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Industrial Electrical Engineering and Automation

Solid State Fuses for Commercial Vehicles - Limitations and Possibilities

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– Limitations and Possibilities

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A Master of Science in Control and Automation Engineering thesis, written at Lund University, based on work performed at Scania CV AB in the spring of 2015.

Abstract

This thesis, written at Scania CV AB in Södertälje, Sweden, during the spring of 2015, treats the subject of Solid State Fuses and the possibility to use these in heavy vehicles.

A Solid State Fuse is a device containing only solid state components, implementing a function to protect wiring harness and connectors from damage caused by electrical faults. The device should contain circuit breakers able of breaking a worst case fault current, which have been found to be inductive currents. Other challenges are regenerative currents, over voltage and voltage transients. Solutions for these challenges are suggested. One challenge that remains to be solved is heat dissipation. Due to high ambient temperatures, a method to divert heat remains to be investigated.

When these challenges are overcome, the Solid State Fuse offers a wide range of advantages. These include, but are not limited to, advanced fault detection, automatic reset, diagnostics and relay functionality.

Most important, it is found that today's technology, particularly the MOSFET, is sufficient for implementing Solid State Fuses meeting standards and requirements.

In addition, a study of load and fault characteristics is made, the Smart Power Switch is investigated and a concept using MOSFETs for breaking regenerative currents is realized with successful results.

Acknowledgements

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Finally, I am most grateful to my loving family who have shown nothing but support and encouragement throughout my entire work.

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Nomenclature

A

AFS. *Active Fuse System, a system developed by Sjöberg and Steen in 2008*
ATO-type. *A type of blow-out fuses*
AVR. *A type of MCU*

B

BTS. *An Infineon brand SPS*

C

CAN. Controller Area Network
CEU. *Central Electric Unit*
CMRR. *Common Mode Rejection Ratio*
CUV. *Control Unit Visibility*

E

EBS. *Electronic Brake System*
ECU. *Electronic Control Unit*
EMC. *Electromagnetic Compatibility*
EMF. *Electro Motoric Force*
EMI. *Electromagnetic Interference*
EMS. *Engine Management System*
ESD. *ElectroStatic Discharge*

F

FMEA. *Failure Mode and Effect Analysis*
FPGA. *Field Programmable Gate Array, a programmable logic device*

G

GND. *Electric ground*

I

IGBT. *Insulated Gate Bipolar Transistor*

M

MCU. *Microprocessing Unit*
MOSFET. *Metal Oxide Semiconductor Field Effect Transistor*

P

PDU. *Power Distribution Unit, a device developed by Volvo in 2004*
PROFET. *Protected FET, a MOSFET-based device with additional protective features*
PTC. *Polymeric Positive Thermal Component*

R

RS232. *Protocol for serial communication*

S

SMS. *Suspension Management System*
SPS. *Smart Power Switch, a MOSFET-based device with additional protective features*
SSF. *Solid State Fuse*

V

VGT. *Variable Turbo Geometry*

Units

Abbreviation	**Unit**	**Physical quantity**
A	*Ampère*	Current
℃	*Celsius*	Temperature
C	*Coulomb*	Electrical charge
F	*Farad*	Capacitance
H	*Henry*	Inductance
s	*Second*	Time
V	*Volt*	Voltage
Ω	*Ohm*	Resistance

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1 Introduction

In the electrical system of any vehicle, it is inevitable that faults occur. It may be because a cable is worn out and breaks or because someone by accident connected positive supply to the chassis frame. In either case, it is important to break the fault current as to prevent further damage or even fire. Traditionally this has been accomplished by so called blow-out fuses which melt, or trip, when the current has been too high for too long. A major drawback of these is that when they trip, they do so irreversibly and needs to be replaced in order to restore function to the circuit.

Today, semiconductor devices are used in many components around the vehicle and are proven to fulfill their task and more. Because of this, it is interesting to investigate whether the transition from blow-out fuses to semiconductor based fuses could be made in heavy commercial vehicles and what additional possibilities they bring.

The work described in this thesis was carried out at Scania CV AB in Södertälje, Sweden, during the spring of 2015. Its main topics have been to investigate how to use semiconductors to form a solid-state fuse that fulfill requirements set out and the limitations that are equipped with their use.

1.1 Background

A fuse is, according to ISO 8820-1:2014 Road vehicles — Fuse-links —, a

> *"protective device that interrupts the circuit irreversibly when the current flow reaches a specified value for a specific time".*

It is for this kind of device existing standards and requirements are formulated. It is however not specified that the device may not have any additional functionality or features.

A fuse's primary function is to protect wiring harness, connectors and electrical equipment. Blow-out fuses accomplishes this and combine long component life with low component cost. They do however carry several disadvantages; they trip irreversibly and need to be replaced in order to restore function, they need to be accessible in order to do so and they are sensitive to the installation environment. In addition, manufacturing tolerances allows for currents significantly larger than nominal, leading to the need to over-dimension wiring harness in order to prevent damage.

Electronics allow for reduced production tolerances and a semiconductor based fuse has the potential of reducing wiring dimensions. The solid-state fuse would also allow for being remotely reset, which may be done using for instance the vehicle CAN-network. This in turn allows for access-free installation. It also means that environment-proofing the unit is made a lot easier and it may therefore, at least in theory, be located outside of the cab. A Central Electric Unit (CEU) that could be located elsewhere allows for a distributed power system, meaning potential in reducing wiring lengths and thereby cost.

