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Development of a Fluxgate Magnetometer Model

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Development of a Fluxgate Magnetometer Model

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PHYS797 Senior Design Project
Project Advisor: Professor Matthew Argall
Abstract

As a part of the UNH SWFO-L1 mission to monitor space weather and the sun’s behavior, the fluxgate magnetometer is an important component to measure external magnetic fields. The basic principle of a fluxgate magnetometer is to detect changes in the ambient magnetic field by inducing a magnetic field in a ferromagnetic material via a drive winding. Each magnetometer is unique due to the ferromagnetic properties of the core material which can be seen in the hysteresis loop which is a relationship between the magnetic field strength (H) and the induced magnetic field (B). Measuring the hysteresis of a fluxgate magnetometer is important because the uniqueness of each magnetometer makes them difficult to model. In this project I am taking laboratory measurements from a fluxgate magnetometer to determine its hysteresis loop. Future projects will use this data and a similar setup of the SWFO-L1 magnetometer to compare to existing models and create a performance model.
# Table of Contents

Abstract ....................................................................................................................................................... 2  
Background and Literature Review ........................................................................................................... 4  
Design Problem and Objectives .................................................................................................................. 6  
Individual Contribution ............................................................................................................................. 7  
MultiSim Test Plans and Results ................................................................................................................. 7  
Laboratory Test Plans and Results .............................................................................................................. 10  
Bill of Materials ........................................................................................................................................ 12  
Future Efforts ........................................................................................................................................... 13  
Conclusions .............................................................................................................................................. 13  
Bibliography ............................................................................................................................................ 14  
Appendices .............................................................................................................................................. 16  
  Circuit Tutorial ......................................................................................................................................... 18
Background and Literature Review

One essential part of the exploration of space includes predictions of the sun’s behaviour. The purpose of this work with the magnetometer for the SWFO-L1 mission is to predict the consequences of the sun’s behaviour. One example where the magnetometer may be useful is in the detection of a Coronal Mass Ejection (CME) at L1, where it can give useful information about how much time before it will arrive at the Earth and if the consequences will be severe enough to warrant turning satellites off. With more accurate measurements of the solar magnetic field, more accurate conclusions can be made. There are multiple devices that can measure magnetic fields, including fluxgate, search coil, pumped, and nuclear precession magnetometers. Pumped and nuclear precession magnetometers are scalar magnetometers which measure the magnetic field magnitude, and fluxgate and search coil magnetometers are vector magnetometer which measures the three components of the magnetic field. Fluxgate magnetometers are the most accurate and least power consuming devices to use for magnetic field measurements in space. This technology has been used from the first fluxgate magnetometer in space on the Soviet satellite “Sputnik 3” in 1958, to very recent space exploration missions such as NASA’s Parker Solar Probe (PSP), which was the first satellite to enter the upper atmosphere (the corona) of the sun on December 14th, 2021.

While this project is specifically for the SWFO-L1 mission, UNH has been involved in multiple missions and sounding rockets where fluxgate magnetometers have been and currently are being used. One example that UNH is involved in where fluxgate magnetometers are being used is on-board the Parker Solar Probe. There were four major scientific instruments, including the Solar Wind Electron Alpha and Protons investigation (SWEAP), the Integrated Science Investigation of the Sun (ISIIS), the Wide-field Imager for Solar Probe Plus (WISPR), and the FIELDS instruments. The FIELDS instruments include two fluxgate magnetometers, which will contribute to measuring DC and fluctuation magnetic and electric fields, plasma wave spectra and polarization properties, spacecraft floating potential, and solar radio emissions. Specifically, the fluxgate magnetometers will measure the magnetic field at the sources of the fast and slow solar wind to study the coronal processes that lead to heating of the solar corona and understand why the temperature of the solar corona is significantly higher than the temperature at the surface of the sun.

The purpose of fluxgate magnetometers is to measure external magnetic fields, and primarily the constant or very slowly changing component of the magnetic fields. Since the invention of the fluxgate magnetometer in 1936, there have been many modifications to the initial design, especially in the core design. Historical designs have included rod cores, wire cores, tube cores, racetrack cores and the now well-established ring core design.

