Use of Hall Effect Sensors for Protection and Monitoring Applications

A report to the Relaying Practices Subcommittee I
Power System Relaying and Control Committee
IEEE Power & Energy Society

Prepared by Working Group I-24

Working Group Assignment

Report on the use of Hall Effect Sensors for Protection and Monitoring Applications. The report will discuss the technology, and compare with other sensing technologies.

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TABLE OF CONTENTS

TABLE OF FIGURES

1 Introduction

The Relaying Practices Subcommittee ("I" SC) of the PSRC develops, recommends, and establishes standards on protective relaying practices for electrical power systems. Among other responsibilities, this includes characteristics and performance of instrument transformers and evaluation of other pertinent aspects of protective relaying not addressed by other PSRC Subcommittees. Furtherance of this mission includes the evaluation and encouragement of technologies that may be useful to advance the art of protective relaying, for example, technologies that may be useful for power system measurements or fault detection. The Working Group I24 was formed in May 2013 to investigate the use of Hall Effect Sensors and application of this technology to protective relaying. The I-24 Working group assignment is to "Develop a Report on the Use of Hall Effect Sensors for Protection and Monitoring Applications. The report will discuss the technology and compare with other sensing technologies." This report of the I-24 WG is intended to serve as an introduction to the Hall Effect, current sensing applications based on the Hall Effect, considerations that may be useful to protective relaying applications, and a survey of any existing applications that make use of this technology in protective relaying or related fields that may find application in protective relaying. Hall Effect sensors can be used to measure both moving magnetic fields (i.e., rotating machinery) and stationary magnetic fields (i.e., power lines). This report has focused on applications of measurement of stationary magnetic fields.

2 Theory – What is Hall Effect

The Hall Effect is the voltage potential produced in a conductor as a result of interaction of the perpendicular magnetic field and the current flow in an electrical conductor. This effect was discovered by Edwin Herbert Hall in 1879 while he was working on his doctoral degree at Johns Hopkins University in Baltimore, MD. In the presence of a magnetic field, the moving charges that carry the current are subjected to the Lorentz force $F=q\cdot(E+v\times B)$ resulting in a buildup of charge on one side of the conductor and a depletion of charge along the other side. The charge buildup results in an electric field and potential difference, the Hall Voltage, that resists the further buildup of charge. The Hall Voltage is proportional to both the perpendicular component of the magnetic field and the bias current and depends on the material properties and geometry.

The flow of current in a conductor produces a magnetic field according to Ampere's circuital law. For a simple geometry such as an isolated current-carrying conductor, the magnetic field is symmetrical around the conductor, is directed perpendicular to a plane containing the conductor, and has magnitude that is proportional to the current and inversely proportional to the distance from the conductor. A Hall Effect sensor that detects the magnetic field can provide an indication of the magnitude of the current that produced the magnetic field if the distance to the conductor is known and there are no interference effects from other nearby current sources.

A Hall Effect sensor is a transducer that outputs a voltage in response to the magnetic field generated by the current flow. The sensor is used to accurately measure primary conductor current without affecting the circuit.

This report provides a description of the different types of Hall Effect sensors used, the response characteristics of these sensors and how they might be applied for relay protection and monitoring applications.

3 Current Sensing Hall Effect Sensors

A primary requirement in protection is obtaining a continuous signal that is proportional to the current flowing in the protected system. To obtain this signal for measurement and processing, linear Hall Effect sensors may be used. These devices deliver an output signal which is a linear function of the magnetic flux density passing perpendicularly through its Hall element.

Although the direct measurement of the magnetic field of a conductor is possible, in practice most Hall Effect current-sensing requirements do not develop adequate magnetic fields without the use of a Field Concentrator. Field Concentrators often consist of a soft magnetic material (high permeability and low remanence) that surrounds the conductor. A gapped or slotted toroidal core is often used to concentrate (and focus) the induced flux field at the Hall Effect Device (HED) as illustrated in Figure 3.1.

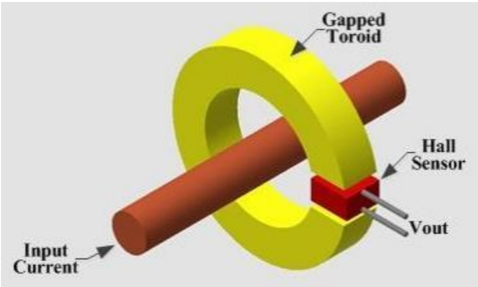

Figure 3.1: Toroid Concentrator

Based upon the HED component and the core materials selected, currents of significant magnitude (that is, more than 15 A) may induce adequate field intensities that allow passing the current-carrying conductor straight through the center of the toroid. Lower currents (less than 15 A) may require winding sufficient turns on the gapped toroid core to induce adequate flux strength to develop a suitable signal voltage as illustrated in Figure 3.2.

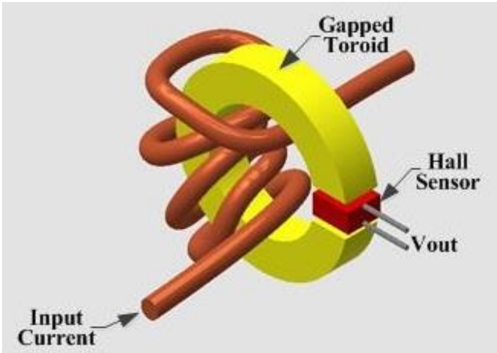

Figure 3.2: Multiple Turns to Increase Flux Strength

4 Sensor Types

Hall Effect sensors come in two basic types, Threshold (alternatively called digital, or on-off) or Linear (analog output) Hall Effect sensors.

4.1 Threshold sensor

A Threshold sensor will operate similar to a switch and produce an on/off type output when the impressed field strength reaches a certain amplitude and/or polarity. An example of a threshold sensor is shown in Figure 4.1. There are many different threshold device configurations such as latching devices which turn on when a positive field strength reaches the threshold but only turn off under a negative field of the same strength, devices which turn on when only a positive field reaches a certain threshold and are off otherwise, or devices which turn on when either a positive or negative field reaches the threshold and are off otherwise.

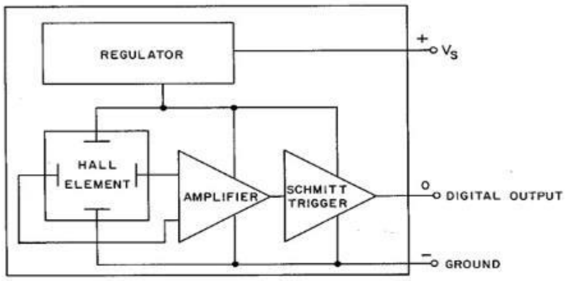

Figure 4.1: Example of a Threshold Hall Effect Sensor

4.2 Linear sensor

A Linear type sensor, as illustrated in Figure 4.2, will produce an analog output that is proportional to the strength of the impressed magnetic field upon it. The orientation of the surrounding magnetic field determines the polarity of the voltage swing. Linear devices can be used for both ac and dc current measurements.

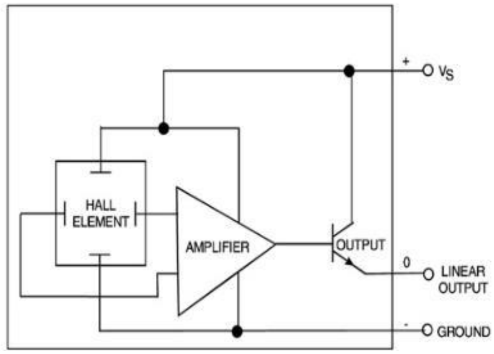

Figure 4.2: Example of a Linear Hall Effect Sensor

5 Current sensor configurations

When utilizing a Linear Hall Effect sensor for current measurements, the sensor/concentrator is usually configured either in an open-loop or closed-loop configuration. An open-loop Hall Effect sensor uses the Hall voltage directly to produce its output signal that is proportional to the impressed magnetic field generated by the sensed current signal. This has the advantage of being simpler to implement, but measurement accuracies may suffer due to nonlinearities in both the sensor and the concentrator when operating over its current sensing range and over variations in operating ambient temperatures.

A closed-loop sensor/concentrator has a coil that is actively driven to produce a magnetic field that opposes the field produced by the current being sensed. The Hall sensor is used as a null-detecting device, and the output signal is proportional to the cancelling current being driven back into the coil, which is proportional to the current being measured. This method is more complex than the open-loop method, but it eliminates nonlinearities associated with the Hall sensor and the concentrator, since they are now being operated at a single constant point within their operating range.

On the downside, a closed loop current sensor draws substantially higher supply current and the measurement range may be reduced by the driving limitation of the feedback circuitry. The closed loop design is more complex and aspects like stability have to be addressed. The setup also requires more circuit components and additional coil windings, resulting in a higher price tag than the comparably simple open-loop configuration.

