Switchgear Condition Monitoring

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ABSTRACT

Electrical switchgear is a key component in electrical power systems and is used to both distribute electrical power and to selectively isolate electrical loads. Because switchgear distributes electrical current, heat build-up becomes an important characteristic to monitor. In particular, unexpected temperature rise at a particular location could indicate corrosion or some other type of defect. Thermal effects are especially visible in medium voltage switchgears used in distribution networks, where electrical currents may rise to few thousands of amperes. Thus keeping switchgears in proper condition over their long life becomes a critical issue.

Currently, switchgear bus temperature monitoring is either done periodically by manual inspections using IR cameras or is implemented by fibre-optic systems. Both have limitations like inaccurate and infrequent readouts, high implementation cost and limited monitoring area. In this paper a modern approach to implementation of condition monitoring is presented. The new design is based on passive, SAW-based, wireless sensors, reducing installation costs and enhancing monitoring by allowing measurements in previously unreachable locations. This article shows a practical implementation of the wireless condition monitoring system as a part of a general, built-in, switchgear diagnostics and maintenance system.

KEYWORDS

Condition monitoring; Switchgear; Wireless sensors

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1. ELECTRICAL POWER SYSTEMS – OVERVIEW

Safety of power systems network is critical for every utility. Every and even small disturbance of energy distribution system leads to serious problems that include failure costs and require adjustment of energy flow and even causes lack of power in large areas. One of the key components in electrical power systems are medium voltage switchgears which are used to distribute electrical power, selectively isolate electrical loads and protect loads from cascading failure. Switchgears are produced in many forms, but typically include a combination of electrical elements such as disconnectors, fuses, circuit breakers and distribution bus bars arranged in a lineup of frames. Switchgears are located anywhere electrical distribution, isolation and/or protection may be required. These locations may include, for example, generators, motors, transformers, factories and substations.
Because switchgear distributes electrical current, heat buildup becomes an important characteristic to monitor. The most significant amount of heat dissipation is on distribution elements like bus bars. As bus bars are not made of single piece of copper, the hotspots usually appears on connectors (used to attach breakers to the installation) or joins which normally connects bus bars and output cables. Moreover, every switchgear is dedicated to operate under some maximum load (maximum current flowing through distribution components). The certification process defines maximum temperature the distribution elements, switching elements and bus-bar joints may reach under maximum load to keep the system safe [7]. Unexpected temperature rise at a particular location could indicate corrosion or some other type of defect. If left uncorrected, this defect could result in catastrophic failure resulting in deactivated loads and potentially hazardous conditions to personnel.

2. TEMPERATURE MONITORING SYSTEMS FOR SWITCHGEARS

Monitoring the temperature of switchgear components, especially for medium voltage switchgear, is difficult task. Most of the problems are generated by high voltage and high current flowing though distribution components that requires proper insulation and shielding. Every switchgear frame is divided into number of cubicles, and each of these contains different switchgear component. A sample switchgear frame arrangement is shown in the Figure 1.
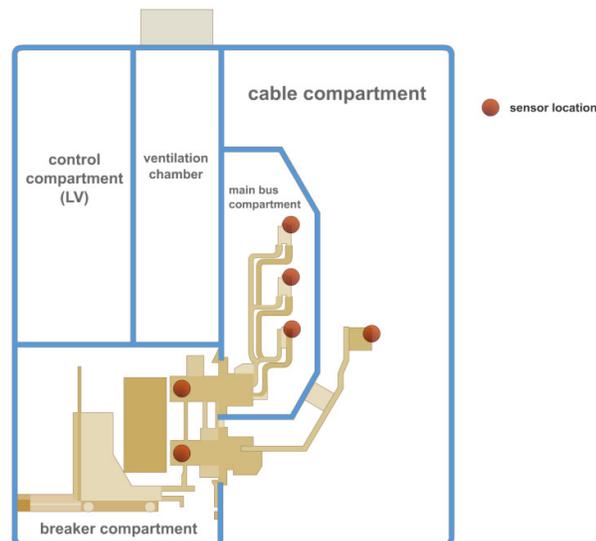
Figure 1. Typical switchgear frame arrangement.
Potential hotspot points are marked.

