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Temperature Monitoring in Switchgears

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Abstract

This thesis focuses on the problem of temperature monitoring inside electrical switchgears. The outcome of this work is a developed sensor prototype. This solution can monitor multiple bus bar and cable joints in switchgears using a single thermopile IR sensor. The measured temperatures are saved in a multipixel array, and they can be shown to the system operator using the application's HMI. The main function of the application is to alarm the system when temperature hot-spots start to develop.

The specifications for the developed temperature monitoring application are laid out. Theory about IR temperature measurement is presented, and the function principle of thermopile sensors is described. Different solutions to the known reflectivity problem of bus bars are discussed. The presented solution to this problem is to apply high-emissivity paints or tapes close to potential hot-spots.

The developed application's functions are shown in simple terms. A proof-of-concept test is made for the developed prototype application and different tapes and paints are also tested. The results of the test indicate promise for the developed prototype and the full application. Finally, a discussion is held about the test results and further product possibilities.

This thesis was made for Arcteq Ltd in Vaasa.

Language: English Key words: IR, temperature, switchgear

EXAMENSARBETE

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Titel: Temperaturövervakning i ställverk

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Abstrakt

Detta examensarbete behandlar problemet med temperaturövervakning i ställverk. Resultatet av detta examensarbete blev en utvecklad prototyp för en temperaturgivare. Den slutgiltiga lösningen kan övervaka flera kritiska anslutnings- och förgreningspunkter genom att använda endast en IR-givare. De mätta temperaturerna kan sedan visas för systemets opertör via systemets HMI. Systemets huvudsakliga funktion är att alarmera när temperaturen i en punkt överskrider en alarmnivå.

Specifikationerna för den utvecklade temperaturövervakningsapplikationen framställs. Teorin som användes för temperaturmätningen med IR-givaren presenteras. Dessutom presenteras teorin som möjliggjorde mätningen med termoelement, vilket är centralt till den valda givartypen. Olika lösningar till det kända reflektivitetsproblemet diskuteras. Den valda lösningen var att applicera tejp eller målfärg nära samlingsskenornas potentiella hetpunkter.

Den utvecklade lösningen beskrivs i enkla termer. Ett test utfördes för att bekräfta den utvecklade prototypen och olika tejper och målfärger testas också. Resultaten är lovande för den utvecklade givarprototypen och lösningen som helhet. Slutligen hålls en diskussion angående testresultaten och produktens framtidsutsikter.

Arbeter gjordes åt Arcteq Ab i Vasa.

Språk: engelska Nyckelord: IR, temperatur, ställverk

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Tiivistelmä

Tämä lopputyö käsittelee lämpötilan valvontaa sähkökojeistossa. Tuloksena kehitettiin anturimoduuli, joka pystyy valvomaan useita kohtia kojeistossa käyttäen ainoastaan yhtä IR-anturia. Mitatut lämpötilat voidaan näyttää järjestelmän valvojalle järjestelmän HMI-ikkunassa. Järjestelmän päätehtävä on varoittaa kun tietyt lämpötilarajat ylittyy.

Kehitetyn lämpötilamittausjärjestelmän vaatimukset esitetään. IR-anturin lämpötilamittauksen teoriaa käsitellään ja termoelementin käytäntö esitellään. Eri ratkaisuista sähkökiskojen reflektio-ongelmalle keskustellaan. Valittu ratkaisu on peittää mittauskohdat materiaalilla jossa on korkea emissioarvo.

Kehitetyn aplikaation testit suoritettiin ja erilaisia teippejä ja maaleja testattiin. Testien tulosten perusteella prototyyppi ja koko applikaatio näyttää lupaavilta. Lopuksi kesustellaan testituloksista ja tuotteen tulevaisuuden mahdollisuuksista.

Tämä opinnäytetyö on tehty Arcteq Oy:lle Vaasassa.

Kieli: englanti Avainsanat: IR, lämpötila, kojeisto

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Abbreviations

IR	Infrared Radiation
Switchgear	Section of a power distribution network
Bus bar	Electrical conductor of large currents
PCB	Printed Circuit Board
Thermopile	Temperature measuring sensor
FOV	Field-Of-View
HMI	Human-Machine Interface
Emissivity	A materials ability to emit electro-magnetic radiation
Reflectivity	A materials ability to reflect electro-magnetic radiation
Blackbody	Theoretical, perfect emitter of electro-magnetic radiation
IC	Integrated Circuit

Acknowledgements

The development of the smart sensors was started in the Spring of 2017. The task of developing the smart sensor module, both software and hardware, was given to me. The IR sensor aspect that became the ground for this thesis was but a part of all the work that went into developing the smart sensors. The thesis work followed the smart sensor development side by side. One year later, the smart sensor prototype is close to being finished.

I have learned a lot during this year. The project requires an understanding of several different domains. The group discussions have ranged from tapes and material properties to data communication protocols and hardware components. I have also gained a lot of knowledge about the power distribution industry and its practices. This work has also given me deeper insights into the development cycle of PCB products and embedded devices in general. This knowledge will be very useful for my future work. As a sign of gratitude, I want to give my thanks to the people that have been closely connected with this project.

Thanks to Franz Villavicencio for his help on the communication protocol that was developed for the smart sensors. Thanks also to Adis Tosumovic for making the TempMonitor software that was extensively used for the testing the sensors.

A lot of gratitude goes to Antti Koksalo for his insights into the challenges ahead and for guiding the development in the right direction.

Finally, special thanks to Samuel Dahl and Juha Arvola for giving me such an interesting, yet challenging thesis work.

Johan Granlund

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1 Introduction

Operating temperature is one of the most important variables that influence the life-time of joints in electrical switchgears. Bad connection points between bus bar joints or cable connections lead to temperature hot-spots over time. When left unchecked, the increasing temperatures can lead to arc faults and other system failures which are both expensive and dangerous. Using appropriate temperature monitoring systems, maintenance of switchgears can be better planned, and dangerous situations can be prevented. Consequently, the demand for better temperature monitoring systems and pre-fault recognition is constantly increasing. (Perdon, et al., 2017)

1.1 Background

There is an ever-increasing demand for temperature monitoring and disturbance recording in power distribution systems. There are two main approaches to this problem that have been used in the industry so far.

The first approach consists of having periodic inspection of switchgear. Expensive, high-resolution IR cameras are used to monitor the switchgear temperatures, typically once a year by a professional. This approach, however, only measures the switchgear one moment in a day in the entire year. The switchgear might not be under as heavy loads as it might be at other times and faulty connections or situations might not present themselves. The inspection itself is not always easy, as some switchgears come in very compact designs, and the critical spots might not be visible to the IR camera.

The second approach is to install a permanent system that continuously monitors temperatures at critical points. This often requires one sensor per point to measure. As a result, the complete system often requires a lot of cabling, which makes the installation costly. These systems also tend to be more dangerous, since the increase of cables close or attached to the bus bars, significantly increases the chances of an arc flash-over.

In recent years, new thermopile IR array sensors has opened the possibility of monitoring multiple bus bar joints using a single IR sensor element. These non-contact IR sensors offer a cost-effective alternative to previous solutions.

In 2017, Arcteq started developing a new series of arc protection relays. This series would include the use of smart sensors. The new thermopile IR sensor technology was researched and chosen to be integrated into the smart sensors simultaneously as the smart sensors were being developed. This thesis focuses on the temperature monitoring solution part of the smart sensors development.

1.2 Goal of the thesis

The aim of the thesis was to develop an IR temperature module for monitoring potential temperature hot-spots within switchgears. This sensor will differ from other temperature monitoring solutions since one single sensor can monitor several spots at once, given the right conditions. In short, these sensors would work like permanently installed, inexpensive IR cameras. This developed solution displays the temperatures inside the switchgear cubicle and alerts the system operators when abnormally elevated temperatures start to develop. The developed solution offers a cost-efficient alternative to other solutions on the market. The developed product will be used with other products developed by Arcteq.

1.3 Scope

The complete product development included both software and hardware design work. This paper only includes the development of the temperature measuring part of the smart sensors. As a result, the following parts are outside the scope of this thesis:

- The hardware development of the PCB that integrates the chosen IR sensor
- The software developed for the microcontroller used on the PCB
- The sensor’s communication with other devices

These aspects will only be discussed briefly to better describe the whole temperature monitoring solution that was developed.

2 Problem description

The central challenges concerning the developed sensor module can be summarized into to following three groups:

- Selection of the right IR sensor
- Placement of the sensor in the switchgear
- Reflectivity problem of bus bars to be measured

These subchapters explain in detail these challenges that were recognized early in the product development. The selection of the right IR sensor will be explained in chapter 4.

