Hall Effect Sensor Design for Transformer Protection

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Abstract

The purpose of this project was to design a sensor circuit that can detect when transformers are experiencing internal faults (turn to turn) or not operating within their normal specifications. Transformers experience failures caused by Internal Arcing, Geomagnetically Induced Currents, Phase to Ground or Phase to Phase Faults, and Magnetic Core Damage. The developed sensor circuit helps detect when the transformer’s performance is compromised. Three situations can be revealed by the sensor; 1.) Normal Operation, 2.) Insipient Damage, 3.) Potential for catastrophic damage. Theoretically analysis is confirmed by a prototype.
Executive Summary

Solar activity can have a negative effect on the Earth’s electricity distribution systems. With a constantly growing reliance on electricity it is important that these distribution systems are protected from events that can cause them damage. Solar Flares from the sun release immense amounts of energy, particles and ions. The Earth’s Magnetic Field deflects most of the material released from the sun, but some is able to penetrate the field and reach the Earth. When this material reaches the Earth, the particles and ions can negatively affect transformers and transmissions lines. They cause induced currents in the transmission lines which create an offset. This offset of current creates a DC component to the current in transformers. The extra current can cause damage to the transformer over time and in some cases can cause them to fail. Transformers are expensive to replace and can leave areas without electricity.

There are methods in place to try to detect when material from solar flares are going to make it through the magnetic field and affect electrical systems. NOAA is an organization that monitors the Sun’s activity. They use satellites to detect the amount of material ejected during these flares. Using the data from its satellites, scientists are able to predict the effect a solar flare will have on Earth. These predictions aren’t always 100% accurate. Sometimes they think a flare is going to have an effect on Earth and there ends up being very little effect and there are times that scientists expect nothing and the Earth gets effected by solar material.

Transformers can also experience internal faults. Shorts between windings of the primary or secondary coils can cause an imbalance of currents within the transformer. This can cause insulation to break down and depending upon the level of the fault, the transformer can fail. Differential Circuit are used to ensure that there is not an imbalance of currents between the coils and that the transformer is
working properly. Once the imbalance reaches a certain point then a relay trips and shuts down the transformer. At this point there could already be serious damage done to the transformer.

The designed circuit will be able to be used to detect increases in the magnetic field as caused by geomagnetically induced currents by the use of a Hall Plate. A small increase in the magnetic field will result in a voltage across the hall plate. This voltage is then amplified to a measureable level and connected to 2 Schmitt Triggers. These Schmitt Triggers have different turn on voltages to show different levels of danger. The output of the Schmitt Triggers are connected with a series of NAND gates which are in turn connected to 3 different colored LED’s. Only 1 LED will be on at a time and each LED shows a different state of the transformer.

The designed circuit can also be used for differential protection. Instead of using a Hall Plate, the input to the Amplifier would be the voltage across a resistor in the differential circuit. When there is a fault within the transformer the differential circuit will show an imbalance of currents and there will be a voltage drop across the resistor. The designed circuit would be able to detect the fault and would display the correct LED to show the state of the transformer.
Background

Solar Activity

Solar Storms start out as what’s called a Solar Flare. “A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released” [1]. There are 3 stages of a Solar Flare: the Precursor stage, the Impulsive stage and the Decay stage. During the first stage, a burst of magnetic energy in the solar atmosphere is released. This magnetic energy is built up over time because of the material in the sun at the equator moves faster than at the poles which cause the magnetic fields lines to become intertwined. This results in a cooling in the sun which results in a sunspot. “When the magnetic field is strong enough – and twisted enough – jet streams of flowing currents create ropes of magnetism. Most of the rope lays inside the sun, but part of it may break through the visible layer, where it is viewed in the form of two sunspots” [2]. When bursts occur, radiation is emitted that covers all of the electromagnetic spectrum. This is the second stage of a solar flare. The radiation, that includes radio waves (long wavelengths) all the way to gamma waves (small wavelengths), is emitted in all directions from the focal point of the solar flare. Along with radiation, particles such as electrons and protons are heated and accelerated through the sun’s atmosphere. Since these are only emitted from where the flare occurs, only a small portion of it actually comes in contact with the Earth. In the final stage, “the gradual build up and decay of soft X-rays can be detected” [1].

When the particles and radiation, also referred to as Solar Wind, from these solar flares reach the earth they interact with the Earth’s atmosphere. Not all of the material from the sun actually makes it to the Earth’s surface though. The Earth’s main layer of defense against the sun is magnetosphere. The magnetosphere is an “area of space, around a planet, that is controlled by the planet’s magnetic field” [3]. It acts like a shield from solar winds deflecting most of it away into space.
As shown in Figure 1, some of the material from solar flares does manage to penetrate the magnetosphere at its weakest points, the poles. When this occurs a phenomena that is called auroras are seen in the skies where the particles enter the atmosphere. Depending on how much material enters the atmosphere and the intensity of the solar winds, the auroras can be stronger or weaker and stretch down towards lower latitudes.

