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

Technology Description and Case Studies

Presented By

Amir Makki
Softstuf, Inc.
Philadelphia, PA

Co Authored By

Sanjay Bose
Con Edison of New York
West Edison, NJ

Tony Giuliante
ATG Consulting
Galloway, NJ

John Walsh
SBTS, LLC
New Hyde Park, NY

Presented before the:

The 2010 Georgia Tech
Fault Disturbance and Analysis Conference
Atlanta, Georgia
May 3rd - 4th, 2010

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

Sanjay Bose, Tony Giuliante, Amir Makki, and John Walsh

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 relay trip operation. The second study describes how the sensors were used in a switching station to measure harmonic content during capacitor bank switching operations. And, the third case study describes how a potential hazard was inadvertently discovered while using the sensors to capture trip and secondary current signatures in a distribution substation.

The paper also describes the unique characteristics of the Hall-effect sensors and the process of preparing them for use in the substation environment. The types of enclosures used and the needed recording requirements are also discussed. The intent of the authors is to present the reader with a novel tool that is truly helpful for identifying problems with major substation equipment.

BACKGROUND

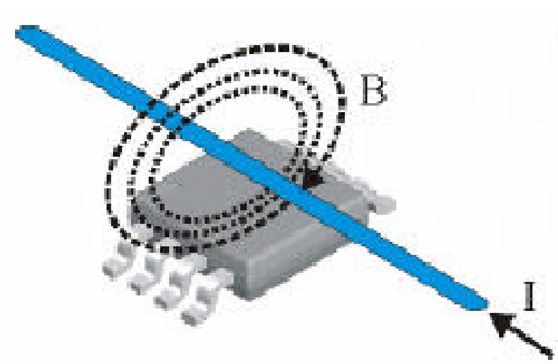

Figure-1, Hall-effect transducer with applied magnetic field

Hall-effect sensors use small, current-to-voltage transducer that respond to magnetic fields and are therefore useful for monitoring both direct and alternating currents (AC and DC). These types of transducers have seen widespread use in industrial-process and automotive applications. A typical 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. As for sensitivity, the transducer output is -2.5 to 2.5 volts. In a well shielded environment and with the current carrying conductor touching the transducer surface (as shown in Figure-1), the transducer output measures 1 millivolt for every 20 milliamps of induced current making it capable of sensing currents up to 50 amps.

With the above 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 electromechanical relay targets, monitoring DC control circuits, recording breaker trip signatures, measuring inrush currents, and monitoring current transformers (CTs).

INTRODUCTION

A novel Hall-effect sensor with a non-intrusive, clothespin-like enclosure is shown in Figure-2. The actual transducer is visible in the center of the 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 type of enclosure provides for simple installation on live wires in harsh environments without the necessity for removing equipment from service.

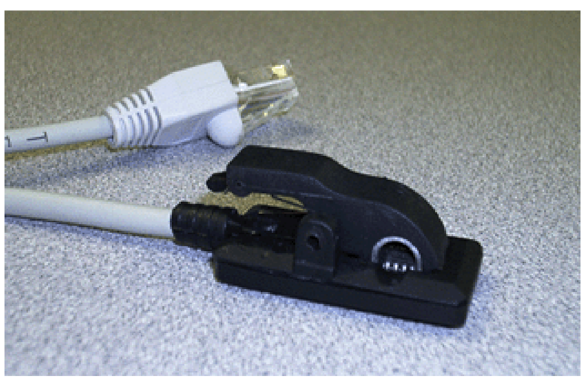

Figure-2, Hall-effect sensor with shielded clothespin-like enclosure

With "proper recording", the voltage outputs from the sensor become accurate representations of the currents being monitored. The term "proper recording" means, among other things, minimization of measurement and timing errors induced by digitization and signal conditioning methods. Good accuracy can be achieved when recording with a resolution of 16-bits and at a sampling rate near or above 2,400 Hz. An off-the-shelf recorder that provides such performance is shown in Figure-3. The recorder has 8 channels for connecting sensors and samples simultaneously on all channels (each channel has its own controller and the controllers are synchronized with a skew-factor under 1 degree).

