Using Hall-Effect Sensors to Add Digital Recording Capability to Electromechanical Relays

Technology Description and Case Studies

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ABSTRACT

The paper describes the use of Hall-effect sensors for adding digital recording and harmonic analysis capabilities to major substation equipment such as electromechanical relays, circuit breakers, and power transformers. Three case studies are presented describing the use of these sensors as tools for diagnosing problems and identifying root causes of equipment failures. The first case study describes how the sensors were used in a generating plant to identify the cause of a transformer differential trip operation. The second study describes how the sensors were used in a switching station to identify the root cause of the damage to solid-state relays during capacitor bank operations. And, the third study describes how a potential hazard was inadvertently discovered while recording trip and secondary current signatures in a distribution substation.

The paper also describes the unique characteristics of Hall-effect technology and the process of preparing it for use in the substation environment. Requirements for the type of enclosure used and for the needed recording parameters are also described. The intent of the authors is to present the reader with a novel tool that is truly helpful for solving problems with major substation equipment.

BACKGROUND

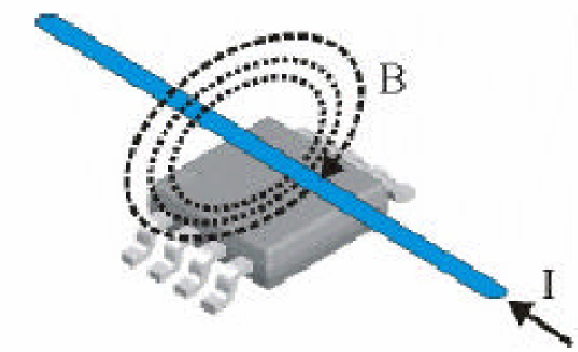

Figure-1, Hall-effect transducer with applied magnetic field

Hall-effect sensors are current-to-voltage transducers that have seen widespread use in industrial process and automotive applications. Unlike traditional iron-core current transformers (CTs) which respond to magnetic flux, Hall-effect transducers respond to magnetic fields and are therefore useful for monitoring both direct and alternating currents. A Hall-effect transducer with an applied magnetic field is shown in Figure-1. The transducer produces a voltage output that is proportional to the magnitude of the applied field. The response time is in the 10 microseconds range making the transducer capable of measuring high order harmonics from 50 and 60 Hz sources (up to the 900th). As for sensitivity, the transducer output is 0 to 5 volts and in a well shielded environment with the current carrying conductor touching the transducer surface as shown in Figure-1, the transducer output measures 1 millivolt for every 10 milliamps of applied current (saturation occurs at 50 amps).

With the above mentioned capabilities, and with the proper enclosure, recorder, and data formats as described in the next section, the Hall-effect transducer is ideal for a wide range of equipment monitoring applications including, but not limited to, capturing targets from electromechanical relays, recording breaker trip and close signatures, measuring transformer inrush currents, and monitoring secondary phase currents.

INTRODUCTION

A Hall-effect transducer with a novel enclosure is shown in Figure-2 (hereinafter, clothespin sensor). The actual transducer is visible in the center of the clothespin sensor and is covered by a curved strip of mu-metal used for shielding against external magnetic fields and for amplifying internal ones. The voltage output from the transducer is provided over a shielded RJ45 cable. This novel enclosure allows for clipping sensors on live wires in harsh environments.