2.1 The sensor placement

It was decided in an early stage that it should be possible for the sensor to be installed retrofit into existing switchgear cubicles. Since switchgears differ from one another a lot, cases exist where the sensor cannot be installed in a decent spot. Such cases might not be suitable for this solution, since this type of sensor requires an unobstructed view of the spots to monitor. There are also some cases where the sensor will not fit at all, or it would simply have to be mounted so close to the bus bars that a completely open FOV (Field-of-view) of several hot-spots is impossible. With these limitations in mind, there are certainly customer cases that allow for good sensor placement and an unobstructed view of potential hot-spots.

2.1.1 Switchgear design

Since switchgears are made in many different forms and sizes depending on the customer's needs, the bus bars used in these switchgears also come in many varied sizes. The bus bars can be of different width, thickness and length. Some switchgears are isolated (also thermally) and in such cases, this solution will might not be able to measure the true temperature of the potential hot-spots. (Meulenbroeks, 2014)

This large variation in construction design means that the IR sensor will have to be placed at different distances, depending on the construction. The angle might also be other than front-on, making the total FOV estimation more difficult. Since the places where hot-spot develop are connected to the different junctions of the bus bars, the hot-spot areas are grouped together into *zones*. One of the goals of this sensor is to enable monitoring of several “junctions” or hot-spots in a switchgear cubicle. Usually, there are three different junctions that exist close together in a switchgear zone, since one junction represents one phase that connects to some other switchgear component. There are also cases where more bus bar and cable junctions could be monitored with a single sensor, but as a general goal it was set to monitor three hot-spots at once. The zones are centered around incoming and outgoing connections as well as the connections from and to the circuit breaker (Figure 1).

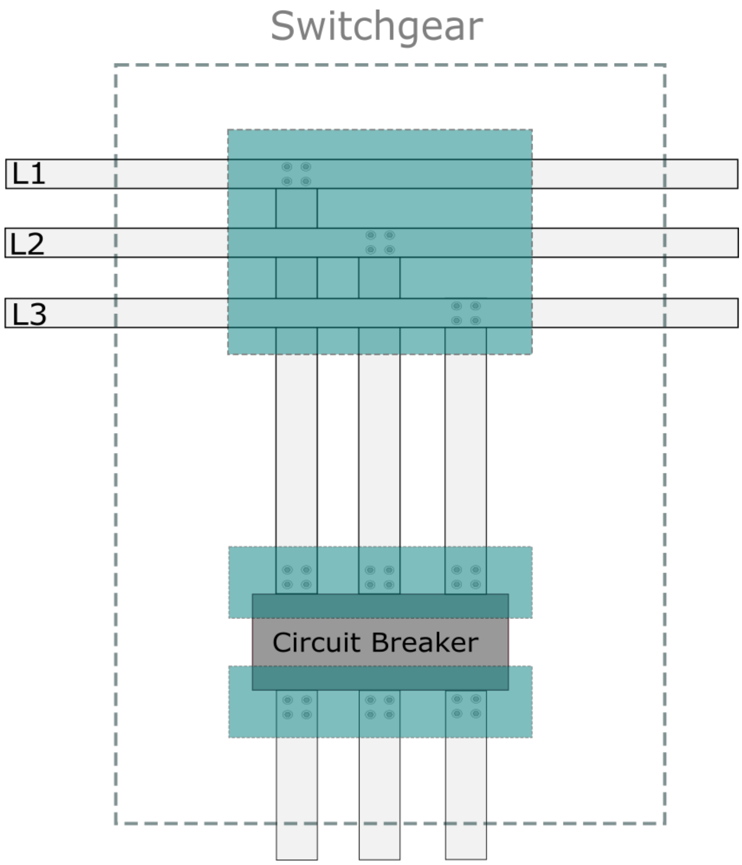

Figure 1 - Temperature hot-spot zones in switchgears

2.1.2 FOV & Resolution

The IR sensor component itself must have the right FOV for its mounting distance and a sufficient number of different “pixels” that it measures. The pixel resolution is critical, since there must be at least the number of pixels needed to differentiate the three bus bars or cables from one another. The sensor might not be mounted in an optimal spot at the customer site, and the mounting angle might not be ideal. Depending on the mounting distance and angle, the junction’s temperatures might be seen on several pixels and not just one. This makes the case for an increased number of pixels, so that more overhead is left for the person doing the installation.

Furthermore, the pixel density must be enough so at least two pixels in both directions can fit inside the width of the bus bar, given a certain mounting distance. This is important since otherwise there might not be a pixel that is fully on the inside of the spot to monitor. If this were to happen, the temperature measured for the hot-spot will be fundamentally false, since it is partly measuring the temperature for the adjacent objects and calculating a temperature as an average of radiation received from these areas. This is further explained in Chapter 3.

2.2 Emissivity & reflectivity

It is a well-known problem in thermography that metals generally have a low emissivity constant and as a result they are difficult to measure using IR technology. In power distribution systems the conductors are sometimes bare metal bus bars, which present the same problem when trying to measure their temperatures.

2.2.1 Reflective surfaces

Most power distribution bus bars are often made of copper, but aluminum is also used. Copper and aluminum have such reflective surfaces that measuring the surface temperature using IR technique is fundamentally inaccurate. Consequently, the apparent temperature of a hot-spot is not the same as its true temperature. The temperature seen is an average temperature of the hot-spot itself, and the temperature reflected from surrounding objects. The reflective surface acts as a mirror in the IR bandwidth and the measurements gained from such a surface will not yield usable data. (Clausing, 2007)

This problem was known from the very start of the product development and the most important one to solve. It was critical to find some other kind of material to apply on top of the hot-spot sections so that the temperatures could be better measured.

2.2.2 Emissivity difficulties

One of the most difficult problems concerning IR temperature measurement is that dissimilar materials emit varied amounts of IR radiation. This implies that one must know to what degree a material emits IR radiation so that the correct temperature of the object can be calculated.

In this application the reflectivity of the object is of great concern. This is because metals generally have reflective surface which makes it extremely difficult to measure the actual temperature of the bus bars. The margin of error also increases when the reflectivity of the object is high. The reflectivity and emissivity properties are further discussed in the next chapter.

3 Theory

Infrared radiation is type of electromagnetic radiation that all object with a temperature over absolute zero emit. When measuring the IR radiation emitted to the IR sensor, together with a close approximation of the object's emissivity, the true surface temperature of an object can be calculated.

3.1 Blackbody radiation

A perfect emitter of electromagnetic radiation is called a blackbody. However, all real-world objects emit only a fraction of the radiation emitted by a blackbody. The property of materials to emit energy in the form of electromagnetic radiation is called *emissivity*.

All materials have an emissivity constant that is:

$$1 > \varepsilon > 0 \qquad (1)$$

Where ε is the emissivity of that material. This value is crucial to all temperature measurements done using IR technique. The emissivity of the material largely depends on the surface structure and the temperature of the material. (Rosenström, 2012)

3.2 Stefan-Blozmann law

The power emitted from a graybody object, P, can be calculated using Stefan-Bolzmann law as follows:

$$P = \varepsilon\sigma T^4 \qquad (2)$$

Where ε is the emissivity value of the object, σ is the Stefan-Bolzmann constant ($\sigma = 5{,}67\cdot10^{-8}Wm^{-2}K^{-4}$), T is the surface temperature of the object in Kelvin. Thus, the temperature of the object can be calculated as:

$$T = \sqrt[4]{\frac{P}{\varepsilon\sigma}} \qquad (3)$$

3.3 Apparent and true temperature

The measured temperature in the IR sensor is not the same as the objects true surface temperature. When the emissivity of the measured object is low, most of the IR radiation received by the IR sensor is radiation from surrounding sources that have been reflected from the objects surface. The measured and calculated temperature will be affected by the ratio between emitted and reflected radiation and the temperatures of the sources. The apparent temperature measured by the IR sensor will be lower than the true temperature of the object if the reflected sources have a lower temperature then the object. If the surrounding sources have a higher temperature than the object, the object will appear hotter than it is. (Clausing, 2007)

For better accuracy, it is critical that bare bus bars are covered with a high emissivity material, such as black tape or paint, at the junctions that are measured. The difference between bare bus bars and painted or painted bus bars are illustrated in Figures 2 and 3.

