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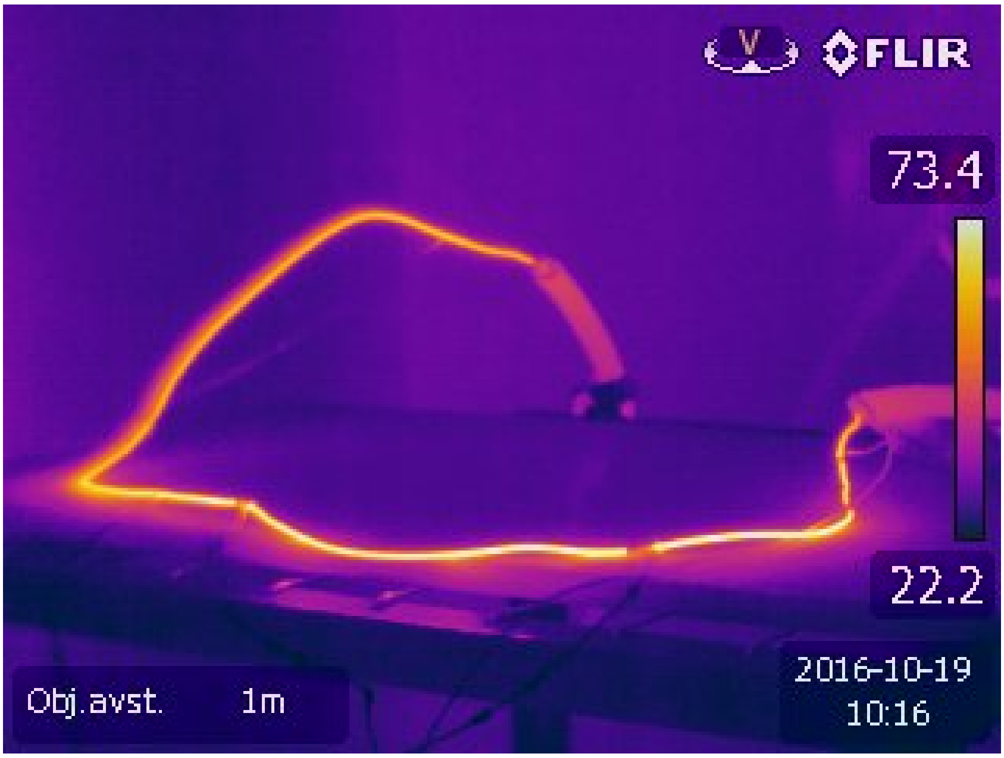

Electrical fires in heavy-duty vehicles

Bachelor's thesis in electrical engineering and mechatronical engineering

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Gothenburg, Sweden 2017

Bachelor's thesis 2017

How and why electrical fires can occur in heavy-duty vehicles.

A report containing studies and experiments on cables to further understand how and why they can lead to electrical fires occurring in heavy-duty vehicles as well as what precautions can be taken to decrease the chance of a electrical fire occurring.

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Bachelor's Thesis 2017
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Cover: Infrared photograph of a cable during a test.

Typeset in LaTeX
Printed by Serviceenheten Lindholmen
Gothenburg, Sweden 2017

Abstract

This research focuses on the electrical wiring of heavy-duty vehicles and how heat in cables are developed when setup in different configurations as well as how a increase in voltage from 24 [V] to 48 [V] effects the risks of potential fires when the system is overloaded. This is achieved by supplying the test cables with currents simulating an overload similar to when the fuses are at their breaking point.

From the results, three conclusions can be made based on the data that were extrapolated. The first conclusion answers if it is possible to use 48 [V] without generating too much heat when the same current is applied. As the data shows, it is possible to incorporate 48 [V] without any greater effects on the cables. However, there was still an increase in temperature, approximately 1–3 [$°C$] and the resistance of the components which the cables are connected to would have to be higher to not cause larger currents.

The second conclusion was made when observing the long single conducting cable test at 24 [V] and 55 [A] (4.10). This experiment showed that as the temperature rose, the resistance increased which affected the electronic load machine to lower its resistance in order to keep a constant current. As the resistance got higher, the machine could not keep up and as a safety mechanism, had to lower the current as well to not break the circuit nor the machine.

The third and final conclusion analyses the effect of bundling multiple cables together. As shown by the graphs, increasing the number of cables decreases the transfer of heat from the cables towards the surrounding. The cables in a bundle have a noticeable insulating effect which is seen in the mixed data test (4.20).

Keywords: electrical fire, heavy-duty vehicle, cable, fuse, bus.

Acknowledgements

For helping us complete this bachelor's thesis, we would like to thank our supervisor Lennart Widén at Chalmers University of Technology, for being a great support and a excellent sounding board, with both tricky questions and leads to results crucial for the final conclusions of this report.

We would also like to dedicate a thank you to our supervisor at SP, Ola Willstrand, for assigning this thesis to us, putting heat on us by grilling us with tough questions, helping us with getting a hold of the equipment need for our experiments and last but not least: giving us the opportunity to perform experiments at a real science facility.

We would also like to give our thanks to Fredrik Nyth and Sonny Oskarsson at Volvo Bussar AB in Göteborg for giving us a tour of the office and factory as well as sponsoring us with the material needed for our research and experiments. A second thank you to Volvo Bussar AB in Borås for giving us a tour of the factory and sponsoring us with material needed for the experiments.

A special thank you to Max Rosengren at SP for supplying us with your expertise in the field, connections at Volvo Bussar AB to receive material needed for our experiments.

We would like to dedicate a very special thanks to Alison Traynor at Chalmers Writing Guide for providing us with help both writing and correcting this report.

Last but not least, we would like to thank Sakib Sistek and Dr. Robert Svensson for moral support and being a great source of inspiration as both teachers and friends.

Tomas Lukas Szulc, Mikael Nyberg, Gothenburg, February 2017

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1 Introduction

The introductions chapter presents the topic of this thesis about electrical fires in heavy-duty vehicles and what errors might lead to a electrical fire occurring in a heavy-duty vehicle.

1.1 Context

This topic will explain how electrical fires can occur in heavy-duty vehicles and the problems that it entails, such as damaging the components in the vehicle, causing economic damage to the vehicle or injuring the people in the vehicle. Therefore, the studies conducted will indicate how well the current wire setup can handle electrical loads over a prolonged time followed by experiments which will test extreme loads over a short time to examine the heat development. This leads to conclusions based on the results which could potentially lead to being implemented as a precaution into heavy-duty vehicles.

1.2 Background

Since public transport is a vital function in a society, it is important that it works with few or no errors. However, when a error occurs it can be due to multiple factors such as; daily usage or large strains on the vehicles which causes wear on the different parts and components. If there is no service performed on the vehicle the possibility of an accident happening increases over time, under some circumstances and environments such as during icy conditions in Sweden when the roads are treated with salt which can lead to corrosion. These are not all of the possible factors that might lead to a short circuit of the system, thus creating an electrical fire in a vehicle.

One common reason for electrical fires to occur is due to short circuit caused by for instance, wear and tear on cables or failing components such as faulty installation of a fuse, over- or underdimension of components. Therefore, it is important to examine what can happen to a cable when a short circuit occurs. Currently existing buses and their cables have to follow current EU regulations. However, this leaves a lot of room for interpretation on what might be regarded as a safe standard in one country may not be regarded safe in another country. One example of this is the following:

"In critical areas thermoresistant wires shall be used." (*United Nations Economic Commission for Europe 2014/E /ECE/324/Rev.2/Add.106/Rev.6 –E/ECE/TRANS/505/Rev.2/Add.106/Rev.6*).

This example does not specify how thermal resistant the wire has to be, only that it has to, which can lead to varying levels of safety precautions on the wire depending on the circumstances.

If an electrical overload develops in a bus, the current generated in the circuit increases to such a high level that the heat produced might cause a fire to occur. This thesis will set out to examine how cables are affected by supplying them with a higher than usual current over a prolonged time under different circumstances such as: different lengths and if the cable is in a bundle. By creating theories about the different scenarios and testing them by conducting experiments on the cables and analysing the data.

This research is performed due to a lack of previous investigation of this topic and to make a foundation upon which further research can be based. Because of the lack of previous research in this field, the purpose for this thesis is to extract data from the experiments, examine it, present it in a user-friendly way, draw conclusions and from then on further advance the research.

1.3 Limitations

Some of the factors for electrical fires in heavy-duty vehicles mentioned in the background are to hard to replicate due to a time constraint, therefore in order to keep consistency in the experiments, for example wear, corrosion and failing components. This limits the experiments to faulty chosen fuses and over- or underdimensioned cables since these factors are hard to replicate in a controlled environment.

Another limitation is that the equipment for the experiments is in Borås whilst other school related activity is located at Lindholmen, meaning that the number of occasions for experiments are limited.

Another limit of the thesis was not having the research material required and having to search for a sponsor to provide the research material, therefore time was a limitation for the thesis that was implemented as a factor in the planning of the project.

1.4 Overview of the thesis

The thesis covers the relevant theories needed for performing the experiments, aquire the results and when testing its validity and explain its relevance to the reader, as well as explaining the current studies and their relevance to the research followed by explaining phenomenons that might occur during the experiments.

Thereafter, the results are presented from the experiments beginning with explaining how the experiments were set up and how they were performed, followed by each test and explanation of each test and the results acquired.

Lastly in the thesis are some reflections of what to improve on in future experiments and what conclusions that can be made from the data gained during the experiments are discussed.

2
Theory

In the following sections, the fundamental theories of the project will be presented and how the relate to the research and study and then compared against the results gained from experiments.

2.1 Relevant theories

As the development of eco-friendly vehicles increases, so does the need for eco-friendly buses, thus studies and research on different types of combustion systems needs to be expanded. Because of this demand, studies on electrical systems in busses have to be expanded upon to find alternatives, for example: the propulsion system might become based more on electrical motors and less dependent on combustion engines or even creating a hybrid system.

This might lead to a change of the standard voltage in busses from 24 [V] to 48 [V]. This potential change demands research into how the current electrical system handles the increased voltage as the electrical effects will become different. In theory, double voltage will lead to a doubled electrical power and thus an increased heat development.

The first equations is Ohm's law which shows how the voltage [U] is based on the current [I] times the resistance [R] flowing over the circuit, if applied to the second equations showing the electrical power [P] being equal to the current times the voltage. However, by expanding the second equation with the first equation's results in the electrical power being the result of multiplying the resistance with the current squared, which is what needs to be utilized when calculating the electrical power in cables, based on these equations:

$$U = R * I$$

$$P = U * I = R * I^2$$

In some cases, the cables in a bus are designed in such a way that the some of the cables are drawn from one end of the bus to the other end, thus making the length of the cables approximately the same length of the bus or even longer. An increased length of the cable means that the electrical resistance in a longer cable will be higher than in a shorter cable, given that the cross section area of the cable is constant. The equation shows how the resistance is equal to the resistivity of the material [$\rho = 1.68 * 10^{-8}\ \Omega m$] which is copper in this study, times the length of cable [L]. The numerator is then divided by the cross section area of the cable [A], however, this equation will only work when the temperature is assumed to be approximately 20 [$°C$] or approximately room temperature.

$$R_{cable} = \frac{\rho * L}{A},\ at\ 20\ [°C]$$

This, in and of itself, does not mean that the heat of a cable will reach a higher temperature than a shorter cable. However, a longer cable will not be affected equally as much as a shorter cable when it comes to heat dispersion throughout the ends of the cable. With this in mind, the electrical resistance of a cable might increase with a greater impact as the temperature increases [ΔT] according to:

$$R = R_{cable}(1 + a * \Delta T)$$

When it comes to the heat transfer from the electrical conducting copper to the surroundings there is some factors that affect how well the heat from the cable is transferred towards the surroundings. The fundamental theory of this is that the transfer of heat is dependent of the temperature difference and the thermal resistance, how well the heat is being transferred, according to the equation:

$$\dot{Q} = \frac{T_{\infty_1} - T_{\infty_2}}{R_{Thermal}}$$

The numerator in this equation in the case with the cable system is the difference between the core temperature of the cable and the temperature of the encasing air, [$T_{\infty_1} - T_{\infty_2}$]. In the equation mentioned above the denominator represents the thermal resistance [$R_{Thermal}$] of the material between the heat source and the surrounding environment. This resistance from the cable towards the surrounding is both that of the resistance from the inside of the isolating material of the cable to the outside and from the surface of the isolation material towards the surroundings.

The thermal resistance of the isolation material consists of a logarithmic fraction between the inside radius and the outside radius of the isolation material in the numerator and combined with two pi and the length in the denominator leads to an approximated volume that combined with the thermal conductivity constant for the material [k] in the denominator gives the total thermal resistance of the cable. This gives the an equation as following:

$$R_{Thermal} = \frac{ln(\frac{r_2}{r_1})}{2 * \pi * L * k}$$

The transfer of heat from the surface of the cable to the surrounding air through convection is only dependent of the surface area [A] and a transfer constant [h] according to the following equation:

$$R_{Conv.} = \frac{1}{h * A}$$

According to the aforementioned equations, it can be concluded that if several cables are arranged in a bundle, the bundled cables might reach higher temperatures than if every cable was not bundled. This is both the result of the surrounding of every individual cable being changed and the cables having a warming/isolating effect in the bundle itself.

2.2 Relevant studies

This study set out to be a part of a larger research as to why electrical fires occur in heavy-duty vehicles. To get a better understanding of this in the thesis, some case studies, reports and documents were examined to find a common denominator as to where electrical fires begin and why they start in the first place.

The studies needed to create the foundation for this research consist of multiple reports and multiple different investigations displaying the amount of accidents, cause of the accidents, and source of the accidents. By analysing these statistics one major cause of fire can be concluded to be heat produced by electrical faults such as breakdown of components, short circuit or faulty fuses and other electrical and non-electrical faults.

The first study by MFSA [1], indicates that amongst a number of reasons for ignition is due to heat development in for instance the engine compartment with multiple different ignition sources. However, it is not specified which is the most common reason nor how frequent the ignition is for each source.

This report is based on a compilation of multiple different U.S. government sources, for example the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) and the U.S. Fire Administration's (USFA) National Fire Incident Reporting System (NFIRS) database. This altogether gives a independent overview without regard of different automotive manufacturers and points out that electrical fires are a problem for heavy duty vehicles when or if accidents occur.

The second study by Hartwood Consulting [2] supports the claims of the first source by confirming why electrical fires in heavy-duty vehicles occurs as well as providing possible solutions on how to prevent electrical fires from happening. The investigation of the Hartwood report has shown that some existing precautions for preventing electrical fires are not always efficient.

"*Fire may result when surrounding flammable materials experience elevated temperatures from the resistor overheating. A circuit breaker cannot protect against this because the resistors limit the current to tolerable levels.*"

This proves that further research is needed and further precautions are in need of being developed or utilised in order to solve this problem.

The third study by SP [3] reinforce the claims from the two aforementioned studies by showing different kinds of statistics on the frequency of accidents and breakdowns or different types of heavy-duty vehicles from different countries in the form of graphs. As to how this study contributes to this research is by indicating a more solid claim that electrical fires is a problem as the number of heavy-duty vehicles in use increase each year.

In general, therefore, it seems that electrical fires in heavy-duty vehicles are a reoccurring problem based on the above mentioned studies.

3
Methods

This chapter will cover the necessary steps to the project, what prerequisites will be needed for it and how the data correlates with earlier studies as well as theory.

3.1 Procedure

To get a better understanding of the project and how it was performed, certain steps have to be made in a consecutive order to fully understand and grasp the methodology of the research and experiments.

3.1.1 Pilot studies

The pilot studies is the first step in the project to get a fundamental understanding of how and why the electrical fires occur in heavy-duty vehicles and what precautions can be made. In the pilot studies, literature studies surrounding the subject will be read and used as a source for the theory about heat development in cables as well as the inner resistance of the cable and how the resistance increases as the temperature increases.

Chalmers library databank will be utilised for its vast amount of sources such as e-books; reports; studies and articles and will thus provide the necessary resources needed for this project. Previous studies made by different institutes and associations will be read and analysed for data to further understand the topic and may be used in the theoretical calculations for the experiments, which have been explained previously in the document. All of the resources and calculations will become the basis for the the experiments which will determine the conditions behind heat development in cables.

All of the above mentioned studies will be made through out a period of approximately four weeks and all the data gathering will be made simultaneously as well as to equally share the work load between the participants.

3.1.2 Experiments

When the above mentioned points have been accomplished, only then can the experimentation stage begin. The experiment stage will begin by connecting the rigging station for the experiments. The experiments will consist of measuring the heat development of the cables by sending different voltages and currents through them. When performing the experiments, different parameters will be changed to acquire the data, for example varying lengths of the cable; different cross section areas of the cable; which setup of cables produces more heat, one cable or a bundle of cables.

This stage in the process is scheduled to take five to six weeks because of varying results, thus the experiment stage will be more fluid than the other stages and may change to adapt to the circumstances of the experiments.

