET'S MOVER CONFIGURATION

Both yield the same output. Difference only in the stroke length as magnets with spacer requires longer stroke length.

4.3 STATOR WINDING CONFIGURATION

The values tabulated below are based on the maximum magnitude (ignoring the polarity) since only the objective of the experiment is too obtain the average magnitude current and voltage produced by each design

Table 4 Prototypes' Output Current and Voltage

Design 1	Run 1	Run 2	Run 3	Run 4	Average
Current (A)	0.15	0.09	0.10	0.06	**0.100**
Voltage (V)	0.07	0.11	0.14	0.04	**0.090**
Design 2	Run 1	Run 2	Run 3	Run 4	**Average**
Current (A)	0.12	0.05	0.14	0.08	**0.098**
Voltage (V)	0.30	0.20	0.30	0.30	**0.275**
Design 3	Run 1	Run 2	Run 3	Run 4	**Average**
Current (A)	0.04	0.035	0.03	0.05	**0.038**
Voltage (V)	0.15	0.18	0.30	0.28	**0.228**
Design 4	Run 1	Run 2	Run 3	Run 4	**Average**
Current (A)	0.05	0.08	0.07	0.07	**0.068**
voltage (V)	0.12	0.22	0.17	0.19	**0.175**
Design 5	Run 1	Run 2	Run 3	Run 4	**Average**
Current (A)	N/A	N/A	N/A	N/A	**N/A**
voltage (V)	0.29	0.23	0.20	0.28	**0.250**

4.4 DISCUSSION

Design 1: Vertically Coiled Winding

In the experiment, Design No. 1 is the pioneer of the other designs. As per advised by the Supervisor, the winding is coiled vertically and output is observed. Design No 1 is actually a good design. However, its efficiency is affected by the strength of the magnet. Theoretically, if the winding is too thick that it reaches a point where the outer turns are no longer interact with the magnet's magnetic flux, the total area of the winding in contact with the magnetic flux is too small compared to the total available. Thus the efficiency will be low.

Design 2: Horizontally Coiled Winding with Spacer

Design No. 2 is the extension of the previous design. It improves design No.1 by reducing the winding thickness and still maintains the number of turns. Both have 2000 turns, Design No. 1 has its 2000 turns in 1 slot. Design No.2 breaks down the turns into 4 slots of 500 turns each. Each turns will be able to interact with the magnetic flux thus increasing the efficiency compared to the previous design.

Design 3: Horizontally Coiled Winding without Spacer (Single Layer)

Design No.3 on the other hand is the extension of design No.2. This time, the thickness is drastically reduced to only 1 layer of winding in order to make sure that all windings are in the reach of the flux line. However, in order to maintain the stroke length, the number of turns is reduced to 500 turns. Theoretically, this design produces a high amount of current with such a small number of turns which should make it the best design for the configuration. However, the design is hard to manufacture and the arrangement easily spoiled if exposed to physical contact (the windings tends to overlap each other if in contact). Thus it cannot be finalized as the best design.

Design 4: Horizontally Coiled Winding without Spacer (Multiple Layers)

Design No.4 is also the extension of design No.2 which reduces the winding thickness while remaining the number of turns which in the end produces an overlapping turns. The output obtained is not as good as the one obtained from design No.2 due to the crossover between the wires. Based on Data & Computer Network Theory, wires crossing over other wires may interrupt the data (voltage & current signal) carried by the wire as each wires carries their own magnetic fields. Crossover effect is prevented by twisting the wire (as normally seen in power cables and signal cables) which brought us to the next design.

Design 5: Horizontally Coiled Winding (Twisted)

Design No.5 is supposed to improve design No.4. Based on the results obtained, the design produced better output voltage compared to design No.4. However, the output current of the design is not available. After a few tests done in different sessions, the result was still the same. It might be due to unseen technical error. The shown values in the graphs are the default values when the prototype was connected to the interface of the software. Theoretically, this design should be a promising design as its winding is fully in contact with the flux and there are fewer crossovers between the turns. However, since the output is not available, the efficiency of the design cannot be proved.

Based on the table, design No 1: Vertically Coiled Winding produced the highest voltage while design No 2: Horizontally Coiled Winding (with spacer) produces the highest current. In overall, design number 2 produced the highest output. Design No.2 excels in both criteria while the other designs might excel in one criterion but no in the other one. Thus, it can be concluded that the best configuration for Components Configuration is design No 2.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 RECOMMENDATIONS

Based on the results obtained, the best design would be Design No.2: Horizontally Coiled Winding with Spacer. The design can be further improved by minimizing the size of the spacer so that more turns can be made out of a given length. The role of the spacer in the design is to reduce crossover between the turns which the main factor that causes Design No.4 to not performing well. The alternative that can be used to replace the spacer would be by tying the wires into bundles before coiling them to the cylinder. When the wires are tied into bundles, they will only cross over with the other wires in the same turn and will not be able to reach/crossover with the other turns. Hence, this method reduces crossover.

Another method to improve the design is by changing the magnet of the mover. Currently the magnets used have their poles on the flat surface (back and front surface). The flux line is perpendicular to the coil but parallel to the motion. To get a better output, magnets having its flux perpendicular to both coil and motion should be used. Thus, to improve the design, the magnets should have their flux line coming out of the curved surface and cut across the coil perpendicularly.

Figure 5.1 Ring and Segmented Magnet

The diagram shows an example of a magnet that has its flux line coming out from the curved surface. The outer and the inner curved surface has different polarity. In between them, an iron core is inserted so that the magnets will not push each other due to having the same polarity next to each other.

5.2 CONCLUSION

Based on the consideration made on the sub factors discussed in the project, in terms of Components Configuration, it can be concluded that the best design for the Linear Generator would be the combination of:

- Moving Magnet (Mover-Stator Configuration)
- Magnet without Spacer (Magnet Configuration)
- Horizontally Coiled with Spacer (Stator Winding Configuration)

The study on Linear Generator's application and design is a promising field to be focused on. The potential of Linear Generator to become the main source of renewable energy is great especially in Tidal Wave Power Generation. Given a suitable condition, it may perform better and more reliable compared to Solar and Wind Generator. Given a small size application, it may also replace the Piezoelectric Generator.

References

[1] Oskar Danielson, Design of Linear Generator for Wave Energy Plant, Uppsala University, Sweden

[2] Fuad Jamaludin, Design of Linear Generator, Universiti Teknology Petronas, Malaysia

[3] "Electrical Generator Basics" http://www.wisc-online.com

[4]"Magnetic Field Line" http://www.ece.neu.edu/faculty/nian/mom/work.html

[5] "Analysis of Tubular Linear Generator for Free-Piston Engine", Sun-Ki Hong, Ho-Yong Choi, Jae-Won Lim, Hyo-Jae Lim and Hyung Kyo Jung, School of Engineering, Seoul University, Shilim-Dong, Seoul, Korea, Hoseo University, Baebang-myun, Korea

[6] "Permanent Magnet Linear Alternator, Part II : Design Guidelines", I.Boldea, Senior Member IEEE, Polytechnic Institute, Romania, S.A Nasar, Fellow, IEEE, University of Kentucky

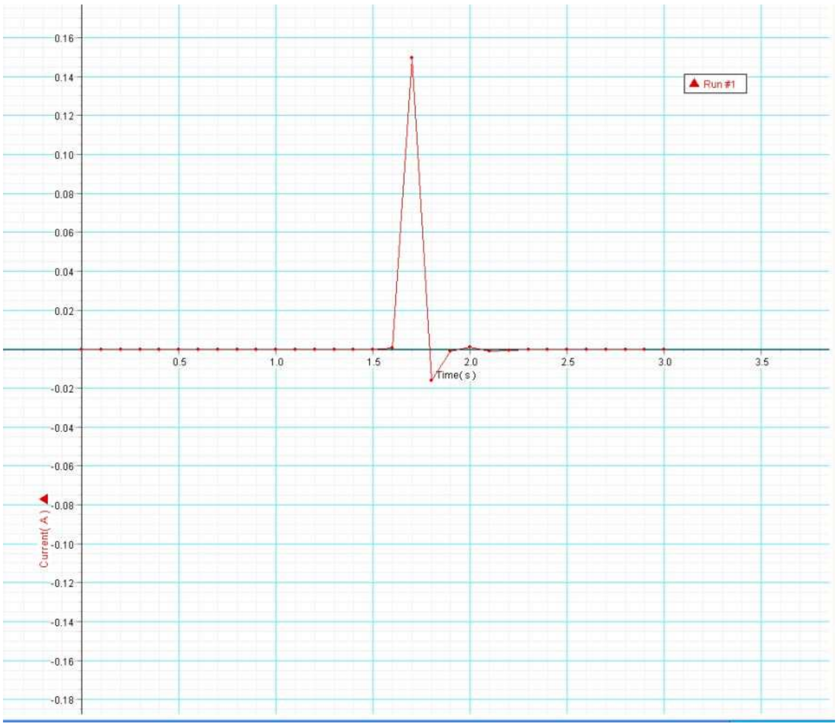
[7] "Permanent Magnet Linear Generator for Renewable Energy Applications: Tubular vs Four-sided Structure", C.A Oprea, C.S Martis, F.N Jurca, D. Fodorean, I. Szabo, Technical University of Cluj-Napoca, Romania

[8] "Novel Permanent Magnet Linear Generator for Wave Energy Converter", Lorand Szabo, Claudiu Oprea, Ioan Adrian Viorel, Karoly Agoston Biro, Technical University of Cluj-Napoca, Romania

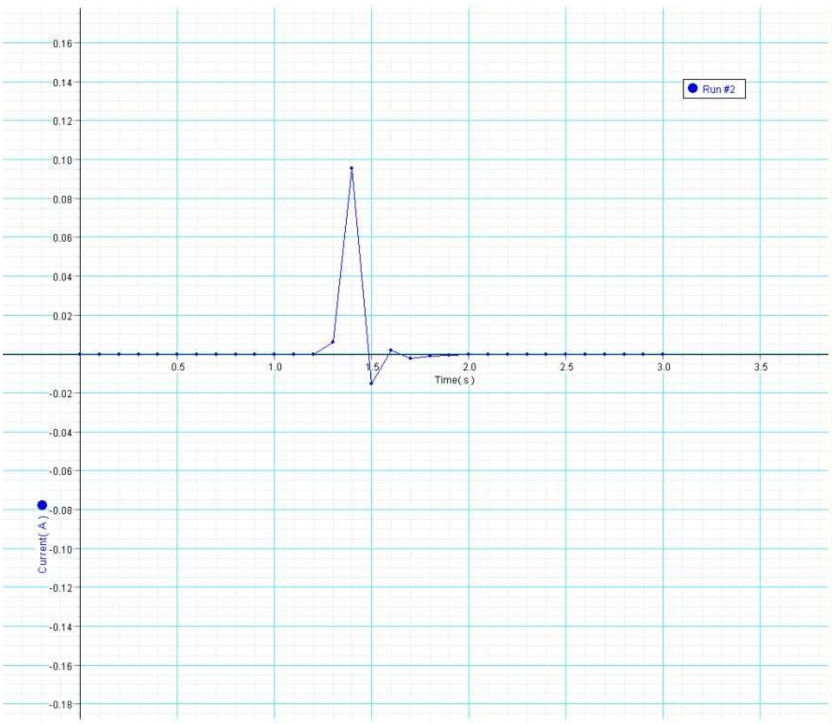
Appendices

Appendix

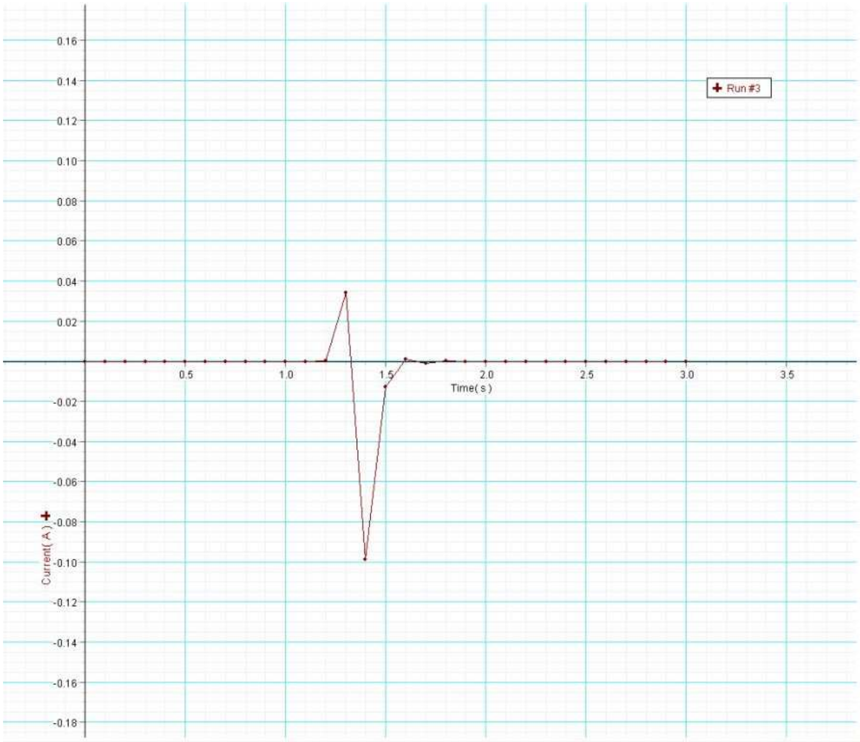
Design 1: Vertically Coiled Winding Output Current (A)