The most obvious monitoring system, based on sensors wired to a control box, is not an option in the industrial environment because of the insulation issues. A typical voltage level of 15kV requires high insulation. Even a very small degradation of sensor wire insulation can short-circuit phase to the

control box, switchgear cubicle and ground that trips the breakers, disconnects power or – in the worst case – can destroy the switchgear.

There are several existing solutions for monitoring temperature of the switchgear components. Some of them allow gathering temperature online while other requires manual inspection, but every solution has a strong requirement that after switchgear is energized, measurement must be done without opening the cubicles.

There are three solutions for the switchgear components temperature measurement, which are most commonly employed these days:

- Fiber-optic sensors, which provides galvanic insulation between sensor and control box. Such installation requires to be put in place during assembly phase as optic fibers must be attached and organized in the switchgear and directed to single control box, usually mounted in one of the low voltage cubicles. The solution is very expensive but in most critical applications this is the most reliable kind of measurement.
- Infrared (IR) temperature sensors, which measure IR radiation of the component and calculate temperature based on the amount of emitted IR radiation ([6], [8]). The solution is relatively inexpensive but there are several disadvantages. First, the sensor must be directed towards observed component very precisely and in most cases there is no possibility to install such system on assembled switchgear. Second, since components to be measured are typically enclosed within an insulation boot in the switchgear the temperature readout is not very precise.
- The most common and cost-effective solution is installation of IR sightseeing windows in the cable compartment. Problem with this solution is that it requires manual, scheduled inspection and thus relies on human discipline and precise operation of an IR thermometer. Moreover, the same problem as with previous system occurs when monitored components are enclosed within insulation boots. But the most important limitation is that measurements are possible only in cable compartments and there is no possibility to measure temperature of the breaker connectors or main distribution bus-bar joints

Figure 2. IR-transparent windows for manual inspection of the temperature.

3. WIRELESS SENSORS FOR TEMPERATURE MONITORING

The most troublesome issue in building a reliable condition monitoring system is wires that are used to get temperature readouts from the sensors. Elimination of wires required for constant communication with the sensor unit would provide a huge opportunity to build a temperature measurement system that from one side is easy installable, even on the already assembled switchgears, and from the other side provides online temperature measurements.

Technology progress in wireless systems and devices introduces every year at least a few new wireless solutions so that there are several mature technologies used to implement wireless sensor solutions. The most important standards for short-range communication are IEEE802.15.1 [1] (Bluetooth) and IEEE 802.15.4 [1] that is utilized by variety of high-level protocols like ZigBee [2] and WirelessHART [3]. Unfortunately, because of the fact that such wireless sensors are battery-powered, the lifetime of the sensor is limited to at most few years. For mission critical application the average switchgear lifetime is about 30 years thus condition monitoring system should last for the same time. However, a major maintenance interval of 5-7 years is not uncommon. There are also solutions based on custom protocol stack optimized for wireless temperature monitoring like one provided by Schneider-Electric [5], but similarly to the standard sensors, the lifetime of the solution is limited by battery capacity.
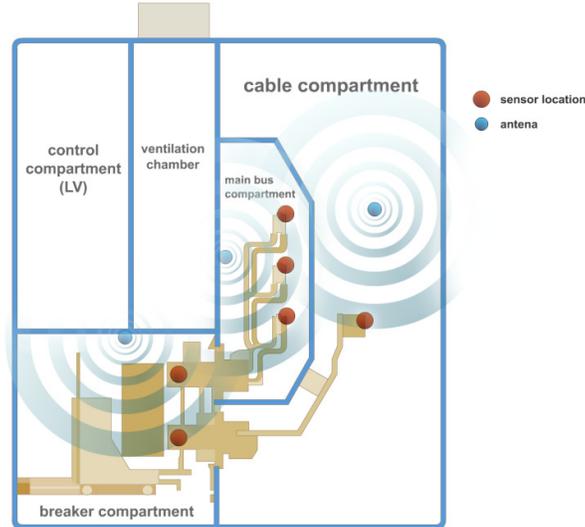
**Figure 3. Cross section of the switchgear frame divided by compartments.
Wireless sensors antennas and their operation range are marked.**