As for how the experiments took place, the equipment was connected so that the power supply was directly connected to the electronic load via power cables and then to the testing cables. In order to protect the equipment from eventual damage because of the heat developed from the experiments, the experiments were translocated into a fume cupboard via extensions from the power supply and electronic load using power cables. Between the power cables from the equipment the testing cable/cables were connected and monitored with the help of thermocouples connected to a logging device and a thermal camera. The sample rate from the logging device was one sample per second. The thermocouples were fastened to the test cable both directly on the copper, though scaling away about 1 [cm] of isolation, and by being wrapped around the isolation. To make sure that there were less external errors a humidity- and airflow-meter combined with the fact that the test cables are at the same temperature as the surrounding was the basis for the tests. The investigation of airflow was made at different points, especially around corners where the airflow usually is greater than normal, and in different axes.

So before each of the tests the following were checked:

- The length and diameter of the cable.
- The originating temperature, air-humidity and maximum airflow.
- The supply voltage, the passing current and the estimated effect on the entire cable.
- The number of samples and where the thermal couplers were placed.
- The settings of the thermal camera.

3.1.3 Writing the report

The writing part is the final stage in the process and will be a compilation of all the data acquired through out all the stages of the process. The data will then be compiled into multiple pictures; graphs and charts comparing all of them with the theories followed by observations from the different experiments. The report ends with a result and a conclusion to the project.

3.2 Material

3.2.1 Cables

To be able to conduct any research, cables of varying lengths, diameters and area of use had to be acquired. Because of the vast variety of cables and their applications in heavy-duty vehicles, some standard specifications for the experiments had to be made.
To perform realistic experiments, some cables were donated by Volvo Buses AB with the following standards:

Table 3.1: Specifications of the power cables.

Power cables					
	Cable #1	Cable #2	Cable #3	Cable #4	Cable #5
$Length_{Cable}$	3.74 [m]	1.32 [m]	1.70 [m]	2.92 [m]	3.18 [m]
$Area_{Cable}$	70 $[mm^2]$	95 $[mm^2]$	50 $[mm^2]$	25 $[mm^2]$	50 $[mm^2]$
I_{Max}	195 [A]	240 [A]	155 [A]	96 [A]	155 [A]

Due to the thickness of the power cables and the high current safety, smaller cables were also donated.

3.2.2 DC power supply – Model 62000P series

The first piece of laboratory equipment was supplied by the electronics department of SP Technical Research Institute of Sweden and contained of a programmable DC power supply (MODEL 62000P SERIES) [4]. This part of the equipment was used to supply the electricity used in the experiments as the source of voltage and current, replacing what would in normal cases be the battery of the vehicle.

3.2.3 DC electronic load – Model 63200 series

The second piece of laboratory equipment that was supplied was a programmable DC electronic load (MODEL 63200 SERIES) [5]. To complement the power source of the experiments and as a precaution this component is used as a constraint when it comes to the current accruing in the experiments. The precaution of this machine if that it can not let the experiment go out of control, in other words, the electronic Load can not evade being a electric load by for example not being able to have a zero resistance. This precaution is to avoid really dangerous short circuits when the material experimented upon might change properties due to heat etc.

3.2.4 Data acquisition system – Fluke 2638A HYDRA series III

The third piece of the equipment [6] was used to interpret the information from the thermalcouples placed on the cable. This machine read the information from the thermalcouples on decided intervals called samples. It had a maximum capacity of twenty thermalcouples and a accuracy of up to five decimals. This was the primal source of recording information for the data in this report.

3.2.5 IR camera – FLIR T420

The fourth piece of equipment was a IR-camera [7] able to detect infra red light, also known as heat, with consideration of distance, emissivity and the surrounding temperature. The camera had features like recording, taking pictures (see appendix) as well as measuring temperatures at specific points chosen by the user.
This part of the equipment was used to check for any abnormalities and to verify the results from the thermalcouples as well as scanning for eventual errors in the experiments.

3.2.6 Other

The fifth piece of equipment was a Testo 445 – VAC measuring instrument [8] which was used to measure the air velocity in the test chamber. To eliminate as many sources of possible errors, this task was performed before each experiment.
Another environmental test was to observe the surrounding temperature and the air humidity, to eliminate as many sources of error as possible.

As the data from the Fluke 2638A was stored in CSV-files, MATLAB was used to extract useful data such as the measured temperature over time as well as plotting the data into graphs. MATLAB also provided with the possibility to extract specific data from different experiments into one graph suited for comparison for the results, an example of the code can be seen below.

```
hold
plot(Record,Ch101C)
plot(Record,Ch102C)
plot(Record,Ch1030C)
plot(Record,Ch1040C)
plot(Record,Ch1050C)
plot(Record,Ch1060C)
grid on
xlabel('Time [s]');
ylabel('Temperature [\circC]');
legend(gca,'show','Location','southeast');
set(gcf,'PaperPositionMode','auto');
savefig('Name_of_figure');
print('Name_of_figure','-dpng','-r0');
```

As for knowledge for analysing the tests, the two participants have a combined understanding when it comes to electrical properties, making measurements and thermal dynamics. The results from the tests will give information that will be supported by the theoretical knowledge of the participants.

3.3 Participants

This project is done as a bachelor's thesis at Chalmers University of Technology in cooperation with SP technical research institute of Sweden and Volvo Buses AB. This project is conducted by two students studying electrical- and mechatronics engineering.

4

Results

The results in this chapter will be summarised into lists of specifications, under what circumstances the experiment were made and graphs depicting the heat development of the cable over time.

4.1 Standardisation of experimenting

The experiments that were made encapsulated how cables heat development were affected by the following factors:

- The length of the cable.
- The diameter of the copper in the cable.
- The voltage and the current passing over the cable.
- Whether the cable is in a bundle or not.

Because of these factors, testing standards were set in place to always measure using the same method to minimise faulty data or acquiring non-useful data.

All of the experiments took place in a chamber with a manual switch to control air-flow; a transparent, plastic cover that could be moved up-and-down to minimise the amount of smoke to escape from the test chamber. Before each experiment, the air-flow was measured using an air velocity measuring instrument to approximate the air velocity in the test chamber. However if the velocity of air-flow is less than or equal to 0.20 [m/s], it is considered to be "windless" according to the lab technicians at SP and as such will not have any greater affect on the thermalcouplers. The room temperature was measured using a regular wall thermometer and is assumed to have an even temperature in the testing chamber.

In the testing chamber, a plank made out of promatec was set up between two metallic pillars for the cables to rest on, the thermal properties of promatec allows for minimal heat transferring from the cable to the material.

The source and load were both placed outside of the testing chamber and facing away from it to not create an airflow into the testing chamber by the exhaust fans at the back of the machines, this was done as to not air cool the thermalcouples and measure faulty temperatures.

The data acquisition machine was placed on top of the source and the load, outside of the testing chamber to minimise the interference with the experiment or the cables going out from the source and the load. On the backside of the machine there are outgoing ports to connect up to ten thermalcouplers and a USB memory stick to transfer all the measured data in to.

The settings on the machine were:

- Measure the temperature in degrees Celsius.
- To measure every second, i.e 1 sample of data/second.
- Measure the average temperature of every sample, meaning that the machine measures several values each second and calculates an average value per second, which is then recorded on to the machine or to a USB memory stick.

For each experiment, six data points were used to collect data (if nothing else is specified), each representing a thermalcouple placed on the testing cable. For each experiment a thermalcoupler was placed on either directly on the copper or on the isolation material around the copper. This decision was made to acquire data on the temperature difference between the two measuring points. Each thermalcoupler was then placed at a set distance from the positive side on the cable, meaning where the current entered the cable.

The last piece of equipment used was a infrared camera which was used to record the heat development and take pictures of the heat emitting from the cable. The camera was placed approximately 1.0 [m] from the testing cable

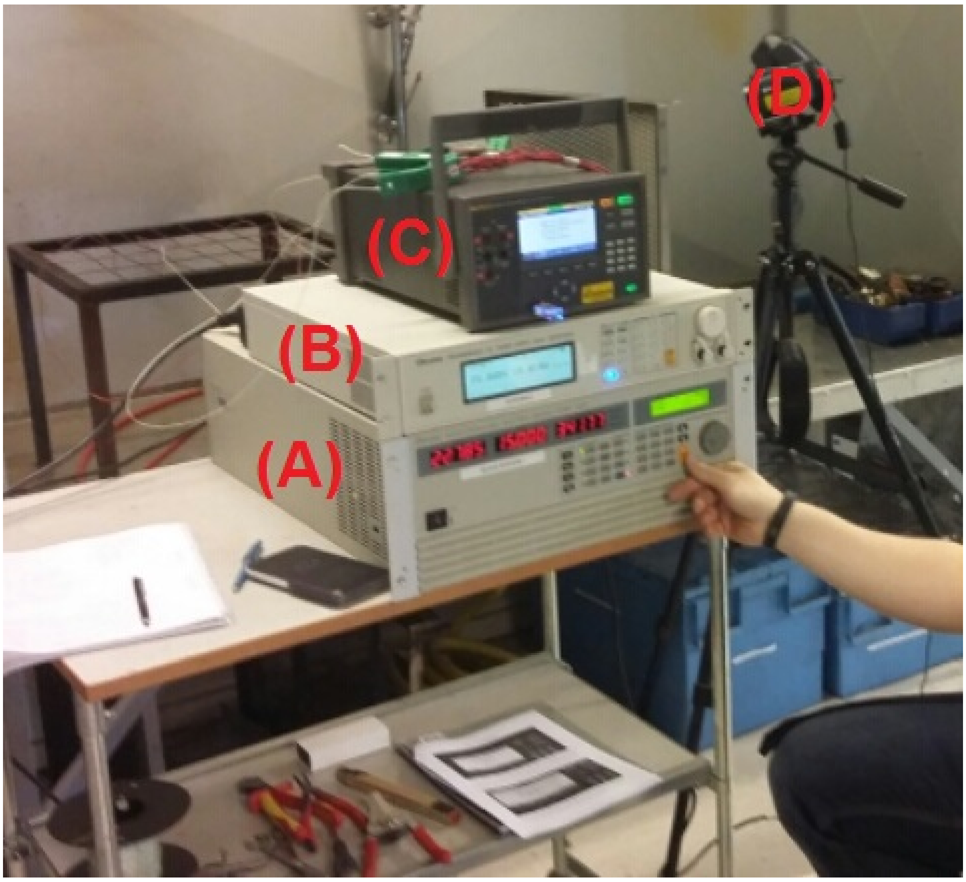

Figure 4.1: Picture of the test rig in use, in the picture the (A) electric load, (B) electric source, (C) data acquisition machine and the (D) infrared camera.

When conducting each experiment, the same cable was used through out the whole experiment as long as the integrity of the cable was not compromised. By utilising the same cable, the margin of error is reduced and a consistency of all the specifications remain constant. After each experiment a new cable was selected for the specific experiment.

When setting up the cables in the testing rig, using power cables with the lowest resistance as the connecting wires, see R_3, R_4 and R_5 in figure, to connect the DC_supply with the Electronic_load and the R_cable. As the the DC_supply and the Electronic_load was not only separate units, but also not in the testing chamber, connections had to be made to have as little interference as possible on the cables and rhermal couplers.

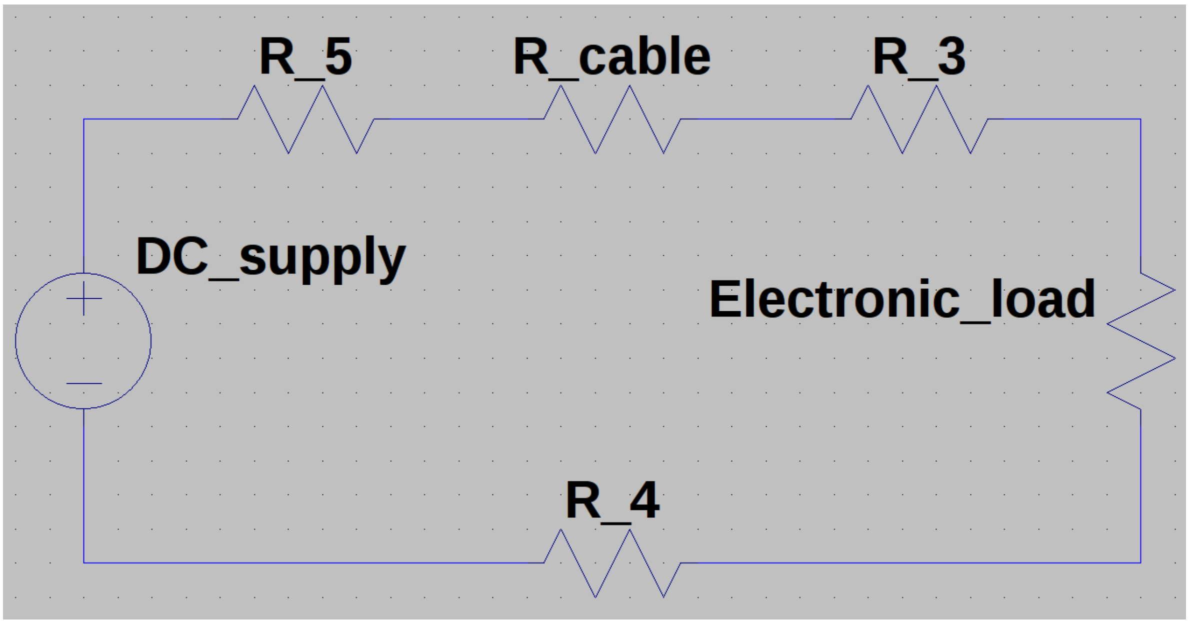

Figure 4.2: Picture of the electrical circuit used for the testing rig complete with each resistance demonstrating which cable was used.

4.2 Single conductive cable test

The first experiment was the single conductive cable test and was made to measure the heat development on the cable when supplying different currents and voltages over the cable.

The single conductive cable test consists of testing a 1.0 [m] long cable as it was the most appropriate length due to the access of cables as well as making it easier to calculate heat emission and other variables with 1.0 [m] long cable. Out of all the donated cables, a cable with a thicker copper diameter was used as to be able to conduct experiments which allows for the use of a higher current without the temperature melting the isolation completely off.

The temperature of the room was measured using a wall thermometer in the room and it is assumed that the temperature measured in the room is approximately the same as in the testing chamber. Air flow was measured with a dedicated machine and was measured to 0.0 [m/s], probably because of the valve for air intake was turned off and did not allow for any air to flow out.

When the experiments were conducted the maximum current was limited to 30 [A] due to the fact that the cables and their respective fuses are rated to only withstand 30 [A], any higher current with a constant voltage of 24 [V] or higher will result in too much heat generating and melting the isolating material.

All of the experiments performed will not be shown in the result chapter but can however be found in the appendix on page (IV).

The specifications of single conductive cable test (4.1) present the values each aspect of the cable, such as the total length of the cable used, the diameter of the copper in cable, the calculated cross section area of the copper in the cable etc.

The second table consists of the data points going from the data acquisition machine to the testing cable, each data point representing a thermalcoupler which was used to sample data. To gather good, usable, and representable data in the form of charts, the thermalcouplers were then carefully placed at the points specified in table (4.2). The table references how far in on the cable each thermalcoupler was placed and if the thermalcoupler was placed directly on the copper or on the isolating material.

Table 4.1: Specifications of the single conductive cable test.

Specifications	
$Length_{Cable}$	1.00 [m]
$Diameter_{Copper}$	1.60 [mm]
$Area_{Copper}$	2.00 [mm^2]
$Temperature_{Room}$	$\approx$ 21.2 [$°C$]
$Air\ velocity_{Room}$	0.0 [m/s]
Voltage	24/48 [V]
Current	20/25/30 [A]

Table 4.2: Data points of the single conductive cable test.

Data points		
Data1	copper	0.25 [m]
Data2	copper	0.50 [m]
Data3	copper	0.75 [m]
Data4	insulation	0.30 [m]
Data5	insulation	0.55 [m]
Data6	insulation	0.80 [m]

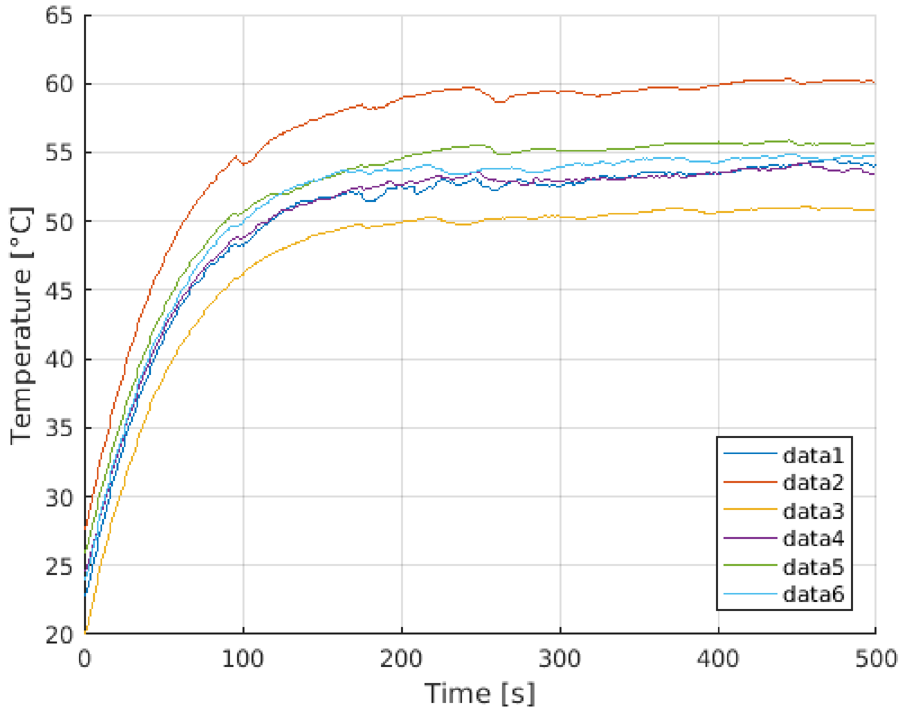

Figure 4.3: Single conductive cable supplied with with 24 [V] and 20 [A].

