Study and Design of Linear Generator for Regenerative Suspension System (RSS)

by

Shahrul Azwan Bin Mohd Taib

13956

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

____

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UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

MAY 2014

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 herein have not been undertaken or done by unspecified sources or persons.

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(Shahrul Azwan Bin Mohd Taib)

ACKNOWLEDGEMENT

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ABSTRACT

Linear generator on active suspension has superior controllability and bandwidth, provides shock load to segregates the vehicle body from road disturbance for steady control, firm vehicle handling and comfortable ride. It is also has the ability to regenerate electricity from the vibration energy rather than dissipated it in passive system which results in increasing the energy efficiency for mobile vehicles. This paper is mainly discussed and analyzed factors that affect the efficiency of linear generator for regenerative suspension system. Materials, dimension, stator-translator configuration, magnets configuration, and winding is taken in consideration in the process design. A series of experiments conducted shows winding with spacer gives better output compared to winding without spacer. The best criteria for each factors will be chosen to propose the optimum linear generator design.

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CHAPTER 1

INTRODUCTION

1.1. Project Background

For decades, energy conversion is still one of the main practices lead by the engineers in the industry. According to the law of conservation of energy, it is stated that “energy cannot be created or destroyed, but it can change form from one state to another”. The revolution in automotive industry make used of this law by harnessing the possible loss of energy to increase the energy efficiency.

Linear generator system is an application of electromagnetic principle are widely used in automotive industry. Even though linear generator is less commonly used compared to rotary generator, in some cases, linear generator can perform better than the latter invention due to its linear motion nature.

As the research on linear generator field is carried on, the researchers have discovered that linear generator can be used as an alternative suspension system which can regenerate electricity by harnessing vibration (kinetic) energy from the road disturbance. This type of suspension usually used in hybrid and electric vehicles.

About 10-16% energy is wasted by vehicle for the fuel energy due to friction and air drag [1]. Yet, regenerative suspension which have the potential in energy recovery have not come into practice. The main purpose of using a suspension on a mobile vehicles is to offer steering solidity with good handling and comfortable ride. The conventional suspension only able to dissipate absorbed energy into heat energy.

Recent researches shows that instead of dissipating the energy into waste heat energy, it is possible to convert the vibration energy into electrical energy by improving the suspension mechanism. The regenerated energy can be used for battery charging or feeding some electric loads for mobile vehicle.

1.2. Problem Statement

A lot of factors need to be taken into consideration in designing linear generator so that it can produce an optimum result. Therefore, study on the system, processes, working principles, configurations, materials, experiments and testing need to be done before we can produce the prototype. This process is crucial as it will affects the linear generator performance.

Currently, there are tremendous researches going on for linear generator design. Each one of them used different kind method, material, configuration and analysis in their design. The design also focused on different objectives and application. However, the design can be improved and enhanced from time to time. As for this project, it will focus on study on the design and conduct experiments for the regenerative suspension system by using linear generator.

1.3. Objectives

The objectives of this project are:

i. To study the effects of different magnet configurations in linear generator design.

ii. To observe the effects of winding design and material selection in linear generator design.

iii. To propose the optimum design in linear generator for regenerative suspension system.

1.4. Scope of Study

The scope of study for this project is to understand and implement the knowledge of electromagnetic mechanism in industrial problem. Four main factors that are influencing the performance of the linear generator are:

i. Stator-Translator Configurations

ii. Magnet Configurations

iii. Material Selection

iv. Winding Configurations

CHAPTER 2

LITERATURE REVIEW

2.1. Underlying Working Principle and Theoretical Background

Before going into designing stage, it is better to have the fundamental understanding on the magnetic flux or magnetic field line of a permanent magnet. Different manufacturer may have produce different kind of magnet poles orientation. Figure 1 below shows some of the possible poles orientation for various types of magnet.

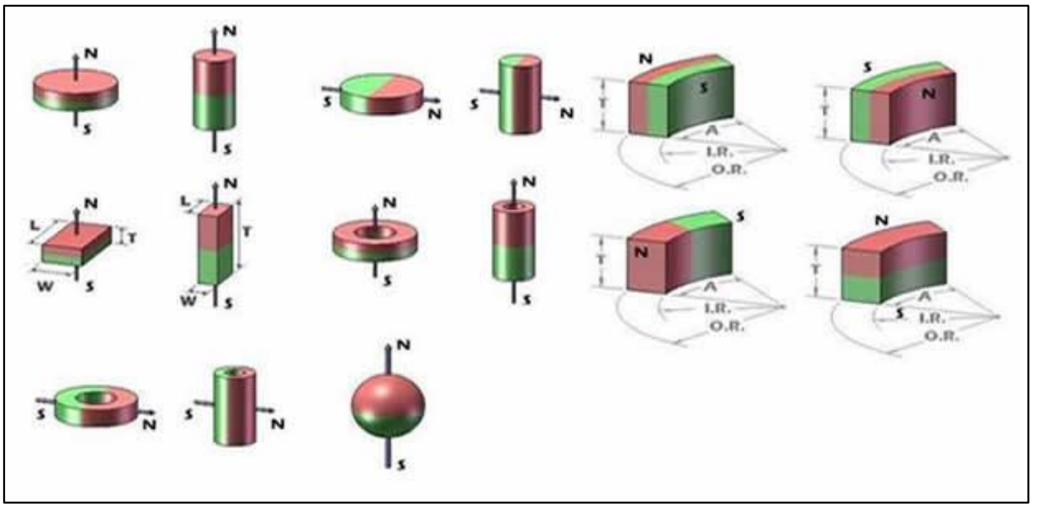


Figure 1: Magnet Pole Orientations with Different Magnet Shapes

Magnet with same poles will repelled each other and magnet will different poles with attracted to each other. The direction of magnetic line is always from North Pole to South Pole.

Figure 2 illustrates the magnetic field lines of bar-type magnet. Magnetic field is strongest at the center poles and degraded as the magnetic flux further apart from its pole.

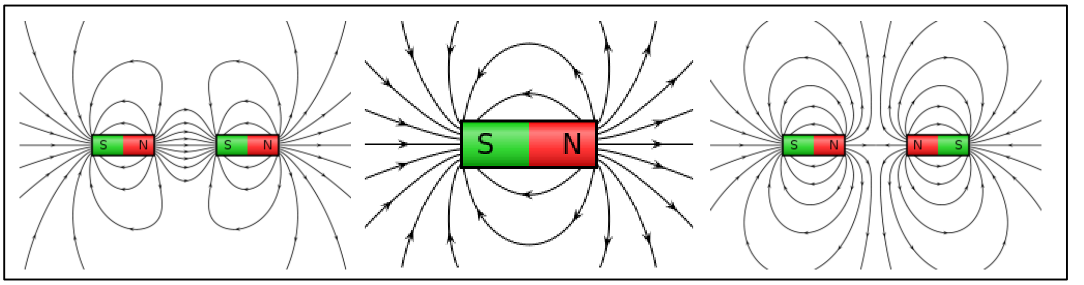


Figure 2: Magnetic Field Lines

Damping Force

According to Lorentz Law, the eddy currents induced in the coil produce a magnetic flux which opposes to the one produced by the permanent magnet assembly. The damping force of each pole is given by the volume integral:

$$F = \int_{\Gamma} J \times B d\Gamma \qquad (1)$$

where Γ, J and B are the conductor's volume, induced current density and magnetic flux density, respectively.

Induced Emf and Flux Linkage

Faraday's law of induction is a basic law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (Emf). The electromotive force induced is proportional to the time rate of change of magnetic flux linkage can be express as:

$$V = -\frac{d\varphi}{dt} \qquad (2)$$

Where V is regenerated voltage and φ is flux linkage. However, it is practically that a circuit consist of coil with multiple number of turn. Therefore, the induced voltage is given by:

$$V = -N\frac{d\varphi}{dt} \qquad (3)$$

where N is number of coil.

For multiple coil, flux linkage is evaluated as the sum of the linkage individual flux:

$$\varphi = \sum_{i=1}^{N} \int BdA \qquad (4)$$

Magnetic Induction

Magnetic induction is the force exerted on the current carrying conductor:

$$B = \mu H \qquad (5)$$

where H is known as the Magnetic Field Intensity.

Magnetic Field Intensity

Current carrying conductor able to produce magnetic field around it. Magnetic field intensity is the magnitude of the magnetic field it is measured in Ampere per meter, A m^{-1} . Assuming that the induced current density is given by:

$$H = \sigma (v \times B) \qquad (6)$$

Where σ and v are the conductivity and the velocity in the magnetic field. Substituting (6) in (1), the damping factor for each pole becomes:

$$F = \sigma v \int_{\Gamma} B^2 d\Gamma \qquad (7)$$

This follows that the equivalent damping coefficient of the device is

$$C = \sigma \int_{\Gamma} B^2 d\Gamma \qquad (8)$$

The generated power can be realized from (3) as

$$P = \frac{V^2}{R} = B^2 v^2 \sigma l A \qquad (9)$$

Equation (9) shows the importance of having high magnetic flux density. It may be shown from equation (3) and (8), the damping coefficient can be relate with electric circuit resistance R and impedance L as

$$C = \frac{1}{R+j\omega L}\left(\frac{d\phi}{dz}\right)^2 \qquad (10)$$

2.2. Principle of Induction Generator

There are two main components in induction generator - stator and rotor. Stator is descripted as non-moving part in the system while rotor is the rotating part of a rotary generator. In linear generator, rotor is descripted as translator or mover as it move in linear motion. The translator act as the source of magnetic field (can be moving-coil, moving permanent magnet or moving iron with current carrying conductor). In between the stator and translator it important to have sufficient air gap. Smaller air gap will produce stronger magnetic field in contact with the coil. However, too small air gap will cause high cogging force to happen which is not good in linear generator design.

2.3. Stator-Translator Configuration

Moving Permanent Magnet

Permanent magnet will be place as the translator with the shaft (center rod) and the coil will be wrapped around a structure (cage). The shaft will be connected to an external moving force.

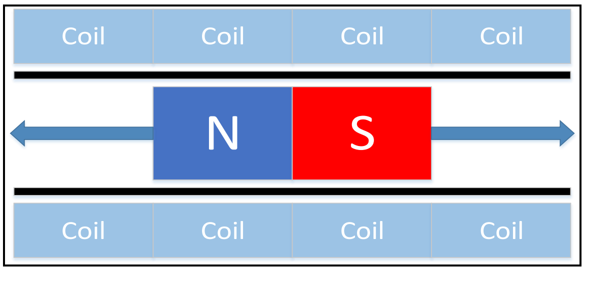


Figure 3: Moving Magnet

Moving Coil

Coil will act as the translator and connected to external force while the magnet will be place as stator. This can be done in two method – moving coil internally or moving coil externally.

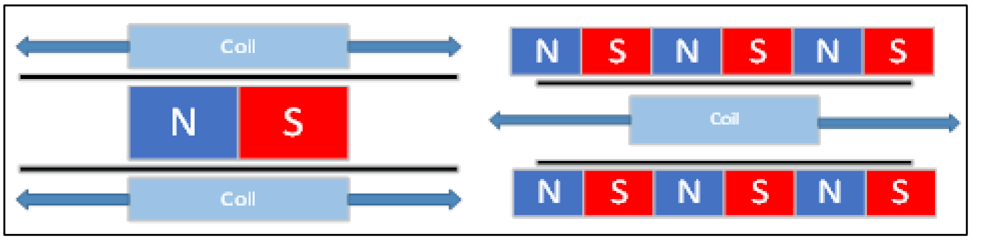


Figure 4: Moving Coil (Externally and Internally)

Moving Iron Core

Magnets will be mounted at the stator. It will magnetize the iron core to make it a temporary magnet. The magnetic field from the temporary magnet will cut across the coil.

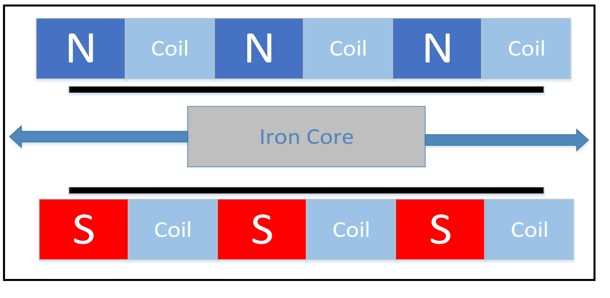


Figure 5: Moving Iron Core

2.4. Vehicle Suspension System

Mobile vehicles are conventionally designed with passive suspension system. A suspension system is a mechanical system of spring and shock absorber that connect to the wheel and axles to the chassis of wheeled vehicles [2].The main purpose of having suspension is to segregates the vehicle body from road disturbance for steady control, firm vehicle handling and comfortable ride [3]. The conventional suspension used by most vehicles is the hydraulic suspension which used hydraulic oil or dry friction as a damper.

Ride is perceived to be in most comfortable zone when the natural frequency is in range of about 1Hz to 1.5Hz. A ride is consider as harsh when the frequency approaches 2Hz [4]. The limitation of the passive suspension system are their components can only store and dissipated energy. Even though the hydraulic systems in passive suspension already proved its potential with active roll control (ARC), taking consideration of it reduction of road vibrations, the performance of the system is still insufficient [5].With the increasing demand in improving vehicle handling and passengers comfort, semi-active and active suspension is introduced.

