Evaluation of thermal imaging system and thermal radiation detector for real-time condition monitoring of high power frequency converters

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Abstract We have carried out at laboratory test to study the feasibility of using thermal radiation detectors for online thermal monitoring of electrical systems in wind turbines. A 25 kW frequency converter is instrumented with a thermal camera, operating in the 8–14 μm wavelength range, and a single-pixel thermopile sensor, operating in the 4–8 μm wavelength range, to monitor the temperature development of the power electronics under various load sequences. Both systems performed satisfactorily with insignificant temperature deviations when compared to data from calibrated point contact sensor. With spatial averaging over a 7 mm $\times$ 7 mm for the camera and temporal averaging over 60 s for the thermopile sensor, we reduce the root mean square noise to 45 mK and 68 mK respectively. The low cost and simple operation of the thermopile sensor make it very attractive for condition monitoring applications, whereas the attractive feature of the camera is the possibility of multi-point or distributed temperature measurements.

Keywords Temperature measurement · Condition monitoring · Frequency converter · Wind turbine

1 Introduction

Cost effective operation and management of offshore wind turbine systems demand advanced condition monitoring systems. To reduce failure rates and decrease down time,

we need high quality data as input to algorithms for fault diagnosis and prognosis.

Recent studies of failures in wind turbines have demonstrated that failures in the electrical systems contribute significantly to generator downtime [1]. Electrical systems account for 13%–18% of the failures [2]. Condition monitoring of transformers and rotating electrical machinery has already been proven cost effective in the power generation industry, and condition monitoring methods used in the power generation industry have been adapted for commercial use in wind turbines. However, the operation and maintenance cost remains too high, and there is a need for better condition monitoring methods of the electrical systems.

Insulated gate bipolar transistors (IGBTs) account for 15% of the failures in a power converter [3]. A major reason for the failure of IGBTs is bond wire lift-off [4], which results from the thermal cycles that the device is subjected to in operation. Recent studies have demonstrated that reliable lifetime estimation can be predicted from historic junction temperature variations [5]. Thus online monitoring of IGBT temperature will be very useful for enhancing the reliability, cost effectiveness and performance of the power electronic system [6]. However, it is difficult to obtain the actual junction temperature since it cannot be measured directly with conventional sensors [7]. It is common to use measured heat sink temperatures to compute dynamic junction temperature. However, unless very advanced thermal models are used, the uncertainty in the predicted junction temperature may be too large for good lifetime prediction. Additional temperature measurements on the IGBT modules can possibly be used to reduce the uncertainty in the junction temperature prediction.

Monitoring a high power frequency converter is challenging both in terms of electromagnetic interference and

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Fig. 1 **a** Gobi 640GigE infrared camera (the camera measures 49 mm × 49 mm × 77 mm and weights about 500 g (without lens) and **b** The TI TMP006 single pixel thermopile sensor kit (the thermopile chip package measures 1.6 mm × 1.6 mm (*lower image*))

high voltages. In this paper we present preliminary result from an evaluation of two non-contact temperature measurement systems, an infrared camera and a single-pixel thermopile sensor, for online thermal monitoring of IGBT load terminals and heat sink of frequency converters in wind turbines.

2 Measurement systems

2.1 High resolution thermal imaging system

The thermal imaging system was based on a commercial high resolution camera from Xenics interfaced to a custom written LabVIEW application [8]. The Gobi 640GigE camera (see Fig. 1a) is a 0.3 megapixel (640 × 480) camera based on uncooled micro-bolometer technology operating in the 8–14 μm spectral band. It is the smallest thermal imaging camera using GigE vision interface standard, allowing fast data transfer to the PC (<50 Hz). The measurement range is from $-25\text{ }^{\circ}\text{C}$ to $125\text{ }^{\circ}\text{C}$, and the resolution is specified to 50 mK [8]. The camera has some valuable features regarding use in wind turbine converter diagnostics like operating temperature range (from $-40\text{ }^{\circ}\text{C}$ to $70\text{ }^{\circ}\text{C}$), shock (70 G) and vibration conditions (4.5 G for frequency 5–500 Hz). The camera is equipped with an 18 mm lens and has pixel pitch of 25 μm . During testing we operate the camera with an object distance of 52 cm, resulting in a spatial resolution of 0.7 mm (limited by the pixel).