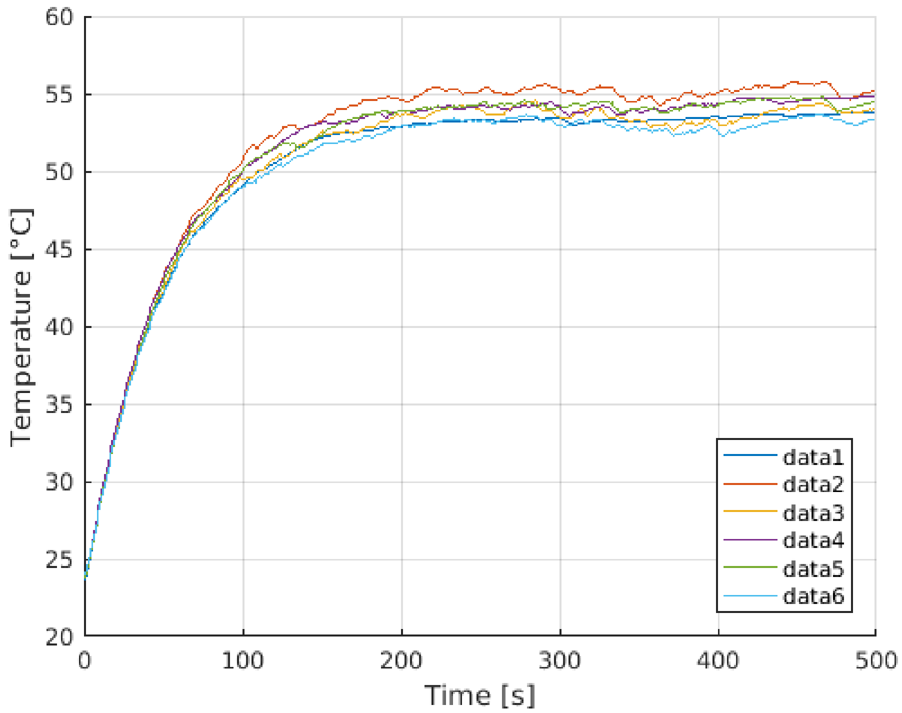

Figure 4.4: Single conductive cable supplied with with 48 [V] and 20 [A].

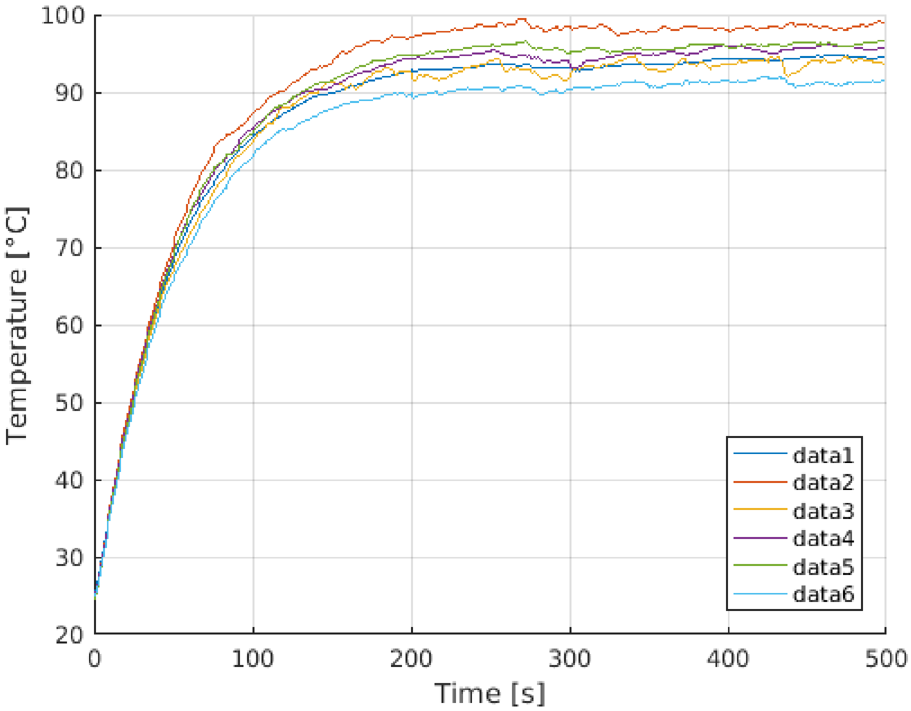

Figure 4.5: Single conductive cable supplied with with 24 [V] and 30 [A].

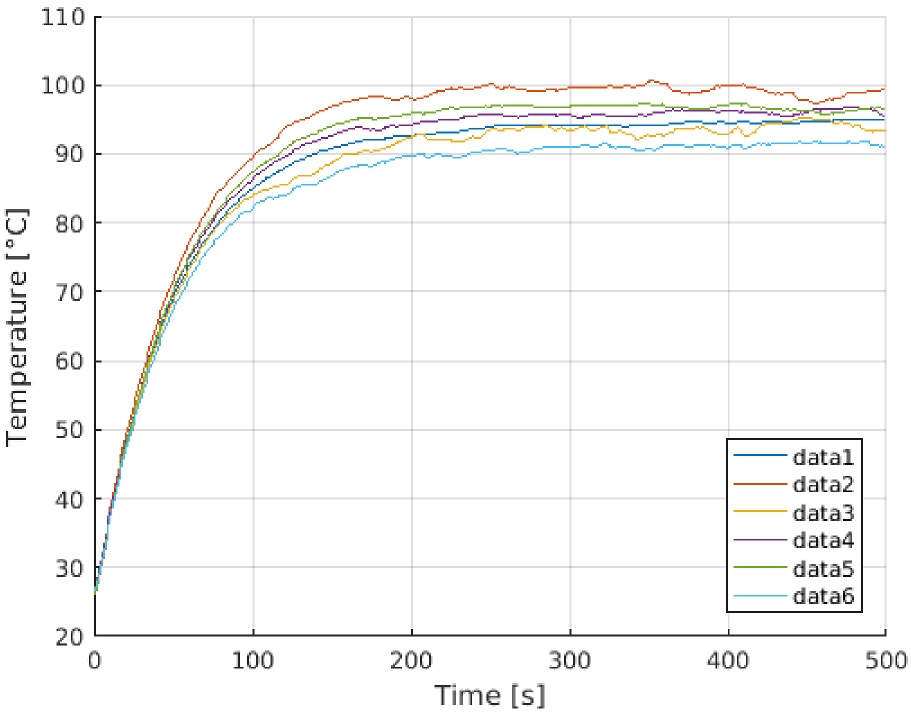

Figure 4.6: Single conductive cable supplied with with 48 [V] and 30 [A].

4.2.1 Results of single conductive cable test

- As seen in figures (4.3–4.6), the temperature increases in unison as the current is increased. Although the maximum temperature differs between the currents supplied to the cables.
- By observing the different data points, the hottest point on the cable can essentially be observed in the middle of the cable, i.e data2 or data5 as seen in figures (4.3–4.6)
- The temperature in each experiment can be observed to even out after approximately 150 [s].

4.3 Long conductive cable test

For this experiment, a longer cable was used which is a possible length, among many other lengths of cables used in a bus. Therefore this experiment is made with the purpose of giving perspective about how a longer cable's characteristics might differ to those of a shorter one.

Being limited to the cables donated to the research, a longer cable for the experiment had to be provided privately, thus the type of cable used in the following experiment is not a type of cable found in buses but rather in construction. The characteristics of the cable, such as the length and diameter of the copper differ from the other cables, as seen in table (4.3) and the the copper in the testing cable consisted of a solid, single core of copper rather than several, smaller threads of copper in the other cables as well as different isolating material.

The currents chosen for the experiment regulate to the same standards as the earlier experiment as well as to keep a consistency through out the experiments. On the final experiment, 55 [A] was supplied over the cable to simulate an extreme case of overloading the cable to gather data on how a longer cable handles higher currents, the temperature development in the cable and how fast the rate of change of the temperature is.

A secondary purpose of the experiment was to examine if there is a possibility of a fuse not breaking when intended during a short circuit or an overload and by testing the impact of temperature being a function of current and how temperature affects the temperature of the cable.

All of the experiments performed will not be shown in the result chapter but can however be found in the appendix on page (VI).

The specifications of the long conductive cable test differ from the other experiment due to a different type of cable was used, as mentioned earlier. The most important aspect of the experiment was the length of the cable. Any other aspects such as the diameter or cross section area of the copper were negligible as not having any greater impact on the experiment nor the results.

As seen in table (4.3), all of the thermalcouplers were only attached on the isolation of the cable. This decision was made as to have more of the same type of data to analyse.

Because of the length of the cable, more thermalcouplers were attached on to the cable to gather more accurate data to analyse. The amount of thermalcouplers was increased from six to ten, as seen in table (4.4). Due to the amount of available thermalcouplers, they were placed approximately every other metre with an exemption on the first and last metre of the cable. The first and last thermalcouplers were placed as such to gather data on how much heat is transferred away from the testing cable to the connecting points.

Table 4.3: Specifications of the long conductive cable test.

Specifications	
$Length_{Cable}$	20 [m]
$Diameter_{Copper}$	$\approx$ 1.38 [mm]
$Area_{Copper}$	1.5 [mm^2]
$Temperature_{Room}$	$\approx$ 21.0 [$°C$]
$Air\ velocity_{Room}$	0.23 [m/s]
Voltage	24/48 [V]
Current	20/25/30/55 [A]

Table 4.4: Data points of the long conductive cable test.

Data points		
Data1	insulation	1.0 [m]
Data2	insulation	3.0 [m]
Data3	insulation	5.0 [m]
Data4	insulation	7.0 [m]
Data5	insulation	9.0 [m]
Data6	insulation	11.0 [m]
Data7	insulation	13.0 [m]
Data8	insulation	15.0 [m]
Data9	insulation	17.0 [m]
Data10	insulation	19.0 [m]

In figure (4.7) it is shown how the experiments were set up and performed as well as how and where the thermalcouplers were placed on the cable.

In order to conduct the experiment inside of the testing chamber, the cable was wrapped around a piece of promatec which could affect the results by transferring heat from the cable on to the piece of plaster.

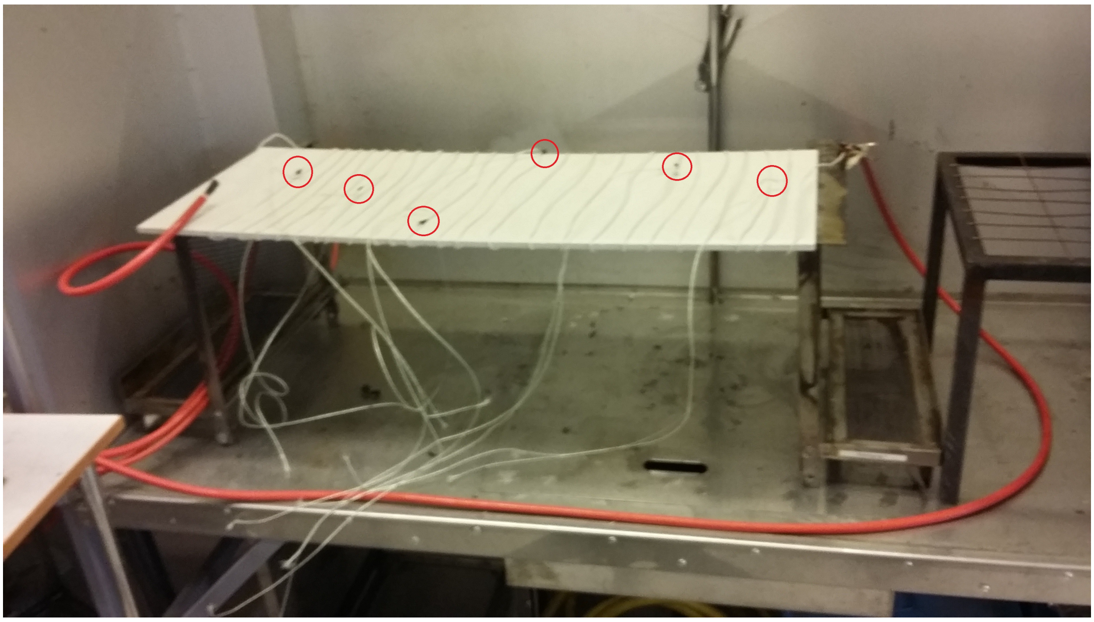

Figure 4.7: Test rig of the long cable test with thermalcouples encircled.

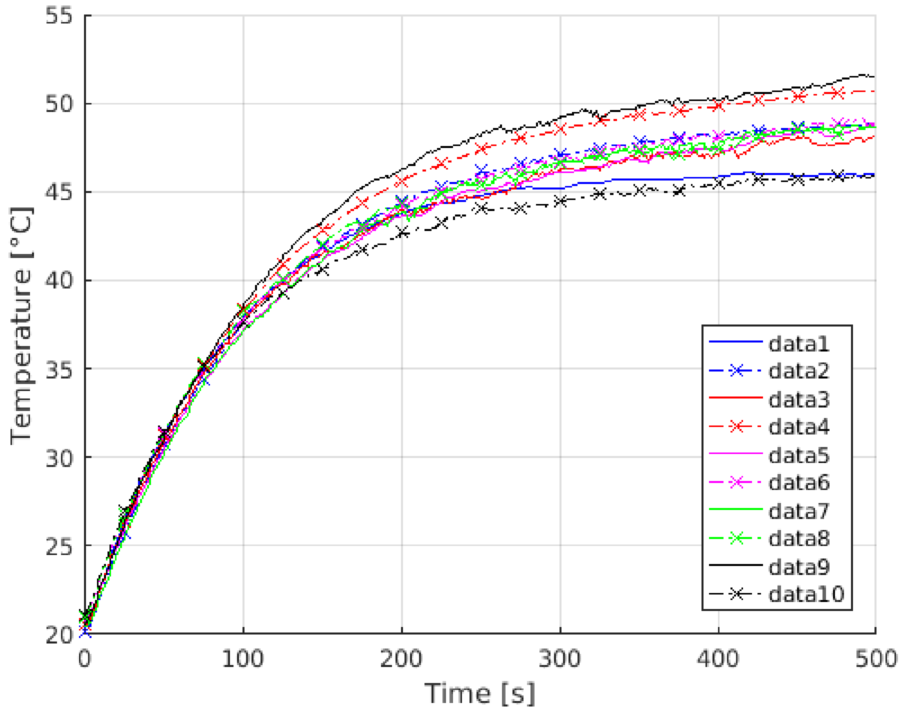

Figure 4.8: Long cable test supplied with 24 [V] and 20 [A].

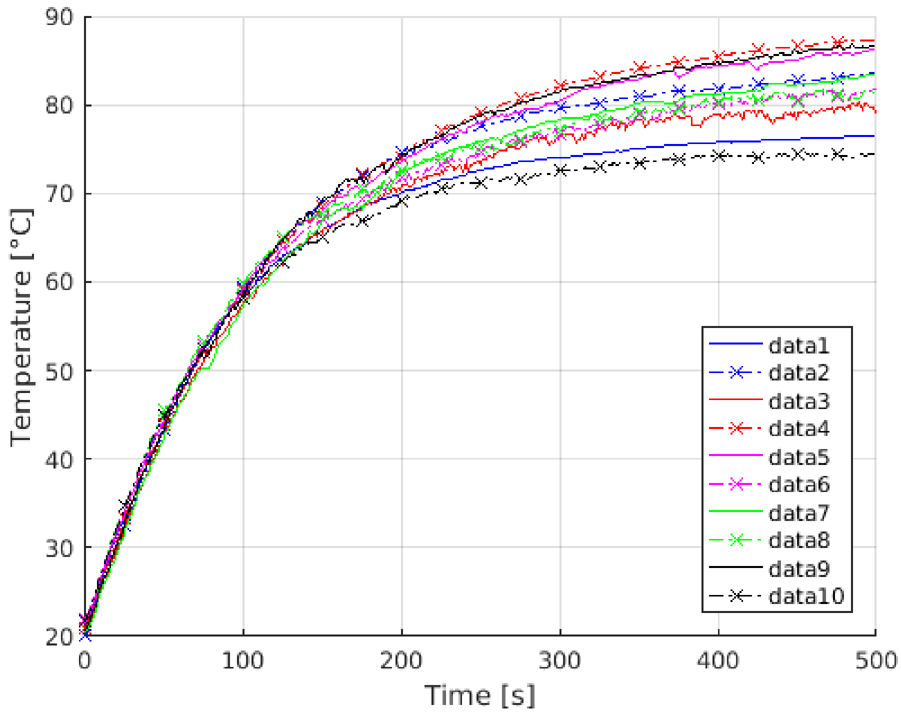

Figure 4.9: Long cable test supplied with 24 [V] and 30 [A].