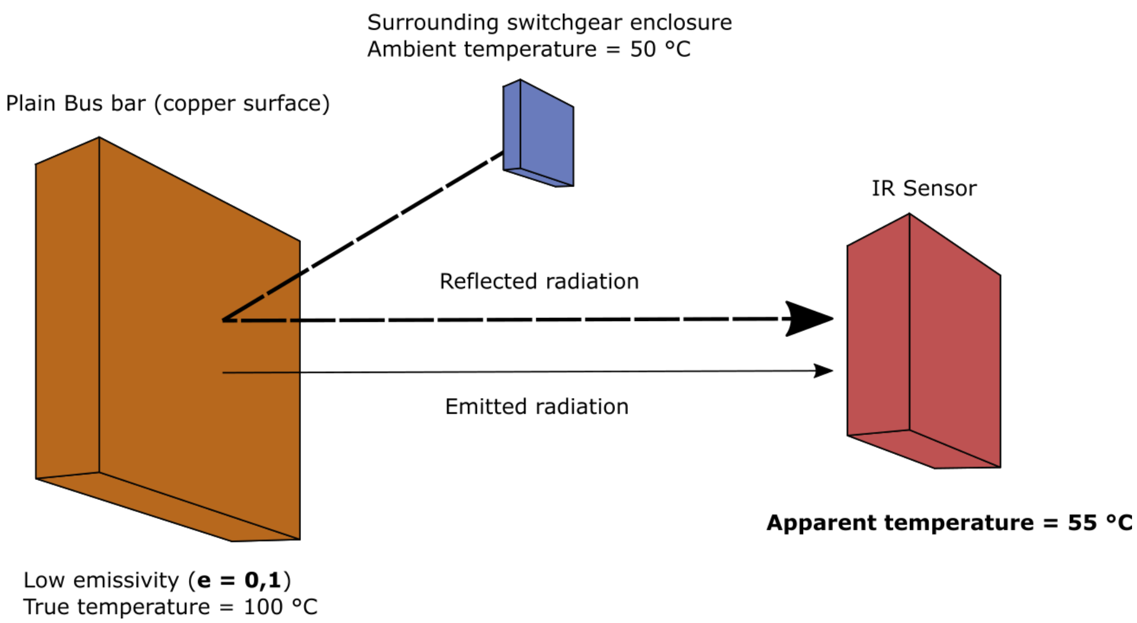

Figure 2 - Apparent temperature of a low emissivity surface

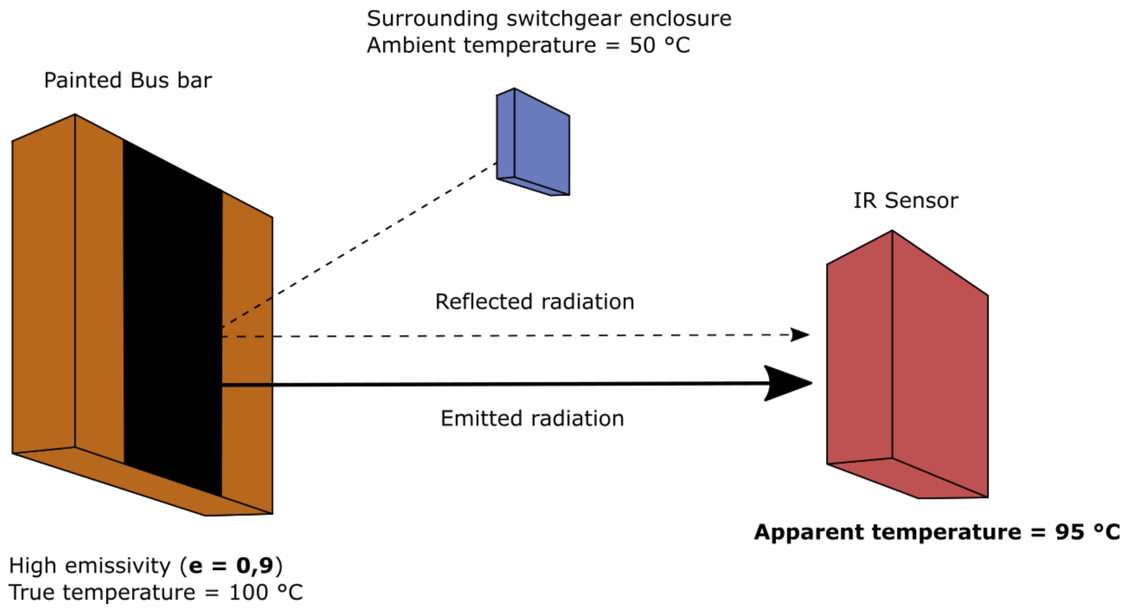

Figure 3 - Apparent temperature of a high emissivity surface

3.4 Thermopile function principle

Thermopile sensors work in principle the same way as thermocouple sensors. The thermopile sensors are thermocouple sensing elements that have been connected in series. Some sensors also use multiple thermopile elements per pixel. The incoming IR radiation is focused onto the absorbing material using a silicon or germanium lens. The heat produced in this area then gives rise to the Seebeck effect, which produces a voltage that is proportional to the temperature difference between the cold and hot junction of the thermocouple. (Xu, et al., 2017)

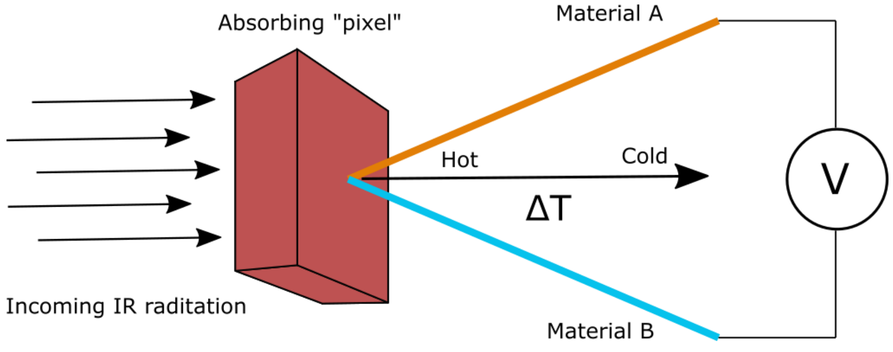

Figure 4 - Function principle of a thermoelectric IR sensor

The voltage produced in the cold end can be calculated as:

$$V = (\alpha_A - \alpha_B)\Delta T \qquad (4)$$

Where V is the voltage generated, α_A and α_B is the Seebeck coefficients for materials A and B, and ΔT is the temperature difference between the cold and hot junctions.

4 Selection of IR sensor

There was a lot of thermopile IR sensors available that did not measure up to the predefined specifications. The specifications that were discussed and produced excluded a lot of the sensors that were available on the market.

4.1 Sensor specifications

The following specifications were made for the sensor element that was going to be selected. The sensor must be able to:

- Measure object temperatures from -20 °C to +150 °C
- Be placed within a switchgear such that:
  - The total FOV of the sensor covers at least the whole zone
    - At least three junctions should be seen in the total FOV
  - Each pixel's FOV covers an area no more than half of the bus bar's width
  - Hot-spots are detectable
    - It must be possible to distinguish which loose joint is causing the hot-spot
- Refresh all pixel temperatures of the sensor at least once a second

Thermopile IR sensors consisting of many pixels, was a new concept during this products development period. Sensors with one, two or four pixels were easy to find. However, IR array sensors consisting of larger arrays were new, and there were only a few products that were seriously considered. Some alternatives were also too expensive to be considered in this case. The IR sensor that was finally selected had a decent number of pixels, good FOV options, large measuring range and a comparatively inexpensive price.

5 Product development

The development process started in the spring of 2017. One year later, the sensor prototype was developed and ready to be tested.

5.1 Development strategies

The sensor software was developed using an evaluation board from Atmel. Arcteq was given a handful of sensor samples to work with during this time. The manufacturer also provided a c-code to be used by the microcontroller connected to the IR sensor. This was used to get the sensor running, get raw temperature readings and finally to calculate the real temperatures of the pixels. During this time, the overall smart sensor functionality was being developed as well as the hardware to be used in the developed sensor prototype.

5.2 Calculations

Two different calculations were at the heart of the challenges facing this solution. The first challenge was the FOV calculations that were different for the FOV optics considered. The second problem was the calculation of the temperatures for each pixel. The IR sensor contains certain chips that process the measured signal. As such, the values obtained from its measurements and how to further process them into values that can be used in calculations, is completely manufacturer-dependent. Thankfully, the post-measurement processing was done in the c-code that was provided.

5.2.1 FOV calculation

The full field-of-view can be calculated as:

$$w = 2 * \tan \alpha_h * d \qquad (5)$$

Where w is the width or length of the area, α_h is half of the viewing angle of the sensor in the direction being calculated for and d is the distance from the sensor to the object. The FOV for a pixel can be calculated by dividing the calculated distances for height and width with the number of pixels in each row and column.

5.2.2 Temperature calculation algorithm

The microcontroller communicates with the IR sensor using the I2C protocol, where the microcontroller is the master and the IR sensor is the slave. The IR sensor contains an EEPROM chip where the factory calibration constants are stored. It also contains a RAM memory where measurements are stored. Some registers are written to when the user wants to configure the IR sensor.

An accurate calculation can be done when the user knows the target's emissivity. The sensor itself is factory calibrated and needs no further calibration. The values that are read from the sensor is then calculated according to the Stefan-Bolzmann law in the microcontroller into real temperature values.