Passive suspension system is still favored by many automotive company due to its market value and simplicity. The damping force is set and fixed to a constant value. Semi-active suspension system make use of the road input to improve vibration isolation by changing damping force according to road profile. Active suspension system applies external force from actuator to counter the vibration from ground to achieve excellent vibration migration. The existing models for each suspension categories (passive, semi-active and active) are shown in Figure 6.

Active suspension offers much greater potential due to absence of any mechanical transmission [6]. The active suspension with the implementation of electromagnetic linear generator is much more energy efficient since its can convert the vibration energy to electrical energy instead of dissipating it as heat energy [7].

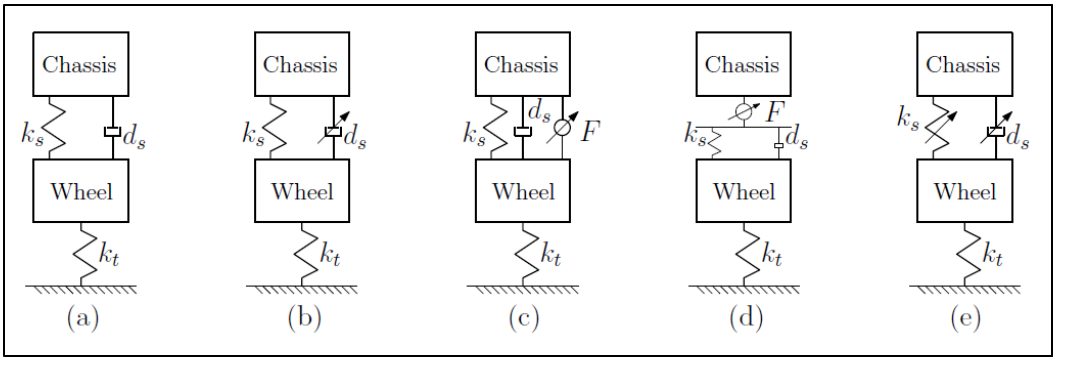


Figure 6(a) Quarter car model for passive suspension, (b) semi-active suspension model, (c) parallel active suspension model, (d) series active suspension model, (e) electromagnetic suspension model

2.5. Electromagnetic Active Suspension System

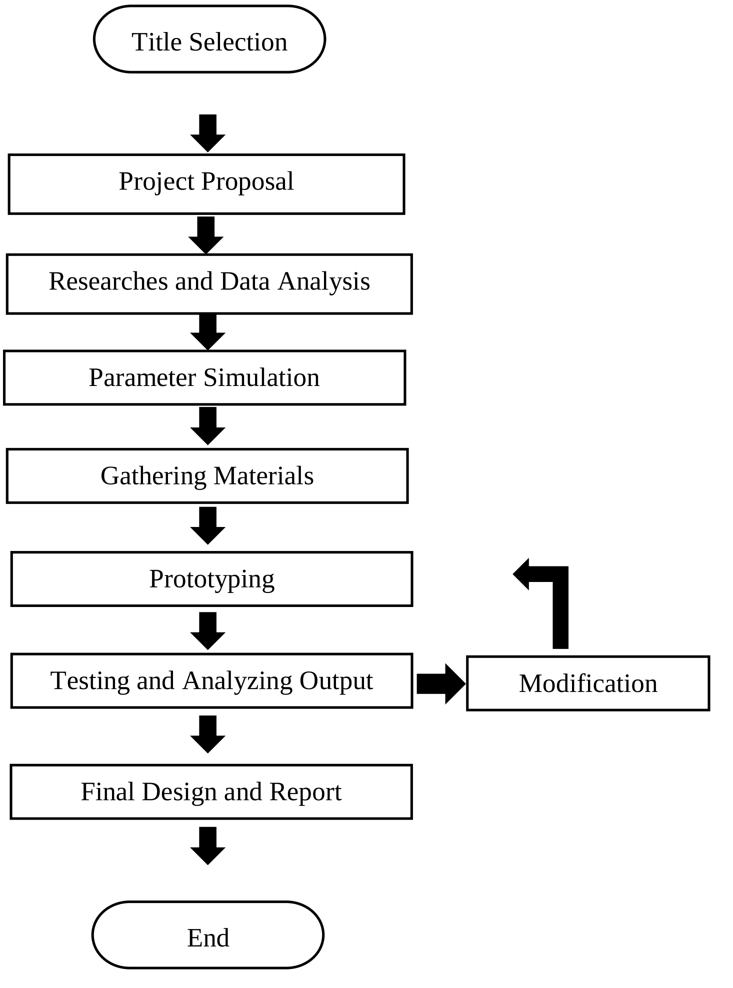
Electromagnetic suspension system can produce an AC voltage caused by the relative movement between permanent magnet stacks and armature winding. The regenerative energy of active suspension system is studied in [8]. The working principle is based on Faraday's law. When there is current passing through wire coil, magnetic field is generated, the magnetic field generated by current will react to the magnetic field of permanent magnets. The direction on force depends on the direction of current flow. There are three types of linear generator, moving coil, moving iron and moving magnets. The linear generator – actuators in practical, are simple to design and manufacture, but the stroke is limited and output force is relatively small.

Various electrical machine and topologies can be used in designing active suspension system [9]. Out of the possible topologies, tubular linear motor is said to be the most suitable used in designing electromagnetic suspension. Tubular linear have a comparatively high force density that can control the vehicles body vibration same as hydraulic damper [5, 10, 11]. Quasi - Halbach permanent magnet array claimed to have highest output force and reduce the translator mass by removing the permanent back iron [12].

CHAPTER 3

METHODOLOGY

3.1. Project Flow Chart



3.2. Project Activities

3.2.1. Permanent Magnet Configuration

Difference magnets arrangement and configuration will have different effects on the flux linkage inside the air gap. Basically there are only two ways of PM arrangement – axially or radially. Figure 7 shows the poles of magnet arrangement where red indicate North poles and blue indicate South poles.

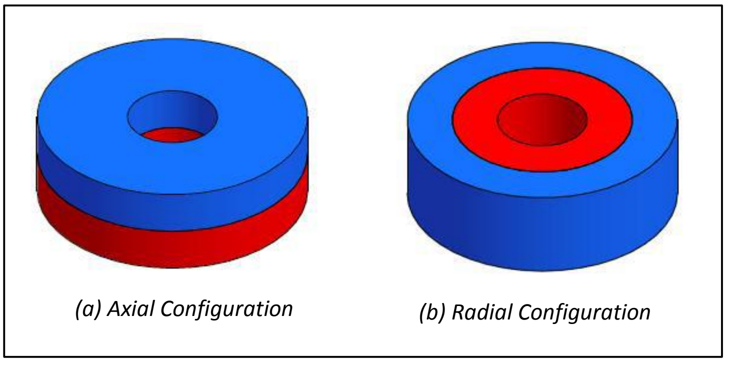
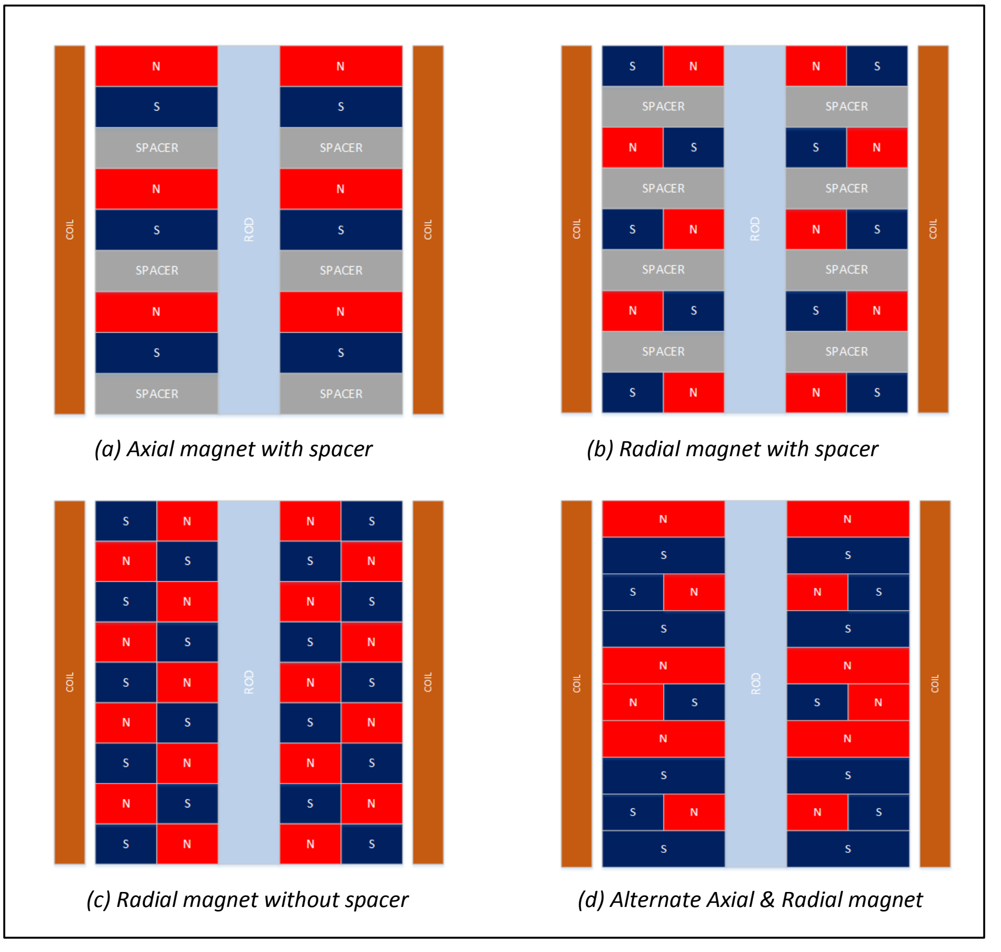


Figure 7: Permanent Magnet (a) Axially arranged (b) Radially arranged

Four different magnet configuration are determined and compared is shown in Figure 8. First arrangement is composed of axial magnets with iron spacers in between. The same pole facing each other will push the flux to sides. The second arrangement to the right only applied radial magnets with iron spacer in between. The flux loops are clearly revealed with this arrangement. The three arrangement used radial magnet without spacer. This design will be used to study the effect of spacer. Lastly, the combination of axial and radial magnets configuration. The axial and radial magnets are arranged alternately so does the orientations. All these configuration will be simulated by using ANSYS to study the effect of different magnet configuration. The results will be discussed in the next chapter.



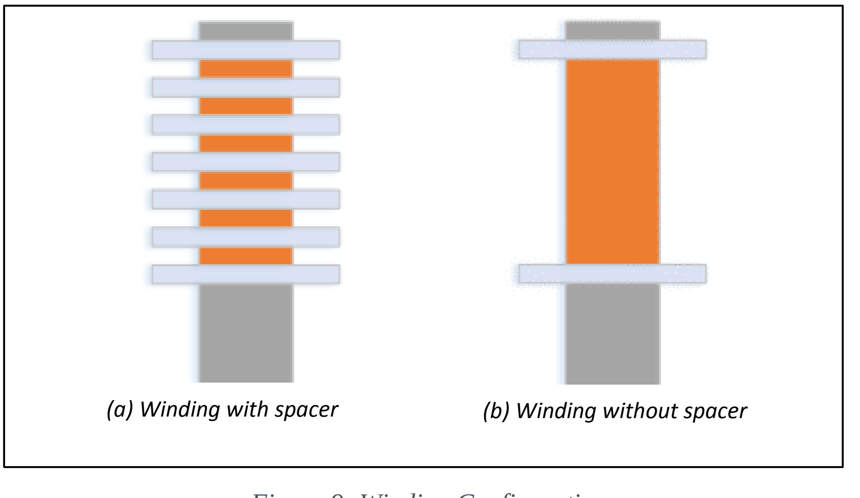
(a) Axial magnet with spacer (b) Radial magnet with spacer

(c) Radial magnet without spacer (d) Alternate Axial & Radial magnet

Figure 8: Magnet Configurations

3.2.2. Winding Configuration

For this project, two types of winding configuration are studied – coil winding with spacer and winding without spacer. Single phase winding is used for this study. Figure 9 shows the design used for prototype.



(a) Winding with spacer (b) Winding without spacer

Figure 9: Winding Configuration

In design (a), there are six slots winding separated by 4mm perspex. The spaces between slots are fixed at 20mm. Each slot are winded with 20 turns of copper wire which makes 120 turns for design in (a).

In design (b), there is only single layer of copper wire. Number of turns is which is 120 turns kept constant in the experiment.

For the coil winding, two different copper wire diameter is used to study the effect of cross sectional area of the wire in the system for both design. Theoretically, bigger cross sectional area with give out more power output which is desired in the experiment.

