Temperature Monitoring System Using Passive Wireless Sensors for Switchgear and Power Grid Asset Management

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INTRODUCTION

There is an increasing demand for continuous asset monitoring of critical assets in the evolving world-wide Smart Grid. One critical parameter of interest is the contact temperature of critical electrical connections throughout the T&D infrastructure.

Traditional measurements have required either IR thermal imaging or one or more wired or battery operated active wireless sensor systems. IR is a periodic asset monitoring method and is unable to alert the operator to a real time event. Wired and optical fiber methods fail to a short circuit, resulting in flash-over paths in medium voltage systems. Battery-operated active sensors require inopportune periodic maintenance in the medium voltage cabinet.

An improved approach is desired that offers no connection between the sensor and instrumentation (wireless), requires no power at the point of measurement (passive, batteryless) and may be integrated into SCADA.

This paper will detail the system, its competitive advantages, and its installation formats as it applies to these pilots and deployments.

THE APPROACH

Monitoring the temperature of moving portions of machinery and other mechanical systems can present challenges where real-time remote data communication is required. Traditional methods of measuring temperature have relied on the temperature dependence of resistance (thermistors or Resistance Temperature Detectors - RTDs), a variety of different types of thermometers, the temperature dependence of a diode junction (silicon), or the emission of infrared radiation from heated objects (IR thermometers). For the applications considered herein, passive devices, e.g. thermocouples, RTD and quartz thermometers, for example, have historically required cabled connections, slip-ring contacts, rotating connections, or battery-powered transmitters to communicate information.

Similarly, measuring the temperature of contacts and connections in high voltage switchboxes and transmission lines presents challenges. A standard requirement for these structures is that there be no metallic or fiber optic cabling from the contact or connection of interest to the supporting structure or frame, as this can cause a dangerous and potentially explosive path to ground.

Infrared thermometry is sometimes employed, but this requires direct line of sight to the area of interest, which should be clean for the best accuracy. IR is usually used for spot checking on a periodic basis and therefore not continuous monitoring. Typically the infrared measurement systems used for this type of monitoring are cost prohibitive.

Battery-powered temperature transmitting systems have drawbacks related to typical physical size and the need for oftentimes rather inconvenient periodic replacement of the battery. In general, batteries are not well suited for high temperature operation, especially above 150 ˚C.

In these types of applications, SAW-based passive wireless temperature sensing technology offers distinct advantages over these traditional measurement methods, including

- Passive operation, since SAW-based temperature sensors require no batteries or external power-supply. The resulting advantages over actively powered sensing solutions include:
    - Low environmental foot print as passive SAW temperature sensors avoid the adverse environmental impact of batteries.
    - Logistical advantage: The burden of regularly needing to monitor remaining battery life and replace them is eliminated.
- Electrically non-invasive solution: by not requiring wires to power/read sensors, a SAW-based temperature measurement solution can provide an electrically non-invasive solution for high power equipment such as switchgear and other Smart Grid applications.
- Wireless interrogation: SAW-based temperature sensors can be read wirelessly. This makes them well suited for rotating applications and for those applications where sensors are placed in difficult to reach, isolated, or electrified locations.

The SenGenuity wireless SAW resonator (SAWR) based temperature sensing solution consists of a reader (RF

Transceiver) RF or capacitively linked to one or more SAWR sensing elements as depicted in Figure 1. The system operates in a range from 428 MHz to 439 MHz and allocates six distinct, 1.4 MHz wide, sub-channels to six distinct SAWR modules.

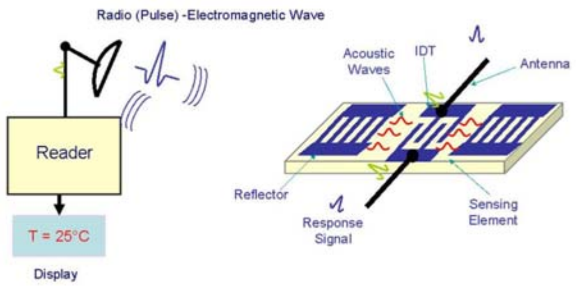

Figure 1: Wireless SAW Temperature Sensing System

SAW-based temperature sensing involves electrically inducing an acoustic wave into a piezoelectric material and then reconverting the energy of the wave (influenced by the temperature to which the sensing element is exposed) back into an electrical signal for temperature measurement. One significant advantage of SAW devices is their passive operation, which makes them very amenable to operation in harsh environments via wireless interrogation. Passive, wireless, SAW-based sensing systems have been described in many publications [1-5] and some systems are now being offered.