The intensity of the solar winds depends on what class the solar flare from the sun is. There are 5 classes of solar flares: A, B, C, M and X. The classes measure the X-Ray flux in $W/m^2$ and each class is 10 times stronger than the previous with A being the weakest at $<0.1 \mu W/m^2$ and X being the strongest starting at $0.1 mW/m^2$ [4]. There are also numbers 1 through 9 that get paired with each class that act as a multiplier so an A2 solar flare is twice as strong as an A1 solar flare. Since the X Class is the highest class, the numbers that are associated with it don’t stop at 9.
A and B Class flares don’t have any effect on the Earth. C Class flares can have a very small effect on the earth only if they are long in duration and happen to produce a Coronal Mass Ejection (CME). M Class flares are medium to large flares. They can cause small to moderate radio blackouts on the daylight side of the Earth. Strong M Class flares which are long in duration paired with a CME can cause the aurora effect to appear on middle latitudes. X Class flares are the strongest type of flare. These are the most dangerous to Earth and can cause strong radio blackouts, strong solar radiation and strong magnetic storming when the CME hits the Earth. The strength of X Class flares can also damage satellites orbiting the Earth [5].

The highest recorded solar flare was an X28. The X-Ray sensor was actually saturated at X17.4 for 12 minutes from the radiation but after further analysis it was concluded that the flare peaked at X28. Thankfully for us this burst was not directly in the path of the Earth and only grazed a small portion of us. If it was aimed at the Earth, scientists feared it would have been a “space storm unlike anything seen in the Space Age” [6]. The only other comparable solar event to this was one that occurred in 1859 and has been called the Carrington Event. Unfortunately the flare was observed before the technology was available to record how big it was but the effect was definitely noticed. Auroras were visible all over the United States and seen as far south as Cuba. Telegraph operators, the biggest form of communication at the time, reported sparks leaping from their equipment and in some cases causing fires to start. If this size strength flare were to hit the Earth today with the amount of electronics that we use, there would be immeasurable damage [7].

Luckily solar flares like these don’t happen too frequently. The sun actually follows what scientists call a Solar Cycle which is the periodic change in solar activity. Figure 2 shows the history of the solar activity since 1940.
A solar cycle lasts on average 11 years. The variation throughout each cycle results in changes in the amount of sunspots, solar flares and CME’s as well as affecting the weather here on Earth. Just because a cycle isn’t at its peak for activity doesn’t meant that strong flares can’t occur. Sunspots are caused by the shifting of magnetic fields. The shifting of the magnetic fields causes the temperature to drop in those spots resulting in what appears to be darker areas on the sun. In reality they are still extremely bright but they just appear to be darker than the remainder of the sun. When the magnetic field in the spots gets strong enough a flare occurs so the more sunspots that are on the sun the greater chance of a solar flare occurring.

When the particles from a flare or a CME reach the Earth all electrical devices are at risk of being damaged. All electrical devices have certain specifications for maximum voltages, currents, temperatures, etc. If any of these are exceeded then the part will not function as intended and can damage the part to the point of not working at all. These particles from the sun can cause the maximum specs to be exceeded without being known to its user.
Solar Flares Effect on Earth

According to the Biot-Savart Law when current passes through a wire there is an induced magnetic field around the wire. The field is stronger closer to the wire and can be stronger depending on the amount of current flowing. In an infinitely long wire, the formula to determine the magnetic field ($B$) at a point that is a distance of $X$ from the wire is the following:

$$B = \frac{\mu_0 I}{4\pi X}$$  \hspace{1cm} (1)

This principle also works in the opposite direction. If a changing magnetic field is introduced to a conducting loop, a current will be induced upon the circuit. This is called Electromagnetic Induction. If the magnetic field is placed near or within the loop there will not be an induced current. The fact that the field is moving along a wire or loop causes the electrons to also move which in turn creates a current. Again, the strength of the magnetic field and the distance from the circuit affect how much current will be induced.