A more flexible solution with no loss of functionality is provided by passive wireless sensors, e.g., those based on SAW technology [4]. The general idea is to trigger the sensor with radio wave at exact frequency, which generates RF responses. The frequency response shape and spectrum is dependent on measured quantity. As the measured quantity is calculated from the frequency range, every sensor must occupy its own frequency range, which limits number of sensors in range of single antenna to no more than a few. This limitation may have significant impact on the applicability of SAW sensors for complex condition monitoring of switchgear components as average frame contains about 12 hotspots: three each for main bus, for cable terminators, for breaker inputs and for breaker outputs. Moreover, switchgear interiors contain a lot of conducting metal plates and other components that reflect and degrade radio signals. In consequence, to apply a set of SAW sensors to measure temperature in all 12 locations, a dedicated layout of the sensors was required. With cooperation of external sensor vendor, sensors were located in required locations and transmitted power of the antenna was tuned so that shielding capabilities of the switchgear cubicle boxes divided switchgear into sections that contain sensors operating at different frequencies, while frequencies in different sections were duplicated. The sample layout of the switchgear, as well as signal propagation inside the compartments is shown in the

Figure 3. Antennas were mounted on the switchgear walls in locations that prevent short-circuit or damage by the current flowing though bus bars. To complete temperature measurement system, antennas were connected to SAW sensor readers linked with industrial RS485 cable.

4. EMBEDDED CONDITION MONITORING SYSTEM

The goal of the new design was to gather most valuable aspects from existing solutions and combine into a single, complete condition monitoring system that can be embedded in the switchgear hardware. The system was designed not only as a temperature monitoring system but also as a complete condition monitoring solution including historical data storage, support for different measurement types, variety of sensor types and condition monitoring engine that analyzes gathered data in order to provide reliable and human-readable messages. The general architecture of the system is shown in the Figure 4.
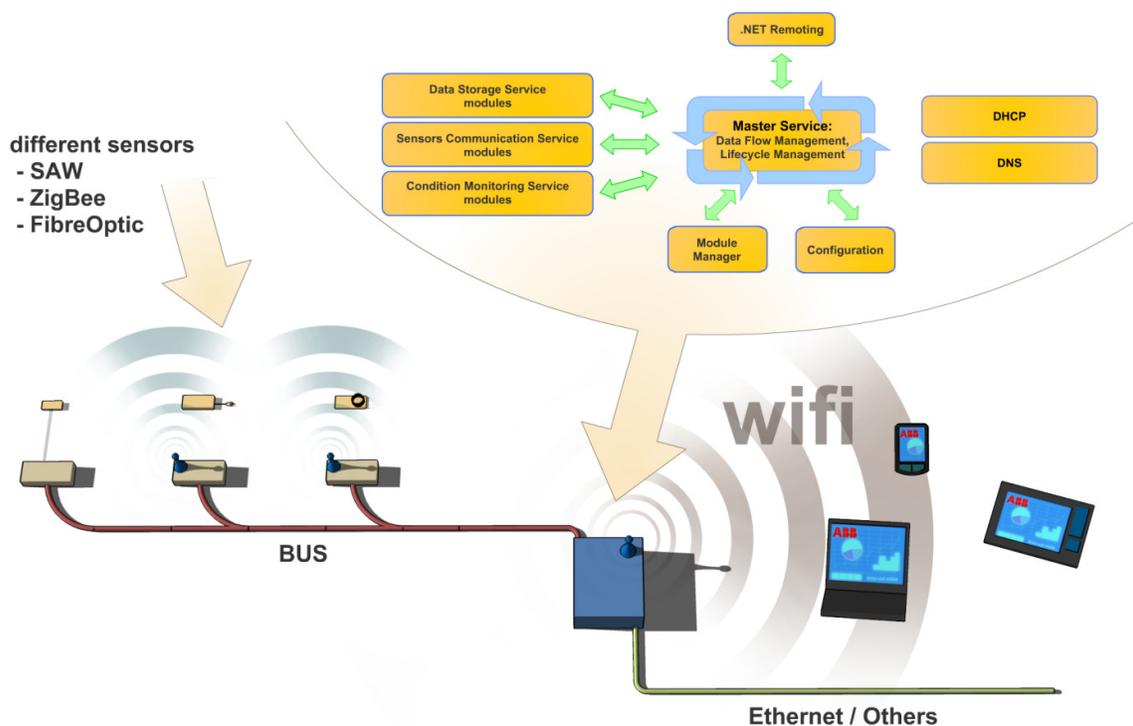