Racetrack cores were popular up to about the 1980s but are now rarely used because of the difficult manufacturing process. When low power consumption, great stability and low noise levels are required, they still have some space applications but due to the shape of the core, the excitation coil must be hand wound. The difficult manufacturing process makes the racetrack core much more expensive and today the ring core is the most commonly used design.
The basic design of a fluxgate magnetometer consists of four components: a core material, an excitation coil (drive coil), a pickup coil (sense coil), and a feedback coil (null coil). Every magnetometer core is unique due to ferromagnetic properties. The principle of the fluxgate magnetometer operation starts with a signal generator, which provides an AC current in the excitation coil (see Figure 1). That causes a magnetomotive force, which will result in a time dependent magnetic field strength \( H \), that is proportional to the current \( I \), and may be calculated as seen in Equation 1. The current through the coil induces magnetic flux, \( B \), in the ferromagnetic core material. The induced magnetic field \( B \) generates EMF in the pickup coil, which is proportional to the time rate of change of the induced magnetic field \( B \), as given by Equation 2. The frequency of the output voltage is a harmonic of the drive frequency of the AC current provided in the excitation coil. Sometimes, an additional feedback coil is used as a control signal to compensate for the ambient magnetic field. The current in the feedback coil is then adjusted until the even harmonics of the input signal disappear.\(^{18}\)

One very complex and interesting physical aspect of the magnetometer is the hysteresis loop that comes from the ferromagnetic properties of the core material. After removing any external magnetic fields, magnetic materials have the property that a remaining magnetization is still present, and the alignment is retained. This phenomenon is called remanence and that is the reason for the formation of a hysteresis loop when relating the induced magnetic field \( B \) and the magnetic field strength \( H \). The function has a multivalued character that is due to the remanence of the ferromagnetic material. It is necessary to measure the hysteresis loop to learn more about the noise and energy loss properties of the magnetometer and it can also be used to tune a model for the specific fluxgate magnetometer.
A ferromagnetic material consists of atomic magnetic dipoles. Even in the absence of an external field, the dipoles are spontaneously oriented parallel to each other. The magnetization curve for a ferromagnetic material is the relationship between the internal magnetic field (B) in the material and the external magnetic field (H) starting from zero initial fields, where B and H are obtained from Equation 1 and Equation 3 respectively. As the internal magnetic field (B) reaches saturation, the field will not return along the magnetization curve when the external field (H) is decreased, but rather hit the vertical axis ($H = 0$) close to the saturation value (see Figure 2). When the external magnetic field is reversed ($H < 0$), the internal magnetic field is reversed and reaches negative saturation. Once the saturation is reached, the hysteresis curve is unique for every core. Permanent magnets are characterized by a “fat” hysteresis loop and ferromagnetic materials that are subjected to alternating fields, such as the fluxgate magnetometer core, must have a “thin” hysteresis loop to limit the energy loss per circle. The energy loss is determined by the area enclosed by the hysteresis loop and is due to the magnetization and demagnetization of the core as AC current is flowing in the excitation coil. The area represents the energy to complete one full circle of magnetization and demagnetization of the core.\(^{x}\)

While it is possible to model the magnetic hysteresis, the model will probably not be a good match to the hysteresis loop created from the magnetometer data. For the model to be more accurate, it must be fitted to the data. Due to the uniqueness of every core material, it is important to measure the hysteresis loop and compare it to the model.

**Design Problem and Objectives**

To make more precise and accurate measurements in space, it is essential to develop the scientific instruments on Earth before using them for space research. The intention of this project is to make a fluxgate magnetometer performance model to be able to create a good representation of future missions with certain requirements in noise, dynamic range, and accuracy.
The intended objectives of the project can be split into three parts, where each step builds off the other. The first part is to create an analytical model of the fluxgate magnetometer hysteresis loop, noise, and performance. This will be done in a computer programming software such as Python or MATLAB. There are two commonly used models to account for the hysteresis phenomenon, known as the Preisach and Jiles-Atherton models, respectively. Another student was working on this part of the project and was using the Preisach model.

The second part of the project is to perform laboratory measurements of the hysteresis loop by designing, purchasing, building, and testing a fluxgate magnetometer circuit.

The final objective of the project is to compare the hysteresis loop of the analytical model to that of a ring core magnetometer to evaluate and tune the model. The hysteresis circuit and model can then be applied to the SWFO fluxgate magnetometers, which are currently under development. With the hysteresis loop, the fluxgate magnetometer performance can be modelled by flying a virtual spacecraft through a simulation or model magnetic field (IGRF magnetic field\textsuperscript{[10]}) to get the external magnetic field. From the hysteresis loop it is then possible to get a performance model which will take into account noise, dynamic range and accuracy, and which may ultimately be used to improve magnetometer measurements for future missions.