Solar Storms affect all types of electronic devices from small devices such as cell phones to bigger ones such as high power transmission lines. Transmission lines are large wires that are coupled with transformers to transfer power from power plant to power plant until the power reaches its end location whether that is a house or a business. When electricity is run through the transmission lines, it is first passed through a transformer which lowers the current and raises the voltage to minimize the amount of power lost when being transmitted through the lines. The higher the current the more energy is lost through the heating up of the wires which lowers the overall efficiency. Figure 3 shows the typical path that electricity takes to get to a house.
When the solar storms affect the electronic devices they are increasing the magnetic field that the devices are in. When the magnetic field increases around the device, the current will also increase in the circuitry. In the case of transmission lines, when this current increases it can result in the transformers overheating, stop functioning or in rare cases explode. Traditionally current flows through transmission lines in a sine wave with an offset of 0A but when there is a magnetic presence the offset will change. This offset causes the transformers to saturate and overheat which can lead to malfunctioning and the burning out of them.

When transformers are broken and not working, the time to needed to replace them can be two months if there is a spare transformer available. If there isn’t one readily available then the time to replace them greatly increases as they would likely need to be custom ordered from the supplier. If a small number of transformers are broken the overall system could still work but if there was an event that knocked out multiple then there would be an extended period of time before they could all be
swapped out. This would leave customers and businesses without power until the transformers are operating again [9].

**Types of Transformer Protective Systems**

Scientists have ways to monitor the Sun’s activity to predict the effect it will cause on the Earth. They predict that 2013 will be a peak year for solar activity and the National Oceanic and Atmospheric Administration (NOAA) issued a warning about solar flares hitting the Earth in 2012 and 2013. The NOAA uses satellites to monitor the sun along with other conditions that are occurring in space. They collect data that is transferred down to Earth to be interpreted by researchers [10]. There is also the Solar Shield Project which runs simulations based on data similar to that collected by NOAA to make predictions about solar storms. “When an operator sees an eruption on the sun, he or she will derive the three-dimensional parameters of that eruption, such as size, speed, and direction” [9]. This data can provide a day or two notice to researchers if there is strong solar activity heading towards the Earth. In the case of strong storms, electricity distributors can adjust the flow of power away from certain transformers if they are aging and are in need of repair. In a juristic case the power could be turned completely off to prevent damaging the system but this would result in a blackout. When the storm had fully passed the system could be turned back on and the power restored.

Even with all of this technology being used to keep tabs on the sun’s activity not all CME’s are detected and can surprise us here on Earth. There are also instances where a solar storm is predicted to hit us and nothing ends up happening. It is better to air on the side of caution when dealing with solar storms rather than have massive electrical damage to the systems on Earth. That is why I have designed a simple sensor circuit that can detect a rise in the offset of a transmission line.
There are also other issues within transformers that can cause damage over time. Turn to turn shorts and turn to ground shorts change the ratio of the primary to secondary turns in a transformer. When shorts occur between turns on the primary coil, the output of the secondary coil will increase and can cause damage to the insulation within the transformer.

Differential Protection is a technique used to keep transformers from malfunctioning. Current transformers are connected at the primary and secondary coils. These are connected together as shown in Figure 4.

![Figure 4 - Differential Protection Circuit](image)

The Protected Element is the transformer and the primary and secondary coil have a current transformer connected to each of them. A relay is placed in parallel between the positive and the negative terminals. If the transformer is working ideally then there will be no currently flowing through this additional circuit. When there is a fault within the transformer, current will flow though the circuit and into the relay. Most differential relays are set to trip a switch when the current hits a certain value. This prevents the transformer from experiencing severe damage from high currents. Unfortunately, if there is a small fault within the transformer, the necessary current level to trip the relay might not be reached leaving the transformer at risk for damage over time.

Instead of using a Differential Relay, the circuit being designed in this project can be used to detect small faults between turns or from a turn to ground. Instead of a relay connected in parallel, a resistor would be used in its place. The current would flow through the resistor instead of the relay.
Similarly to the use for detecting dangerous levels of geomagnetically induced currents, this circuit could be used to measure the voltage across the resistor. This would be able to detect when there were faults within the transformer so they could be changed before more damage was done to the transformer. By changing certain aspects of the design for this project, the sensitivity can be adjusted for each necessary application.
Procedure

Transformer Sensor Design

The design intent for this project was to create a circuit that can detect when there is an increase in the magnetic field at low frequencies. The first step was to research ways to detect changes in the magnetic field. There were a couple ways that this could be done. The Hall Effect and Giant MagnetoResistance (GMR) were the two most common ways. GMR is “the change in electrical resistance of some materials in response to an applied magnetic field” [12]. Hall Effect is a phenomenon when a magnetic field is introduced perpendicular to a semiconductor with a constant current flow through it. The combination of the magnetic field and constant current flow create Voltage difference across the semiconductor that is perpendicular to the flow of current.

Figure 5 - How Hall Effect Works [13].