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

In an effort to validate the use of Hall-effect sensors for monitoring substation equipment, a benchmark test was conducted. The test utilized a power system simulator to play back an “A” phase to ground digital fault record into a numerical relay. The Hall-effect sensors were mounted on the phase currents of the power system simulator as depicted in Figure-4. The digital fault record was captured by a quality digital fault recorder (DFR) and the measured fault magnitude was 60 amps which was also ideal for challenging the 50 amp range of the Hall-effect transducer being used (other models support higher ranges).

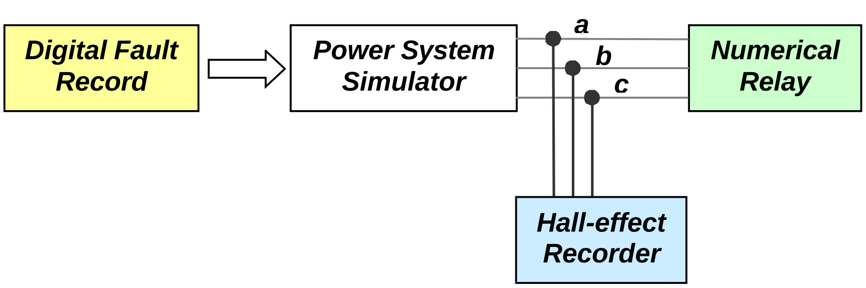

Figure-4, Hall-effect sensors benchmark test (DFR record play back)

After the test, the resulting fault records from the relay and Hall-effect sensors were compared with the original DFR record. The results were remarkable in that the fault records were almost exact replicas even though they were captured by different instruments having different resolutions and sampling rates. Figure-5 shows the captured “A” phase waveforms from each instrument. The Hall-effect waveform clearly shows that the sensor flat-lines at the 50 amps range which is a desirable outcome because the actual peak can be calculated using sinusoidal interpolation (it does not collapse as in the case with CT saturation).

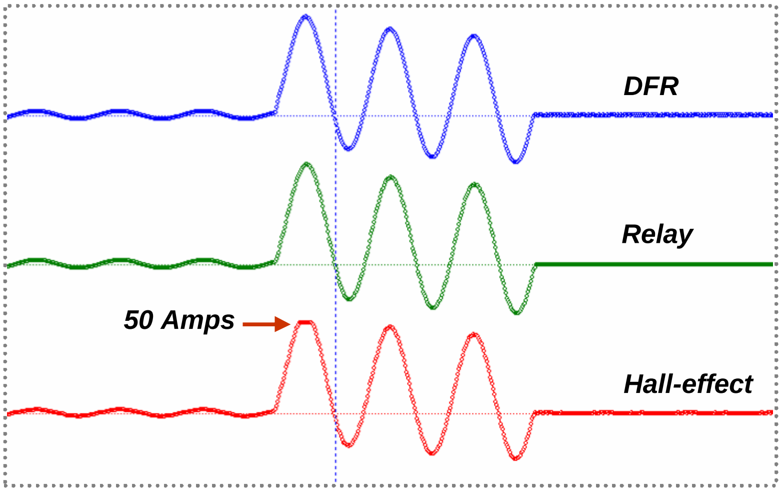

Figure-5, DFR, numerical relay, and Hall-effect waveforms ("A" phase)

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 needed data storage, management, analysis, and exchange requirements. This entire experiment with Hall-effect sensors was designed around these standards. The level of simplicity and commonality in analysis as shown throughout the next sections would not have been possible without the full utilization of these standards.

The combination of Hall-effect sensors with proper recording and IEEE data formats provides a robust and friendly system for monitoring major equipment in the substation. The system can be mounted inside a relay panel for real-time monitoring 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 the Hall-effect sensors 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 relay trip operation in a generating plant, the second identifies harmonic content during capacitor bank operations in a switching station, and the third case was conducted to monitor and time breaker operations in a distribution substation.