TECHNICAL DETAILS OF THE SYSTEM

Description of the Interrogation System

The present system employs completely passive, batteryless, wireless sensors that are affixed directly to the desired points of measurement. In the present system, resonators [6] are employed having a linear dependence of their resonant frequency on temperature. A short RF pulse – about 20µs long – causes the resonator to energize if the resonant frequency of the resonator overlaps the frequency spectrum of the pulse. When the transmitted pulse ends, the resonance decays and, if the resonator was energized by the interrogation pulse, a long ringing signal is rebroadcast by the resonator. The received signal is amplified, filtered, digitized and analyzed. Analysis of one or more such pulse echoes allows the reader to determine the frequency of the resonator and, using stored calibration data, to determine a temperature from the resonator frequency.

A simple algorithm allows the reader to find a resonant frequency and obtain an accurate frequency reading in under 100 ms. Using more complex tracking algorithms, measurements can be obtained in under 5 ms with averaging or at a rate of 2 000 samples per second without averaging. The stability and resolution depends on ambient noise, resonator Q, and the RF losses between the interrogation system and the sensor. Standard deviations as low as 500 Hz are obtained whereas the frequency dependence of the resonators is 7 KHz/˚C [7, 8].

Six distinct resonator designs with well separated nominal resonant frequencies allow frequency division multiplexing (FDM) to identify and address six unique points of measurement. Systems incorporating more than six points of measurement must rely on a multiplicity of instrumentation with each channel of instrumentation seeing only one sensor at each nominal frequency. This requires physical shielding of the radio frequency signals between chambers within a switchgear and between switchgear systems – a condition that is not strictly met in all cases.

Interrogation antennas broadcast interrogation pulses and receive the sensor return signals. The interrogation antennas are located in the medium voltage chamber and are connected to instrumentation that is located in the low voltage chamber. The overall instrumentation provides passive interrogation of the sensor module temperatures using methods analogous to radar systems.

Resonator Properties

The SAW resonators employed must, of course, be designed for the temperature range of interest, the frequency vs. temperature excursion limits which can be of both sensitivity and regulatory concerns, the accuracy required, etc. When the system relies on a single resonator's frequency to indicate and correlate to temperature, calibration of the sensor element may be required, depending on the accuracy required.

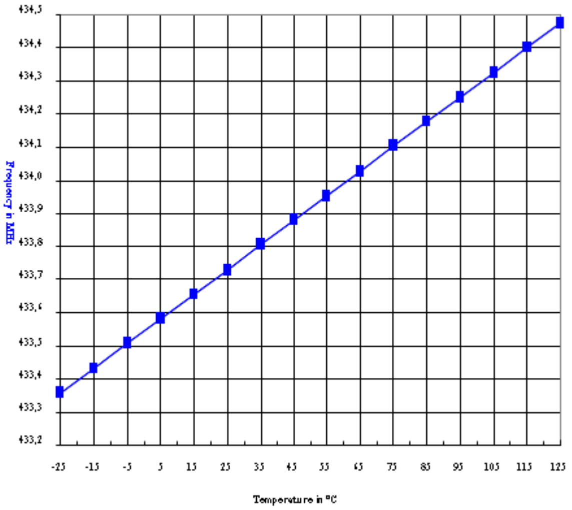

Figure 2. Typical frequency vs. temperature curve for a sensor module designed for the European ISM band.

In the present system, resonators are designed having a nominal sensitivity of 7 KHz/˚C, as seen in Figure 2, and intended for operation from at least -20˚C to at least 120˚C (0.980 MHz) while keeping all resonant energy frequencies within a 1.4 MHz sub-channel and allowing for manufacturing variations. The nominal frequencies are design values and the frequency limits of the sub-channels are firmware defined, in principle allowing different temperature limits to be defined.