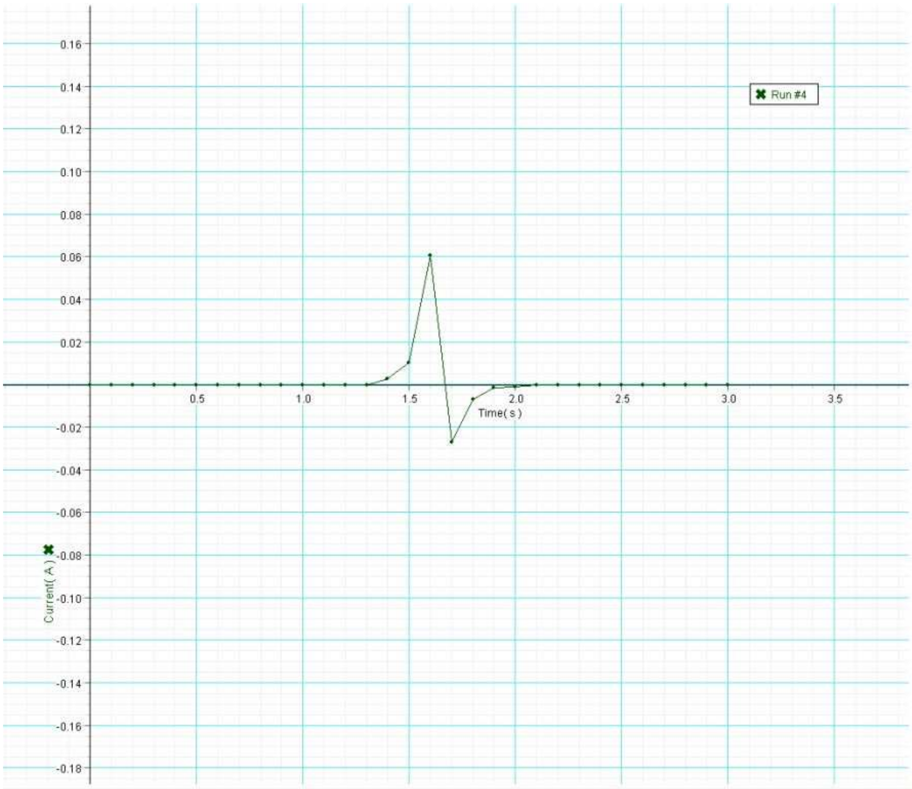
Run 1



Run 2

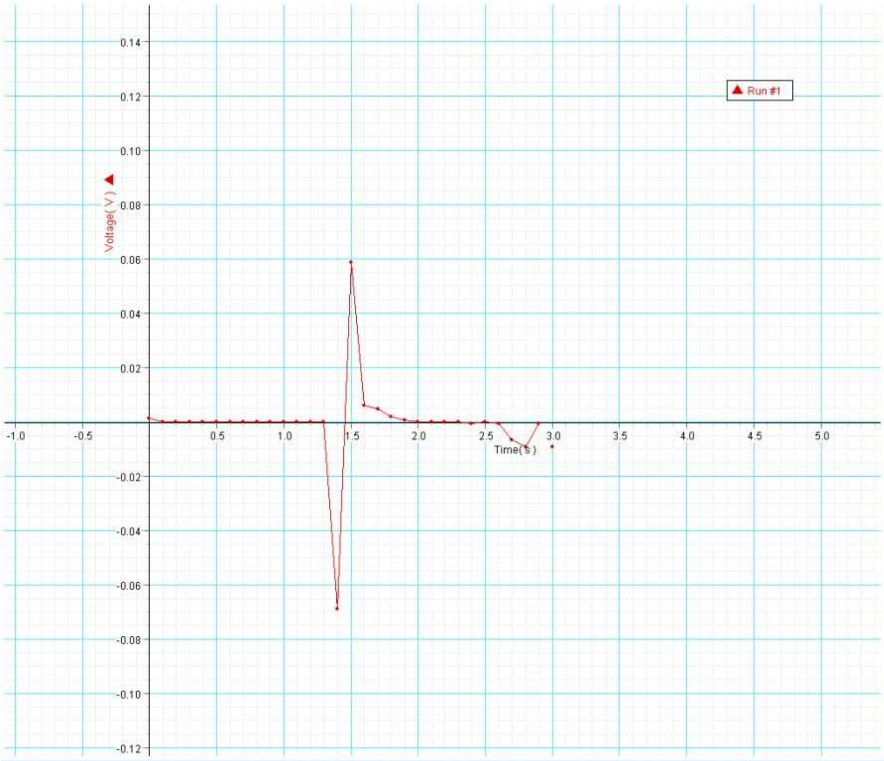

Run #3
Current(A)
Time(s)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Run 3

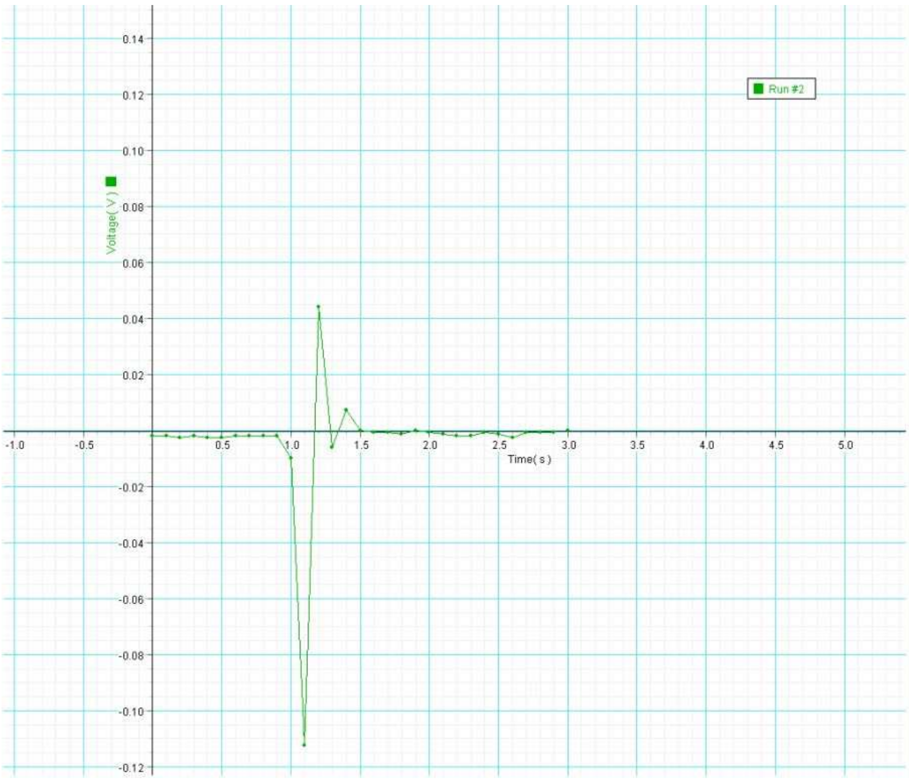

Run #4
Current(A)
Time(s)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Run 4

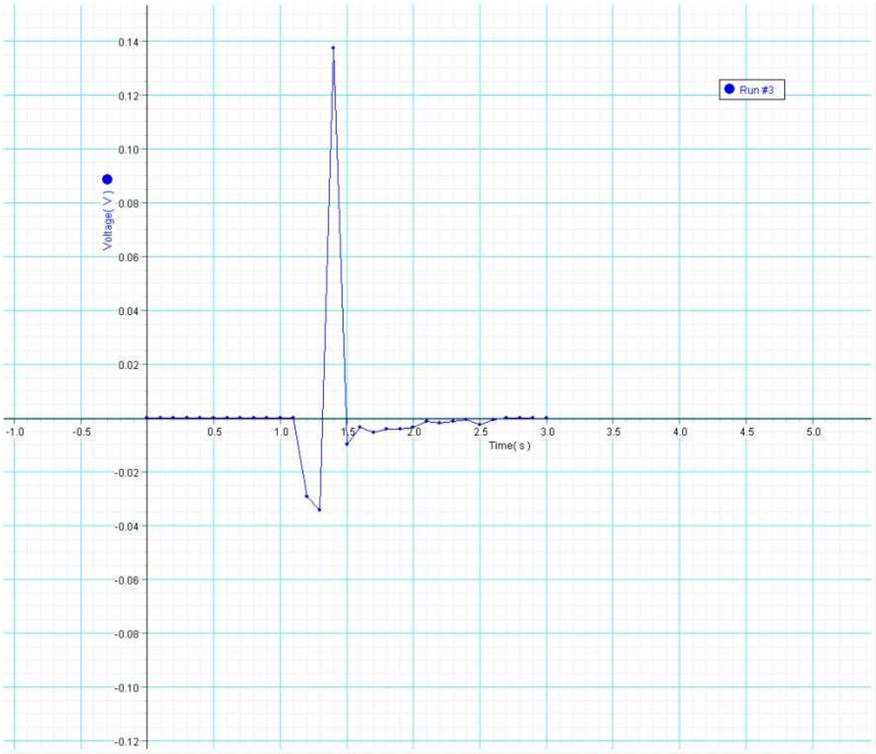
Design 1: Vertically Coiled Output Voltage (V)