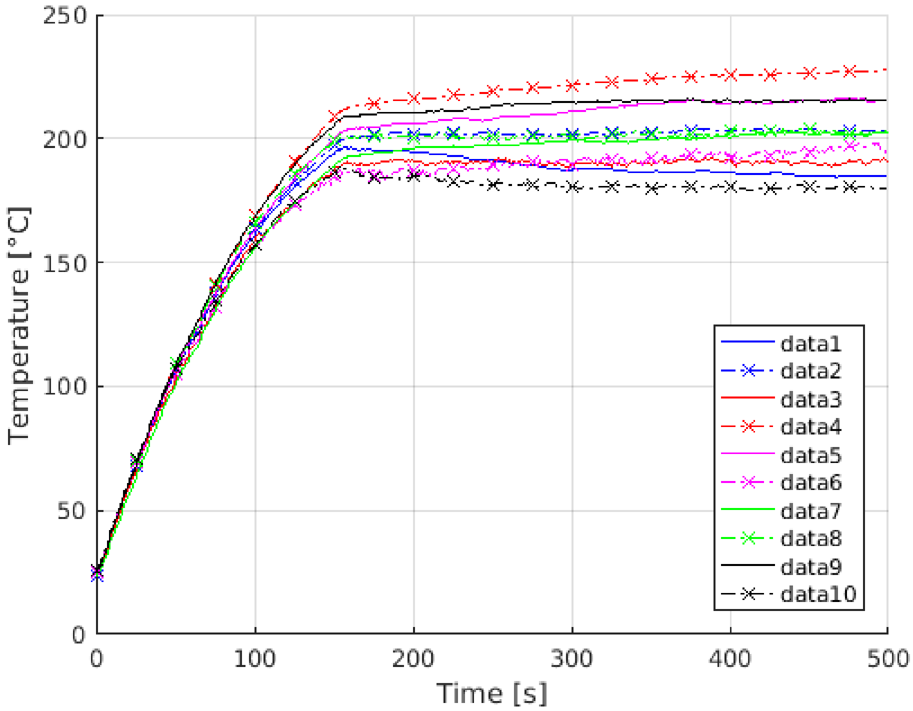

Figure 4.10: Long cable test supplied with 24 [V] and 55 [A].

4.3.1 Results of long conductive cable test

- The spread of the temperature along the cable is the same in every experiment.
- The temperature increases uniformally across the whole cable in every experiment.
- The spread of the temperatures between each data point starts to differ and become noticeable after 150 [s], and the maximum temperature measured at each data point along the whole cable begins to flat line after 400 [s] as seen in figures (4.8–A.10)

4.4 Bundle test – single conductive cable

The bundle test was made to measure the effect of having one cable conductive and isolated with other non-conductive cables in a bundle and examine the heat development.

The two possible outcomes of having cables in bundles were either that the surrounding cables would lead the heat in a more efficient way or transfer the heat in a less efficient way towards the surrounding.

The bundles of cables that were donated to research had different configurations and ratios to how many cables each bundle consisted of. The range was from four cables entering a connector to twelve cables. From each connector end, the cables were bundled together and secured together using electrical tape to keep the cables in place. Thereon the cables enter a bigger cluster of other bundles creating a bigger bundle, also secured and with electrical tape.

Because the cables were already bundled, there was no option of choosing what cross section area the copper to use. This decrease in area limits the experimentation stage by not supplying the cable with a higher current than 25 [A], to not risk melting the isolating material and compromising the integrity of the cable.

All of the experiments performed will not be shown in the result chapter but can however be found in the appendix on page (VIII).

The experiment set out to experiment and gather data on how much heat is transferred from a single conductive cable to a non-conductive cable. Therefore, the placement of thermalcouplers were arranged differently in comparison to the other experiments, as seen in table (4.6). The first four thermalcouplers were placed similarly as in single conductive test, however data5 and data6 were attached on the same cable which was non-conductive and on the isolation.

To gather as much data across the whole cable, the placement of thermalcouplers were spread out to cover as much relevant area as possible. The distance between each thermalcouple was set to minimise the interaction between them to not measure faulty data.

Table 4.5: Specifications of the bundle test – single conductive cable.

Specifications	
$Length_{Cable}$	1.00 [m]
$Diameter_{Copper}$	≈ 1.13 [mm]
$Area_{Copper}$	1.00 [mm^2]
$Temperature_{Room}$	≈ 21.0 [$°C$]
$Air\ velocity_{Room}$	0.23 [m/s]
Voltage	24/48 [V]
Current	20/25 [A]

Table 4.6: Data points of the bundle test – single conductive cable.

Specifications		
Data1	copper	0.35 [m]
Data2	copper	0.75 [m]
Data3	insulation	0.45 [m]
Data4	insulation	0.65 [m]
Data5	insulation, non–conducting	0.40 [m]
Data6	insulation, non–conducting	0.70 [m]

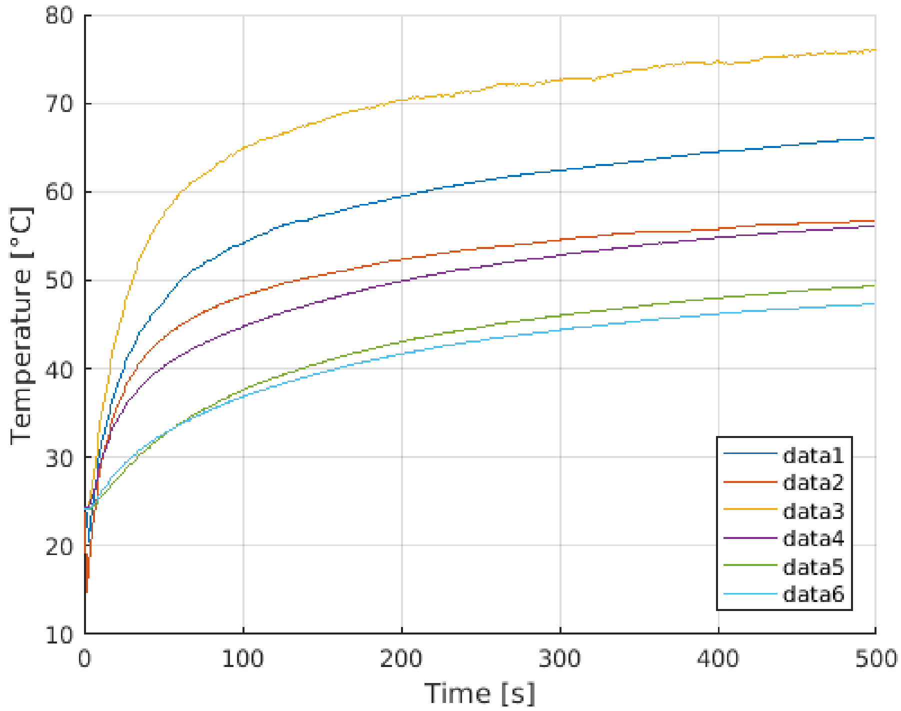

Figure 4.11: Bundle test – single conductive cable supplied with 24 [V] and 20 [A].

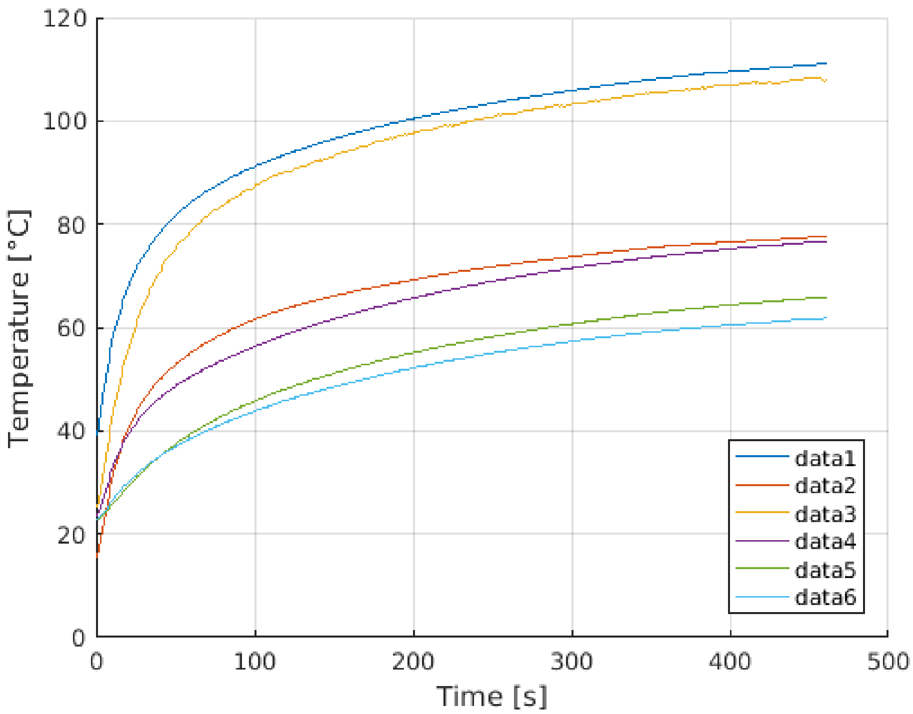

Figure 4.12: Bundle test – single conductive cable supplied with 24 [V] and 25 [A].

4.4.1 Results of bundle test – single conductive cable

- In figures (4.11–A.11) the temperature peak can be observed on data3, whilst in figures (4.12–A.12), the temperature measured on data1 surpasses data3.
- The temperature is overall higher in figures (4.11–A.12) than in the single conductive tests. Supporting the theory that the surrounding temperature affect the final temperature of the cables and the bundle.
- In these experiments, the measured temperature is higher in the odd numbered data points than the even numbered data points.
- The surrounding cables isolates the conductive cable, absorbing some of the heat emitted from the conductive cable, see figures (4.11–A.11).
- In comparison with the previous experiments, the temperature along the cable evens out faster and starts to even out approximately after 100 [s], however it does not flat line, as seen in figures (4.11–A.12)

4.5 Bundle test – multiple conductive cables

The bundle test with multiple conductive cables is conducted as it represents a more realistic scenario of all the cables being conducting instead of having a bundle with only a single conductive cable. Another reason the experiment is conducted is to examine if there is an additive temperature gain effect of having multiple cables be conductive.

The experiment consisted of four, equally dimensioned cables each having a copper diameter of 1.0 [mm] which is shown in table (4.7). However, the configuration of the experiment was made so that each cable was conducting and that the total current used for each experiment is split evenly between all of the four cables.

According to Kirchhoff's current law (A.8), the current is divided between the four conductors in the bundle, thus making the electrical effect lower, i.e the final temperature lower in correlation to the current. By applying Kirchhoff's law to the circuit, the current is evenly distributed to each cable which allows for experiments with higher currents.

Therefore, in the bundle test – multiple conductive cables, each cable is supplied with 6.25 [A] over it while in the bundle test – multiple conductive cables supplied with a car battery, the cables are supplied with four times as much current or 25 [A] as the aforementioned experiment.

There was a second type of experiment made with the intention to see what happens if multiple cables are short circuited at the same time with a current that would break a fuse. This was relevant because many cables are in bundles, if a bundle of cables were to short circuit or overload at the same time. Among the cables donated to this project was a bundle of four cables that, like previous experiments, resemble a realistic scenario.

A possible cause to a short circuit might be due to faulty installation of short circuit breaker, faulty cable installation or cable damage. The used the same configuration as the earlier bundle test, four equally large and a combined total diameter and cross section area. This experiment was the worst type of scenario with four cables being short circuited at the same time.

All of the experiments performed will not be shown in the result chapter but can however be found in the appendix on page (IX).

Table 4.7: Specifications of the bundle test – multiple conductive cables.

Specifications	
$Length_{Cable}$	1.00 [m]
$Diameter_{Copper}$	$\approx$ 1.00 [mm]
$Area_{Copper}$	$\approx 0.79\ [mm^2]$
$Temperature_{Room}$	$\approx 21.3\ [°C]$
$Air\ velocity_{Room}$	0.32 [m/s]
Voltage	24/48 [V]
Current	20/25/30/40/50/100 [A]

Table 4.8: Data points of the bundle test – multiple conductive cables.

Specifications		
Data1	copper	0.25 [m]
Data2	copper	0.50 [m]
Data3	copper	0.75 [m]
Data4	insulation	0.30 [m]
Data5	insulation	0.55 [m]
Data6	insulation	0.80 [m]

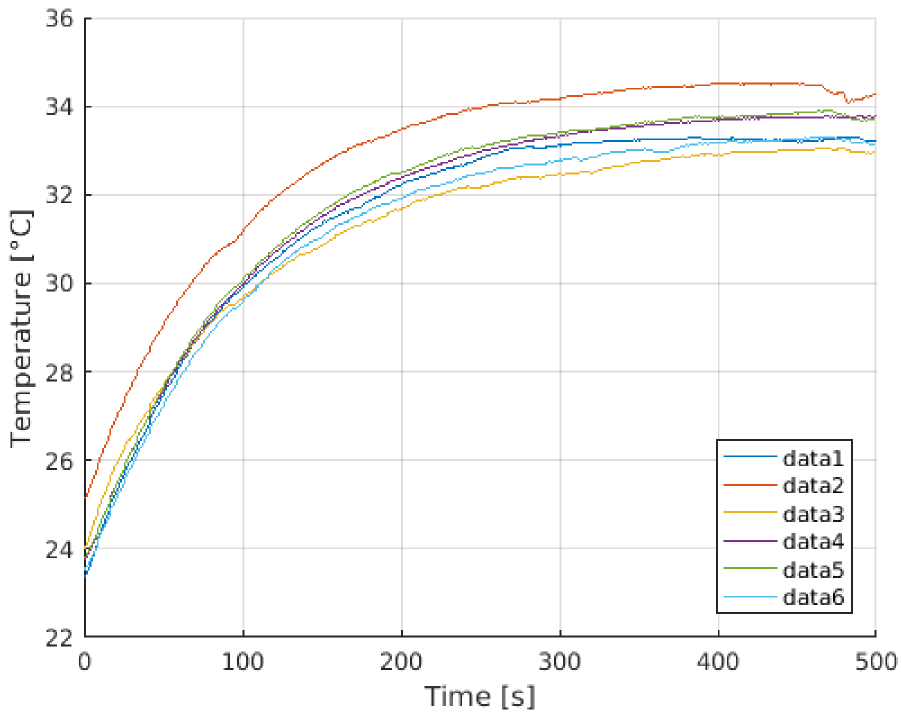

Figure 4.13: Bundle test – multiple conductive cables supplied with 24 [V] and 20 [A].

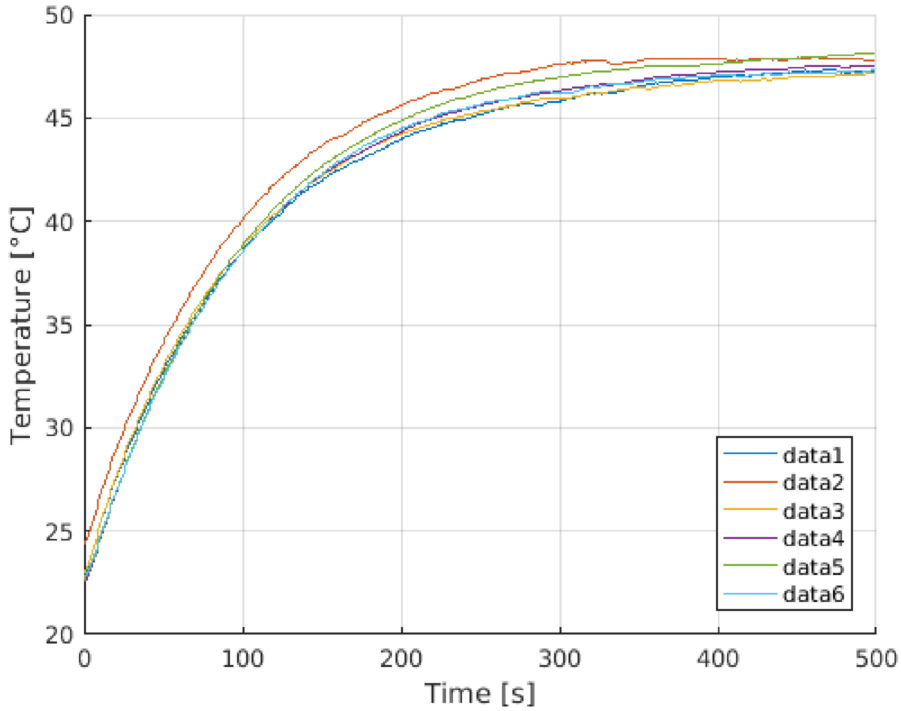

Figure 4.14: Bundle test – multiple conductive cables supplied with 24 [V] and 30 [A].