5.1 Closed Loop/Null Balance Sensor Theory of Operation

In the open loop configuration, most errors are caused by the variations in the sensed current magnitude causing magnetic flux density variations in the concentrator that do not exhibit a perfect linear relationship due to core losses and other material properties. Because of these nonlinearities, it is best to operate the concentrator material at a single point of approximately 0 gauss or zero flux. The Hall sensor accuracy will also be highest at this 0 flux point because multiplicative sensitivity errors are decreased and only the comparably small additive offset errors remain. To achieve this 0 flux magnetic field in the concentrator loop, a closed loop circuit design can be utilized that produces a counteracting feedback current (I_F) that creates a magnetic flux that will oppose and cancel that generated by the primary sensed current (I_{in}).

Closed loop sensors amplify the output of the Hall Effect sensor to drive a current through a wire coil wrapped around the core. The magnetic flux created by the coil is exactly opposite of the magnetic field in the core generated by the conductor being measured (I_{in}). The net effect is that the total magnetic flux in the core is driven to zero, so these types of sensors are also called null balance current sensors.

This feedback current can be scaled by adjusting the turns ratio of the primary to feedback current windings in such a way that only a fractional amount of the primary current (I_{in}) is required in the feedback loop to null the magnetic flux in the measurement gap. Deviations from zero magnetic flux are sensed by the linear Hall Effect sensor inserted in the field concentrator gap. Both primary and feedback conductors must act on the same magnetic concentrator as shown in Figure 5.1.

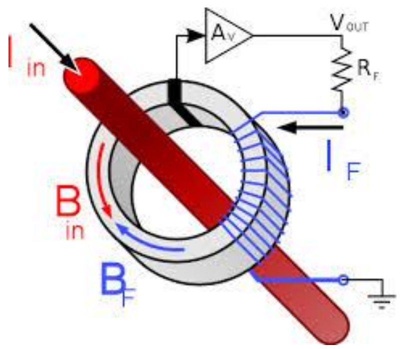

Figure 5.1: Closed Loop Sensor

By supplying the appropriate amount of compensation feedback current (I_F) through the negative feedback loop, the linear Hall Effect sensor output is driven towards a level that represents an output of 0 gauss. The magnitude of the feedback current can then be measured using a small sense resistor R_f. The secondary conductor contains many windings, multiplying its flux generating ability, thus the amount of compensation current can be significantly reduced. For example, a module with a 1000 turn feedback coil would provide an output of 1 mA per Ampere-turn in the primary circuit.

5.2 Commercially available Hall Effect current sensor Configurations

Most currently produced Hall Effect Sensors are of the form of a discrete component or an integrated circuit that provides an output signal proportional to the overall strength of a magnetic field created by a permanent magnet or a current carrying conductor. Integrated circuit (IC) sensors often incorporate additional circuits for biasing, offset reduction, temperature compensation, and signal amplification. The integration improves the performance of the sensor, along with reducing the number of parts for detection and use.

Shown below are a few typical commercially available Hall Effect Sensors that can be utilized for current sensing applications.

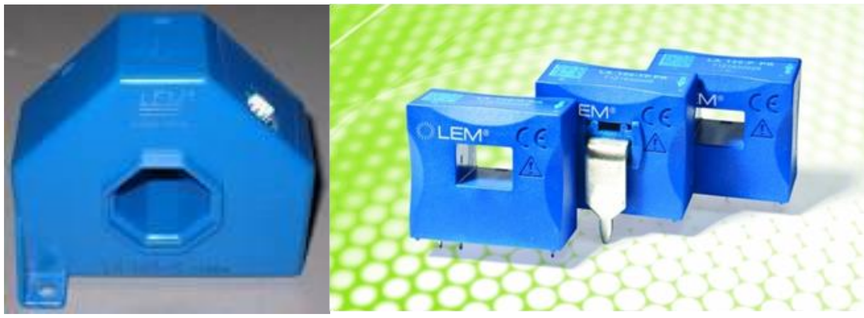

Figure 5.2: Linear Current Sensing Hall Effect Sensors, [LEM USA, Inc., www.lem.com]

The sensors illustrated in Figure 5.2 are similar to that of a toroid current transformer, in that the current carrying conductor is routed through the center opening. These sensors are linear closed loop types that will accept either an ac or dc current for measurement.

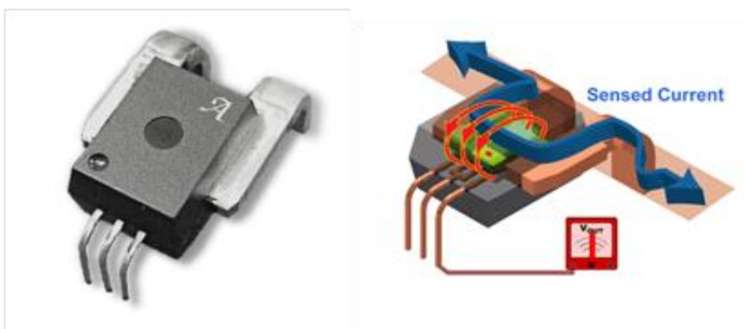

Figure 5.3: Integrated Circuit Hall Effect Current Sensor [Allegro MicroSystems, LLC, www.allegromicro.com]

The sensor illustrated in Figure 5.3 is intended to be directly mounted to a printed circuit board. Currents from ±50 A to ±200 A can be directly measured through the Hall Effect sensor contained within the IC, and provide electrical isolation between the detection circuits and the monitored current source.

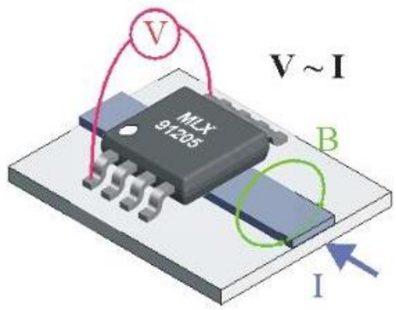

Figure 5.4: Integrated Circuit Hall Effect Current Sensor [Melexis Semiconductors, www.melexis.com]

In Figure 5.4, a printed circuit mounted sensor is illustrated that directly monitors the current flowing in a circuit board wiring trace located directly below the IC component. The circuit trace may be located on an interlayer or bottom layer of the printed circuit board, in order to increase dielectric isolation from the sensor.

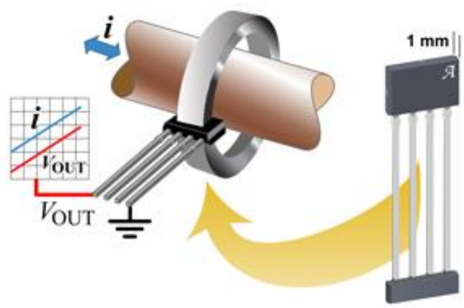

Figure 5.5: Integrated Circuit Hall Effect Sensor [Allegro MicroSystems, LLC, www.allegromicro.com]

Figure 5.5 illustrates the use of an IC sensor mounted within a concentrating core, to provide an output that is proportional to the current flowing through the conductor. The sensor IC would typically be mounted to a printed circuit board that includes additional circuitry for measurement or detection.

A clamp-on Electronic Current Transducer (ECT) sensor constructed using Hall-effect materials is shown in Figure 5.6. The sensor is an open loop design that uses a clothespin-like enclosure. The actual transducer is visible in the center of the sensor and is covered by a curved strip of high-permeability material, such as mu-metal, used for shielding against external magnetic fields and for amplifying internal ones. The output from the transducer is provided over a shielded RJ45 cable. This type of enclosure provides for simple installation on live wires without the necessity for removing equipment from service. [5.1]

Figure 5.6: Hall-effect ECT Sensor with Shielded Clothespin Enclosure

6 Calibration and Construction Details

Hall-effect materials are used to make electronic current transducers (ECTs). Depending on the intended use, ECTs can produce voltage or current outputs. If the transducers are within proximity of the recording equipment, then voltage outputs are sufficient. Otherwise current outputs are preferable because of voltage drops that occur over long runs of cable. When placed on a cable, the transducers provide outputs that are proportional to the electromagnetic fields induced by the currents flowing through the cable. The outputs are linear within the sensitivity range of the transducers. The application of a constant scale factor and an offset are therefore sufficient for calibrating the transducers.

The sensitivity range of Hall transducers varies depending on model type and manufacture. For example, the sensor shown in Figure 5.6 that was used for the testing presented in section 7 has a range that may vary from 1 A to 150 A. Other sensors may have different measurement ranges. The distance from the transducer to the cable also affects sensitivity. The further the transducer is from the cable the less sensitive it is because the strength of the induced magnetic field weakens as the transducer moves away from the cable (reciprocal of the distance). Transducers are intentionally placed a fixed, controlled distance away from the sensed conductor in order to increase dynamic range because lower sensitivity increases measurement range of maximum current that can be sensed before saturation of the transducer.