3.3. Prototypes

Design 1: Coiled Winding without spacer (0.80mm)

Figure 10: Coiled Winding without spacer (0.80mm)

Design 2: Coiled Winding with spacer (0.80mm)

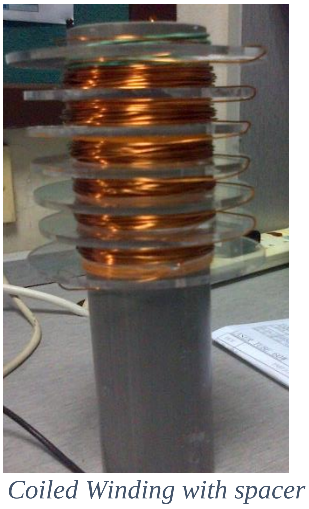


Figure 11: Coiled Winding with spacer (0.80mm)

Design 3: Coiled Winding without spacer (0.315mm)

Figure 12: Coiled Winding without spacer (0.315mm)

Design 4: Coiled Winding with spacer (0.315mm)

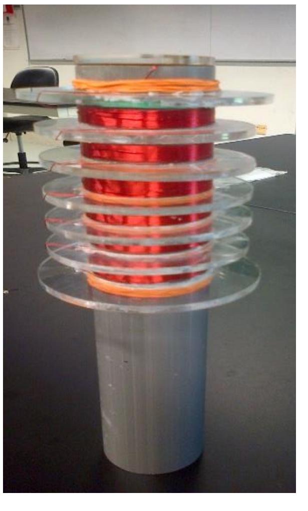


Figure 13: Coiled Winding with spacer (0.315mm)

3.4. Benchmarking Experiments

Due to limited budged and cost for the project, the desired ring magnet be used as the magnet configuration design unable be used. Instead, for the sake of continuing and investigating the effect of winding configuration, Alnico bar magnet from the lab is used in the experiment. Four alnico bar magnets are tied with the center rod to imitate the ring magnet configuration for stability.

Figure 14: Alnico Bar Magnet (151mm x 12mm x 5mm)

Figure 15: Science Workshop 750 Interface

Figure 16: Current Sensor with 1 ohm internal resistance

Objective:

To measure the output current and voltage for the prototypes

Apparatus:

Prototype

Current Sensor (1ohm internal resistance)

Connecting wires & crocodile clips

Data Studio Software

Science Workshop 750 Interface

4 Alnico Bar Magnets

Part 1: Measuring Voltage

Procedures

i. The apparatus is set up as shown in the figure below.

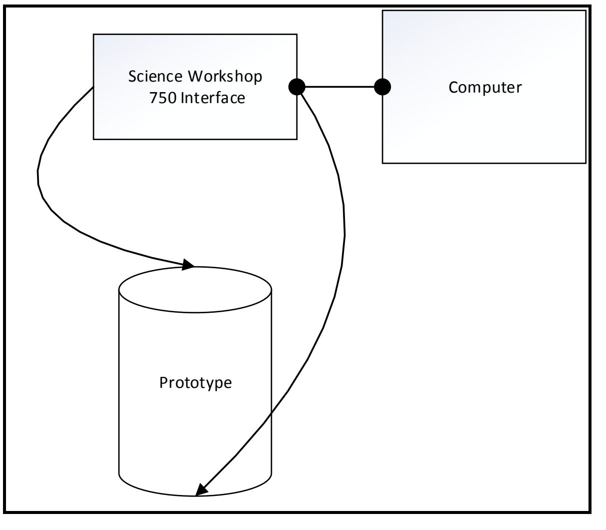


Figure 17: Measuring Voltage Set up

ii. End of coil are connected by wires and crocodile clips. The other ends are connected to the port A of Science Workshop 750 Interface.

iii. Data Studio is set up with voltage sensor with port A to receive input.

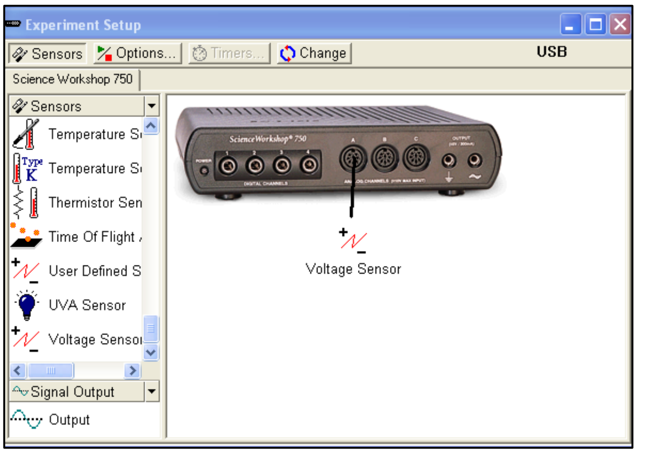


Figure 18: Data Studio Set up for voltage sensor

iv. Magnets are placed with the center rod.

v. Magnets are stroked manually with maximum stroke of 60mm for 15 seconds.

vi. The experiment is repeated for 3 runs.

vii. The output is captured and recorded by the Data Studio in the computer.

viii. Step (i) to (vii) are repeated with different set of prototype (winding with spacer and without spacer) and coil winding diameter (0.8mm and 0.315mm)

Part 2: Measuring Current

Procedures:

i. The apparatus is set up as shown in the figure below

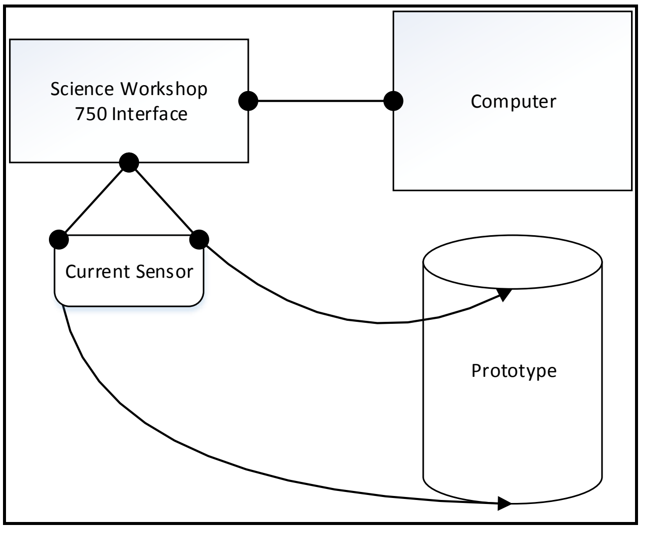


Figure 19: Measuring Current Set up

ii. End of coil is connected by wires. The other ends are connected to the port A of Science Workshop 750 Interface.

iii. The current sensor is connected to the port A of Science Workshop 750 Interface.

iv. Data Studio is set up with current sensor with port A to receive input.

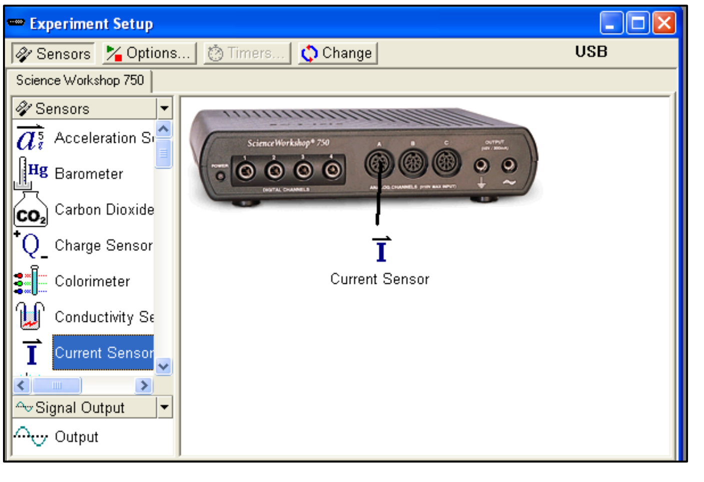


Figure 20: Data Studio Current Sensor Set up

v. Magnets are placed with the center rod.

vi. Magnets are stroked manually with maximum stroke of 60mm for 15 seconds.

vii. The experiment is repeated for 3 runs.

viii. The output is captured and recorded by the Data Studio in the computer.

ix. Step (i) to (viii) are repeated with different set of prototype (winding with spacer and without spacer) and coil winding diameter (0.8mm and 0.315mm)

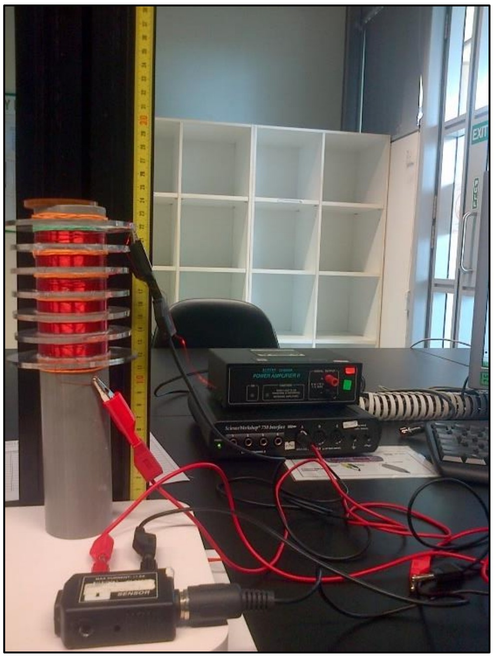


Figure 21: Experiment Set Up

3.5. Gantt chart and Key Milestone.

The Gantt chart is prepared as a guideline to make sure the project can be completed within the time frame. The milestone are indicated with blue dot while process are indicated with blue strip. Table 1 shows Gantt chart and suggested milestones for FYP I. Table 2 shows Gantt chart and suggested milestones for FYP II.

Table 1: Gantt Chart for FYP I

Activities	**WEEK**													
	FYP I													
	01	02	03	04	05	06	07	08	09	10	11	12	13	14
Project Title	■	■												
Preliminary Research		■	■	■	■	■								
Project Proposal						●								
Establish Design Parameters							●							
Project Design								■	■	■	■			
Proposal Defense								■	■					
Parameters Simulation									■	■	■	■		
Material Selection												●		
Interim Report													■	■
Submission Interim														●

Table 2: Gantt Chart for FYP II

Activities	**WEEK**													
	FYP II													
	01	02	03	04	05	06	07	08	09	10	11	12	13	14
Develop Prototypes	■	■	■	■	■	■								
Benchmarking Experiments				■	■	■	■	■	■	■				
Data Analysis							■	■						
Submission Progress Report								●						
Pre- SEDEX										●				
Submission Final Report												●		
Submission Technical Paper														●
Viva														●
Submission of Dissertation														●

CHAPTER 4

RESULT AND DISCUSSION

4.1. Permanent Magnet Configuration

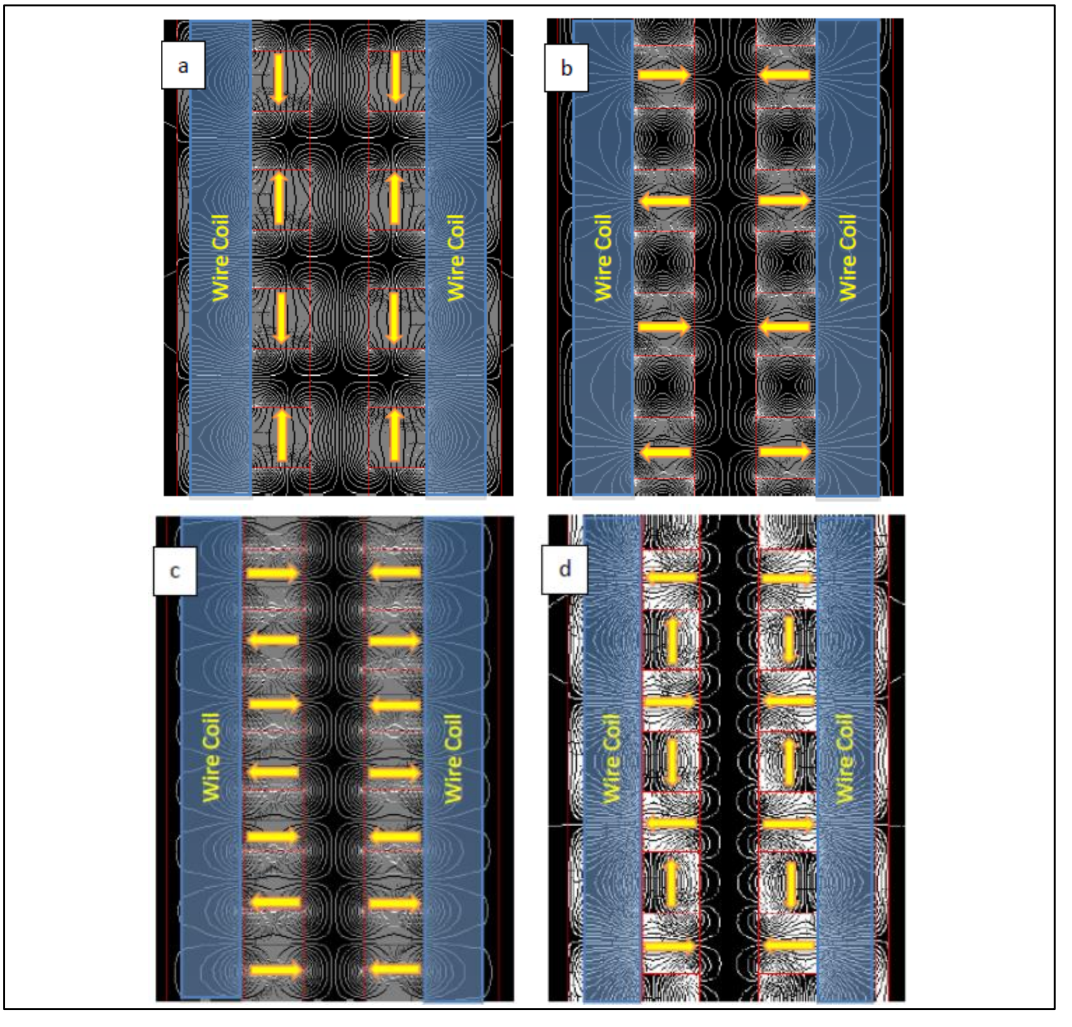


Figure 22: Magnetic Flux Plots of Permanent Magnet

Figure 22 shows the magnetic flux lines inside the air gap for each arrangement. Arrangement *a* and *d* shows the most flux lines compares to *b* and *c*. Arrangement in *d* excel in the permanent magnet design due combination of axial and radial magnet in the design. The combination forms flux loops mostly passing through the air gap. Arrangement in *a* is good enough because the flux loops are evenly distributed in both air gap and center rod when only axial magnets are applied.