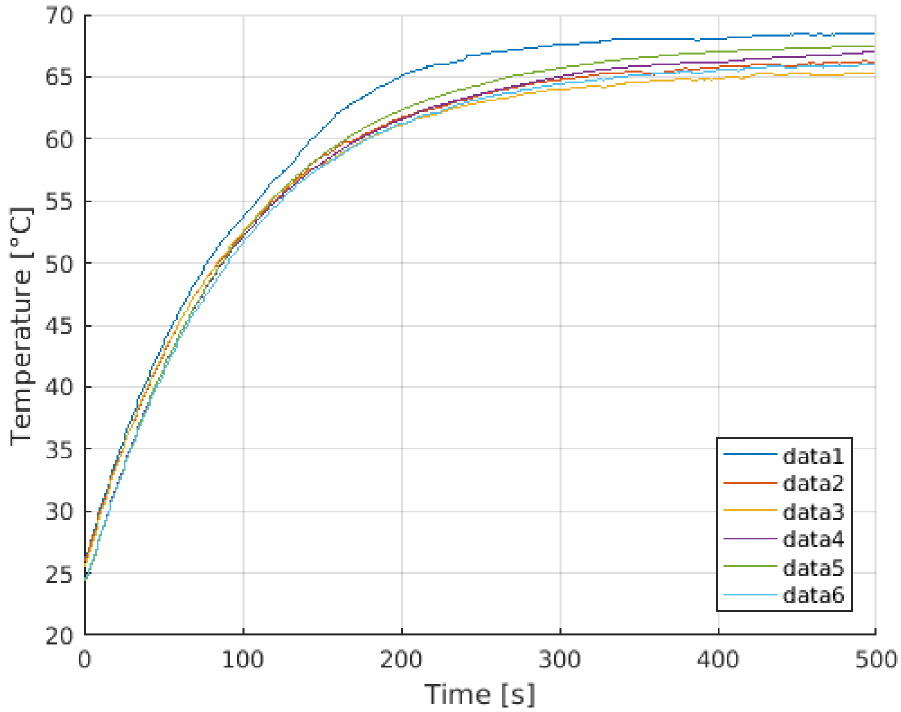

Figure 4.15: Bundle test – multiple conductive cables supplied with 24 [V] and 40 [A].

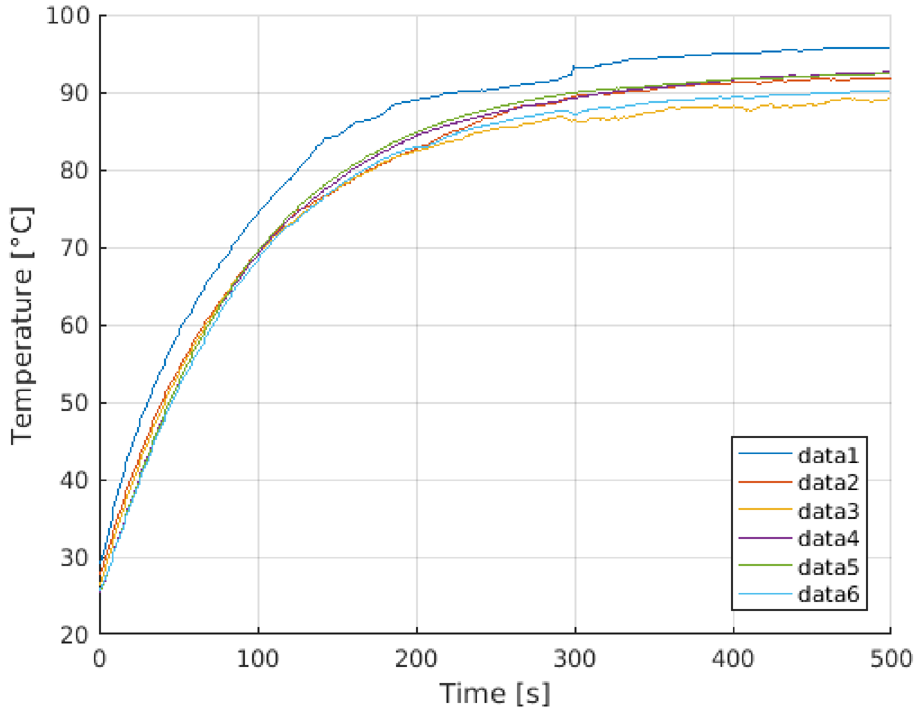

Figure 4.16: Bundle test – multiple conductive cables supplied with 24 [V] and 50 [A].

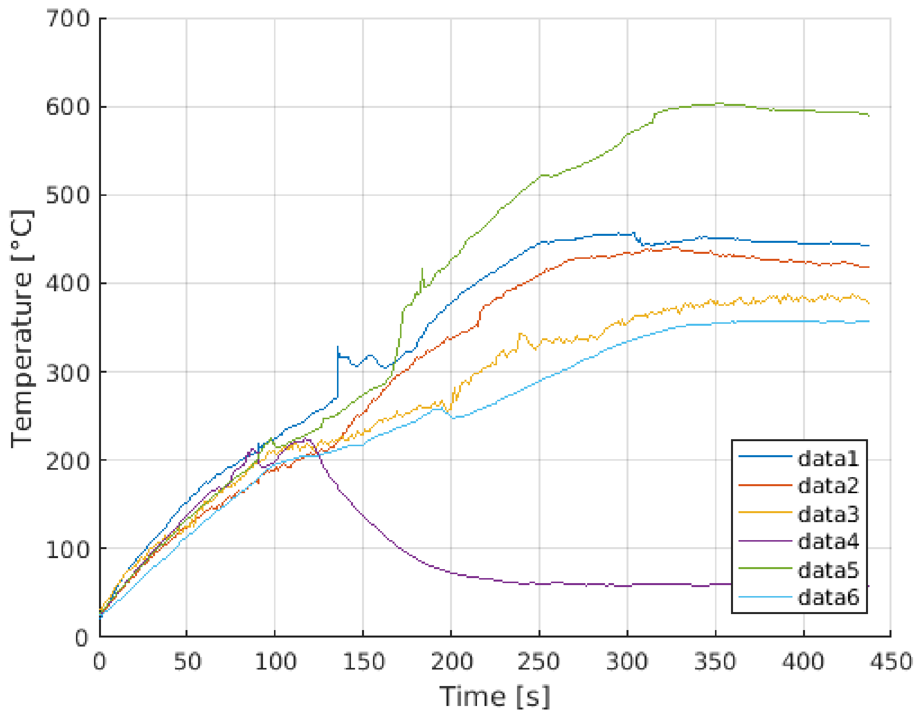

Figure 4.17: Bundle test – multiple conductive cables supplied with 24 [V] and 100 [A] with a car battery.

4.5.1 Results of bundle test – multiple conductive cables

- When comparing figures (4.13–A.13) and observing the data2 with data1 the temperature peak differs depending on if the voltage was set to 24 [V] or 48 [V].
- The first 100 [s] of the experiment in (4.17), the temperature increase steadily over time across the whole cable. After the 100 [s] the temperatures start to differ between the different data points. After approximately 300 [s] the temperatures essentially reaches a steady state, however that level is different for each data point.

4.6 Power cable test

The power cable test was made to see how well a power cable can handle higher currents under a prolonged time and this type of experiment representing a very close to real-world scenario.

Another type of cables that were donated for research were power cables which are used to connect between for example; the battery and generator. These types of cables are meant to withstand higher currents under a prolonged time without generating a lot of heat. The cables that were provided were double isolated with the outer isolating material being a type of soft plastic while the inner isolating material being made out of a harder type of plastic.

The experiment was limited to only testing 24 [V] due to the maximum effect the electronic load is able to withstand and can not be supplied by electronic source, without decreasing the voltage. The experiment was also limited to only testing one type of power cable as the other had a greater copper cross section area, thus greater resistance and being rated to withstand higher currents through them.

Table 4.9: Specifications of the power cable test.

Specifications	
$Length_{Cable}$	2.92 [m]
$Diameter_{Copper}$	≈ 5.64 [mm]
$Area_{Copper}$	25 [mm^2]
$Temperature_{Room}$	≈ 21.2 [$°C$]
$Air\ velocity_{Room}$	0.00 [m/s]
Voltage	24 [V]
Current	80/105 [A]

Table 4.10: Data points of the power cable test.

Specifications		
Data1	insulation	0.15 [m]
Data2	insulation	0.70 [m]
Data3	insulation	1.15 [m]
Data4	insulation	1.60 [m]
Data5	insulation	2.15 [m]
Data6	insulation	2.80 [m]

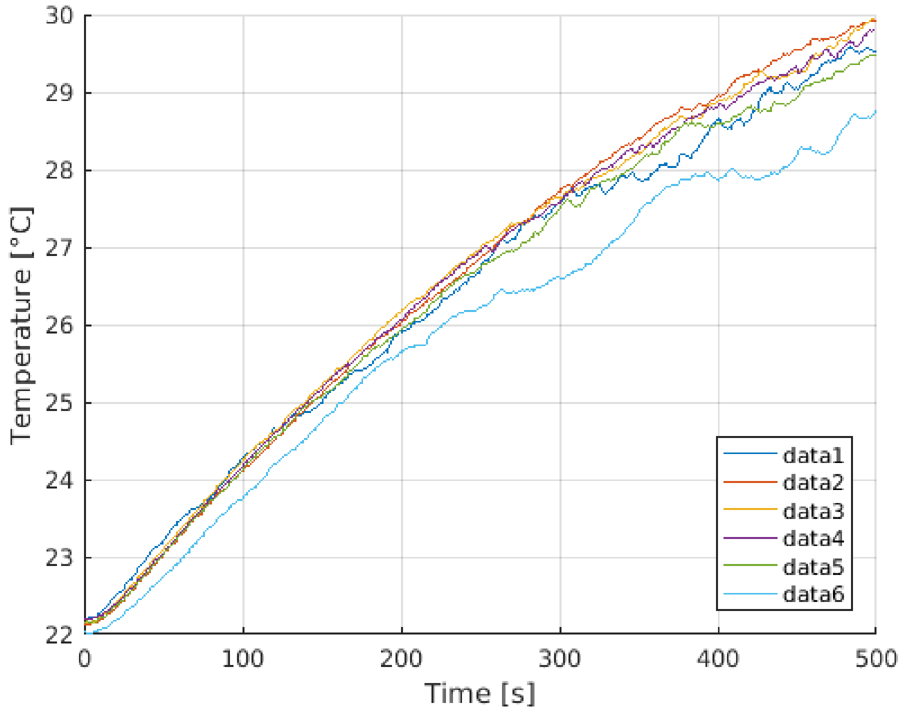

Figure 4.18: Power cable supplied with 24 [V] and 80 [A].

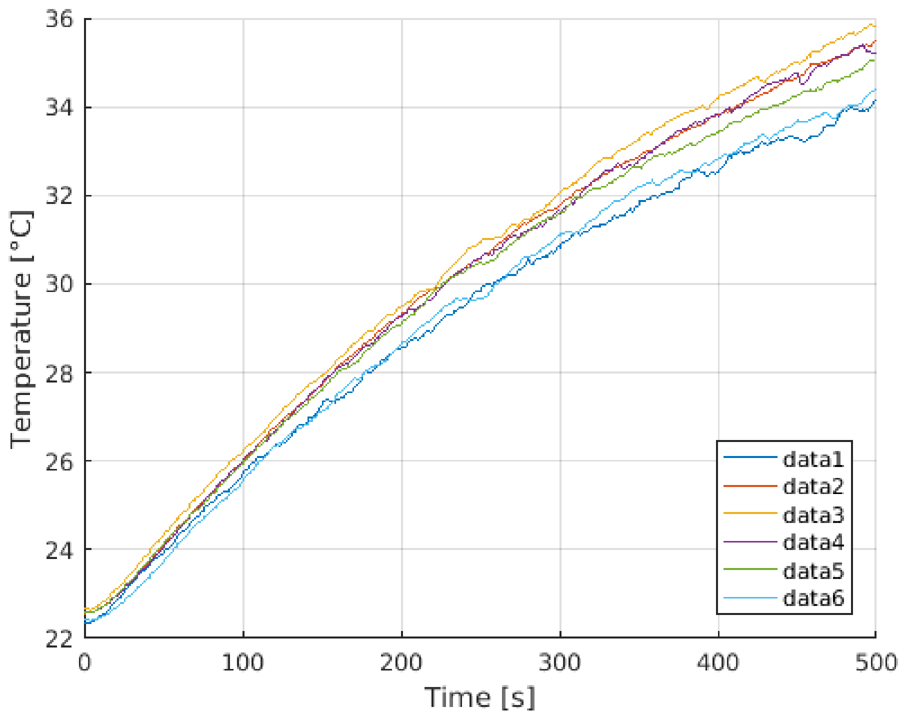

Figure 4.19: Power cable supplied with 24 [V] and 105 [A].

4.6.1 Results of power cable test

- The hottest measured point on the cable is shown in data2, which is placed close to the centre of the cable as seen in figure (4.18). However, in figure (4.19) the temperature peak is shifted to data3 which is closer to the centre.
- The increase of the temperature shows a very low heat development by approximately +1.68 [$°C$] per minute in figure (4.19), thus indicates that any critical temperatures will not be reached under the circumstances of the experiments conducted.

4.7 Mixed data test

The mixed data sub-chapter will consist of and compare all of the above experiments into two separate graphs. Each data point in the mixed data test will be represented by a specific data point from that specific experiment. However, the mixed data test and its graphs will use data and compare using the same voltage, current and approximately the same measured points.

When choosing what data to use to examine and compare, several factors had to be in common across all of the experiments. Therefore, the most common factors were the 24 [V] at 25 [A] experiments, thermocouples being placed both on the conductive copper and the isolating material, and the thermalcouplers being placed approximately in the middle because they are the least affected by the connecting points at each end.

However, the data used in figure (4.21) is excluded from the factors mentioned above as there were no experiments conducted with those factors.

In table (4.11), the first column indicates what data points were used in the graphs below. In the middle column is the type of experiment the data was extracted from and the last column represents what data is shown in graphs (4.20) and (4.21).

The comparison between the two experiments shown in table (4.12) was made to demonstrate how the temperature differs when supplied with 25 [A] in total and 25 [A] per cable, which might indicate why there should not be one fuse per bundle and instead one fuse per cable.

Table 4.11: Data points of the single conducting cable test.

Specifications		
Data2/5 (A.5)	Single conductive	**Data1/2**
Data4/5 (A.8)	Long conductive	**Data3/4**
Data1/3 (4.12)	Bundle – Single conductive	**Data5/6**

Table 4.12: Data points of the multiple conductive cables test.

Specifications		
Data2/5 (A.14)	Bundle – Multiple conductive	**Data1/2**
Data2/5 (4.17)	Bundle – Multiple conductive supplied w/ a car battery	**Data3/4**

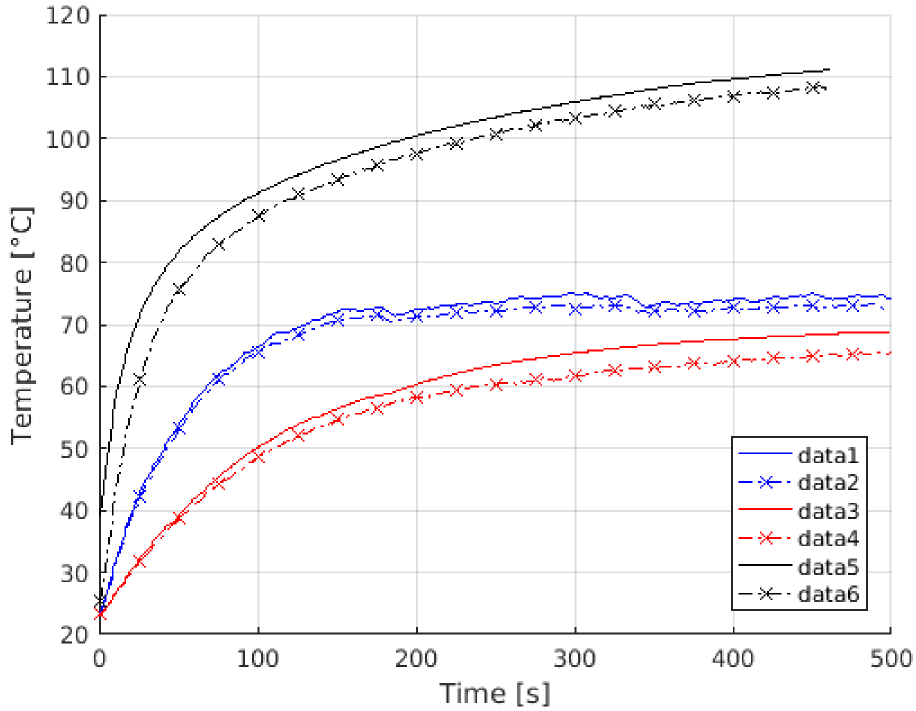

Figure 4.20: Mixed singe conducting cables test supplied with 24 [V] and 25 [A].