**Individual Contribution**

Useful skills for this project include knowledge in programming language, and electricity and magnetism. While it is for another student to focus on creating an analytical model of the hysteresis loop, noise and performance in a computer programming language, my contributions consist of modelling the fluxgate magnetometer in an RLC circuit representation and to set up and take measurements from the fluxgate magnetometer in the lab.

**MultiSim Test Plans and Results**

To perform an RLC representation of the fluxgate magnetometer, the MultiSim software was used. The excitation coil may be modelled with a voltage source providing AC current going through a resistor, a capacitor, and an inductor (see Figure 3). The resistor represents the resistance in the copper wire, the capacitor represents the inter-winding capacitance, which is caused by the adjacent wires in the coil, and the coupled inductor represents how the magnetic field in the core induces a current in the pickup coil. The alternating current in the excitation coil creates an induced magnetic field in the core, which results in EMF in the pickup coil. The system of the excitation coil, the ferromagnetic core material and the pick-up coil may be represented by a coupled inductor between the excitation and the pickup coil. A simplified initial model of this can be seen in Figure 3 and it was inspired from the general fluxgate magnetometer block diagram in Figure 10.
The signal generator on the left side of the circuit is generating an AC current, which creates a magnetomotive force, a magnetic field strength (H), and an induced magnetic field (B) in the core. The induced magnetic field (B) generates EMF in the pick-up coil, and hence the coupled inductor is used between the excitation coil representation and the pick-up coil representation. Similar to the excitation coil, the pickup coil can be modelled as an RLC circuit where the resistor represents the small resistance in the wire, the capacitor represents the inter-winding capacitance caused by the adjacent wires in the coil, and the inductor represents the induced current in the coil.

To incorporate hysteresis in the circuit representation, a voltage hysteresis block is used. The oscilloscope in the circuit is used to measure and visually see the input and output voltage. By using Equation 3 and Equation 1 respectively, the induced magnetic field (B) and the magnetic field strength (H) can be calculated and a relationship between the induced magnetic field and the magnetic field strength can be represented in a hysteresis graph.

To determine the individual values of the resistors, capacitors and inductors in the representation, a lumped model can be used. The individual values are given by Equation 4 for the resistance, Equation 5 for the capacitance, and Equation 6 for the inductance. These values are dependent on properties of the coils and the circuit and can be obtained from measurements and specifications of the fluxgate magnetometer in the laboratory and is documented in Table 2.

In addition to the initial MultiSim model of the fluxgate magnetometer, other components in the circuit were added. The $C_{\text{integrator}}$ and the $R_{\text{integrator}}$ components were added to integrate the voltage in the pickup coil to give the magnetic field as given in Equation 2. The circuit diagram with the excitation coil, the pickup coil, the core, the hysteresis block and the calculated resistor, capacitor and inductor values based on the circuit in the lab can be seen in Figure 4 and a summary of the component values can be found in Table 2. The input signal is measured in channel B of the oscilloscope and gives a sine wave, and the integrated output voltage is measured in channel A of the oscilloscope, and the graphs is plotted in Figure 5. By plotting channel A versus channel B, a hysteresis graph can be seen in Figure 6.

Figure 3. Initial model of a fluxgate magnetometer RLC circuit representation
Figure 4. MultiSim circuit representation of the fluxgate magnetometer

Figure 5. Channel 1 and Channel 2 versus time as sine waves in the oscilloscope view in MultiSim

Figure 6. Channel 1 versus Channel 2 in the oscilloscope view in MultiSim
Laboratory Test Plans and Results

Laboratory test plans include building the fluxgate magnetometer circuit, where the focus is to model the core. A more detailed tutorial of how to set up the circuit, run it and capture the data using the Digilent-AD2, can be found in Figure 12, Figure 11, Figure 13, Figure 14, Figure 15 and Figure 16 in the Appendices. After initial caliper measurements of the core thickness, inner and outer diameter, the excitation coil windings around the ring core were made by hand. To make this task less time consuming and for the purpose of getting a model to start with, initial number of windings for the excitation coil were limited to 50 turns. For simplicity, the number of windings for the pickup coil were also set to 50 turns. After trials where the two windings were connected due to cracks in the wires, methods of how to insulate the two wires from touching each other were discussed. After considering 3-D printing a shell for the core to wind the pickup coil around, the solution that was chosen was to put electric tape around the excitation coil (see Figure 7). To measure the connection of the ends of the different wires, a voltmeter was a quick approach to troubleshoot potential problems in the circuit.