Figure 4. General concept of embedded condition monitoring system for switchgears.

As shown in Figure 4, the system consists of several, loosely coupled subsystems, which can be tuned depending on specific requirements:
- Database engine – used to store historical data and to provide persistent storage for conditions and events
- Data collector – responsible for querying sensors basing on predefined schedule and provide results to the master service. The schedule can be based on simple, constant sampling rate or can utilize information about switchgear condition to apply adaptive schedule. For example, sampling interval can be decreased when switchgear condition indicates potential failure, or increased when switchgear normal condition is observed.
- Condition monitoring (CM) modules – provide pluggable algorithms for calculating condition of the switchgear. Every CM module can calculate condition of a particular location or

4

complete switchgear and provide this information to the master service. Later on, master system calculates worst-case condition basing on all results from the CM modules and provides this information to the user

- Sensor modules – provide pluggable, hardware-dependent endpoints, that implement low-level communication between condition monitoring system and particular sensor hardware
- Wired and Wireless link – provide communication to outer world. This can be a SCADA system, desktop system or wireless, handheld or tablet PC. Built-in DNS/HDCP server provides zero-configuration connectivity to wireless network of the CM system while build-in web server generates user interface on demand. This allows non-SCADA clients to operate the system with no additional software (web browser is required).

Implementation of the system was optimized for low power, industrial-class PC operating under Windows XP, Windows Embedded or Linux systems.

5. INCREASING CONDITION MONITORING ACCURACY

The default implementation of the condition monitoring module compares temperature readouts to threshold values (WARNING, SEVERE), which are defined during commissioning phase. Temperatures below WARNING threshold value indicate that switchgear is operating properly. Temperature exceeding WARNING but below SEVERE threshold indicates switchgear probably under heavy load but still in the certified range while exceeding SEVERE threshold indicates that some failure is imminent.
Simple temperature readings alone may provide only information whether switchgear operates in certified temperature range and may not provide sufficient information for diagnosis of switchgear defects. This is because temperature fluctuations are not only caused by defects, but are also closely tied to external conditions and current loading levels. The first issue is easily solved by providing one per-switchgear or one per-frame temperature sensor that measures ambient temperature. Modified condition monitoring module differs from basic implementation in a way that it subtracts ambient temperature from hotspot temperatures and adds the certification specified ambient temperature. The enhanced version gives results that are more reliable but still cannot detect defects. The most reliable version requires additional current readouts to be combined with temperature data. However, because of space and cost constraints, providing a current measuring device at each important node or connection point is impractical. The single-phase current readout sensor located on every switchgear input and output is sufficient to calculate currents flowing through every distribution component. The assumption is that there is no variation in current flow compared phase to phase. This assumption is valid for the distribution networks as no (or very little) variation is observed. When currents and temperatures are known for every location, the thermal model of a bus bar can be applied and theoretical temperature rise (or drop) can be calculated and compared to the measured value. The defect can be observed if temperature rise (or drop) exceeds specified ranges, even if the absolute temperature is below regular WARNING threshold value.
There are more options to enhance defect detection. As system provides open architecture, additional quantities (e.g., humidity) can be applied and more reliable results can be obtained or more sophisticated algorithms can be applied (e.g., for analyzing daily/weekly or monthly trends).