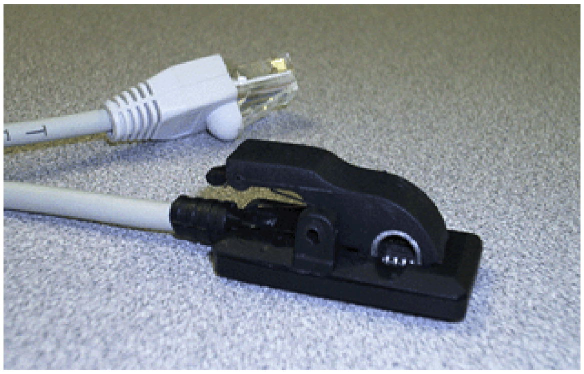

Figure-2, Hall-effect transducer in a novel clothespin like enclosure

With proper recording, the voltage outputs from the clothespin sensors become accurate digital representations of the currents being monitored. The term “proper recording” means, amongst other things, minimization of errors in measurements and time stamping induced by digitization and signal conditioning methods. A measurement accuracy of 2% can be achieved (in the range 0.25 to

50 amps) when recording with a resolution of 16-bits at a sampling rate near 2,400 Hz. An off-the-shelf recorder that provides such performance is shown in Figure-3. The recorder has multiple RJ45 channels for connecting up to 8 clothespin sensors and is capable of recording simultaneously on all channels (skew factor is under 0.2 degrees).

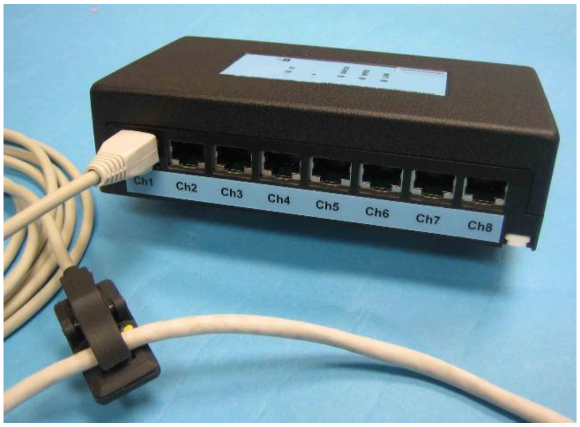

Figure-3, Off-the-shelf recorder with one clothespin sensor shown

As for data formats, the term “proper recording” also means full utilization of IEEE Standards C37.111-1999 (COMTRADE) and C37.232-2007 (Naming Convention for Time Sequenced Data Files) for all of the data storage, management, analysis, and exchange needs. This entire experiment with Hall-effect transducers was designed around these standards. The level of simplicity and commonality in analysis as shown throughout the next 3 sections would not have been possible without the full utilization of these standards.

This combination of Hall-effect sensors, recorders, and IEEE data formats provides a robust and friendly system for monitoring substation equipment. The system can be mounted inside a relay panel as a real-time monitor or can be used with a laptop as a portable diagnostic instrument for troubleshooting control circuits, CTs, motor currents, and so forth. A number of case studies were conducted with this Hall-effect system and the results are very telling. Three of these cases are outlined in the next sections. The first case investigates the root cause of a transformer differential trip operation, the second investigates the cause of damage to solid-state relays during capacitor bank switching, and the third was conducted to monitor and time breaker operations.

CASE I – TRANSFORMER INRUSH

At a generating plant, an attempt was made to energize a generator auxiliary power transformer. When the transformer was energized, it tripped on phase AC differential relay. After this event, the phase AC differential relay was tested and the results were satisfactory. The connected buses were tested to determine the area of the fault and they too tested satisfactorily. The protective relay wiring and CTs were also tested with satisfactory results. After a considerable amount of testing and analysis, the root cause of the trip could not be determined.

At this point, the “AC” phase relay was replaced, a number of Hall-effect sensors were connected to the relay circuits (at the panel), and the transformer was again energized. The transformer tripped again, but this time sensors were available and they captured the waveform data shown in Figure-4. The waveform data clearly shows standard inrush current signature for the first 4 cycles but degrades over the next 8 cycles and then the differential relay operates.

