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Non-Invasive Detection of Faults in Power Lines

A Major Qualifying Project Report:

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Abstract

The goal of this project was to design a product that could detect faults in a transmission line system and relay that information back to a control center. To accomplish this, pickup coils were installed in the proximity of the transmission lines and were used to monitor the magnetic fields produced by the lines' currents. Theoretical and actual simulations were completed successfully and demonstrate that it is possible to determine with great accuracy the type and time of the fault.

Acknowledgements

We would like to thank our advisor, Professor Alexander Emanuel, for his guidance throughout the course of this project. He helped us immensely with both the technical and administrative aspects of our work. Without his advice and supervision, this project would not have been possible. We would also like to thank all of our friends and family for their love and support.

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$\hat{V}$ = Peak voltage sensed by the coil

N = Number of turns in each coil

A_e = Effective area of the coil

l = Length of each side of the coil

μ_0 = Permeability of air

d = Coil's distance from the conductor

$\hat{I}$ = Peak current through the conductors

ω = Frequency (in radians) of signals

B = Magnetic flux density

φ = Magnetic flux

θ = Phase angle of the signals

L = Length to the conductor

h = Height from the conductor

Introduction

This report outlines all the aspects of the design and implementation process for creating a non-invasive way to detect of faults in a power system. Although this may not be the only way to accomplish this task, it is an effective and efficient way. There are many additional features that could have been added to optimize its performance, but to keep the cost down, this method was chosen.

The report begins with background information to better understand the need for a product like this. The process of energy delivery from the power plants to the end user is briefly discussed as well as the magnetic fields produced by the current carrying conductors. The methods used to construct this device will be more understood from this knowledge.

A market analysis was done to ensure the originality of this device. The market analysis was also used as a guideline for determining specifications and features. Another resource used for determining the specifications and features was the customer requirements. Multiple companies were surveyed to determine the ultimate design of the product. The survey included questions about maintenance, cost and additional features. From this research the final design specifications were determined and an analysis to the competition was done.

Once the specifications were determined the design of the product had to be completed. An outline of each module's design is included in the report. The majority of the original designs did not perform optimally so testing and redesigning was done until its functionality was acceptable. The results from the simulations can also been seen in this report.

The last part of this report was to complete a cost and failure and hazard analysis. Knowing the actual parts that were used in the product and assuming that in mass production the costs would be slightly less, a manufacturing and selling price were determined. These numbers were compared to the competition to see how the product would do in its market. The failure and hazard analysis is also a good this to know before using this product.

A timeline is very essential tool to making sure the project finishes on time and is not rushed near the deadline. The timeline set for this project can be seen in Appendix II. This timeline was set according to approximations of the detail required, difficulty and amount of errors that may occur in each step. This is the ideal timeline however unexpected issues may occur and delay a few of the steps. Extra time was allotted at the end of the project for any unexpected issues.

Problem Statement

The product to be designed will be a self-sustaining, all-in-one unit. It will be able to power itself while consistently monitoring the electromagnetic fields around the power lines above. It also will have the ability to transmit the presence of faults to the operator of the power system. The entire unit must be designed so that all of these functions can perform accurately and reliably for very long, extended periods of time. The sensing of the electromagnetic fields will be done via inducting coils wrapped around cubes. Multiple coils will be used because numerous conducting lines will all generate individual electromagnetic fields that will interfere with one another. The multiple coils, which detect fields in different directions, allow for enough data to determine the condition in all of the conducting wires. With that information, faults can be detected instantaneously without any equipment interfering with the monitored system itself.

Background Research

To truly understand the need for this product, the knowledge of where power lines come from and their need must be comprehended. This section of the report briefly describes the process of delivery the energy from the power plants to the end users of that power. The current technique used for detecting faults in the system is also briefly discussed. The next subsection discusses the magnetic fields that are produced by these current carrying conductors. The magnetic fields that are produced enable the ability to determine the actually current running through the conductors and from that establish any faults in the system. Some important calculations can also be seen in this section.

Power Lines

Electrical power lines are used to distribute electricity from power plants to the end consumers. The process is broken down into two main steps, transmission and distribution. The electrical power is generated at the power plants, stepped up and are then carried through transmission lines. That electrical power is then stepped down and carried through distribution lines and delivered to consumers.

Transmission lines are responsible for getting electricity from the power plants to substations near populated areas. Power plants generate three-phase alternating current (AC) therefore three lines, known as conductors, are required to carry this electric power. They are extreme high voltage lines which are generally classified as anything over 110 kV. Lower voltages such as 69 kV are considered sub transmission and anything under that is used for distribution. In the United States a typical maximum transmission line distance is about 300 miles traveling between 60 and 140 feet in the air.

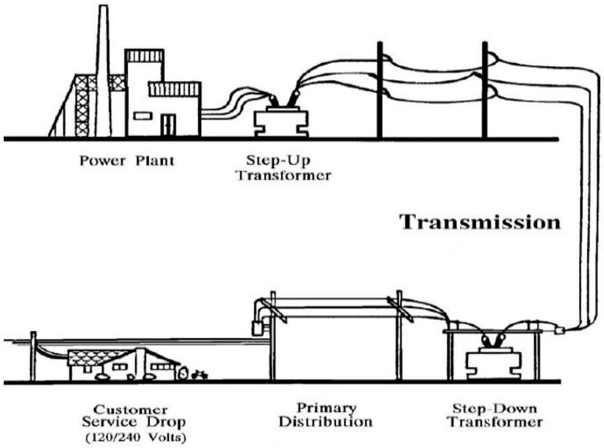


Figure 1: Simplified Electric System

Transmission lines end at power substations where their voltages are then stepped down to be carried by distribution lines. The substations also contain busses to split the power off into multiple directions and circuit breakers in order to disconnect a line when necessary. Distribution lines are used to get electricity from the substations to the end consumers. Typical voltages for distribution lines are anywhere between 35kV and 110 volts. Things such as regulator banks are used to help control the level of this voltage. These lines are generally shorter lines and are on average 40 feet in the air. Finally the voltage is tapped off to a single phase and stepped down one last time to be delivered to houses at 120/240 volts.

Electricity can be distributed through overhead power lines as seen in Figure 2 or through underground power lines in densely populated areas, such as New York City. Both overhead and underground systems are highly complex and have a large number of components. Because of the complexity of the systems there is a great deal that can go wrong and cause damage to the system or the consumer’s property. These systems have many protective devices such as covered conductors, insulators, and circuit breakers, but it is impossible to protect against everything.

Figure 2: Overhead Electrical Power Lines

Magnetic Fields

Electromagnetic fields (EMFs) are regions of space through which energy passes that has been created by electrically charged particles. EMFs are produced by things such as power lines, electrical appliances, radio waves and microwaves. Two types of fields are produced, electric and magnetic. Electric fields result from the strength, or voltage, of the charge and magnetic fields result from the motion, or amperage, of the charge.

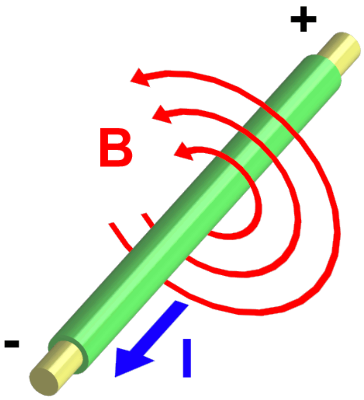


Figure 3: Magnetic Field (B) induced from current (I)

For the scope of the project only the magnetic fields produced by power lines will be discussed. When current (I) is run through the conductors, magnetic fields are produced. The magnetic field strength (H) is used in the calculation for the magnetic flux density and is measured in amperes per meter.

$$H = \frac{I}{2\pi d} \tag{1}$$

Using the magnetic field strength from equation 1 and multiplying it by the permeability of air it is possible to determine the magnetic flux density (B). The expression for the magnetic flux density can be seen in equation 3, which is measured in Teslas. The permeability of air has to be taken into effect. Permeability is the measure of the change in magnetic induction produced when a magnetic material replaces air, expressed as a coefficient or a set of coefficients that multiply the components of magnetic intensity to give the components of magnetic induction. The expression for the permeability of air can be seen in equation 2.

$$\mu_0 = 4\pi 10^{-7} \tag{2}$$

$$B = \mu_0 H \tag{3}$$

Once these expressions are known it is possible to put them together to re-express equation 3. Equation 4 is an alternate way of expressing the current seen in equation 1. Equations 1, 3 and 4 are now combined to re-express equation 3.

$$I = \hat{I} \sin(\omega t + \varphi) \tag{4}$$

$$B = \mu_0 \frac{1}{2\pi d} \hat{I} \sin(\omega t + \varphi) \tag{5}$$

Magnetic fields cannot be directly measured however. To measure magnetic fields a voltage must be induced, made by constructing a coil of conducting material, copper in this case. The number of turns in the coil affects the amount of voltage that is induced by any given magnetic field.

In an ideal power system the magnetic field strength should be zero regardless of the large currents passing through the wires. Research has proven that exposure to strong magnetic fields can cause an increased risk of cancer (NCI, 2005). To avoid this, power companies shift the phase in each of the lines by 120 degrees, which allows the magnetic fields to cancel out.

Power System Faults

Faults in a power system can be very damaging and potentially extremely hazardous to power system equipment and property. Faults can occur for a number of different reasons and can also have many different effects depending on the severity of the fault. Many precautions are taken to avoid these faults, but it is nearly impossible to avoid them all.

When a fault occurs in a power system, it is difficult to pinpoint the exact location and cause of the fault, but experts in the field can often decipher this information. If the fault can be cleared by the power company then locating the fault is not a big deal. However if the fault cannot be cleared it becomes much more necessary. If the fault occurs in an urban area line-men can drive along the line until the source is located. If the fault occurs in a more obscure area then alternate techniques must be used. One method that could be used would be a fault locating system (FLS). These systems send signals through the faulty lines in order to determine the location of the fault. Faults can occur from many different types of human or natural disasters such as a car accident knocking over a pole, a bird landing on a non-insulated wire, a tree falling on the wires or failed equipment such as lightning arresters, transformers or switches.

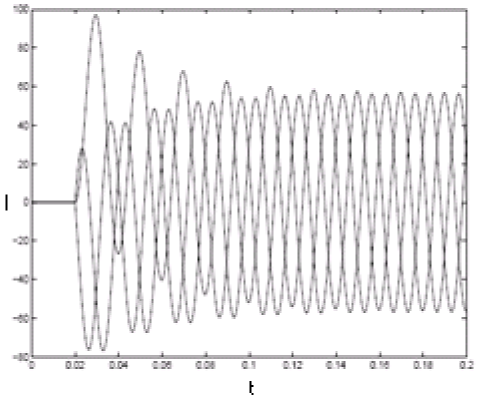


Figure 4: Typical Fault Currents

In a typical short circuit faults, the highest current takes place immediately after the fault occurs. An example of a typical fault can be seen in Figure 4. The largest mechanical force put on the system will also occur at the beginning of the fault; therefore the most damage is done to the system at the initial trip of a fault. It would be ideal to avoid this damage since it could be at a high cost to the electric company and in turn to the end users. In general, power system equipment is rated to be able to handle a current spike of about two and a half times the rms rated value. Even this does not always protect the power system's equipment. To avoid this power companies use protection devices such as fuses and circuit breakers that can trip during faults.

Another issue with faults is thermal stress. With such high currents running through the wires there is a major rise in temperature. These extreme temperatures can cause the conductors to meltdown and be destroyed. Depending on the fault current, material and size of the wire determines the actual time before the conductor will meltdown and be destroyed. This device will not be able to stop the immediate peak currents because it is a non-invasive device and does not have any tie in to the line to stop it, but it will help with the ongoing fault currents. If the power system equipment is not destroyed by the initial peak current, this device will notify the power company about the fault with its conditions.

The initial peak currents can cause a breakdown in insulation and will just require the cable to be repaired. If the fault current is allowed to persist the conductor may be damaged and the cable will then need to be replaced. Also if the fault current persists not only will the conductor be damaged, but other equipment such as circuit breakers, transformers or even generators will be damaged as well. Repairing and replacing a wire is not too costly, but replacing some of the other equipment can not only be costly, but require a long time to repair. When the system is down, customers are out of power and customer satisfaction is down which is never good for the power company.

Fault Conditions

In order to see what is going on inside of the power lines when a fault occurs, computer simulations were run. For this application of power system modeling the computer program PSpice was utilized. In order to get a visual of the system however, Multisim was used for the modeling purposes. The circuit was set up as seen in Figure 5. The resistors and inductors to the right of the first three sensors and to the left of the second three sensors are the resistance and inductance of the conductors on either side of the fault. All faults were simulated between the points 3, 9, 15, and 0. In this case the fault was assumed to be exactly in the middle of the line. The resistance and inductance located at the end of the line were used to represent the electrical load at the end of the line. Three typical 20 kV sources, each 120 degrees out of phase, were set up at the beginning of the line.

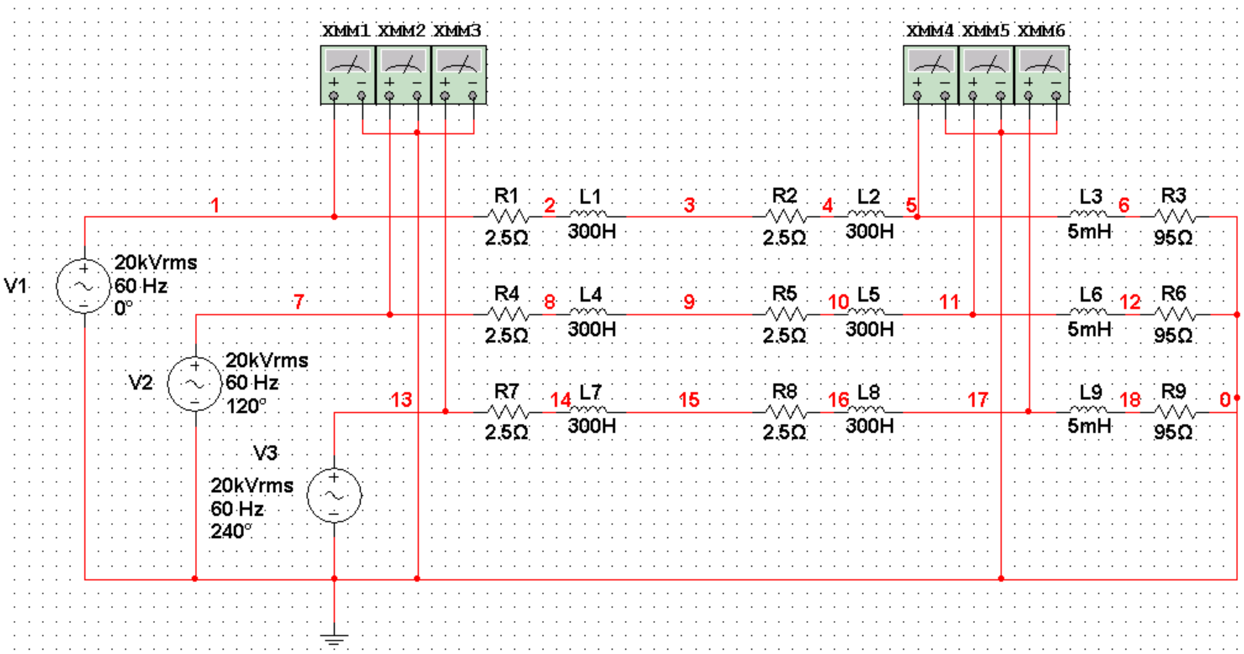


Figure 5: Power Line System Simulation Set Up

Multiple fault cases were tested in order to get a true feel for how different types of faults affect the different lines. The faults that were tested were line to line faults between points 3 and 9, line to line to line faults between points 3, 9 and 15 and a line to ground fault between point 3 and 0. The graph seen in Figure 6 demonstrates how the amperage in the power lines are affected by a line to line fault between points 3 and 9. The first half of both graphs is equal at 200 amperes. At 50 ms, half way through the graph, the top graph has lines A (green) and B (red) dropping down to 100 amperes and becoming in phase. The third line, line C (blue), remains unchanged throughout the fault. The top graph shows what happens in the lines past the fault (the second set of sensors). On the second half of the bottom graph, line A and B jump up to about 6,920 amperes. This graph shows what happens in the lines before the fault (the first set of sensors).

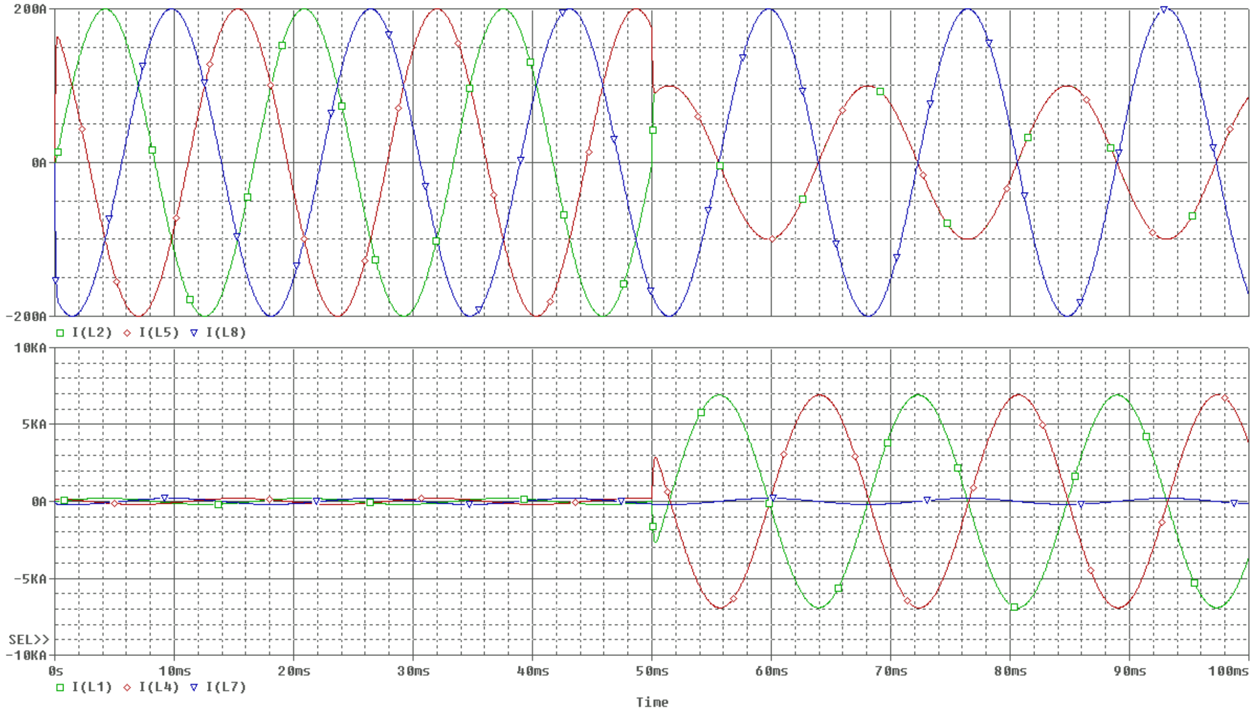


Figure 6: Line to Line Fault Between Nodes 3 and 9

The transition of the fault on the source side can be seen in Figure 7. This graph is the voltage in the X-direction plotted against the voltage in the Y-direction. Under normal operating conditions, 200A in all three lines 120^o out of phase, the inner ellipse is the graph. When the fault occurs the ellipse affected greatly by lines A and B causing a large skew. The transition of the fault on the load side can be seen in Figure 8. All other fault transitions can be seen in Appendix II.