![Figure 7. Ring core with excitation coil covered by electric tape to create an insulating layer to the pickup coil which is visible in the image.](image)

After overcoming the issues of windings in the core, it was possible to create a graph representation of the induced magnetic field versus the input signal but there was no hysteresis present. To increase the magnetic field to drive the core into saturation and get a hysteresis loop, the decision to switch to a pre-wound core was made. By doing this, it was possible to get a greater number of excitation coil windings and a stronger magnetic field strength as given by Equation 1. To further increase the current, the value of the resistor \(R_1\) in the circuit was decreased. The resulting relationship between the input signal and the output signal can be seen in Figure 8.
During the laboratory measurements, a voltage generator was used to provide an input signal to the excitation coil and an oscilloscope was used to visually observe the output signal. For a more effective way to express the result and to import the data to a computer, the Digilent-AD2\textsuperscript{xiii} and the WaveForms software were used. The measurements from this can be seen in the WaveForms oscilloscope in Figure 9. In the hysteresis loop, a non-linear behavior was seen but it was not reaching saturation. The maximum voltage from the power supply was 5V, which created a current with a magnitude in the mA range in the excitation coil. To drive the fluxgate magnetometer into a saturated hysteresis loop, the power given by Equation 9 as a function of the current and the voltage would have to be increased. The main problem was that even though the power supply could provide a high voltage, it would have to generate a current closer to 10-15A for a hysteresis loop to be shaped.

Figure 8. Hysteresis loop with input signal of 10V and resistor value, $R_1$, of 25$\Omega$.

Figure 9. The left graph is showing the input (yellow) and the output (blue) voltages versus time with a 2.1V, 8kHz voltage generator. The right graph is the hysteresis loop formed by plotting the input versus output signal for the fluxgate magnetometer.
One solution that was investigated to increase the current in the coil was to create resonance in the circuit with the induction coming from the coil and adding a capacitor in parallel. The value of the capacitor to create resonance in a circuit is given in Equation 8. By connecting the capacitor in parallel with the inductor (the coil), the response of the circuit will peak at the resonance frequency. By creating resonance in the circuit, the signal will become greater, and the hysteresis loop will be visible. This approach turned out to be more complicated than expected, as the system is complicated with the pickup coil adding additional capacitance and inductance in the circuit. To determine the correct resonant value, the general Equation 8 to create resonance would not be accurate and more work is necessary to continue this project and the method would include trial and error to figure out the capacitor value to make the circuit resonant.

Another potential solution to the current limitation problem was to use a more powerful DC power supply and a transformer to step up or step down the current. To do this, transistors and resistors would be used. One possible solution to increase the power in the circuit could be to use a Variac power supply, where the AC voltage can be controlled by the transistor. By plugging the Variac into a wall outlet, the AC voltage can easily be adjusted by a knob on the Variac, and it can range both below and above the outlet voltage of 120V.

**Bill of Materials**

Materials used in this experiment can be seen in Table 1. Most of the materials were already provided in the lab and did not need to be bought specifically for this project.

<table>
<thead>
<tr>
<th>Material</th>
<th>Model</th>
<th>Quantity</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Electric tape</td>
<td>-</td>
<td>1</td>
<td>$5</td>
</tr>
<tr>
<td>Resistors</td>
<td>30Ω, 10kΩ</td>
<td>2</td>
<td>$1</td>
</tr>
<tr>
<td>Capacitor</td>
<td>1nF</td>
<td>1</td>
<td>$1</td>
</tr>
<tr>
<td>Jumper wires</td>
<td>30AWG</td>
<td>12</td>
<td>$5</td>
</tr>
<tr>
<td>Wires</td>
<td>Elektrisola 34/36 AWG</td>
<td>2 m</td>
<td>$10</td>
</tr>
<tr>
<td>Alligator Clips</td>
<td>Mueller #34</td>
<td>4</td>
<td>$10</td>
</tr>
<tr>
<td>Multimeter</td>
<td>Fluke 177</td>
<td>1</td>
<td>$388\textsuperscript{vii}</td>
</tr>
<tr>
<td>Digilent-AD2</td>
<td>410-321</td>
<td>1</td>
<td>$399\textsuperscript{viii}</td>
</tr>
<tr>
<td>Variac power supply</td>
<td>-</td>
<td>1</td>
<td>$500\textsuperscript{xx}</td>
</tr>
</tbody>
</table>