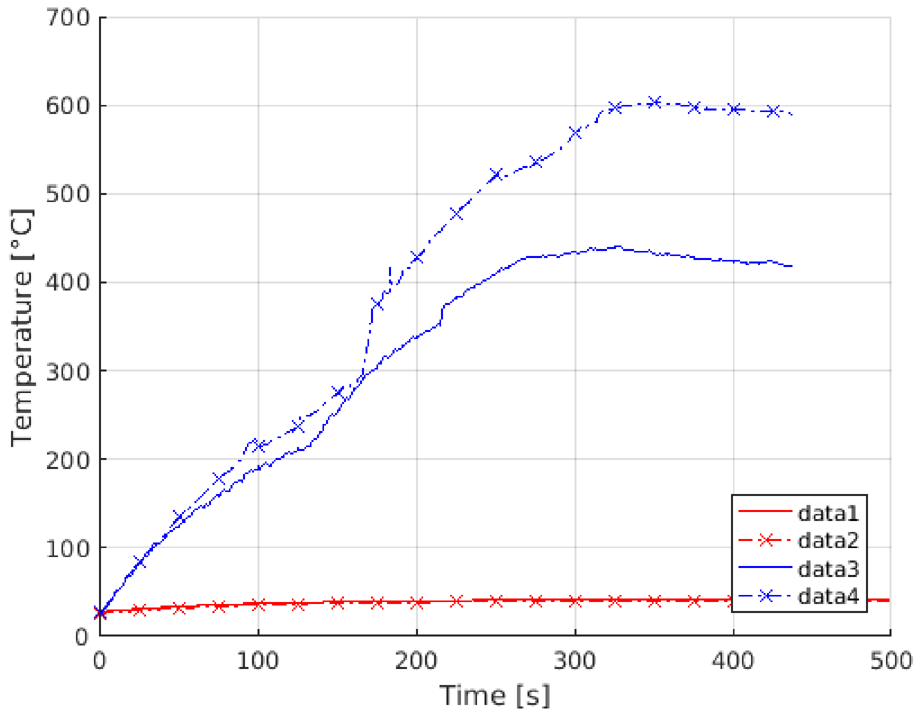

Figure 4.21: Mixed bundle test with multiple conductive cables supplied with 24 [V] and 25 [A].

4.7.1 Results of mixed data test

- When comparing the data points in figure (4.20), the temperature in data3 and data4 corresponding the long conductive cable test shows a lower temperature than data1 and data2 corresponding to the single conductive cable test.
- The increase in current results in 10 times greater temperature, measured on the copper or approximately 15 times as much on the isolating material after approximately 400 [s].
- In figure (4.20), the rise time of the temperature in data5/6 is shorter than the other data points, proving that a cable in a bundle reaches its maximum temperature faster than a cable not in a bundle.

5

Discussion

This chapter will provide an discussion and an interpretation of the conducted experiments and their results as well as the similarities between the results and graphs.

5.1 Discussions about the results

5.1.1 Single conductive test

- The cross section area of the copper in the cable affects the heat development immensely in comparison to a cable with smaller cross sectional area, (A.5) (A.6) As seen in the aforementioned equations, as the cross section area decreases, the resistance of the cable increases and thereby the heat development increases, compare for example the power cable tests on page (39) with the single conductive cable test on page (21).
- When comparing tests with 24 [V] and 48 [V] passing over the cable, the total voltage does not have any bigger difference in heat development. Because of the constant current being supplied in the tests, the voltage drop is the same over the cable, however the total electric power is doubled with 48 [V].
- Because of the connection between the testing cable and the power cables there is a different cross section area with the power cable having a bigger one, thus, a lot of the heat developed at the ends are instead transferred to the power cable from the testing cable.
  This effect is reduced when the cross section area of the test cable is increased, making the transaction from power cable to testing cable smaller and thereby making the difference between the cross section areas smaller. This as it will be demonstrated in later graphs, see figure (A.16).
- The temperature of the cable evens out after approximately 150 [s] in all graphs and its temperature is affected and dependant on its surrounding i.e, the temperature of the testing chamber, air flow in the testing chamber cooling the cable or if the cable is placed in a group of other cables or a single cable.
- When performing the experiments, some inconsistent data will still be acquired due to some error, such as how the thermal couplers were attached to the testing cable or simple human error. Therefore some data may not agree with the theory or some data points may even be "extreme" outliers to the usual data, see data2 in figure (4.3).

5.1.2 Long conductive test

- The data point from data9 measures faulty data in all of the experiments that were conducted, probably because of wrong fastening of the thermalcoupler on the isolating material. This is based on other experiments and their respective results, the temperature at the end of the cable should have lower temperature.
- When observing each data point more closely, the maximum temperature is observed in data4 as seen in figures (4.8–A.10). The minimum temperature can be observed in data1 and data10 which are placed at each end of the cable, also seen in all the above figures. The fact that data1 and data10 in figure (4.8–4.10) is affected could mean that the other tests, such as the single conductive test, are more affected by the heat transfer towards the power cables than first expected.
- Since this experiment utilised a longer cable than the rest of the experiments conducted, it shows how big of an influence a longer cable has on heat transport towards the surrounding and how more even the temperature is spread out through out the cable due to less effect of heat being transferred towards the connecting points at the end of the cable.
- The experiment with a simulated overload with 55 [A] passing over the cable, different characteristics can be seen in the graph, see figure (4.10), the "bend" at 150 [s] of the curves can be explained with the help of Ohm's law (A.4) and Kirchhoff's voltage law (A.8).
  As the temperature of the copper rises, the resistance in the cable is increased and because of the constant current, the voltage drop over the cable increases. Hence, when the temperature in the cable increases the electronic load could not create a complete short circuit, meaning that it could not have a zero resistance as a safety measurement in the system and in order to continue the electronic load had to limit the current. What can be seen in this experiment is a large increase of temperature that is increasing the resistance to such a degree, that the resistance of the cable itself is limiting the current in the cable.
- Another type of fuse that is triggered by current could be implemented to minimise this risk. A previous bachelor's thesis conducted at Chalmers examined a type of fuse which detonates when a too large current is passed through it. Instead of depending on a wire melting due to the current, this kind of fuse reacts instantaneously.

5.1.3 Bundle test – single conductive cable

- By adding more cables and creating a bundle out of them, the cables start to act as insulators against each other thus increasing the overall maximum temperature as opposed to having a single conductive cable. This can be explained with how the thermal resistance increases due to the surrounding cables, making it harder to transfer heat to the surroundings.
- By observing the data points in all graphs, that are fastened in the first half of the bundle of cables the temperature measured is always higher than the data points on the second half of the bundle of cables. This could be because of these data points being closer to the middle of the cable.
- It might worth to observe and conduct further tests on different sized bundles with more or less surrounding cables isolating a single or multiple conducting cables.
- Since multiple cables act as insulators, the overall temperature will reach its steady state a lot faster than if no surrounding cables would be present to stall the emission of heat to the surrounding, as seen in figure (4.20).

5.1.4 Bundle test – multiple conductive cables

- When comparing all the graphs from the bundle test, one type of result can be observed in almost all of them, which is that the maximum temperature is shifted between further towards the start of the cable when 48 [V] is applied and closer toward the middle when 24 [V] is supplied through the cable, see figure (4.13–A.13) and (A.14–A.15).
  This phenomenon can however not be explained with any presented theory and should therefore be experimented further on to test if this type of occurrence is consistent or not.
- Defections of the measured values can occur due to a number of different reasons and more specifically for the bundle test – multiple conductive cables supplied with a car battery, because of the high temperature, as seen in figure (4.17)
- Because of the high temperature, the isolation material around the copper melted away from the copper completely, which affected the thermal couplers in several different ways.
  - Because of the high temperature and the isolation melting off, the thermal coupler would detach from the point it was attached to on the cable.
  - If the thermal coupler did not detach from the cable it could have fused together with the molten isolation material, thus isolating the thermal coupler.
- The thermal couplers that were used for this experiment are only rated to 510 [$°C$], what happens beyond that temperature point might result in inaccurate data measurement.
- Data4/5/6 were placed in between the four intertwined cables instead of directly on the isolation, when the isolation material melted away, the thermal couplers did not have any surface to measure.
- In figure (4.17), between 100 and 150 [s], data4 lost its connection with the cable which is why the measured temperature decreased instead of increasing like the other data points.
- Due to the isolation melting during the test shown in figure (4.17), the data collected between 100 [s] and 200 [s] is corrupted. After 200 [s] the increase in temperature resumes as normal. This is probably because of the isolation material melting at this point, making the thermal couplers change hold of the cable.
- Data5 indicates a warmer temperature than the rest of the measured data points of the cable. This could have been caused by the way the cables were intertwined and the thermal coupler being placed in between the cables causing an isolating effect. The sudden increase of temperature between 150 and 200 [s] can be due to the isolating material carbonising.

5.1.5 Power cable test

- As shown in figure (4.18) and (4.19), the low temperature increase over time can be affected by the structure of the cable. Meaning, the cable is double isolated using two separated types of material, the inner one being a type of PVC plastic and the outer isolating material being a type of soft plastic. This transaction between two layers have an additive effect when it comes to thermal resistance, meaning that the two layers of isolation makes it more resistant to transfer heat to the surrounding.
- There is a low probability of a fire occurring if the cable is exposed to higher current close to the limitations of this test.

5.1.6 Mixed data test

- The results indicate how much the temperature differs between the different cable setups, even when the same length, diameter, voltage, current, and measuring at the same point on the cable.
- Further research should be conducted using varying diameters of the copper and different isolating materials, to gather further data on how the characteristics of the cable behave during short circuiting as well as different setups.
- The data points used in the graphs were chosen because multiple factors, such as:
  - The data points were present in all of the experiments, meaning that the data pool was the greatest thus allowing for more data to be analysed.
  - Only data points which were placed closed to the centre of the cable were chosen as those thermalcouplers were the least affected by the connecting points of the testing cable, as well as including two data points per experiment establishes more depth of the data analysed.
  - The maximum temperatures reached at 25 [A] are higher than 20 [A], giving a closer comparison to when a fuse would break. Comparing the 30 [A] experiments were omitted as there were less experiments conducted and thus, less data to compare.
- The graphs represent the hottest points i.e the middle of the cable which are the least affected by the power cables connected to the ends of the tested cable.

5.2 Limitations of the experiments

One type of test that could not be made during the experiments was the test with a warmer surrounding temperature. This test would result in a different perspective when it comes to how the transfer of heat was affected by the surrounding temperature. The test was an impossibility because of the fact that that type of experiment could not have been performed in the "ovens" available. When an attempt was made to transport a heated testing cable from an oven to the testing chamber, half of the temperature had emitted out in to the air and three-quarters when all of the thermal couplers had been connected and begun the test.

Another limitation of the equipment used for the experiments was the electrical load that had a maximum electrical effect of 2600 [W] that limited the capability to test high currents in the bundle tests and the power cable test. Those experiments require more current than two car batteries connected in series can supply in comparison to what a heavy-duty vehicle can supply, the problem with this setup was that the batteries drained very fast which lead to the starting voltage was not the same as when the test had finished, ergo the effect dropped as well during the test.

In all of the accomplished tests, the human factor was always a present, possible error, for example: how the thermal couplers were fixated on the cables. The thermal couplers were attached on the smaller cables by twining them around the isolation or intertwined directly with the copper, whilst on the power cables, the thermal couplers were fixated with adhesive fibreglass tape. When minimising the sources of errors for the above mentioned, the number of thermal couplers used could have been increased as well as spot welding the two wires from the thermal couplers instead of twining them. Another improvement could be to have the thermal couplers placed alongside with the length of the cable to minimise the risk of the point of measurement not being in contact with the cable.

A factor that could have simplified the experiments were the cables that were supplied for the experiments. They were not longer than approximately 2.0 [m] which meant that a different cable had to be used in construction with different isolation and a solid core was used for the experiments. The data from these tests was still useful, but could be improved if the supplied material would have been long enough so the exact same cable could have been used and the consistency of the test in all the tests.

When starting the tests and activating all of the different machines, the start temperature in each test may vary to some degree. This was probably due to manually starting the electronic load, electronic source and the data acquisition system. Thus, when activated manually, the electronic load, electronic source and the data acquisition system do not start at the same time creating a time difference and temperature difference as indicated in the graphs. A room for error when it comes to displaying the starting temperature.

The rate of change in temperature and maximum temperature is different in each test when different currents pass over the cable. However by observing each type of test, the temperature always evens after the same amount time independently on what current is passing over the cable.

5.3 Future areas of improvement

When conducting further experiments, some aspects could be further explored such as:

Expand the amount of bundle tests, i.e test for example different numbers of cables in the bundles. If further research would have been conducted it could lead to a better understanding of the isolating effects between the cables in the bundle. Another method to progress with the tests would be to experiment with different currents passing over in each single cable. The aim would be to investigate the isolating and warming effects the cables with a fixed current would have on the cable when short circuited, giving a realistic scenario.

Analyse the heat development when a fuse is connected to the cable to see how high temperature the cable will reach before it interrupts the circuit. This would determine if the fuse would activate fast enough to close the circuit during a short circuit, thus, avoiding creating a fire. For example, in the long conductive test with 55 [A] (4.10) the current was reduced at approximately 150 [s] probably due to the increase of temperature in the cable which lead to an increased resistance in the cable and according to Ohm's law (A.4) decreases the current.
A followup to the test would give a broader understanding of how the risk of fires occurs would be affected by the dimension of the fuse.

Perform the test in a heated environment to examine how the cables characteristics behave and react, which would give a more realistic data that corresponds with a real-world scenario. This type of test is relevant and equally important because not all environments are the same in a testing chambers as it is in the engine compartment of a bus. Therefore different types of tests need to be performed.

Attach more thermal couplers on different points on the cable to minimise the risk of not having data over a greater area of the cable. Due to the presence of faulty data points in the earlier experiments, there are measurements that are outliers, as seen in data4 in (4.17) or data9 in (4.8). These data measurements would not be present if there would have been more thermal couplers attached to the cables thus minimising the amount of outlying data measurements. If more thermal couplers would have been used, they would probably provide more accurate reading of the temperature over the cable and as well as visualise in more the how the cable is affected by the surrounding environment.

Create a mathematical model of the heat development as a function of the current. Based on this mathematical model, simulations can be made and displayed how different currents affect the temperature of the cable. However, to create these type of models it would require more tests and data from a realistic environments, such as the engine compartment of a bus. For example, a mathematical model made based on a experiment in a testing facility would represent a model of a experiment in that specific environment. Therefore, in order to make a more realistic model, the experiments would have to be made in an simulated environment more realistic than previously made.

5.4 Sustainable development

A key aspect of this research is its impact on how electrical fires in heavy-duty vehicles can affect its environment directly, such as plastic and metallic material in the vehicle burning, creating toxic fumes and smoke. By decreasing the number of electrical fires happening each year, these emissions would decrease as well.

A decrease of emissions could be possible by using fewer resources when constructing a vehicle, such as utilising less plastic when isolating the wires in the vehicle. This example can be implemented by a 48 [V] system instead of the current 24[V] system. As the need for a certain cross section area of the cables would decrease, the amount of copper and isolating material needed would decrease as well.

As the need for resources for the manufacturer to construct a vehicle would decrease, so would the cost of production. Thus, a differently designed electric system would decrease the need for material and decrease the risk of electrical fires in heavy-duty vehicles.

6 Conclusion

This section will present the results which were extrapolated from the data and give our ideas to what course of action should be undertaken on the conclusions presented.

As mentioned in the theory and methods chapter and then proven in the results chapter, the dimensions of a cable such as, supplied voltage over the cable, the length of the cable, and the configuration of cables all matter.

The scope of the thesis is to study how and why electrical fires can occur in heavy-duty vehicles and what preventative actions can be made to minimise the risk of a fire developing or even to nullify the risk of a fire developing. However, the thesis and its work has developed during its time and has progressed to analyse how different dimensions of cables and their configurations can lead to a fire developing.

6.1 Minor temperature difference in 24 [V] and 48 [V]

The research conducted has lead to the discovery of a minor temperature increase across the whole cable when it is supplied with 48 [V] instead of a standard of 24 [V]. An increase in temperature can be explained by combining the law of electrical effect (A.6) and Ohm's law (A.4), proving that the increase in resistance as the temperature in the cable rises has minimal effect when compared to the current being squared.

As mentioned in chapter 5 – discussion, attaching more thermal couplers will provide more accurate reading and data and should definitively be further experimented on for a more precise analysis. When comparing the different electrical powers on the load and calculating the difference between 24 [V] and 48 [V], the percentile of electric power loss over the cable is lower in the 48 [V] than 24 [V]. This is probably caused by the law of electrical effect (A.6) and its relation to the current being static and squared while the differences in resistance is extremely small and insignificant on the circuit. This is noticeable in the experiments when the supplied current is higher, i.e the 30 [A] experiments.

Conclusion, supplying a cable with 48 [V] results in a minor temperature increase, and a lower percentile voltage loss over the cable. However, if this is implemented the electrical power of the entire circuit is doubled if a constant current is supplied. Thus, this should be inspected and further researched upon.

