Hot spot

A new infrared sensor measures temperature in generator circuit breakers

STEPHAN WILDERMUTH, ULF AHREND, MORITZ HOCHLEHNERT, MARCO ULRICH – The generator circuit breaker (GCB) is of great importance for the undisturbed operation of a modern power plant. It typically sits between a generator and its transformer to protect this equipment from damage, while handling very high currents – typically tens of kA. With such high currents, even a small increase of resistance in the current-carrying path will lead to a large temperature increase in the breaker – and this can have very dramatic effects. Temperature supervision is, therefore, essential. This, however, can be a very challenging task in the high-voltage (HV) environment so ABB embarked on a development program to produce a new temperature sensor system for GCBs.

1 Pumped storage power plant application with HECPS-3S

GCBs are used, for example, in fossil-fueled, nuclear, gas-turbine, combined-cycle, hydropower and pumped-storage power plants. They have a tough job. During normal operation of the power plant, the GCB has to carry the full nominal current of the generator, which can easily reach 23 kA without bus cooling or over 30 kA with active cooling – all at potentials of up to 32 kV ➔ 1.

At such high currents, even a slight increase of electrical resistance in the current-carrying path leads to a large temperature increase. Increased resistance can arise from connection misalignment, dust inside the GCB or damaged contact surfaces. The consequent heating can lead to damage to internal silver-plated contact areas, such as the bus duct connection zones, the line disconnector and the contact system of the interrupting chamber. Heat removal from the main conductor is partly done by radiation, so paint with high emissivity is usually applied to the conductor – but this cannot cope with significantly elevated temperatures (normal operating temperatures are in the range of 70 to 90°C).

Excess temperature can lead to loss of interrupting capability or even provoke a flashover if components start to melt.

GMS600

ABB's GMS600 is a GCB monitoring system that indicates the need for maintenance and provides early warning to avoid unexpected downtime ➔ 2. The GMS600 calculates remaining time-to-overhaul based on cumulative current interruptions, total number of mechanical operations, time from last overhaul, circuit breaker main drive supervision, SF$_6$ density and so on. One aspect missing from its repertoire was temperature supervision. This was because no commercially available temperature sensing system fulfilled all the technical, commercial and functional requirements for an accurate and reliable temperature monitoring of GCBs during operation.

> At such high currents, even a slight increase of electrical resistance in the current-carrying path leads to a large temperature increase.

This lack of a commercial system is not surprising as the temperature supervision of HV components can be challenging. For example, the temperature sensor has to survive severe electromagnetic conditions and can also be exposed to steep temperature gradients caused by, eg, desert climate.

A new temperature sensor system had to be developed.

Sensor development and design

A detailed technical analysis determined that a temperature measurement scheme based on the detection of infrared radiation (IR) was the best approach. The goal then was to take a commercially available IR sensor element and package it to operate reliably in the demanding GCB environment.

The central component of the IR temperature sensor is the IR detector element itself. Non-cooled Si-based thermopile detectors were chosen due to their good cost/performance ratio. The only way to ensure proper performance of the sensor under the severe conditions encountered in a GCB – spatial and temporal temperature gradients and high electromagnetic

Title picture

Accurate and reliable monitoring of the temperature in GCBs (ABB's HEC8 is shown) is essential as the slightest increase in resistance can lead to a rapid temperature rise because of the very high currents flowing. How can temperature be monitored in such a challenging environment?

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2 Central condition monitoring device GMS600

fields with fast transients – was to appropriately package the IR detector and the electronics.

In addition to the detector ASIC, additional electronics were included to convert the digital SMBus output signal to Modbus. These electronics, too, must withstand the severe EMI (electromagnetic interference) environment of a GCB.

The sensor package, therefore, needs to fulfill three major objectives:

- Suppression of large spatial temperature gradients at the IR sensor element
- Suppression of large temporal temperature gradients at the IR sensor element
- Suppression of EMI

In order to fulfill the first objective, the housing of the IR sensor element was surrounded by a material with high thermal conductivity ➔ 3. This ensures that temperature gradients immediately equilibrate and the thermal field around the sensor remains homogeneous.