In 2008 a thesis work performed at Volvo Technology by Adam Sjöberg and David Steen indicated that a fuse based on semiconductor devices could be created. Their device had losses in the magnitude of a conventional blow-out fuse and switching times significantly shorter than those of the blow-out fuse. Independent of this, Scania has introduced similar functionality in various components, the Control Unit Visibility (CUV) and the Battery Master

Switch being two of them. With the result being satisfactory, it has been considered interesting to investigate whether it is advisable to start a transition from blow-out fuses to solid-state equivalents based on semiconductor technology.

1.2 Purpose and goals

The purpose of the work described in this thesis was, generally speaking, to investigate whether it is advisable for Scania, and to what extent, to start a transition from blow-out fuses to a solid-state solution based on semiconductor technology and find what demands that could be made on such a solution. It also aimed to propose how such a solution could be designed.

Identifying which kind of loads that would benefit from, and allow for, a transition was one area of interest. Another was to find what properties were desirable or necessary for a solid-state solution to fulfil. The latter also opened up for another aspect of investigation; what new possibilities would such a solution allow for? Important was also to find what demands regarding safety and reliability that could be made. Which kind of semiconductors that would be suitable was another area of investigation, as well as verifying theoretical results in practice.

In order to achieve this, a number of goals were formulated and are found below.

1. Explain what solutions that already exist
2. Find limitations and requirements for increased use of solid-state fuses
3. Find what kind of semiconductors that are applicable
4. Recommend choice of technology for installations outside of the cab environment
5. Compile and explain earlier Scania experiences of cable impedances and their effect on semiconductors
6. Design and build a demonstrator for fusing some, in vehicles, common electrical loads
7. Simulate faults in wiring harness, connectors and load and compare the results with those achieved with the demonstrator

1.3 Limitations

Since the time available for the thesis work was limited, the load characterization was limited to six loads and the number of loads to be fused in the demonstrator limited to one. When considering environmental requirements it was assumed that the CEU was to be placed on the engine since this is a worst case scenario. All of the fused loads were selected to have a rated fusing current of less than $30\,A$ and therefore the work was focused towards replacement of blade-fuses.

1.4 Method

In order to achieve results that fulfilled the goals, a literature study was made using primarily sources available on internet. Interviews were conducted with persons who have experience and knowledge in the respective areas of investigation. In addition, practical experiments were made to gain knowledge and find solutions working in practice. Simulations were made.

2 Existing solutions

In this section some solutions found during literature studies and interviewing are presented.

2.1 The blow out fuse

The blow out fuse consists of a conducting wire attached to two contact surfaces in each end. The entire arrangement is encapsulated in some material, not seldom plastic. When a current passes through the wire, it is heated. Under normal operation, the generated heat is dissipated to the surrounding air. However, if a short circuit or over-load occur, excessive heating takes place, and eventually the wire will melt. The fuse has then tripped. The energy heating the fuse is given by

$$E_{heat} = R_{fuse} \int_0^t i^2(\tau) d\tau. \quad (1)$$

From this it is seen that the product I^2t is a valid measure on tripping characteristic and is called characteristic value. A large number I^2t is known as a slow fuse, meaning that a high current may flow through it for a longer time period than for one with low characteristic value, which is known as a fast fuse, before it trips. One common type of fuses for rated currents less than $30\ A$ is the blade-fuse. [1]

2.2 Active Fuse System

In 2008 Adam Sjöberg and David Steen made their master thesis work at Volvo where they investigated the possibility to make a fuse replacement based on semiconductors. The practical result of their work was a prototype which they called an Active Fuse System (AFS).

The AFS was based on MOSFET-technology and had features that included overcurrent protection, over- and undervoltage protection and overheating protection. Sensing and tripping functions were implemented using analogue sensors and logic circuits feeding a tripping signal to a circuit driving the MOSFET-switch. As can be seen in Figure 1 the prototype was built using mainly discrete components.

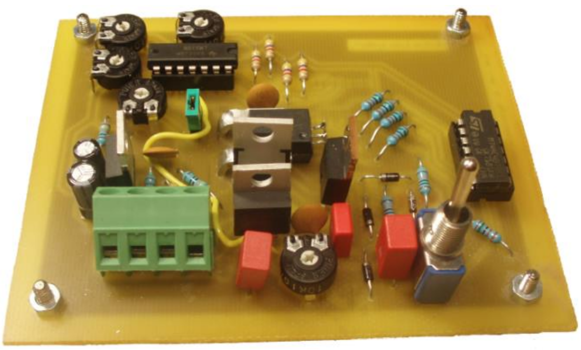


Figure 1: The Active Fuse System prototype built by Sjöberg and Steen in 2008 [2]

Sensing and breaking times were measured to approximately $20\ \mu s$ at $10\ A$. [2]

2.3 Volvo PDU

In the thesis work made by Adam Sjöberg and David Steen in 2008, a unit named Power Distribution Unit (PDU) is described. The PDU is a microprocessor controlled device containing switching modules based on semiconductor technology. Together, these form what was intended to be a replacement for blow-out fuses.

The switching modules are described to be of two different kinds; one kind for currents up to $200\ A$ continuously and one for currents up to $90\ A$. The previous is based on MOSFETs from Intra with on-state resistance of $R_{DSon} = 0.4\ m\Omega$. This MOSFET is able of handling voltage peaks up to $2\ kA$, and the modules were intended for fusing loads including the starter motor, for which two modules were meant to be used in parallel. The modules for lower currents are based on the PROFET BTS660P from Infineon, which is a MOSFET with integrated driving circuit and some protective functions. The PROFET as a device will be described later on in the thesis.