Arrangements *b* and *c* are simply short looped. The flux travels back to south poles without cutting the coil and air gap. Therefore, it is obvious that arrangement *d* won the permanent magnet arrangement. This is because the radial magnet in alternate arrangement compose better loops to guide magnetic flux.

4.2. Material Selection

4.2.1. Centre Rod

Due to limitation in cost, size, material and space, the output power can be intensify by increasing the magnetic flux density. Electrical and magnetic properties of material play important role as the magnetic flux has to travel in a guided loop. Zuo et al [1] built a half scaled linear electromagnetic harvester with single layer magnets with output power of 8 Watts after modifying the materials. He found that the steel and aluminum center rod outside cylinder will have significant effects on guiding magnetic flux to intersect with wire coil, thus more regenerative power can be achieved. Steel can be good guide on magnetic flux due to high relative magnetic permittivity about 100. On the other hand, aluminum relative permittivity is the same as air which is 1. In this case, magnetic flux loops will be pulled by the steel center rod.

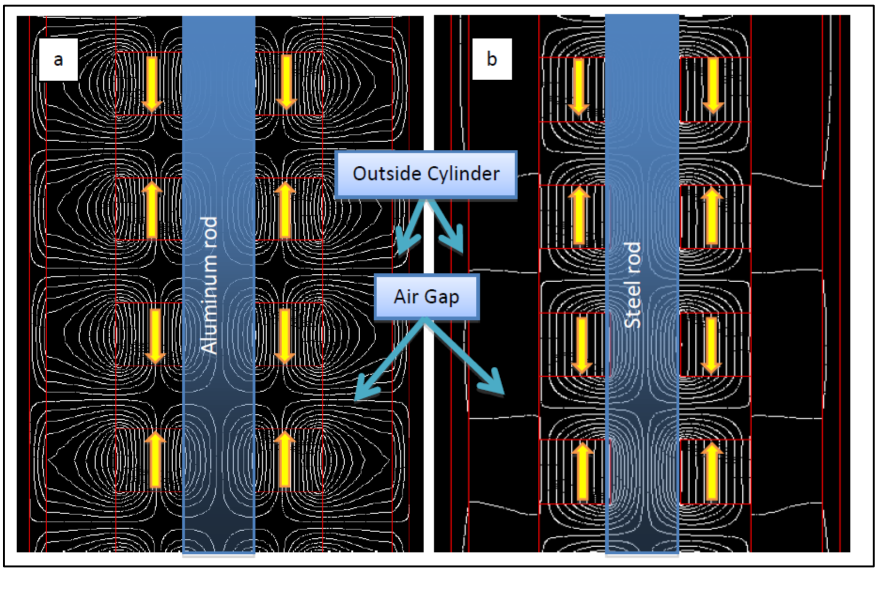


Figure 23: Flux Profile (a) Aluminum Center Rod (b) Steel Center Rod

ANSYS software is used to understand the characteristics and behavior of magnetic flux. Figure 23 shows the comparison between aluminum and steel rod as a center rod. Flux lines are evenly distributed with aluminum as center rod. However, due to the high permittivity of steel, most of flux lines are forced to travel inside the steel rod. Only a few lines inside the air gap. Hence, rod material with low magnetic permittivity is most suitable to be used because shows significant effects on the flux density. In this case, aluminum would be the most appropriate material to be the center rod.

4.2.2. Casing

Since steel having 100 times greater permittivity than aluminum, steel is mostly preferable to be used as the casing. Steel casing can force the magnetic flux to travel through the air gap thus can produce high flux density at the air gap. Table 3 below shows the comparison between air, aluminum and steel permittivity.

Table 3: Permittivity and relative permittivity for air, aluminum and steel

Type of Material	Permittivity, μ [H/m]	Relative Permittivity, μ/μ_o
Air	$1.25663753 \times 10^{-6}$	1.00000037
Aluminum	1.256665×10^{-6}	1.000022
Steel	1.26×10^{-4}	100
Perspex	2.63893×10^{-6}	2.1

4.3. Winding Configuration

From the experiments conducted, all data are tabulated and compared. Only the magnitude from the experiments conducted are considered since the main objective is to get maximum output power by the system. The mean and root mean square (rms) values for each experiment is calculated to obtain the DC equivalent.

Table 4: Design 1 (Coiled winding without spacer 0.80mm)

Design 1	Max Current [mA]	Max Voltage [mV]
Run 1	4.00	8.00
Run 2	4.00	9.00
Run 3	4.00	14.00
Average	4.00	10.33
RMS Values	**2.83**	**7.306**

Table 5: Design 2 (Coiled winding with spacer 0.80mm)

Design 2	Max Current [mA]	Max Voltage [mV]
Run 1	5.00	41.00
Run 2	3.00	29.00
Run 3	4.00	27.00
Average	4.00	32.33
RMS Values	**2.828**	**22.86**

Table 6: Design 3 (Coiled winding without spacer 0.315mm)

Design 3	Max Current [mA]	Max Voltage [mV]
Run 1	0.824	4.00
Run 2	0.931	4.00
Run 3	0.894	5.00
Average	0.883	4.33
RMS Values	**0.624**	**3.06**

Table 7: Design 4 (Coiled winding with spacer 0.315mm)

Design 4	Max Current [mA]	Max Voltage [mV]
Run 1	4.00	5.00
Run 2	4.00	11.00
Run 3	3.00	11.00
Average	3.67	9.00
RMS Values	**2.59**	**6.36**

4.4. Discussions

4.4.1. Winding configuration

Two types of winding are experimented in the experiment – winding with spacer and winding without spacer. Table 4 and Table 6 shows the results of voltage and current for winding without spacer using 0.80mm and 0.315mm copper wire respectively. Table 5 and Table 7 shows the results of voltage and current for winding with spacer using 0.80mm and 0.315 respectively. To study the effect of the winding configuration, the number of turns is kept constant throughout the whole experiments which is 120 turns. It is found that design with spacer between coils have a better output compared to design without spacer between them.

By having slots between winding, each turn are able to interact with the magnetic flux. Spacer between coiled also helps to minimize the cross over between the windings and maintaining its shape. It also let the magnetic flux to have its own flux lines instead of having one big cycle of magnetic flux line. The disadvantage using 0.80mm copper wire as winding is that it is hard to bend to make a perfect winding which leaves a few gap in between the windings. 0.315mm winding is easier to be winded. A proper method needed to be used instead of winded it manually so the design will be more effective.

4.4.2. Coil Selection

From the experiments, copper wire with 0.80mm diameter gives out better output compared to 0.315mm diameter copper wire. Both Design No.1 and No.2 have almost the same amount of current produced but different amount of voltages. 0.80mm copper wire have maximum current carrying capacity of 11A and while 0.315mm copper wire can withstand maximum current of 1.4A before its melt.

For this experiment, since the maximum current produces only in mili range, 0.315mm copper wire seems suitable to be used. Design No. 4 – 0.315mm copper winding without spacer still have half of the space left unused. The design can be improved by having double number of winding since 120 turns only covered half tube. However, the amount of current produces is expected to be much higher than experimental value when using the proposed magnet configuration and material. Bigger copper wire diameter is more suitable for production and manufacturing process.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Based on result and consideration of main factors discusses in the project, it can be concluded that the suitable design for the linear generator for regenerative suspension system would be:

i. Moving Magnet (Stator-Translator Configuration)
ii. Radial and Axial Permanent Magnet Configuration (Magnet Configuration)
iii. Winding
    a. Winding with spacer
    b. Coiled copper wire (0.80mm)
iv. Material
    a. Center rod – Aluminum
    b. Casing - Steel

The best configuration, dimension and material should be combined together to get the best outcome. The study on linear generator's application and design is a promising field to be explored. This project give the general overview on designing linear generator. Even though the value obtain in this experiment is relatively small compared to the power loss in vehicles suspension, the output can be increases when build the upscale prototype and used the suggested material and magnet configuration.

An extended research should be conducted for optimizing the linear generator design since this project only focus on experimenting the some of the factors that might affect the performance of the linear generator design.

5.2. Recommendation

Based on the results from the experiments conducted, coiled winding with spacer perform better than without spacer coiled winding. Design No. 2 seems excel in all criteria. The design can be further improved by having smaller size of spacer so more turns can be made. The spacer used in the design can reduce crossover between windings.

Another method to improve the design is by having smaller air gap between the stator-translator. The prototype air gap using in the experiment is 12 mm which is quite big because the proposed magnet design are not used for the experiments. The air gap size can be reduced to 2 mm so that all magnetic flux can cut through the windings thus more current will be produced. The number of turn per slots also can be increased instead of just having single layer coiled winding. Further research can be done to determine the maximum number of turns can be fitted for one slots for optimizing design.

The magnet poles orientation also can be improved. The magnet used for this project have their poles on the flat surface. The magnetic flux produced is perpendicular to the coil but parallel to the motion. To achieve better output, the magnetic flux should be perpendicular to both coil and motion. The

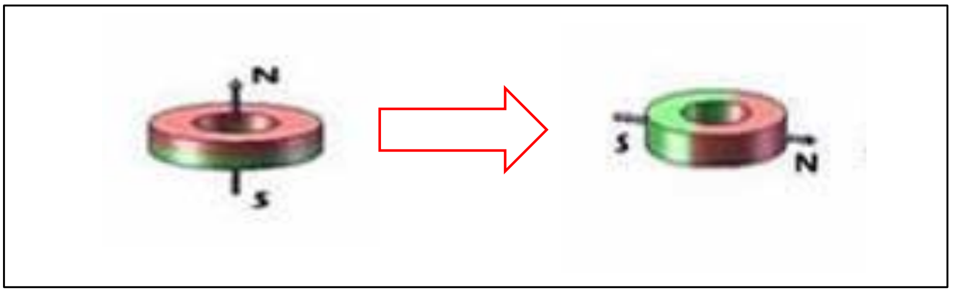


Figure 24: Proposed magnetic pole orientation

Power is proportional to both flux density square and velocity square (refer to Equation 9). By redesigning the linear generator using both axial and radial in double layer configuration can be used so that the magnetic flux in air gap can be increased.