For this project, the Hall Effect will be used. Figure 5 shows the basic setup of a Hall plate. In order to create a constant current through it a 1% tolerance Resistor can be used. The current value doesn’t need
to be specific, but in most cases the Hall plate is small so the current shouldn’t be so large that it damages the semiconductor material.

The formula used to calculate the output voltage from the Hall plate is in Equation 2.

\[ V_H = \frac{I B_\perp}{\rho_n q t} \]  

Equation 2

Where: 
- \( I \) is the current through the hall plate, 
- \( B_\perp \) is the magnetic field perpendicular to the Hall Plate, 
- \( \rho_n \) is the number of charge carriers per unit volume, 
- \( q \) is the magnitude of the charge carriers, and  
- \( t \) is the thickness of the hall plate [14].

With a set hall plate and current going through it, the current, the charge of the carriers and the number of carriers per volume is known. The only remaining variables in this equation are the Hall Voltage and the magnetic field. When a magnetic field is applied perpendicularly to the hall plate the voltage can be measured and used to solve for the actual field being applied. If we say for example that we apply a field of .01T to a copper hall plate (\( \rho_n = 8.47 \times 10^{28} \)) with a constant current of 1mA, the voltage that would be measured would be about .736nV.

Since this value is so extremely small, the first thing that needed to be added to the circuit design is an amplifier to increase the signal from the hall plate. The gain of the amplifier can be selected based on what field level is deemed a threat to the transmission lines. Another requirement for this stage of the design is to be a low pass filter. The incoming material from the sun has long wavelengths and since the power being transferred in the transmission lines has much shorter wavelengths, the sensor being designed will only focus on low frequency magnetics. Once the signal is increased to a value that can be measured, the next thing that will need to be added to the circuit is a Schmitt Trigger. A Schmitt Trigger will take the input signal and output either a logic high or a logic low depending on the amplitude of the input waveform. For this design, two Schmitt Triggers will be used, one for when the field is slightly outside of the normal operating range and the other for when the field is potentially
harming the transformer. Each of these operating ranges, Good, Warning and Alarm, will be signified by different colored LED’s connected to the outputs. In order for only 1 LED to be on at a time, a series of NAND gates will be used to turn on and off each LED. Figure 6 shows the Block Diagram for the circuit to be designed.

![Block Diagram for the Sensor Design](image)

**Simulation**

For simulation the design, MultiSim 12 software was used. The first block that was simulated was the Low-Pass Amplifier Design. There are many different kinds of low pass filters. They differ by the placement and the number of capacitors in the circuitry. The more capacitors there are, the higher the order of the filter. Higher order filters have better cutoff frequencies, but there are resonant frequencies that result in large spikes in the gain of the amplifier. For this design, a 2\textsuperscript{nd} Order Sallen-Key Low Pass filter design was used. There are a couple of factors that need to be chosen when designing a low pass filter: the Cutoff Frequency and the Quality Factor (Q Factor). For a Sallen-Key filter, the formulas to solve for each of these variables are shown in Equation 3 and 4 respectively [17].

\[ 2\pi f_0 = \frac{1}{\sqrt{R_1R_2C_1C_2}} \]  
\[ Q = \frac{\omega_0}{2\alpha} = \frac{\sqrt{R_1R_2C_1C_2}}{C_2 (R_1 + R_2)} \]
The cutoff frequency is when the gain of the amplifier begins to be less than 100% and the output signal begins to lessen in amplitude. The $Q$ factor shapes the gain to frequency plot. The higher the $Q$ factor the sharper the elbow of this graph. Since there are a lot of variables in these formulas, the resistor values and capacitor values can be written in terms of each other to simplify each expression. $R_1$ will be equal to $R$ and $R_2$ will be equal to $m \times R$. The same will be done with the capacitors so $C_1$ will equal $C$ and $C_2$ will equal $n \times C$. When the simplification is done the following formulas in Equations 5 and 6 can be used.

\[
2\pi f_0 = \frac{1}{RC\sqrt{mn}} \quad (5)
\]

\[
Q = \frac{\sqrt{mn}}{m + 1} \quad (6)
\]

Since the $Q$ factor formula has fewer variables this value was determined first. A $Q$ factor of 0.707 was chosen for this design which means that both resistors have the same value and both capacitors have the same value. Now that the $Q$ factor is known and the resistors are the same and the capacitors are the same the cutoff frequency can be chosen. A frequency of 60Hz was chosen for simulations leaving just the actual values for the capacitors and resistors to be chosen. A capacitor value of 0.1µF and a resistor value of 25kΩ were chosen which results in a cutoff frequency of about 60Hz. Now that the filter design is completed the gain of the amplifier needs to be chosen. Using a Non-Inverting configuration the gain was chosen to be 3 for now. Resistor values of 2kΩ and 1kΩ were used to achieve the proper gain. Figure 7 shows the circuit used for simulation.
The gain was the first thing to be verified during simulations. The probes were connected to the input signal (Node 5) which is set to a 1V sine wave to represent a signal from the Hall plate and to the output (Node 2) of the amplifier. Figure 8 shows the Input and Output Waveforms vs. Time.
An AC analysis was also performed on the circuit to observe the gain in comparison to the frequency.