Both the MOSFET and PROFET have integrated temperature sensing and shut down if too high temperatures are measured. For overcurrent protection however, it appears from the thesis as though sensing and turn-off are handled by software in the microcontroller, making the turn-off times random depending on where in the control loop the controller is. In the measures performed by Sjöberg and Steen detection and switching times were measured to be between 2 and 12 ms, whereas the actual switching time was less than $110\ \mu s$ for the PROFET.

The PDU project was ended in 2004 and no further work had been made when Sjöberg and Steen wrote their thesis in 2008. [2]

2.4 Volkswagen group

Inquiries have been made within the VW group in order to find how far research has progressed within the consortium.

2.5 PPTC – Polymeric Positive Thermal Component

The PPTC, commonly known only as PTC, is a device that reaches a high resistance when high current flow through the device. Once the current is removed, the device restores its previous lower resistance. In other words, the device may act as a self-resetting fuse. Two disadvantages of these devices are that they are slow and that their tripping characteristics are temperature dependent. [2]

2.6 Overcurrent protection in motor drives

Overcurrent protection is common in drives for electrical machines since the drive itself is not able to handle an unlimited current. One solution often used is to use the voltage over a shunt resistance as input to a comparator that pulls the transistor gate low if the voltage exceeds a given level. This is an efficient way to provide protection for the motor drive with as short time delay as possible.

If the load has requirements on maximum current, this is often handled in the controller that is necessary for correct switching. In torque control applications, it is preferable to control the current between each switching instant, requiring a controller with a response time in the order of some hundred microseconds, since the switching occur this often. [6]

3 The Solid State Fuse

By a Solid State Fuse, in the following referred to as a SSF, it is intended a device comprising only of solid state components that interrupt power to a load when a fault condition is detected. Solid state components in this case essentially mean that there are no moving or melting parts, for instance the melting wire in a blow-out fuse or the moving parts of a relay.

Looking at the blow-out fuse, it is designed as to detect a fault and break the current, all in the same unit. The SSF may also employ this kind of behaviour. However, looking through large IC manufacturer's catalogues, few dedicated solutions with integrated detection and tripping are found. In addition, it may also be advantageous to have detection and breaking separated into multiple units due to e.g. EMC issues.

In this thesis, SSFs using semiconductor circuit breakers have been studied. For these, the SSF basically consist of four modules; measurement, detection, gate driver and breaker. In the following, these modules and their interaction will be discussed.

A more detailed discussion of how to configure the SSF in a vehicle and which modules may be integrated is found in [2].

3.1 Measurement module

First, the load current, or other relevant quantity[1], needs to be measured since this is the base for detecting a fault. Performing measurements may be done in a variety of ways. The straight-forward method is to measure the voltage drop across a series resistance, i.e. a shunt resistance. The resistance may also be the on-state resistance of a MOSFET which will be discussed later. Other methods include current transformers and Hall-effect based devices. [7]

In either case, an amplifier circuit needs to be used if extensive losses are to be avoided. Achieving accurate measurements in the case of a vehicle is however difficult since there are multiple sources of transient pulses or Electromagnetic Interference, EMI. These pulses may be picked up by the measurement unit and interfere in such a way that the measurements become unusable. Because of this, input impedance and Common-Mode Rejection Ratio, CMRR, of the measurement amplifier should be selected with care. If low-pass filtering needs to be employed, it is a factor that limits the fuse overall response time. [8]

When accurate measurements are obtained, the signal is fed to the detection module.

3.2 Detection module

The detection module may be implemented in a variety of ways, but may be split up into three categories; analogue, digital or hybrid.

Implementing an analogue detection method means using resistors, capacitors, transistors etc. to e.g. perform an integration of the measurement values and comparing the integral value to a pre-set reference level. The simplicity of the analogue method provides for a robust solution, however, it does not leave much room for customization to a specific load or communication with surrounding devices. [7]

[1] See section 9.6

The digital method requires an analogue to digital conversion of the measurement values. Thereafter a variety of detection methods, which will be discussed in chapter 9, may be implemented using a microcontroller (MCU) or some other logic device. This solution is flexible and allows for additional features such as communication over the vehicle network. [9]

One may also implement a hybrid of the two. For instance a rough analogue detection could be used in parallel with a more advanced detection scheme implemented in a MCU. This would provide fall-back protection in case the MCU is malfunctioning for some reason.

In either case, the detection module is inevitably introducing a delay to the system. [6]

Once a fault is detected, a logical signal is supplied to the gate driver module.