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 "A" phase differential relay. After this event, the 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 differential 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 the Hall-effect sensors captured the waveform data shown in Figure-6. The waveform data shows typical inrush current signature for about 3 cycles then degrades over the next 9 cycles during which the differential relay operates to trip the circuit breaker.

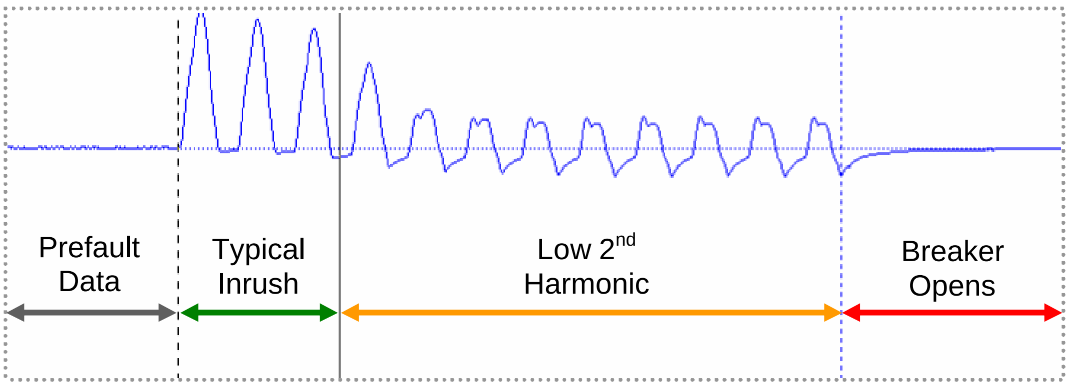

Figure-6, 345 kV transformer differential relay operation

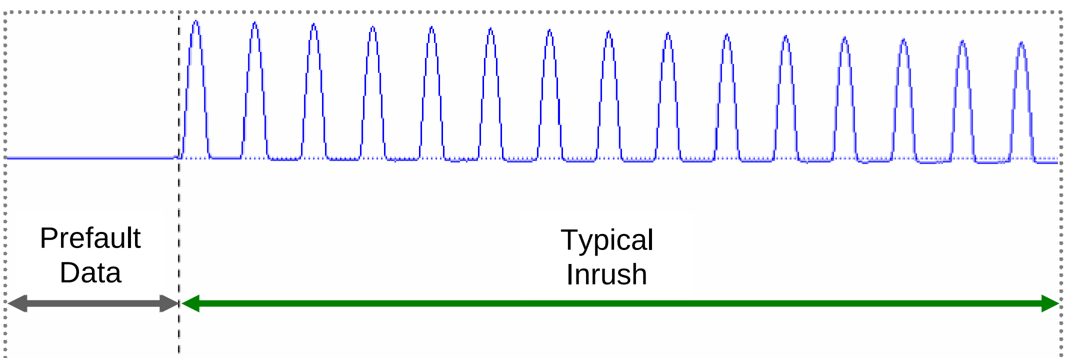

Figure-7, Typical 345 kV transformer inrush current signature

Further analysis of the data reveals that the root cause was CT saturation due to remanent flux. The saturated CT failed to provide the 2nd harmonic content required by the differential relay for restraint, so the relay operated. Corrective actions were then taken and the transformer was restored to service. For comparison, Figure-7 shows a typical inrush current waveform from a similar transformer during energization. The shown waveform contains strong 2nd harmonic content (above 30% of fundamental) and the magnitude slowly decays towards zero (which could take over 10 seconds to complete).