ECT sensors can have wide frequency response and can provide accurate representations of the measured current. It should be noted, however, that the recording equipment in the remainder of the measurement system must also provide sufficient accuracy to the intended purpose. Analog to digital conversion must use sufficient levels (bits) in order to minimize quantizing error and sufficiently high sampling rate must be used along with anti-aliasing filters to provide adequate high frequency response for measurement of harmonics and transients.

The typical equation used to calibrate Hall-effect transducers is Y = AX + B, where:

- Y is the magnitude of the calibrating current flowing through the cable,
- X is the measured output of the transducer,
- B is the measured offset value or zero level (output for 0 A flow), and
- A is the calculated scale factor: (Y – B) / X.

With proper calibration and recording, Hall-effect transducers are useful for a wide range of equipment monitoring applications in the substation. These applications include but are not limited to capturing electromechanical relay targets, monitoring dc control circuits, recording breaker trip signatures, measuring inrush currents, and monitoring phase currents in secondary circuits of current transformers (CTs). It should be noted that in applications monitoring CT secondary currents, any error introduced by the primary CT due to ratio error or saturation effects for example, will not be corrected by the Hall Effect sensor measuring the secondary current.

7 Response Characteristics

The Hall Effect ECT of Figure 5.6 was selected as an example for testing for comparison to other traditional electrical current sensors. The frequency response of the selected Hall-effect ECTs is up to 100 kHz. The response time is in the 10 microseconds range making the transducers capable of accurately representing dc and ac currents including high order harmonics from 50 and 60 Hz sources.

In an effort to measure the response characteristics of the Hall-effect ECTs, members of the working group conducted a series of tests. The tests utilized a set of COMTRADE [7.1] records, a power system simulator (PSS), a digital fault recorder (DFR), the example Hall-effect ECT, and an Aux CT and resistive shunt to benchmark performance. The tests were conducted multiple times using different ECTs and CTs to ensure repeatability. A depiction of the test platform is shown in Figure 7.1.

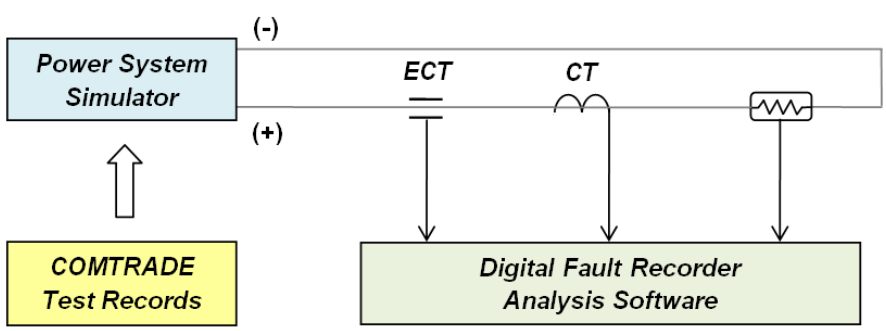

Figure 7.1: Response Characteristics Test Platform using COMTRADE Playback

The tests focused on measuring the ac and dc response characteristics of the Hall-effect transducers and the results were compared to the performance of the Aux CTs as shown in sections 7.1 and 7.2. The temperature response characteristics were also measured from -18° C to 60° C (0° F to 140° F) and the results are shown in section 7.3.

The test results show that the ac magnitude and phase response characteristics of the Hall-effect ECTs are within 1% of the injected PSS magnitude and within 1° of the injected PSS phase angles. The test results further reveal that ECTs accurately replicate dc components and do not offset or saturate like the Aux CTs do. The results also show that the magnitude response of the Hall-effect ECT is affected at temperature extremes but that the phase response is not. The magnitude response is linear in the range 32° F to 100° F (0° C to 38° C). However, the magnitude drifts linearly with temperature by a factor of up to 0.5% as the temperature decreases from 32° F to 0° F (0° C to -18° C), and also by 0.5% as the temperature increases from 100° F to 140° F (38° C to 60° C). Note that these response characteristics are specific to the ECT tested and other devices may have different response characteristics.

7.1 AC Response (Magnitude and Phase)

Figure 7.2 shows a plot of the ECT and Aux CT responses to a 60 Hz ramp waveform injected by the PSS. The injected waveform ramps up from 1 A to 160 A. Each step in the ramp lasts for 4 cycles. The first trace (brown) is the recorded output of the ECT, the second trace (green) is the recorded output of the Aux CT, and the third trace (blue) is the injected waveform through a shunt resistance. Clearly the ECT and CT waveforms accurately replicate the injected waveform. In Figure 7.3, the ECT and CT waveforms are super imposed on top of the PSS waveform. The waveforms mirror the PSS waveform so well that the only visible color is brown.

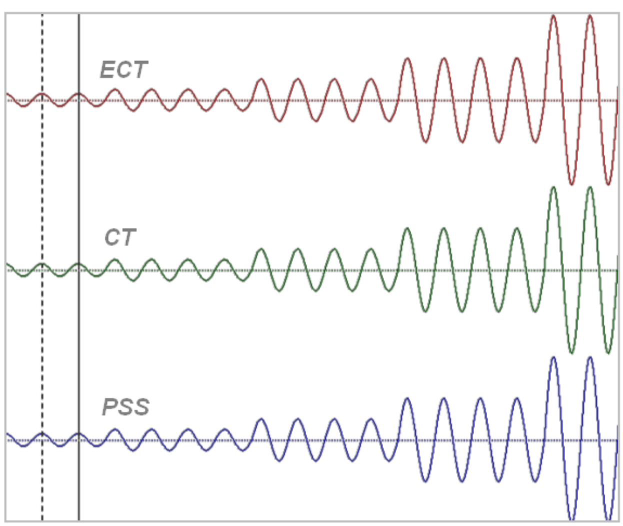

Figure 7.2: AC Response to a Ramp Waveform (1 to 160 A RMS)

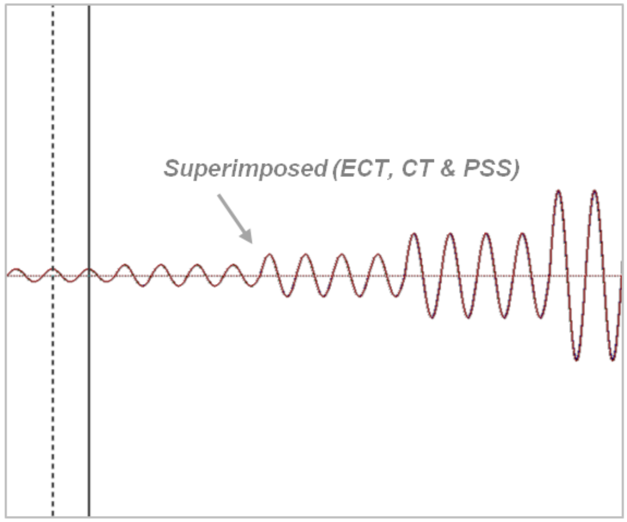

Figure 7.3: AC Response to a Ramp Waveform (Superimposed Traces)

Figure 7.4 shows the percent deviations of the measured ECT and CT magnitudes from the magnitude of the injected PSS waveform. The percent deviations are charted for each ramp within the injected waveform. The chart shows that the magnitude response of the tested ECT is accurate to within 1% of the injected magnitude, and that the tested CT is accurate to within 0.4% of the injected magnitude. In Figure 7.5, the phase angle differences of the ECT and CT from the injected PSS phase angles are charted. The chart shows that the phase angle responses of both the ECT and CT are accurate to within 1 degree of the injected waveform.