3.3 Gate driver module

The gate driver module is essentially necessary for driving a semiconductor circuit breaker, or transistor. Its function is to generate a voltage or current high enough relative to the breaker's output so that the breaker starts conducting. There is a wide range of drive circuits commercially available which are generally controlled by a logical input. Once enabled, the gate driver outputs enough voltage to make the breaker conduct. If then the detection module indicate that a fault has occurred by removing the control signal, the gate driver stops outputting the voltage to the breaker, which will be thoroughly discussed in chapter 4. [6]

3.4 The SSF from a system point of view

When integrating a SSF system in a commercial vehicle, it may be hooked up to the on-board vehicle network, e.g. CAN-bus. Doing this would enable features such as remote reset, diagnostics and using the fuses as relays. What features are available depend on the implementation. For instance an analogue implementation may only provide limited features such as resetting the SSF by a dedicated conductor, whereas an implementation based on a MCU could offer CAN-support. The latter solution is supported by the full fuse demonstrator described in chapter 11, however not implemented in software. [7] [9]

There are different levels of integrating the SSF system with the vehicle information system. These may roughly be separated into

1. Non-communicating
2. Reset and status by dedicated wire
3. CAN-support

where the CAN-supporting unit provides the highest number of features. A non-communicating SSF system requires automatic reset using a pre-defined resetting scheme. The scheme must then both continuously reset the fuse and if the fault is still present once again trip. Otherwise an external reset is required. This would have to be done manually, requiring the SSF system to be accessible.

Using option 2, where a dedicated wire is used for status indication and reset, would allow for external reset of the SSF as well as fault reporting. If it is considered important that the central electric unit should not contain any higher level of logic, this solution allows for a separate control unit. The separate control unit may either be a vehicle coordinator, ECU or a technician's service computer. A drawback of this solution is that each fuse in the SSF system requires a dedicated wire of its own.

Option 3, having CAN-support integrated in the SSF system, enables advanced features like reporting current consumption in real-time and controlling the fuses to act as relays. The tripping scheme may then also be adjusted externally so that even if a load is changed by for instance a bodybuilder, the SSF can easily be reconfigured to fit the new load. This option does however require a higher level of logic to be used within the SSF system.

A fourth option would be a combination of options 2 and 3. For instance MCUs may be integrated in the SSF system, but a connector on the unit could be used for programming and diagnostics instead of hooking it up to the vehicle network. Then communication with the vehicle could still use dedicated wires and multiplexing be used for reducing the number of wires. This is a solution that may be employed if it is desirable to avoid additional units on the vehicle network.

As has been briefly touched, a SSF system may not comprise of only a single fuse unit, but may include several SSFs within the same physical unit. Several fuse units may also share logic. For instance if advanced communication is desired, a single MCU for handling the communication may be shared by all SSFs within the same physical unit. The principle structures for individual SSF units and a SSF system are illustrated in Figure 2.

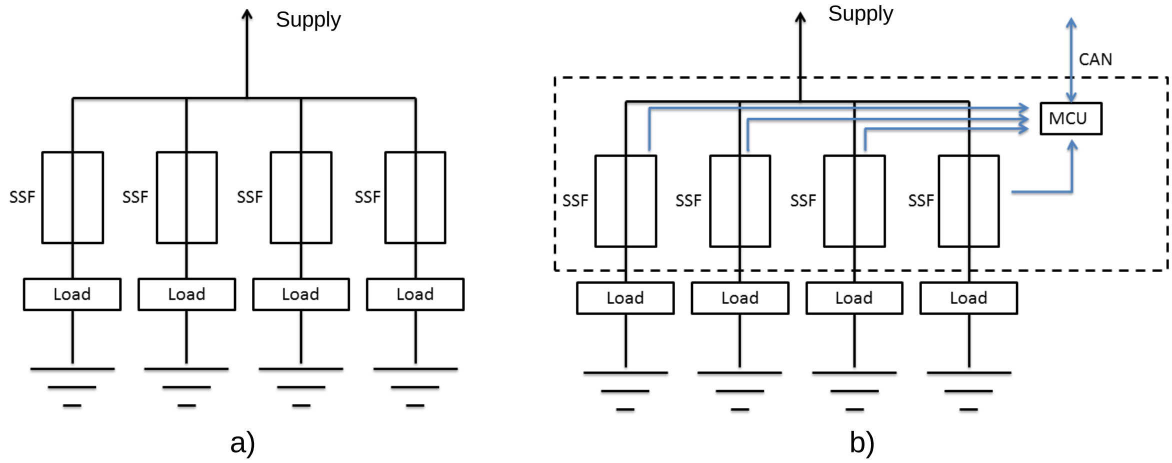


Figure 2: Principle structure for a) individual SSF units and b) multiple SSF units within the same SSF system and physical unit

4 The semiconductor circuit breaker

Since a fuse is supposed to interrupt currents according to section 1.1**Fel! Hittar inte referenskälla.**, a semiconductor based fuse needs a component that is capable of doing this. One category of such devices is transistors. There exist several kinds, but those able of handling strong currents and intermediate voltages are the IGBT and MOSFET. In this section the physics of both components are described in short along with a list of pros and cons.

4.1 MOSFET

The MOSFET is a voltage controlled transistor with capability of very low switching times at the same time as it can handle relatively high currents and voltages.

4.1.1 General description

The physical structure and symbol of the MOSFET are shown in Figure 3. Note that the MOSFET depicted in the figure is of so called n-channel type, which is the kind of MOSFET that will be discussed here. There is also the p-channel type where the doping is opposite of the one depicted in the figure.