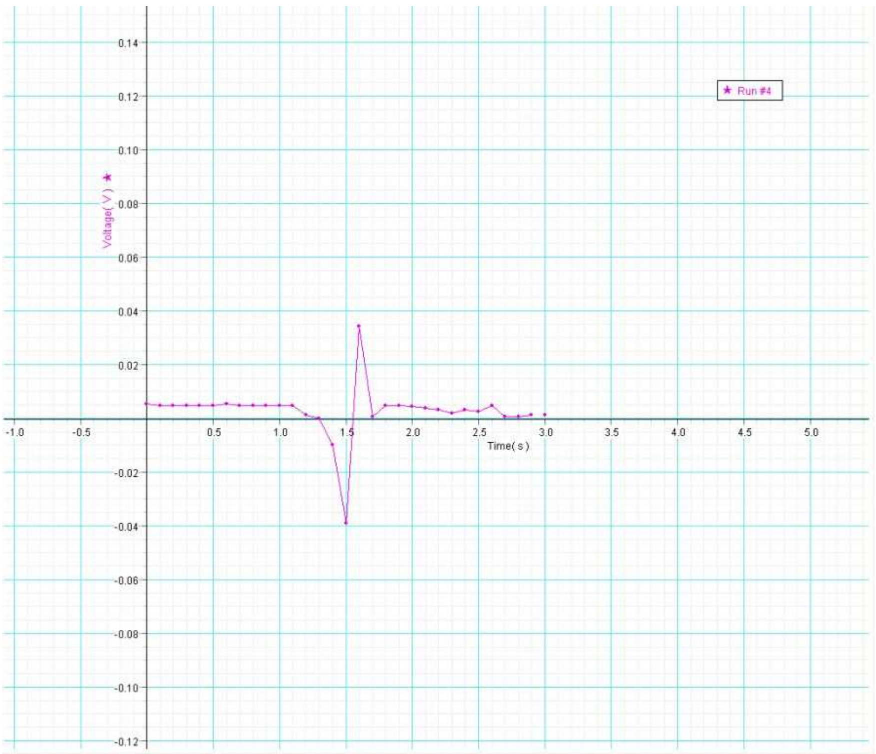
Run 1



Run 2

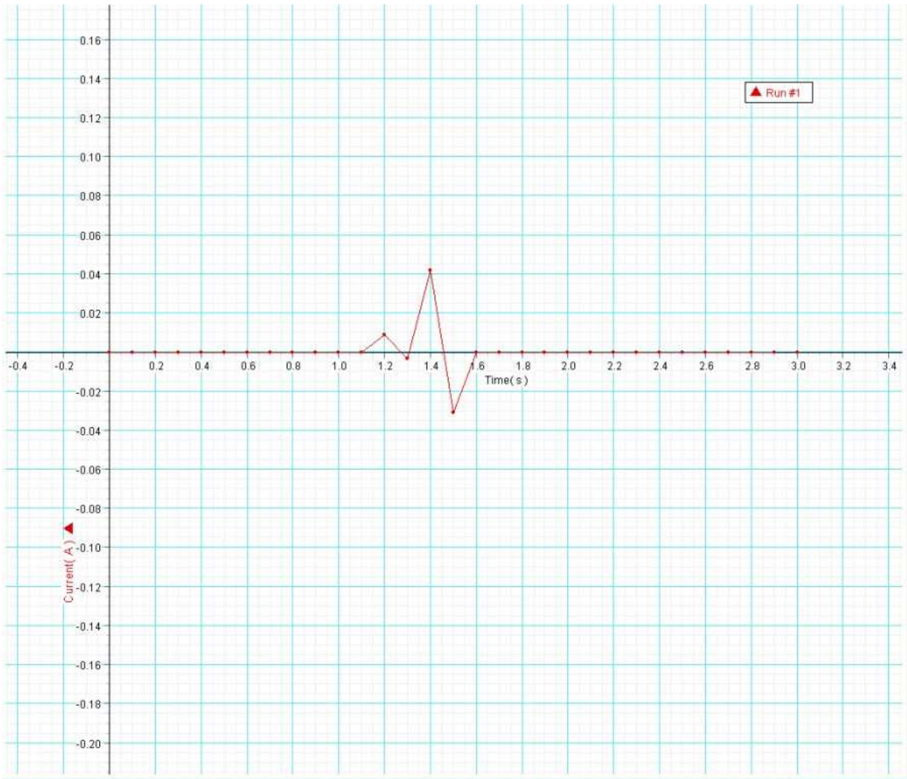


Run 3

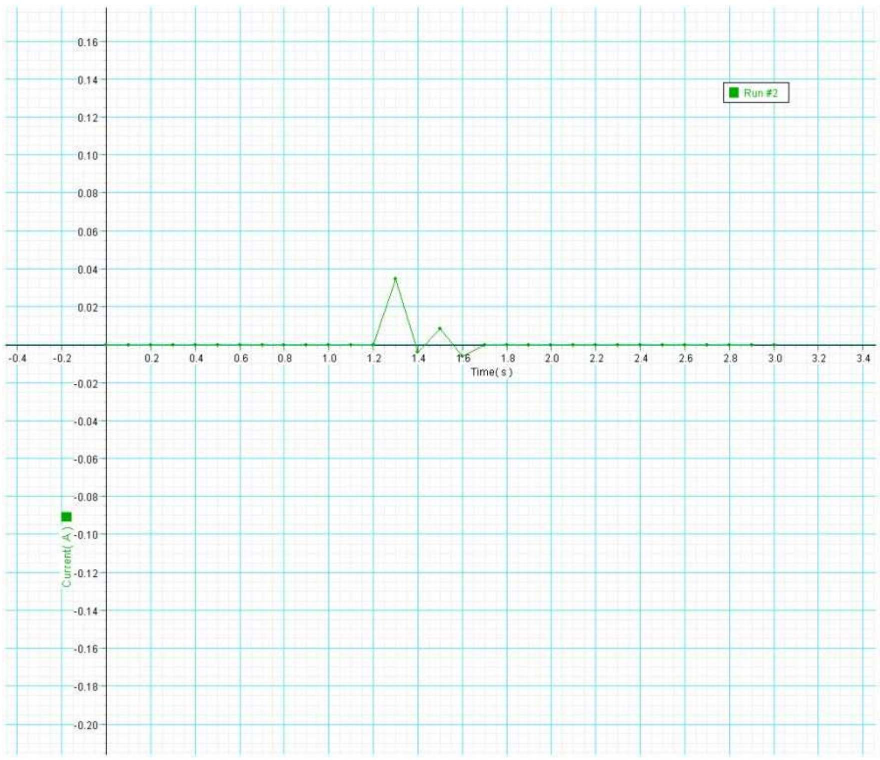


Run 4

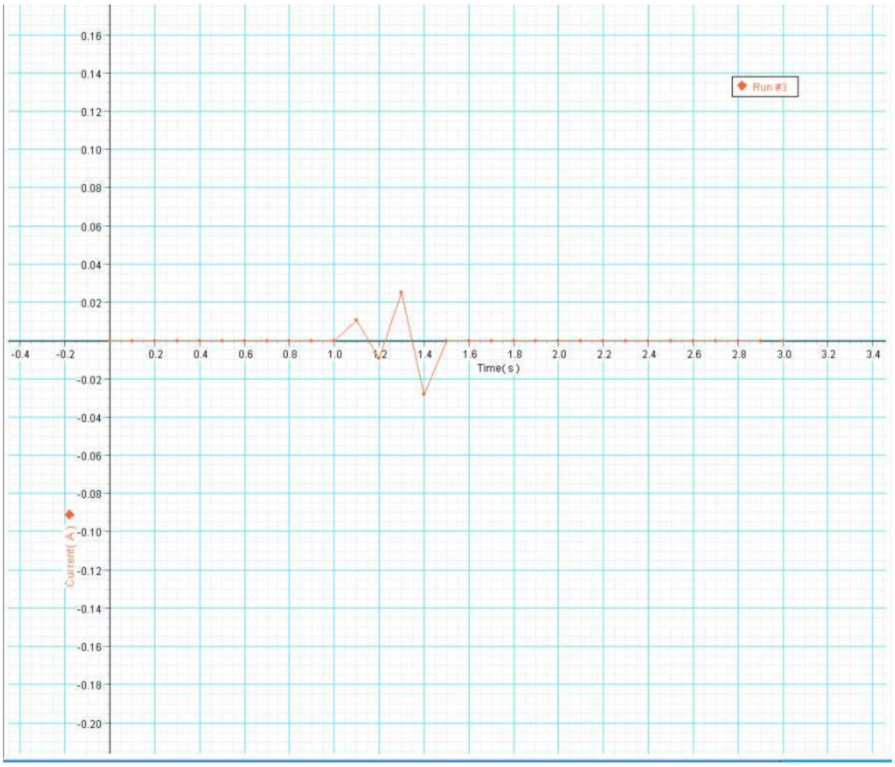
Design 2: Horizontally Coiled Winding with Spacer Output Current (A)