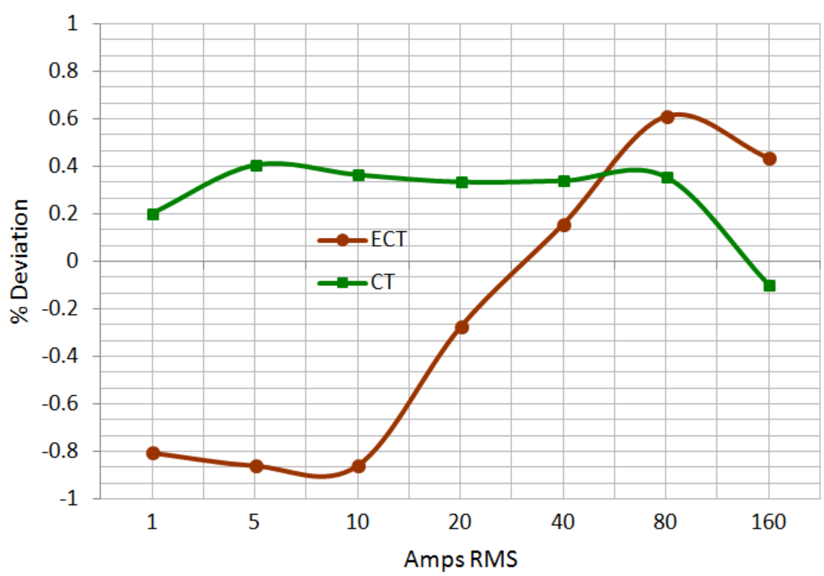

Figure 7.4: AC Magnitude Response

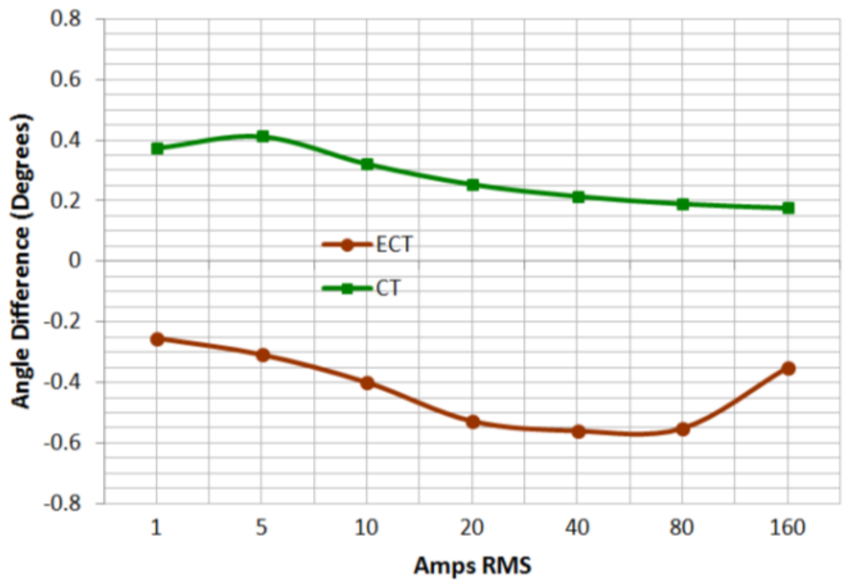

Figure 7.5: AC Phase Response

7.2 DC Offset Response (Magnitude and Phase)

Figure 7.6 shows a plot of the ECT and Aux CT responses to a fully offset 60 Hz waveform injected by the PSS. The injected waveform is the sum of a sinusoidal ac waveform with peak magnitude 80 A and an exponentially decaying dc component with initial magnitude 80 A. The first trace (brown) is the recorded output of the ECT, the second trace (green) is the recorded output of the Aux CT, and the third trace (blue) is the injected waveform recorded through a shunt resistance. Clearly the ECT waveform accurately replicates the injected waveform but the CT waveform reveals significant offset and saturation signatures starting at the second cycle. In Figure 7.7, the ECT and CT waveforms are super imposed on top of the PSS waveform. The ECT waveform reproduces the PSS waveform so well that only one trace is visible, but the CT waveform shows deviation and distortion.

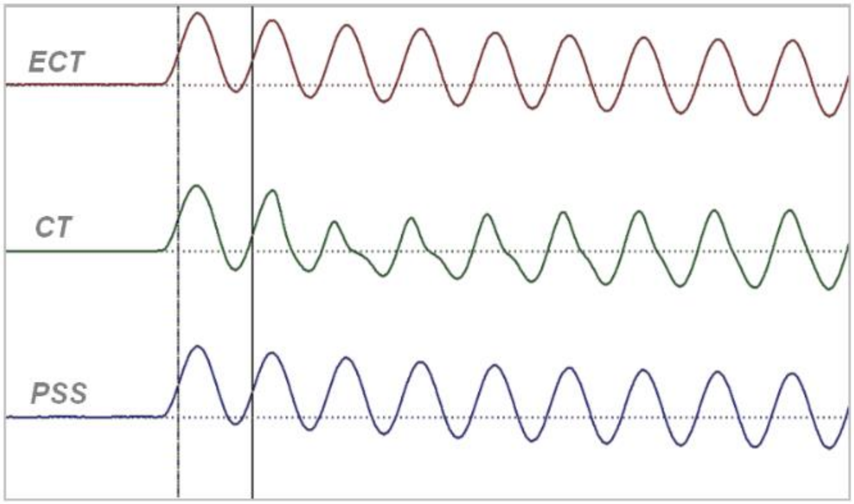

Figure 7.6: DC Offset Response (Magnitude and Phase)

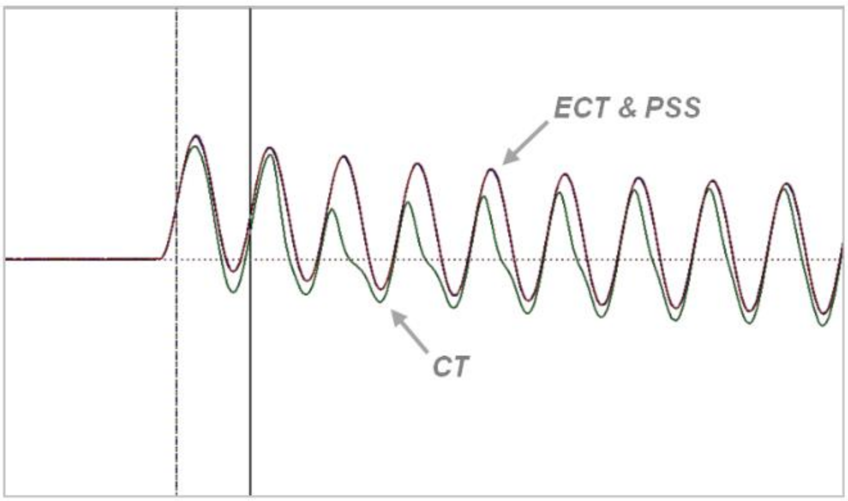

Figure 7.7: DC Offset Response Superimposed

Figure 7.8 shows the percent deviations of the measured ECT and CT magnitudes from the magnitude of the injected PSS waveform. The percent deviations are charted for a set of fully offset waveforms from 10 A to 160 A. The chart shows that the magnitude response of the ECT is still accurate to within 1% of the injected magnitude but that the accuracy of the CT response is now at 5% for magnitudes below 40 A and significantly deteriorating to well over 40% for magnitudes nearing 160 A. In Figure 7.9, the phase angle deviations of the ECT and CT are charted. The chart shows that the phase angle response of the ECT remains accurate to within 1 degree of the injected waveform but that the accuracy of the CT response significantly deteriorates to almost 36 degrees for offset magnitudes nearing 160 A.