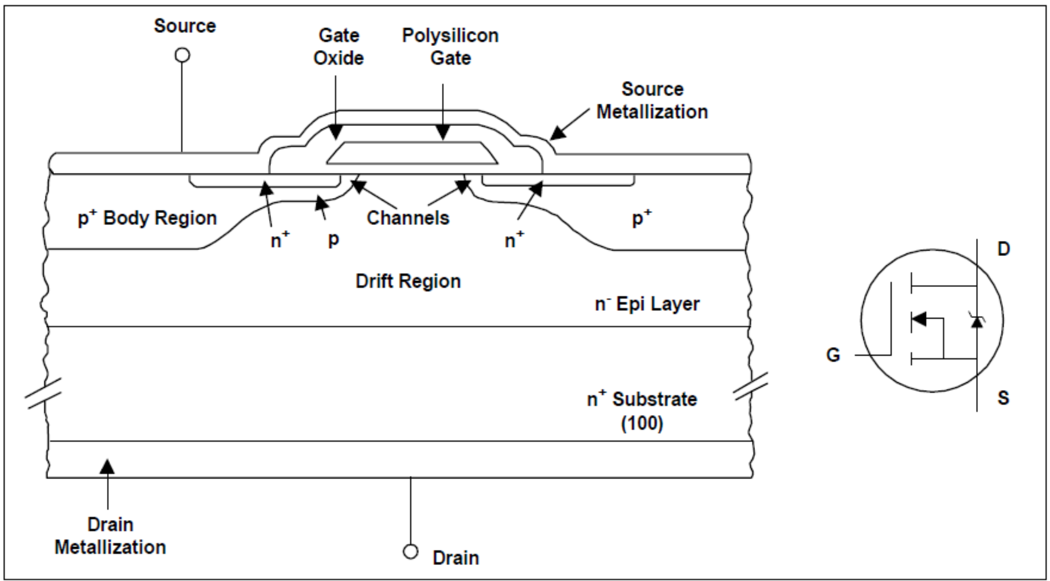


Figure 3: Structure and symbol of the n-channel MOSFET [10]

As a device, the MOSFET has three connectors; drain, source and gate. When applying a positive voltage to the gate, negative charges in the body region move towards the gate and forms a conducting channel between source and the drift region, which means that charges may move between the drain and source connector; the transistor is conducting. Note that no direct current passes from the gate to any other part of the device. The current passing through the MOSFET, between drain and source, is a purely ohmic current, which means that the voltage drop U_{DS} is proportional to the current through the MOSFET. Removing the positive voltage from the gate connector restores the body-region and the MOSFET stops conducting.

In practice, the MOSFET has three different modes of operation. The *ohmic mode*, were the current through the device is independent of the gate-drain voltage U_{GS}, is the mode used as on-state in switching applications. This is because it yields the lowest resistance and thus the lowest voltage drop across the device. The *active mode* occur when

$$U_{GS} \leq U_{DS} + U_{GSth} \tag{2}$$

where U_{GSth} is a threshold voltage and U_{DS} the voltage between drain and source. Active mode means that the current through the device, I_D, is limited so that

$$I_D \propto (U_{GS} - U_{GSth})^2. \tag{3}$$

This mode is primarily used in analogue electronics since it requires a varying voltage level in order to be useful. It may also be entered if too high a current pass through the device in ohmic mode so that U_{DS} increases and equation (2) is satisfied. The last mode is *cut-off*, which means that no current flows through the device. [6] [10] [11]

4.1.2 Parasitic effects and reverse current diode

Due to the physical structure of the MOSFET a number of parasitic effects occur, in particular, there is a bipolar transistor structure within the MOSFET with the body acting as base. In case this structure was trigged, break-down would occur. However, the source metal contact is in practice extended to cover the body, effectively reducing the bipolar structure to an anti-parallel diode, which may be used for free-wheeling in switching applications. It may also be used as a return path for currents originating in regenerative loads. The voltage drop is however constant and losses in the diode may be substantial. In addition, a number of stray capacitances occur within the MOSFET. The most important one being the gate-drain capacitance since this effect is what actually allows the device to conduct. However, in order to attract charges in the drift region, charges have to be moved to the gate in order to build up enough electrical field-strength. If a resistance is added in series with the gate pin, the time required to build up charge in the stray capacitance is increased. This is equivalent to prolonging the opening time of the MOSFET and therefore a way to reduce current transients in the connected circuit.

In addition to the gate-source capacitance, there are stray capacitances between gate and drain as well as between drain and source. In switching applications, these may be used as part of a snubber circuit. [6] [11] [10]

4.1.3 Temperature dependence

The on-state resistance, R_{DSon}, has a positive correlation with temperature, meaning that an increased temperature leads to an increase in resistance, often exponential. For a constant current or constant power load, this means that the losses are increased in the MOSFET and the temperature further increased. Also the threshold voltage U_{GSth} is increased, meaning that it might be necessary to increase the gate voltage in order to remain in ohmic mode.

At a certain junction temperature, the MOSFET breaks irreversibly. This temperature is usually in the range $150°C - 180°C$, meaning that the device needs sufficient heat diversion in order to avoid over-heating. Specified in datasheets is the thermal resistivity of the device, which may be used to calculate the junction temperature based on ambient temperature, heat sink parameters and losses in the device. [6] [11]

4.1.4 Parameters of manufactured devices

For reference, the data of some commercially available devices is included in Table 1.

Table 1: Data for some commercially available MOSFETs [12] [13] [14]

Device	Manufacturer	R_{DSon}	I_D (continuous)	t_{off}	t_{on}
IRF7739L2TRPbF	International Rectifier	$0.7\ m\Omega$	$46\ A$	$98\ ns$	$92\ ns$
IRFB7430PBF	International Rectifier	$1\ m\Omega$	$195\ A$	$260\ ns$	$137\ ns$
IRF7NA2907	International Rectifier	$4.5\ m\Omega$	$75\ A$	$250\ ns$	$165\ ns$

4.2 IGBT

The IGBT is a voltage controlled transistor with capability to handle high currents as well as withstand high voltages.