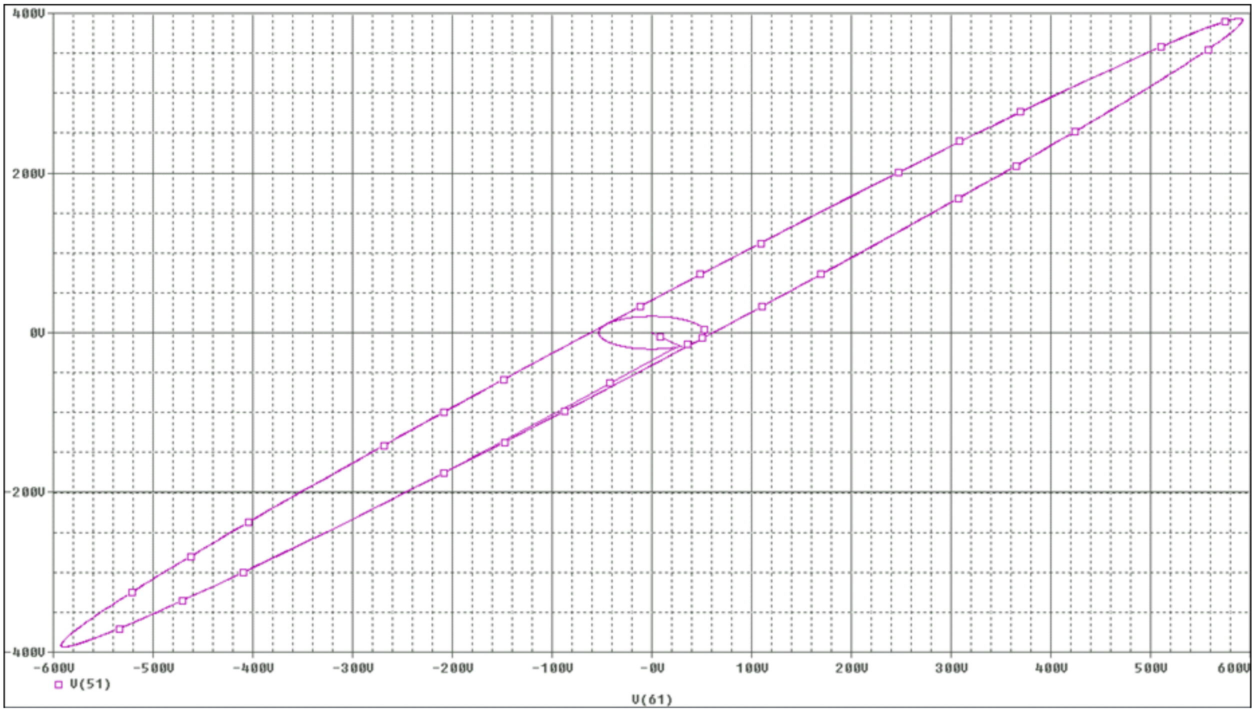


Figure 7: Fault Transition Line A to Line B Source Side

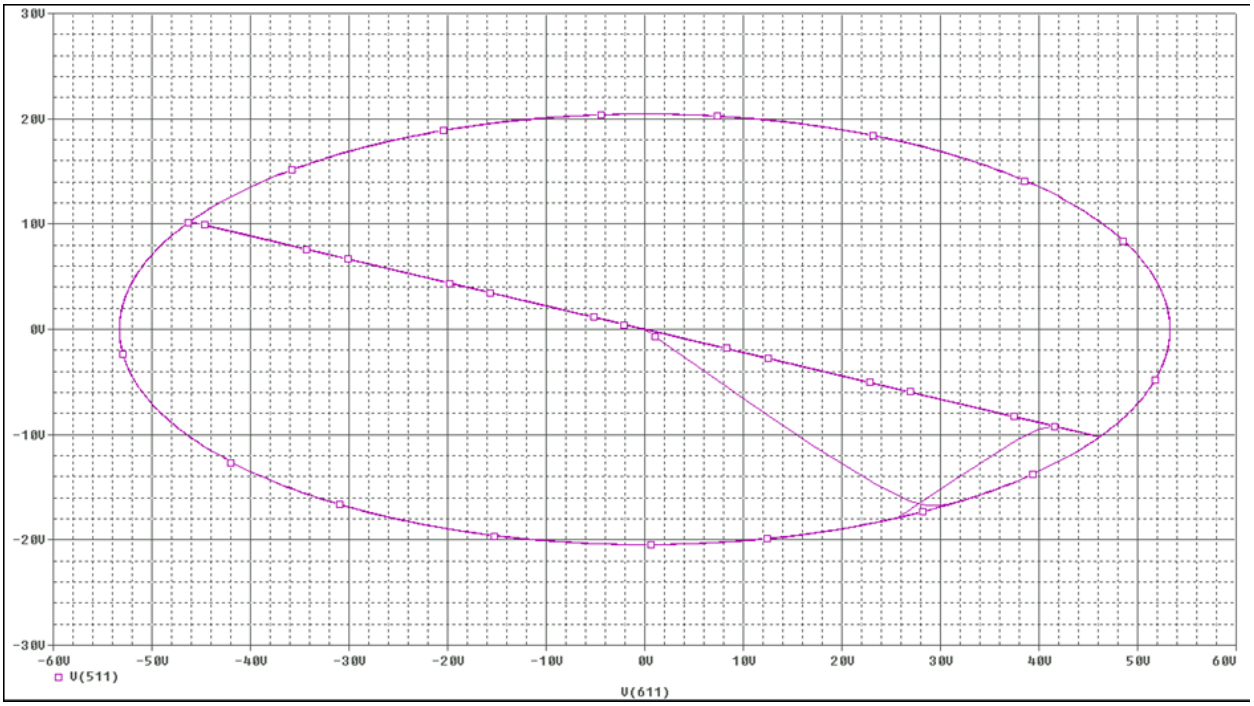


Figure 8: Fault Transition Line A to Line B Load Side

The list of all fault conditions and their corresponding affects on the lines can be seen in Table 1. The simulation set up for a fault 90 percent down the line and the graphs for all other fault conditions can be seen in Appendix I: Fault Conditions for Power System Simulations.

	50% Down the line			**90% Down the line**		
	Before the Fault					
	Line A	**Line B**	**Line C**	**Line A**	**Line B**	**Line C**
Line A to Line B	6,920 A	6,920 A	200 A	3,844 A	3,844 A	200 A
Line to Line to Line	7,990 A	7,990 A	7,990 A	4,440 A	4,440 A	4,440 A
Line to Ground	7,989 A	200 A	200 A	4,439 A	200 A	200 A
	After the Fault					
	Line A	**Line B**	**Line C**	**Line A**	**Line B**	**Line C**
Line A to Line B	100 A	100 A	200 A	100 A	100 A	200 A
Line to Line to Line	0 A	0 A	0 A	0 A	0 A	0 A
Line to Ground	0 A	200 A	200 A	0 A	200 A	200 A

Table 1: Amperage of Fault Conditions

Market Research

This product is being designed for power companies that want a way to monitor their power grid without altering their lines to measure. The device intended would output the characteristics of the power line at its location without being connected to the system at all. Currently, there is no such system available that does what this product is intended for. Therefore, the market research is solely to show that this device would be useful, cost effective, and desirable for companies. This report will demonstrate all of those qualities in its performance.

Market Competition

The only similar products are invasive to the power system, so they don't serve as a solid base for comparison. The product will just have to be appealing to companies. It will have no other product to compete with, but it still must be available at a reasonable cost so that it is more appealing than the less convenient options available for these companies.

The invasive systems are referred to as energy management systems (EMS). It consists of a number of computer tools that aid operators in monitoring, controlling, and optimizing the power grid. The monitoring and control aspects are often referred to as SCADA, which stands for Supervisory Control And Data Acquisition. That term refers to any general monitoring system but applies to EMS, as well. The system will be considered a SCADA system, despite it only performing the monitoring. The companies utilizing the product will obviously still need a control system in place.

These EMS systems currently are in use by most power companies worldwide and are designed by companies like GE and Siemens. They do perform the job that is intended but they are invasive in the grid and that is not ideal for such a system. There is a demand for a non-invasive product in the market.

Similar Technology

There are a number of EMF Detectors on the market however there are no sensors designed to detect faults in a power line system. There are multiple EMF Sensors on the market ranging in price and targeted use. The costs of EMF detectors vary from as little as $30 to over a few hundred dollars. Some EMF detectors such as this personal EMF Alarm can be used for people wearing pacemakers to alert the wearer of strong magnetic fields. The product model can be seen in Figure 10. Other sensors such as the Gauss Master, Figure 9, are used to detect radiation given off from power lines, computers, etc. Again this device is hand held and it is read off of a display on the unit itself. These EMF detectors are also sold for their use in ghost-hunting. The hand-held detectors are common in the market place and many vendors sell them.

Figure 9: Gauss Master

Figure 10: Personal EMF Detector

Customer Requirements

An integral part of designing a new product is to allow the customer, or end user, to have input into the design. In order to assure the products success it must be certain that a customer will purchase the product once it is put into production. In this case the customer will be the electric companies that will mount the device on telephone poles to monitor their current power line systems.

There are multiple ways to get input from customers such as in person interviews, phone interviews, surveys and emails. For this project the most practical way to gather this information was to send out a survey asking the many questions that apply to the scope of the project. In person interviews were also utilized, but the majority of the data came from the surveys.

The survey used for this project can be seen in Appendix III. The purpose of this survey was to get a better understanding of the current methods of detecting faults in power lines and to discover ways that this project could improve that. Questions about the features, pricing, size and maintenance were utilized to gain a better understanding of what would be wanted from the consumers.

Survey Results

The customer survey allowed for the concept of the most ideal product from the perspective of a power company. Several responses were received and they were all very similar. Their similarity was useful, in that it allowed a product design that would fit all of their needs together. The first requirement was the price of the product. Companies did not want to have to invest a lot of money even though they said there was a need for this product. The typical price range that was selected was between $150 and $200.

The next issue was the maintenance of the product. The typical companies did not want to generate any additional work for their workers; therefore a very low maintenance product was desired. A product that would only need to be maintained a few times a year would be ideal. The only maintenance issue would be replacing batteries. If solar panel cells are utilized this would not be an issue and the product would be totally maintenance free.

Along with being maintenance free the product should be durable. If the product is broke very easily, it would also require a lot of maintenance. A product that is weather resistant and can handle the weight of a light animal would be ideal. The product itself was specified to be less than 5 pounds for installation purposes. Also a product that would not fail over time is necessary so companies do not need to replace the product every year.

The safety of workers at power companies is an ongoing and large issue. The product needs to be safe from the installation process to any maintenance that is required. As the product does not require any tie in to the power lines, it is extremely safe. The installation of this product high on a telephone pole is the only concern, but power line workers do this type of work as a profession and have had a lot of experience with this.

The final requirement that the power companies need is accuracy. If the power company is spending money on a product and relying on that product, it must be accurate. If the product is not accurate it may be misleading and not fulfill the intended purpose of it. The companies will not purchase a product that is not accurate.

The customer survey responses were a very good tool to help narrow the scope of this product. By taking the input from power companies, the end users, the product was designed. The overall product design can be seen in the next section of this project. Each individual module is described as well as their performance and results.

Design Approach

Once the product specifications were determined the next step was to design the product. Since the product is fairly complex the report is broken down into each of the different modules of the design. The design of this product was possible from the knowledge gained over the past four years. To truly understand how this product works the understanding of how each module works and how they all connect together. Although each module was individually tested and functioned properly did not mean that once they were all put together that they would still work as well. This section outlines the final design of each module.

Overall System

The overall system should accomplish the task of detecting faults in a power system and when a fault should occur a notification is generated. The different modules include how the device is powered, how the sensors are designed, how that information was processed and how the information will be displayed or sent back to the nearest substation. Each module definition includes circuit design and an explanation of their functionality. Each module's simulations can be found in simulations and results section.

The device should be mounted on a pole a specified distance away from the power lines. As the current is passing through the conductors above they are generating magnetic fields. In order to detect those magnetic fields a sensor was built. After the magnetic fields are sensed they need to be cleaned up in order to have useful information to be able to process. The signal is first sent through an amplifier in order to have a signal with a large enough magnitude for processing. That signal is then filtered to get rid of any excess noise that may be picked up by the sensor coil.

After the signal has been sensed, amplified and filtered it is then ready to be processed. The processing unit will interpret the three input signals in order to determine if there is a fault in the system. The information containing faults and conditions will be then be displayed or relayed to notify the user of the status.

Sensor

The first thing that had to be detected was the magnetic fields coming from each wire. The readings of the magnetic fields can be used to determine the current in each wire. To be able to sense the voltages an inductor had to be built. The inductor reads the magnetic field being produced by each wire. The sensor that was made is a cube with one inch sides and a wire wrapped around the cube one hundred times. Two corners were removed in order to be able to wrap a wire at an angle. The cube is wrapped three different ways: horizontally, vertically and at a 45^o angle all of these coils were wrapped 100 times with a wire that has a gauge of 35 (.142 mm). The setup of the sensor can be seen in Figure 11. The voltage in the x direction can be plotted against the y direction voltage and by looking carefully at this graph faults can be determined.

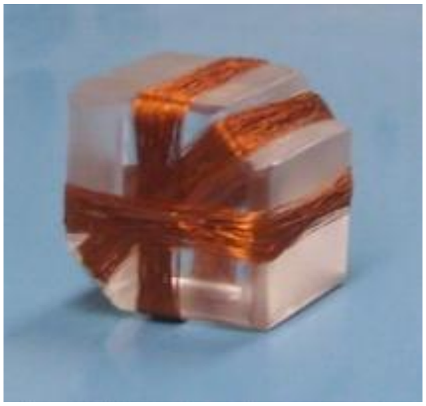


Figure 11: Sensor

Each of these wires read the magnetic field and output a voltage. The voltage is different on each coil because of its orientation to the wire. Each coil has its output amplified and filtered because voltage is very small and quite. The filtered data is what will be processed.

The sensor was the most tested module in this project. The project began with many calculations and computer simulations to figure a way to determine all the needed information from what was being sensed. The next thing to do was to bring the original design up to the lab and run some actual simulations. Due to many inconsistencies this process took a long time and added large delays to the project. The numbers were very different from the computer simulations and calculations therefore many redesigns were done. All of these things can be seen throughout this section of the report.

Filter and Amplifier

The signal coming from the cube is very small and noisy. To remedy this problem an amplifier and filter was built. The signal is first passed through a non-inverting amplifier with a gain of 1960 and then filtered the signal. To design this filter a filter design website was used. The desired characteristics of the filter were entered into the site and it gave multiple choices. The filter used was a second order Butterworth filter. The resistor and capacitor values were given by the site as well. The diagram for the filter can be seen in Figure 12.

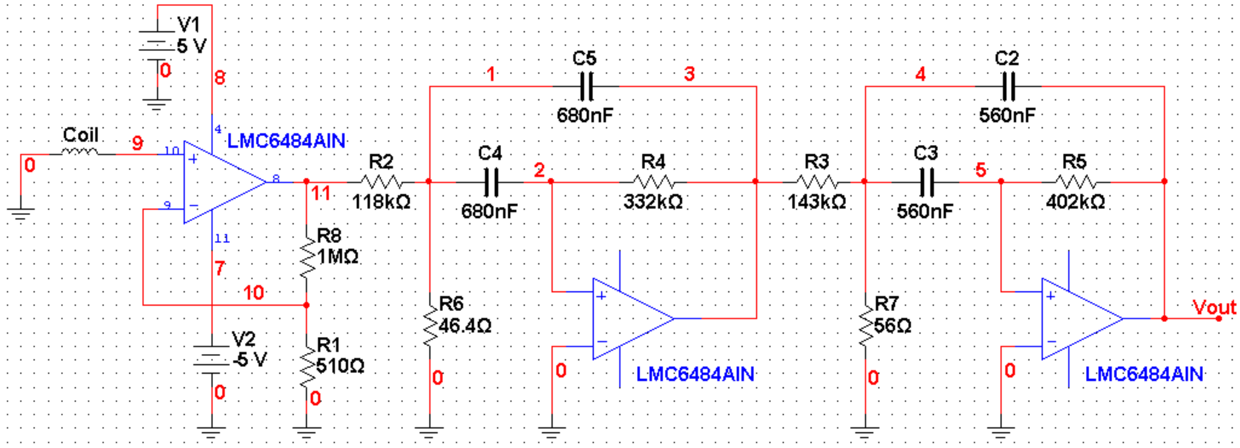


Figure 12: Amplifier and Filter Diagram

Figure 13 shows the implementation of the circuit in the lab. Three circuits had to be built, one for each coil. Each filter was tested extensively to ensure it was accurate as possible.

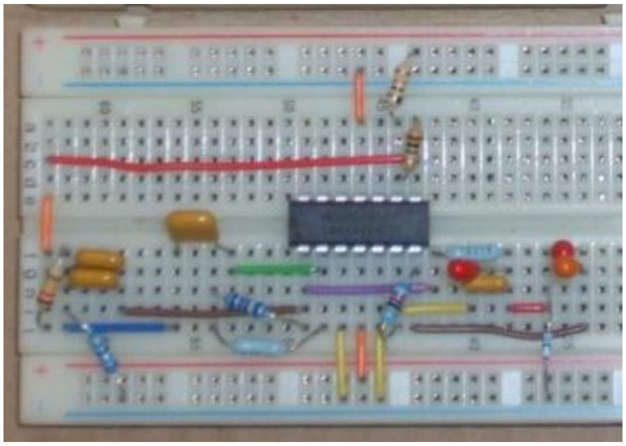


Figure 13: Filter implementation

The frequency response can be seen in Figure 14. The center frequency (Fo) is 60 Hz. The 3dB bandwidth (BW_{3dB}) is 2 Hz. The stop-band attenuation is 5dB. The pass-band flatness is 0.5dB. This response is ideal because the signal is a 60Hz signal and this will greatly reduce the noise that was received giving more accurate and cleaner readings.

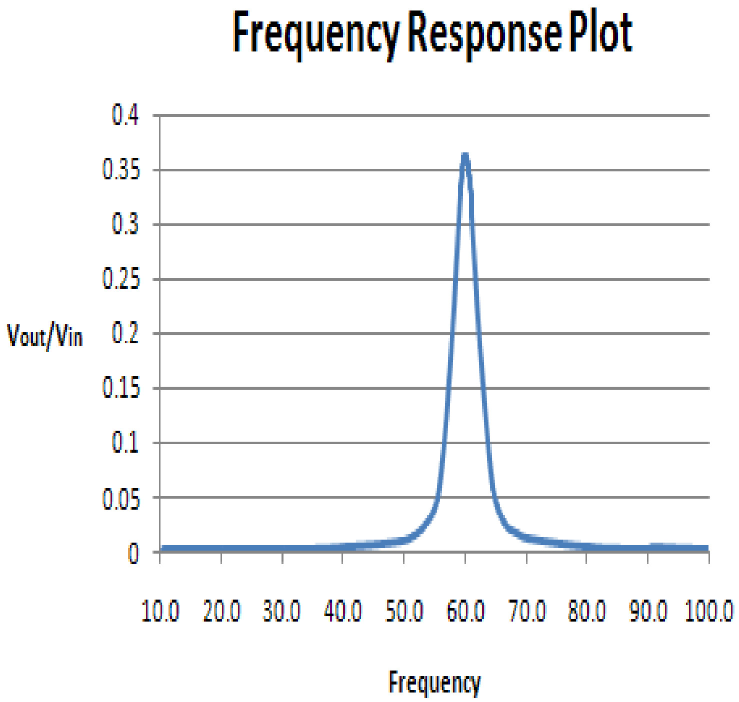


Figure 14: Frequency Response

In lab simulations a signal as small as the one coming from the cube was unable to be produced; therefore the gain of the filter had to be changed to obtain usable output. In this example the gain of the filter used was 100, due to imperfections in the filter the gain is only about 30. This however is acceptable because the filter must reduce the noise as accurately as possible even if the signal is attenuated. A sample output of the filter can be seen in Figure 15.