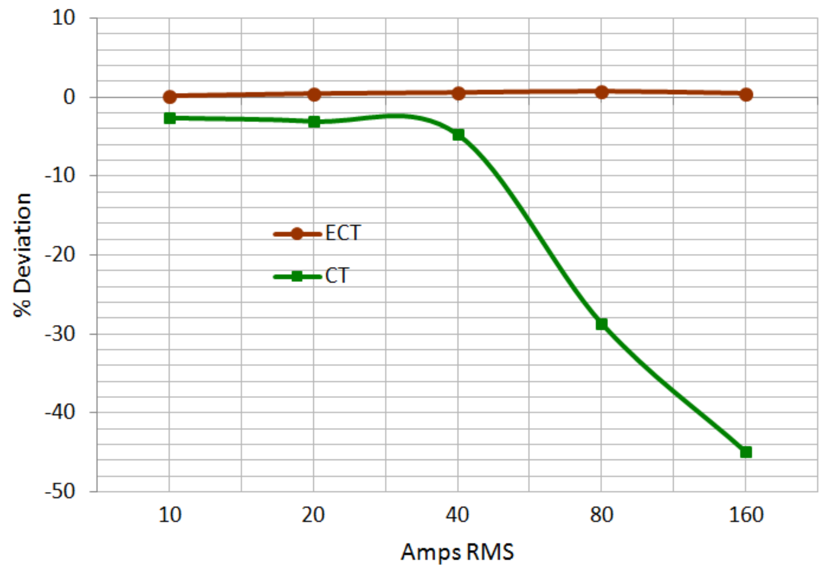

Figure 7.8: DC Offset Magnitude Response

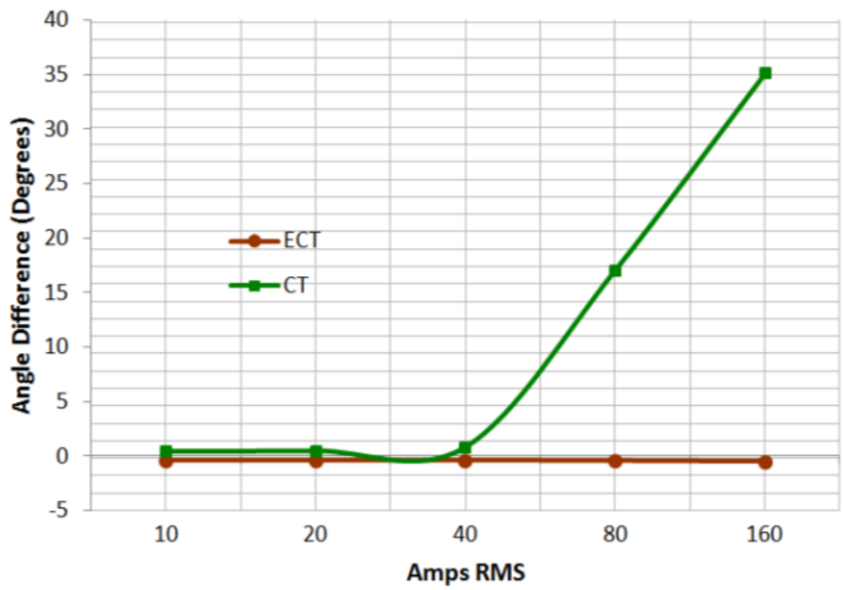

Figure 7.9: DC Offset Phase Response

7.3 Temperature Response (Magnitude and Phase)

Variation of sensor response with temperature is presented in this section. It should be noted again that this variation is specific to the devices tested and that other devices may have response that differs from these illustrative examples. Figure 7.10 shows the percent deviations of the ECT and CT magnitude responses from the injected magnitude of the PSS waveform at various temperatures. The percent deviations are charted for a set of temperatures ranging from 0° F to 140° F (-18° C to 60° C). The chart shows that the magnitude response of the ECT is constant in the range 32° F to 100° F (0° C to 38° C) but that the magnitude drifts linearly from the constant response by a factor of up to 0.5% as the temperature decreases from 32° to 0° F (0° C to -18° C) or increases from 100° F to 140° F (38° C to 60° C). However, the CT magnitude response remains constant throughout the range. In Figure 7.11, the phase angle differences of the ECT and CT are charted. The chart shows that the phase angle responses of both the ECT and CT are not affected by temperature changes and remain accurate to within 1 degree of the injected waveform.

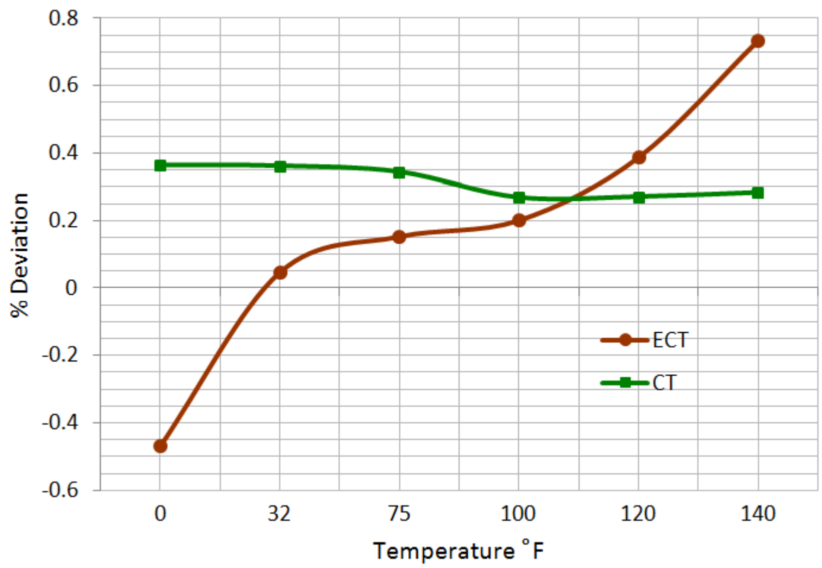

Figure 7.10: Temperature Magnitude Response

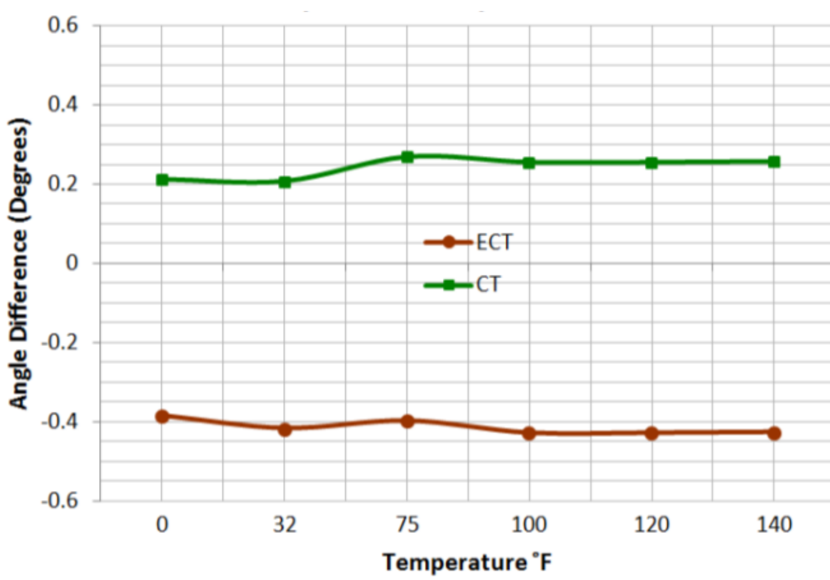

Figure 7.11: Temperature Phase Response

8 Overview of Other Measurement/Sensing Technologies

This section of the report will provide the reader with a brief review of other current sensing technologies. Additional discussion can be found in references [8.1] and [8.2].

8.1 Iron-Core Current Transformers

An ideal bushing-type iron-core current transformer (CT) will operate with the primary current times the primary turns ratio equal to the secondary current times the secondary turns ratio. However, an actual CT does not behave ideally. The CT secondary voltage is generated by the rate of flux change in the core. To produce flux in the CT core, magnetizing (exciting) current is required. This magnetizing current introduces ratio and phase errors. IEEE Std. C57.13 [8.3] specifies CT behavior under steady-state and symmetrical fault conditions. The CT ratio error is specified to be ±10% or less for fault currents up to 20 times the CT rated current and up to the standard burden. However, if symmetrical fault current exceeds 20 times the CT rated current, or if the fault current is smaller but contains dc offset (asymmetrical current), the CT will enter into saturation. The secondary current will be distorted, and the current RMS value will be reduced.

8.2 Gapped-Core Current Transformers

Iron-core current transformers can be designed with or without air gap in the core. In a non-gapped-core CT, a remanent flux may remain in the core after fault current has been interrupted. When grain-oriented iron-core CTs are saturated, a remanent saturation flux of 70-80% may remain in the core. Very little of the remanent flux can dissipate during normal CT operation and it will remain in the core until the CT is demagnetized. An air gap in the core reduces remanent flux. Typically, an air gap of 0.0001-0.0003 per unit of mean length of the magnetic path will reduce remanent flux to an acceptable level. The main advantage of gapped-core CTs are smaller CT size since the air gap reduces the need for a large core sized to avoid saturation. The disadvantage is increased CT phase error and the need for more time to allow stored energy to dissipate.

8.3 Optical Current Transformers (OCTs) and Fiber Optic Current Sensors

Fiber optic sensors are used to measure direct current only in extra high voltage dc (EHVDC) transmission lines. Utilizing the magneto-optic Faraday effect, a single-ended optical fiber around the current conductor measures the dc currents of up to 600 kA with +/- 0.1% accuracy. The benefits of the fiber optic current sensor are that the sensor does not need recalibration after installation at any point throughout its lifetime, and it is unaffected by stray magnetic fields due to its optical measuring technique. Fiber optic current sensors also do not experience saturation effects like traditional current sensors do. The optical phase detection circuit, light source and digital signal processor are contained with the sensor electronics. Measurements are encoded into digital messages and "published" or broadcast onto a process network. Subscribing devices can receive the measurements from any sensors that are connected to the process network bus and multiple devices can receive the same measurement message from one sensor. One fiber optic current sensor can replace the need for many conventional current transformer cores. For further information, refer to [8.1].