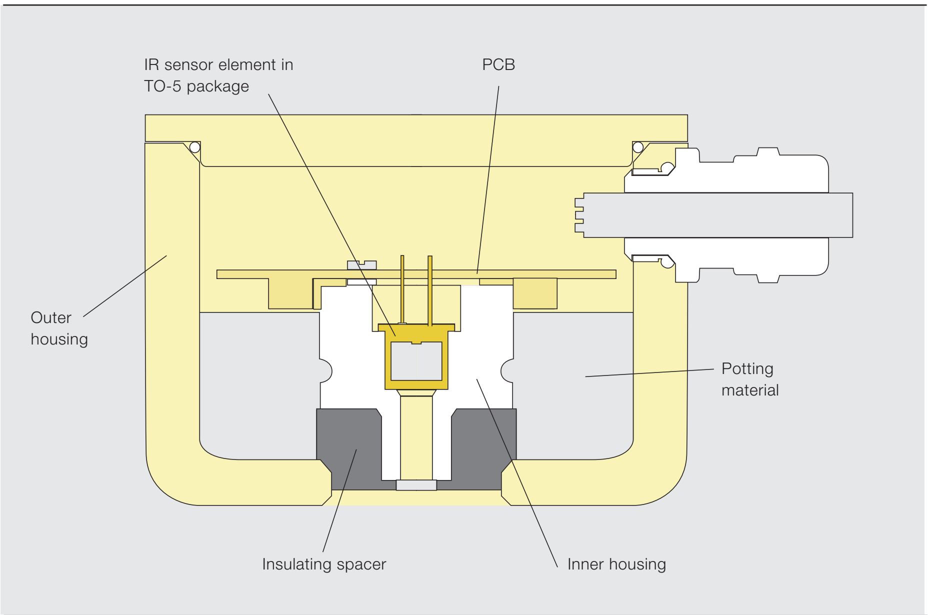
The second objective can be satisfied by choosing a design that leads to a large thermal time constant (in the range of several minutes). The time constant of the sensor package can be increased by giving the sensor and aperture a large thermal mass, and by reducing thermal conductivity around the sensor to delay heat ingress to the sensor.

The housing of the IR sensor element was surrounded by a material with high thermal conductivity.

The package is, therefore, a two-part-housing concept where the inner and outer parts are thermally weakly coupled ➔ 3. This approach inherently satisfies the dielectric and EMI requirements, too: The outer housing acts as a Faraday cage and the thermal insulation acts as an electrical insulator as well as a heat barrier. As an additional EMI countermeasure, the outer housing is grounded through the GCB enclosure and the inner housing is connected to a local ground potential.

Package dimensioning was defined by transient thermal finite element method (FEM) simulations of a simplified thermal model ➔ 4. The design goal was to achieve a thermal time constant greater than 10 minutes. This duration was predicted by the simulation and verified by experimental tests later on.

3 Schematic of the cross section of the sensor package showing the main functional components



The outer housing acts as a Faraday cage and the thermal insulation acts as an electrical screen as well as a heat barrier.

Prototyping and testing

To check the thermal design and to verify good thermal coupling of the IR sensor element to its surroundings, temperature shock experiments were performed. The IR temperature sensor was exposed to an ambient temperature change of 25°C to 70°C. The rise time of 5°C/min was limited by the heating power of the climate chamber used. For the duration of the experiment the IR temperature sensor stared at a black-body radiator held at a constant 80°C. Very good sensor performance (error less than 2°C) was found if the thermal coupling to the inner housing was guaranteed by a thermal grease or adhesive.

Large temporal temperature gradients at the IR sensor element can be avoided by choosing a design that leads to a thermal time constant of several minutes.

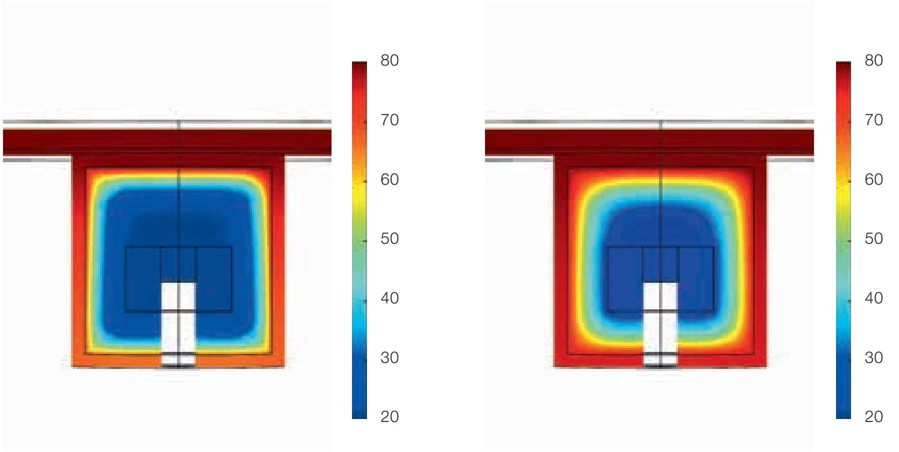
To verify the performance of the IR temperature sensor, 21 sensor prototypes were built and subject to different environmental scenarios simulated by the climate chamber. Sensor response to a black-body radiator temperature range of 30°C to 120°C at a constant ambient (sensor) temperature of 25°C was tested. The sensor response displayed a linear behavior. The linearity error remained below 3°C over the entire object temperature range. The variations (standard deviation) between the individual prototypes were found to be 0.8°C and 1.2°C at an object temperature of 75°C and 120°C, respectively.