4.2.1 General description

The IGBT is mainly a power bipolar transistor with an extra section of doping. This extra section of doping makes the input stage of the IGBT become a MOSFET, allowing it to be voltage controlled. As can be seen from Figure 4, the IGBT and the MOSFET are quite similar in structure, so that when a positive voltage is applied to the gate, a channel is opened between the emitter and base region of the inner bipolar transistor. This allows for a current to pass from the base to the emitter, thus pulling a higher current from the collector such as indicated by the arrows in the figure. The result is a quick input response combined with simple driving, since no base current need to be supplied. As with the MOSFET no current pass from the gate.

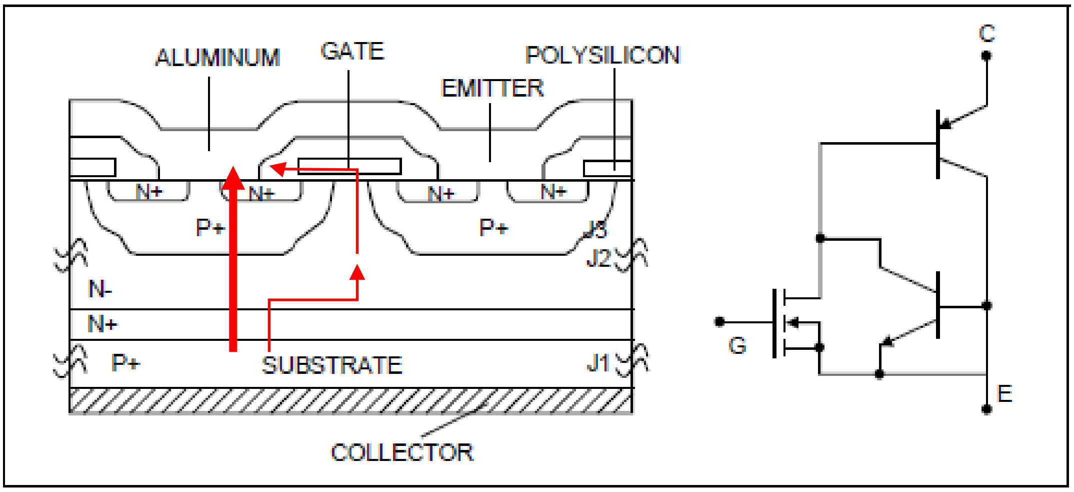


Figure 4: The IGBT structure and equivalent schematic [6]

The current through the IGBT is mainly a diffusion current, meaning that the voltage drop is more or less independent of the collector current, I_c. In practice, it may increase with increasing temperature if the current is high for the device. The losses however are proportional to the current, which makes the IGBT more efficient than the MOSFET at high currents since the MOSFET's losses are proportional to the square of the current. [6] [15] [10]

4.2.2 Latch-up

Whereas the IGBT is good at handling high currents, too high currents may cause problems apart from breakdown. This is because the structure of the IGBT also constitutes a thyristor, which is the two bipolar transistors in Figure 4. This thyristor is triggered either if the collector current is too high, so called static latch-up, or during turn-off where the permissible current level is decreased due to depletion in the drift region, so called dynamic latch-up. For further explanation of the physics behind this, the works [6] and [10] may be consulted.

The problem with triggering the thyristor structure is that there is no simple way to turn the structure off. Even if the gate metal covers the body, internal latch-ups may still occur. It is therefore advisable to control the current through the IGBT so that it does not exceed the limitations. Also, in order to avoid dynamic latch-up, a resistor in series with the gate of greater value than the minimum value specified by the manufacturer should be used. [6] [15] [10]

4.2.3 Parasitic effects and anti-parallel diode

Essentially, the parasitic effects of the IGBT are similar to those of the MOSFET. There is capacitive coupling between all metal contacts, providing the same effects as in the MOSFET. There is however not an anti-parallel diode integrated in the structure for external use due to the extra doping layer. Since anti-parallel diodes are necessary in for instance bridge-applications, a large number of practical components come with a separate anti-parallel diode built in to the capsule. [6] [15] [10]

4.2.4 Temperature dependence

As with the MOSFET, the IGBT breaks at a junction temperature in the range of approximately $150°C - 180°C$, making adequate heat diversion essential. Regarding the voltage drop, also this tends to increase with increasing temperature when the current has reached a certain level. [15]

4.2.5 Data for some commercial devices

For reference, the data of some commercially available devices is included in Table 2.