8.4 Rogowski Coils

A Rogowski coil consists of helical coil of wire wound on a nonmagnetic core (air core) that has a constant cross-section with constant wire density. The coil is placed around the conductor(s) whose current(s) are to be measured. Since the voltage that is induced in the coil is proportional to the derivative (rate of change) of the measured current, the output of the Rogowski coil is usually connected to an electrical (or electronic) integrator circuit to provide an output signal that is proportional to the current. To minimize the influence of nearby conductors carrying high currents, Rogowski coils are usually designed with two wire loops connected in the electrically opposite direction. Ideally, this design will cancel the induced voltages due to external magnetic fields. In practice, complete cancellation is difficult to achieve when the external fields contain severe gradients and curvature. Two loops can be formed by making one winding and returning the wire through the center of the winding. The second method is to make the second winding on top of the first winding but wound in the opposite direction. The third method is to make two separate windings of identical design and having identical number of turns wound in the opposite direction and located next to each other. This type of coil has advantages over traditional style of current transformers because it is not a closed loop which allows the coil to be open-ended and in some cases flexible so it can be wrapped around a live conductor without disturbing it. Because the Rogowski coil has an air core, it has low inductance, it can respond to fast-changing currents, it is highly linear even when subjected to large currents, and it is not subject to saturation. For further information, refer to [8.2].

8.5 Linear Couplers

A linear coupler is an air core mutual inductor that produces output voltage proportional to the derivative of the primary current. Linear couplers are not susceptible to saturation because they do not contain ferromagnetic materials. The number of secondary turns is much greater than those in a conventional current transformer. The linear coupler V-I characteristic is a straight line having a slope of about 5 V per 1000 ampere-turns at the rated frequency. For differential protection of bus bars, linear couplers are typically connected in a voltage-differential circuit. Under normal load or external-fault conditions, the sum of the voltages induced in the secondary circuit is zero, except for very small differences resulting from manufacturing tolerances. If the secondary of a linear coupler is open-circuited, it will not be damaged nor will it create a high-voltage hazard for personnel as can occur with traditional CTs.

9 Advantages, Disadvantages, and Workarounds when using Hall Effect Sensors

The following section outlines a series of categories identifying the advantages, disadvantages, and potential workarounds when using Hall Effect sensors within equipment.

9.1 Mechanical Advantages & Disadvantages

Hall Effect sensors are very small in size, basically a small or micro sized integrated circuit. Because of the small size, Hall Effect sensors can be placed in a variety of configurations ranging from "lumps" in a cable, to flat bolt down components, to mechanically strapped assemblies. In addition to the sensor, the electronics required to read the sensor is well known and can range from a simple analog interface to a microcontroller/CPU with supporting I/O and power supply circuits. In either case, the combined packaging can be small, flexible, and very accommodating to a variance of mechanical placements. This advantage may also enhance the potential of retrofitting new sensors when upgrading equipment.

Because Hall Effect sensors measure magnetic fields, they are prone to errors generated by mechanical movements and changes in distance. If the mounting system is not rigid when placed above/upon the wire or metal conductor, the potential exists to greatly reduce the accuracy of the measurements.

9.2 Potential Mechanical Workarounds or Improvements

To overcome mechanical issues where movement cannot be eliminated or significantly reduced, the industry has moved to using two or more sensors. These designs utilize the placement of sensors located on opposite sides of the conductor, or in sequential alignment with the conductor. There is also a set of methods and sensor designs which allows the measurement of the magnetic field in 90 Degree offsets, which allows algorithms to detect and compensate for mechanical movement. Since Hall Effect sensors have been used in the industry for a very long time, there is a body of knowledge already available to help in the above areas.

9.3 Advantages & Disadvantages found with Sensor Costs

Both Hall Effect sensors and supporting measurement logic are mainly small IC solutions. Depending upon the number of sensing locations, the overall electronic assembly costs are anticipated to be very low and competitive with other sensor types. As outlined in section 9.1 Mechanical Advantages & Disadvantages, this assessment is dramatically impacted by placement and mechanical mounting designs, which can increase the cost of the overall implementation, perhaps much more than the actual costs of the sensor or reading logic.

9.4 Potential Methods for Cost Reduction

This area is highly dependent upon the mechanical placement requirements. In retrofit designs, mechanically strapping or clamping sensors onto the conductor may be a low cost mounting option providing isolation needs can be met. Another option may be removing transformer based connections and inserting solid or wire based conductors with factory mounted sensors.

As identified in the previous section 9.1 Mechanical Advantages & Disadvantages, newly replaced equipment or a field/depot based swap out of modular components would have significant advantage due to ensuring mechanically stable placement of sensors, plus adding the potential of more sophisticated, yet cost reduced, Microprocessor/Firmware based sensor reading methods.

9.5 Safety Advantages & Disadvantages of Hall Effect Sensors

Like many other sensors, an advantage of Hall Effect Sensors in regard to safety is the non-contact nature of the technology, simply because it does not require direct insertion into circuits. This provides a means for most field based retrofit implementations to provide adequate isolation for both physical safety concerns and any electrically conducted safety concerns. Although no circuit connections may need to be broken (i.e., strap/bolt on sensors), retrofit and installation procedures will require the same amount of due diligence to prevent high voltage or high current accidents from occurring.

9.6 Accuracy and Circuit Design Advantages & Disadvantages of Hall Effect Sensors

Hall Effect Sensors have many advantages, benefits, and capabilities. Among them are:

- Wide frequency response. Production of the output voltage depends on the magnitude of the detected magnetic field, not its frequency, allowing accurate measurement from dc through high frequency.
- Hall Effect sensors are non-contact and can be sealed against difficult ambient conditions, such as dust and humidity.
- Hall Effect Sensors can be used for measuring both stationary and rotating machinery applications.
- Hall Effect sensors are designed to be very consistent between the parts provided by the vendor.
- In stationary applications, they can be designed to measure high amounts of current, while not getting hot due to in circuit effects such as would occur with resistive shunts.
- Sensor aging in position sensing applications is better than emitter detector optical pairs.
- In speed and position sensing applications in rotating mechanical assemblies, Hall Effect sensors do not have contact with neighboring mechanical parts, making these sensors physically isolated while still being sensitive enough to detect movement. In this environment, they also provide the following benefits:
    - They can be designed to measure zero speed.
    - They do not wear out over time like mechanical contacts.
    - They maintain reading accuracy over the normal lifetime.
    - In comparison to contact monitoring, there is no contact arcing to worry about.

Hall Effect sensors do have disadvantages that affect accuracy and circuit design. These are primarily based around the mechanical placement with both distance and potential movement (when sensing stationary conductors) impacting the sensor sensitivity, calibration, and operating range. This requires a balanced mechanical and electrical design. Again, Hall Effect sensors measure magnetic / electromagnetic fields and this must be taken into account, which includes being affected by externally generated magnetic fields (mechanical shielding may be needed).

Also, Hall Effect sensors do operate over wide temperature ranges but circuits or software must compensate for variations of performance with temperature.

9.7 Potential Workarounds Improving Accuracy and Impact on Circuit Design

As stated in the Mechanical workarounds section, many commercial industries have used Hall Effect sensors for decades. Plus, there is an industry body of knowledge utilizing multi-sensors to compensate for various limitations, including conductor movement, intrusion or detection of external magnetic fields, temperature compensation, reading accuracy, and signal acquisition speed. Although much of this is compensated by mechanical and software designs, implementation should simply be based upon good design and reuse, rather than requiring significant hard or novel research.

9.8 Advantages and Disadvantages by Sensor Type

For further comparison, the following section highlights the advantages and disadvantages of Rogowski Coils, Current Transformers, Optical Current Sensors, and Hall Effect Sensors.

Type	Avantages	Disadvantages
Rogowski coils	• Due to its low inductance, it can respond to fast-changing currents, down to several nanoseconds. • Because it has no iron core to saturate, it is highly linear even when subjected to large currents, such as those used in electric power transmission, welding, or pulsed power applications. This linearity also enables a high-current Rogowski coil to be calibrated using much smaller reference currents. • No danger of high voltage when opening the secondary winding. • Lower construction costs. • Temperature compensation is simple. • Conventional current transformers require an increase of the number of secondary turns, in order to keep the output current constant. Therefore, a Rogowski coil for large current is smaller than an equivalent rating current transformer.	• The output of the coil must be passed through an integrator circuit to obtain the current waveform. • Integrator circuit performance will dictate bandwidth.