CASE II – CAPACITOR BANK RINGING

Power systems designed to function at 50 and 60 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 capacitor banks themselves were also experiencing failures. After considerable testing and analysis, the root cause of the damage and failures could not be determined. At this point, a number of Hall-effect sensors were installed at the capacitor bank breaker CTs to capture the harmonic content at the time of switching (at both cut-in and cut-out times). A few days later, the switching station was visited and the captured data was retrieved for inspection and analysis.

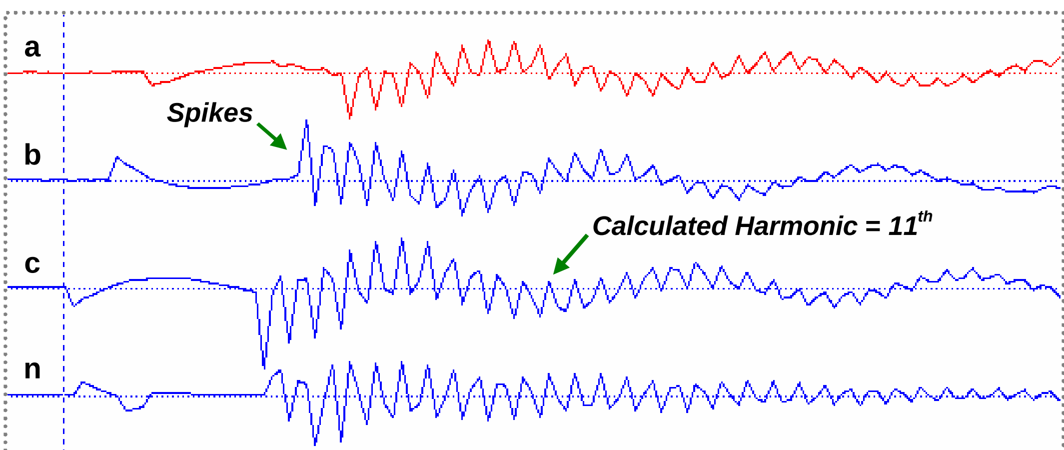

Figure-8, Capacitor bank cut-in waveform at 32 samples per cycle

The retrieved data revealed the presence, during cut-in, of high harmonic spikes with large current magnitudes as shown in Figure-8. This type of phenomenon is called "capacitor bank ringing" and a good mitigation strategy is to install zero-crossing detectors and use them to cut-in the capacitor bank when the individual phase voltages are at zero (this prevents the occurrence of large discontinuities in current magnitudes). As for "careful monitoring", the shown spikes are typical signatures of under-sampling. Using a Fourier filter, the calculated frequency of the spikes is 660 Hz (the 11th harmonic). Knowing that the installed sensors were being sampled at 32 samples per cycle, and seeing the asymmetric, saw-tooth like signature of these spikes, it is clear that the actual frequency should be a number above the 16th harmonic. Figure-9 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.