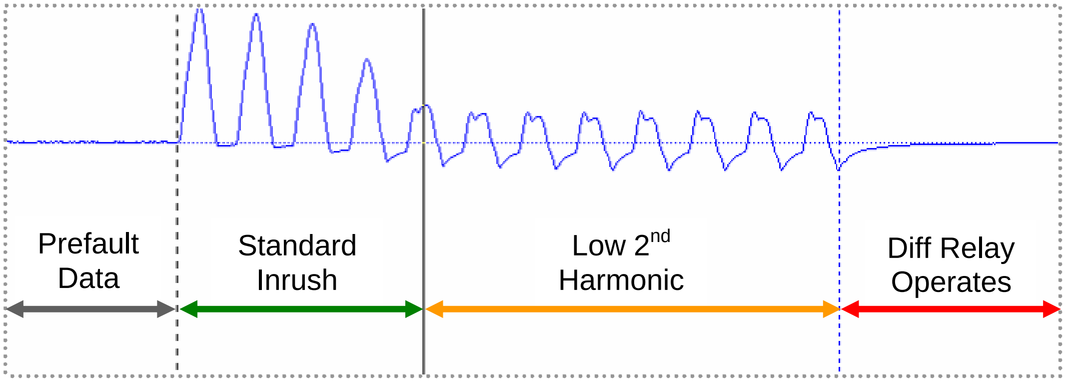

Figure-4, 345kV transformer differential operation (phase AC)

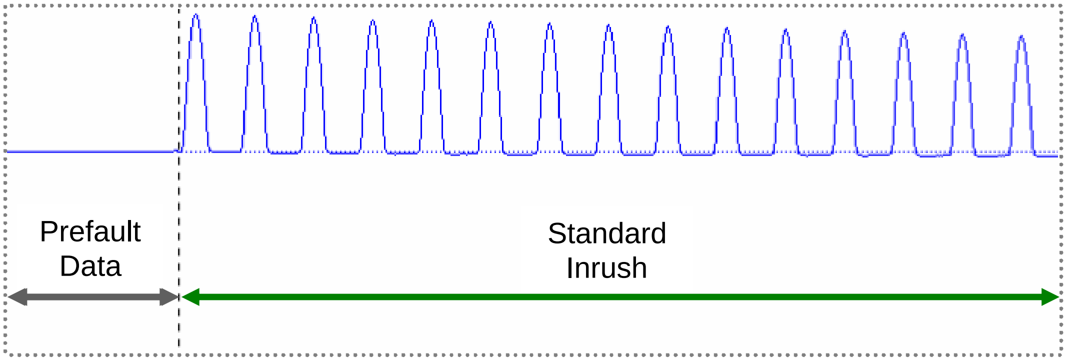

Figure-5, Typical 345kV transformer inrush signature

Further analysis of this data reveals that the root cause of the trip was CT saturation on energization. The saturated CT failed to provide the 2nd harmonic content required by the phase AC differential relay for restraint; therefore, the relay operated. Corrective actions were then taken and the transformer was restored to service. For comparison, Figure-5 shows a typical waveform signature of inrush current for a similar transformer during energization. The waveform signature contains strong 2nd harmonic content (above 30% of fundamental) and slowly decays over a 10 second period.

CASE II – CAPACITOR BANK RINGING

Power systems designed to function at 60 and 50 Hz are prone to experiencing failures when subjected to voltages and currents that contain high harmonic frequency content. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced and with damaging results. The only means of determining the magnitude and type of harmonics is through careful monitoring. Once sufficient data are collected and analyzed then the proper mitigation strategies can be defined and implemented. Here is a good example of “careful monitoring”:

At a 345 KV switching station, capacitor bank switching was causing damage to solid state protective relay equipment and the banks themselves were also experiencing capacitor failures. After considerable testing and analysis, the root cause of the damage proved difficult to determine. At this point, a number of Hall-effect sensors were installed at the capacitor bank breaker CTs and the sensors were configured to capture data at the time of switching (at cut-in and cut-out times). A few days later, the switching station was visited and the captured data was retrieved for inspection.