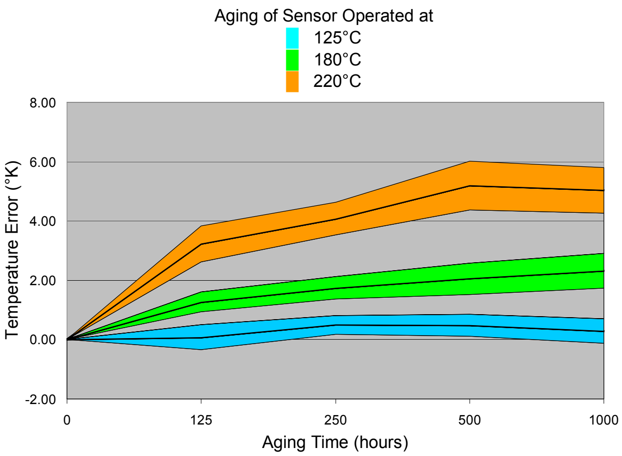

Figure 3. Typical aging curves of 433 MHz SAW resonator sensor elements at three operating temperatures show that the aging stability of the devices is suitable for accuracy requirements of a few degrees. For operation below 125˚C aging is comparable to MIL and Space qualified parts. Prolonged operation at higher temperatures also required modification of the sensor module, notably the use of high temperature circuit board and adhesives.

As well it is quite desirable, especially for high temperature environments, to have a low aging process that offers accuracy over prolonged periods between calibrations. Typical aging curves of specially processed SAW resonators are shown in Figure 3, which shows a very small drift of frequency with time. Use of differential measurements of two resonators with different frequency-temperature characteristics can reduce some of the error terms further.

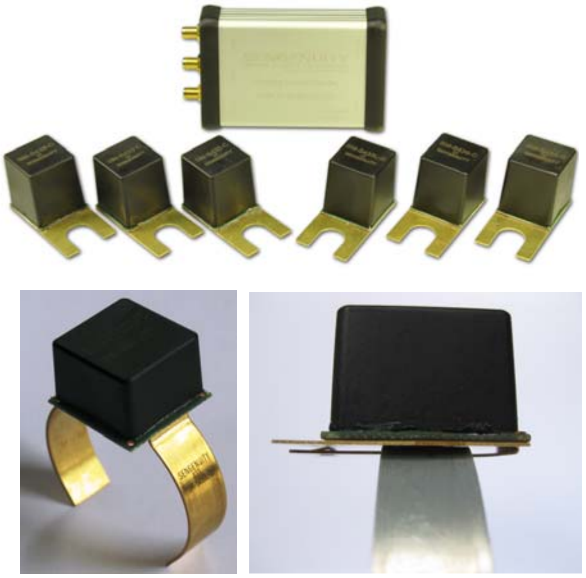

Figure 4. (Top) Three-chamber reader electronics (CAN 2.0B or RS232 version). (Middle) sensor modules for mounting under bolts at connection points such as a cable terminations or bus bars. The total height of these modules is 33mm. (Lower left) C-clip designed for 50mm circuit breaker posts with an 18.5mm low profile format. (Lower right) U-clip designed for band-mounting to arbitrary geometries also has low profile format.

Sensor Module Antenna

Early prototypes employed SMA connectors and commercial, off the shelf antennas typically 35 mm in length for an overall height of the sensor module of under 50 mm. The hand tightened SMA adapters were both a cost and a reliability issue.

The commercial antennas were subsequently replaced by an integrated helically-shortened monopole antenna. Two different antenna designs are provided, one offering the low profile 18.5 mm height for critical spacings applications and the other offering the high profile 33mm height for improved RF coupling. The sensor modules come in several mounting styles and include a high temperature plastic cap for mechanical stability. Figure 4 shows the sensor module designs that are employed in the measurement system.

Electrostatic Discharge and Induced Field Protection

Since the resonators are intended to be located electrically between an electrified bus bar and an antenna, the interdigital transducer (IDT) of Figure 1 must be protected from induced electromagnetic fields. Initial studies on 16 KV transformer contacts suggest that induced voltages as high as 1 KV exist but that these fields are readily eliminated by placing an appropriate inductor in parallel with the IDT.

The inductor appears to be a short circuit at power frequencies and is readily incorporated into the optimized sensor modules of Figure 4.

Testing of high voltage compatibility has been performed by several partners for bus bar voltages from 40 KV to 150 KV without arcing. Pilot tests and deployments in the field range from 11 KV to 40 KV with several 66KV pilot tests planned for early 2011. In two years of deployments since the initial tests, there has never been a flash-over or ESD failure.

System Interface: HMI and SCADA Options

The majority of installations in the field today have been performed by commercial partners in China and Taiwan. One systems integrator provides an OEM product incorporating a reader. Their system directly controls the low level reader settings and operation while providing a proprietary network interface. It is presently deployed in both industrial point-of-use systems, such as electric train substations, and in utility applications, such as distribution substations in Guangxi province. Systems have been deployed for as long as 18 months of continuous operation.