The temperature calculation algorithm in the microcontroller works in the following way:

1. Save a floating-point number of the estimate emissivity of the object to be measured.

2. Initiate I2C communication with the sensor.

3. Read EEPROM and save calibration values in the microcontroller.

4. Calculate these values into the real calibration constants using the provided c-code.

5. Write configurations to the sensor EEPROM.

6. Write to sensor to start measurements.

7. Read pixel measurement values from sensor RAM.

8. Calculate final temperature for each pixel using the read measurement value, the current ambient temperature, the calculated calibration constants and the estimated emissivity value.

9. Repeat steps 7 and 8.

5.3 Prototyping

The programming was done in Atmel Studio 7 for the ATSAMD21 Explained Pro development board. The almost identical ATSAMD21E18A microcontroller was later used in the prototype. The IR sensor was then connected with jumpers to the development board and accessed through the I2C protocol. The different FOV versions of the sensor were tested. With the help of the TempMonitor software, the communication protocol was easily developed and evaluated.

5.4 Code overview

The code was written in Atmel Studio using the c-language. The sensor specific c-code that was provided does post-measurement processing of the measured values and then calculates the temperature for one pixel. This process was made to repeat for each pixel that was selected in the pixel mask.

5.4.1 Default task

The default task of the microcontroller is to calculate one row of IR data into real temperatures for that row. Only pixels that are selected in the corresponding pixel mask will be calculated for. When a row of pixels has been calculated, the sensor checks if the master unit has made a request. If there is a request the sensor responds according to the communication specification. If there is no request, the sensor continues to calculate the temperatures for the next row.

When there is a request for temperatures, the sensor sends the temperatures for the pixels that have been selected in the pixel mask. The protocol allows that pixels or even entire rows are masked. As defined in the communication specification, the whole responding communication frame can fit 96 pixel-temperatures maximum and pixels can belong to ten different rows maximum.

5.4.2 Pixel masking

By using a pixel mask functionality, the user can select which pixels should be calculated and updated. Since the receiving main unit is keeping a copy of the pixel mask present in the sensor, it can distinguish which pixels are being sent and map them onto the right rows. In this way, it is possible to mask away certain pixels that have stopped working correctly. It is also possible to select only certain pixels that the user suspects can develop hot-spots. Selecting only a few pixels makes the temperature calculation faster and the overall view of the temperatures will get a faster refresh rate. Only pixels that are selected in this way count when the system compares them against active alarm levels. This also prevents faulty pixels to cause a false-positive alarm. The temperatures sent by the sensor module is dependent on the pixel mask configuration and the master unit contains an exact copy of this pixel mask. The pixel mask then determines which pixels can trigger alarms when thresholds are reached, and which pixels it should ignore.

The HMI also holds the same pixel mask configuration and uses it to correctly decide which pixels it has received. The temperature monitoring view in the HMI then displays these temperatures in their right spots in a window. It might be suitable, however, that all pixel temperatures are calculated and shown every now and then. The full, updated view might reveal new hot-spot developments and the user can re-configure the pixel mask to account for this new problem area.

5.4.3 Dynamic alarm levels

Since the load in a power distribution system often varies over time, more current is expected to flow during higher loads. As a direct result, the temperatures in the switchgear will rise. This is not an anomality and the alarm levels should not trigger because of this expected temperature increase. The main unit, or the supervisory system, should be able to match take the current flow into consideration before triggering the alarm. This is a configuration that the final application should be able to set. An example of a HMI view used for the finalized application is shown in Figure 5.

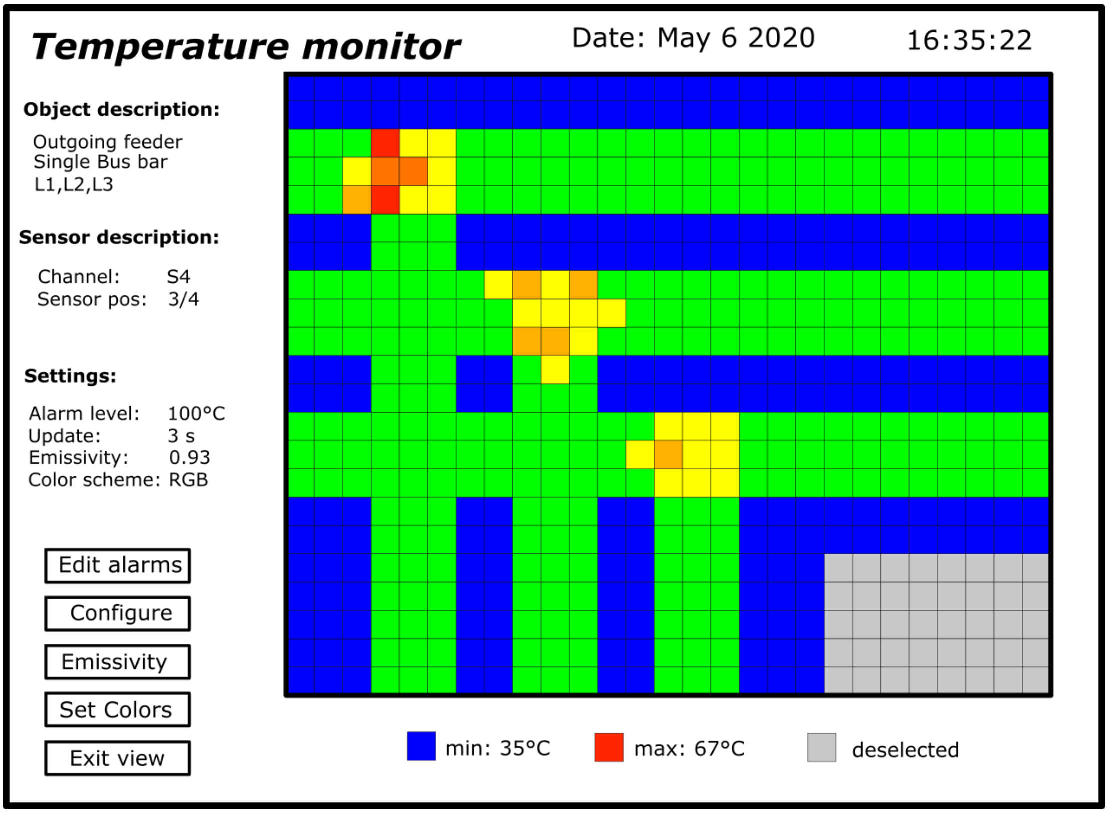

Figure 5 – An example of what the sensor's HMI could look like.

5.5 Specifications for applied material

The tape or paint used on the hot-spot sections need to have the following specifications:

- Operational temperature from 0 °C to +150 °C
- Have a long-lasting hold, over 20 years
- Resistance to vibration, humidity & chemicals
- Resistance to UV-light
- Have an emissivity factor of at least 0,9

The emissivity of the applied material also needs to stay the same over the course of the specified lifespan of the application (10+ years). The aim is also to use such a material that is retains the same emissivity value across the whole temperature range of the application (0°C to +150°C).

6 Testing

The proof-of-concept test was carried out in Technobothia in Vaasa 29.3.2018. The test was made to verify the feasibility of using the developed application for monitoring temperatures in switchgears.

6.1 Background

For temperatures to be readable from the bus bar surfaces, a tape or paint is necessary to apply to the spot to be measured. This step is critical to the accurate measurement of temperatures using IR technique. Consequently, different industrial tapes are also being tested at the same time.

When selecting the materials to be tested for high emissivity, tapes and paint containing silicone were avoided. It is known that is some industries the use of silicone materials is prohibited. Painting and coating industries especially do not allow silicone-based emissions into the air since the silicone contamination can make the surfaces unfit for painting jobs. A decision was made to prioritize tapes and paints for testing that do not contain any silicone. Although some tapes and paints containing silicone were selected for testing, alternatives to these tapes were also carefully chosen.

The test was done to ensure that the sensor element can measure temperatures up to 150 °C. According to its specification it should be able to measure objects with a temperature up to 300 °C. The different tapes and paint tested would show:

- If the material can handle short-time exposure to 150 °C
- If the material has any reflective properties (showing different temperatures than the actual temperature)
- If the material shows any other negative side-effect that would make it unfit for installation

6.2 Equipment being tested

The bus bar rig with the taped and painted areas was put into the oven for heating. These were the products that were tested:

- Bus bar rig with 3 mounted copper bus bars (custom made)
- Tape no. 1: M3 - Scotch tape 27
- Tape no. 2: M3 - Scotch tape 69
- Tape no. 3: M3 - Scotch tape 70
- Tape no. 4: HPX - Stretch & fuse
- Paint no. 1: Maston - High temperature paint
- Paint no. 2: Motox - High temperature paint

This was the equipment that was used to do the measuring and logging of readings from the test:

- The chosen IR sensor
- Laptop with TempMonitor
- USB cable between laptop and development board
- screwdrivers, tapes, measuring tape, pencil
- ULIRvision IR camera (as reference)

6.3 Testing procedure

The procedure was simple to follow. A screenshot of the sensor’s temperature readings from the chosen areas were taken at ten degrees’ intervals, starting at 150 °C.