Table 2: Data for some commercially available IGBT:s [16] [17] [18]

Device	Manufacturer	V_{CEon}	I_C (continuous)	t_{off}	t_{on}
IRG4BC40FPbF	International Rectifier	$1.5\ V$	$27\ A$	$690\ ns\ @150°C$	$46\ ns\ @\ 150°C$
HGTG30N60B3D	Fairchild Semiconductor	$1.45\ V$	$60\ A$	$195\ ns\ @150°C$	$61\ ns\ @\ 150°C$
MID200-12 A4	IXYS	$2.2\ V$	$180\ A\ @\ 80°C$	$700\ ns\ @150°C$	$150\ ns\ @150°C$

4.3 Fundamental limitations of power transistors

As is seen from the sections above, some factors limit the use of the transistor as a switch. The most important ones are blocking voltage and losses. When looking at blocking voltages, the IGBT has an advantage due to its physical structure, which is reflected in the components available on the market. Looking at the losses however, the MOSFET has an advantage up to a certain level of current, as was mentioned in section 4.2.1. This is a relation that has arisen in the last years; in literature it is often mentioned that IGBT have lower losses, but more recent figures from datasheets state otherwise as may be seen from Table 1 and Table 2. [6] [19]

Temperature is another limiting factor that relates closely to losses. The voltage drop across the device has a positive correlation with temperature, meaning that an increase in temperature leads to an increased voltage drop and therefore higher losses. Both the IGBT and MOSFET break approximately at a junction temperature in the range $150°C - 180°C$. In order to avoid heating to these levels, appropriate heat diversion should be included in any application. [6]

Latch-up is a problem with the IGBT, this is however possible to avoid by controlling the current and keeping current derivatives down.

Finally, the stray capacitances of both the MOSFET and the IGBT pose a limitation since too high voltage derivatives may cause unwanted effects, e.g. accidental turn-on. [15] [11]

4.4 Breaking of inductive currents

As mentioned in the previous section, high voltages pose a difficulty for power semiconductors, especially for the MOSFET. When breaking a current that runs through an inductive circuit, voltage peaks are generated. This is because energy is stored magnetically in the circuit when a current flows, and upon attempting to break the current, the stored magnetic energy counteracts the decrease. In the case of a breaker of some kind, e.g. a MOSFET, there is an increase in voltage across its terminals. This might be of significant amplitude depending on the previous current, circuit inductance (capability to store magnetic energy) and how fast the breaker is opened.

Inductance exists in every circuit and is formed by the distance between outgoing conductor and return path. The greater the distance between conductors, the greater the inductance. Inductance is also increased if a material of low reluctance, e.g. the iron in the chassis frame of a truck, partially or entirely fills the space between the conductors. A high inductance means a higher level of stored magnetic energy as is indicated by equation 4 where W_m is the magnetically stored energy, L the inductance and i the current. [19]

$$W_m = \frac{Li^2}{2} \tag{4}$$

In order to avoid voltage peaks, a number of methods may be invoked. These include extending the opening time of the breaker, meaning the voltage drop across it is increased slower and the magnetic energy is dissipated mainly in other parts of the circuit than in the breaker itself. The method does however yield additional losses in the breaker. [20]

Another method is to use a so called snubber circuit. A snubber may be designed in different ways, but the simplest method is to add a capacitor and a resistor, connected in series, in parallel with the breaker. This allows the current to pass the opened breaker until the magnetically stored energy has been dissipated in the series resistor, the circuit or stored in the capacitor. The disadvantage of this method and the previous is that the circuit will continue to carry current until the magnetically stored energy is zero. An example of a snubber circuit is shown in Figure 5. [6]

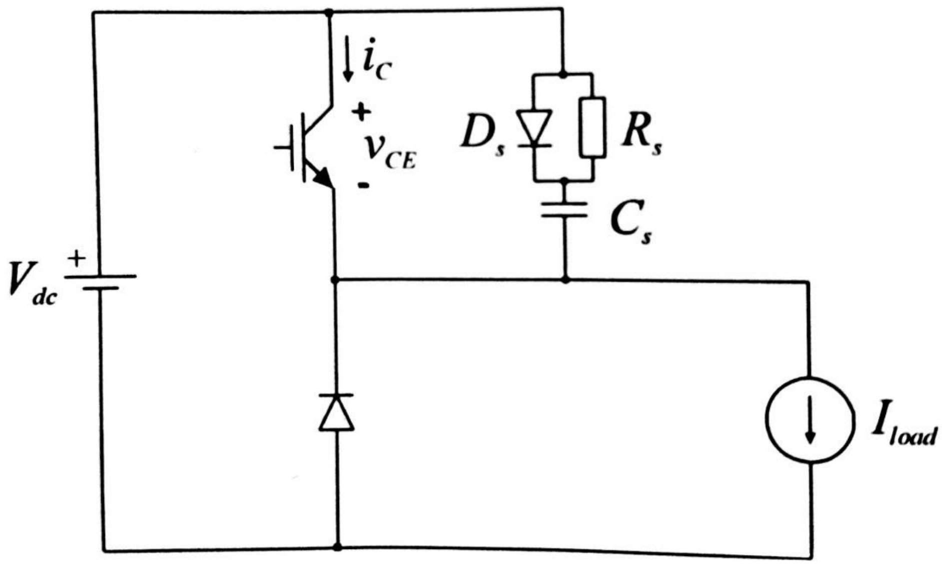


Figure 5: An example of a snubber circuit [6]

One method that avoids currents flowing in the circuit when the breaker is open is to add a zener diode between the breaker's positive terminal and ground. The zener diode is however hard to manufacture if high levels of currents should be handled. [7]

Regardless of what solution is to be used, a free-wheeling diode connected between ground and load side terminal of the breaker should be included to handle inductances originating from the load. [6]

4.5 Breaking of regenerative currents

As could be seen above, the MOSFET-structure includes a parasitic diode, and most IGBT modules have a diode built in. These diodes form a non-controlled path for return currents with a fixed voltage drop. For fusing applications, it is desirable to break currents in both directions. Therefore a solution for breaking also the return current should be implemented. [10]