The stand-alone reader also provides higher level firmware directly in the reader and employs proprietary CAN 2.0B or RS232/485 protocols allowing 15 CAN readers, 127 RS-485 readers, or a single RS-232 readers on a single distributed network. Gateways and multi-port serial adapters allow large-scale integration into dedicated human machine interface (HMI) or SCADA systems.

Another systems integrator is employing RS-485 equipped readers controlled by a local human machine interface (HMI). The local HMI serves the data into a SCADA system using MODBUS-RTU. Three industrial point-of-use substations totaling about 50 switchgear are presently deployed in pilot tests. MODBUS-RTU protocol is being integrated directly into the reader firmware, with final testing presently underway. The intent had been to utilize the HMI as a temporary solution; however the end user now plans to keep the HMI as a local monitor at the substation while still having direct SCAA integration of MODBUS-RTU readers.

A third systems integrator has developed a rack-mounted gateway controlling up to 30 CAN 2.0B readers on two network busses. The gateway serves the reader data into a SCADA system using IEC 60870-5-103. This system is going into field trials in China in one or more utility substations in Q4/2010. There appears to be no reason that IEC 60870-5-103 cannot be similarly integrated directly into the reader firmware.

There is a growing push towards the emerging object oriented standard, IEC 61850. Initial feasibility studies are underway with no technical reasons that future offerings cannot be compatible with this standard. However, this standard will require a co-processor and associated firmware for the protocol implementation and the total scope of such an effort is yet to be fully determined.

TYPICAL SYSTEM INSTALLATION

The instrumentation samples the temperatures of up to 18 contact points with the constraints that each of three switched antennas obtains echoes from only one instance of each of the six resonators. In typical switchgear there is at least partial shielding between an input (busbar) chamber, an output (cable) chamber, and a circuit breaker chamber. A typical installation schematic is shown in Figure 5.

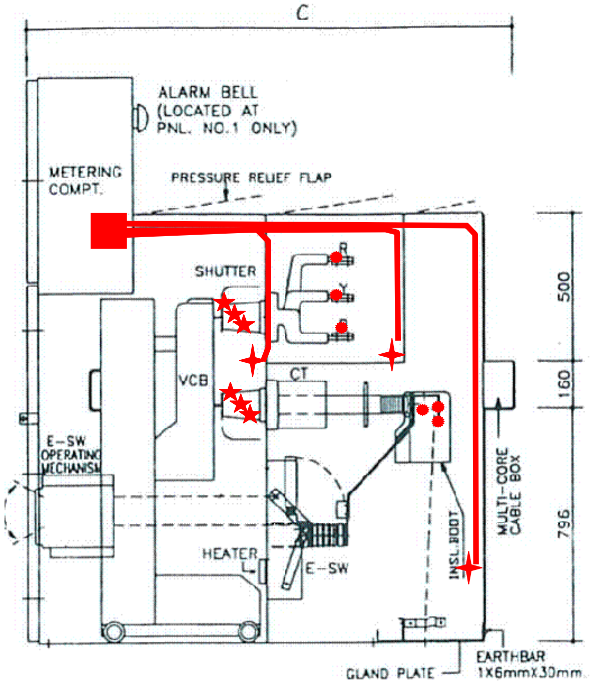

Figure 5. A typical switchgear panel is shown with single bus-bar feed. The reader is located in the metering compartment and RF cables are routed through the switchgear to interrogation antennas (✦). One antenna in the breaker compartment can typically instrument six clip type low profile sensors on the circuit breaker posts, while two additional antennas service the incoming buses and outgoing cable terminations.

In this figure an antenna in the breaker chamber is able to measure six sensors mounted to the posts of the circuit breaker contacts. These might be the C-clip sensor modules on a 50mm post or a U-clip sensor modules with retaining band on generalized contacts. Twelve sensor installations such as shown in the example are common.

In some switchgear the shielding between compartments is not adequate and a smaller number of sensors is mandated in order to avoid inter-chamber reading of multiple sensors at the same nominal frequency. For instance, some switchgear are designed to have the bus chambers contiguous so as to also provide a ventilation path while others have bus feedthroughs with metal shielding between switchgear panels.