Figure 9 shows that the gain stays steady at 3 for all low frequencies. When the frequency begins to approach 60Hz the gain begins to drop towards 0. At about 100Hz the gain of the input signal is at about 1 and at frequencies above 400Hz the gain is less than .1.
The amplifier has increased the signal coming from the hall plate and has filtered out all of the high frequency noise around the circuit. The next step in the block diagram is the Schmitt Trigger. The Schmitt Trigger will be used to create different logic outputs for the circuit depending on the signal from the amplifier. It will create 3 different operating modes. The first will be a Safe Mode where the input signal is under a certain voltage. The second will be a Warning Mode which has a higher voltage than the safe mode and indicates that the transformer is in beginning to get close to an unsafe operating range. The final mode is the Alarm Mode which has an even higher input voltage range and signifies that the transformer is in danger of becoming damaged. With 3 different modes there will need to be 2 Schmitt Triggers.

The trigger levels for each Schmitt Trigger are based on the supply range and the resistors chosen for it. For simulations the supply was chosen to be 5V. Figure 10 shows the basic configuration for a Schmitt Trigger.

For the 3 operating regions the supply range will be divided into 3 areas of equal size. 0V to 1.67V will be the safe mode, 1.67V to 3.33V will be the warning mode and 3.33V to 5V will be the alarm mode. When the output is in a high state it acts like the 5V supply resulting in $R_1$ and $R_3$ being in parallel and then connected to $R_2$ in series. When the output is in a low state it acts like it is connected to ground resulting in $R_2$ and $R_3$ in parallel and then connected in series to $R_1$. Using these 2 formulas resistor values can be chosen for each Schmitt trigger. For the Schmitt trigger with the turn on voltage of 1.67V, $R_1$, $R_2$ and $R_3$ were chosen to be the same value of 1kΩ. This results in a turn-off voltage being 3.33V. For the Schmitt trigger with a turn-on voltage of 3.33V, $R_1$ was selected to be 1kΩ and $R_2$ and $R_3$ were selected to be 4kΩ. This results in a turn-off voltage of 4.167V. Figure 11 shows circuit layout for simulation for both Schmitt triggers.
Figure 10 - Schmitt Trigger Circuit used for Simulation.

The circuit on the top has a turn-on voltage of 1.67V and the circuit on the bottom has a turn-on of 3.33V. An oscilloscope was connected to the input of the voltage source (Node 3), the output of the top Schmitt Trigger (Node 5) and the output of the bottom Schmitt Trigger (Node 4).
Figure 11 - Input and Output Voltages of Schmitt Triggers vs Time.

Figure 12 shows each of the output voltages along with the input voltage. The Blue waveform is the input signal which was set to a 5V sine wave at 60Hz which was used to simulate an output from the amplifier. The Red waveform is the output of the Schmitt Trigger with the 1.67V turn-on. A cursor was used to verify that the output did indeed turn on at 1.67. The Green waveform is the output of the Schmitt Trigger with the 3.33V turn-on and again, a cursor was used to verify the correct turn-on point. When the input signal went negative the output railed because the VEE pin was connected to GND and the VCC pin was connected to 5V. If the VEE pin for the comparator was changed to -5V the turn-on and turn-off voltages would change. Alternatively, if the input signal is strictly positive then the comparator won’t experience this issue.

The hysteresis of each Schmitt Trigger was also simulated. A hysteresis plot shows the input waveform vs the output waveform. Figure 12 shows the hysteresis of the 1.67V turn on Schmitt trigger and Figure 13 shows the hysteresis of the 3.33V turn on Schmitt Trigger.
Since the input signal to the Schmitt Triggers has such a low frequency the transition from the low state to the high state doesn’t happen instantaneously. The output voltages also aren’t hitting the rail so amplifiers will be used to get the desired 5V output.