6. TEST INSTALLATION

The current monitoring modules have already been installed in the switchgears so the possibility and reliability of this kind of measurements is confirmed. Lab tests have proven that wireless communication is possible in switchgear interiors and communication range can be limited by reduction of transmission power, but a pilot installation is always the best proof of concept.
For testing purposes, outdoor switchgear operating on substation in the desert climate of Arizona was selected. Harsh environment with high ambient temperatures seemed to be the worst-case scenario. The switchgear used for testing was composed of six frames and equipped with full set of sensors, thus 72 sensors were utilized to monitor all expected hotspots in the switchgear. Even though system is

ready for handling temperature and current values, the first installation was limited to temperature measurement with simple, threshold-based condition monitoring (see Section 5). The condition monitoring system was installed in the control compartment, connected to wireless sensor readers through RS485 bus and equipped with tablet PC for accessing the switchgear condition and historical data.
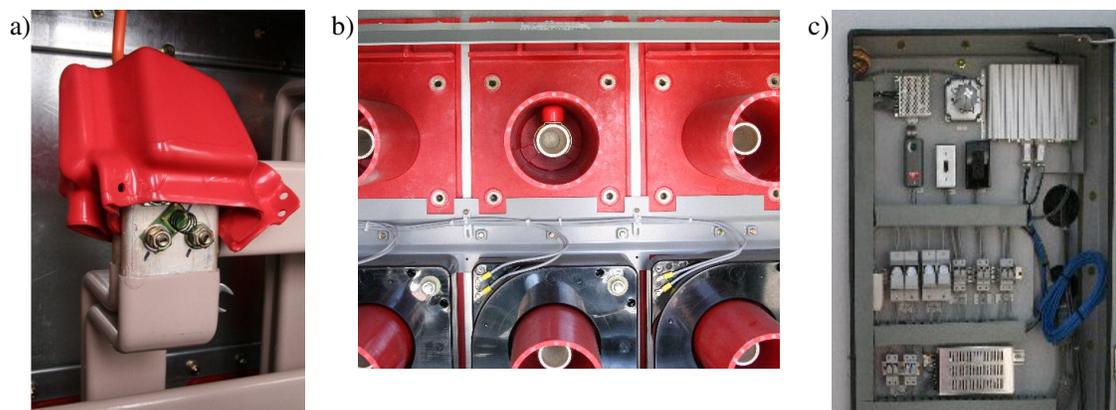
Figure 5. Wireless Condition Monitoring system deployed onsite
a) temperature sensor on the bus-bar joint
b) temperature sensors installed on the breaker connectors
c) control cabinet and embedded system installed (top-right corner)

The system was deployed at a customer site, on already assembled switchgear. Because of customized sensor mounting pads, the installation was successful and pilot installation was started in April 2010.

7. CONCLUDING REMARKS

In this paper, we have presented a concept and implementation of modern condition monitoring system for switchgears. Even though the general concept of wireless monitoring of temperatures of switchgear internals is not new, presented system has a number of advantages compared to existing wireless solutions described in this paper. Utilization of miniature SAW sensors enables monitoring of breaker connectors and non-invasive installation inside the switchgear. The small size of sensors enables system to be extremely flexible in both selection of measurement locations as well as possibility to deploy the system at existing site. Furthermore, passive power supply enables indefinite lifetime of the system regardless of external condition, which are important in self-powering devices. In spite of the fact that first pilot installation was focused only on monitoring temperatures, the overall open system architecture, support for various sensor types (which can be added almost in runtime), and flexible condition monitoring algorithms, open new opportunities for implementing customized condition monitoring strategies for switchgears. The customization can be addressed to different switchgear types, availability of sensors, required condition calculation precision or system price. Intuitive user interface hides complexity of the condition monitoring system behind simple ok-warning-severe indicators. A web based user interface available wirelessly enables quick and easy access for utility personnel, maintenance engineers and servicemen. Furthermore, both wired and wireless communication to the system enables connectivity and cooperation with high-level, enterprise control and management systems.

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