6.2 Alternative solutions to longer cables

It was hypothesised that the thermal conductivity of copper transferred the heat to the connection points in the experiments, however the extent of this was not clear, nor was it clear what effect a longer cable would have on the capability of fuses breaking.

The experiments conducted on long single conductive cable test resulted in lower temperatures when compared to the previous experiments with the single conductive cable, probably because of the slightly different dimensions of the cable. Thus, meaning less resistance and other thermal properties in the isolation. Another disclosure from this experiment was how much the thermal conductivity of the copper affected the test, at least 1.0 [m] at each end was affected.

The experiment with a long conductive cable detected a correlation between the length of the cable in (A.5) and the electrical power in the cable that utilises the theory of how the electrical power (A.8) in the cable would increase with the length of the cable. This means that the two equations could be combined to make the electrical power in the cable a function of the length of the cable.

One unanticipated finding was, as the temperature increased, the resistance of the cable rose to such a level so that the electrical load had to limit the current to not have 0 [Ω] in the electronic load as a safety measure. As mentioned in the results, this explains the characteristics from the 55 [A] test (fig 4.10), what this could mean is that if the circumstances are wrong, there could be a delay in the fuse breaking because of the resistance of the cable limiting the current.

Conclusion, longer cables bear a risk of not allowing the fuses to break due to the greater resistance which leads to lower currents in the cable i.e not blowing the fuses. This can lead to a prolonged time for heat to develop during a short circuit.

6.3 Dangerous effects of bundling cables

When the maximum temperature is reached during each experiment, as mentioned before, the temperature of the cable depends a lot on the surrounding temperature. This is due to how the produced heat is transferred away from the cable in to the air. The surroundings of the tests were in many aspects perfect conditions for electrical systems with a room temperature of approximately 20 $[°C]$ and a setup that allowed good convection from the cable. This however is not often the case in heavy-duty vehicles, where the surrounding temperature can be up to 90 $[°C]$ and in combination with the cables in a bundle, the cables will not have significant convection to the surroundings.

Having the cables in bundles had a significant effect on how the heat was transferred in a less effective way due to the isolating effect of the surrounding cables. What is important to note in these experiments was that only one cable was conductive, meaning that in a vehicle, the surrounding cables would probably be warmer than in the performed tests. Further research should be conducted on heated surroundings to gather further data on how bundled cables react to increased surrounding temperatures to simulate a engine compartment in a heavy-duty vehicle.

Conclusion, there is a clear insulating effect when having cables in a bundle, thus increasing the overall temperature in both the cable and the bundle. In theory, reducing the amount of cables in a bundle should lead to a lower overall temperature in the bundle.

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A
Appendix

A.1 Equations

$$\dot{Q} = \frac{T_{\infty_1} - T_{\infty_2}}{R_{Thermal}} \tag{A.1}$$

$$R_{Conv.} = \frac{1}{h * A} \tag{A.2}$$

$$R_{Thermal} = \frac{ln(\frac{r_2}{r_1})}{2 * \pi * L * k} \tag{A.3}$$

$$U = R * I \tag{A.4}$$

$$R_{cable} = \frac{\rho * L}{A},\ at\ 20\ [^{\circ}C] \tag{A.5}$$

$$P = U * I = R * I^2 \tag{A.6}$$

$$U_{supply} = U_1 + U_2 + ... + U_{n-1} + U_n \tag{A.7}$$

$$I_{tot} = I_1 + I_2 + ... + I_{n-1} + I_n \tag{A.8}$$

$$R = R_0 * (1 + a * T) \tag{A.9}$$

A.2 Figures

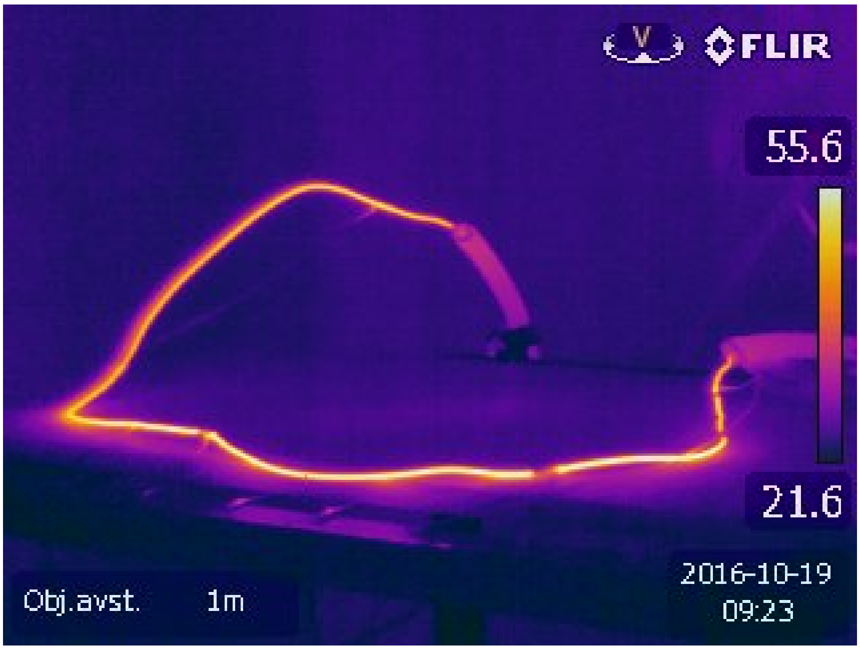

Figure A.1: IR picture of single conductive cable supplied with with 24 [V] and 25 [A].

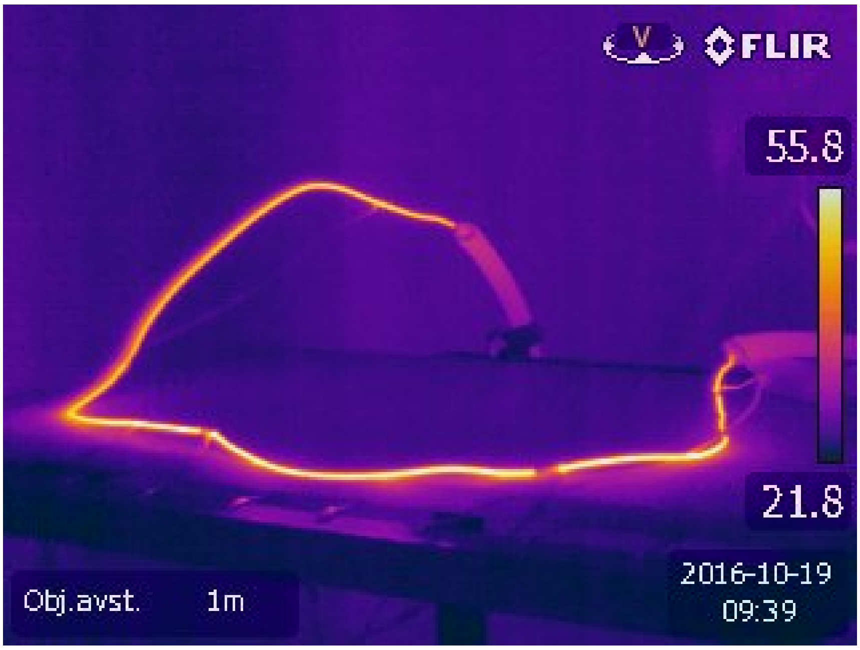

Figure A.2: IR picture of single conductive cable supplied with with 48 [V] and 25 [A].

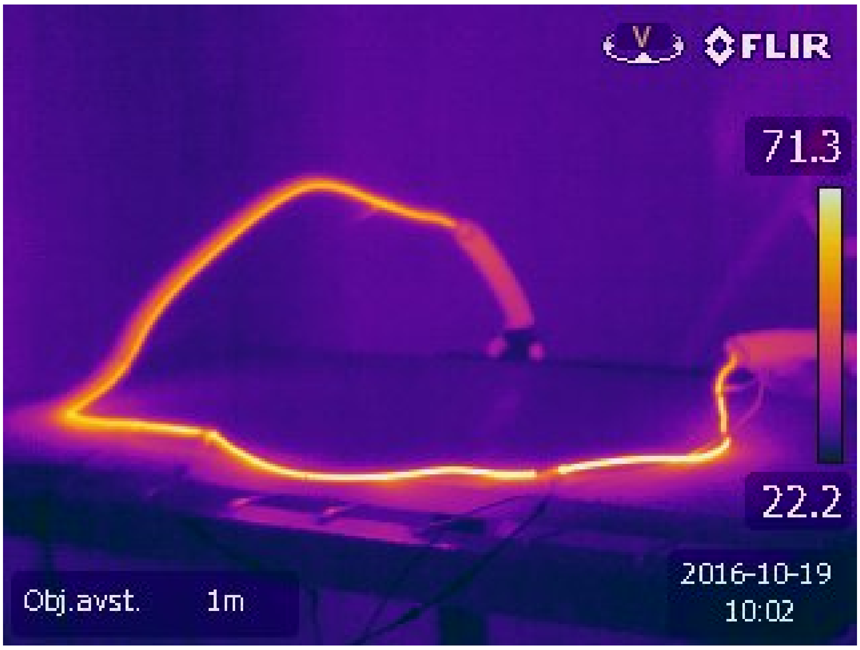

Figure A.3: IR picture of single conductive cable supplied with with 24 [V] and 30 [A].

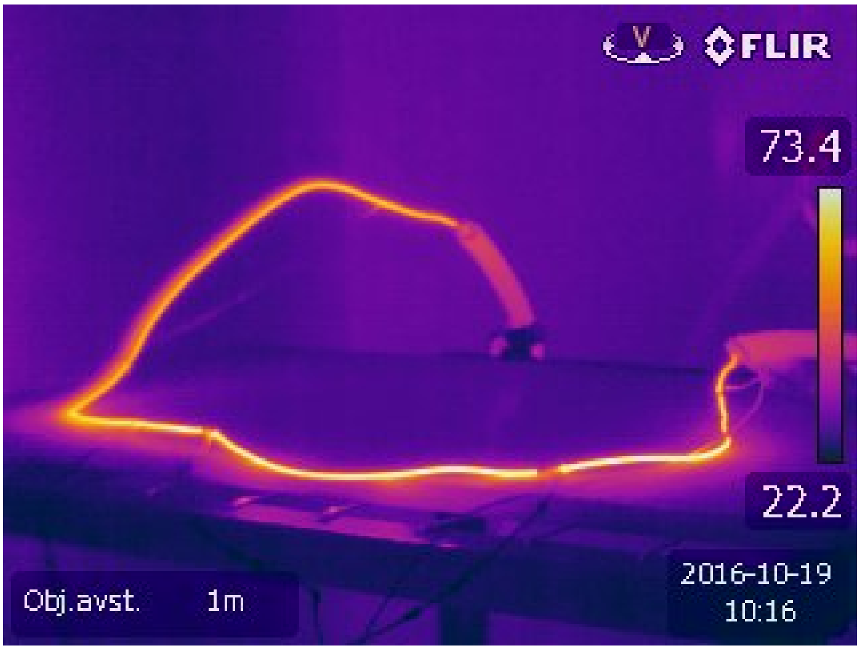

Figure A.4: IR picture of single conductive cable supplied with with 48 [V] and 30 [A].

A.3 Graphs

A.3.1 Single conductive cable test

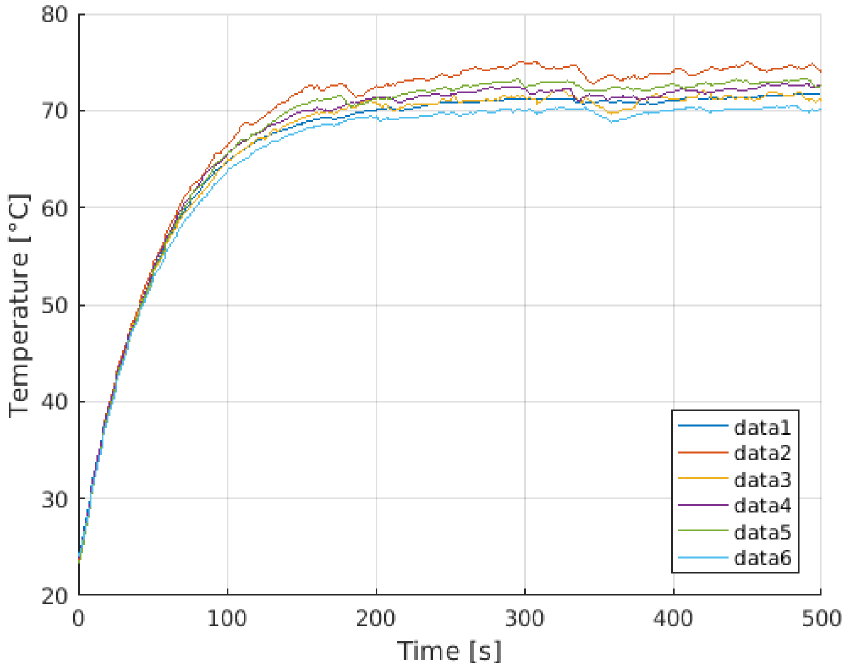

Figure A.5: Single conductive cable supplied with with 24 [V] and 25 [A].

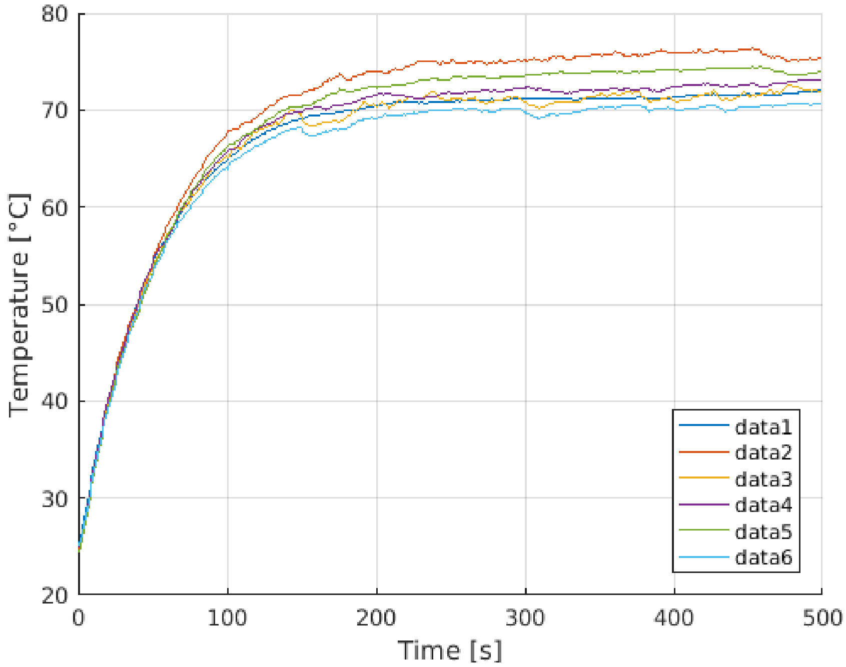

Figure A.6: Single conductive cable supplied with with 48 [V] and 25 [A].

A.3.2 Long conductive cable test

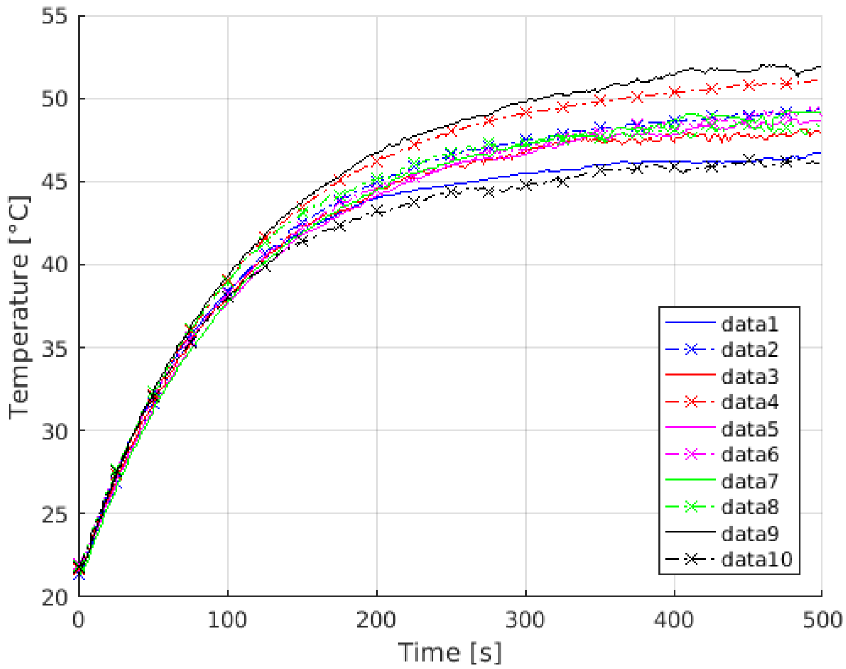

Figure A.7: Long cable test supplied with 48 [V] and 20 [A].