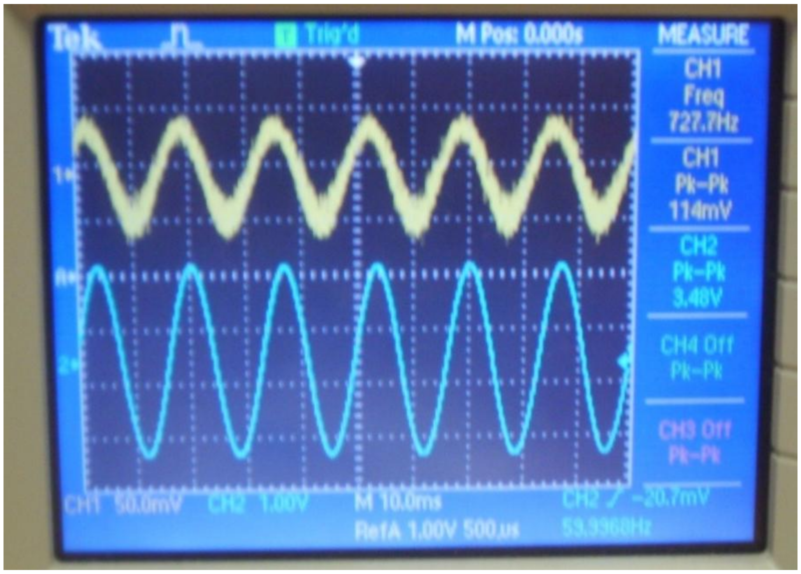


Figure 15: Filtered waveform

Power

The next thing that needed to be designed was the power circuit for the system. Different options were weighed such as batteries, photovoltaic cells and using both together. In the end the system used only batteries to power the system due to time constraints. The system is powered by two 9V batteries. Each battery is connected to a voltage regulator and the voltage is reduced to 5V. This new voltage is used for the +5V and -5V rails which the op-amps of the system use. The processor is bowered by its own 3.3V supply. The circuit for the batteries and regulators can be seen in Figure 16.

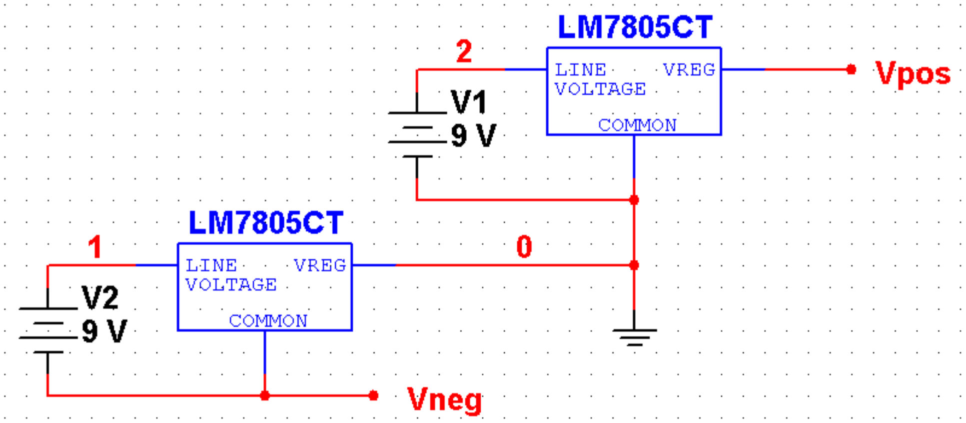


Figure 16: Battery and Regulator Circuit

Ideally the system would be powered by two solar panels. Each solar panel will output 5V allowing the rails to be set to +5V and -5V allowing proper power the filter. This voltage would be regulated to also be able to power the chip. The Voltage-Current Characteristic for a solar panel can be seen in Figure 17. As the voltage needed is increased the current available is reduced. Conversely, as the current needed is increased the voltage available is reduced.

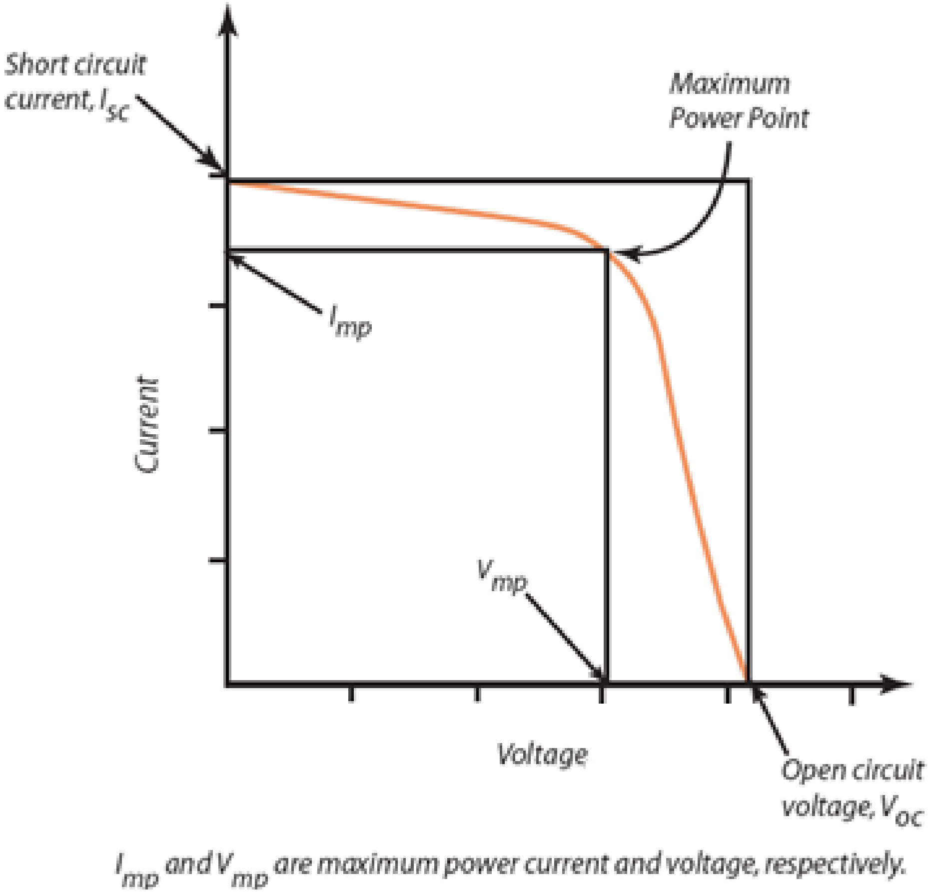


Figure 17: V-I Characteristic

When the sunlight is strong enough the product would be powered by the two solar panels and charge the batteries. When the sunlight is not strong enough the batteries would be used to power the system. This would allow for the product to operate for a long period of time without any maintenance needed.

Processor

The main requirements for this section of the system are low power usage, ease of implementation, and processing capabilities. The processor needs to operate under low power conditions because this unit should ideally be able to run without maintenance for very long, extended times. The solar power and batteries need to be able to power it for, at the least, months.

This module of the design also needs to integrate with the rest of the unit seamlessly. This product requires a lot of precision due to the small scale of the measurements it's making. The level of experience in the group with processors is relatively low so the chip selected must be easy to program and integrate.

The most important requirement for the chip is that it can handle the processing that needs to be done. There will be three sensors, all inputting analog signals. All three of those need to be registered and analyzed in real time. Therefore, the chip must have a capable analog-to-digital converter that can take at least three channels in and analyze them all repeatedly. It must also still have enough spare I/O ports remaining to sufficiently interface with a notification system. The chip that was chosen was the MSP430F449 due to its ample capabilities and the familiarity with it. The chip's capabilities are shown in Table 2 below.

Parameter Name	Value
Architecture	16-bit
CPU Speed (MIPS)	30
Memory Type	Flash
Program Memory (KB)	60
RAM (KB)	2
Temperature Range (°C)	-40 to 85
Operating Voltage Range (V)	1.8 to 3.6
I/O Pins	48
Pin Count	100
Low Power Modes	5
LCD Driver	160 Segments
Digital Communication Peripherals	2-USARTs
Analog Peripherals	1-A/D 8x12-bit
Other Peripherals	Analog Comparator, Hardware Multiplier
Timers	2 x 8-bit, 2 x 16-bit, 1 Watchdog

Table 2: dsPIC30F3012 Specifications

Instead of choosing just a chip, the decision was made to use a development board designed around the chip. The most obvious choice was the Olimex board for the MSP430F449 microcontroller. Its many peripherals built onto the board will allow for a very useful user interface to be programmed. The board has four buttons, an LCD screen, a buzzer, and connector pins built into the board and wired to appropriate ports. Also, the ports available to the ADC were left open for I/O use. Figure 18 is a picture of the development board showing all of its peripherals and the capabilities of the LCD screen.

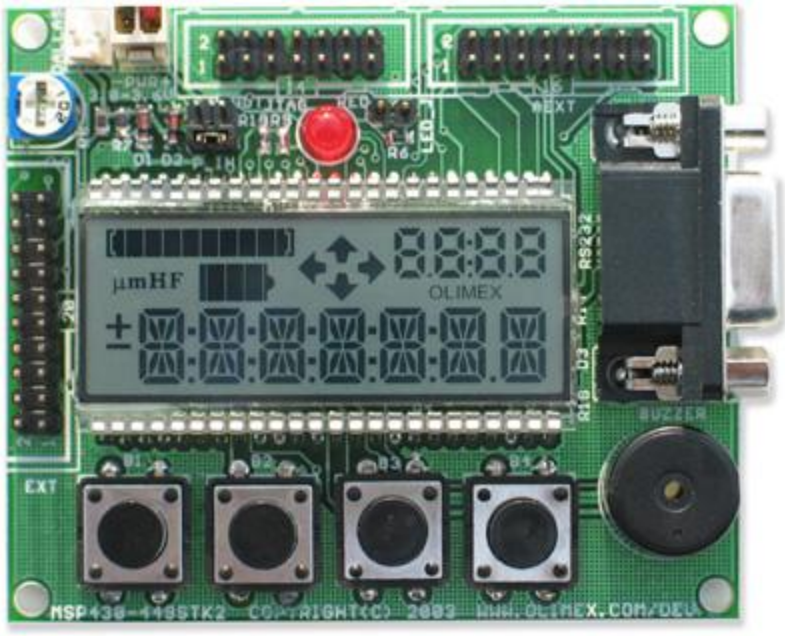


Figure 18: Olimex MSP430-449STK2 Layout

The programming done for this prototype focuses on the detection of faults primarily and is not optimized for user interaction. The conditional statement that was added to detect fault conditions sets ranges around the values from the fault condition calibration that was done. It finds the highest peak over a series of periods. With that, it can analyze all three peaks from the three coils and determine if those values are near any of the simulated faults. It will display a corresponding fault code if the values are within range of a known fault or will just display “UNKNOWN” if the values don’t correspond to any of the simulations. A flow chart outlining its operation is shown below.

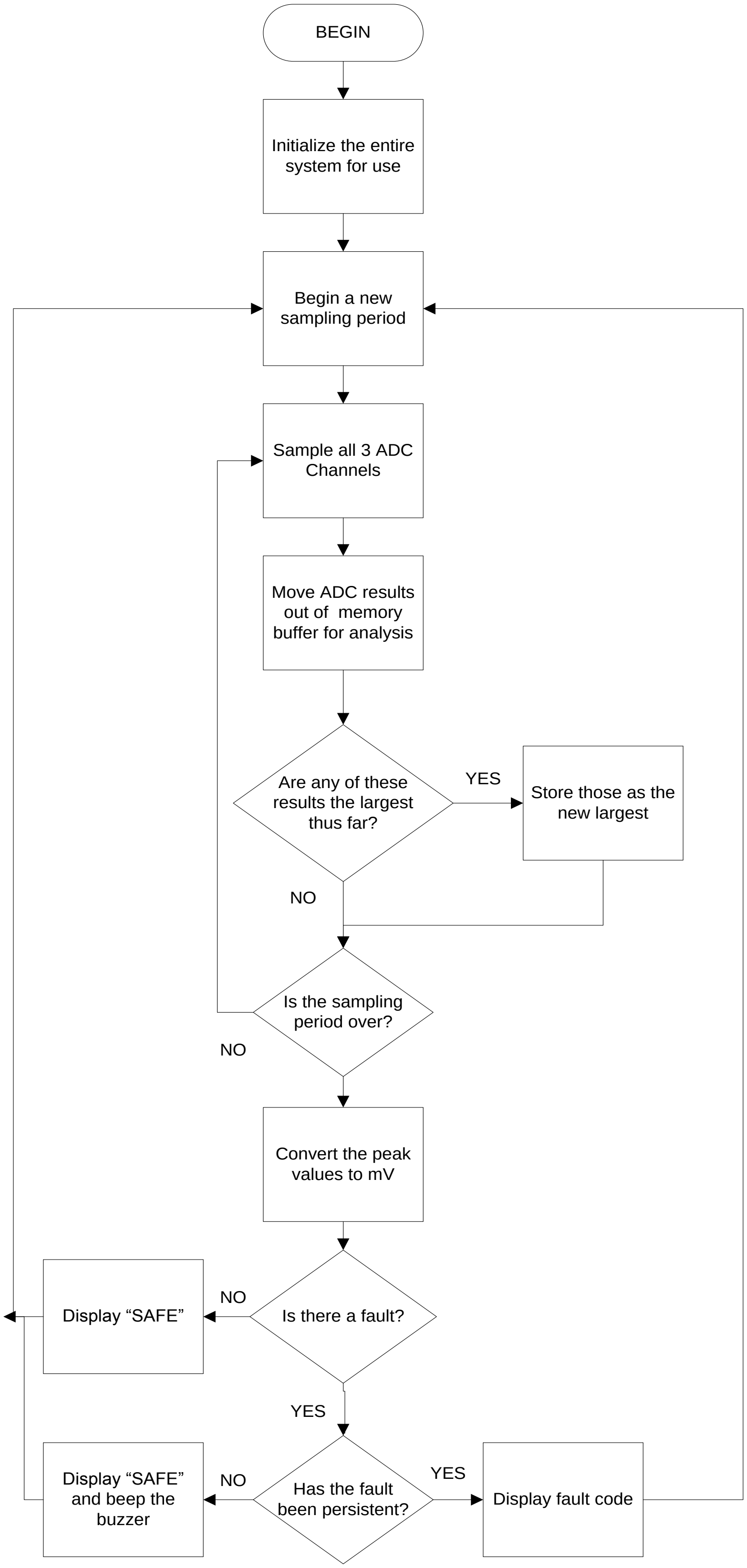


Figure 19: Programming Flow Chart

One of the most important functions of the MCU is to check for fault persistency. It does this by checking at the end of each sampling period if the current fault devised from that period and the one before it are the same. If they are and they are not safe conditions, it will increment a counter variable. Once the same fault sticks around for five cycles, it is considered a persistent fault. If, at any time, a safe condition is found, the problem counter is reset. However, if an error just shows up once, the buzzer will chirp to indicate that some fault had occurred but has not yet proven itself to be persistent.

Sampling periods are defined in the code as a certain number of samples taken by the ADC for all three channels. For the prototype, 1000 samples constitute a period. Therefore, once the ADC has finished its 1000th consecutive sampling, the largest values for all three channels are taken into the fault detection portion of the coding. Once the fault is determined, stored, and acted upon, the code will start a new sampling period. This period can be lengthened for more accurate peak measurements or shortened for quicker fault detection. This chosen period is relatively long, but because the product is meant as a proof-of-concept, accuracy was more important.

The 12-bit resolution of the ADC served its purpose very effectively. The ADC supports the use of internal reference voltages. One of the references offered was 1.5V, which was ideal because the fault conditions never registered any voltages greater than 1.1V. The 12-bit resolution was so large that each bit accounted for approximately 360µA. That is on a very small scale compared to the measurements in the 100mV to 1.1V range, which leads to very accurate readings.

This development board is being used in the prototype as a sufficient way to test the capabilities of a processor while still utilizing the useful output features. However, in a more practical final market product, a custom-made interface should be designed that better suits the need of this product. A more competent LCD screen could be used at a base station so that all of the lines' conditions could be displayed at once. This development board works, but is not ideal for an actual product.

Display

Once the signal has been sensed and processed that information must be conveyed through some sort of display. Without the display the product would be useless to a person attempting to make a critical decision. There are multiple methods that could have been used to perform this task including LCD displays and LCD plotting displays. For the prototype, the display was located on the unit itself, however because the user would not usually be at the unit, a display would ideally be located on a base station unit. These methods are explained in more detail in this section.

This display option is an LCD display. This type of display is more versatile because of the amount and type of information that can be portrayed. With an LCD display it is possible to display any number or letter needed. An example of an LCD display can be seen in Figure 20. Looking at the type of information that will need to be displayed, this type of display may be adequate. This unit would ideally be larger than the one shown in the image. It could be mounted on a unit kept at the power company so that workers could monitor multiple sensor units with one screen. It could be much larger and list all of the conditions for all of the units that the company has installed out on their lines.

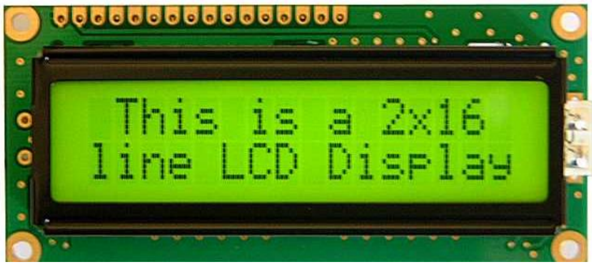


Figure 20: 2x16 LCD Display

This next type of display that was analyzed for use of displaying the needed information was an LCD plotting display. With similar technology to the simple LCD display, it also consumes very low amounts of electrical power. An example of an LCD plotting display can be seen in Figure 21. This type of display would allow for visual representation of the signals that are actually being sensed. The signals would be plotted along an axis with any significant changes to the graphs representing a fault in the system. With the signal being plotted, the information still needs to be analyzed as opposed to solid numbers with the LCD display. Therefore, this could be added as an analytical option in addition to a regular LCD display. The user could select the unit that they want to view and it could plot the waveforms of the induced voltages from each coil in that unit. This may not be very cost-effective for many companies, but is a viable option.

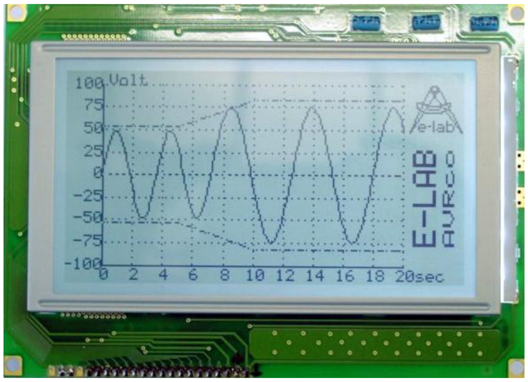


Figure 21: LCD Plotting Display

Wireless

An alternative to using a display directly on the device would be to use a wireless system to transmit the fault information to the nearest substation. If a display is mounted on the unit a worker will have to go out and actually check the numbers, which would be very inefficient. Utilizing a wireless transmission system would decrease the workers time and effort to check for a fault in the system. This would allow the information be readily available at the nearest computer.