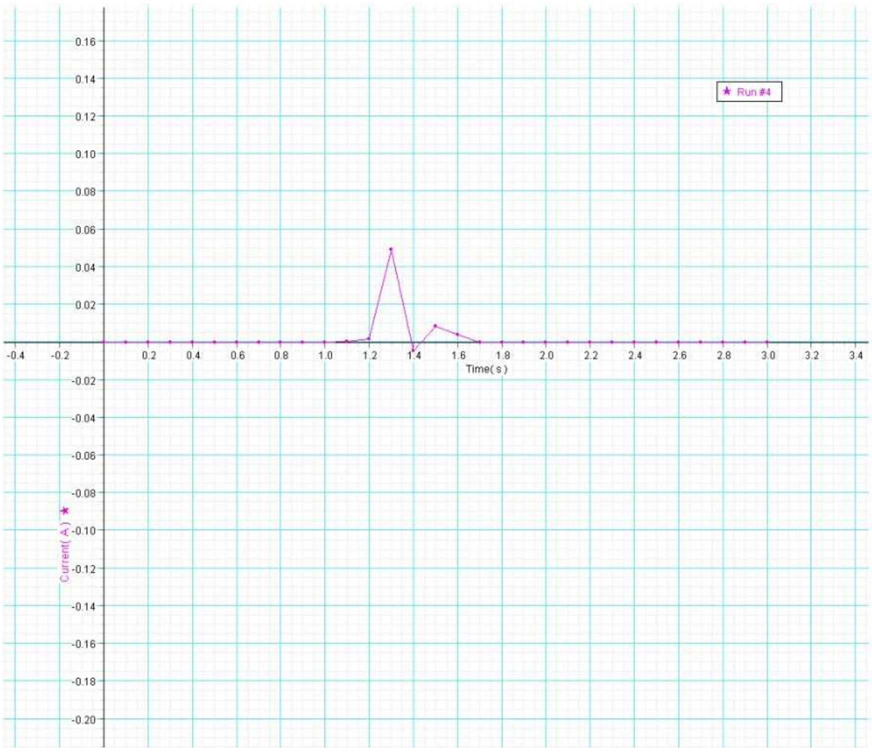
Run 1



Run 2

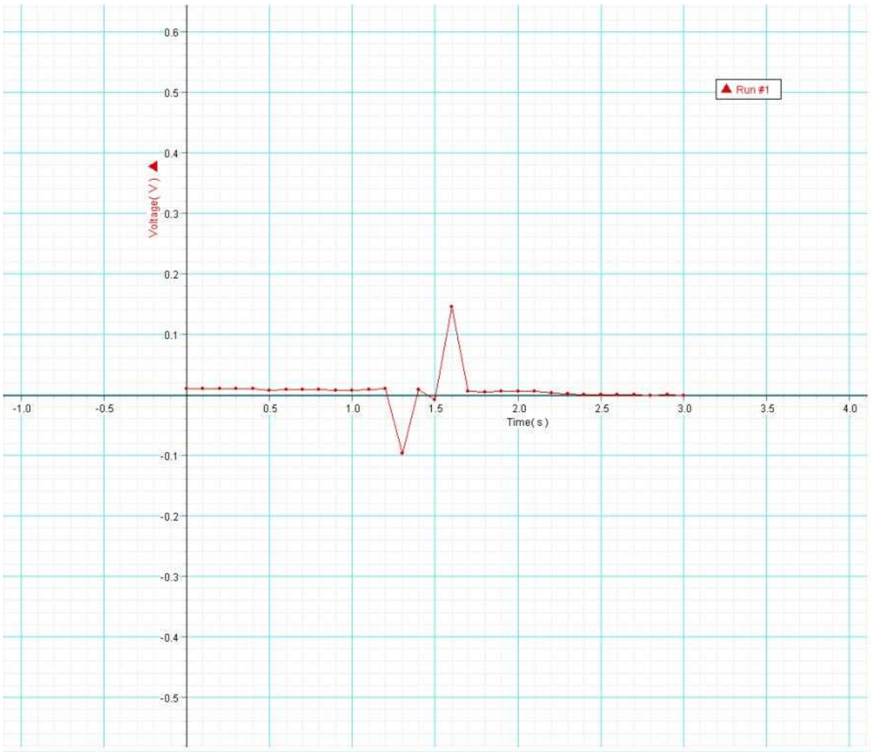


Run 3

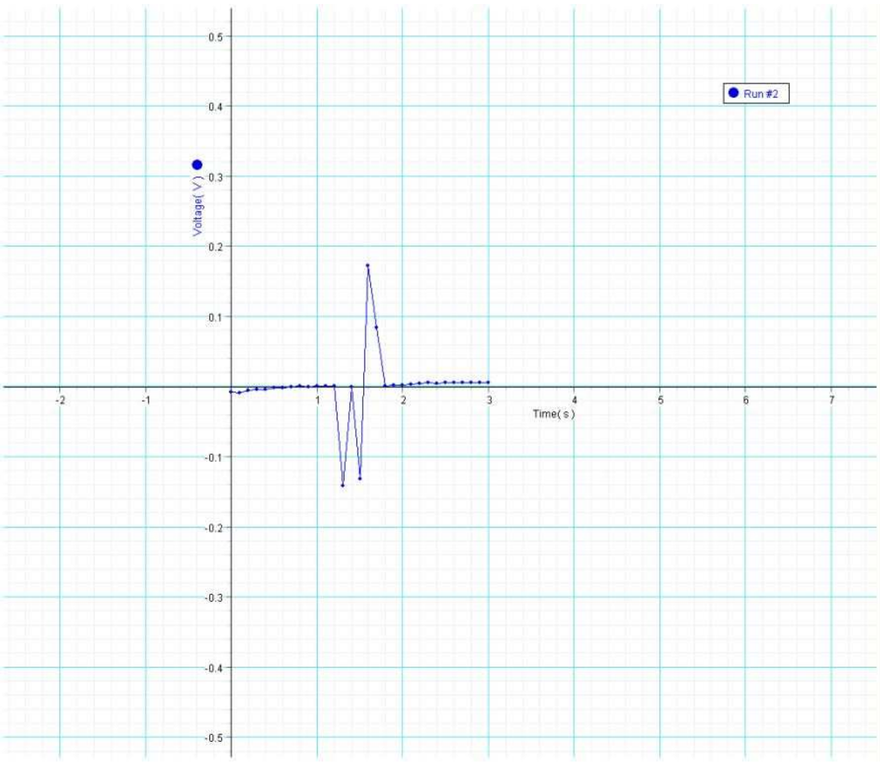


Run 4

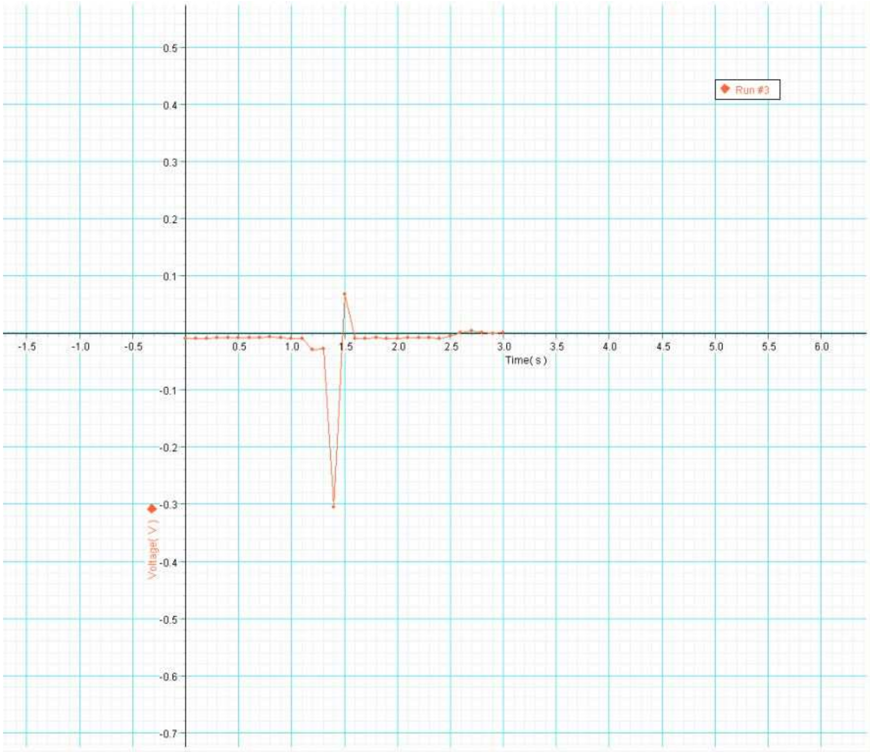
Design 2: Horizontally Coiled Winding with Spacer Output Voltage (V)



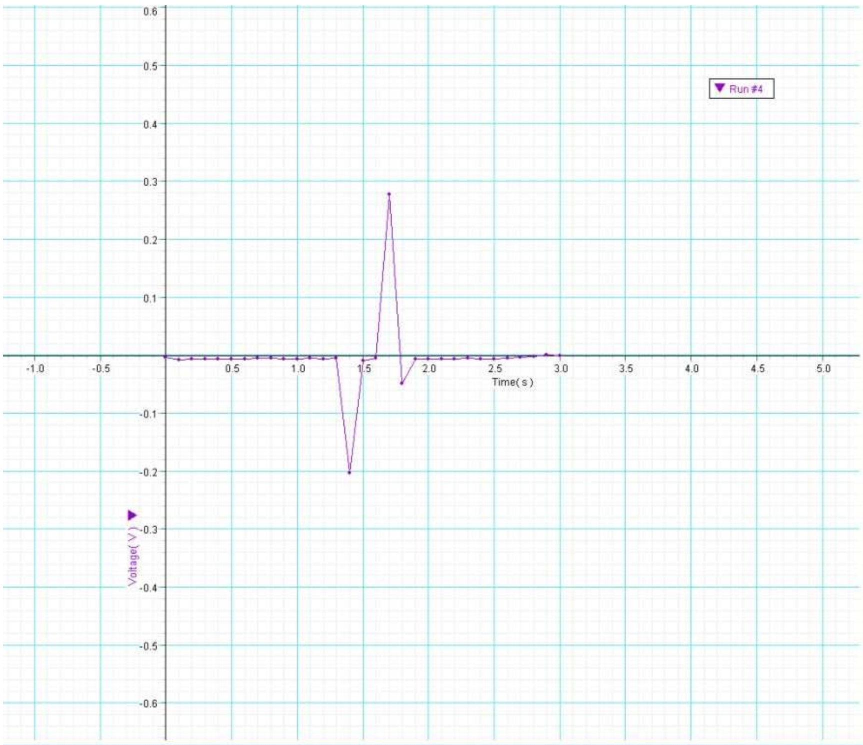
Run 1



Run 2

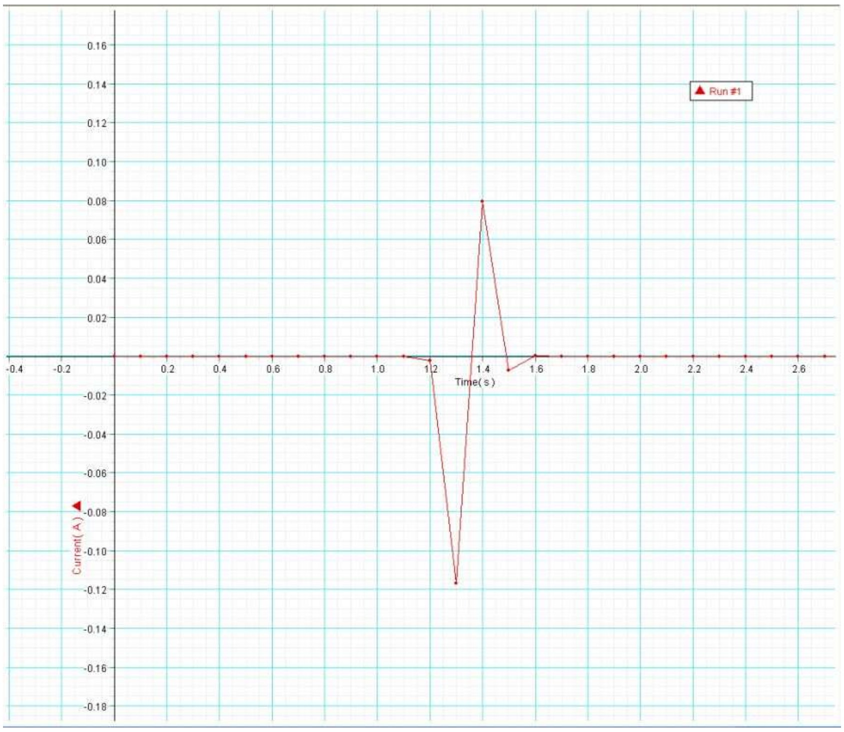


Run 3

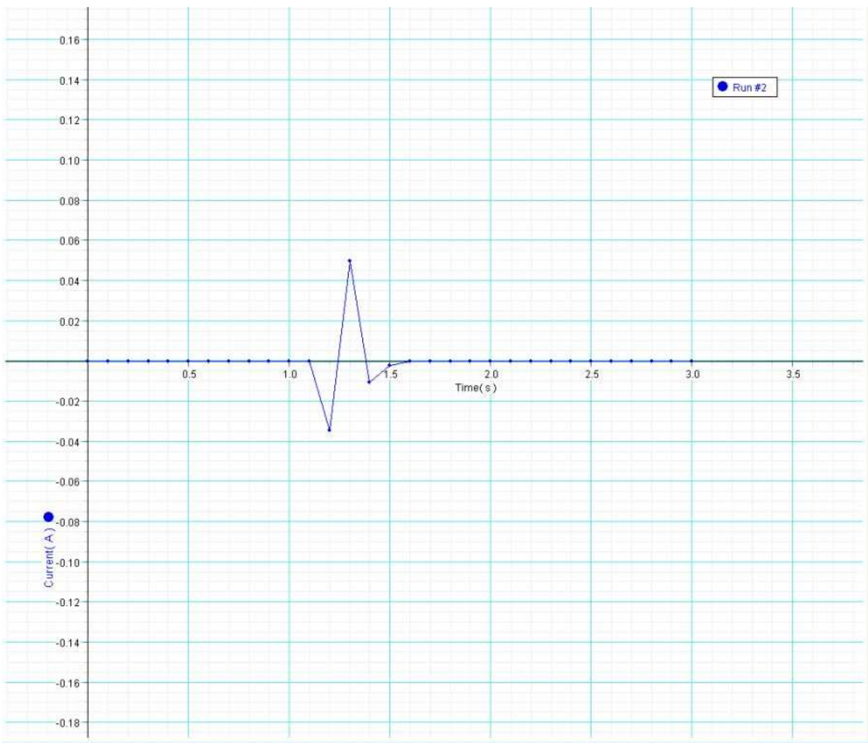


Run 4

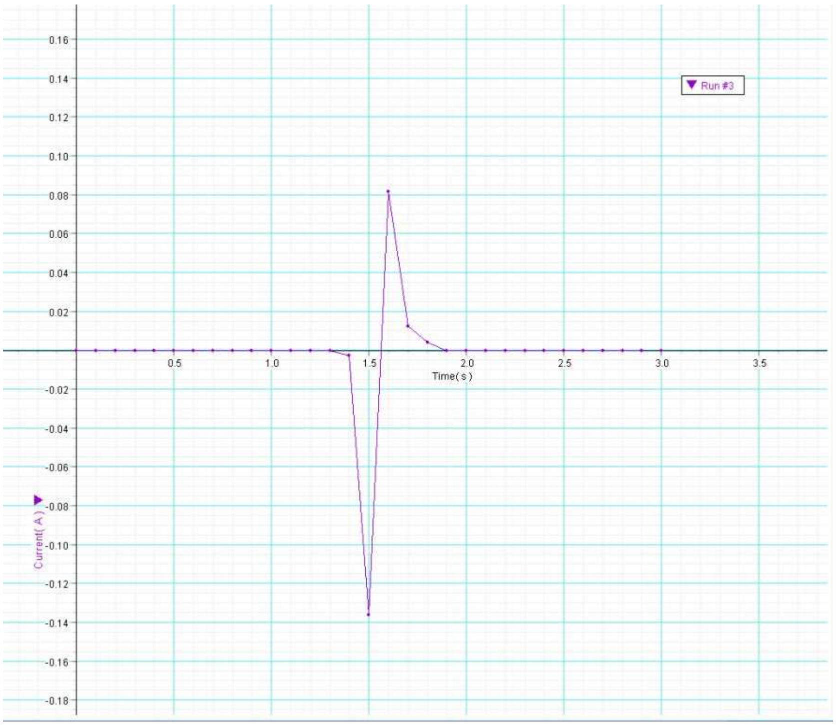
Design 3: Horizontally Coiled Winding without Spacer (Single Layer) Output Current (A)