CE AND FCC APPROVALS

With any wireless system design, the ambient RF noise environment must be understood and addressed. This includes the noise emitted by such systems (EMI) as well as their inherent susceptibility to noise (EMC). Each application area presents challenges requiring engineering support for mounting structures and methods, packaging, antenna design, etc., along with local regulations (e.g. FCC, CE, etc.) regarding emissions and safety requirements in hazardous environments. In the systems described herein, enclosures surrounding the SAW sensors may be well-shielded, allowing system operation without license at relatively high (0.1 to 10 mW radiated) internal power levels and using resonator frequencies that are outside of unlicensed frequency bands. The SenGenuity system operates from approximately 428 MHz to 439 MHz with a single sub-channel falling inside the European ISM band.

Conformance testing of the system as a stand-alone product for use outside of the shielding of typical switchgear has been performed. A single sensor operation is allowed within the 434 MHz ISM band in Europe. CFR47 Part 15 allows the use of the full system in the US subject to periodic emissions constraints.

Figure 6. A small bank of medium voltage switchboxes shows both weather-tight and RF-tight enclosures. Such systems have very low spurious emissions.

Initial data taken on typical switchgear configurations suggests that the system meets CISPR and FCC spurious emissions rules in properly sealed switchgear. Switchgear, such as those shown in Figure 6, will typically meet all EMI standards; however, regulations vary nationally and the requirement for certification, if any, falls to the OEM or systems integrator.

DEPLOYMENTS

Pilot tests are underway in the United States, Germany, Switzerland, India, and Taiwan. Systems have been deployed in China since 2009 in 11 – 33 KV systems. Future pilot projects and evaluations are in initial planning with utilities in India, Korea, Malaysia, and Japan.

Figure 7. Long term installations in China, primarily in Hubei and Guangxi provinces, and in Taiwan and ongoing pilot projects in China, India, Switzerland and the US have validated the technology. Upcoming pilot projects are planned or in discussion in India, Malaysia, Singapore, Korea, and Japan.

SYSTEM PERFORMANCE

Early systems were configured to run independently of one another, executing a continuous loop of temperature measurements and serving data to the central HMI upon request. Even though the individual switchgear were sufficiently shielded to prevent excessive radiated levels for regulatory purposes, neighboring systems still radiated sufficiently strong signals through the shield wall to overpower the much weaker SAWR responses. The immediate solution to this problem was to have the central HMI command a measurement when it required data. This process inherently sequences the readers; however with an average of nine sensors per switchgear and 100 ms per reading, even a small substation with 20-30 switchgear cannot obtain more than about 2 readings per minute.

Instead, the readers were programmed with an option to silently measure interference within their channel. Algorithms were developed based on two simple rules, *“don’t interrupt”* and *“yield to interruptions”*. Of course, these two rules had to be made subject to a timeout such that, under persistent noise, the measurements would still be attempted in a reasonable time interval. It was found that, using this simple collision avoidance algorithm, two completely autonomous readers were able to measure the same set of six sensors in an open room without any mutual interference or interruptions.

There is a trend to less shielded switchgear, especially in industrial point of use applications, in order to reduce the cost of switchgear. This often results in serious cross-talk issues between systems. The former cross-interference is exacerbated by the higher signal amplitudes; however the algorithm is still able to “synchronize” systems autonomously and the *“command to measure”* mode is also still available. A second form of cross talk occurs when a single reader obtains responses from a multitude of sensors at about the same frequency. If the frequencies are close then the weaker signal is a noise source for the stronger signal. If the signal strengths are comparable, then the measurement might jump between the two frequencies.

Generally the signal strength of the response is reduced as $1/R^4$ in free space, making the more distant SAWR response much smaller than the closer one. However, the common bus chamber along a row of switchgear in such open chamber designs serves as a very effective RF waveguide around 433 MHz, and the signals are not nearly so well attenuated. Unshielded chambers do present an installation difficulty; however, in most cases it is possible to develop an installation that comprises the most critical measurement locations.

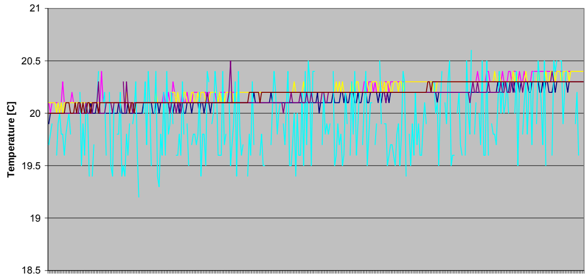

Figure 8. One hours of data taken in ambient conditions with EMI (Nov., 2009) with sensor 4 showing random, persistent interference from an external signal (laptop clock frequency).