As fault information is being received by a main, receiver computer that information could be shared with the entire company through a server. Since the information is being received and sent around via a computer system, the numbers could also be stored. By storing this information, it will be available later for further analysis and possibly future predictions. Many studies are done to prevent outages and understand when and how they occur. Having information as to exactly when faults occur and the severity of the fault would assist research in this area greatly.

The prototype that has been build during this project did not include the wireless transmission unit due to time constraints. The prototype utilizes the Olimex processing board's display, buzzer and LED to notify and relay fault information. The display is similar to the LCD display described in the previous section. The information will still be useful to determine faults in the scaled power system.

Simulations and Results

This section of the report shows all calculations and lab and computer simulations that have been done throughout the duration of this project. These results assisted the decision making for methods and redesigns of each of the modules. The majority of the simulations were done with the sensors, but all modules had to be tested to assure the final products proper functionality.

Calculations

Before the computer simulations could be run, calculations had to be done first. These calculations give a better understanding of the values the cube should be reading and the simulation values that are actually recorded. There were many variables that are used in these calculations, so to better understand these equations, the symbols must first be understood, listed in the table of symbols.

Once the symbols and their meanings are understood, it is easier to understand the following equations. Building off of equation 5 from the background section it is possible to determine the voltage that should be induced each coil of the sensor. Equation 5 is restated below.

$$B = \mu_0 \frac{1}{2\pi d} \hat{I} \sin(\omega t + \theta) \tag{5}$$

The next expression that is discussed is the magnetic flux. The magnetic flux is expressed by multiplying the magnetic flux density by the effective area of the cube. The effective area of the cube is the length times the height of the coil. Since the length and the width in the coil are equal it is possible to just square the length of one of the sides of the coil. The width of the coil is not taken into consideration, which leads to errors. These errors are discussed in the calibration section of the report. The expression for the effective are can be seen in equation 6 and the expression for the magnetic flux can be seen in equation 7.

$$A_e = l^2 \tag{6}$$

$$\varphi = B A_e \tag{7}$$

By combining the expression for the magnetic flux and the magnetic flux density it is possible to re-express equation 7 as seen by equation 8.

$$\varphi = A_e \mu_0 \frac{1}{2\pi d} \hat{I} \sin(\omega t + \theta) \tag{8}$$

After determining the magnetic flux the voltage that would be induced into a coil is finally ready to be calculated. By taking the derivative of the magnetic flux and multiplying it by the number of turns in the coil, the peak voltage that could be sensed is determined. The expression for this can be seen in equation 9.

$$\hat{V}\sin(\omega t+\theta)=N\frac{d\varphi}{dt} \tag{9}$$

This expression can then be broken down by taken the derivative of the magnetic flux equation and multiplying it by the number of turns in the coil. The expression once the derivative is taken can be seen in equation 10.

$$\hat{V}\sin(\omega t+\theta)=NA_e\mu_0\frac{1}{2\pi d}\omega\hat{I}cos(\omega t+\theta) \tag{10}$$

The expression seen in equation 10 is the maximum voltage that could be read by a coil. However, all three of the coils are at an angle with respect to that maximum voltage. In order to determine each component of that voltage equation 10 must be multiplied by a factor of 10. To determine the x-component of the signal it must be multiplied by the height to the conductor divided by the distance from the conductor. This expression is seen in equation 11.

$$\hat{V}_x\sin(\omega t+\theta)=NA_e\mu_0\frac{h}{2\pi d^2}\omega\hat{I}cos(\omega t+\theta) \tag{11}$$

To determine the y-component of the maximum voltage equation 10 must be multiplied by the length to the conductor divided by the distance to the conductor. This expression can be seen in equation 12 below.

$$\hat{V}_y\sin(\omega t+\theta)=NA_e\mu_0\frac{L}{2\pi d^2}\omega\hat{I}cos(\omega t+\theta) \tag{12}$$

The final component of the maximum voltage that was measured is the 45º angle component. To determine that component equation 10 must be multiplied by the length times the square root of two all divided by the distance to the conductor. The resulting expression is seen in equation 13 below.

$$\hat{V}_{45}\sin(\omega t+\theta)=NA_e\mu_0\frac{L\sqrt{2}}{2\pi d^2}\omega\hat{I}cos(\omega t+\theta) \tag{13}$$

Once the components of the maximum voltage are determined, it is understood that there are three overhead conductors that have an effect on each of the coils. In order to account for all of the conductors there must be three equations for each of the coils added together. In the simulations the first conductor is referred to as conductor A, the second as conductor B and the third as conductor C. To note their affect on each of these equations, all affected components are denoted with a small subscript of the affecting conductor. Three more expression resulted from this affect, the x-component, the y-component and the 45-component which were affected by the three lines. The first expression seen is the x-component coil affected by the three conductors which is expressed by equation 14.

$$\hat{V}_x \sin(\omega t + \theta_x) = NA_e\mu_0 \frac{\omega}{2\pi}\left(\frac{h_a}{{d_a}^2}\hat{I}_a cos(\omega t + \theta_a) + \frac{h_b}{{d_b}^2}\hat{I}_b cos(\omega t + \theta_b) + \frac{h_c}{{d_c}^2}\hat{I}_c cos(\omega t + \theta_c)\right) \tag{14}$$

The next expression is the y-component which is affected by the three overhead conductors. The expression can be seen in equation 15.

$$\hat{V}_y \sin(\omega t + \theta_y) = NA_e\mu_0 \frac{\omega}{2\pi}\left(\frac{L_a}{{d_a}^2}\hat{I}_a cos(\omega t + \theta_a) + \frac{L_b}{{d_b}^2}\hat{I}_b cos(\omega t + \theta_b) + \frac{L_c}{{d_c}^2}\hat{I}_c cos(\omega t + \theta_c)\right) \tag{15}$$

The final expression that was needed was the 45º component which is affected by the three overhead conductors. The expression for this can be seen in equation 16.

$$\hat{V}_{45} \sin(\omega t + \theta_{45}) =$$

$$NA_e\mu_0 \frac{\omega}{2\pi}\left(\frac{L_a\sqrt{2}}{{d_a}^2}\hat{I}_a cos(\omega t + \theta_a) + \frac{L_{\mathrm{b}}\sqrt{2}}{{d_b}^2}\hat{I}_b cos(\omega t + \theta_b) + \frac{L_c\sqrt{2}}{{d_c}^2}\hat{I}_c cos(\omega t + \theta_c)\right) \tag{16}$$

Simulations

In the computer lab, MatLab simulations were run and plots of what the graphs are supposed to look like were seen. The simulation was set up so that all three wires had current flowing in the same direction and the distance between line A and line C was four feet with line B in the middle. The sensor was placed ten feet under the wires and the lines were all 120° out of phase. The diagram for the system can be seen in Figure 22.

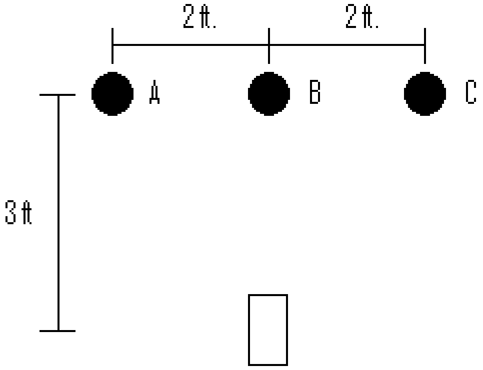


Figure 22: System Diagram

Figure 23 shows what the graph should look like when there are no faults present in the power line system with all the wires at 200 Amps.

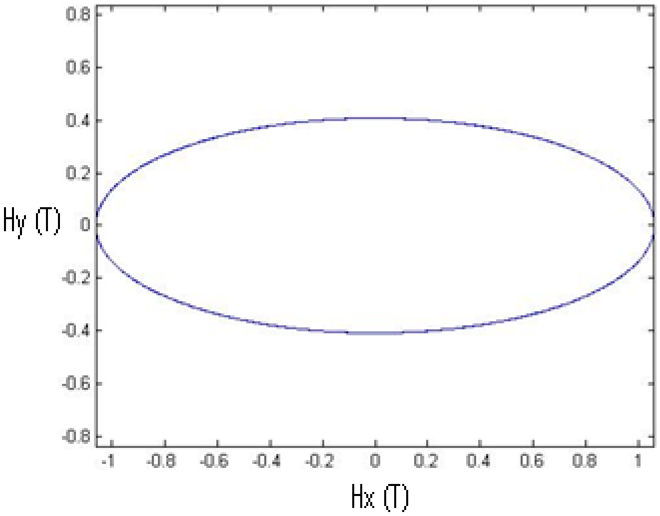


Figure 23: 200 Amps in all lines

Now that it is known what the graph is supposed to look like when there are no faults, faults can start to be introduced to determine what the faulty systems will look like. Figure 24 shows what the graph looks like when the Amperes in line A are decreased. The more the Amperes are decreased the more vertical the graph becomes with points on the top left and bottom right acting as the pivot points.

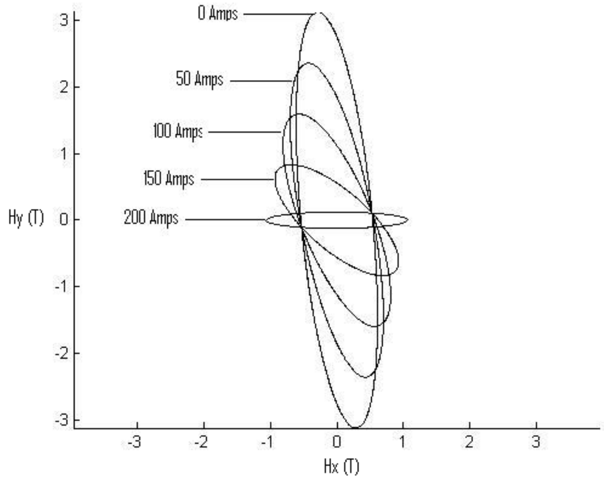


Figure 24: Decreasing Amperes in Line A

The current being decreased in line A produces a similar effect. The graph again becomes more vertical and rotates around the same points. This graph however is not as steep and the graph is growing in a counter-clockwise motion as opposed to a clockwise motion. This can be seen in Figure 25.

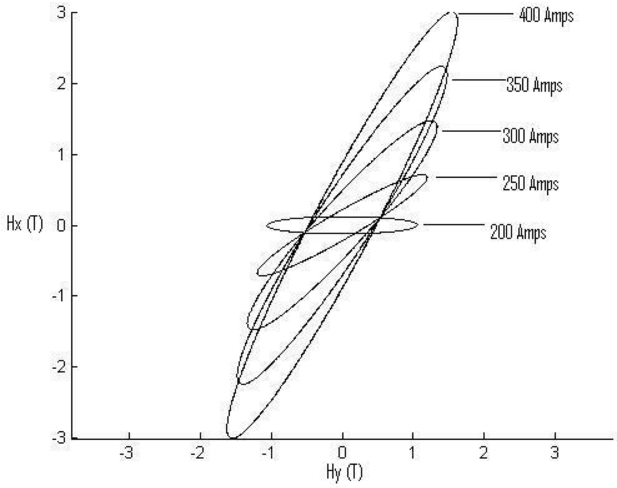


Figure 25: Increasing Amperes in Line A

Decreasing the Amperes in line B the graph stretches vertically and the points on the X-axis are the points of rotation. The graph for this situation can be seen in Figure 26.

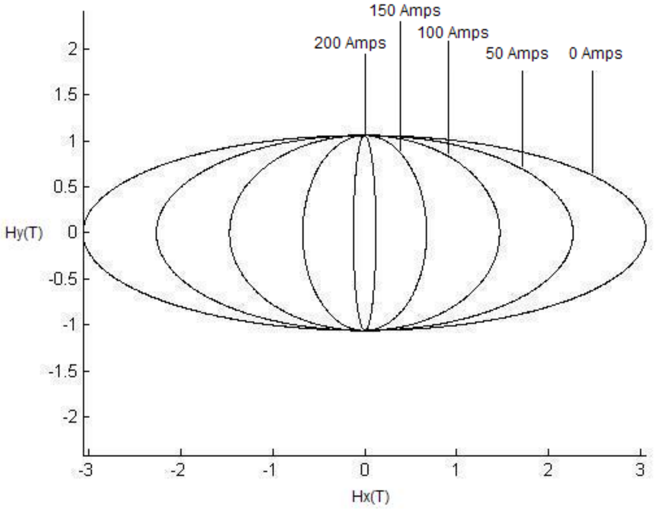


Figure 26: Decreasing Amperes in Line B

Faults in line B were also looked at; when the current is increased in line B the graph grows vertically. The rotation points are the points on the X-axis. When the current is decreased or increased in line B the graph grows vertically. This makes it hard to determine whether the fault is because of a high or low current in line B but the fault itself can be easily seen. This can be seen in Figure 27.

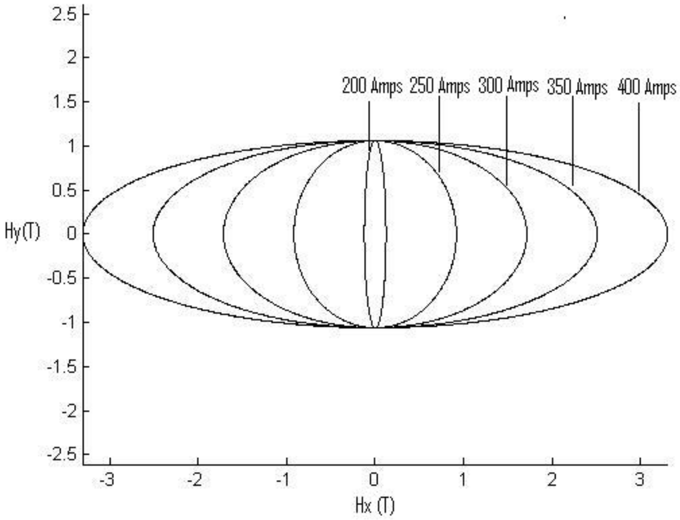


Figure 27: Increasing Amperes in Line B

When faults occur in line C, the graph shows opposite effects of what happened in line A. When the Amperes are decreased the Figure 28 and when the Amperes are increased the graph can be seen in Figure 29.

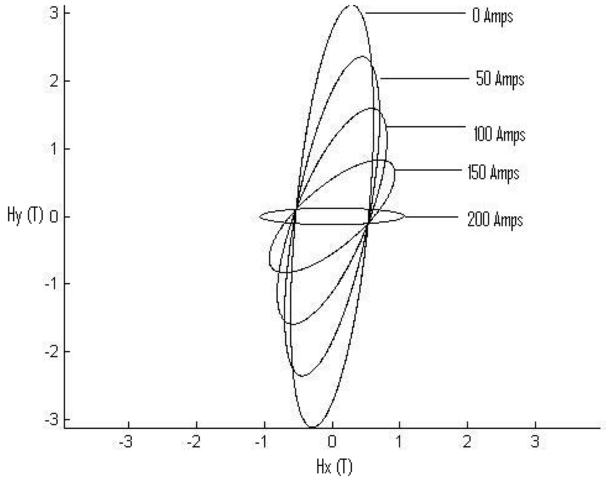


Figure 28: Decreasing Amperes in Line C

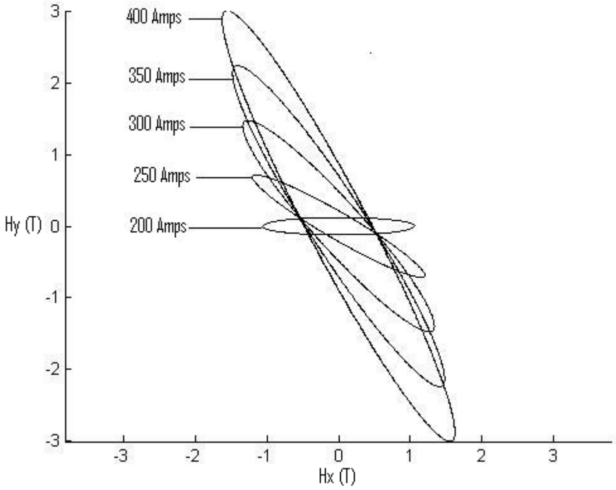


Figure 29: Increasing Amperes in Line C

Laboratory Simulations

The next step in the project was to simulate a real system in the lab. The system down first had to be scaled down to a useable level. The diagram shown in Figure 30 was used to model the power line system.

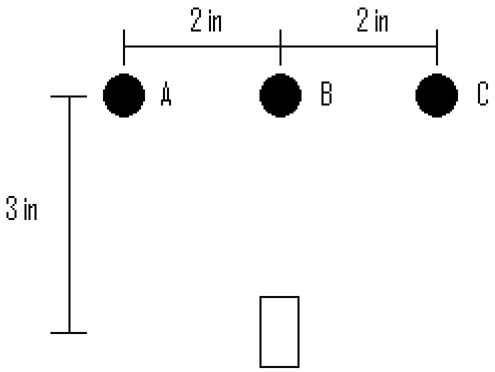


Figure 30: System Model

All three lines are in parallel and they are two inches apart. The cube was then placed 3 inches under the lines beneath the center wire. A system had to be built so that it would not vary at all between uses and also had to be convenient and have little or no setup time. Figure 31 shows the implementation.

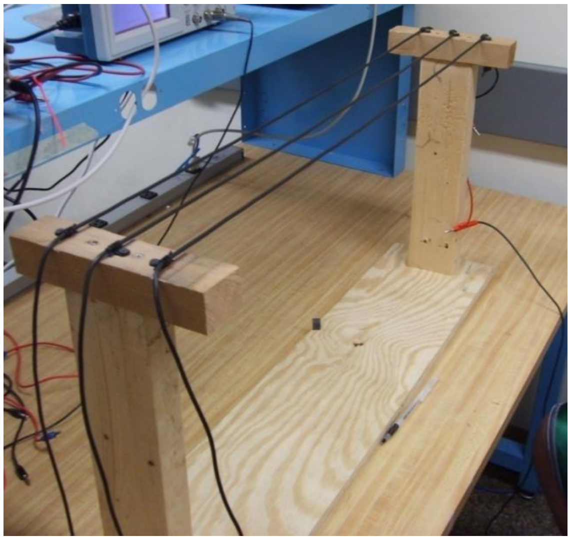


Figure 31: Lab setup

A current of 1.5A was run the same way through each wire, each of these currents was 120^{o} out of phase. The magnetic field was then read using the sensor. The sensor's output was input into the amplifier and filter. The output from the filter can be seen on the oscilloscope as shown in Figure 32.

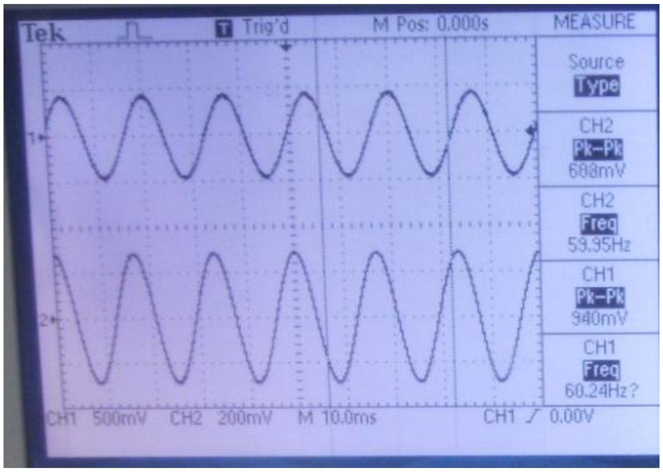


Figure 32: Oscilloscope reading

To generate the signals that were needed two variacs were used. The entire setup of the generator can be seen in Figure 33. This system allows for three different phases and allows for two different current levels by changing the variac. This enables simulation of all of the fault conditions that are able to be detected.