Type	Avantages	Disadvantages
Optical Current Transformer (OCT) and Fiber Optic Current Sensor	• High degree of immunity to Electromagnetic interferences. • Wide frequency response. • Large Dynamic Range. • Low voltage outputs-compatible with the inputs of digital to analog converters. • OCT analog output may have significant white noise, but the white noise does not affect the accuracy or protection performance. • Can be resilient to high temperatures affecting performance. • No requirement for oil or gas insulation system, environmentally safe. • No magnetic core ferroresonance or saturation limits. • Total isolation from surges.	• Vibration could affect the accuracy. • Requires mechanical enclosure around the sensor. • Excessively high magnetic fields can affect measurement accuracy.
CT	• Can be very accurate, but depends upon instrument calibration. • Isolates the measuring circuits from high voltages.	• Can be affected by high temperatures. • Susceptible to ac and/or dc saturation during faults.
Hall Effect sensors	• Wide frequency response. Production of the output voltage depends on the magnitude of the detected magnetic field, not its frequency. • Hall Effect sensors are not affected by ambient conditions, such as dust and humidity. • Hall Effect Sensors can be used for measuring both stationary and rotating machinery applications. • Hall Effect sensors are designed to be very consistent between the parts provided by the vendor. • In stationary applications, they can be designed to measure high amounts of current, while not getting hot due to in circuit effects caused by resistive load (i.e., shunt).	• The distance and any potential movement when monitoring stationary conductors will impact the sensor sensitivity and operating range. • Although Hall Effect sensors do operate over wide temperature ranges, temperature compensation does need to be implemented. • Hall Effect sensors can be impacted by externally generated magnetic fields.

10 Examples where Hall Effect Sensors are Applied

Hall Effect sensors can be used in power system protection and controls designs for monitoring and measurement of dc currents flowing on the power system primary conductors. Such sensors are not commonly applied in power system protection schemes as the protection system design engineer is most often interested in the impacts on the ac system voltage and currents. However, there are applications where measurement of a dc or very low frequency current waveform can provide valuable information to protection engineers and system operators.

10.1 Detection of Geomagnetically Induced Current (GICs)

GICs will flow when two or more points on a power system are connected to ground, in the presence of an electromagnetic field that results from a geomagnetic disturbance at the earth's magnetosphere. These GICs can have a significant, adverse impact on power system voltage stability and/or equipment integrity due to the tendency of these quasi-dc currents to saturate power transformers. Use of Hall Effect sensors on the star-ground connection on 3-phase, 2- or 3-winding transformers or autotransformers can provide valuable information related to the sensitivity or susceptibility of the power system to GICs. The same can also be applied on single phase power transformers.

For two or three-winding transformers, this measured GIC value would represent the corresponding GIC-induced flux in the core. However, for autotransformers (three-terminal devices), dc monitoring at the neutral alone will not provide the information necessary to determine the equivalent GIC flow in the transformer windings.

When considering autotransformers, real time changes to the High Voltage (HV) and Low Voltage (LV) networks must be factored into the measured data as changes in the HV and LV network could result in changes to the GIC flow in the series winding that are disproportionate to changes in common winding. This variability is difficult to capture through the application of dc monitors on the autotransformer neutrals.

A more precise means of determining the equivalent GIC flow in an autotransformer (and by extension, the dc flux in the core) would require a second dc monitor on the LV or HV terminals. Such a sensor with the necessary HVAC ratings has yet to be developed. Equipment capable of sensing dc current flow at these terminals (or on transmission lines) would allow for greater confidence in the accuracy of the system model. Such equipment could also play a key role in advancing the knowledge and understanding of the impact of GIC on the degree of saturation in autotransformers.

Reference [10.1] discusses measurement of GIC in transformer neutrals and provides some guidance on the use of Hall Effect current sensors for this purpose. The non-intrusive installation is advantageous as is the ability to measure low-frequency and dc current. Such sensors would typically be mounted outdoors, so mounting in a weather proof enclosure is typical and a sensor adequate for the expected environment and temperature range is required.

Reference [10.2] mentions the possible use of a Hall Effect current sensor as a component in an automatic protective device designed to block the flow of quasi-dc GIC by opening a neutral switch and shunting current to a capacitor when GIC is detected.

10.2 Circuit Breaker Trip Circuit Monitoring

Certain utilities use Hall Effect Sensing Devices (HESD) for monitoring trip coil energization, where the output of the sensor is used as an input to the event recorder for trip coil energization verification. The information from these sensors would provide a more positive indication that a trip coil has been energized as opposed to the traditional use of circuit breaker auxiliary contacts which indicate the position of the circuit breaker. Time of actual energization of the trip circuit is another piece of information that can be useful in de-bugging relay operation events.

Detection of the trip coil energization is the accurate way of determining the operation of the protection scheme with time stamping the output of the HESD. This kind of signal is normally supplied to station Sequence of the Event Recorder and is used for post fault analysis.

Many utilities today are utilizing IED Solid-State Relay (SSR) trip output contact to detect energization of the trip coil. There are instances, due to the human error, that can contribute to generating false information regarding the operation of a breaker. Failure to close back the blocking switch is a good example.

Another obstacle could be the IED SSR trip operate time. In many designs this time is 4 ms or higher, so the time lag from actual trip coil energization to the indication by the IED SSR may be objectionable.

Figure 10.1 depicts typical scheme utilizing HESD.

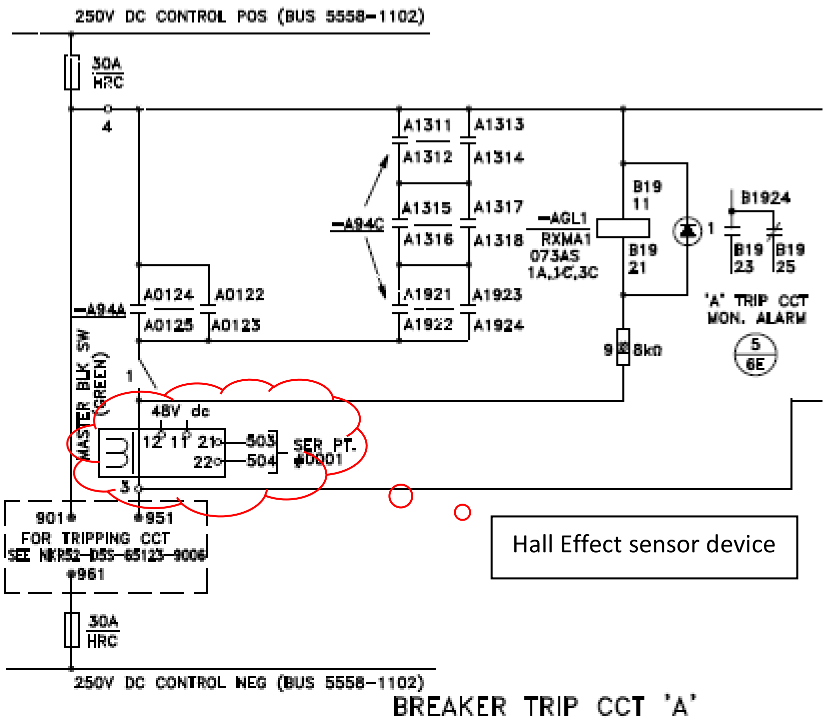

Figure 10.1:Trip Coil Energization Detection using Hall Effect Sensor Device

HESD consists of a sensor and high speed transistor output. Current detection is achieved by running a conductor through the center hole of a sensor magnetic core. The corresponding output (Transistor output) is achieved when the dc current in the through conductor is above the pre-configured threshold and the Hall Effect sensor picks up. HESD is able to function without any electrical connection to the trip coil circuit, thus not affecting the reliability of the protection scheme in any way.

When the trip command is initiated by protection IED or by an auxiliary relay, the breaker trip circuit will see sudden change in dc voltage and the trip coil will be energized. The wiring connection to the trip coil is done through the Hall Effect sensor hole; therefore, the dc current in the trip coil circuit can be monitored and sensed by the HESD.

The transistor switching output of the HESD will pick up anywhere between 100 microseconds and 1 millisecond, depending on the level of trip coil dc energization current.

Generic scheme of the Hall Effect Sensor device is shown in Figure 10.2 below.

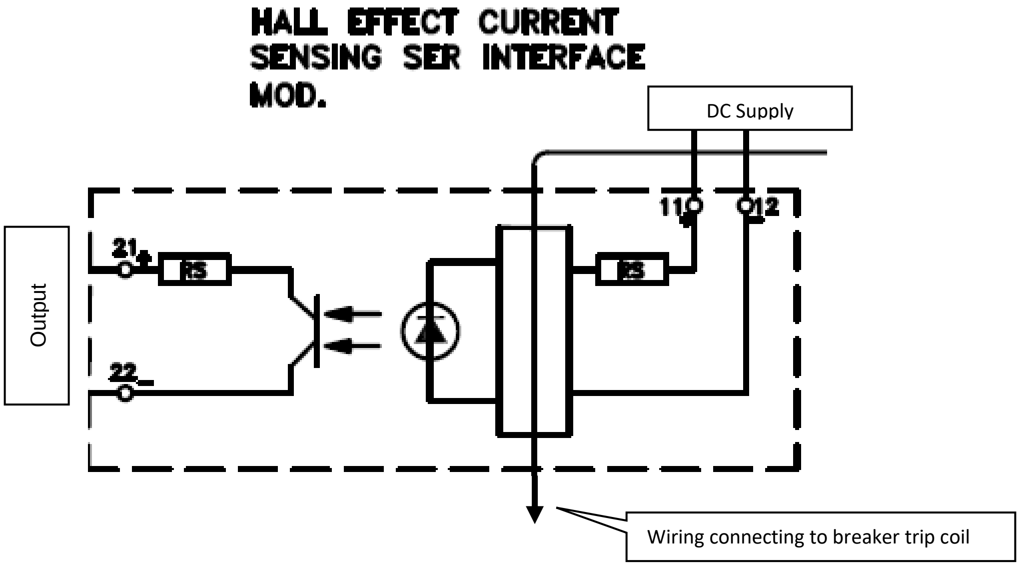

Figure 10.2: Generic Scheme of the Hall Effect Sensor Device

Typical installation inside relaying rack is shown in Figure 10.3 below.