Now that the outputs of the Schmitt Triggers are set to turn on at the desired inputs, the final stage of the circuit is to show using LED’s what state the transformer is in. This was done by using Logic Gates and different colored LED’s. The safe operating state is when both trigger outputs are low and is denoted by a green LED. If either or both of the triggers are in a high output state then this LED will turn off so signify that the transformer is no longer in its typical operating range. This can be made using an XOR logic gate. The warning operating state is when only 1 trigger is in the high output state and will result in a yellow LED turning on. This can be made using a combination of an AND gate and an Inverting Gate. With the configuration of the Schmitt triggers, the trigger with the 1.67V turn-on will be the only
one that can be on at once. If the trigger with the 3.33V turn-on is on then so will the 1.67V trigger because the same input signal is used for both. The alarm operating state occurs when both triggers have high output states and is signified by a red LED. This can be made by using an AND gate. Each of the logic gates needed for this step of the circuit was simulated using the NAND gates equivalents. Figure 14 shows the Logic Gate configuration.

![Logic Gate Configuration](image)

4 NAND gates were used to achieve the safe operating state, 3 for the warning operating state and 2 for the alarm state. When both J1 and J2 are connected to GND only the green LED is on. When J1 or J2 is connected to the 5V supply only the yellow LED is on. When both J1 and J2 are connected to the 5V supply only the red LED is on.
Results

Just like the simulations, each part of the circuit was tested in steps. The first circuit to be tested was the amplifier circuit. A function generator was set up to output a 1V sine wave with a frequency of 1Hz. Two 1.5kΩ and two 1µF capacitors were connected as shown in the simulation circuit in Figure 7. The amplifier being used is aUA741CN chip and it has the same pin layout as the LM741CN used in the simulation. A voltage supply was used to generate the 5V supply and the -5V supply for the rails of the amp. A 2kΩ and a 1kΩ resistor were used to create a gain of 3 from the input signal to the output signal.

Figure 15 - Input and Output Voltages of Amplifier vs Time at 10Hz.

Figure 15 shows the input signal from the function generator (CH1 yellow) along with the output signal of the amplifier (CH2 blue). The peak of the input signal is 1V and the peak of the output signal is 3V which is the desired gain for the circuit. The frequency of both waveforms is 10Hz. When the circuit was designed the cutoff frequency was chosen to be 100Hz so the input waveform’s frequency was adjusted to 40Hz and 100Hz to view the attenuation of the output waveform. Figure 16 and 17 show the Input (CH1 Yellow) vs Output (CH2 Blue) waveforms at those frequencies.
As expected, as the input waveform’s frequency gets closer to the cutoff frequency of the low pass filter, the overall gain becomes less and less. The phase of the output is also shifted as was expected.
The next circuit to be tested was the Schmitt Triggers. The comparators used for the Schmitt Triggers are LM311N chips. The three 1kΩ resistors were connected as shown in the circuit diagram in Figure 10 for the top Schmitt Trigger and the 1kΩ and two 4kΩ resistors were connected to the other Schmitt trigger. The input waveform was set up using a function generator to ensure it was working properly before connecting the amplifier circuit. The initial waveform being sent to the comparators was a 3V peak to peak sine wave at 10Hz. To simulate the effect of an increasing magnetic field at the hall plate sensor the offset of the function generator was increased to bias the signal going into the Schmitt Triggers. As the signal was increased both Schmitt Triggers turned on as Figure 18 shows.

Figure 18 shows the input signal (CH1 Yellow) which is a 3V peak to peak waveform that has been offset to result in a maximum peak of 5V. The total range of the waveform is about 2V to 5V. As the output of the 1.67V Schmitt Trigger shows (CH2 Blue), the output is almost always in the high state. The other Schmitt Trigger’s output (CH3 Pink) begins turning on at around 3.33V. The main issue that can be seen in Figure 18 is the noise that occurs during the output transitions low to high and high to low and on the
high output signal of the 3.33V turn-on Schmitt trigger. Figure 19 shows a zoomed in inspection of this occurrence.

![Figure 19 - Noise on the Output Transitions of Schmitt Triggers.](image)

Further investigation of the datasheet for the LM311N confirmed the issue. “… when the input signal is a voltage ramp or a slow sine wave, or if the signal source impedance is high (1kΩ to 100kΩ), the comparator may burst into oscillation near the crossing-point. This is due to the high gain and wide bandwidth of comparators like the LM111” [15]. The datasheet had a couple of suggestions on how to remove these oscillations but none of them worked. They needed to be removed because it was affecting the output of the next stage of the circuit which is the Logic Gates and LED’s. Without a smooth transition and a smooth output high value the Logic Gates will have multiple LED’s on rather than just one showing the correct state of the transformer.

This wasn’t observed in the simulations because the amp was in ideal conditions so the best way to find a fix for these oscillations was to add components to the output in the lab. After the suggestions in the datasheet didn’t work, a 10pF capacitor was added from the output to GND to try to clear up the
output. This also had no effect on the output. Finally a 1kΩ resistor was also added from the output to GND and the signal was cleared up, but the output voltage was lower. By adjusting the resistor value the output voltage would increase but the noise would also increase. Figure 20 shows the input (CH2 Blue) and output (CH3 Pink) waveforms from the 1.67V turn-on trigger with the 1pF and 1kΩ components connected in parallel from the output to GND.