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APPENDICES

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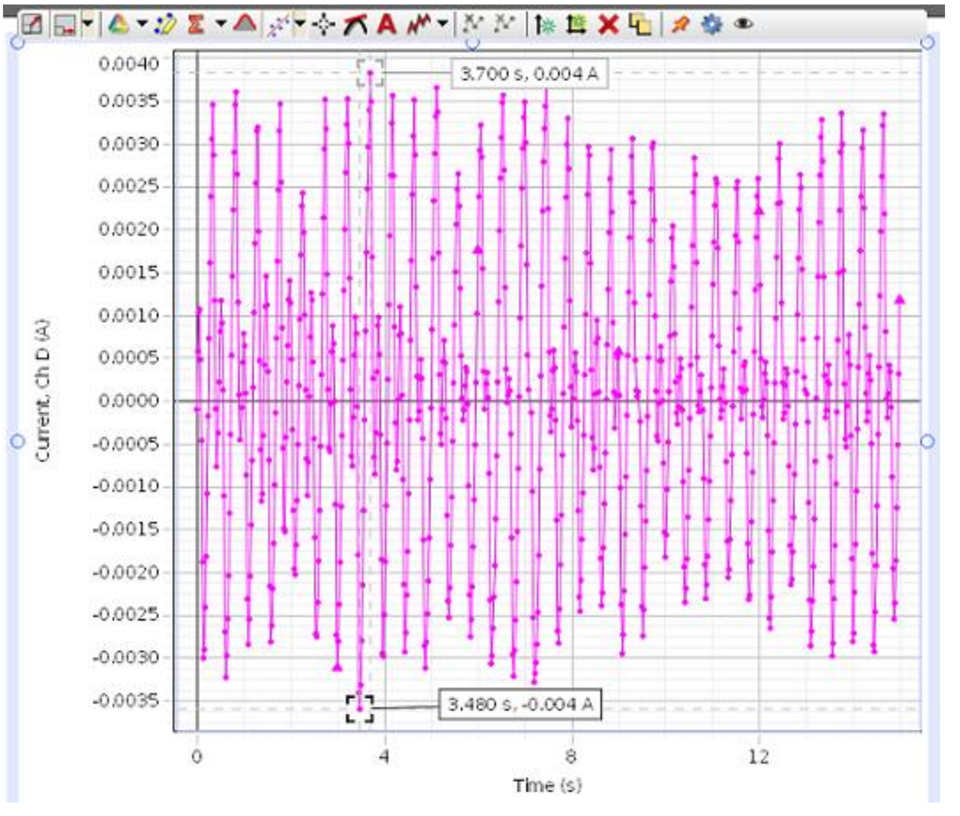

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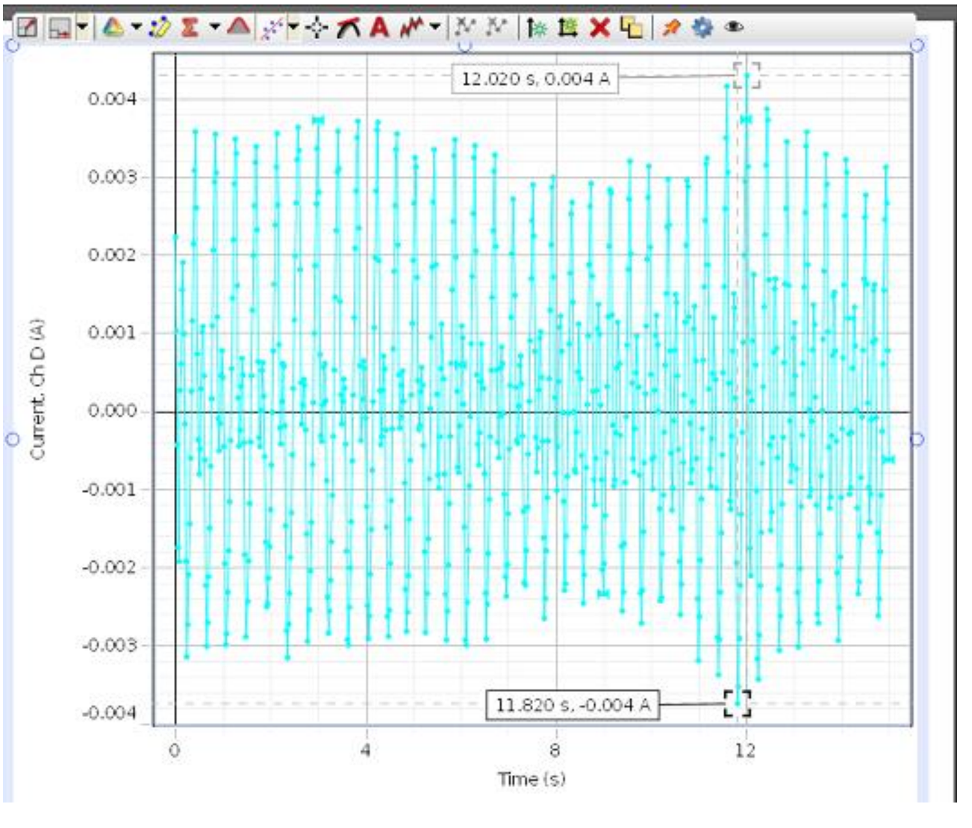

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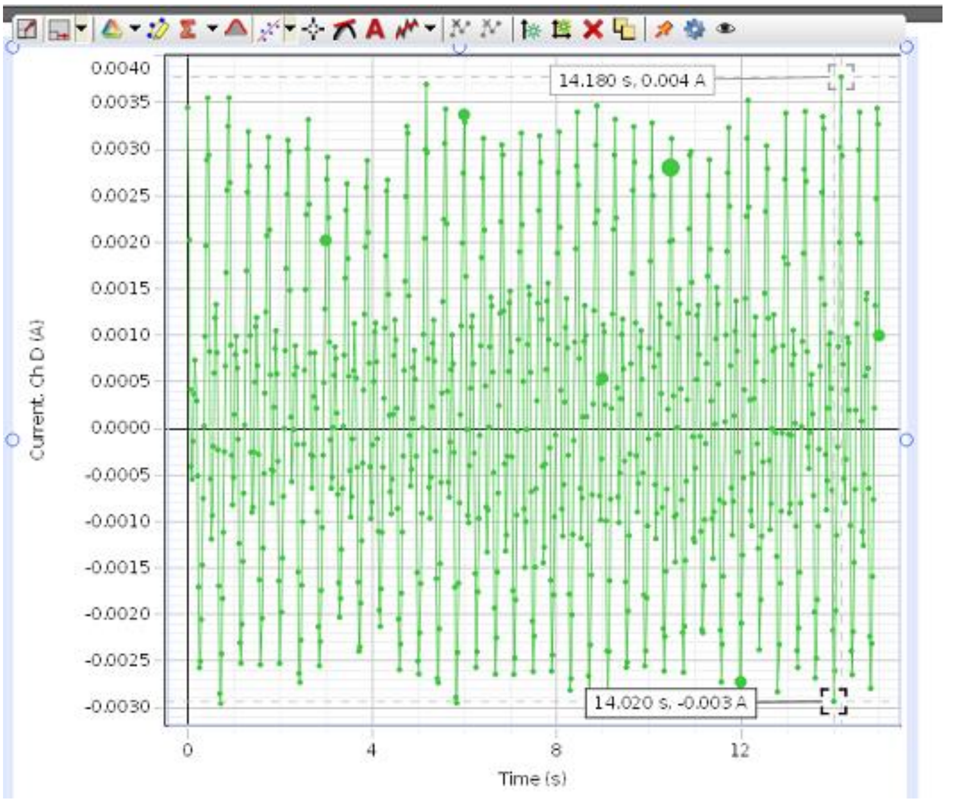

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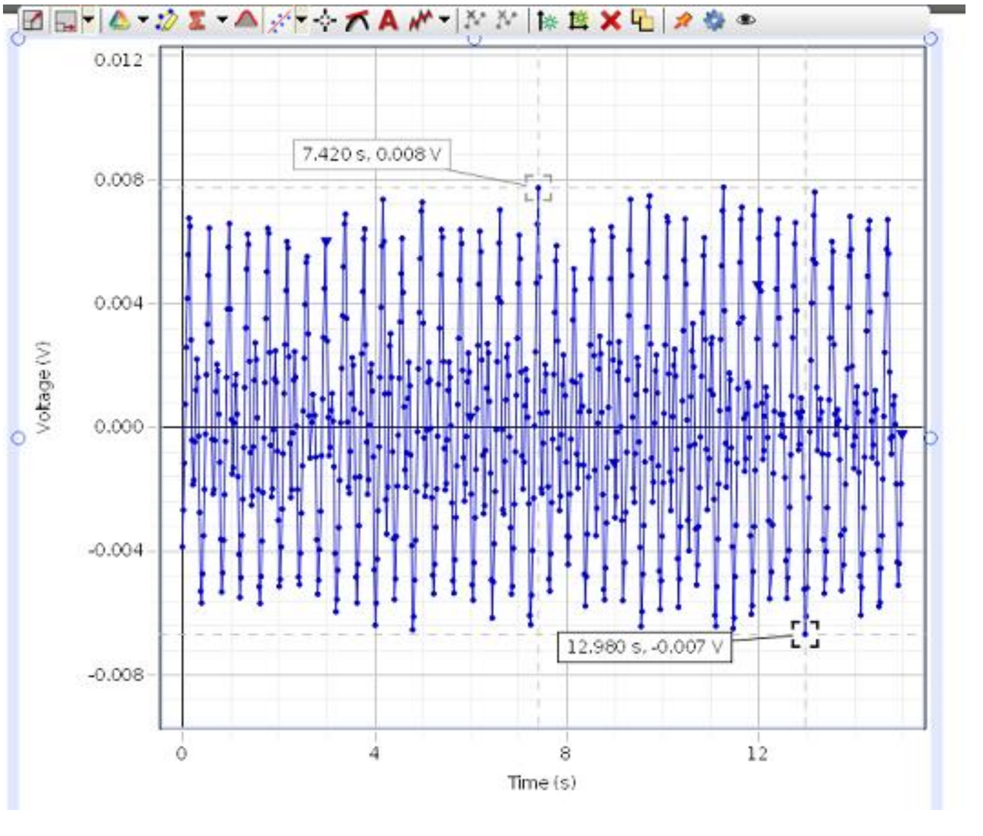

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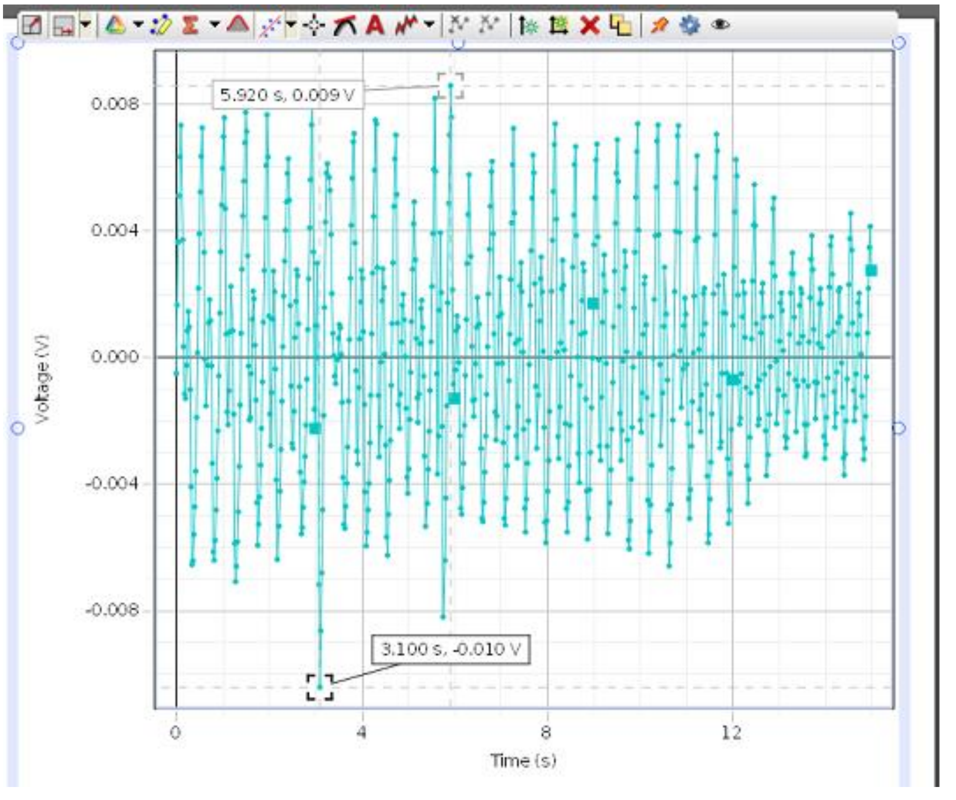

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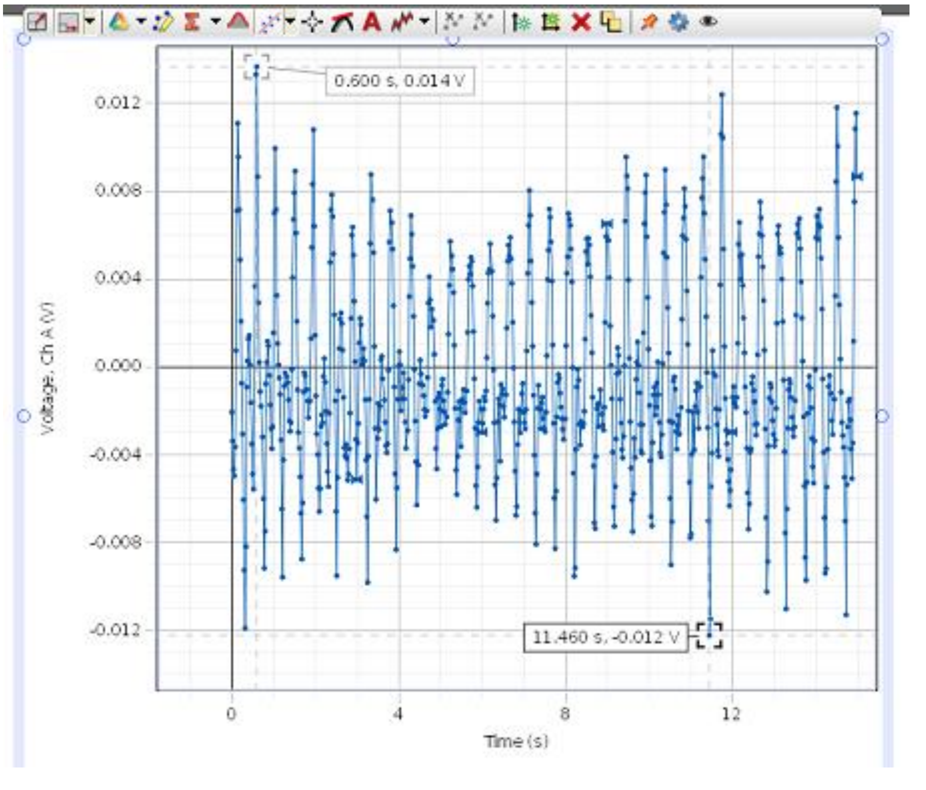