The Gobi 640GigE camera can be easily integrated with LabVIEW programming environment. For integration purposes we used LabVIEW vision package, which supports connection by using GigE vision protocol. After connecting to the camera the program loads the calibration file provided by the manufacturer and creates the calibration table where the relationship between the digital pixel values and the

temperature is stored. In order to store the number of frames, the points or areas of interest may be set by the user. Figure 2 shows the LabVIEW application user interface.

The part of the program that is responsible for point and area temperature data analysis uses LabVIEW MathScript add-on module, which enables use of Matlab functions during the data analysis. Currently, the program calculates the mean temperature value over the selected area of interest. The data presentation phase is realized by temperature graph plotting.

2.2 Single pixel infrared thermopile sensor

The single pixel sensor is a model TMP006EVM from Texas instruments. It is an infrared thermopile sensor with digital output realized by integrated circuit. The measurement frequency can be adjusted and varied from 0.25 Hz to 4 Hz [9]. The sensor has a wide operating temperature range from $-55\text{ }^{\circ}\text{C}$ to $125\text{ }^{\circ}\text{C}$ and measurement range from $-40\text{ }^{\circ}\text{C}$ to $125\text{ }^{\circ}\text{C}$. The sensors temperature error is specified to (± 1) $^{\circ}\text{C}$. The temperature resolution depends on the number of averages, varying from 500 mK to 125 mK, for 1 and 16 averages respectively. The TMP006EVM has a very large field of view of 90° [10]. The sensor output is influenced by all the objects within the field of view of the sensor. This fact influences the practical application areas of the sensor. The sensor is the best fitted for the relatively big surfaces and for little distances between the object and the sensor. The recommended operating distance is equal or less than half the object radius. The field of view may be reduced using pin-hole in a low emissivity shield around the sensor.

We perform the evaluation using the default software provided by Texas instruments. The software is written in LabVIEW, and TI gives access to the source files. Therefore, future developments are possible on basis of original virtual instrument files.

2.3 Other installed temperature sensors

The frequency converter was also instrumented with a SENTRY temperature monitoring system from Kongsberg [11]. This is a wireless sensor system suitable for high-voltage applications. The mounted sensors are individually scanned by a multiplexing central unit using low energy radar pulses. The sensors respond to the pulses with a temperature dependent pattern. The system has a measuring range from $0\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$. The thermal resolution of the sensor system at the test facility is configured to 1 K, with an accuracy of 2 K. The central unit (signal processing unit) operating temperatures are between $40\text{ }^{\circ}\text{C}$ and $85\text{ }^{\circ}\text{C}$, and the antennas operating temperatures are from $0\text{ }^{\circ}\text{C}$ to $110\text{ }^{\circ}\text{C}$.

Fig. 2 Thermal camera LabVIEW application interface

3 High power frequency converter

The high power frequency converter used for testing is a prototype 25 kW converter at the NTNU-SINTEF Renewable Energy Systems Laboratory [12]. The heart of the converter contains four IGBTs (400 A, 1,200 V) Semikron modules. The converter modules, capacitors, inductors, and control module are mounted in a standard 48.26 cm rack, as shown in Fig. 3. The frequency converter is fed from a generator driven by an electrical motor, as illustrated in Fig. 4. Generator speed and motor torque are controlled by software.

Location of reference temperature sensors, wireless SENTRY sensors on high voltage points, and thermocouples at ground potential (heat sink) is illustrated in Fig. 4. The thermal camera is used to monitor the generator side of the converter, whereas the single pixel thermopile sensor is used to monitor the heat sink.

4 Evaluation results

The thermal camera is positioned on the outside of the transformer rack imaging area around the emitter/collector terminals of the IGBT modules on the generator side. The

distance from the camera objective to the IGBT terminal is 52 cm (see phase A). This allows us to monitor the surface temperature of the terminal of all three phases, as well the surface temperature of the IGBT module casing. The single pixel sensor is placed 4 cm above the heat sink on the generator side.

Temperature measurements based on the thermal radiation are strongly dependent on emissivity of the measured object. To circumvent the emissivity issue, we coat the surfaces of interest with electrical non-conducting tape with emissivity ε around 0.97. For more advanced tests the high thermal emissivity spray coating should be used. The plastic casing has emissivity close to 1 and there is no need for additional coatings.