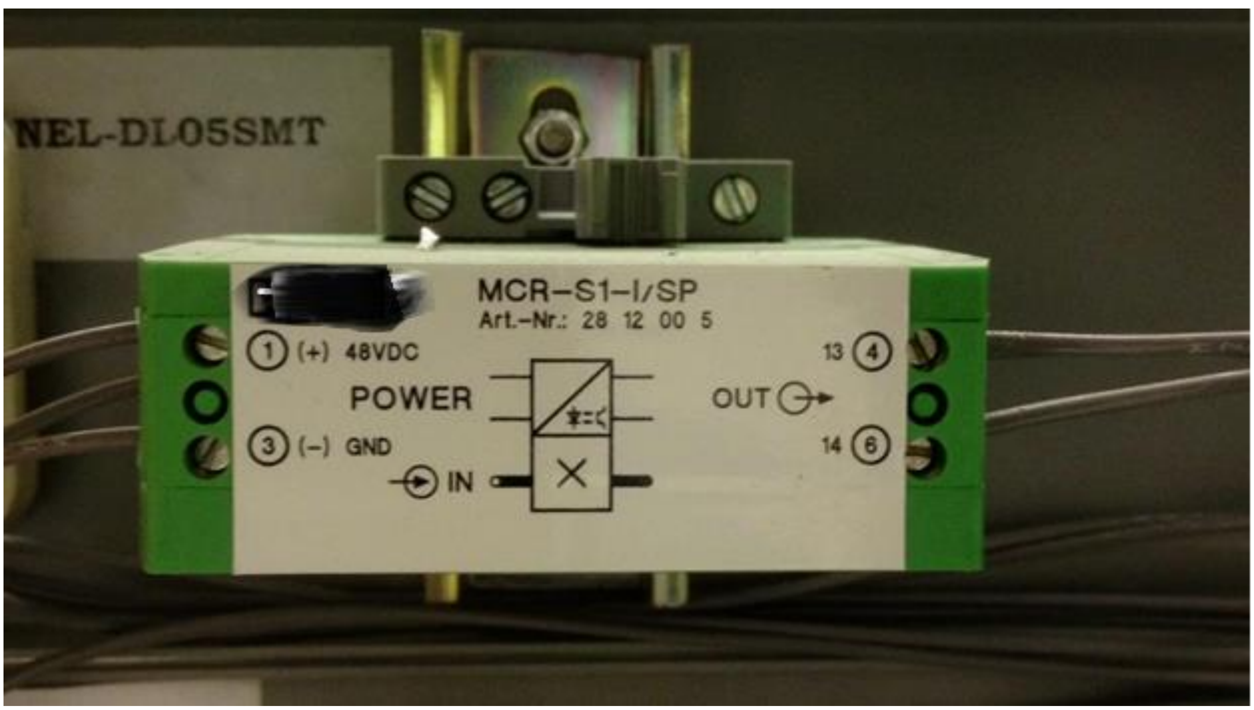

Figure 10.3: Typical Hall Effect Sensor Device Installation Inside Relaying Rack

HESD performance characteristics are as shown below:

Input:	- Measurement DC Current
	- Operating current 0.25 to 1 A
Type of connection:	Pass through connection 24 to 14 AWG
Maximum current:	Determined by physical size of wiring
Output:	Transistor output 30mA or greater
Response time:	100 µs to 1 ms (10^{-4} to 10^{-3} seconds)
Other requirements:	Power supply 125 / 250 VDC
Operating temperature range:	-30°C to +55°C

10.3 Manufacturing Applications

It is to be noted that there are many other sensors, outside the scope of this report, that utilize the Hall Effect in their operation. Hall Effect sensors are commonly used to measure certain process parameters where "touchless" measurement is required (process fluid flow, pressure, etc.). These are also used in rugged manufacturing environments where speed and position indication are required.

11 Application Considerations

11.1 Shielding

Shielding is important so that current in adjacent cables does not interfere, cancel or add to the signal sensed by the Hall Effect sensor. A shield about 0.025 inch (0.635 mm) thick of primarily nickel can shield against outside currents very well. Distance between conductors may eliminate the need for a shield. Care should be taken if a shield is used so that the shield doesn't have sharp edges that can damage conductor insulation of the measured conductor or surrounding circuits; the shield may need to be electrically insulated. It is also important to consider that the shield can cause a gain or loss to the output signal depending on the orientation and shape of the shield.

11.2 Noise Pickup

The problem of noise is usually that the signal is too small compared to noise. If high sensitivity is needed in the circuit, then noise can be large compared to the sensed signal. Hall Effect chips are available with different sensitivities (mV/T) which will help to amplify the output compared to noise. Also analog or digital filtering can be employed to mitigate noise.

11.3 Grounding

Two considerations of grounding are the potential difference that may exist between the sensor and the circuit being monitored and the reference for the signal from the sensor. Sufficient insulation should be used from the sensor to the monitored circuit so that even under fault conditions the potential rise will not cause arcing to the sensing circuit. The sensor should have an isolated power supply and the output of the sensor must be isolated so that the connection to recording equipment that may be grounded or referenced to one side of a station battery would still work correctly.

11.4 Lead Length (Loading)

If the signal from the Hall Effect sensor is to remain an analog signal and travel over a significant distance on a cable, then an amplifier may be needed. Transmission line effects can cause phase delays if not properly handled. Low impedance inputs may be used to reduce noise that can be picked up in the lead length but can increase loading effects on the sensor. Careful design of the analog circuit is required to mitigate noise pickup.

11.5 Mounting (Proximity to the Sensed Signal)

The sensitivity of the Hall Effect sensor is affected by the distance to the conductor to be monitored. At small separation distances, the sensor will be greatly affected by small changes of distance to the monitored current. Even differences in the thickness of the insulation of a conductor can change the readings of the chip. Calibration should be carefully done and consistent distance from the conductor is important. Some sensors are mounted with a clearance of less than 10 thousandths of an inch (0.010 inch, or 0.254 mm) from the surface of the wire being monitored for good results.

12 Conclusion

Current transformers (CTs) are traditionally used for current measurements within the power system for protection, monitoring and control. CTs for use with protective relays must be properly selected to maintain security and reliability of the protection system. When using iron core CTs for protective relay applications, consideration must be given to the possibility of ac saturation, dc saturation and residual flux during and following a fault event. This report examined the use of Hall Effect sensors as an alternative method to measure current for both protection and control applications. The report illustrated that with the proper interface and consideration for maximum range of current measurement, Hall Effect sensors can be utilized in place of CTs for the measurement of current in many applications.

When using a Hall Effect sensor for current sensing, relay settings and coordination are based on the same rules as for conventional iron-core CTs. The relay settings take into account load currents and available fault currents. A properly applied Hall Effect sensor will not exhibit ac or dc saturation or residual flux. Although Hall Effect sensors will not exhibit saturation as may be present in an iron core CT during a faulted or inrush condition, they may exhibit a clipping of the waveform peak values due to their bounded range of measurement. Selection of the proper Hall Effect sensor scaling and operating range must be examined to assure the full required linear measurement range of the sensed current is addressed. Since the output of the Hall Effect sensor will include the dc component of the sensed current in its entirety, the peak values of an offset current waveform that is often present during an energization or fault event must be evaluated for inclusion within the measurement range of the Hall Effect sensor.

The output of a Hall Effect sensor may provide an accurate output representation of a sensed current waveform with a much wider frequency range than that of an iron core CT. Frequency response of a Hall Effect sensor may extend from as low as dc (0 Hz) to high into the kilo-Hertz range. This response capability may provide improved waveform duplication for protective applications that depend highly upon high frequency transient response and specific waveform characteristics.

Reference [12.1] provides interface connectivity requirements for modern power-system signal transducers and protective relays and other substation monitoring equipment using low-energy analog transducers. This IEEE standard includes Hall Effect current sensing devices as a magnetic current transducer. Alternative interfaces using digital encoding of the measured values as described in reference [12.2] may also be possible with some protective relays.

13 References

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