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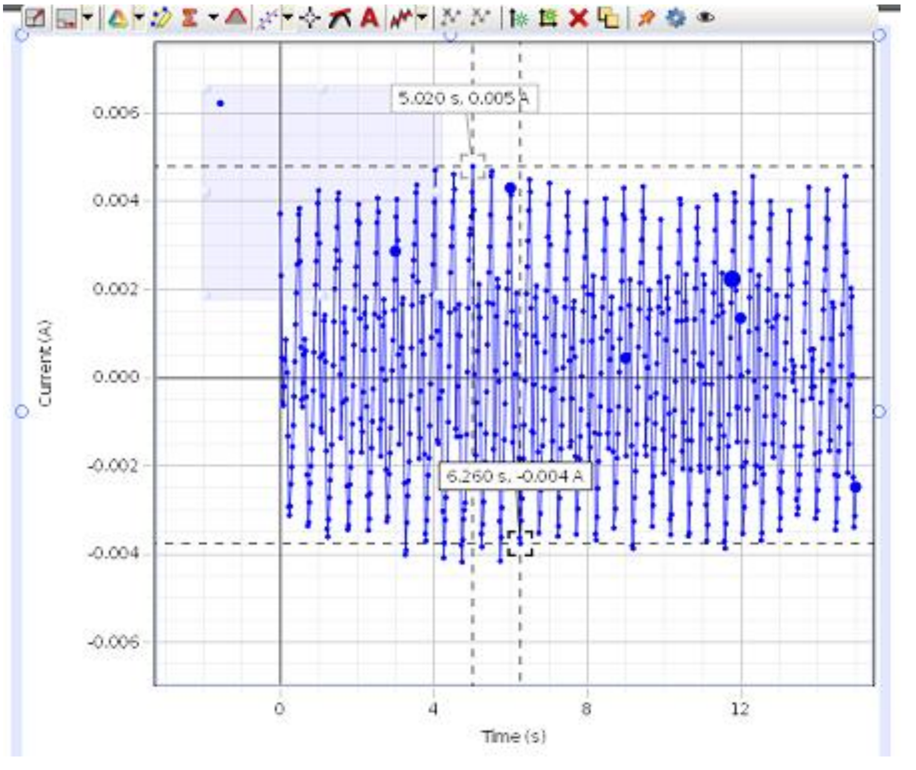

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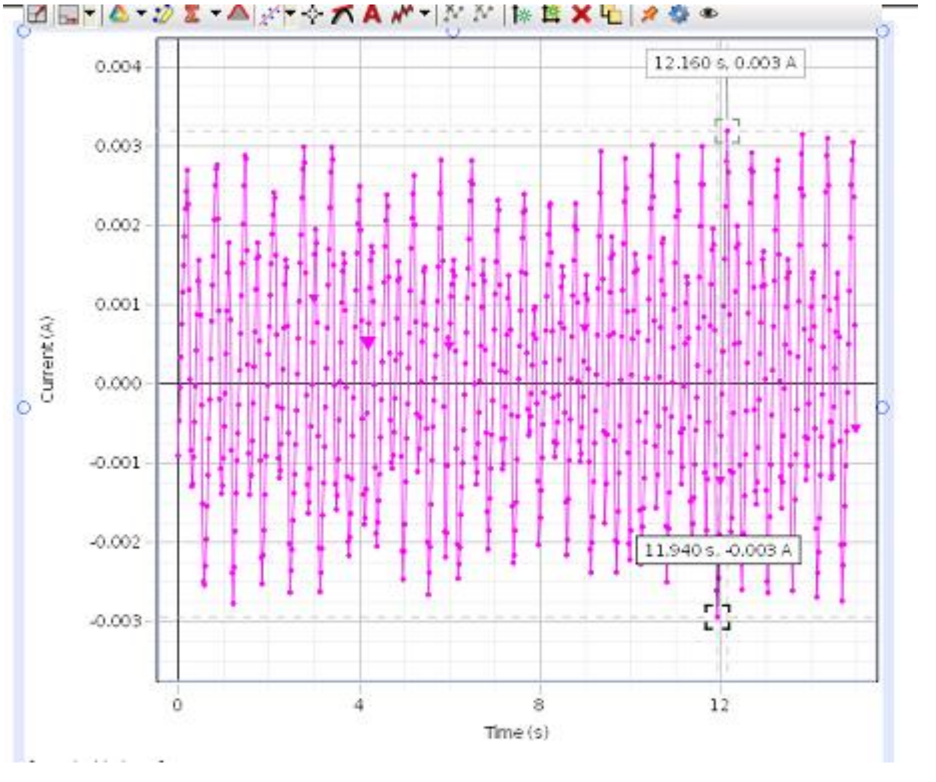

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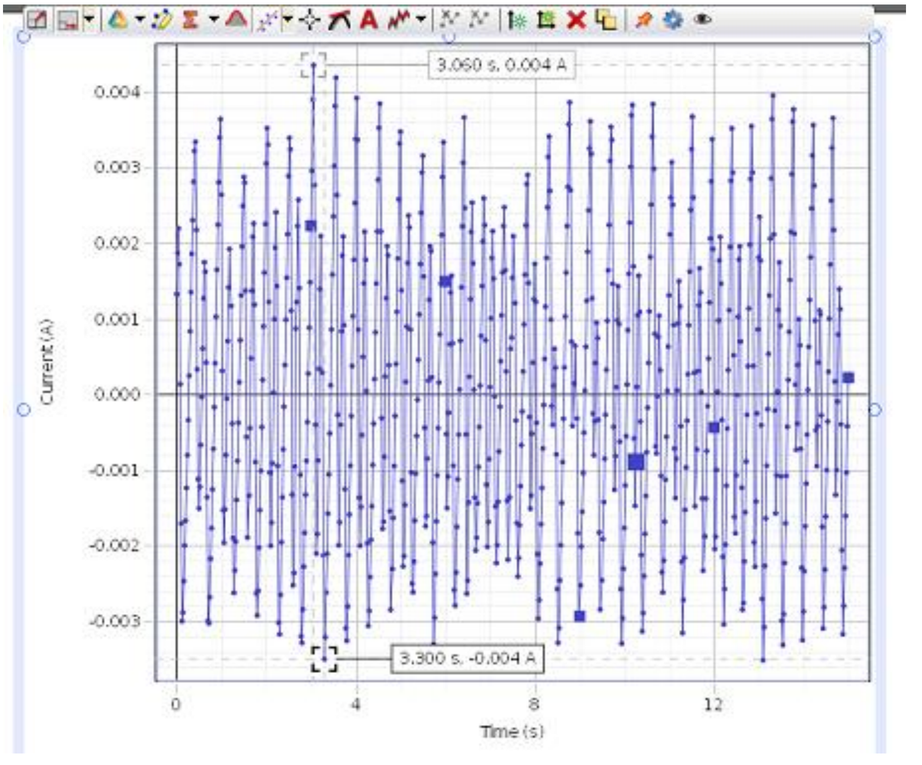

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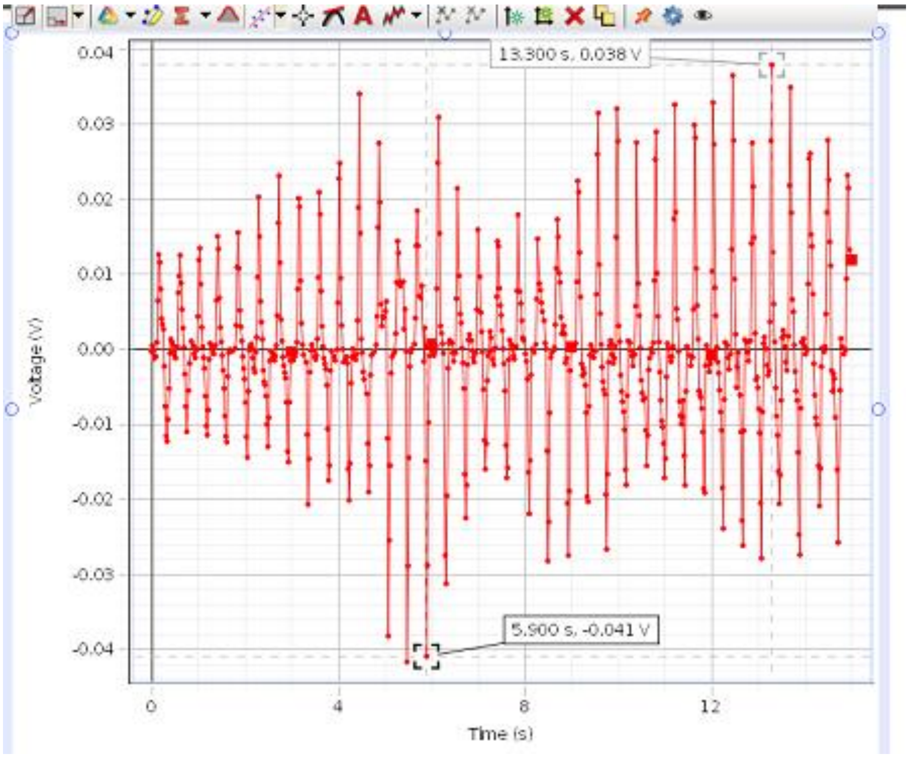

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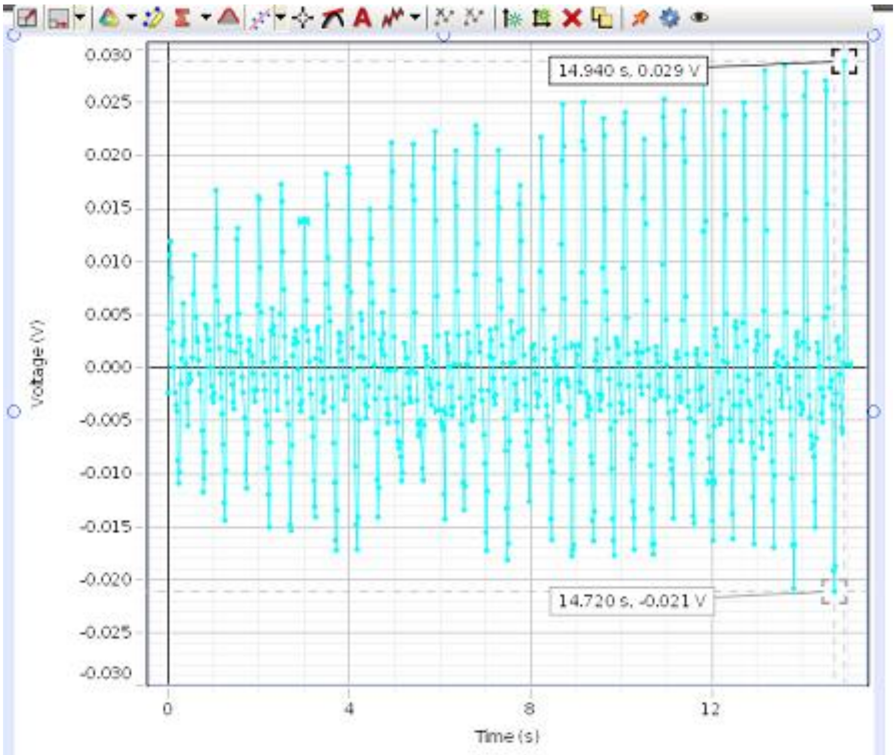

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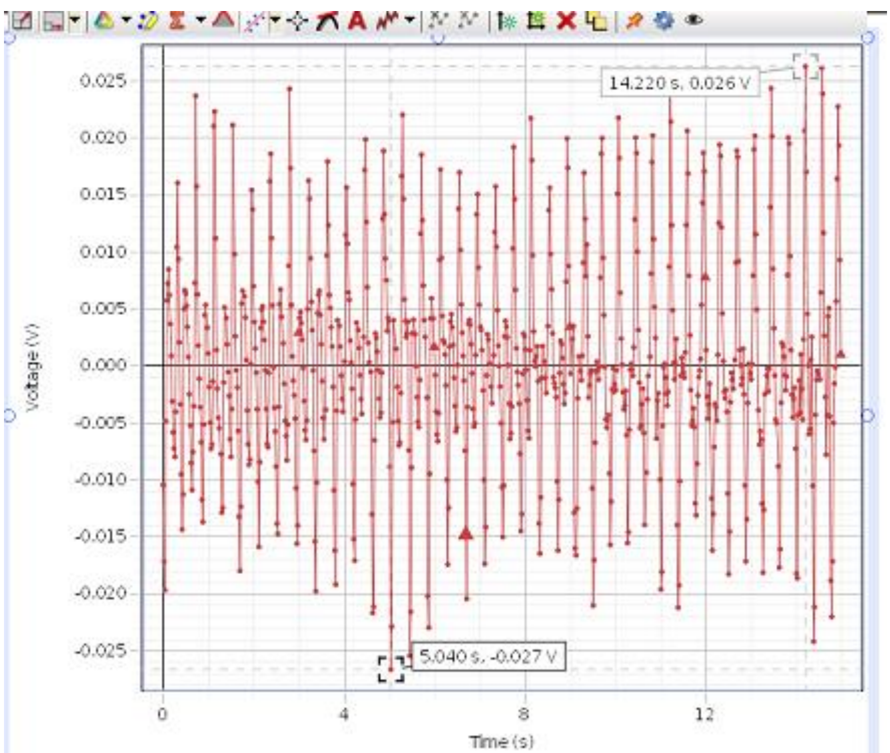