![Figure 20 - Input and Output Voltages of 1.67V Schmitt Trigger vs Time.](image)

As the input (CH2 Blue) signal’s offset was increased, the first Schmitt Trigger’s output (CH3 Pink) was constantly high. Once the second trigger’s turn-on voltage was hit the second output (CH4 Green) began to switch to a high state. The 1pF capacitor and 1kΩ resistor were also added to this circuit from the output to GND. Figure 21 shows this.
Since the outputs from the Schmitt Triggers are operating correctly and without noise the final portion of the circuit can be tested. Three MC74AC132N chips were used to get the necessary number of NAND gates. Each chip has 4 NAND gates so each LED had its own chip. The circuit was wired just as shown in Figure 14. A voltage supply set to 5V was used to simulate a high pulse from the outputs of the trigger. As expected, the NAND Gate configuration works and each LED turns on for each condition it was supposed to.

When the circuit was connected all together for testing, it was observed that even though the output of the Schmitt triggers was in a high state, it wasn’t at the necessary voltage for the NAND gates to see it as a high pulse. The 1.67V Schmitt Trigger was only reaching 1V in its high state and the 3.33V Schmitt Trigger was only reaching about .7V. To fix this issue another set of amplifiers were added to the output of each Schmitt trigger to increase the signal to 5V. This allowed for a 5V high pulse to be sent to the NAND Gates and the LED’s to be on in a bright state. Figure 22 shows the final scope measurements from each major point of the circuit.
Figure 22 shows the input voltage (CH1 Yellow) at 1V peak to peak from .2V to 1.2V. The output of the amplifier (CH2 Blue) shows the input signal getting amplified 3 times to have a range of .6V to 3.6V. The output of the 1.67V Schmitt Trigger (CH3 Pink) is switching high and low properly and has a larger voltage than before to correctly use as an input signal to the NAND Gates. The output of the 3.33V Schmitt Trigger (CH4 Green) is also switching high and low properly and has a the necessary voltage for the NAND Gates.

**Differential Protection**

When a transformer is working properly the input voltage and output voltage can be calculated based on the ratio of inductance in the primary to secondary. The current in the primary and secondary coils is the inverse of the voltage ratio which follows the Law of Conservation of Energy. Figure 23 shows...
a circuit with the primary coil in the transformer broken out into 2 sections and the secondary core in 1 section.

Figure 23 - PSpice Transformer Circuit

The input voltage waveform is set to a 10V sine wave at 60Hz. To get a voltage ratio of 2 to 1 for the transformer, the primary coil will need to have an inductance of 10H if the secondary coil has an inductance of 2.5H as shown in Equation 7 [18].

\[
\frac{V_1}{V_2} = \frac{\sqrt{L_1}}{\sqrt{L_2}}
\]  

(7)

Since the primary coil is broken into 2 sections, Equation 8 was used to solve for the inductance of each inductor [19].

\[
L_{eq} = L_1 + L_3 + 2M
\]  

(8)

M is the mutual inductance between the 2 inductors. Equation 9 is used to substitute in for M and is used to solve for L_1 and L_2.
\[
M = k \sqrt{L_1 L_3}
\]  \hspace{1cm} (9)

For simulations, \(k\) which is the coupling between the coils was selected to be 1 and \(L_1\) was selected to be 4H. In reality the coupling between coils can never reach 1, there will always be some level of leakage between the coils. Knowing that the equivalent inductance needs to be 10H, \(L_3\) was solved to be 1.35H. The circuit in Figure 15 was simulated to verify correct voltage ratio. Figure 24 shows the input and output voltages vs time.

![Figure 24 - Input and Output Voltage Waveforms vs Time.](image)

Differential Protection circuits use current transformers on both sides of the transformer to determine when there is an imbalance between the current in the primary coil and the current in the secondary coil. The ratio of current between the primary and the secondary coils is the inverse of the voltage ratio. In the simulations, the voltage ratio is 2 to 1 therefore the current ratio is 1 to 2. Dummy Voltages were used in the Transformer Circuit on each side of the transformer. The current through
these voltage sources are used for each current transformer in the sub circuit. Figure 25 shows the sub circuit.

![Differential Protection Circuit](image)

**Figure 25 - Differential Protection Circuit.**

Since the current in the secondary coil is twice that of the current in the primary coil, G1 is equal to the current through VD times 2 and G2 is equal to the current through VF. This will result in a net current of 0A in the sub circuit and no voltage drop across R3.