A very important task for the IR temperature monitoring system is the detection of GCB overloading, when the temperature of the main conductor can approach 120°C. This scenario was simulated by changing the object temperature range from 80°C to 120°C ➔ 5. The IR sensor accurately captured this temperature change and the measurement deviation stayed well within the required accuracy interval of ± 3°C.

To assess the influence of changes in ambient temperature, the IR temperature sensors were exposed to three consecutive temperature cycles from –5°C to 60°C at a rate of 0.1°C/min. This rate of temperature change was chosen to simulate a typical day/night scenario.

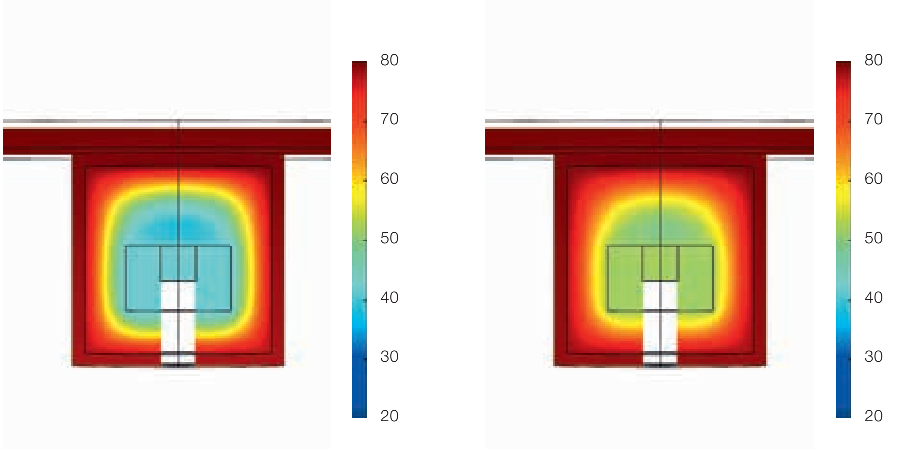
The only way to ensure proper performance of the sensor under the severe conditions encountered in a GCB was to appropriately package the IR detector, the enclosure and the electronics.

4 FEM simulation of the sensor package heating. This gives a first estimate of the thermal time constant of the whole sensor package and was used to define the package dimensions



4a After 73 s

4b After 200 s



4c After 400 s

4d After 600 s

Again, typical sensor measurement error remained below 3°C. Furthermore, in humidity tests, the sensor measurement error was less than 2.5°C up to 90 percent relative humidity, at an ambient temperature of 60°C.

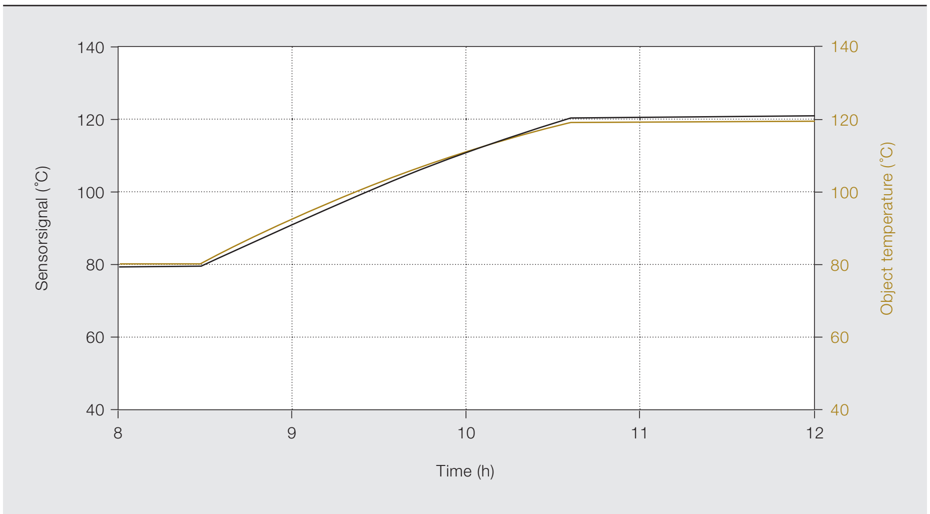
The IR temperature sensors were also tested for other disruptive factors encountered in a GCB environment. This included extensive vibration testing to simulate mechanical shock experienced during GCB switching operations. Electromagnetic immunity was tested according to IEC 61000-4 and IEC 61000-6, addressing immunity to RF electromagnetic fields and electrostatic discharges, as well as electrical fast transient tests (severity level 3 required). All tests were successfully passed and the sensor system thus qualified for operation in a GCB.