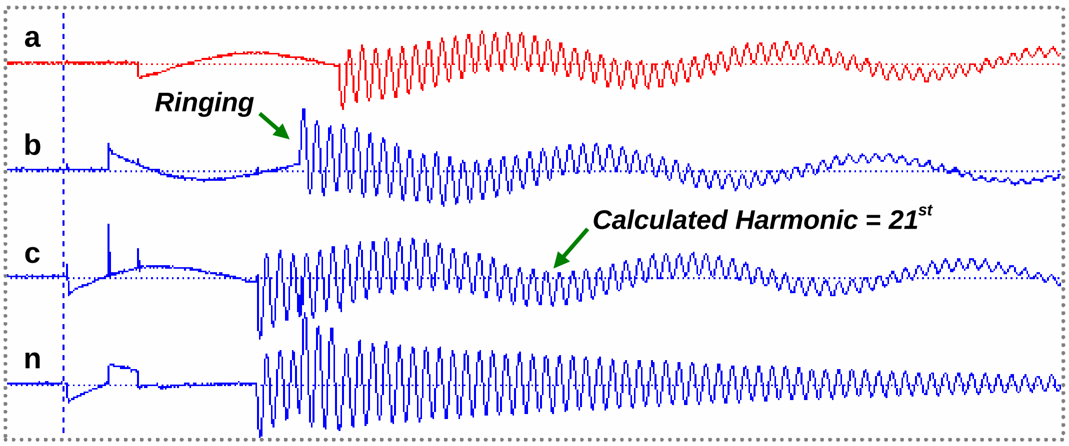

Figure-9, Capacitor bank cut-in waveform at 320 samples per cycle

CASE III – BREAKER TIMING

At a distribution substation, the 27 kV capacitor bank vacuum tube breakers were experiencing failures. The breakers are typically operated twice a day for controlling voltage and reactive power and over time they 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 substation was visited and the waveform data was retrieved. The DC captures indicated that the breaker timing was within specification but the AC captures showed considerable transients immediately after the breaker opened as shown in Figure-10.

Further analysis of the transients revealed that the vacuum tube bottles were breaking down. Such breakdowns pose a danger of damage to surrounding equipment and more importantly they pose a safety concern for operations personnel. Racking out a failed vacuum tube circuit breaker from its cell is a serious arc-flash-hazard to operations personnel. Clearly, such potentially life threatening events can be avoided with proper monitoring.

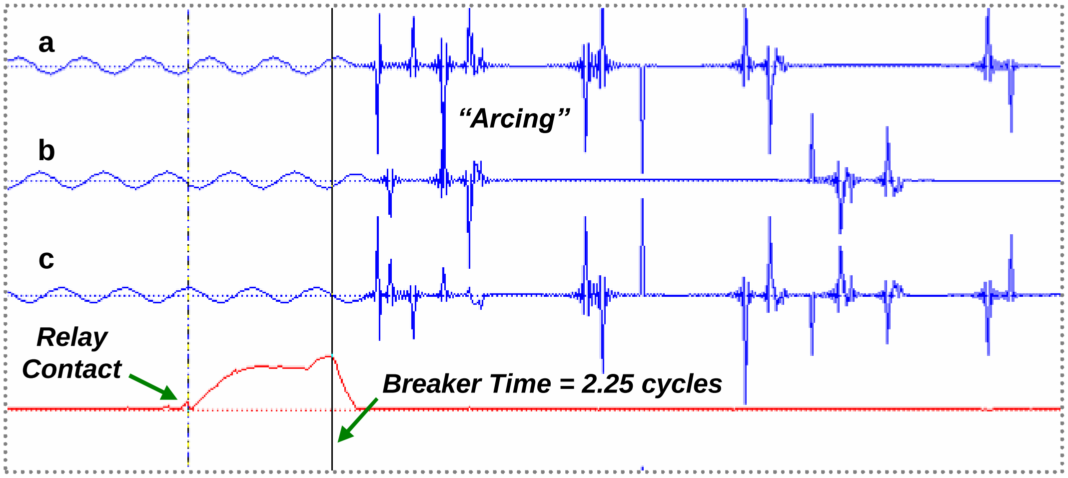

Figure-10, Vacuum bottle breakdown (27 kV capacitor bank breakers)

CONCLUSIONS

The paper presented a number of successful case studies using Hall-effect sensors for monitoring major substation equipment. The studies highlighted the benefits of using the Hall-effect sensors to diagnose problems and identify root causes of equipment failures. The studies were conduct at a generating plant, at a switching station, and at a distribution substation. The capability of the sensors to accurately monitor DC control circuits, as well as high AC harmonics from secondary phase currents, was also successfully demonstrated.

The sensors are non-intrusive and inexpensive. They can be deployed in a timely manner and without having to remove equipment from service. With proper enclosures and recording instruments and with careful selection of resolution and sampling rates, Hall-effect sensors are useful for a wide range of monitoring applications including capturing relay targets, timing circuit breakers, measuring inrush currents, and diagnosing DC control circuits. Other exciting applications include embedding Hall-effect sensors directly into equipment designs and especially in electromechanical relay designs.