6.3.1 IR Sensor

The IR sensor is connected to the development board and the development board is connected to a laptop computer. The sensor is started, and temperatures are being sent to the computer and displayed in the temperature monitoring software. The sensor is then mounted on a tripod at appropriate height and distance from the testing table. The sensor is now left to continuously monitor the place where the bus bar rig is going to be placed. The sensor mounted 50 cm from the bus bar rig.

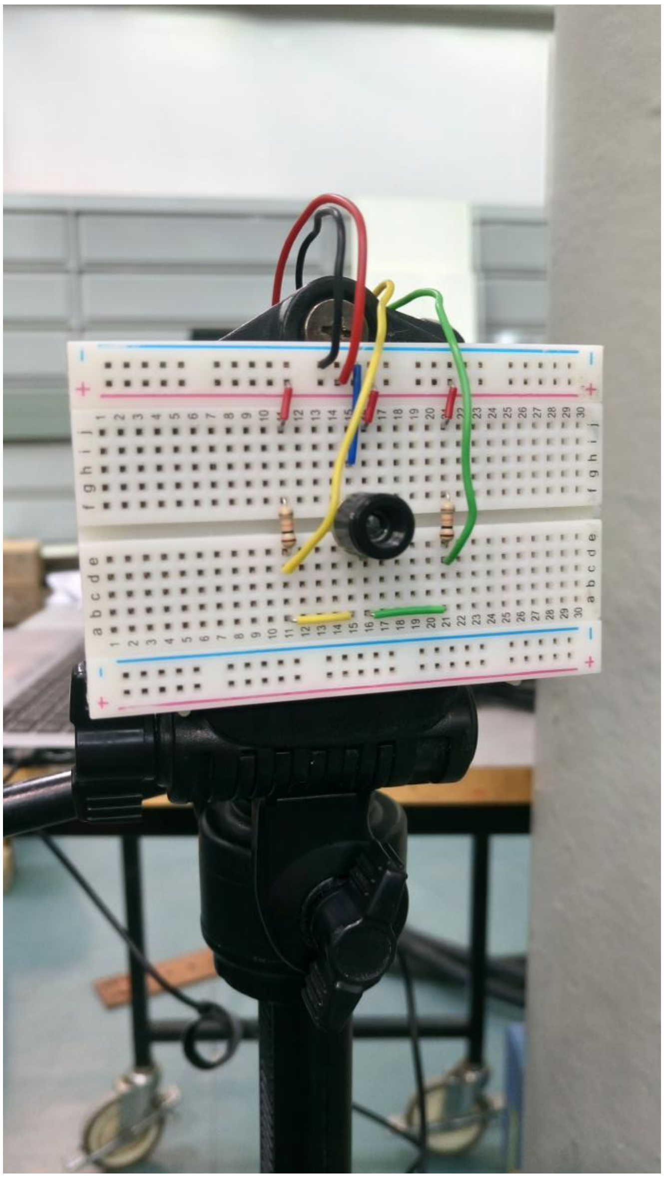

Figure 6 - IR sensor mounted on a tripod

6.3.2 Bus bar rig

Different tapes are fastened onto a custom-made bus bar rig. TC thermometers will also be fastened to the backside of each spot which has been covered with tape or paint. This rig is then placed in a testing oven and heated until 150 °C. The rig is then removed and placed on a table in front of the measuring IR sensor. Now the rig is left to cool slowly from 150 °C until 30 °C.

A frame was made from pieces of wood and copper bus bars were attached with screws to this frame. Three bus bars were mounted in parallel on this frame and various kinds of materials were applied to the surfaces of the bus bars. Each bus bar was painted or taped at three different spots with enough room between the spots. The materials applied were the materials to be tested.

6.3.3 Temperature references

An industrial, handheld IR camera was being used as backup reference. Every time this device measures a decrease in spot temperature by 10 degrees (150, 140, 130, 120, 110 …) the IR sensor’s view is saved onto the laptop computer. TC thermometers are also mounted on the backside of each spot on the bus bar that is painted/taped to be measured. Technobotnia provided the reference measurements.

6.3.4 Expectations

The test is done successfully when at every ten degrees decrease in temperature the IR sensor’s view has been saved and logged. The aim is for the IR sensor to accurately measure the bus bar temperatures from the spots covered with tape or paint. If the measurements from one or several areas differ no more than 5 degrees from what is measured by the IR camera, the test can be said to be a success.

The precision of the measurements is not critical since the different tapes are expected to yield different results anyway. This is due to the different material composition of the tapes and to the different emissivity values that they therefore have. Their individual emissivity values are also not known beforehand, since the manufacturers of these tapes have not tested this property. One goal is to see which of the material have the highest emissivity value, without the need to know the exact value. Since the bus bars and the spots measured will have a higher temperature than the surroundings, the higher the temperature reading from a spot is, the higher the emissivity of that material is going to be.

7 Test results

The tapes and paints tested withstood the elevated temperatures in the oven. The following chapters describe who each of the tapes and paints performed.

7.1 Measured temperatures

It is important to note that the temperatures read from the varying surfaces are not a decisive factor which one is the best tape or paint. The emissivity used in calculations was set to 0.95. The tapes and paints that displayed a lower temperature than the reference simply have a lower emissivity constant, which can be adjusted. The temperatures measured at different temperatures are shown in Table 1. Figures 7, 8 and 9 further illustrate the differences and errors between the materials. Figures 10 and 11 show the testing setup.

Table 1 - Measured temperatures

TC references	#1 - Scotch 70	#2 - Scotch 27	#3 – Maston high temp paint	#4 - HPX stretch & fuse	#5 - Scotch 69	#6 – Motox high temp paint
130	120	124	126	119	119	127
120	115	118	119	115	112	117
110	106	109	110	107	104	107
100	97	99	99	97	94	99
90	88	89	90	90	86	89
80	77	79	78	78	76	77
70	68	69	69	69	68	70
60	59	59	59	59	58	59
50	50	50	49	51	48	50
40	39	41	39	42	38	40
35	34	36	34	36	34	35