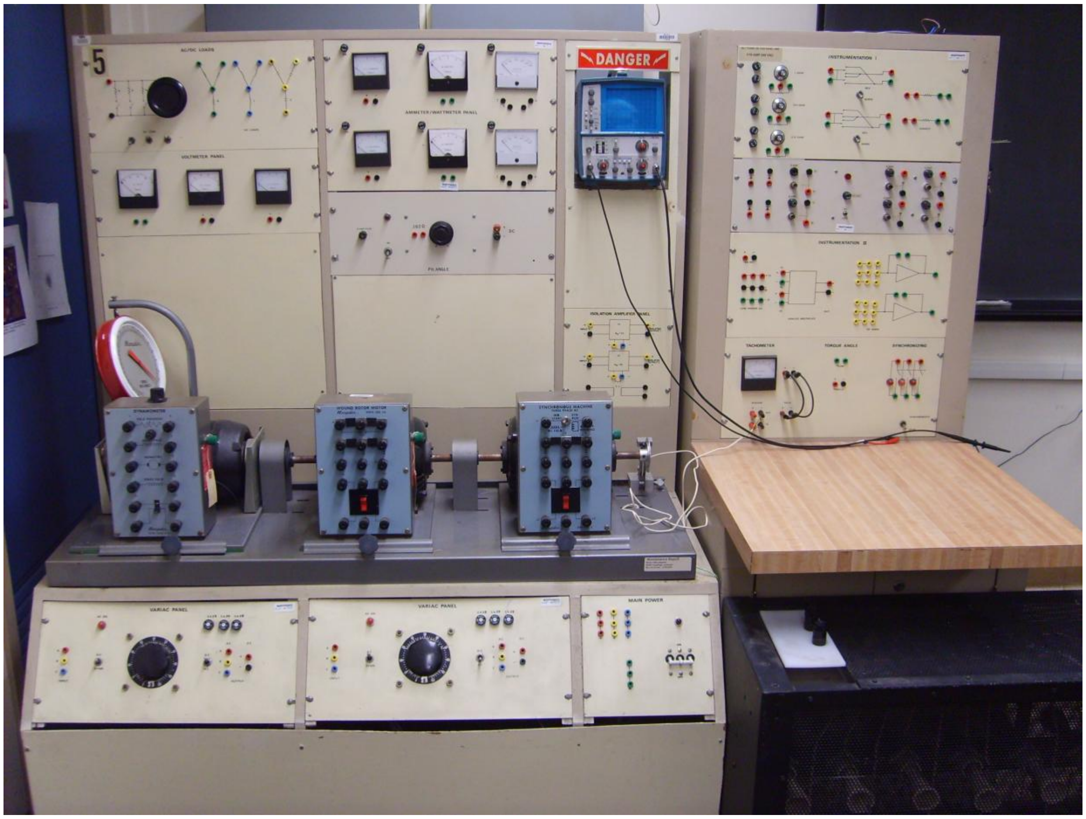


Figure 33: Signal Generator

The expected values that were calculated using equations 14 through 16 can be seen in Table 5. After running the lab simulations it was seen that they were much different than the expected values. A lot of time was spent checking and rechecking the circuitry for faulty components. Knowing that the circuit design had been tested in the lab previous to combining it with the sensor; it was realized that the sensor must have been at fault for such a large difference. Therefore it was determined that the sensor needed to be calibrated.

Calibration

The original simulations that were run left a very large error. After analyzing the properties of all of the components involved, it was determined that this was due to the sensing coils being very large compared to the size of an ideal coil, which the calculations were tailored for. When the coil grows in size, the induced voltage is much greater near the top of the coil because it is closer to the conducting wires. Inversely, it tapers down to a much smaller value near the bottom. An illustration of this concept can be seen in Figure 34. The ideal model's coil essentially has a diameter of zero. The calculations focus on just that one dimension and don't account for the variation of the larger diameter. Therefore, instead of trying to perfect the equations used and complicate the situation further, it was decided to calibrate the experimental results to the theoretical values. With a solid set of data for many situations, it can accurately be determined by the current in the wires by a ratio obtained through the calibration.

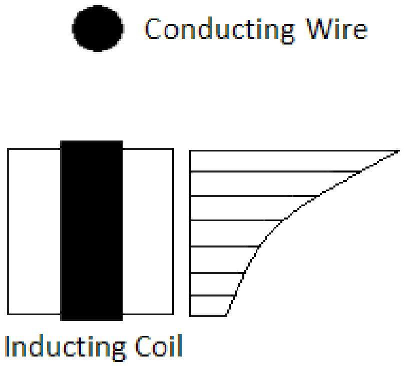


Figure 34: Field Strengths Relative to the Cube

To calibrate the system, the same overhead system setup as previously discussed was used. One line was turned on at a time to see that lines effect on each of the three coils. The induced voltage was measured from each of the coils. The voltages and line currents can be seen in Table 3.

Left Line	Middle Line	Right Line	X-Direction	Y-Direction	45º-Direction
3A	Off	Off	970mV	560mV	76mV
Off	3A	Off	1.10V	272mV	344mV
Off	Off	3A	860mV	59mV	444mV

Table 3: Each Line's Effect Calibration Numbers

The next step was to see what the voltages were at the different fault conditions. Every fault condition was simulated in the mock power line system. The measured values for each fault can be found in Table 4. With this knowledge, it was possible to accurately create bounds for each coil's induced voltages that would indicate specific faults. These bounds were later used in the microcontroller's programming to flag those faults.

Left Line	Middle Line	Right Line	X-Direction	Y-Direction	45º-Direction
1.5A	1.5A	1.5A	88mV	220mV	178mV
0A	1.5A	1.5A	460mV	104mV	210mV
1.5A	0A	1.5A	444mV	290mV	180mV
1.5A	1.5A	0A	480mV	218mV	172mV
4.0A	1.5A	1.5A	784mV	704mV	138mV
1.5A	4.0A	1.5A	1.07V	300mV	420mV
1.5A	1.5A	4.0A	704mV	272mV	518mV
4.0A	4.0A	1.5A	964mV	624mV	404mV
1.5A	4.0A	4.0A	936mV	304mV	552mV
4.0A	1.5A	4.0A	736mV	752mV	500mV
4.0A	4.0A	4.0A	336mV	672mV	496mV

Table 4: Calibration Numbers for Fault Conditions

Left Line	Middle Line	Right Line	X-Direction	Y-Direction	45º-Direction
1.5A	1.5A	1.5A	2.34E-04 V	6.08E-04 V	3.49E-04 V
0A	1.5A	1.5A	6.75E-04 V	3.51E-04 V	4.76E-04 V
1.5A	0A	1.5A	5.27E-04 V	6.08E-04 V	4.41E-04 V
1.5A	1.5A	0A	6.75E-04 V	3.51E-04 V	5.21E-04 V
4.0A	1.5A	1.5A	7.88E-04 V	1.15E-03 V	1.03E-03 V
1.5A	4.0A	1.5A	1.50E-03 V	6.08E-04 V	1.13E-03 V
1.5A	1.5A	4.0A	7.88E-04 V	1.15E-03 V	6.78E-05 V
4.0A	4.0A	1.5A	1.31E-03 V	1.15E-03 V	1.22E-03 V
1.5A	4.0A	4.0A	1.31E-03 V	1.15E-03 V	9.55E-04 V
4.0A	1.5A	4.0A	6.44E-04 V	1.62E-03 V	8.40E-04 V
4.0A	4.0A	4.0A	6.25E-04 V	1.62E-03 V	9.30E-04 V

Table 5: Expected Numbers

Product Results

This prototype was completed on a relatively large scale and was designed for the mock system that had been constructed. It's housed in a large box with the development board mounted in a hole to allow the user to interact with the board and to showcase the LCD that will display error codes. This unit is a proof-of-concept system that could be modified in a number of ways for detection in actual large-scale power systems, wireless transmission, and many other useful features. The unit can be seen in Figure 35.

Figure 35: Final Prototype

Currently, the code is set to constantly take readings from all lines in succession, and then compare them to a temporary variable that stores the largest value obtained during that sampling period. The peaks are analyzed compared to each other and the processor makes a decision on the type of fault that is causing the problem, if any. It's method of decision involves comparing them to the calibrated numbers for faults and seeing if it falls within range of the measurements. Because of this, there is a possibility that the system could be unable to determine the cause. In this case, the system still confirms there is a fault, but no cause is given via a fault code. An example of the error-checking system is shown below for a line-to-ground fault.

	X-Direction	Y-Direction	45°
Pk-Pk Simulation Results	460 mV	105 mV	210 mV
Upper Peak Value	230mV	52.5 mV	105 mV
Code's Detection Range	210-250 mV	32-53 mV	85-125 mV

Table 6: Error Checking System

That buffer will allow for a more reliable detection scheme. If the buffers were too small, the readings would have to come out close to exactly the same as the simulations. Faults in real systems will not likely be that predictable. Obviously, the set of all of the fault conditions won't account for every possible combination of coil readings. However, the code was programmed with a generic fault for any combinations that don't drop into these ranges. This could later be optimized by adding new conditions or more rigorous testing. The current prototype can detect ten different faults that are combinations of line-to-line and line-to-ground faults.

Project Conclusion

The goal of this project was to design a product that could detect faults in a transmission line system and relay that information back to a control center. It was first necessary to gain a better understanding of how power systems operate. The general overview of power systems were researched as well as specific fault conditions that may occur. From these faults conditions, it was then possible to perform some computer simulations to determine currents under normal and fault conditions. Since a non-invasive technique was to be utilized in the product, it was determined that measuring the electromagnetic fields that were produced by the lines was a good method to determining faults. The background research that was performed is discussed and analyzed in the background section of the report.

It was then necessary to understand the companies who would be interested in a product of this type. A market analysis was performed and determined that power companies were the ideal target market for this product. Similar products were looked at as well to determine the uniqueness of this product. In this research similar products were found, but none that were the same. Once this was determined a customer survey was sent out to a number of power companies. The true scope of the project was drawn out from the replies of the power companies. Things such as the features, pricing, size and maintenance were established.

The background research that was performed helped determine which modules would need to be designed. The modules that were designed were a sensor, an amplifier and filter, a power supply, and a processor. Each module was designed for optimal performance including accuracy, low power consumption and size. Each of the modules was individually tested for their proper functionality before the full system could be combined together.

The ideal values that should have come from the sensor, amplifier and filter were calculated using a number of different equations. These equations were found from various sources and all put together in this report. These calculations were key to understand the values that should be obtained and could also be used later to determine the actual current and phase of each of the power lines. A set of ideal values were determined, which were later used as a comparison.

The final step was to put the sensor, amplifier and filter together and test them for their actual lab simulation numbers. Once these values were determined they were compared to the ideal simulation numbers. The numbers varied greatly which, in the end, resulted in a calibration of this portion of the product. A set of calibration numbers were measured which were then sent to the processor.

The processor was the able to take in the calibration numbers and determine when faults occurred. Another slight calibration was needed at this point however because the processor dropped all of the voltages by another hundred mV or so. In the end the processor was able to display a fault code for each type of fault which can be used to determine the type of fault.

This project was successful in the essence the product was able to detect faults in the power line system and display the fault codes; the simulations that were run in lab were successful. However a unit to mount on an actual transmission line system or transmit the data wirelessly unable to be built. The theoretical and actual simulations completed demonstrate that it is possible to determine with great accuracy the type and time of the fault.

Works Cited

(Unknown). In G. e. al, *Overhead Line Fault Location Based on Traveling Waves & GPS* (pp. 11-7.1 thru 11-7.13).

Brown, G. W. (1998). *Patent No. 5729144.* United States.

GlobalySecurity. (2006). *Electrical Distribution System Overview*. Retrieved 08 2007, December, from GlobalSecurity.org: http://www.globalsecurity.org/security/intro/power.htm

Matsuura, K. (2000, February). Ground Faults on Distribution Lines. Osaka, Japan.

NCI. (2005, April 21). *Magnetic Field Exposure and Cancer*. Retrieved February 10, 2008, from National Cancer Institute: http://www.cancer.gov/cancertopics/factsheet/Risk/magnetic-fields

Ohrstrom, M. (2003). Fast Fault Detection for Power Distribution Systems. Stockholm, Sweden.

Public Service Commision of Wisconsin. (2002, December). *Electric Transmission Lines.* Retrieved December 04, 2007, from Public Service Commision of Wisconsin: http://psc.wi.gov/thelibrary/publications/electric/electric09.pdf

Taylor, L. (1993, July). Animal-caused Faults in Power Distribution Systems. Charlotte, NC, United States.

U.S. Department of Energy. (2004, December). *Electrical Distribution.* Retrieved November 26, 2007, from US DOE Electric Distribution Program: http://www.electricdistribution.ctc.com/pdfs/MYRD_ElecDist_11-3_rv9.pdf

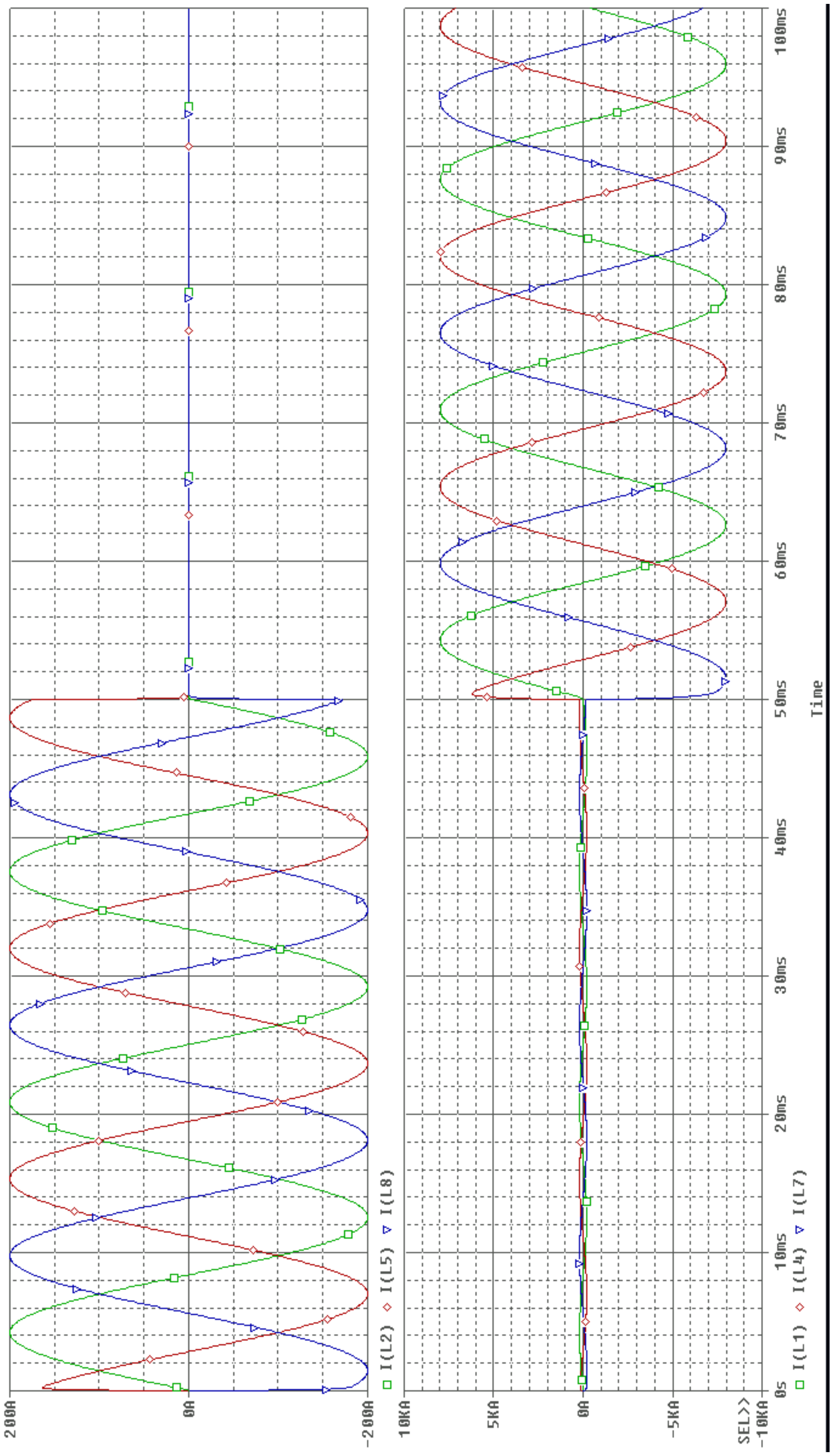
Appendix I: Fault Conditions for Power System Simulations