Productization phase

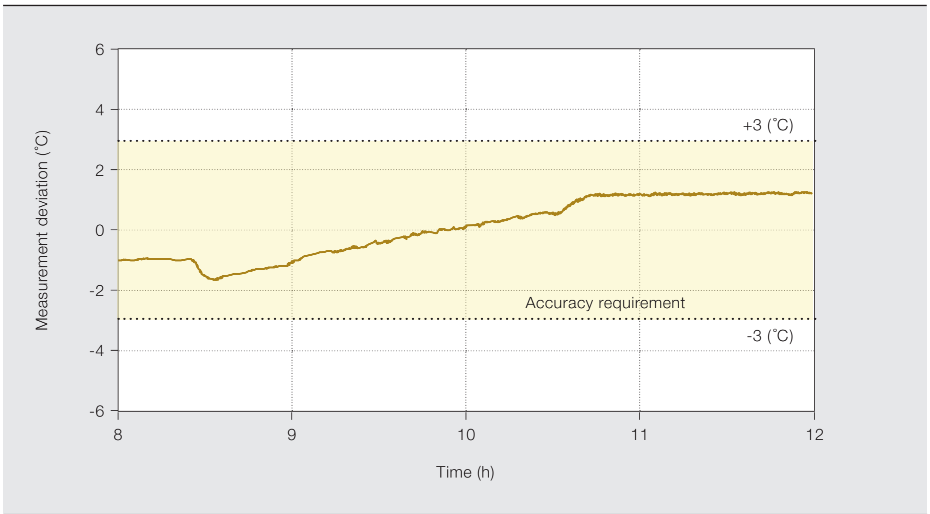
The involvement of a potential manufacturer early on in the project resulted in a very mature technology demonstrator. Only a few changes were necessary for full productization.

Productization was done in parallel to the adaptation work on the sensor itself. This covered the sensor assembly, cable harness design, mechanical integration of the sensors into the GCB enclosure, routing of cables, and a GMS600 monitoring software update to log, store and present the temperature data to the customer for nine sensors (three per phase). The supply chain was put in place in cooperation with the manufacturer, who also preassembles sensors and cables on a mounting rack to speed installation in the GCB.

5 Climate chamber simulation of GCB overheating: IR temperature sensor response



5a IR temperature sensor signal at an object temperature from 80°C to 120°C over several hours



5b Measurement deviation stays well within the required accuracy interval of ± 3°C during the entire temperature ramp.

> To check the thermal design and to verify good thermal coupling of the IR sensor element to its surroundings, temperature shock experiments were performed.

Extended service

Cost-efficiency can be significantly improved by intelligent service approaches, such as predictive maintenance. However, efficient, adaptive and sustainable predictive maintenance and equipment life strategies are highly dependent on meaningful sensor signals from the field.

The robust and cost-effective temperature sensor system described here enables reliable temperature monitoring of GCBs during operation. In combination with other sensor information (eg, vibration or contact ablation) a clear picture of a device's health condition can be derived and predictive maintenance strategies formulated. This is especially important for GCBs where overheating of the main conductor can lead to the power plant shutting down, which can result in high cost and potentially disastrous equipment damage.

Access to this kind of condition data also enables new service concepts and business models to be created, and provides valuable feedback for the design of new devices. Finally, statistical analysis of data from an entire fleet of devices can reveal information unobtainable from a single device. This opens up new opportunities and value propositions for ABB to offer to end customers through its service portfolio.

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