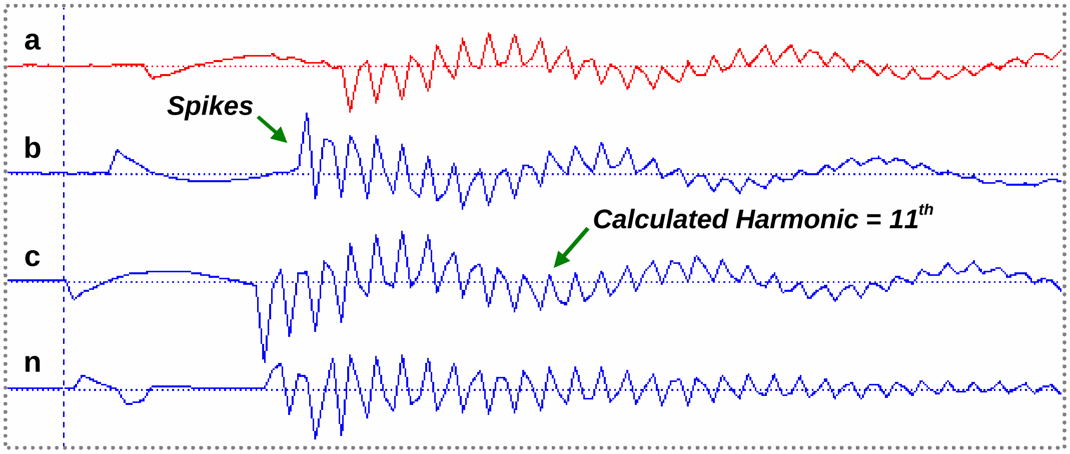

Figure-6, Capacitor bank cut-in waveform at 32 samples per cycle

The retrieved data revealed the presence, during cut-in, of high harmonic frequency spikes with large current magnitudes as shown in Figure-6. The large currents were propagating back onto the station battery and that was the root cause of the damage to the solid state relays. This type of phenomenon is called “capacitor bank ringing” and a good mitigation strategy is to install zero-crossing detectors on the capacitor banks and set them to cut-in when the individual phase levels are at zero (this prevents the occurrence of such large discontinuities in current magnitudes).

As for “careful monitoring”, it is worthwhile to mention that the spikes shown in Figure-6 are typical signatures of under-sampling. Using a Fourier filter, the frequency of the spikes was calculated and the answer was the 11th harmonic. Knowing that the sensors were being sampled at 32 samples per cycle, and seeing the decaying, asymmetric, saw-tooth like signature of these spikes, it is clear that the harmonic frequency is not the 11th harmonic and that it should be a number above the 16th harmonic. Figure-7 shows the same cut-in event but with a sampling rate of 320 samples per cycle. Clearly, the capacitor banks were not ringing at the 11th harmonic, they were ringing at the 21st harmonic. Careful monitoring requires a solid understanding of the events being observed and of the nature of the waveform signatures being captured.