*Table 1. Bill of materials for the laboratory setup of the SWFO-L1 core*
Future Efforts

The prioritized future effort includes to increase the current in the circuit to create a saturated hysteresis loop. The method to achieve this would be a combination of looking more into the Variac power supply, a DC to AC converter and creating resonance in the circuit. Once the current issue is solved, it would be recommended to use a potentiometer to adjust the resistor ($R_1$) value and hence the amplitude of the current to demonstrate when the hysteresis curve is going into saturation. The goal of this project was to create a performance model to use for future missions. Once a saturated hysteresis loop is obtained, the next step is to compare the results to an analytical model to tune the model. This project turned out to be more complex and time-consuming than anticipated due to the issue of limited power supply to the coil.

There is motivation to continue this project to get a tuned model and better be able to predict the consequences of the sun’s behaviour.

Conclusions

Getting saturated hysteresis loop measurements from the fluxgate magnetometer turned out to be more difficult than expected. This project started off by winding the excitation and pickup coils around the magnetometer core. A circuit for the drive circuit with a resistor was created for the induced magnetic field and an integrator circuit with a resistor and a capacitor was created for the magnetic field strength. Trouble-shooting efforts involved increasing the number of windings for the excitation and pickup coils and research parallel resonant circuit components to increase the current in the excitation coil. While it was possible to graph the B versus H relationship, the saturated hysteresis loop was not visible. Future work should be centered around the attempt to increase the power of the circuit which would involve increasing the current in the circuit. This could be done with a combination of a power supply that is not a signal generator such as the Variac, with a DC to AC converter which could be done with a transformer circuit of transistors and resistors, and by creating resonance in the circuit by adding a capacitor. There is clearly motivation to continue this project as it is directly applicable to the SWFO-L1 mission as well as other future missions carrying fluxgate magnetometers.
Bibliography


Appendices

\[ H(t) = \frac{l(t)w_1}{l_c} \]

Equation 1. Magnetic field strength as a function of time. \( I \) is the amplitude of the input current, \( w_1 \) is the number of turns of the excitation coil, and \( l_c \) is the length of the magnetic circuit.

\[ u(t) = -w_2 \frac{d\Phi}{dt} = -w_2 s \frac{dB}{dt} \]

Equation 2. EMF in the pick-up coil as a function of time. \( w_2 \) is the number of turns in the pickup coil, \( \Phi = B \times s \) is the magnetic flux in the core, and \( s \) is the cross-sectional area of the fluxgate core.

\[ B(t) = \int_0^t \frac{u(t)}{-w_2 s} dt \]

Equation 3. Induced magnetic field in the core material as a function of time.

\[ R_1 = \rho_c \frac{l_w}{\pi d^2} \]

Equation 4. Resistance in the lumped value of the fluxgate model, where \( \rho_c \) is the electrical resistivity of the coil wire, \( l_w \) is the length of the coil wire, and \( d \) is the radius of the wire.

\[ C_l = \frac{4\pi^2 \varepsilon_0 (b + a)}{\log \left( \frac{b + a}{b - a} \right)} \]

Equation 5. Capacitance in the lumped value of the fluxgate model, where \( a \) is the internal radius of the coil, and \( b \) is the external radius of the coil.

\[ L_1 = \frac{\mu_0 N^2 d_{rc} \log \left( \frac{b}{a} \right)}{2\pi} \]

Equation 6. Inductance in the lumped value of the fluxgate model, where \( N \) is the number of turns, \( d_{rc} \) is the diameter of each loop in the coil, \( a \) is the internal radius of the coil, and \( b \) is the external radius of the coil.

\[ f = \frac{1}{2\pi RC} \]

Equation 7. Frequency/resistor/capacitor relationship for circuit integration.

\[ C = \frac{1}{4\pi^2 f^2 L} \]

Equation 8. Series capacitor value to achieve resonance in the series.

\[ P = IV = R l^2 \]