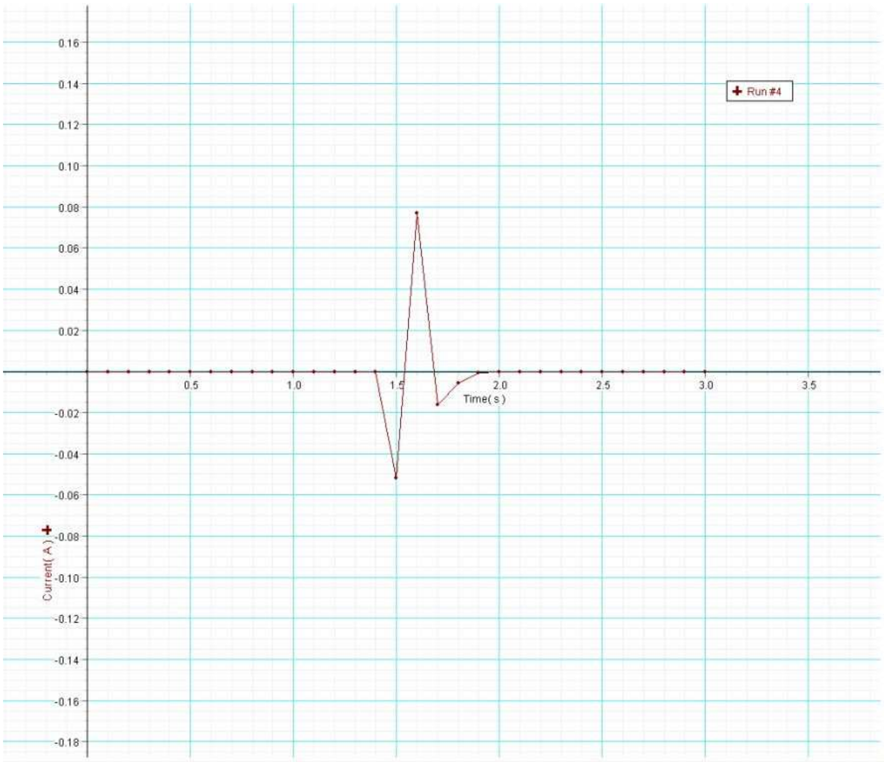
Run 1



Run 2

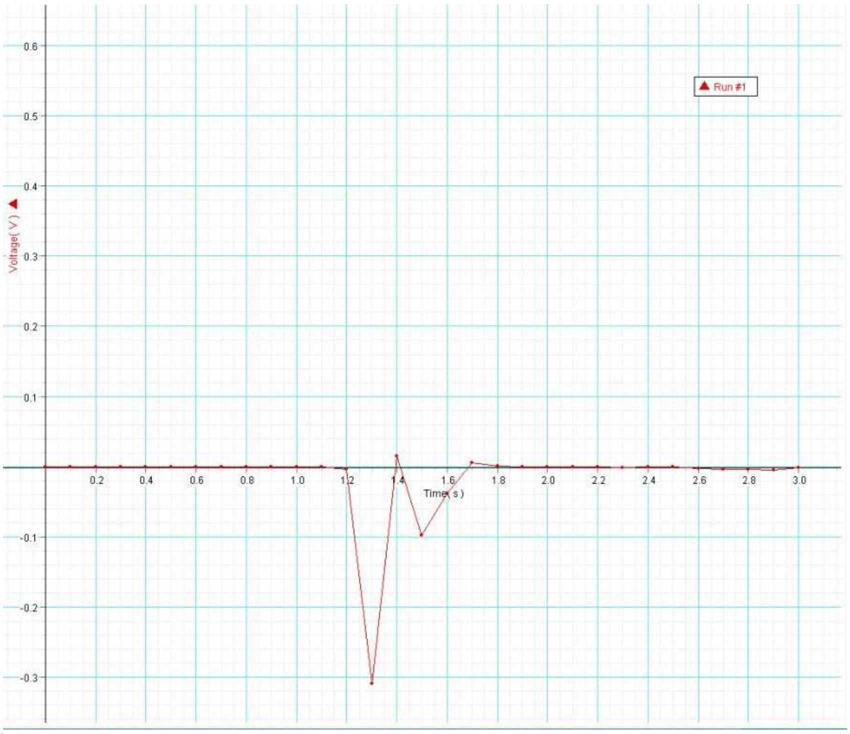


Run 3

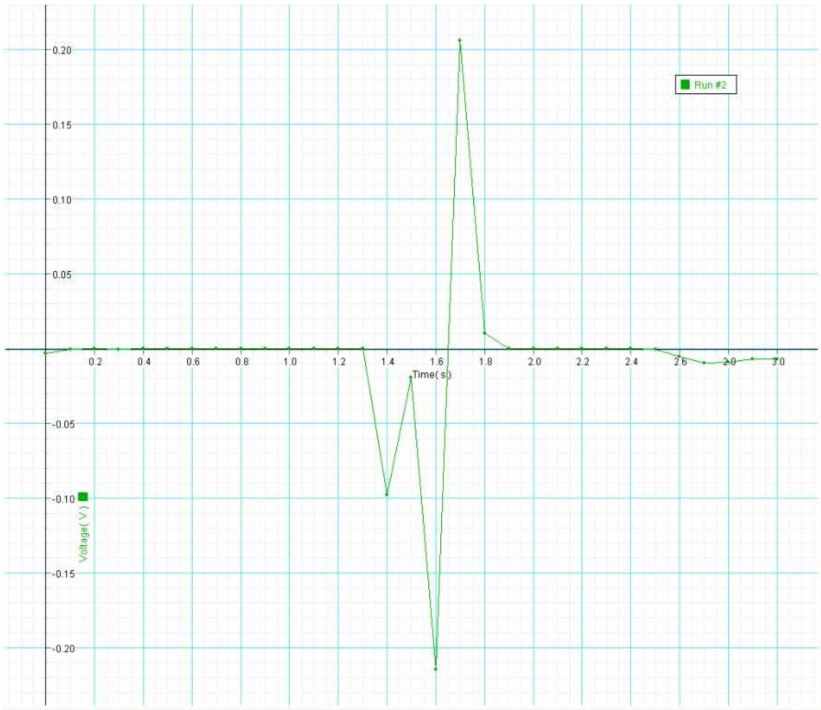


Run 4

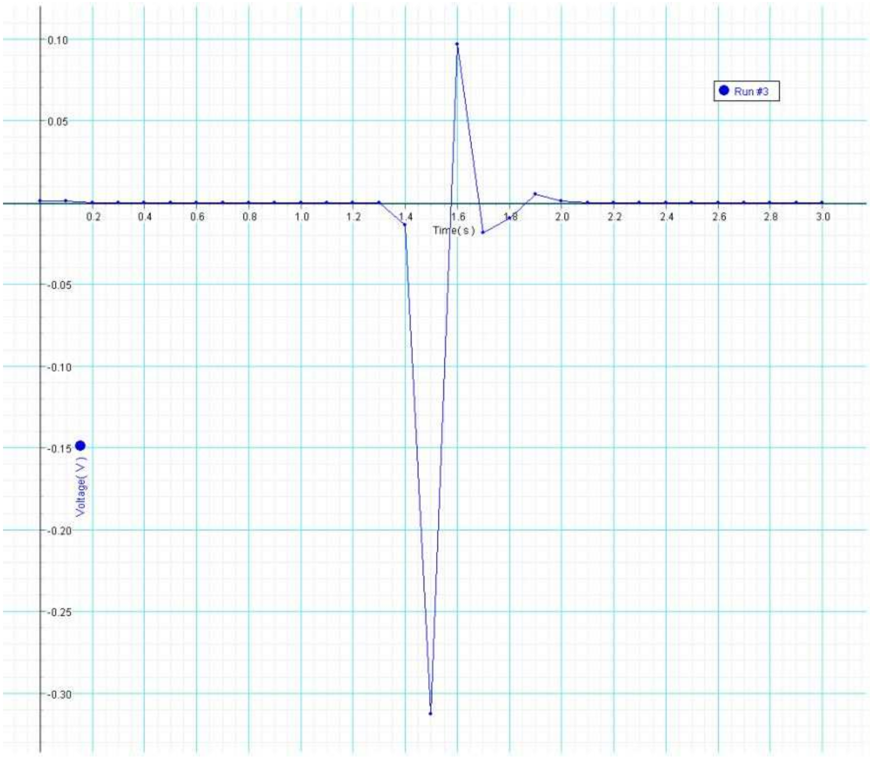
Design 3: Horizontally Coiled Winding without Spacer (Single Layer) Output Voltage (V)