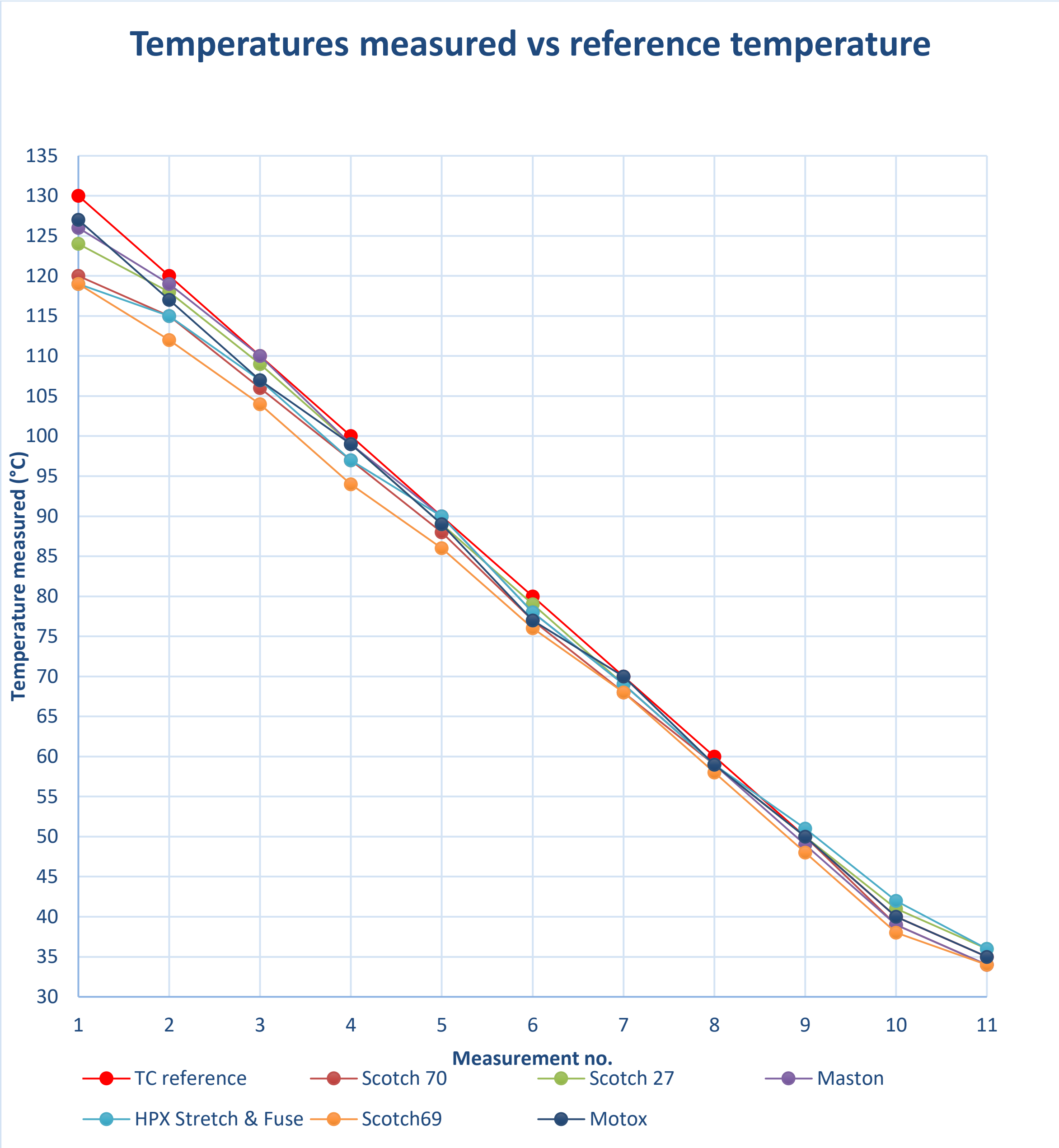

Figure 7 - Measured temperatures in the test

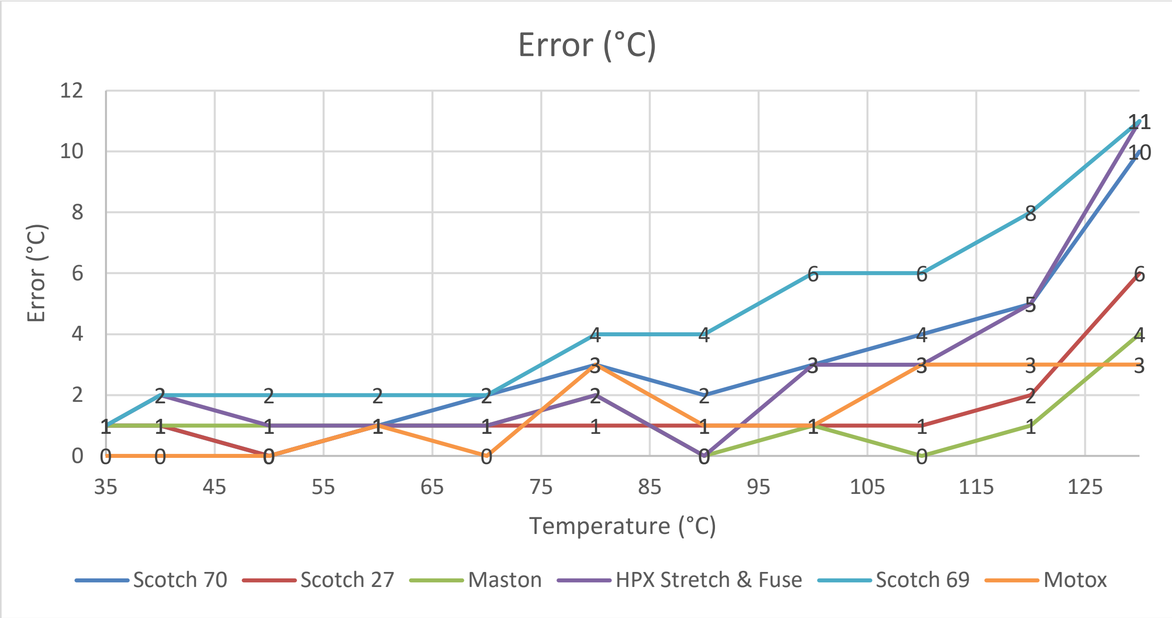

Figure 8 - The error margin at different temperatures

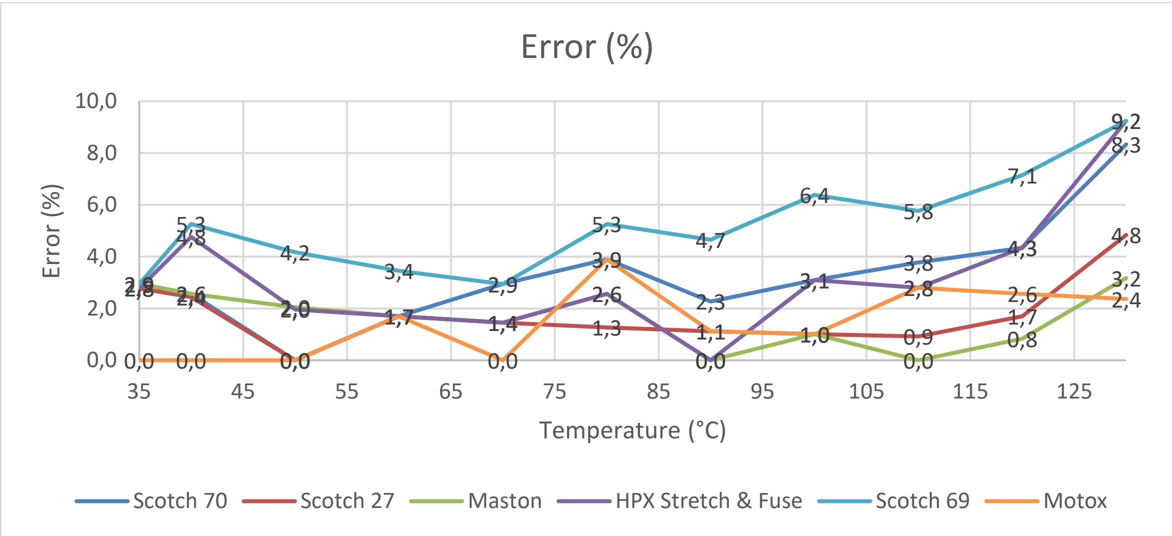

Figure 9 - The error presented in %-units

Figure 10 - The bus bar rig inside the oven

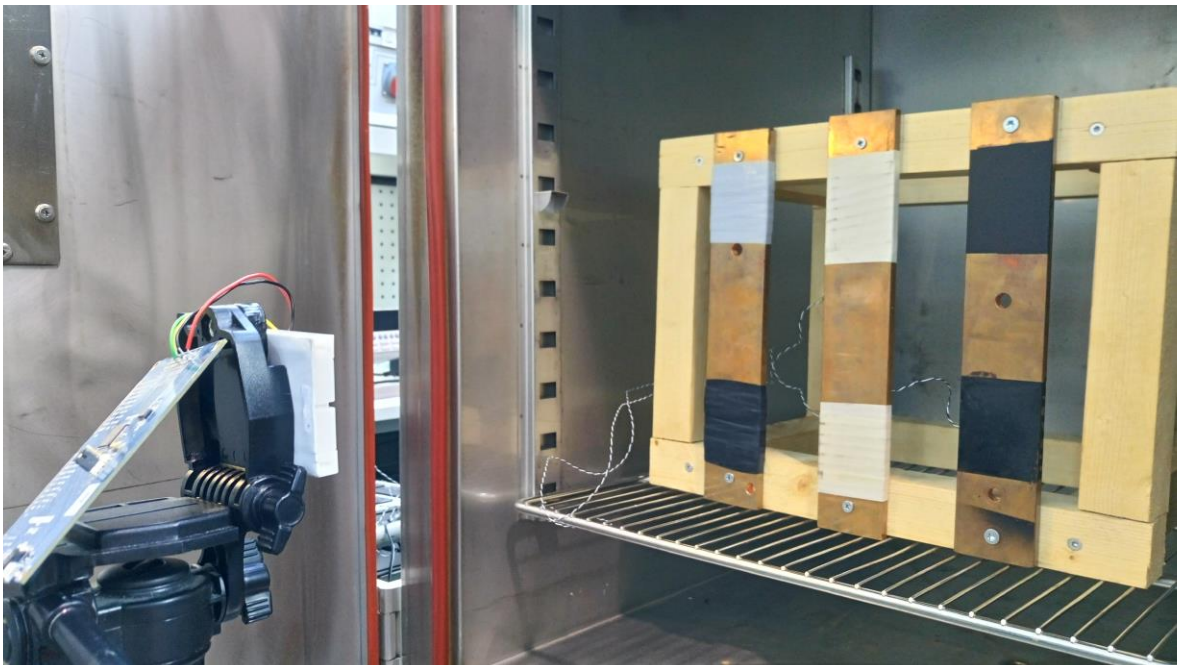

Figure 11 - The IR sensor is mounted to measure temperatures from the bus bar rig

7.2 Test conditions

When the door to the oven was finally opened, the bus bars started to cool very quickly. Unfortunately, when the IR sensor was all set to measure, the bus bar had already cooled down to under 140 degrees. However, from 130 degrees and downwards, the measurement was done at exactly 10 degrees interval.