Table 2. Component values for the fluxgate magnetometer representation

<table>
<thead>
<tr>
<th>Component</th>
<th>Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core internal radius (a)</td>
<td></td>
<td>0.0226m</td>
</tr>
<tr>
<td>Core external radius (b)</td>
<td></td>
<td>0.0276m</td>
</tr>
<tr>
<td>Electrical resistivity of coil wires ($\rho_c$)</td>
<td>Theoretical value</td>
<td>17.2nΩm xxii</td>
</tr>
<tr>
<td>Length of excitation coil ($l_w$)</td>
<td>Measured</td>
<td>0.5m</td>
</tr>
<tr>
<td>Length of pickup coil ($l_w$)</td>
<td>Measured</td>
<td>0.5m</td>
</tr>
<tr>
<td>Radius of excitation coil wires (d)</td>
<td>36 AWG</td>
<td>0.0635mm</td>
</tr>
<tr>
<td>Radius of pickup coil wires (d)</td>
<td>34 AWG</td>
<td>0.0800mm</td>
</tr>
<tr>
<td>Number of turns of excitation coil</td>
<td>Estimated using inner circumference of core</td>
<td>800 turns</td>
</tr>
<tr>
<td>Number of turns of pickup coil</td>
<td>Wounded by hand</td>
<td>50 turns</td>
</tr>
<tr>
<td>Diameter of each loop in excitation coil ($d_{rc}$)</td>
<td>Estimated based on core thickness</td>
<td>0.005m</td>
</tr>
<tr>
<td>Diameter of each loop in pickup coil ($d_{rc}$)</td>
<td>Estimated based on core and tape thickness</td>
<td>0.007m</td>
</tr>
<tr>
<td>$R_{\text{excitation coil}}$</td>
<td>Equation 4</td>
<td>0.679Ω</td>
</tr>
<tr>
<td>$R_{\text{pickup coil}}$</td>
<td>Equation 4</td>
<td>0.428Ω</td>
</tr>
<tr>
<td>$C_{\text{excitation coil}}$</td>
<td>Equation 5</td>
<td>18.2pF</td>
</tr>
<tr>
<td>$C_{\text{pickup coil}}$</td>
<td>Equation 5</td>
<td>18.2pF</td>
</tr>
<tr>
<td>$L_{\text{excitation coil}}$</td>
<td>Equation 6</td>
<td>0.217µH</td>
</tr>
<tr>
<td>$L_{\text{pickup coil}}$</td>
<td>Equation 6</td>
<td>77.8µH</td>
</tr>
<tr>
<td>$R_{\text{integrator}}$</td>
<td>Equation 7</td>
<td>10kΩ</td>
</tr>
<tr>
<td>$C_{\text{integrator}}$</td>
<td>Equation 7</td>
<td>1nF</td>
</tr>
<tr>
<td>$R_1$</td>
<td></td>
<td>30Ω</td>
</tr>
</tbody>
</table>
Figure 11. Circuit diagram for the fluxgate magnetometer

Figure 12. Laboratory setup for the excitation coil (left) and pickup coil (right) circuits
To use the Digilent-AD2, the software WaveForms is necessary and free to download. The color combination for the Digilent-AD2 can be seen in Figure 13, where the Scope Channel 1 and 2, the Wave Generator and Ground color probes was used.

![Figure 13. Digilent-AD2 color probe diagram](image)

To create a signal input and to add an oscilloscope, the Wave Generator respectively the Scope functions in WaveForms were used as demonstrated in Figure 14.

![Figure 14. Instructions of how to add a Wave Generator and an Oscilloscope from the WaveForms start page](image)

In the Scope tab, the default graph is plotting the Oscilloscope Channels 1 and 2 versus time, but by adding a graph of Channel 1 versus Channel 2, we can see the hysteresis loop. The process to add the additional graph is demonstrated in Figure 16. After setting the preferred AC voltage amplitude and frequency settings in the Wave Generator tab (see Figure 15), the
signal and the oscilloscope is being run once the green buttons is hit as seen in Figure 16. The resulting output can be seen in Figure 9.

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**Figure 15.** Screen capture of how to adjust the AC voltage amplitude and frequency

**Figure 16.** Instructions of how to add a Channel 1 versus Channel 2 graph from the Scope start page and how to start the simulation

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VARIAC, Portable, 120VAC Input, 0-140V Output. ISE. (n.d.). Retrieved May 3, 2022, from https://iseinc.com/_shop/variabletransformers/variac-portable-units/variacportable120vacinput0-140voutput/?pageId=2

VARIAC, Portable, 120VAC Input, 0-140V Output. ISE. (n.d.). Retrieved May 3, 2022, from https://iseinc.com/_shop/variabletransformers/variac-portable-units/variacportable120vacinput0-140voutput/?pageId=2