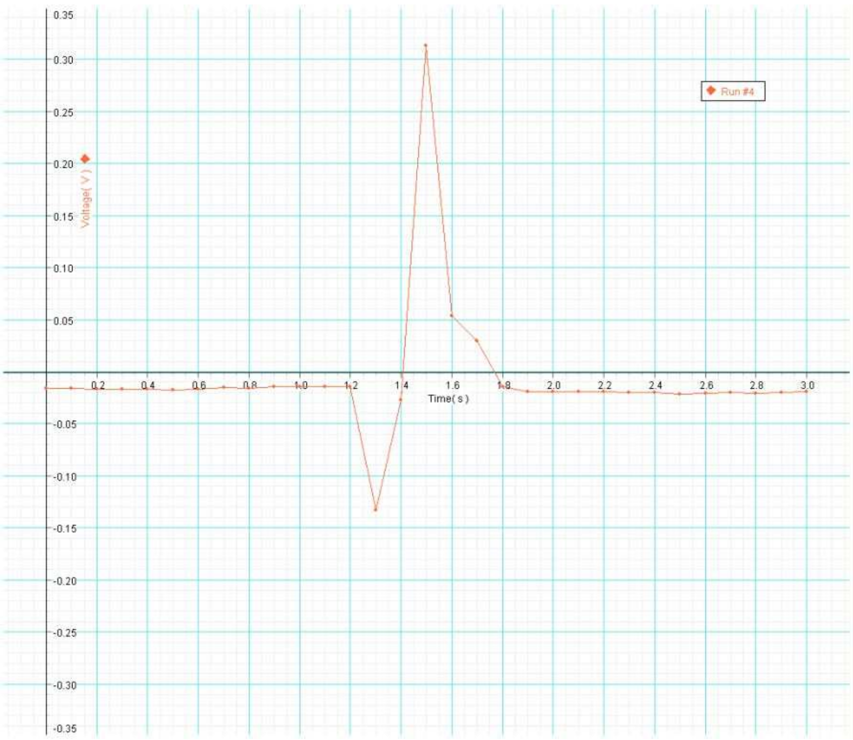
Run 1



Run 2

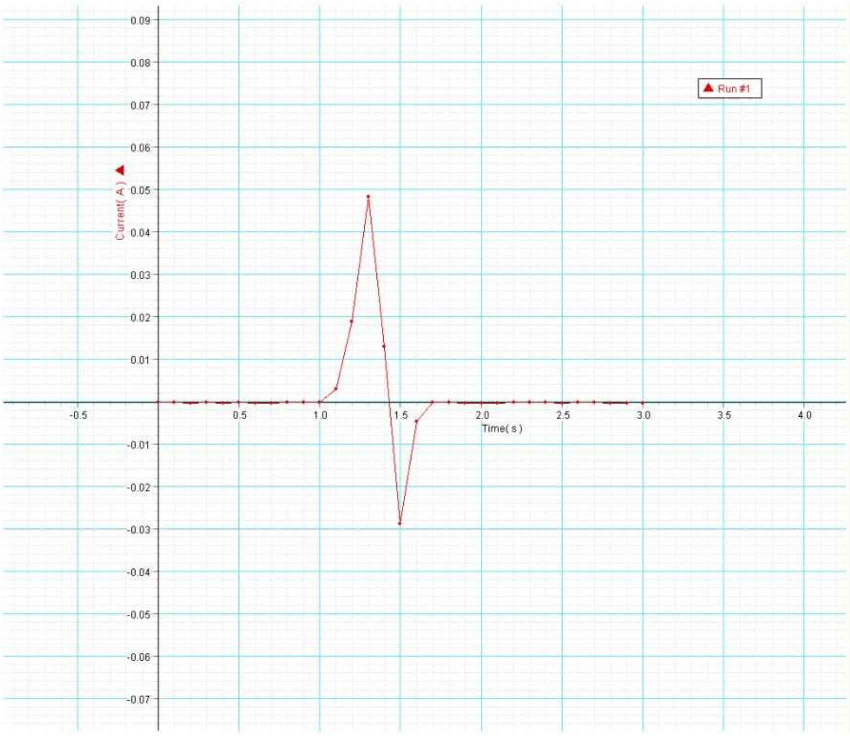

Run #3
Voltage(V)
Time(s)
0.10
0.05
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

Run 3

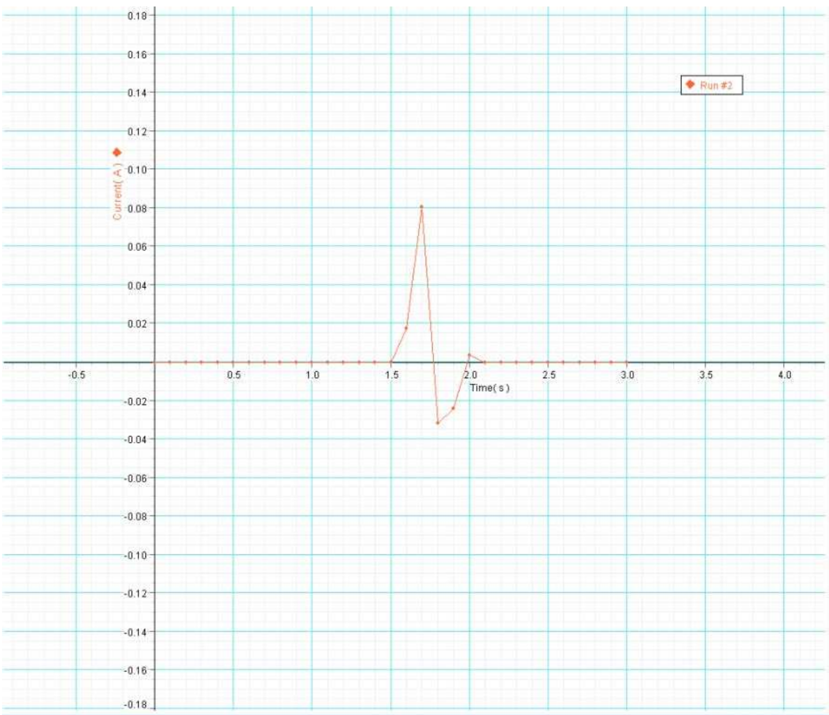

Run #4
Voltage(V)
Time(s)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

Run 4

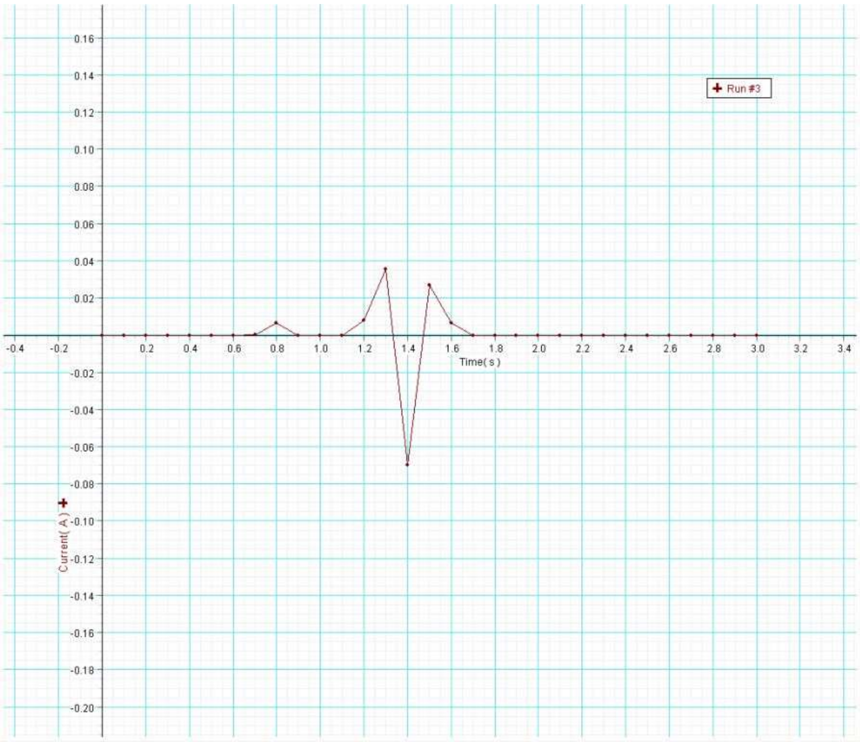
Design 4; Horizontally Coiled Winding without Spacer (Multiple Layers) Output Current (A)