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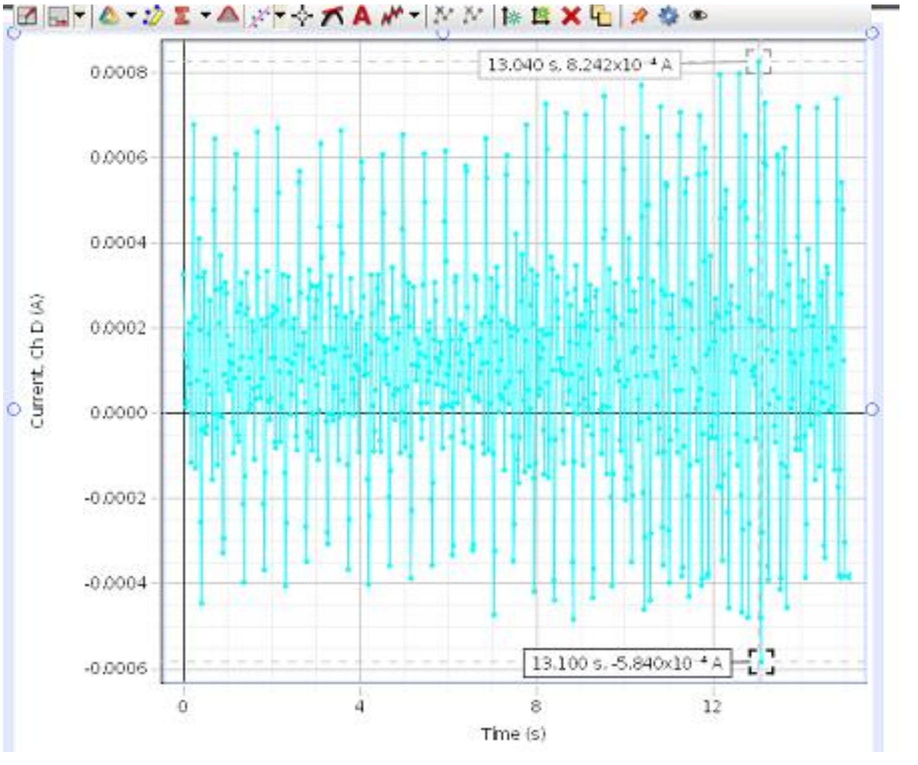

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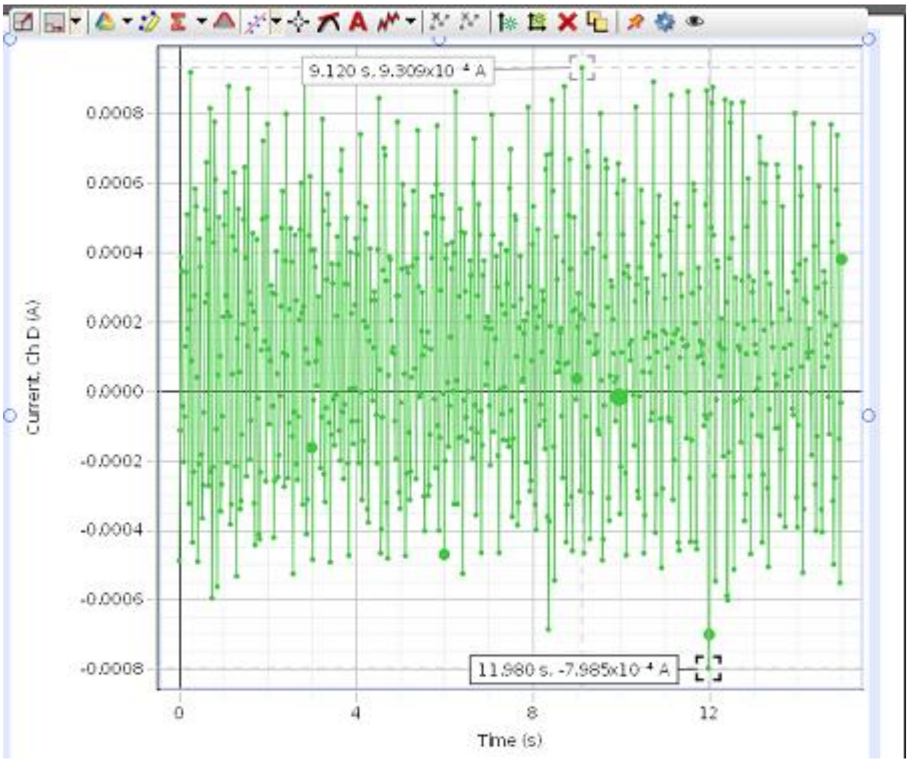

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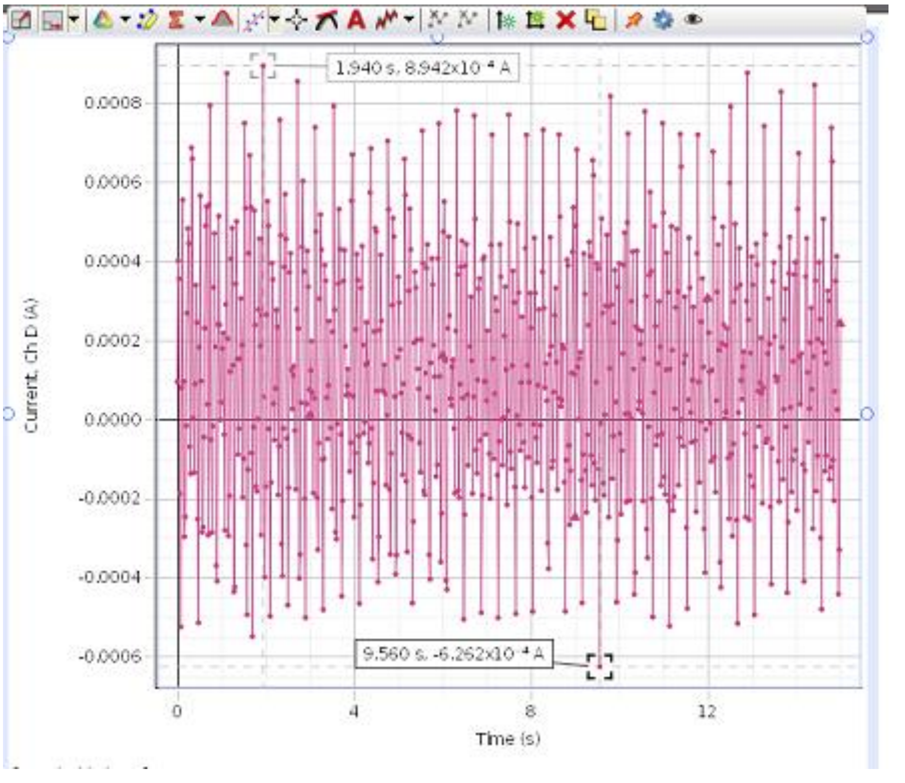

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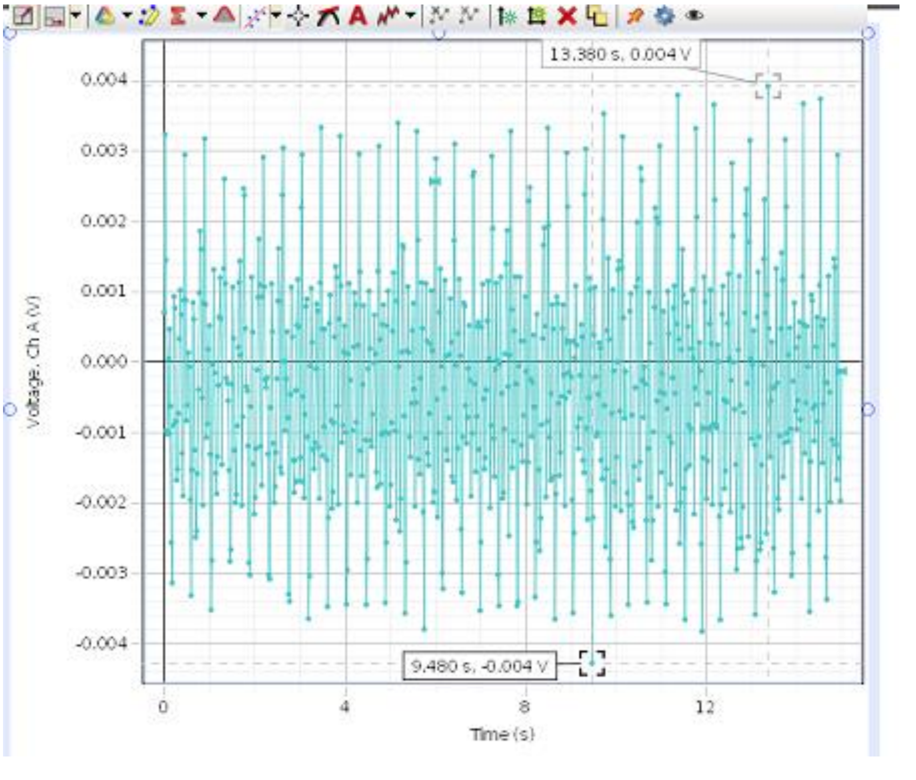

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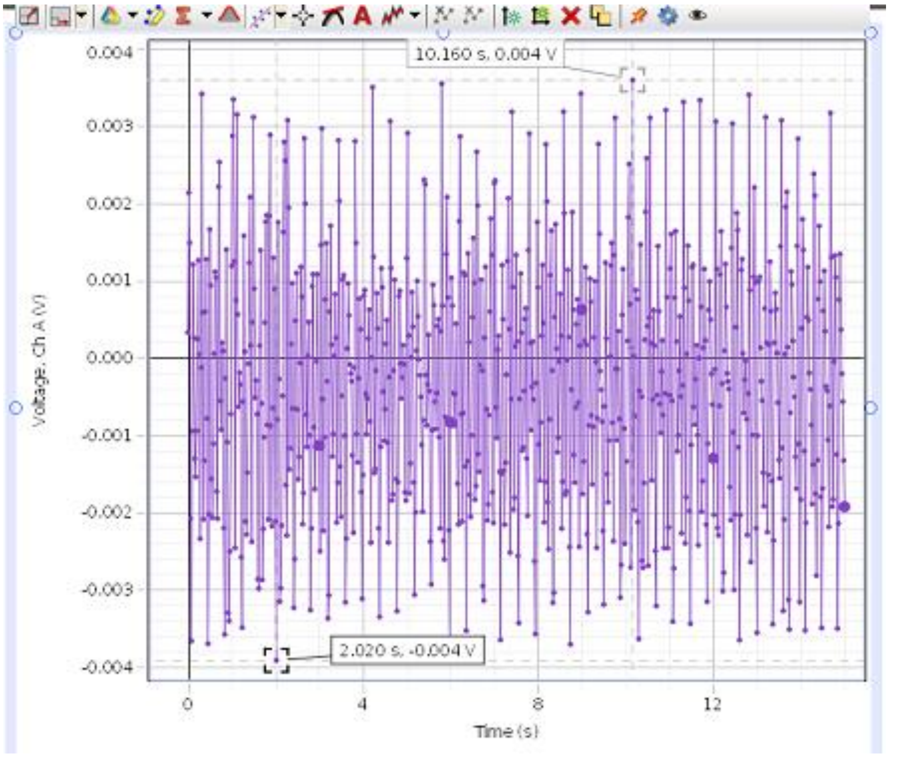