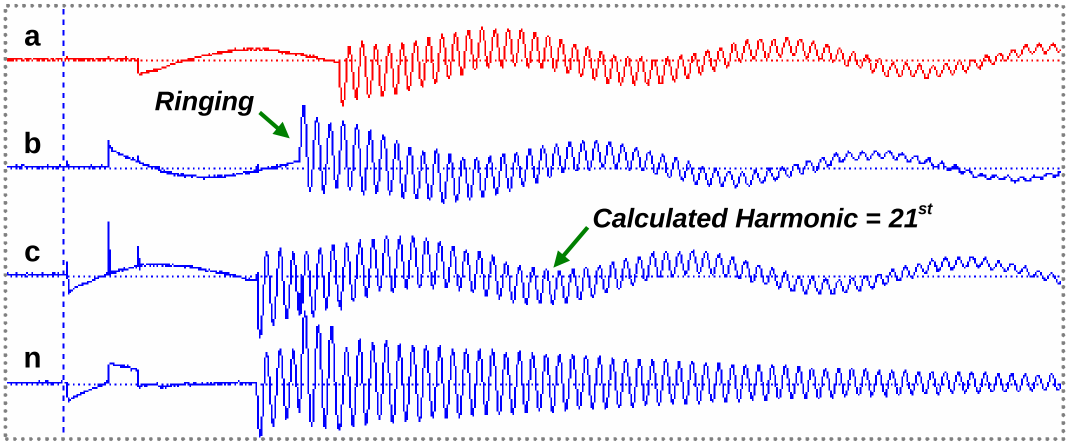

Figure-7, Capacitor bank cut-in waveform at 320 samples per cycle

CASE III – BREAKER TIMING

At a distribution substation, the 27 kV capacitor bank breakers were experiencing failures. The breakers are typically operated twice a day for controlling voltage and reactive power, and over time these breakers accumulate a significant number of operations. To help troubleshoot the failures, a number of Hall-effect sensors were installed to monitor both the trip coils of the breakers (DC captures) and the CTs of the capacitor bank feeder (AC captures). A few days later, the distribution station was visited and the waveform data was retrieved. The DC captures indicated that the breaker timing was within specification, however, the AC captures showed considerable transients on the waveform data immediately after the breaker opened (see Figure-8).

Further analysis of the transients shown in Figure-8 revealed that the circuit breaker vacuum bottles were breaking down. Vacuum bottle breakdown poses a danger of damage to surrounding equipment but more importantly it poses a safety concern for maintenance personnel. Racking out a failed circuit breaker from its cell is a serious arc-flash-hazard to personnel. Clearly, such potentially life threatening events can be avoided with proper equipment monitoring.

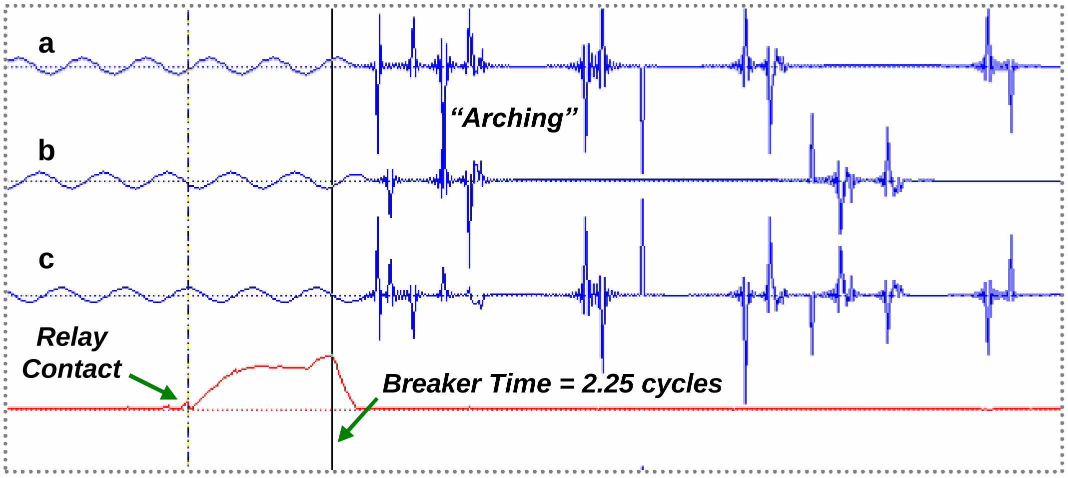

Figure-8, Vacuum bottle breakdown (27kV capacitor bank breaker)

DISCUSSIONS

Today, and in general, real-time monitoring of transmission and distribution systems is mostly performed using SCADA information. The information includes status of breakers (trip/close), transformer loads, voltage levels, and tap changer positions. Such information meets the needs of system operators but provides minimal information to equipment and maintenance engineers and to protection engineers who also need waveform data to evaluate performance and help make major decisions. To that extent, major equipment is periodically removed from service for testing and lengthy diagnostic procedures.