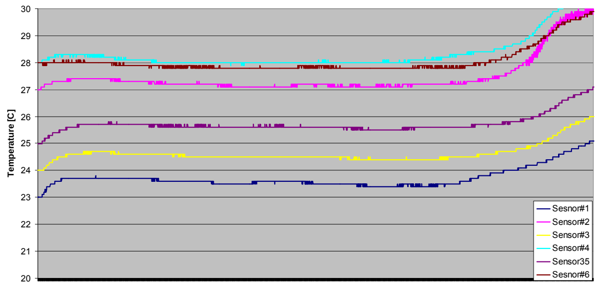

Figure 9. Ten hours of data taken on a 16KV transformer (May, 2009) with sensors 2, 4 and 6 showing the higher temperature of the higher current secondary connections. Data was taken without interfering signals.

Figure 8 shows the influence of persistent, external noise. Several laptops radiate low levels (compliant with CISPR) that can interfere with unshielded interrogation of sensors. The self-synchronization is unable to avoid such noise. Figure 9 shows a similar laptop measuring sensors in a poorly shielded transformer. Despite large openings in the enclosure of the transformer, no interference is seen with any of the sensors.

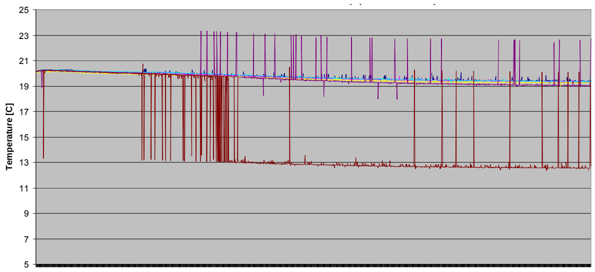

Figure 10. Thirteen hours of data taken on an 11KV switchgear with incomplete shielding of nearby sensor modules. One of the sensors is seen to occasionally measure the alternate sensor (purple, upward spikes) while another jumped from one sensor to the other. These "alternate sensor" interference errors are addressable by careful installation design and verification.

Figure 10 shows the effect of additional unshielded sensors within the read range of the system. The additional sensors provide noise signals as they respond to interrogation signals and even offer a signal sufficiently large to dominate the intended sensor in special cases. The simplest solution is to judiciously place sensors in only the critical measurement points with sufficient separation between same-frequency sensors in unshielded environments.

CONCLUSION AND FUTURE WORK

A system for the passive, wireless and battery-less measurement of the temperature of critical junctions in the electric grid is presented. The system has been proven in field deployments ranging from 11 KV to 33 KV with pilot deployments planned at 66 KV and with failure testing performed from 40 KV to 150 KV.

The sensor operates on a resonant time stretching echo of short interrogation bursts of RF signal. The surface acoustic wave resonators (SAWR) sensors and their critical materials are manufactured to provide high reliability and low aging, resulting in stable operation of the system for long operating lifetimes. Only high reliability, passive components (sensors and antennas) are located within the medium voltage and high voltage cabinets.

The interrogation is performed by a radio frequency (RF) burst. The reader contains the RF circuit, a digital signal processor, and an interface engine such as CAN 2.0B or RS-485. The reader contains firmware and calibration data to allow it to autonomously monitor the temperature of up to 18 points of measurement, with a maximum of six points in any of three separately shielded environments. Systems integration is based on several HMIs, developed by ourselves and our partners, and through SCADA integration using MODBUS-RTU and IEC 60870-5-103.

The need for IEC 61850 protocol compliance is understood and initial efforts to define the project scope are underway.

Electromagnetic compatibility problems with multi-reader systems have been addressed in well-shielded systems. In less shielded systems, a suitable solution has been found in all systems evaluated to date.

In addition to MV switchgear, there are proposed future solutions for low voltage switchgear, for transformer contacts, and for buried cables, that will be explored in the future.

Measuring the connections to transformers has already been demonstrated in Figure 9. The challenges associated with this application for permanent deployments include weatherizing the system since many installations are outdoors and complying with radiated emissions rules without the benefit of a shielded metal cabinet.

Solutions to buried cables are reasonably straight-forward using capacitive coupling; however, the logistics of running power to the readers and transporting data back to the head end power plant have not yet been evaluated.

More immediate effort is addressing the protocol and integration requirements of the utility and point of use customers, including requests for an integrated turnkey system with universal power supply and the need for IEC 61850 GOOSE and other protocols.

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