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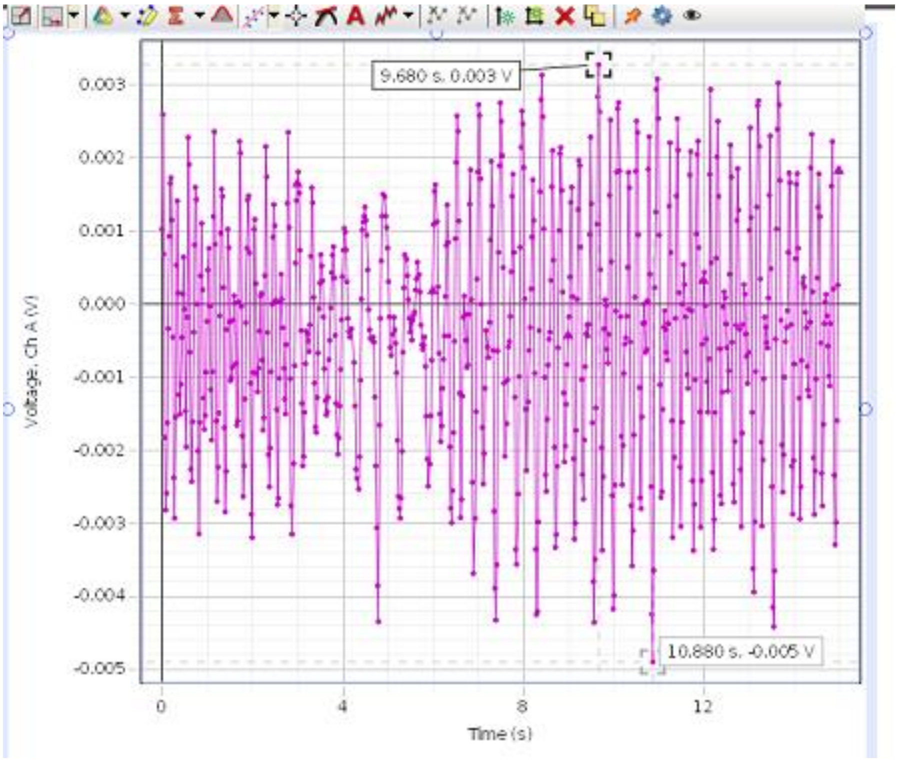

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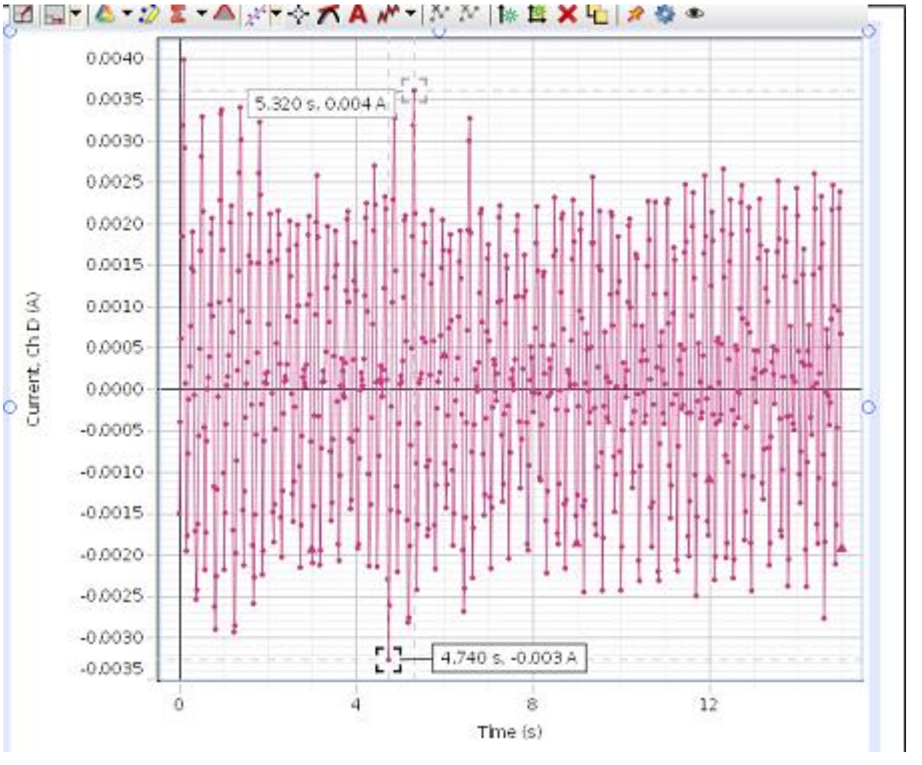

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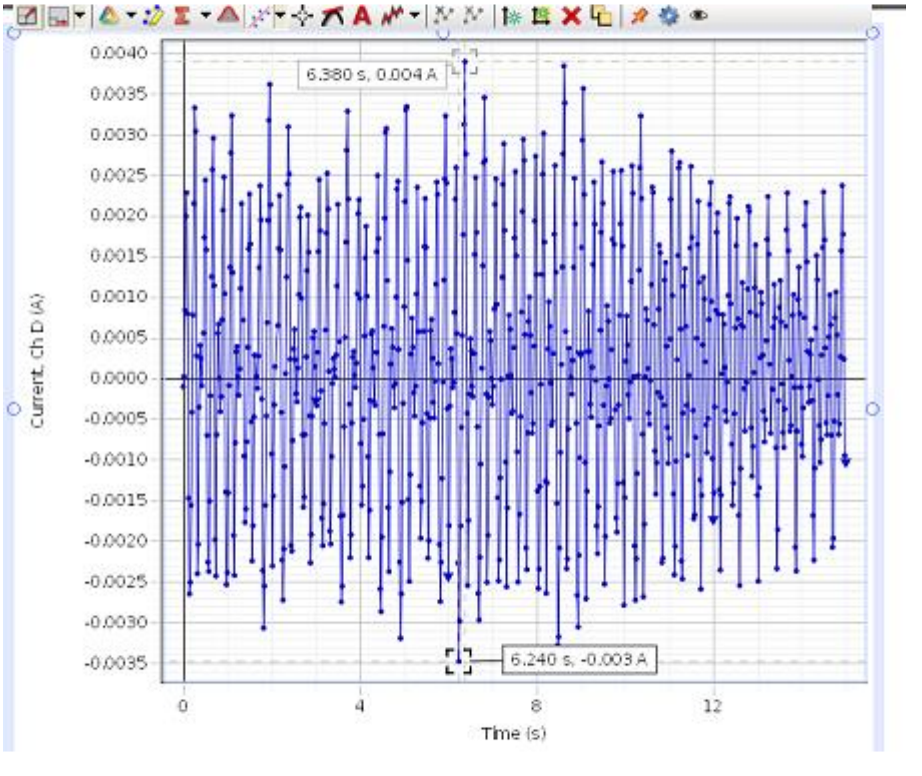

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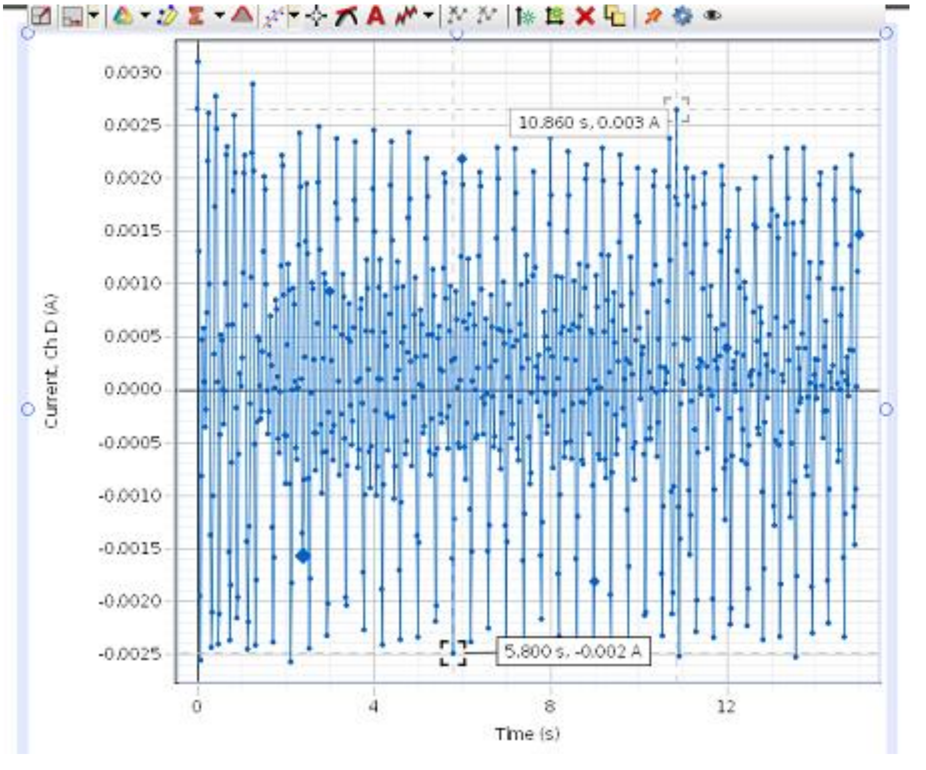

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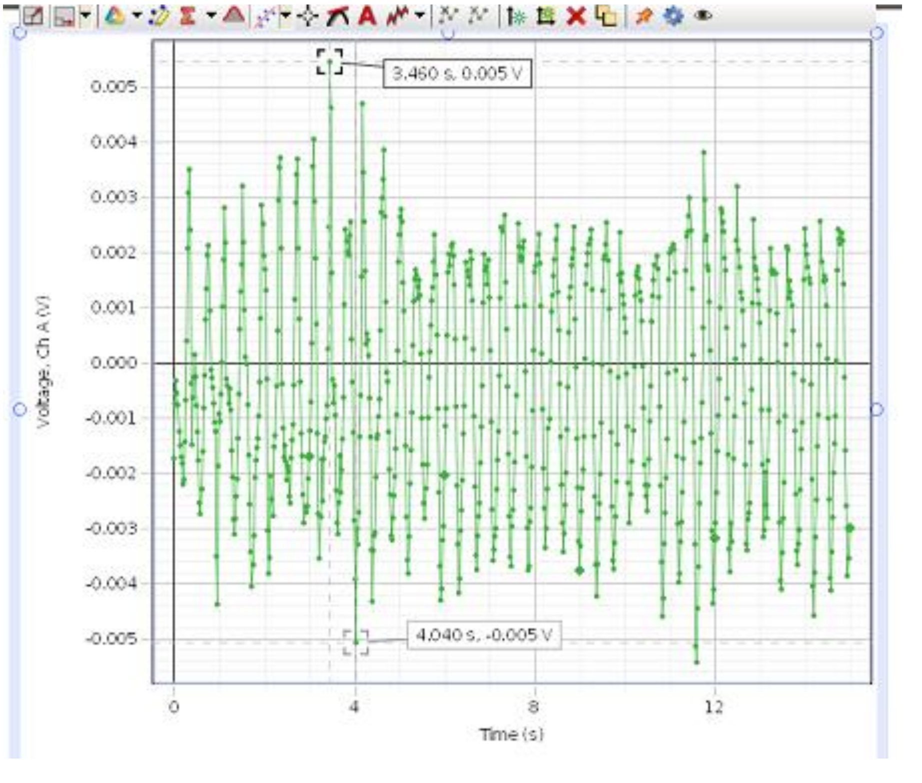

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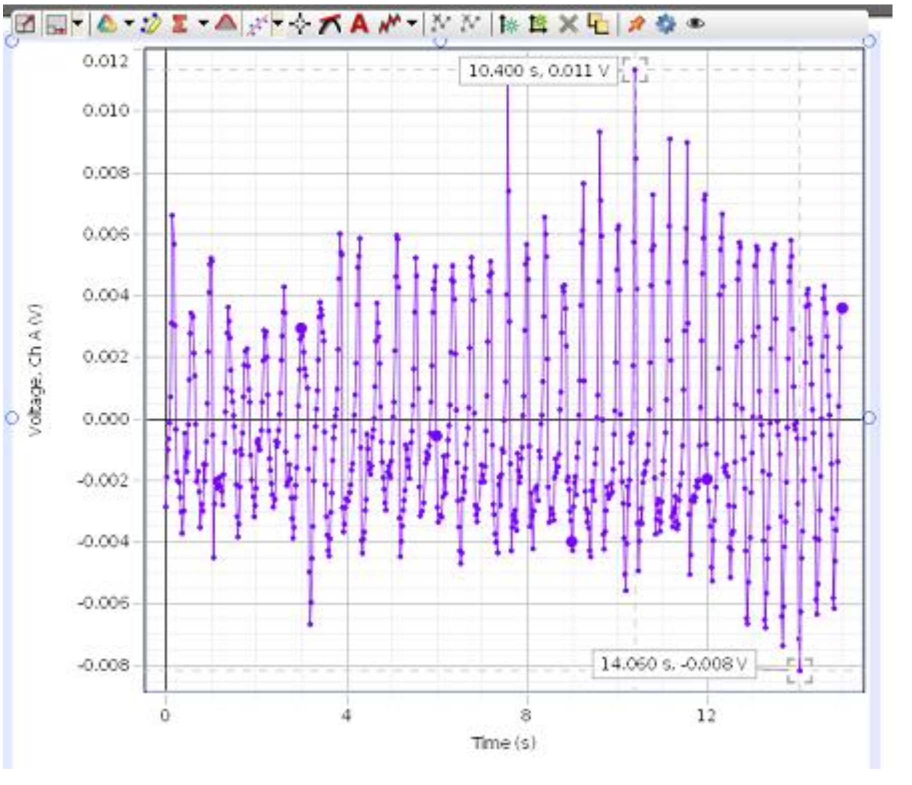

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