Appendix I-1: PSpice Code for Power System Simulations

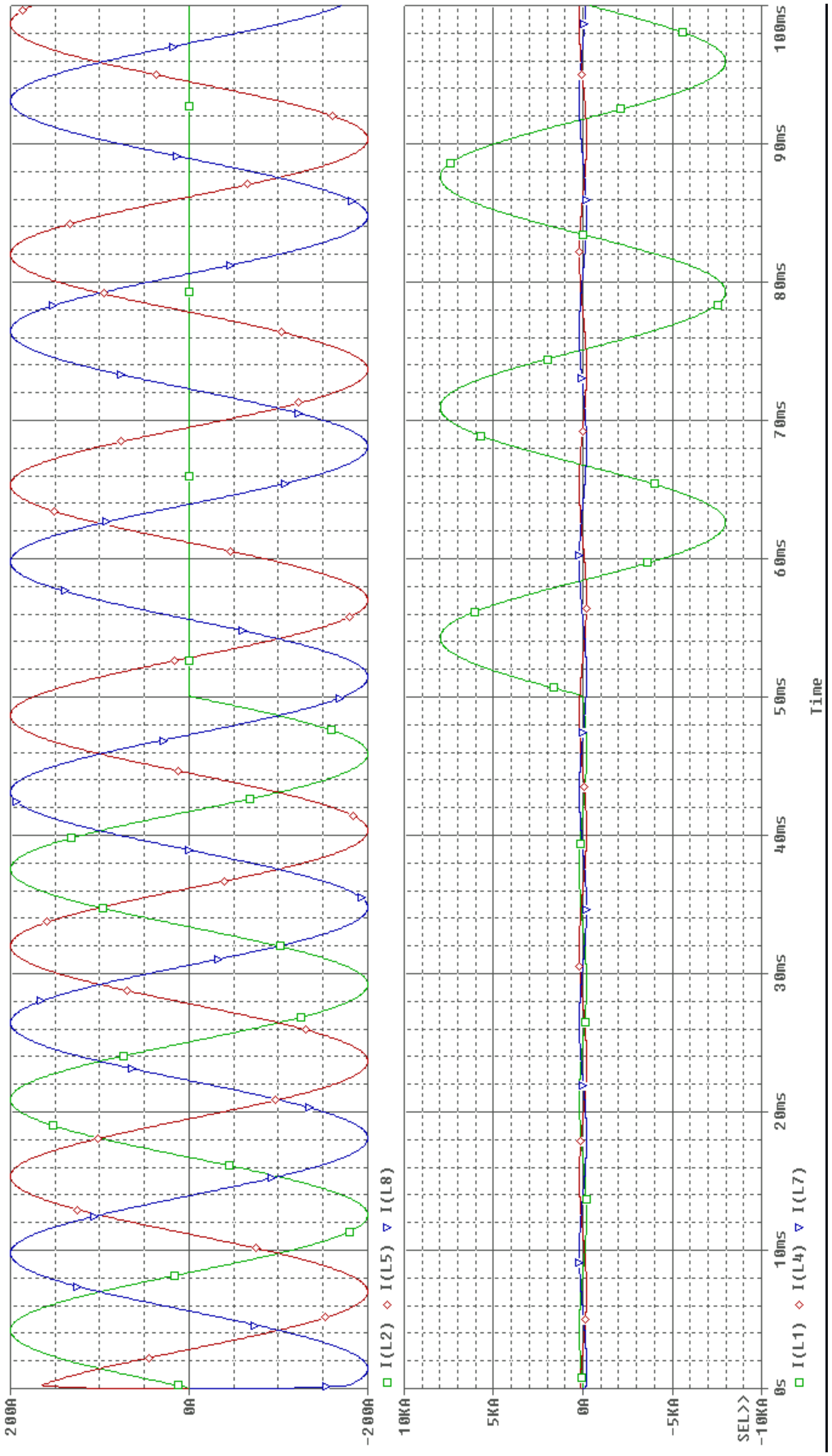
```
.TITLE SameSim

*******Source, conductor, switch (fault) and load (A)*******
V1 1  0  SIN(0 20k 60 0 0 0)
VDA 1 20 0
R1 20  2  4.5
L1 2  3  540u IC=0
*S  3  0  50 0 ZWIK
*.MODEL ZWIK VSWITCH(RON=1m ROFF=1MEG)
*VC 50 0 PULSE(0 10 50m 1u 1u 1 2)
R2 3  4  .5
L2 4  5  60u IC=0
VDA2 5 21 0
R3 21  6  95
L3 6  0  5m IC=0

*******Source, conductor, switch (fault) and load (B)*******
V2 7  0  SIN(0 20k 60 0 0 120)
VDB 7 30 0
R4 30  8  4.5
L4 8  9  540u IC=0
*S1  9  0  60 0 ZWICK
*.MODEL ZWICK VSWITCH(RON=1m ROFF=1MEG)
*VC1 60 0 PULSE(0 10 50m 1u 1u 1 2)
R5 9  10 .5
L5 10 11 60u IC=0
VDB2 11 31 0
R6 31 12 95
L6 12 0  5m IC=0
```

```
*******Source, conductor, switch (fault) and load (C)*******
V3 13 0  SIN(0 20k 60 0 0 240)
VDC 13 40 0
R7 40 14 4.5
L7 14 15 540u IC=0
S  15  0  70 0 ZWIK
.MODEL ZWIK VSWITCH(RON=1m ROFF=1MEG)
VC2 70 0 PULSE(0 10 50m 1u 1u 1 2)
R8 15 16 .5
L8 16 17 60u IC=0
VDC2 17 41 0
R9 41 18 95
L9 18 0  5m IC=0


*******Magnetic fields on the source side of the fault********
Ehx 0 51 VALUE = {(I(VDA)*0.230769231 + I(VDB)*.333 + I(VDC)*0.230769231)}
R50 51 0 100

Ehy 0 61 VALUE = {(-I(VDA)*0.153846154 + I(VDC)*0.153846154)}
R60 61 0 100

*******Magnetic fields on the load side of the fault********
Ehx1 0 511 VALUE = {(I(VDA2)*0.230769231 + I(VDB2)*.333 + I(VDC2)*0.230769231)}
R501 511 0 100

Ehy1 0 611 VALUE = {(-I(VDA2)*0.153846154 + I(VDC2)*0.153846154)}
R601 611 0 100

.PROBE
.TRAN 100m 100m 0 50u UIC
.END
```

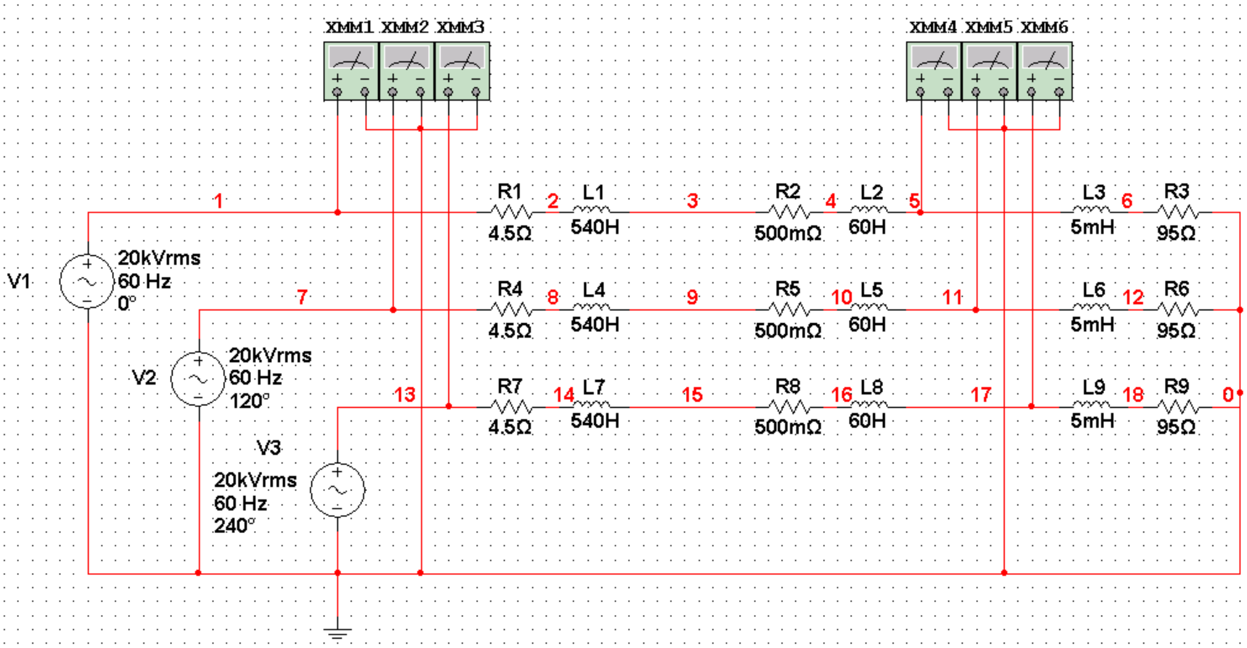
Appendix I-2: Line to Line to Line Fault at Middle of the Line



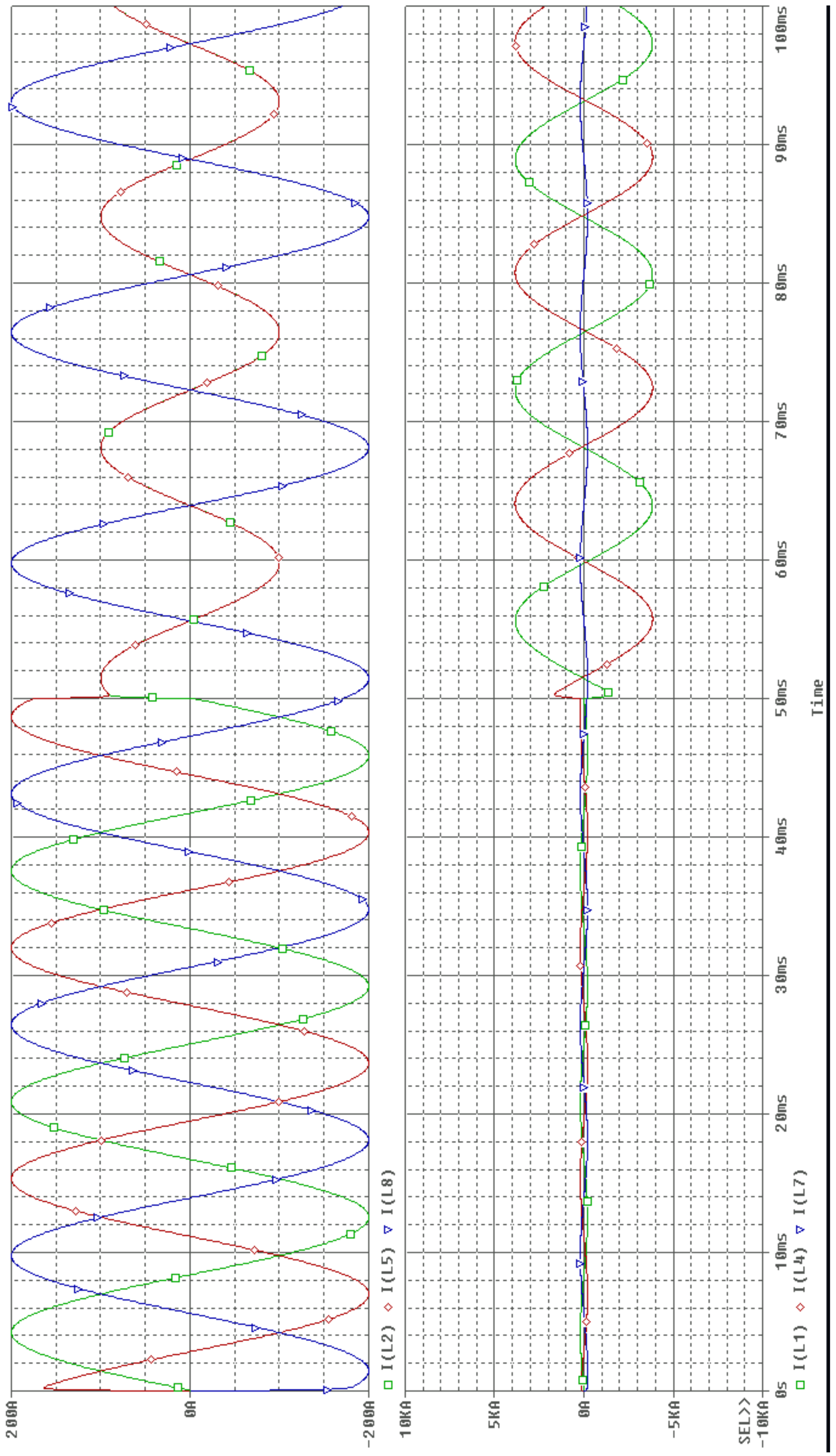
Appendix I-3: Line 1 to Ground Fault at Middle of the Line



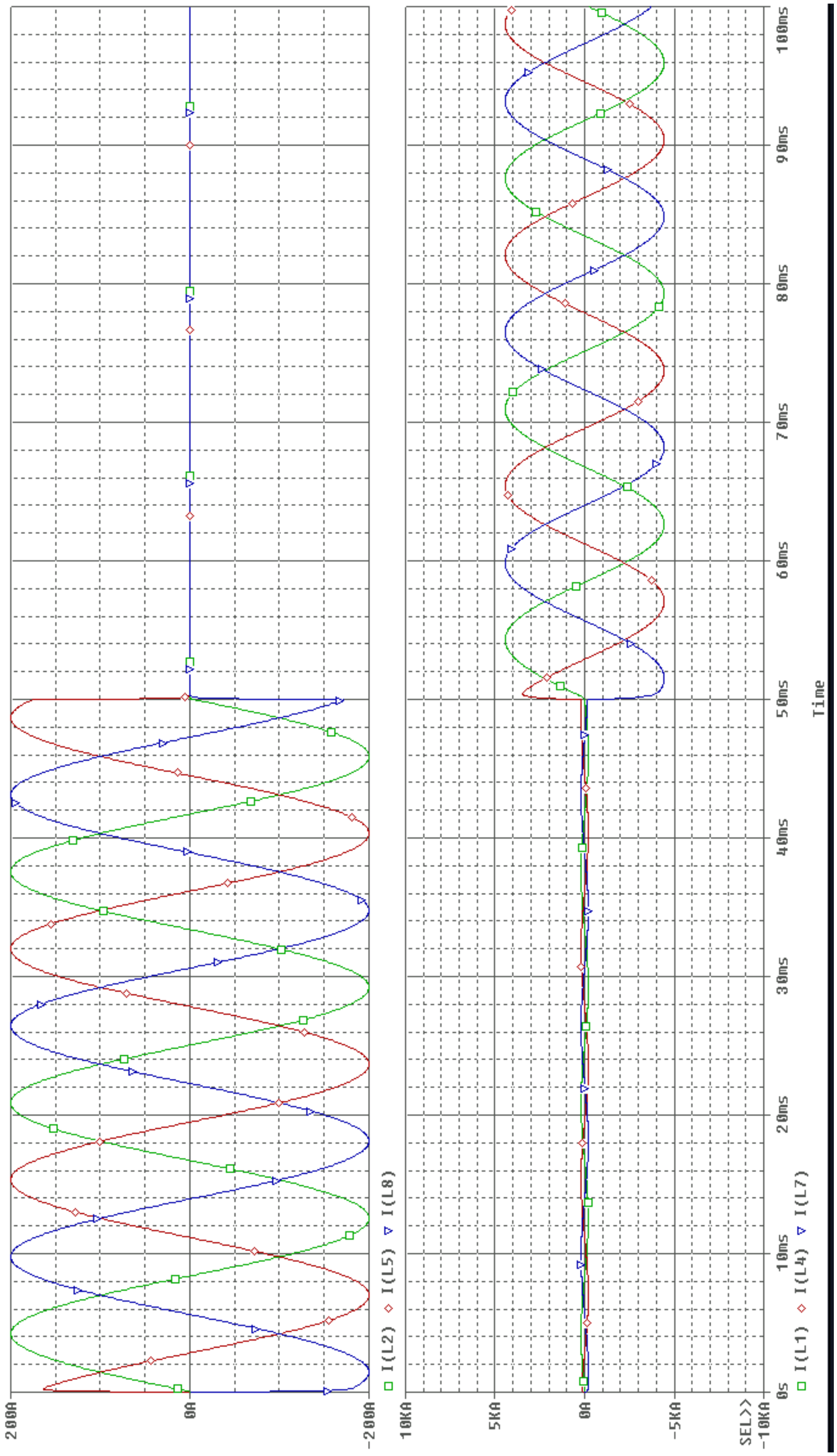
Appendix I-4: Simulation Set Up for Fault 90 Percent Down the Line



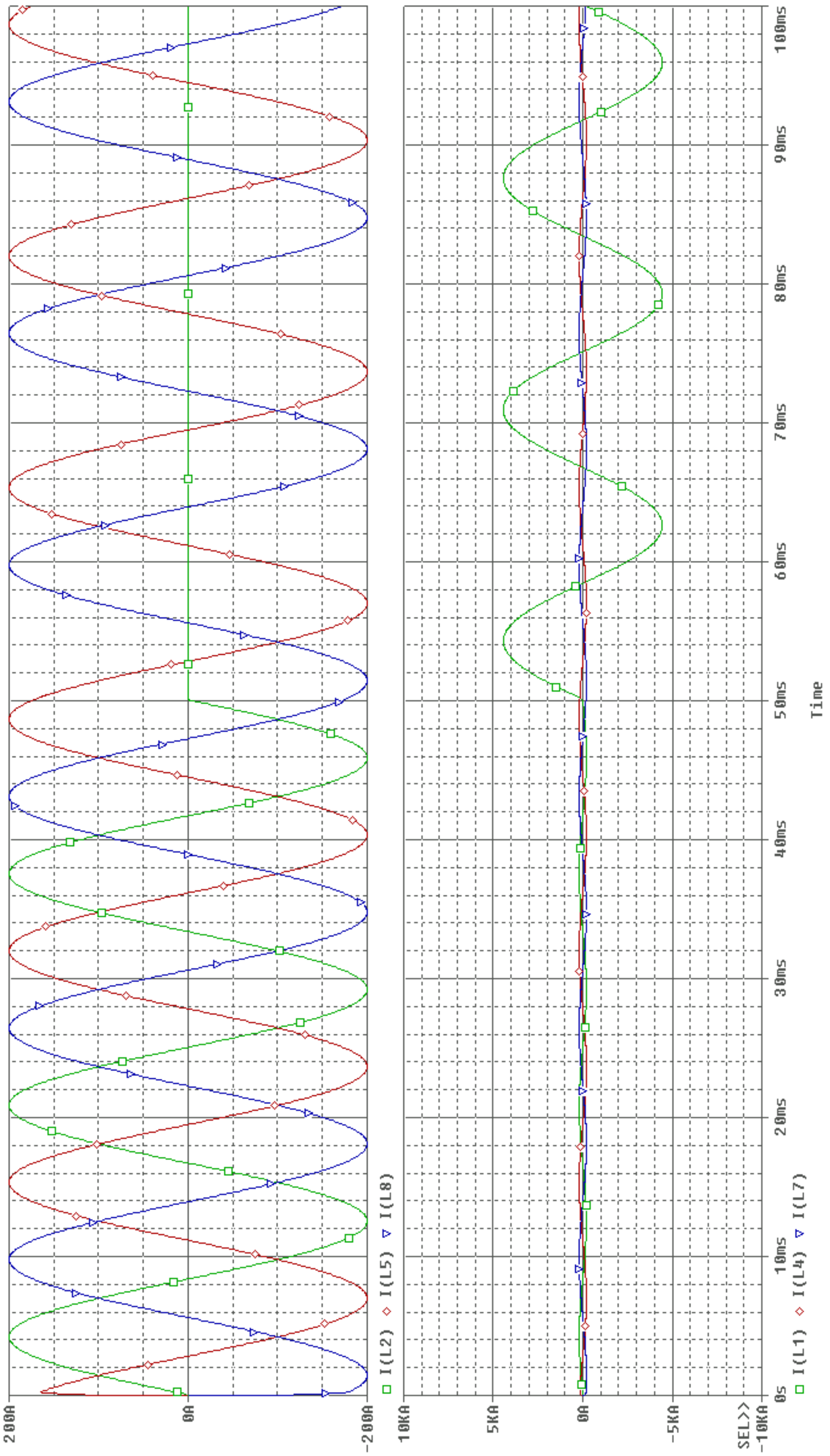
Appendix I-5: Line 1 to Line 2 Fault 90 Percent Down the Line