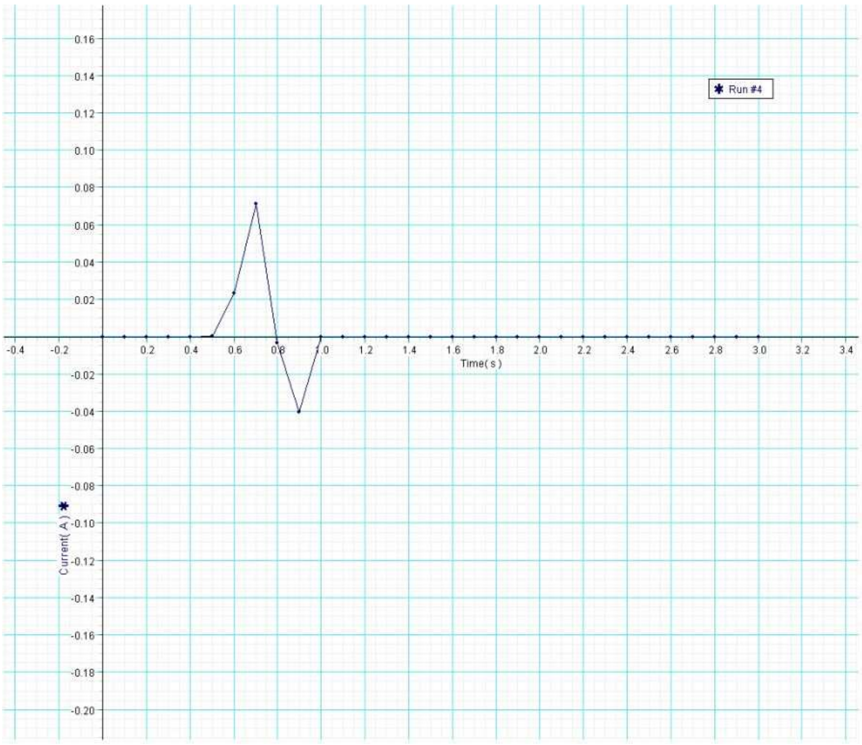
Run 1



Run 2

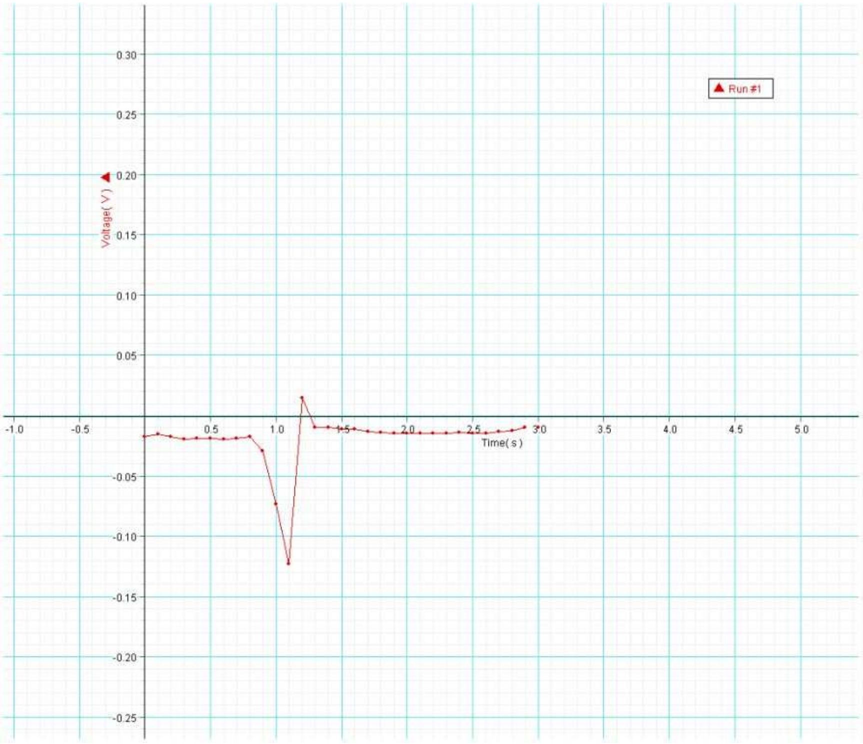


Run 3

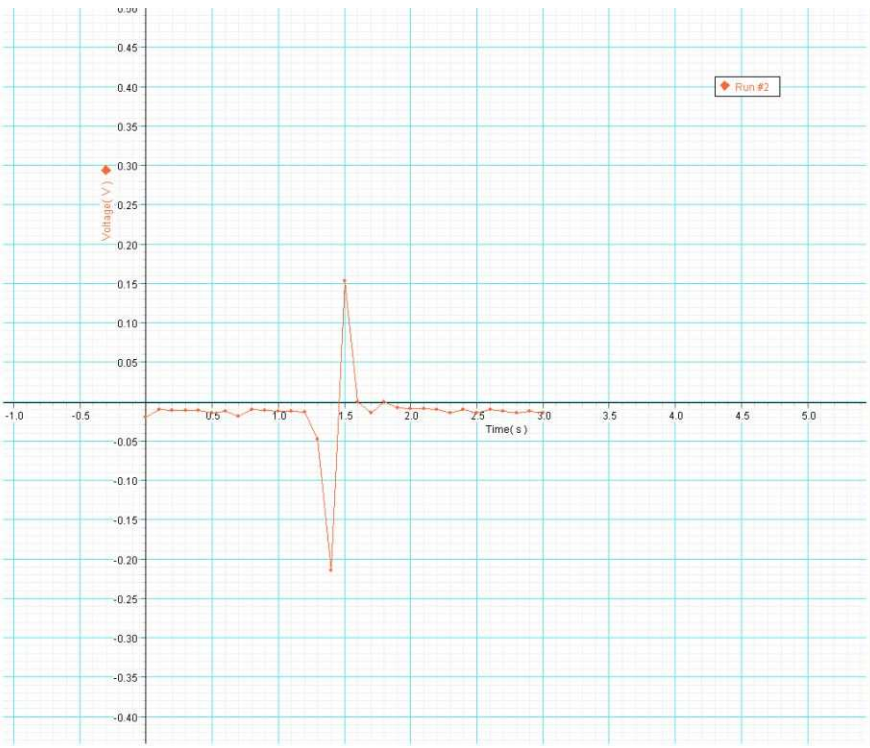


Run 4

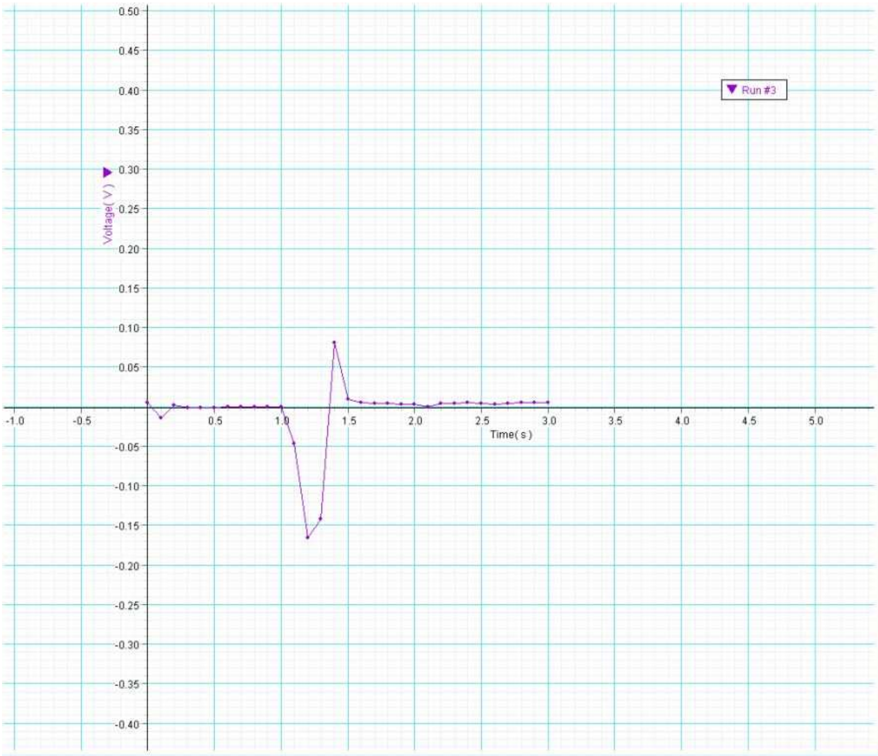
Design 4; Horizontally Coiled Winding without Spacer (Multiple Layers) Output Voltage (V)



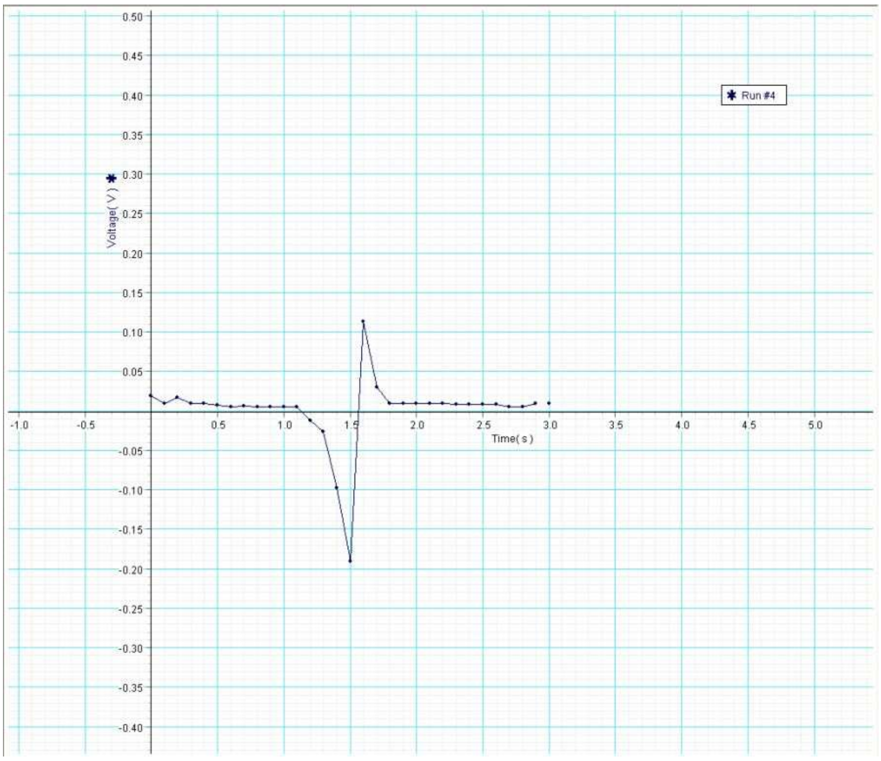
Run 1



Run 2

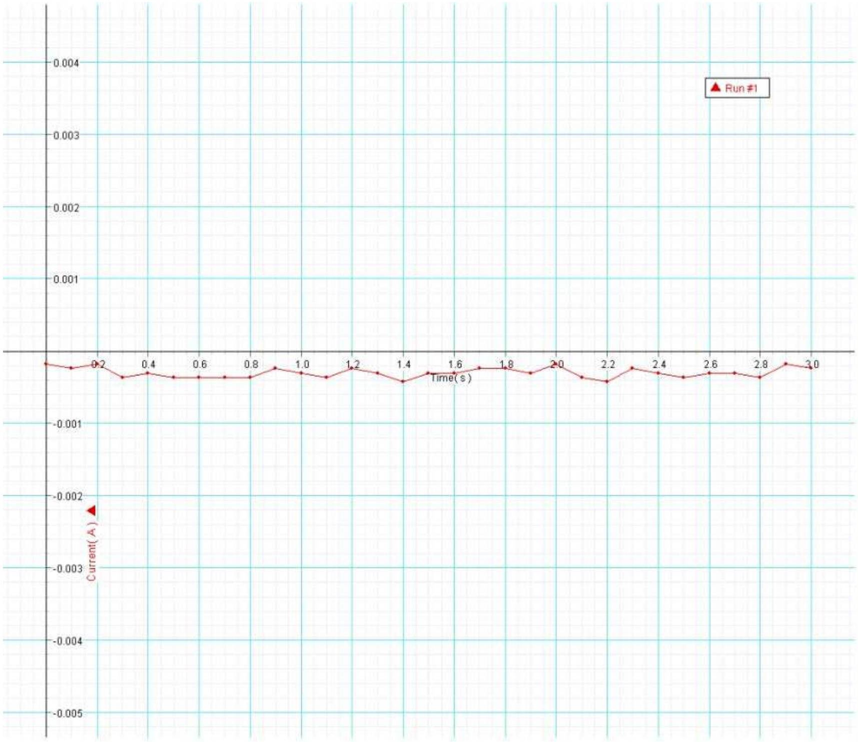

Run #3
Voltage(V)
Time(s)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-1.0
-0.5
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Run 3

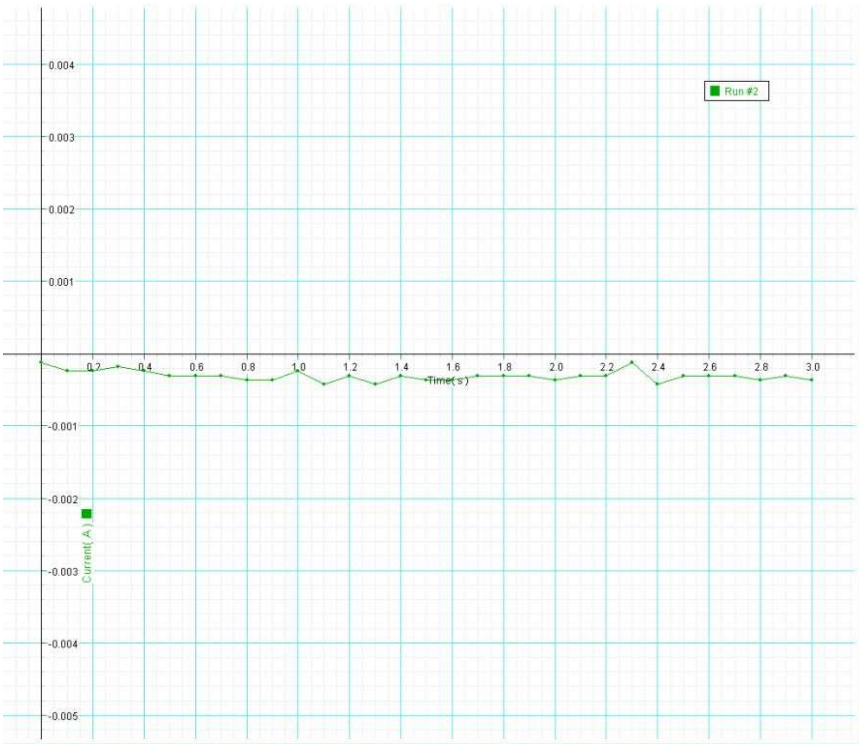

Run #4
Voltage(V)
Time(s)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-1.0
-0.5
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Run 4

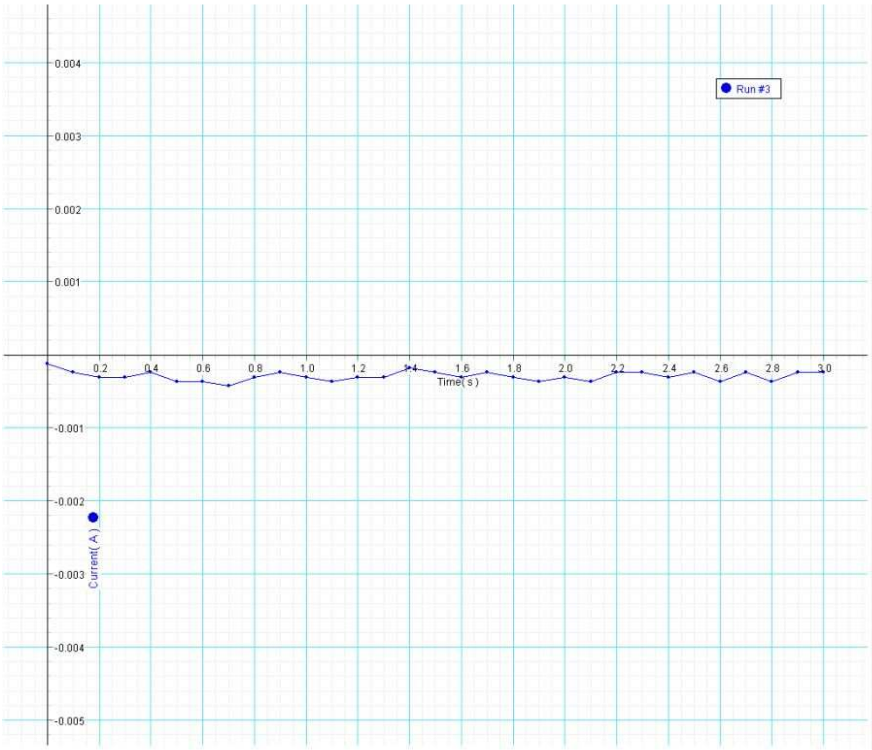
Design 5: Horizontally Coiled Winding (Twisted) Output Current (A)