Using Hall-effect sensors to monitor major substation equipment is also in line with today's "Smart Grid" initiatives. Such monitoring provides enhancements in maintenance and engineering that are extra ordinary. Imagine the benefits of learning about equipment failures upon occurrence, or even better, imagine the benefits of catching potential failures before they occur. Access to such knowledge helps utilities increase grid reliability, reduce maintenance costs, restore lines faster, and extend the service life of major equipment. Clearly, in conclusion, using Hall-effect sensors helps make our “legacy” substations similar to our newest substations.

ACKNOWLEDGMENTS

The Hall-effect sensor is a patented design by Con Edison, Softstuf, and ATG Consulting. The first case study was a collaborative effort including personnel from Softstuf, Exelon, and ABB. The second and third case studies were efforts including personnel from Softstuf and Con Edison. The clothespin sensors and recorders are manufactured by TIS Labs, LLC. The waveforms shown are screen captures from the Wavewin™ software (trademark by Softstuf, 1991-current).

The authors extend their thanks to all persons involved in the three case studies presented in this paper. Especial thanks are extended to:

- Maria Makki (software development),
- George & Hamid Semati (hardware development),
- Mark Taylor (product development),
- Frank Rothweiler (product testing),
- Shi Jiang (case studies at Con Edison),
- Dwight Smith (case studies at Exelon), and
- Bob Wilson (publication planning).

REFERENCES

The following listing of books, articles, and standards is provided as a source for additional information:

[1] IEEE Std C37.111-1991, Standard Format for Transient Data Exchange

[2] IEEE Std C37.111-1999, Standard Format for Transient Data Exchange

[3] IEEE Std C37.118-2005, Standard for Synchrophasors for Power Systems

[4] IEEE Std C37.232-2007, Recommended Practice for Naming TSD files

[5] S, Bose et al, “US Patent Application 12/249,547”, Current Measuring Device

[6] S, Bose et al, “US Patent Application 12/505,947”, Relay Behavior Patterns

[7] Blackburn and Domin, “Protective Relaying”, Third Edition; CRC Press, 2007

AUTHOR BIOGRAPHIES

Amir Makki is the Chairman and Co-founder of Softstuf, Inc (1991-current). His professional contributions include over 50 publications and patents. He holds BS and MS degrees in Electrical Engineering from Tennessee Tech University and pursued his Ph.D. studies in Software Engineering at Temple University. Amir is a senior member of IEEE Standards Association and is an active member of the Protection Systems Relay Committee (PSRC). He is the past Chairman of the H8 working Group which produced IEEE Std. C37.232 (Recommended Practice for Naming Time Sequence Data Files), and currently serves as Chairman of the Cyber Security Task Force for Protection Related Data Files.

Sanjay Bose is employed by the Consolidated Edison Company of New York (1986-current). He is currently the Vice President for Substation Operations. In this capacity, he is responsible for the overall operation, maintenance, repair and upgrade of all Transmission and Distribution Substations and of all Public Utility Regulating Stations. Prior to this, he held various positions at the Company including General Manager for Protective Systems Testing, Senior System Operator at the Energy Control Center, and Design Engineer supporting substation construction activities. Sanjay holds a BS degree in Power Electrical Engineering from Birla Institute of Technology, Ranchi, India (1985), and is an active member of EPRI and the IEEE.

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 & 1969).

John Walsh is the President and Founder of Sean Breatnach Technical Services (SBTS) LLC, a consulting firm that provides solutions in managing legacy infrastructure to utility companies and utility contractors. He has degrees in Electronic Technology and Industrial Management from The College of Staten Island, New York. He has worked as a Technician, Supervisor and Manager in electrical substation commissioning, relay protection testing and maintenance for 35 years. He consults regularly with companies on substation automaton, product development, substation testing protocols and project management. Prior to his current position, he managed a Protective Systems Testing team at The Consolidated Edison Company of New York.