4.1 IGBT load terminal temperature monitoring

For the first test we monitor the temperature of phases A and B while running the generator and converter for approximately 2 h, as illustrated in Fig. 5. Figure 6 shows the IGBT load terminal temperature developments as measured using thermal camera and the point-contact sensors (Sentry). Temperature data for both a single camera pixel and an area of 10×10 pixels were logged. This corresponds to terminal areas of $0.7 \text{ mm} \times 0.7 \text{ mm}$ and

Fig. 3 High power frequency converter at NTNU-SINTEF Renewable Energy Systems Laboratory used for testing (the image on the *right* shows the IGBT module mounted on the heat sink)

Fig. 4 Location of reference temperature sensors

7 mm $\times$ 7 mm respectively. As expected the temperature response is dominated by a “fast” (10 min) and a “slow” (h) time constant. The agreement between the different sensors is as expected. The small deviations of around 0.5° can be attributed to the physical configuration and

mounting of the point-contact sensor, and the emissivity error of the thermal camera system.

From Fig. 6b it is clear that there are two different noise mechanisms involved in the thermography system including a white noise from the radiation detector and

Fig. 5 Generator input sequence for test 1

electronics and a low frequency technical noise. The low frequency noise is due to periodic compensation of the cameras internal temperature. The technical noise due to camera internal adjustment has peak-to-peak amplitude of 500 mK, dominating the white noise.

The white noise contribution is reduced by spatial averaging over several pixels. The root mean square noise in the one pixel measurement in the time interval between the two first camera adjustments (51.3–52.6 min) is 90 mK, while the corresponding root mean square noise for the 10×10 pixels measurement is 45 mK. Noise reduction of only factor two indicates that noise from neighbouring pixels is correlated.

The low frequency technical noise can in principle be reduced by proper filtering at the expense of time resolution. However, the time interval between internal corrections generally increases with time interval since the camera system is powered, and with room temperature variations. In Fig. 7 we have plotted the deviation between the camera signal (10×10 pixels) and the same signal smoothed using a moving average filter over 120 data points (4 min). This plot clearly illustrates how the time interval between the internal camera adjustments increases with time, starting at around 1.3 min at the beginning (@ 50 min) and increasing to 4.4 min towards the end (@ 150 min).

4.2 IGBT module casing temperature monitoring

The temperature of the IGBT module casing may also be of interest for condition monitoring, e.g., to monitor material degradation. Figure 8 shows the measured case temperature

Fig. 6 **a** Temperature development on IGBT terminal phase B as measured by the SENTRY-sensor and the thermography system and **b** detailed temperature signal from the thermography system for 1 pixel and for area of 10×10 pixels

Fig. 7 Deviation between the camera signal (10×10 pixels) and the same signal smoothed using a moving average filter over 120 data points (4 min)

Fig. 8 Temperature measurement on the IGBT module casing compared to the terminals for phase A

compared to the terminal temperature for phase A. The quality (S/N) of the casing temperature data is identical to the quality of the terminal data. As expected the case temperature is significantly lower than the terminal temperature. The terminal temperature is close to the junction temperature and the thermal gradient from the junction to the case increases with temperature due to the low thermal conductivity of the case material.

4.3 Single pixel infrared thermopile sensor measurements

For the first evaluation of the infrared thermopile sensor we monitor the heat sink temperature. Figure 9 shows the generator input (from wind profile data) and the resulting temperature measurements. The thermopile sensor signal is noisy, but gives an accurate representation of the heat sink temperature dynamics. For these low temperatures, the higher noise in the thermopile compared to the camera is expected, since the thermopile operates at shorter wavelengths.

We note that before cooling fan 1 is turned on the measured temperature is essentially identical to the temperature from thermocouple 1 mounted in the heat sink wall. With cooling fan 1 the measured temperature is essentially identical to the temperature from thermocouple 2 mounted in the airflow.

For comparison we have also included the IGBT load terminal temperature. As expected this temperature is close, but not identical, to the heat sink temperature (thermocouple 1) throughout the measurement cycle. The small temperature difference for the highest temperature may be used for accurate junction temperature estimation.

Fig. 9 **a** Generator input sequence for test 1 and **b** heat sink temperature measurements using the IR-thermopile sensor and two thermocouples

We estimate the root mean square noise of the thermopile sensor to 490 mK, however signal averaging will reduce this. The sampling time in the data in Fig. 9 is 1 s, filtering the signal using a moving average filter over 30 points and reducing the root mean square noise to 94 mK. This reduction is close to the expected factor $\sqrt{30}$, assuming uncorrelated noise. The root mean square noise is reduced to 68 mK by reducing the bandwidth even further by averaging over 60 points. This is comparable to the noise in the thermal camera system (no averaging).

4.4 Future work

We are currently building a multipoint temperature system using multiple thermopile sensors in order to monitor all load terminals and possibly additional point on casing and heat sink.

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