In addition, digital relays and fault recorders, where installed, provide fault data but do not provide equipment monitoring needs because they mostly capture data when faults occur. Equipment maintenance is generally time-based, or by number of operations, there is no predictive element in the process. This lack of predictive maintenance means failures arrive unannounced (often at a critical time where it has a large impact on the operation of the system). For example, when a circuit breaker has not been operated for a long time, the first operation is significant because the lack of exercise can often affect operation time. After the breaker is operated, it usually returns to normal specifications and a slow breaker goes undiagnosed. Breaker timing can reveal such anomalies and provide a predictive maintenance tool for the equipment and maintenance engineers. This leads to identifying poor performers and increasing their maintenance cycle while decreasing the cycle on breakers with good performance.

The Hall-effect sensor technology as demonstrated in this paper can provide a solution to the lack of information described above and especially so because the technology is non-intrusive, it is small in size and can be used in a distributed topology. The technology is also being mass produced. To that extent, the technology can be deployed in a rapid and cost effective manner, and can be used to provide accurate monitoring of both types of direct and alternating currents from both types of legacy and modern day equipment. Such monitoring of major equipment, including electromechanical relays, circuit breakers, transformers, and ancillary equipment, is akin to adding a considerable measure of intelligence to the existing electrical substation infrastructure.

CONCLUSIONS

The paper presented a number of successful applications of Hall-effect technology for monitoring major substation equipment. Three case studies were presented highlighting the benefits of using this technology to monitor equipment at a generating plant, at a switching station, and at a distribution substation. The capability of using Hall-effect sensors to accurately monitor currents in control circuits as well as high frequency harmonics from alternating phase currents was also successfully demonstrated.

With proper enclosures and recording instrumentation, and with careful selection of sampling rates and scale factors, Hall-effect sensors are useful for a wide range of monitoring applications such as capturing electromechanical relay targets, recording breaker operations, measuring transformer inrush currents, and monitoring CTs. Other exciting “future” applications include embedding Hall-effect transducers directly into electromechanical designs.

Using Hall-effect technology to monitor major substation equipment is also in line with today’s “Smart Grid” initiatives. Such monitoring provides extra ordinary enhancements in maintenance and engineering. Imagine the benefits of learning about equipment failures upon occurrence or, better yet, imagine the benefits of catching potential failures before they occur. Access to such knowledge helps utilities increase grid reliability, reduce maintenance costs, restore services faster, and extend the service life of major equipment.

ACKNOWLEDGMENTS

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AUTHOR BIOGRAPHIES

Amir Makki is the chairman and cofounder of Softstuf, Inc (founded in 1991). His professional contributions include over 50 publications, patents, and trademarks. He holds BS and MS degrees in Electrical Engineering from Tennessee Tech University (1984 and 1986), and received a fellowship from Temple University where he pursued his Ph.D. studies in Software Engineering (1986-1991). He is a senior member of IEEE and a member of the Standards Association and the HKN honor society. He is also an active member of the Protection Systems Relay Committee of the Power Engineering Society.

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Tony Giuliante is the president and founder of ATG Consulting. Prior to forming his company in 1995, Tony was executive vice president of GEC ALSTHOM T&D Inc. - Protection and Control Division, which he started in 1983. From 1967 to 1983, he was employed by General Electric and ASEA. In 1994, Tony was elected a Fellow of IEEE for "contributions to protective relaying education and their analysis in operational environments." He has authored over 50 technical papers and is a frequent lecturer on all aspects of protective relaying, including electromechanical, solid state and digital based equipment. Tony is a past chairman of the IEEE Power System Relaying Committee 1993-1994, and past chairman of the Relay Practices Subcommittee. He has degrees of BSEE and MSEE from Drexel University 1967 and 1969.