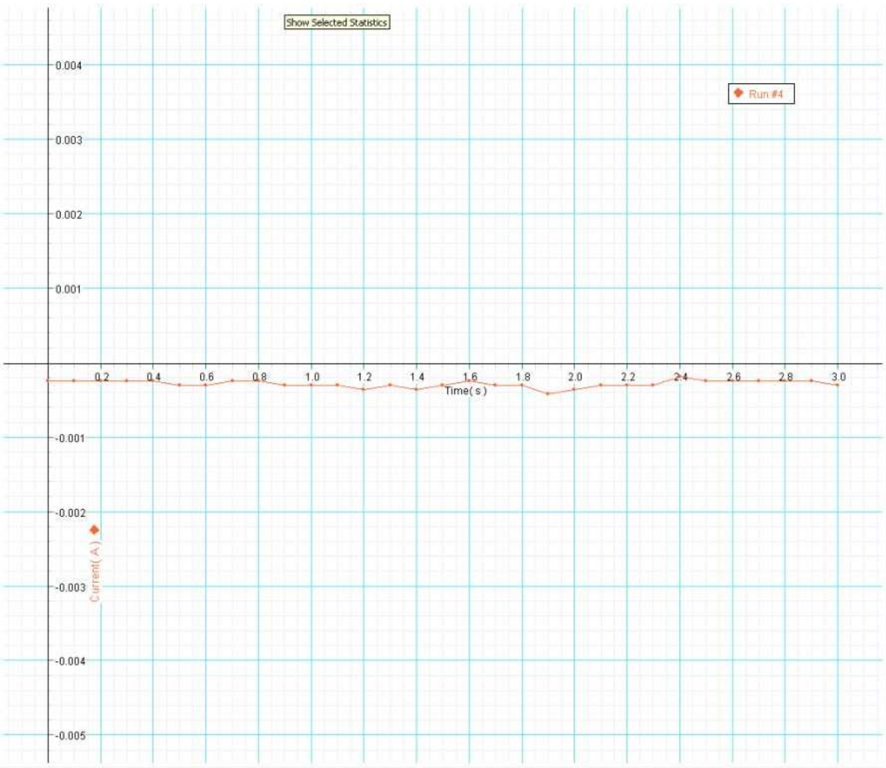
Run 1



Run 2

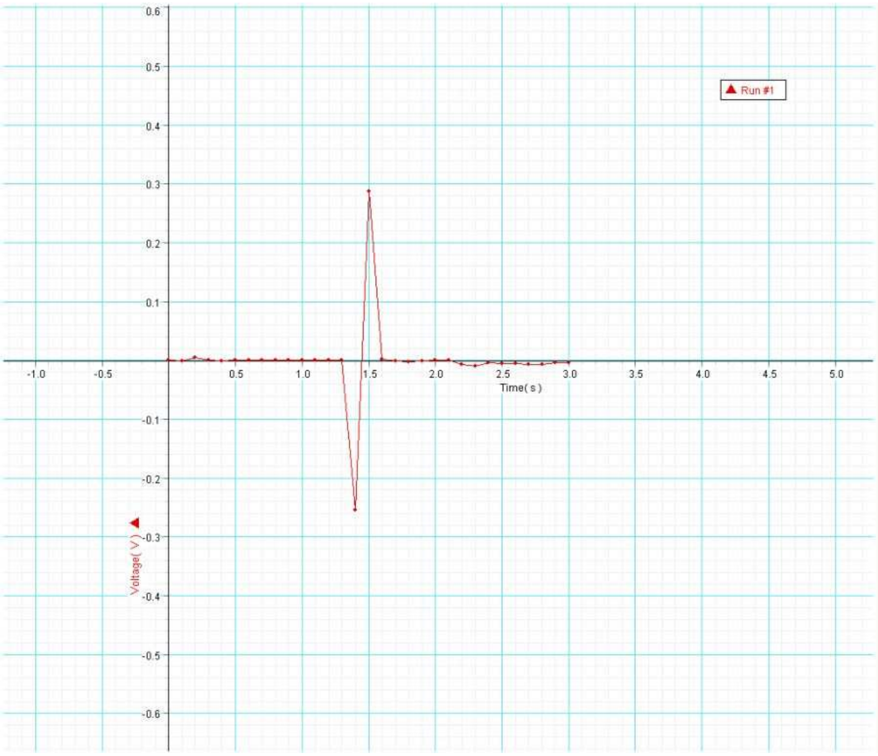

Run #3
0.004
0.003
0.002
0.001
-0.001
-0.002
-0.003
-0.004
-0.005
Current(A)
Time(s)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

Run 3

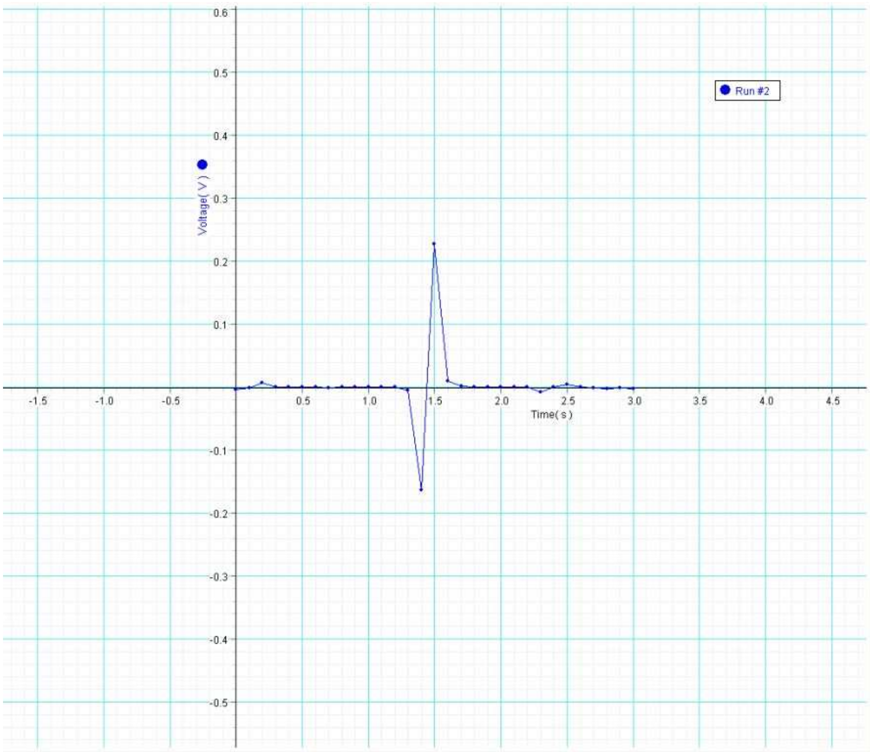

Show Selected Statistics
Run #4
0.004
0.003
0.002
0.001
-0.001
-0.002
-0.003
-0.004
-0.005
Current(A)
Time(s)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

Run 4

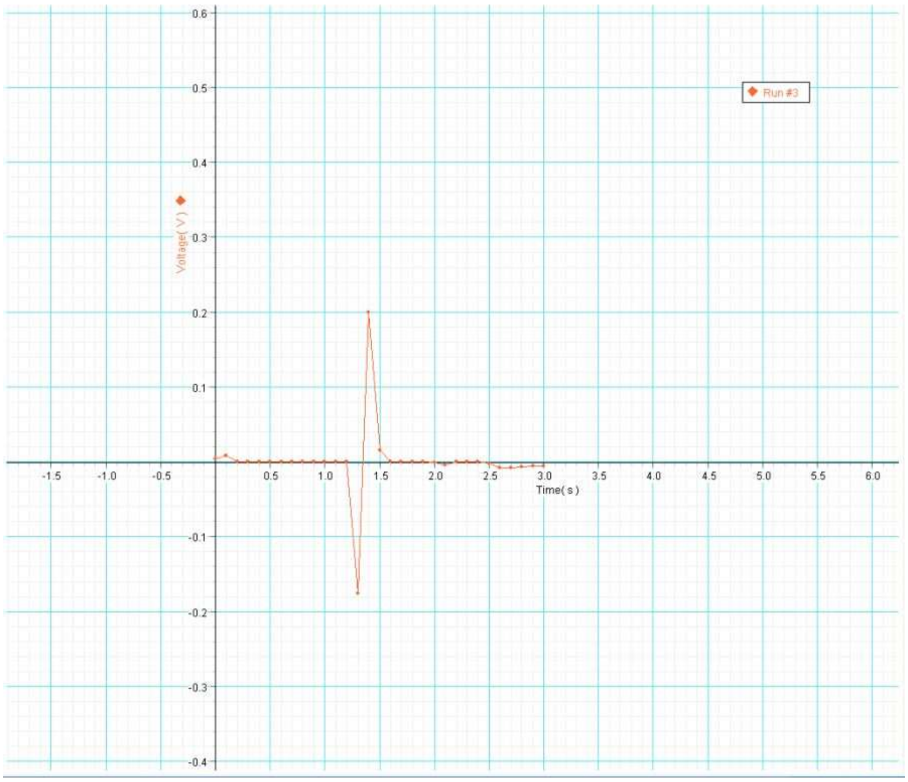
Design 5: Horizontally Coiled Winding (Twisted) Output Voltage (V)



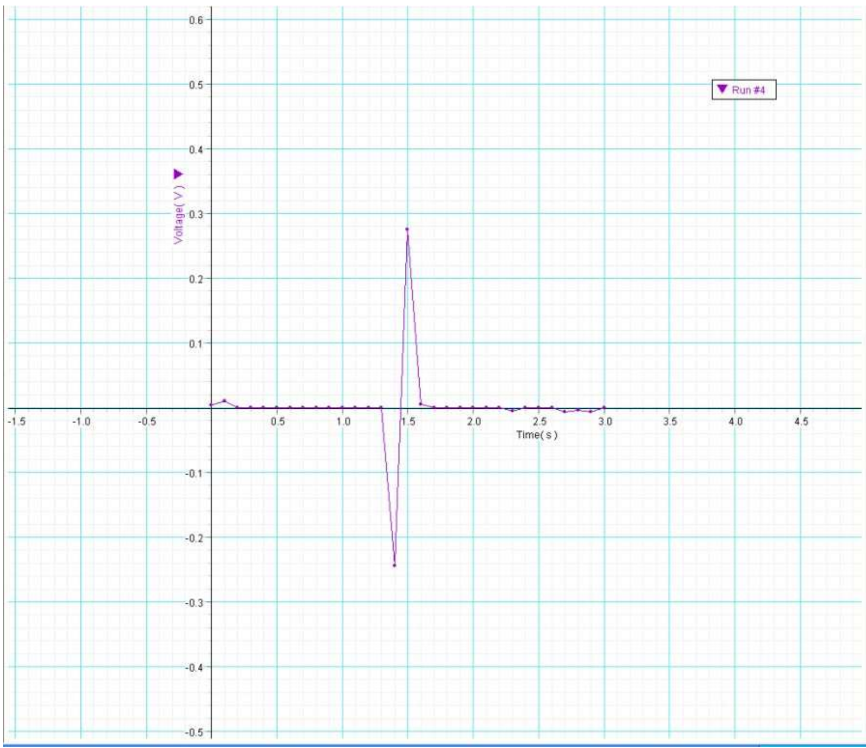
Run 1



Run 2



Run 3



Run 4