In order to simulate a fault within the transformer, a voltage controlled switch VP was used to short L3. When L3 is part of the circuit, the current in the differential circuit should be 0. When the switch is close and L3 is shorted, there will a voltage drop across R3. Figure 18 shows the Voltage across R3 when L3 is connected to the circuit and when L3 is shorted. L3 is shorted at 100ms.
As the coupling between the inductors change, the output waveform in the differential circuit also changes. Not all transformers are designed the same so each current transformer would be adjusted to match the currents in the primary and secondary to ensure that 0 current is flowing through the differential circuit when the transformer is operating properly.

The $k$ between the inductors was changed from .999 to .99 to see the effect on the output waveform. Figure 27 shows this.
Figure 27 shows the voltage across $R_3$ with $k = .99$ instead of .999. The voltage across $R_3$ is not exactly 0 in this situation because the equivalent inductance of $L_1$ and $L_3$ is not 10. With the values for those inductors already being selected to be 4H and 1.35H, changing the $k$ factor changes the value for $M$. The voltage across $R_3$ when $L_3$ is shorted is also much less than when $k = .999$. When $k$ is changed again to .9 instead of .99 the voltage will increase when $L_3$ is part of the circuit and the voltage will drop when $L_3$ is shorted from the circuit.
If the coupling between the inductors is known then the equivalent inductance for the primary could be used to calculate out the actual inductance ratio. This would allow the current transformers to be properly selected to guarantee 0 current though the differential circuit when the transformer is operating properly.

The Sensitivity of the transformer circuit was also simulated. $R_S$ is connected into the circuit when the switch is closed and shorting out $L_3$. $R_S$ was varied from 0.1Ω to 10kΩ. The changing of this resistor changes the current in the primary coil. This change in the input current also means that the current in the secondary coil also changes. With $L_3$ shorted the voltage across the resistor $R_3$ in the differential circuit experiences different amounts of voltage depending on the value of $R_S$. Figure 29 shows the voltage across $R_3$ vs. the current when $L_3$ is shorted.
As $RS$ is changed from $.1\Omega$ to $10k\Omega$, the input current to the transformer gets smaller and smaller which in turn results in the voltage across $R3$ to be smaller and smaller. By varying the value of $RS$, the sensitivity of the output can be changed. The designed sensor circuit can detect very small faults by decreasing the value of $RS$ or it can ignore smaller faults and only detect large faults by increasing the value of $RS$. 

![Sensitivity Graph](image)

**Figure 29 - Voltage across $R3$ vs Fault Current**
Conclusion

The purpose of this project was to design a sensor that can detect when there are dangerous geomagnetically induced currents within transformers caused by solar flares. These currents can cause transformers to overheat and breakdown. There are methods in place such as NOAA to predict when transformers are at a higher risk of being affected by geomagnetically induced currents. Unfortunately these predictions aren’t 100% accurate and induced currents can affect transformers without a warning. The designed circuit will be able to detect small changes within the transformers’ operation and alert its user.

The designed circuit can also be applied in a differential protection circuit to detect when there is a turn to turn fault within a transformer. Instead of using a differential relay between the primary and secondary windings, this circuit could be placed with a resistor in place of the Hall Plate. The voltage changes across that resistor would act like the output of the Hall Plate and the designed sensor circuit would be able to detect small faults within the turns of the transformer.

By changing the gain of the amplifier stage of the sensor design or the turn on voltages for the Schmitt Triggers, this circuit could be configured specifically for any transformer. By using this circuit, faults caused by geomagnetically inducted currents and faults within transformers can be detected and used to prevent serious damage to transformers.
Appendix

* Differential Circuit for MQP

V1 1 0 sin(0 10 60)
R1 1 2 1m
L1 2 9 4 IC=0
L2 3 0 2.5 IC=0
L3 9 4 1.35
K1 L1 L2 0.999
K2 L1 L3 0.999
K3 L2 L3 0.999
R2 3 5 1000
VD 4 0 0
VF 5 0 0
VP 10 0 PULSE(0 10 100m 1u 1u 2 4)
S 9 4 10 0 ZWICK
.MODEL ZWICK VSWITCH(RON=1m ROFF=1MEG VON=1 VOFF=0)

RS 4 40 {PA}
.PARAM PA=1
.STEP PARAM PA LIST .1 .1 10 1000 10000

G1 0 8 VALUE=I(VD)*2
*RG1 6 0 10

G2 8 0 VALUE=I(VF)
*RG2 7 0 10

R3 8 0 10

.PROBE

.TRAN 200m 200m 0 100u UIC

.END
Works Cited