Appendix I-6: Line to Line to Line Fault 90 Percent Down the Line

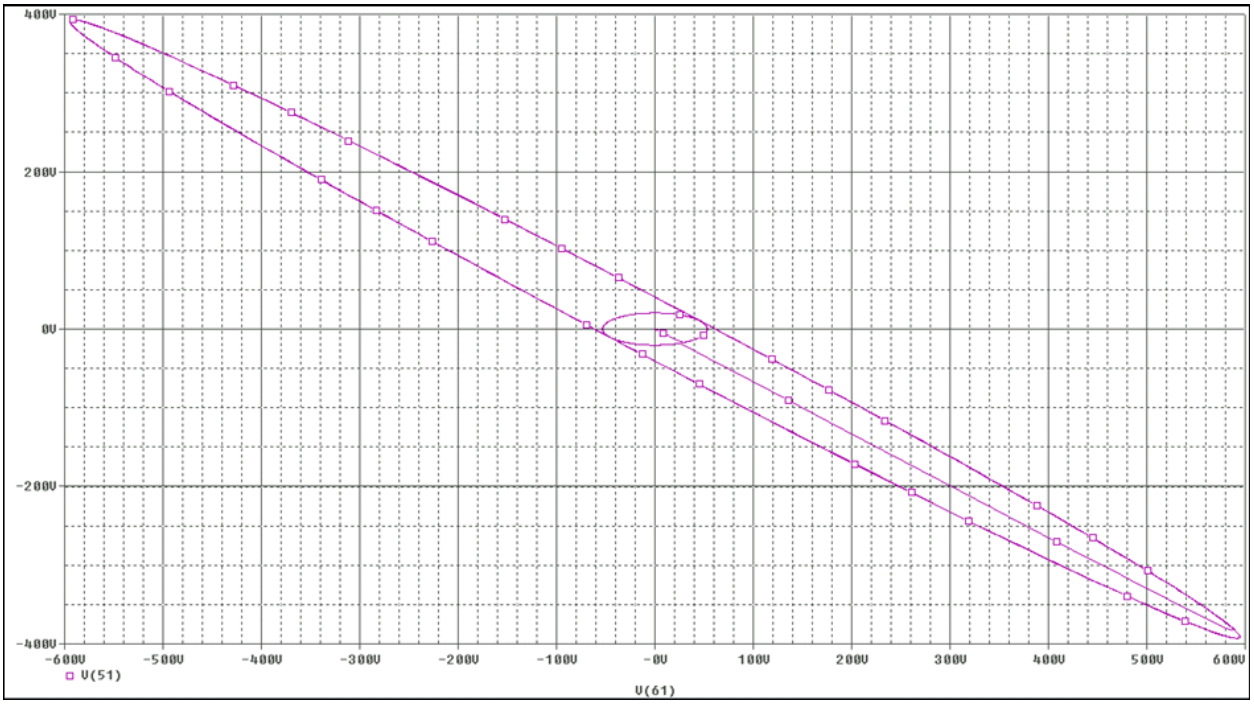


Appendix I-7: Line 1 to Ground Fault 90 Percent Down the Line

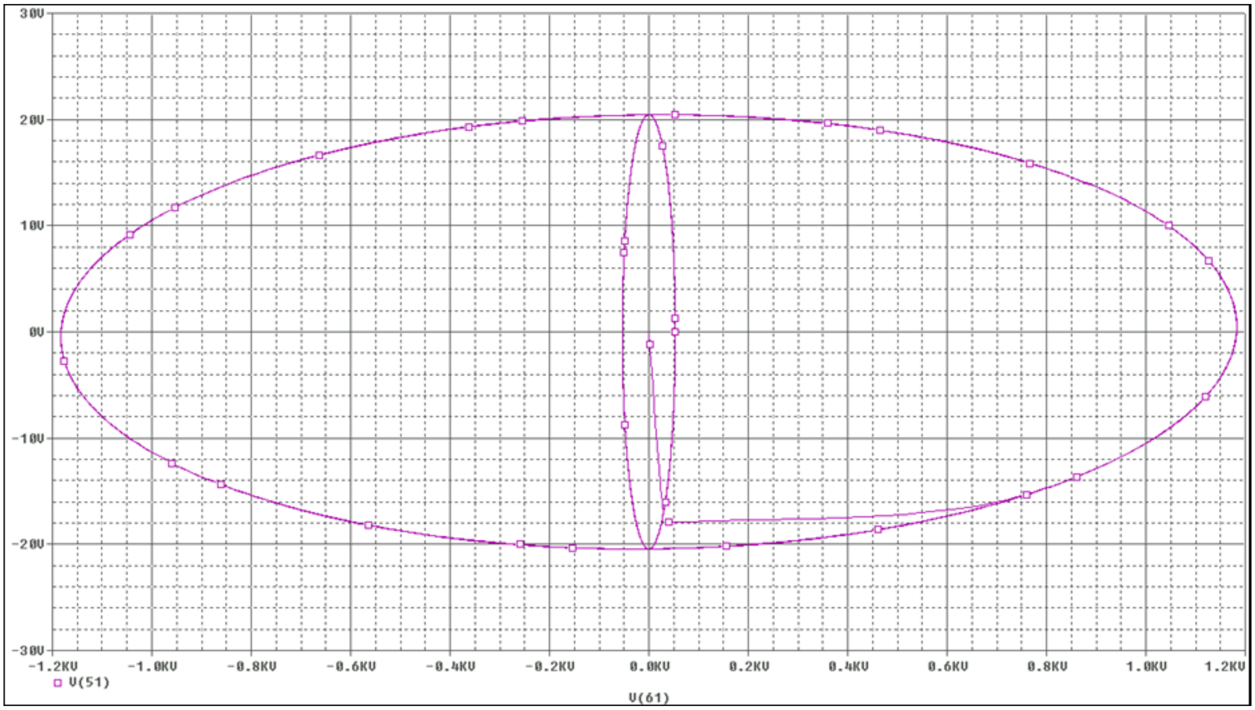


Appendix II: Fault Transitions

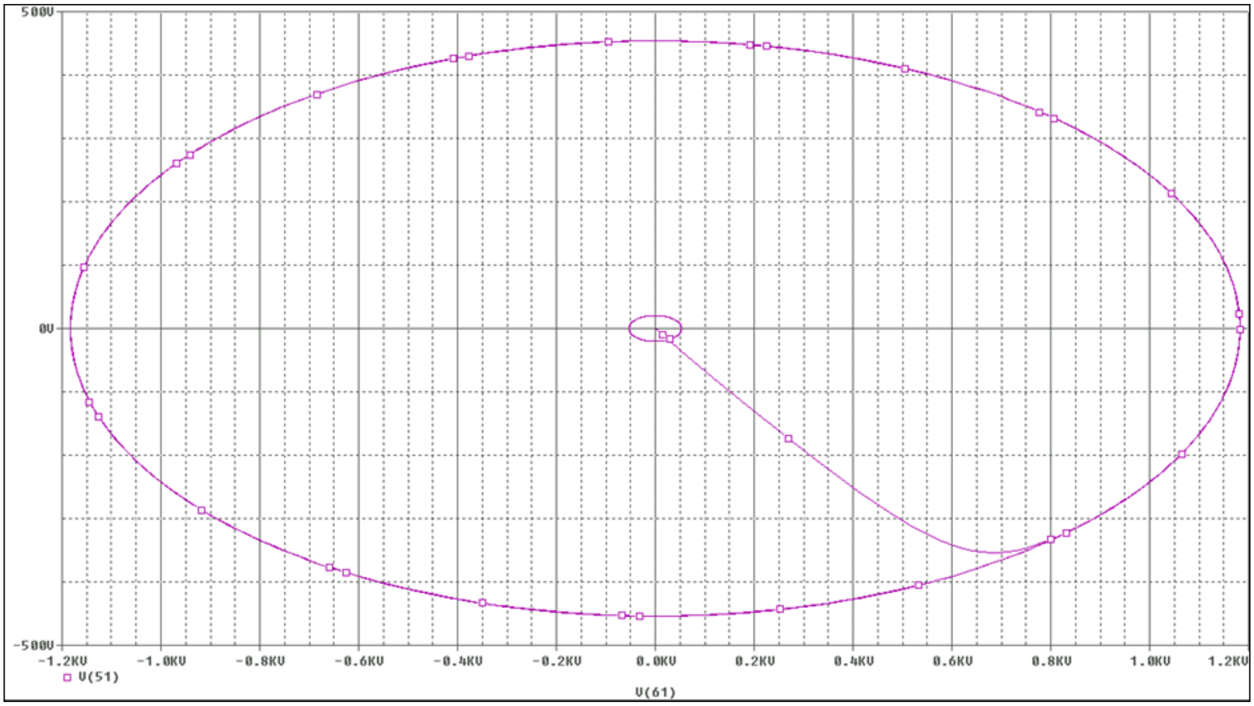
Appendix II-1: Line B to Line C Source Side



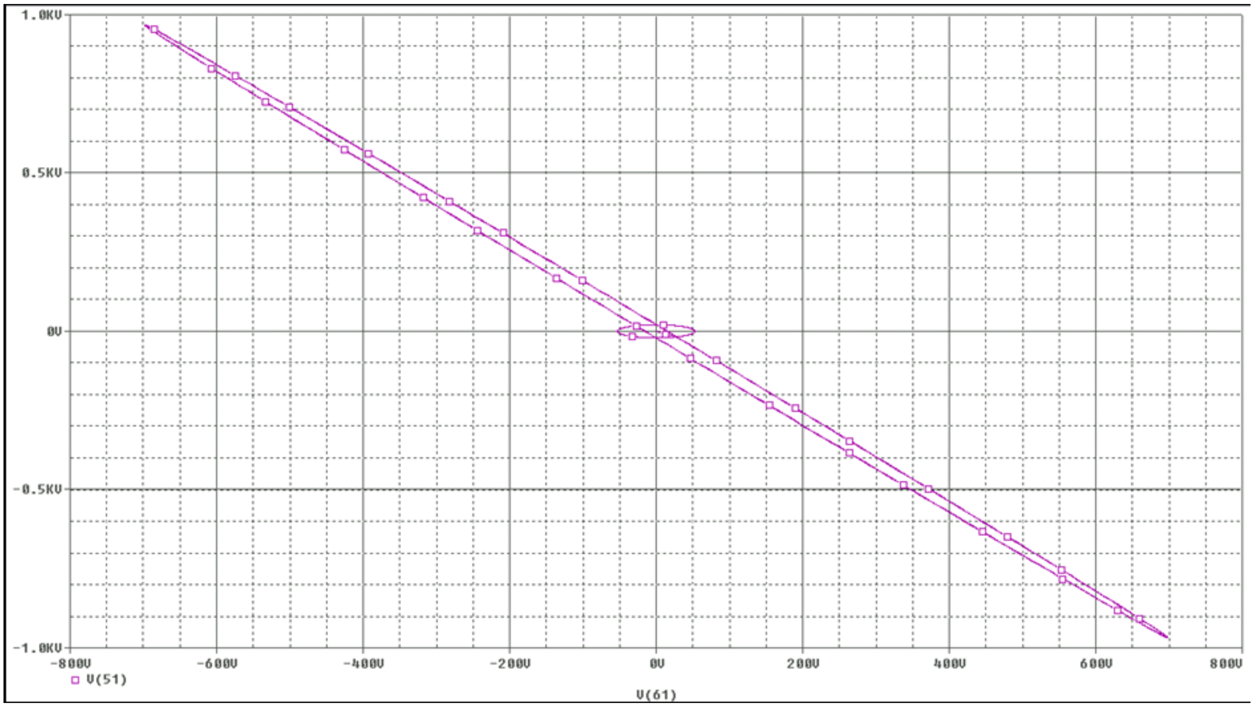
Appendix II-2: Line A to Line C Source Side



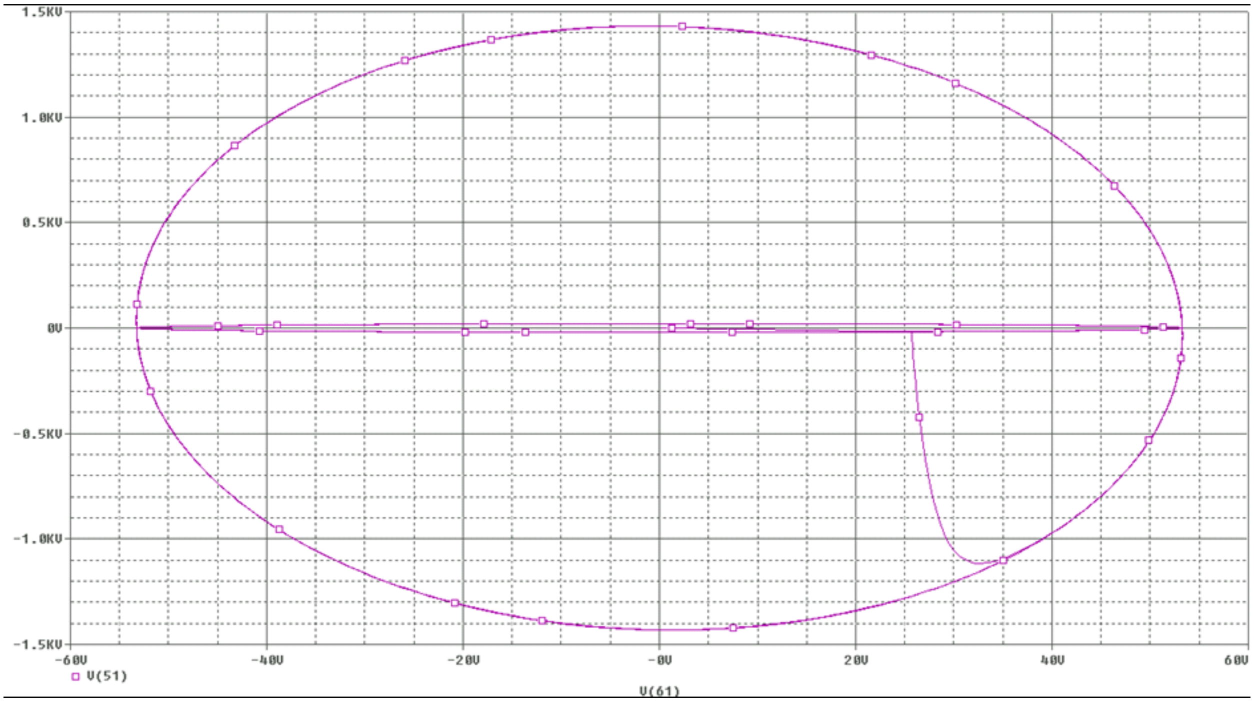
Appendix II-3: Line to Line to Line Source Side



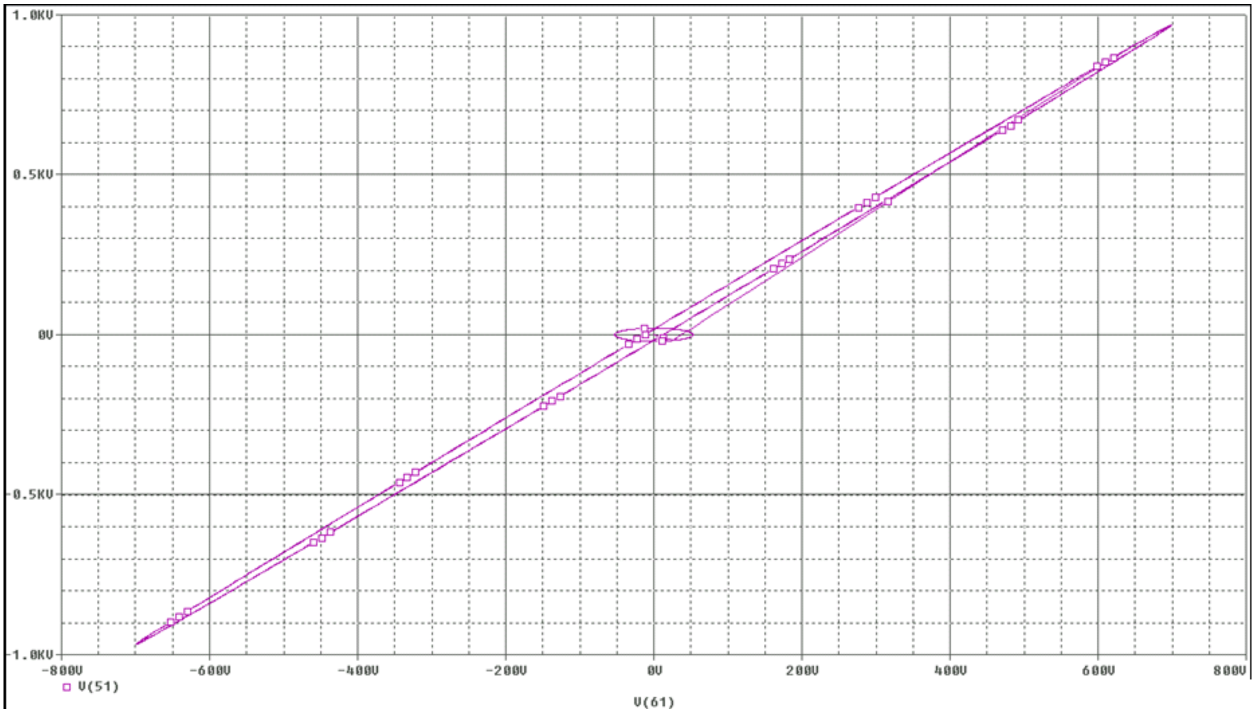
Appendix II-4: Line A to Ground Source Side



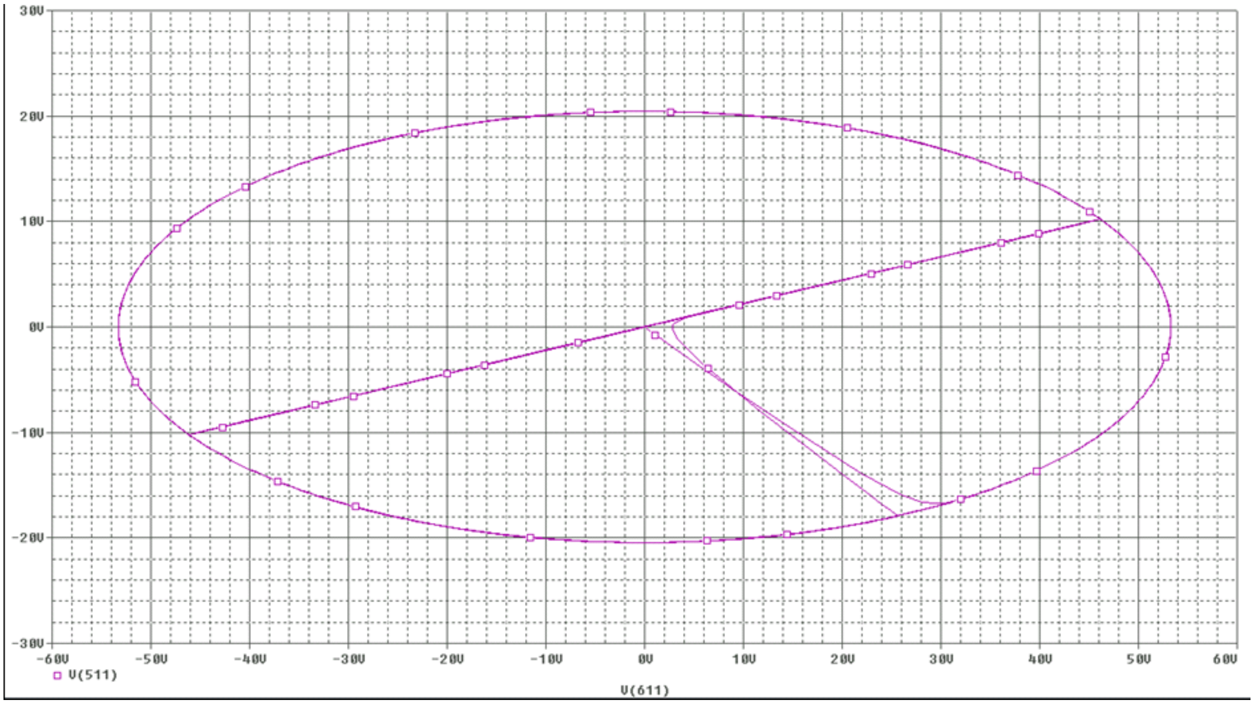
Appendix II-5: Line B to Ground Source Side