The developed TempMonitor HMI was able to update the temperatures in the monitoring window. Refresh rate for the whole view was about 1 Hz. The view of the bus bars is shown in Figure 12. The view of the temperatures measured at 50 °C and 100 °C are shown in Figures 13 and 14.

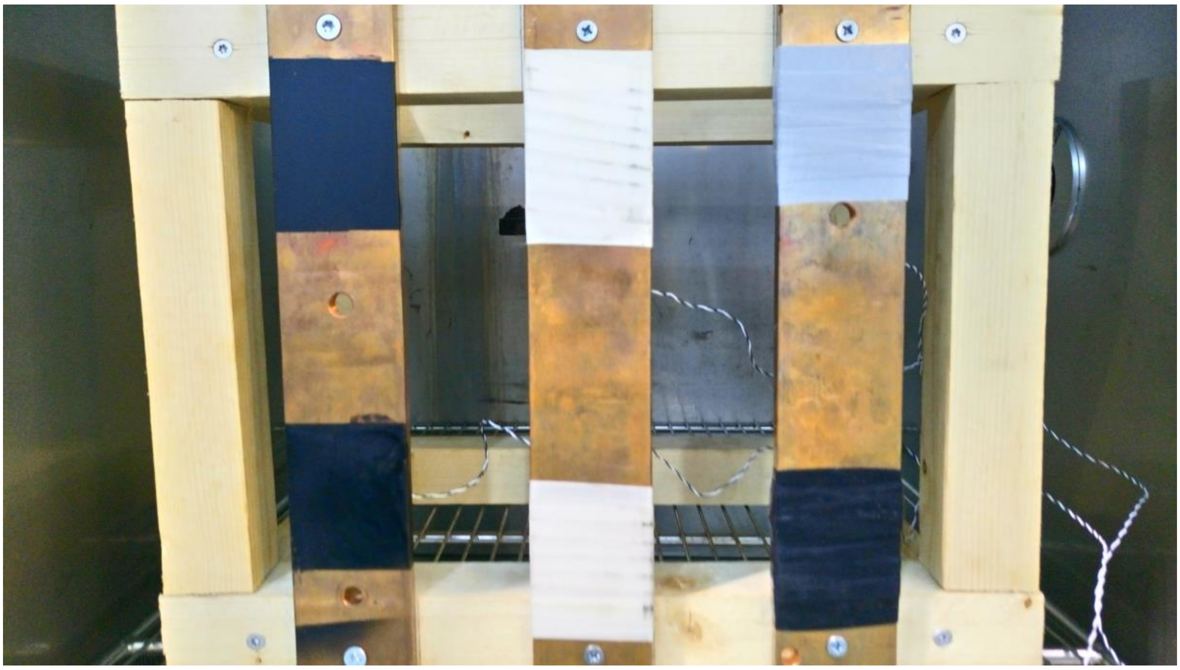

Figure 12 - The sensor's view of the bus bars

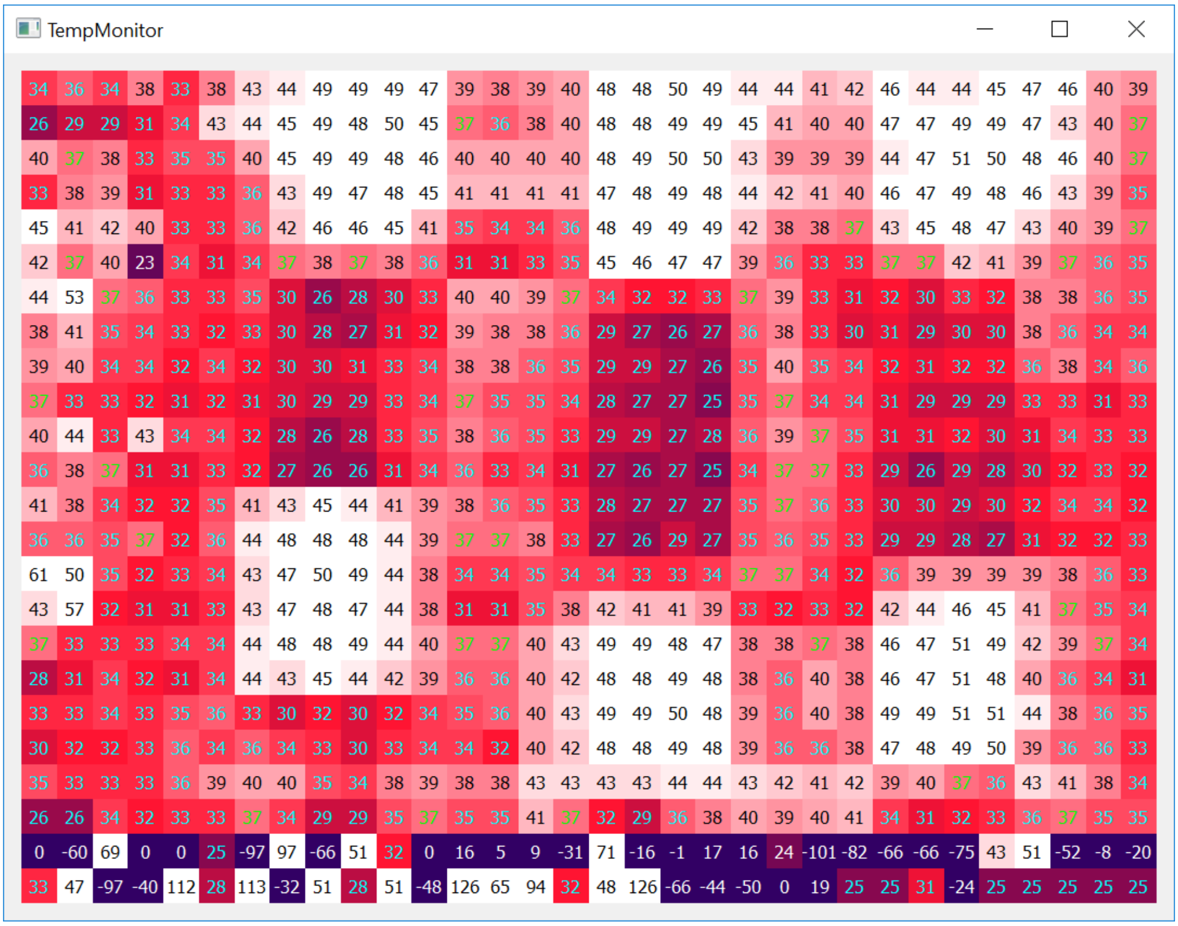

Figure 13 - Temperatures displayed in the TempMonitor software at 50 °C

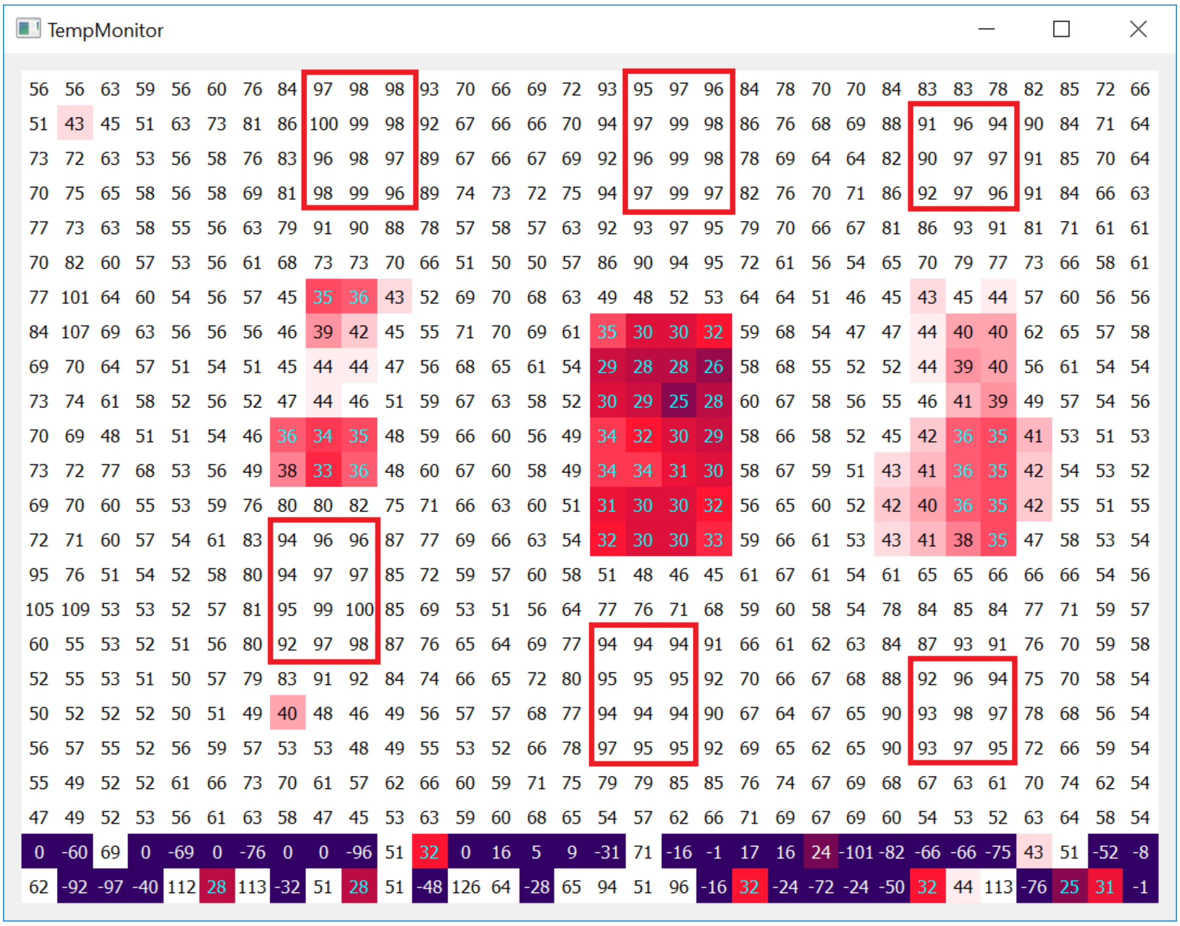

Figure 14 - Temperatures displayed in the TempMonitor software at 100 °C

7.3 Test conclutions

The test was carried out according to the test plan. The TempMonitor software reveals that the two bottom rows didn’t work properly. This is probably due to some software bug. These rows didn’t affect the measurements due to them being outside the measured areas. Some pixels around the borders also showed random values and behavior. This can perhaps be explained by the fact that the IR sensor used in the test is in fact a prototype and the pixels might be broken.

Unfortunately, the temperature was dropping fast once the door to the oven had been opened. The tripod needed some adjustments and the TempMonitor software started to have some hiccups. As a result, temperature measurements were logged after the temperature of the bus bars had already cooled down to 130 °C. Otherwise, the test was a success and helpful deductions can be made.

7.3.1 Applied materials & characteristics

Some of the materials showed excellent properties and temperatures were close to that of the reference measurements. Materials with the highest emissivity values were:

- Maston - High Temperature Paint
- Motox - High Temperature Paint

A common characteristic of the materials with the highest measured temperature across the testing range is that they have black backing. However, the Motox paint might see limited use in this application since the use of aerosol paints on bus bar installations might be prohibited. The other materials may also be useful if the emissivity value is set to the correct value in the sensor.

Some of the materials showed a large error % when the reference temperature was over 100 °C. The following tapes showed the largest errors at high temperatures:

- HPX - Stretch & Fuse
- 3M - Scotch 69
- 3M - Scotch 70

Again, this error is probably due to these tapes having a lower emissivity value, which is inducing a greater error when the ambient temperature differs a lot from the object temperature.

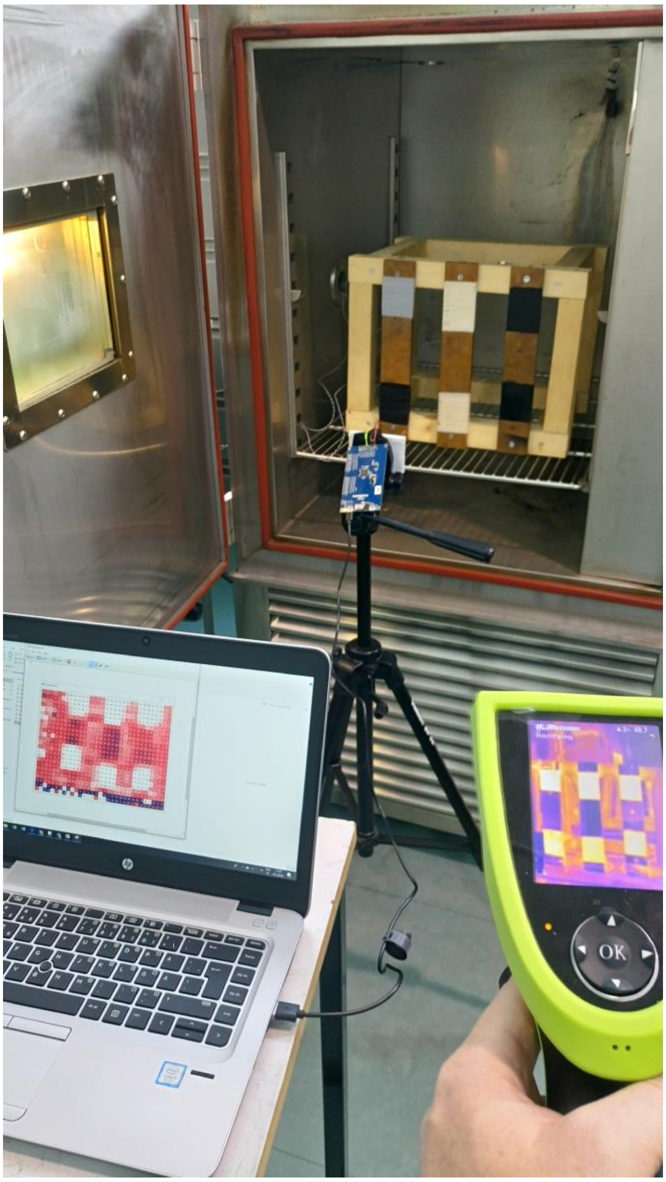

Figure 15 – View of the test setup, TempMonitor’s view and the IR camera's view

8 Discussion

The development of this prototype application has been a challenging task that has presented problems from multiple domains. The whole development has been going on for about one year with varying intensity.

8.1 The sensor prototype

The prototype developed showed a lot of promise. Temperatures measured in the test did not differ too much from the reference temperatures. The sensor was able to measure hot temperatures as expected and communicate using the defined protocol to the host device. The developed prototype’s hardware will not be discussed in detail. The developed prototype shares functionalities with the hardware setup being used in the test.

8.2 Materials, emissivity & FOV

Variations in emission values might become a problem over time. The goal should be to get as accurate temperature measurements as possible. In certain cases, however, it might be enough that the customer can detect hot-spots, without having accurate temperature measurements of the area. Measuring from bare bus bar surfaces are not recommended since readings will be most inadequate. Even if the emissivity value of such a surface is correctly guessed, the error margin will be huge with its low emissivity. This value can also change during the lifetime of the switchgear, which will lead to the user having to recalibrate the emissivity value several times.