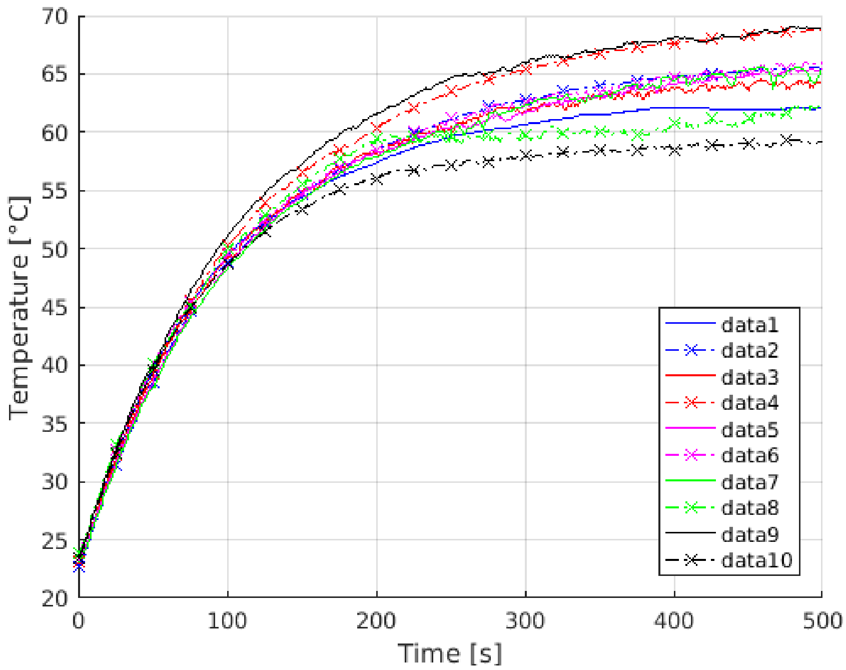

Figure A.8: Long cable test supplied with 24 [V] and 25 [A].

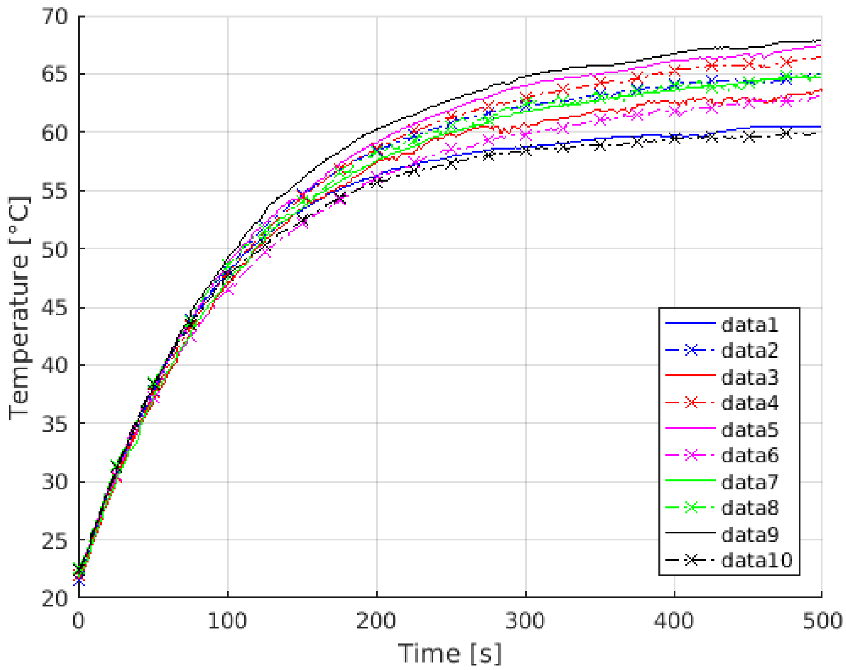

Figure A.9: Long cable test supplied with 48 [V] and 25 [A].

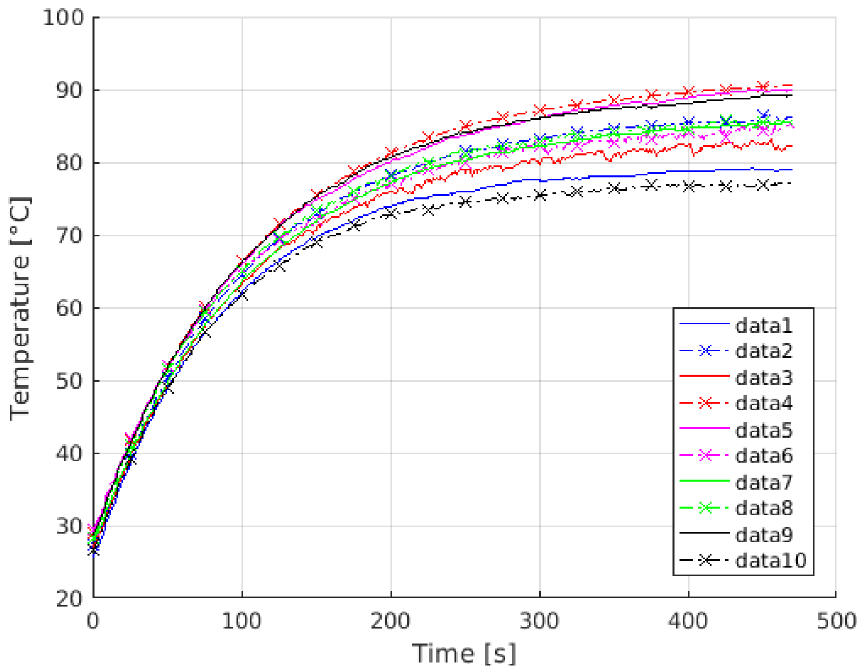

Figure A.10: Long cable test supplied with 48 [V] and 30 [A].

A.3.3 Bundle test – single conductive cable

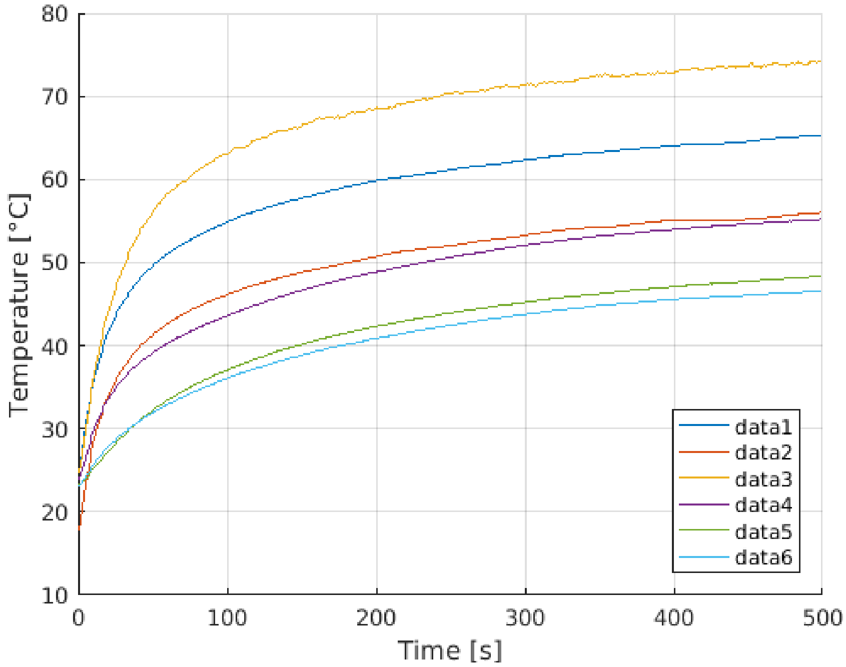

Figure A.11: Bundle test – single conductive cable supplied with 48 [V] and 20 [A].

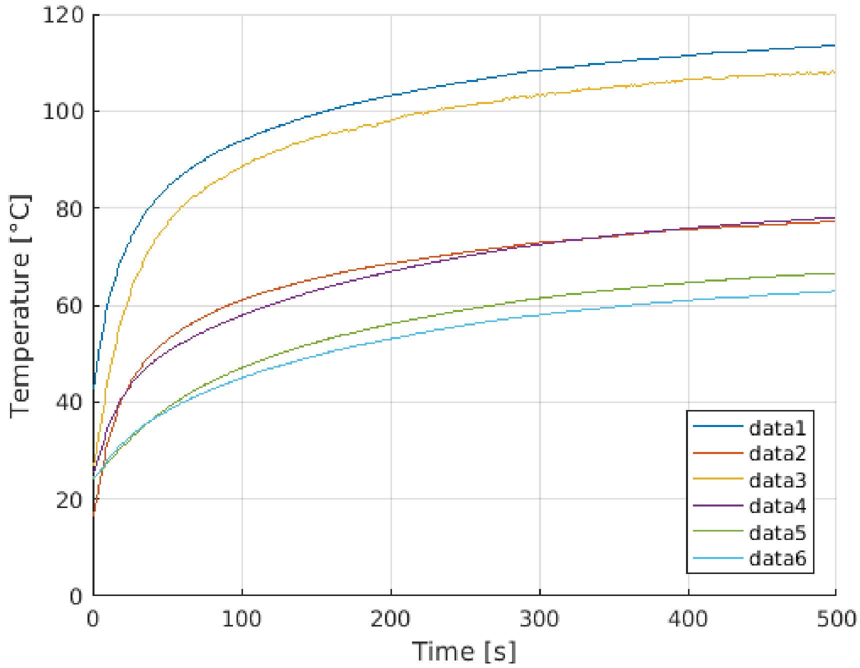

Figure A.12: Bundle test – single conductive cable supplied with 48 [V] and 25 [A].

A.3.4 Bundle test – multiple conductive cables

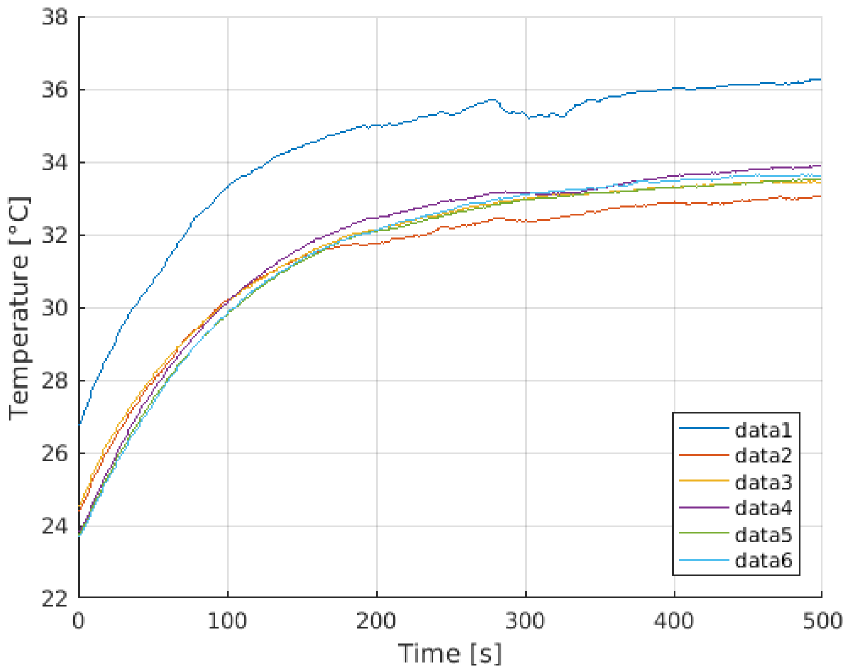

Figure A.13: Bundle test – multiple conductive cables supplied with 48 [V] and 20 [A].

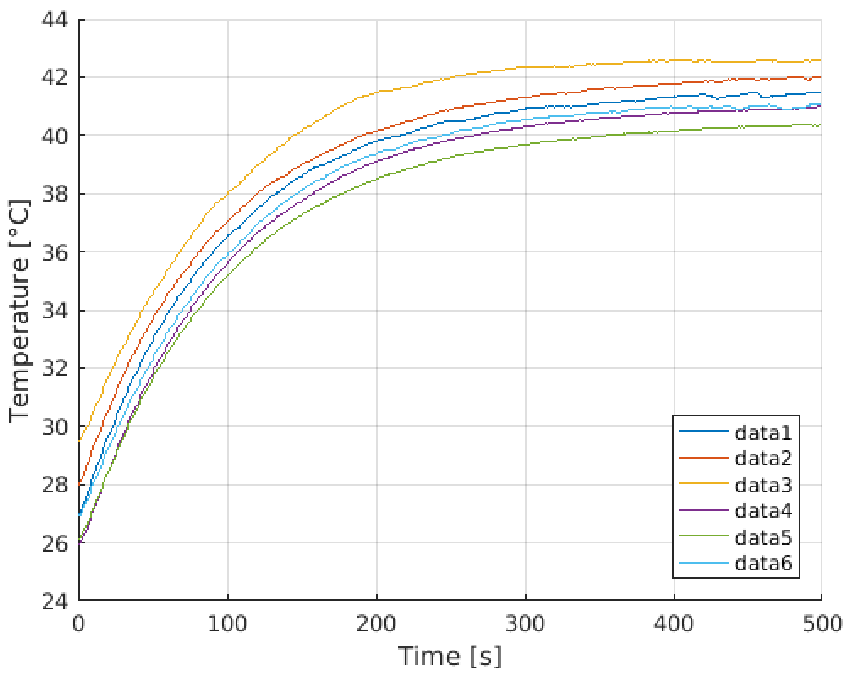

Figure A.14: Bundle test – multiple conductive cables supplied with 24 [V] and 25 [A].

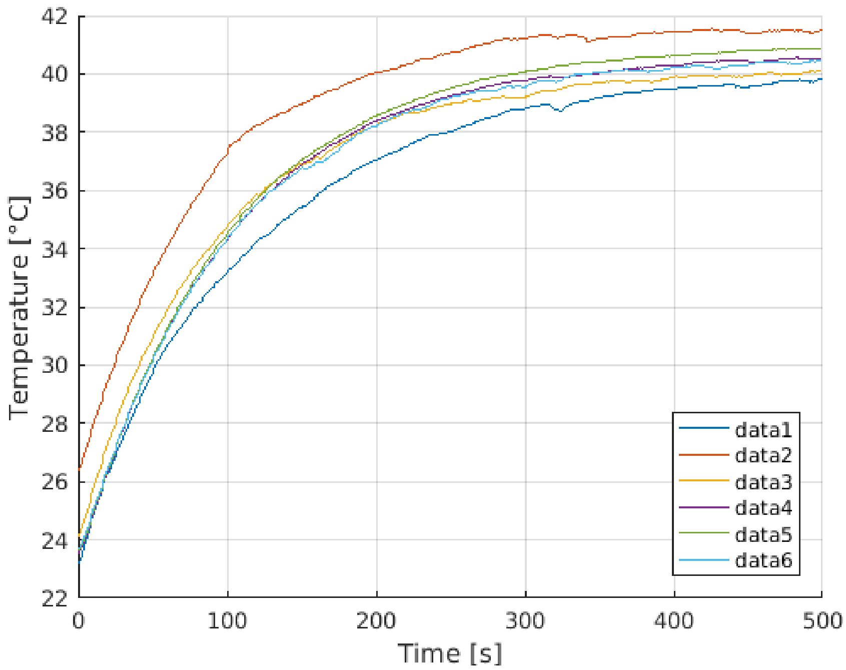

Figure A.15: Bundle test – multiple conductive cables supplied with 48 [V] and 25 [A].

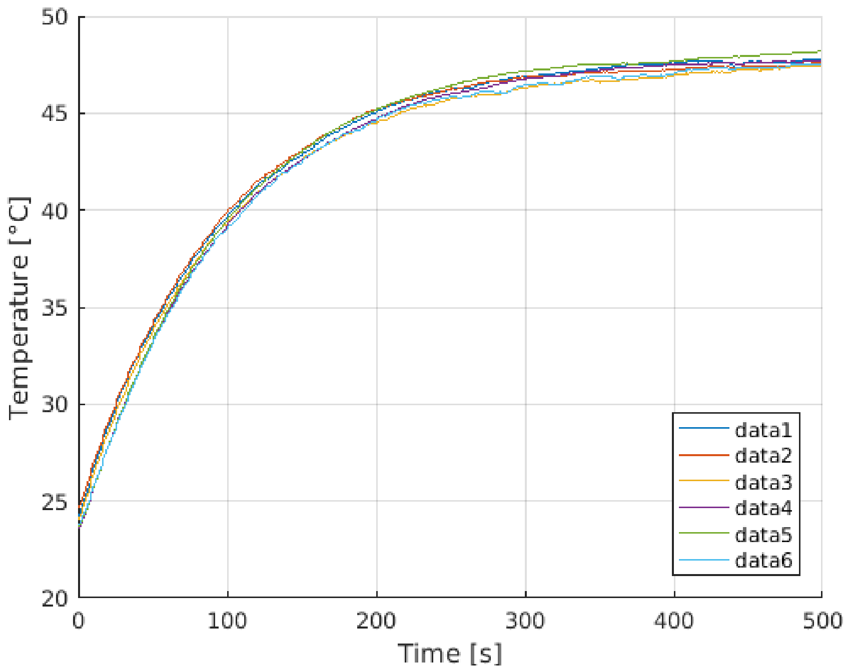

Figure A.16: Bundle test – multiple conductive cables supplied with 48 [V] and 30 [A].