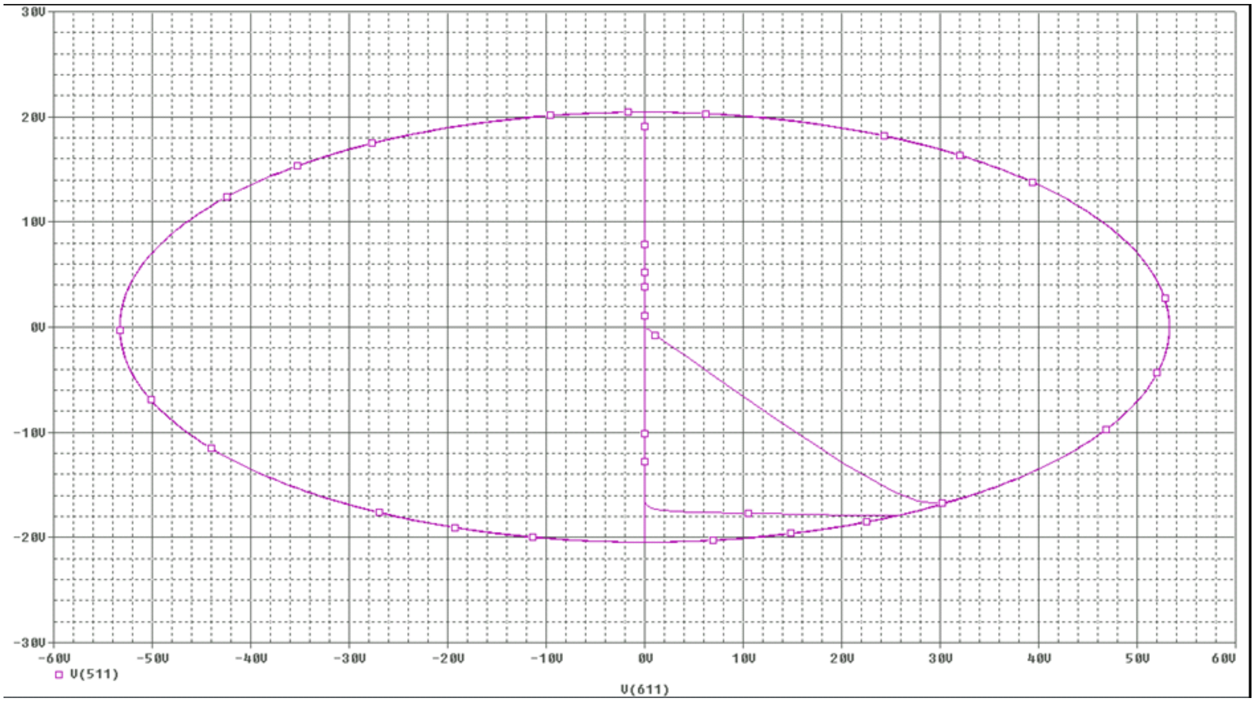
Appendix II-6: Line C to Ground Source Side



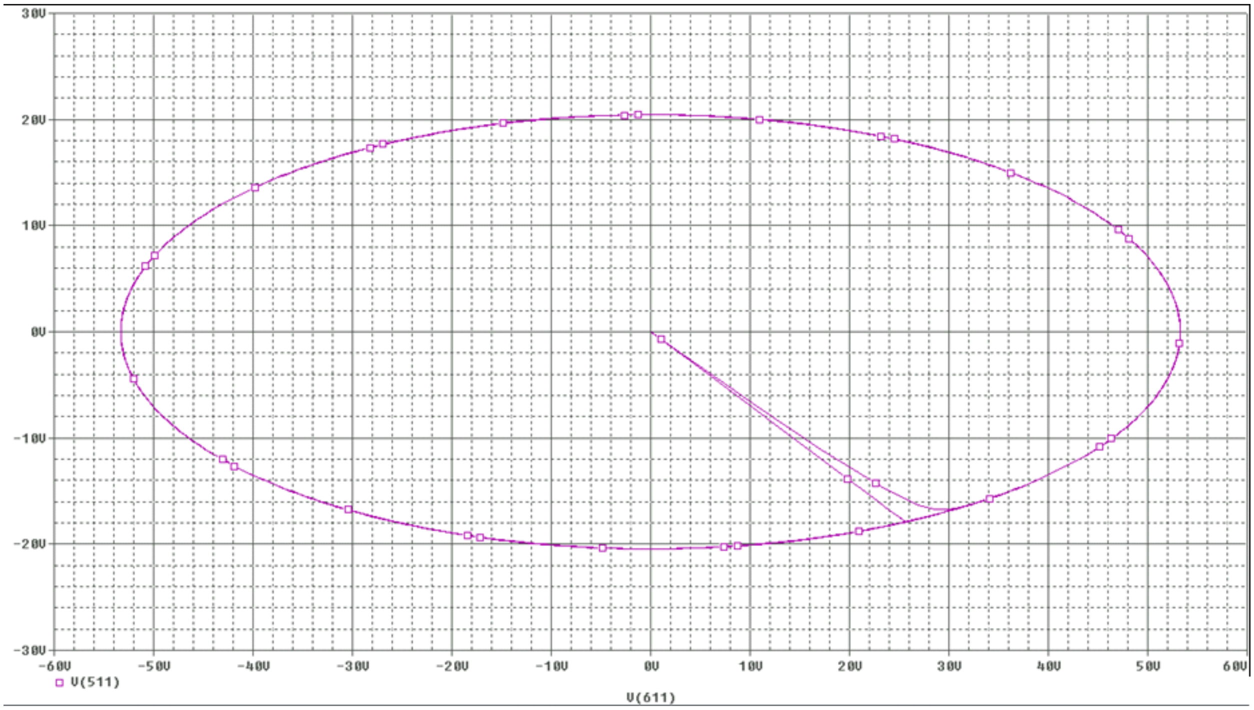
Appendix II-7: Line B to Line C Load Side



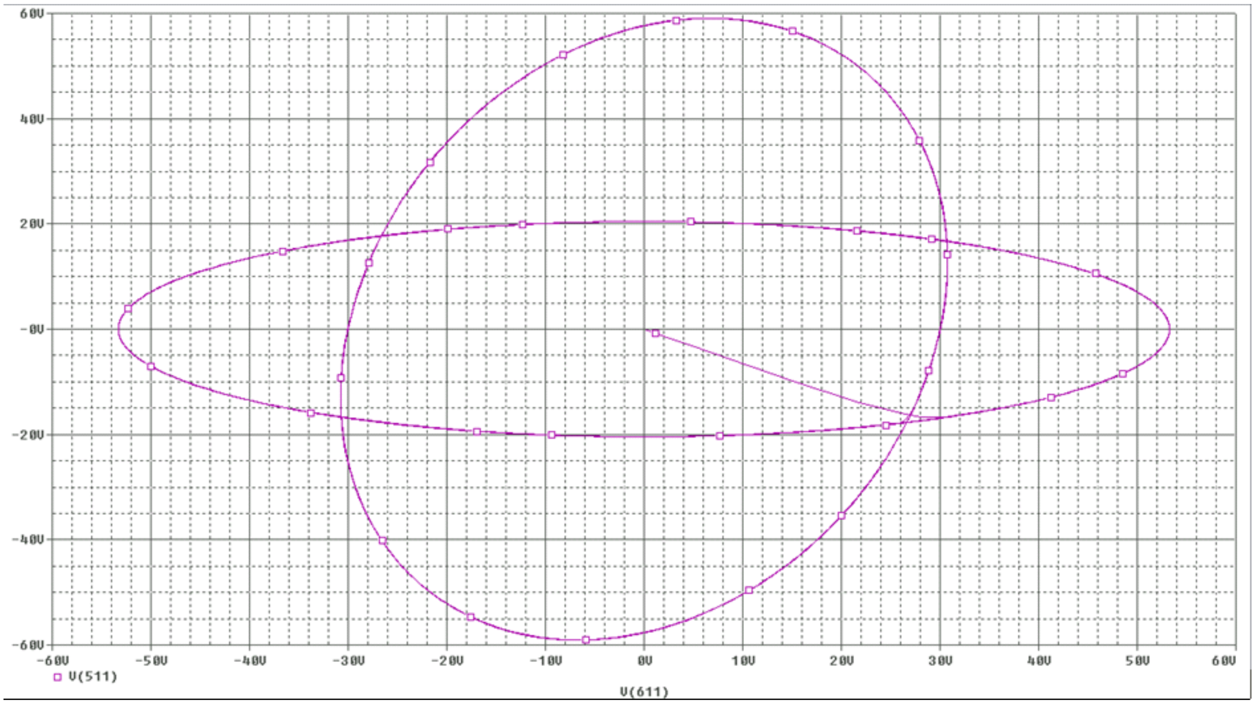
Appendix II-8: Line A to Line C Load Side



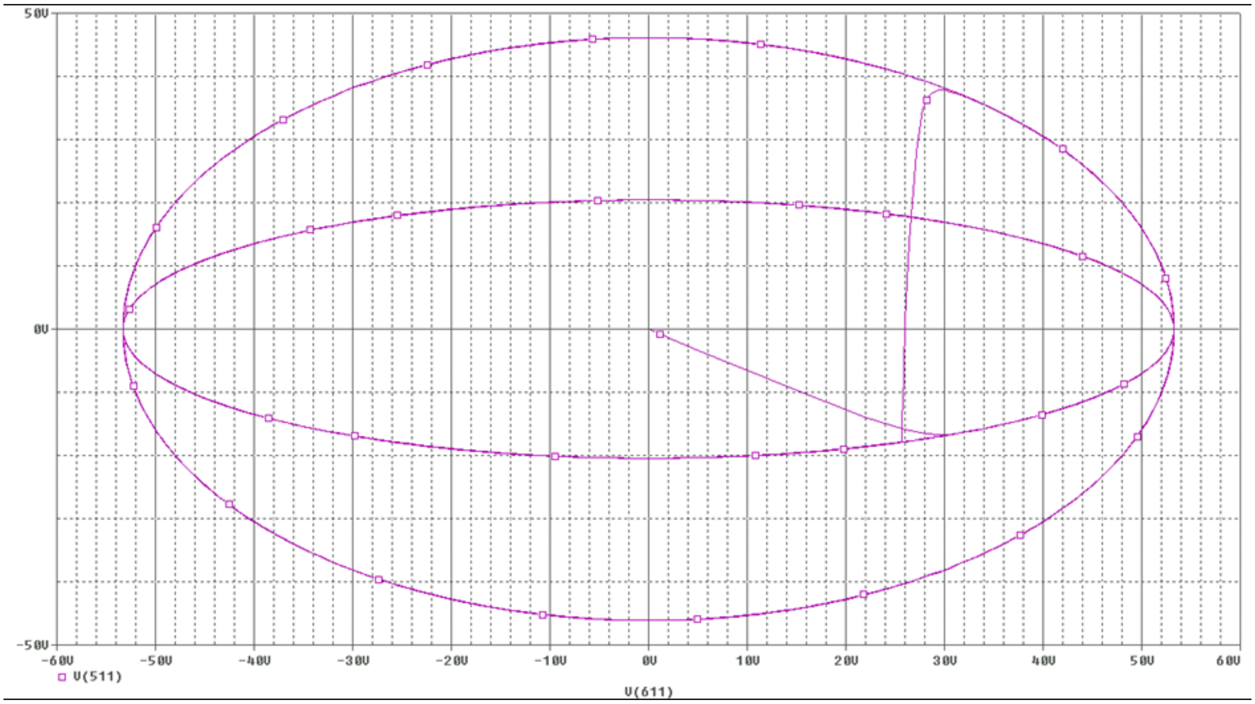
Appendix II-9: Line to Line to Line Load Side



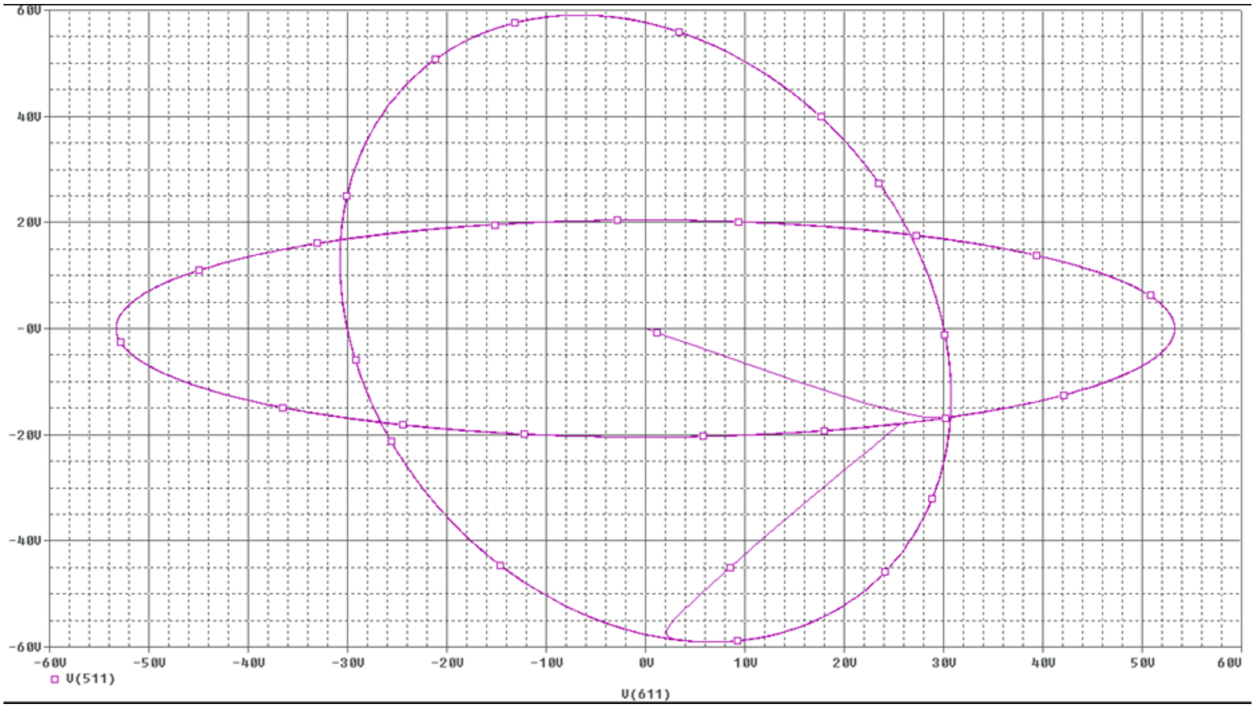
Appendix II-10: Line A to Ground Load Side



Appendix II-11: Line B to Ground Load Side



Appendix II-12: Line C to Ground Load Side



Appendix III: Customer Survey

Non-invasive Detection of Faults in a Power System

A WPI Major Qualifying Project

Product Description

The idea behind our product is to be able to non-invasively detect faults in a power line system. By sensing the magnetic fields produced by overhead conductors or cables it is possible to determine the current magnitude and phase for each line. Ideally we would install our product on a pole under the power lines, or near the monitored cable. The current and phase readings can be wirelessly transmitted to the nearest substation or electric utility building. When a fault occurs in any power line a warning signal will be sent wirelessly as well.

Why your input is important

Your input is going to help us understand if our product is useful and if it has the potential to be marketable. It will help define what specifications are necessary and which are not needed. This survey will shape the design of the size, maintainability and general need for this product on the market. All information that you can contribute is greatly appreciated. We would like to thank you in advance for completing this survey and helping us understand what is needed from a customer's point of view.

Customer Information

Name: ______________________________

Company Name: ______________________________

Phone Number: ______________________________

Email Address: ______________________________

Would you like to be informed of the project's completion?

How do you currently detect faults in your power system? Do you rely on end users?

What features would you like to see from a product like this?

How often would you be willing to perform maintenance on this product?

Is the size of the product a large concern? If so what is the maximum size you would want?

Would you like the information transmitted only when faults occur? If not how often?

Mark all boxes that apply with an X:

What information would you like to be displayed?

☐ Current through Each Wire
☐ Phase of Each Wire
☐ EMFs Detected

How would you like to be able to view this information?

☐ LCD Display on Unit
☐ LCD Plotting Display on Unit
☐ Wireless Transmit to Computer

How much would you pay for a product like this?

☐ Less Than $100
☐ $100 to $200
☐ More Than $200

Rate the following categories from 1-5 with 5 being the highest:

The idea of the product =

A need for a product like this =

Your interest in purchasing this product =

Any additional comments or suggestions that you may have are greatly appreciated:

Appendix IV: MatLab Code

```
function labsim

% Start from -2pi and go to +2pi, incrementing by 0.01 each step
t = (-2*pi):0.0001:(2*pi);

%The height from the cube to A, B and C (in meters) is...
ha = 0.0762;
hb = 0.0762;
hc = 0.0762;

%The length from the cube to A, B and C (in meters) is...
%Cube in middle...
La = -0.0508;
Lb = 0;
Lc = 0.0508;
% Cube under left...
% La = 0;
% Lb = 0.0508;
% Lc = 0.1016;
%Cube under right...
% La = -0.1016;
% Lb = -0.0508;
% Lc = 0;

%The distance from the cube is...
Da = sqrt(La^2 + ha^2);
Db = sqrt(Lb^2 + hb^2);
Dc = sqrt(Lc^2 + hc^2);

%The frequency (in radians per second) of each of the currents is...
w = pi/3;

%The derivative of the current in wires A, B and C is...
Ia = 6000*w*(cos(w*t));
Ib = 6000*w*(cos(w*t-(2*pi/3)));
Ic = 200*w*(cos(w*t-(4*pi/3)));

%The number of turns in the cube is...
N = 100;

%The effective area of the cube (in meters squared) is...
Ae = 0.00258064;

%The permiability of air is...
uo = 4*pi*10^(-7);

%The x component of the voltages are...
Vax = N*Ae*uo*(1/(2*pi*Da))*Ia*cos(atan(La/ha));
Vbx = N*Ae*uo*(1/(2*pi*Db))*Ib*cos(atan(Lb/hb));
Vcx = N*Ae*uo*(1/(2*pi*Dc))*Ic*cos(atan(Lc/hc));
```

```
%The y component of the voltages are...
Vay = N*Ae*uo*(1/(2*pi*Da))*Ia*sin(atan(La/ha));
Vby = N*Ae*uo*(1/(2*pi*Db))*Ib*sin(atan(Lb/hb));
Vcy = N*Ae*uo*(1/(2*pi*Dc))*Ic*sin(atan(Lc/hc));

%The 45° component of the volatges are... .969
Va45 = N*Ae*uo*(1/(2*pi*Da))*Ia*0.79139;
Vb45 = N*Ae*uo*(1/(2*pi*Db))*Ib*(sqrt(2)/2);
Vc45 = N*Ae*uo*(1/(2*pi*Dc))*Ic*0.272386;

%Adding all of the x components together...
Vx = (Vax + Vbx + Vcx);

%Adding all of the y components together...
Vy = (Vay + Vby + Vcy);

%Adding all of the 45° components together...
V45 = (Va45 + Vb45 + Vc45);

% Plot Vy, Vay, Vby, Vcy vs time...
figure(1);
plot( t, Vay, '-r')
hold on
plot( t, Vby, '-b')
plot( t, Vcy, '-g')
plot( t, Vy,  '-m')
hold off
title('Vy magenta is combined value');

%Plot Vx, Vax, Vbx, Vcx vs time...
figure(2);
plot( t, Vx, '-m')
hold on
plot( t, Vax, '-r')
plot( t, Vbx, '-b')
plot( t, Vcx, '-g')
hold off
title('Vx magenta is combined value');

%Plot V45, Va45, Vb45, Vc45 vs time...
figure(3);
plot( t, V45, '-m')
hold on
plot( t, Va45, '-r')
plot( t, Vb45, '-b')
plot( t, Vc45, '-g')
hold off
title('V45 magenta is combined value');

%Plot Vy vs Vx… gives the ellipse figure
figure(4);
plot( Vy, Vx, '-m')
```