Using temperature resistant paints or tapes is recommended, since it is guaranteed to increase the emissivity value of the spot to monitor. However, it is always up to the customer to decide which material to use or not to use. The final application could make use of the tapes and paints tested in this thesis. These materials could perhaps be sold as an addition to the product. The HMI might make use of the calculated emissivity values of these materials and apply this value to the temperature calculations when the corresponding material is selected in the HMI.

Certain tapes and paints might not be suitable in certain industries. Tapes and paints containing silicone is known to not be acceptable in some places. The test tried materials containing silicone and materials without and found useful product in both categories. The customer might also use a different tape or paint than those listed here or simply choose to not apply any material at all. In this case, the customer should be aware of the difficulties that this approach presents.

The test done in Technobothnia reveals that all the materials tested could be used with the IR sensor application. It is perhaps easiest from a delivery standpoint if one tape is found to be useable in all customer cases and the emissivity value used in calculations is set according to the chosen one by default. The test presented in this thesis does not take into consideration the tapes exact emissivity value or which one will be the final choice, this will be tested in the future.

8.3 Installation & usage

The customer needs to know if applying tape or paint on the bus bars is accepted on the installation site. If not, the sensors might not be able measure the temperatures with enough accuracy. The customer might have use of a user guide that will help with the mounting of the sensor. A calculated table for the different FOV options can be used as in the guide to help the customer chose the right FOV model for the installation. The right placement of the sensor is critical to its functionality.

8.4 Usefullness of the thesis

It has been established that the chosen IR sensor prototype is usable for a potential product. This thesis also brings forth the FOV aspect validated the need for high emissivity tape or paint near the monitored spots. This prototype and the aspects tested in this work will be used for developing the final product.

8.5 Continued development

Since IC’s are getting smaller every year, there might come a time when a microcontroller is integrated into the actual sensor element along with the other IC’s. This would allow the final temperature calculation to take place inside the sensor itself. This would reduce engineering time considerably for implementation into other systems. It would also make the code execution faster in the external microcontroller, since the temperature calculations would be done in the IR sensor itself. In this developed solution, each pixel’s final temperature is calculated in the microcontroller, which takes up a lot of time in the code execution.

A HMI can be developed, were several IR sensors' views can be seen at the same time. In this way, the customer can get an easy and complete view of the entire switchgear if several IR sensors are in use. The customer might also find an application case that is not mentioned in this thesis. In the end, the usefulness of the IR sensor application is case-dependent, and it is up to the customer how it is implemented.

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