One such solution is to use two anti-serial MOSFETs. Since the MOSFET's channel is also able of conducting in its reverse direction if the gate terminal is biased it may conduct currents with low losses in both directions. In addition, when the gate is unbiased, there is no path through both of the MOSFETs. This is because also the parasitic diodes become anti-serial with respect to each other. The concept is illustrated in Figure 6 and an evaluation of it may be found in section 11.2. [10]

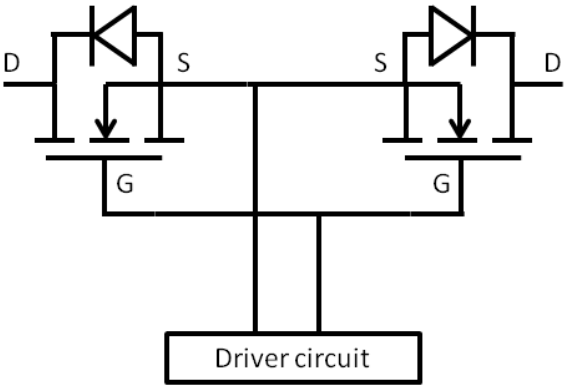


Figure 6: Anti-serial MOSFETs for breaking of regenerative currents

4.6 The Smart Power Switch (SPS)

A term that has come to existence during the last 20 years is Smart Power Switch, or SPS. The SPS is a power transistor with additional features within the same package. Usually there is a driving circuit and a charge pump so that the SPS may be used as a high-side switch without the need of additional circuitry. Also, there is often some kind of logic built in as to protect the device and connected load from short-circuits and over-temperature within the device.

A great number of semiconductor manufacturers provide some kind of SPS. Infineon for instance have the PROFET. These devices are based on MOSFET-technology and combine the short switching times of the MOSFET with plenty of protective circuitry as well as gate driver circuits and diagnostic output. A schematic block diagram of their BTS555 is shown in Figure 7 where modules for over- and undervoltage protection, ESD protection, current limitation and overtemperature protection may be seen. [21]

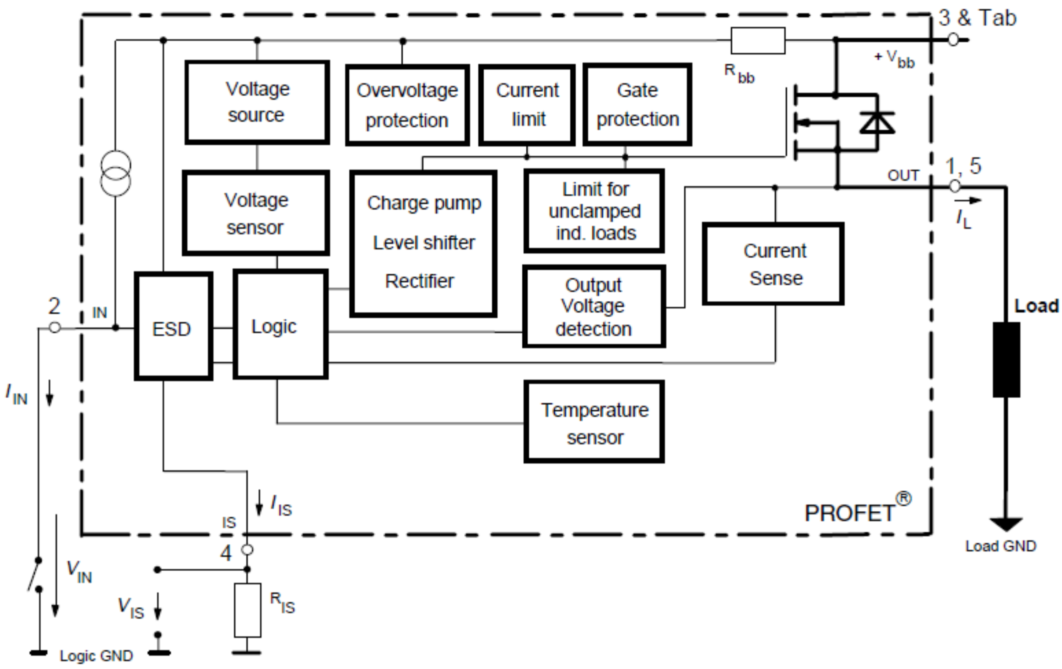


Figure 7: Schematic functional diagram of the Infineon BTS555 [21]

4.6.1 The SPS in fusing applications

The protective circuitry of the SPS makes it ideal for fusing applications in theory. In an application note from Siemens [22] PROFETs function in fusing applications is investigated. Here the tripping is made by the overtemperature protection circuit, which is found to be an unreliable method if a precise tripping characteristic is desired regardless of ambient temperature. It is proposed that on PROFET devices where an analogue current sense signal is available, external circuitry could be used to obtain desired tripping characteristics. This circuitry may consist of analogue electronics as well as a microcontroller. Heat diversion must however be employed in order to not have undesired tripping when fusing loads that, at any point of operation, draws a current that otherwise would set of the overtemperature protection.

It is described that the internal mechanism for overcurrent protection consist of two mechanisms; first a current limitation, that reduce the gate-voltage on the internal MOSFET so that the resistance is increased, if the current exceed a certain level and second, MOSFET turn-off if the temperature is increased to a certain level. These two mechanisms form an internal tripping characteristic in the current-time plane, which is illustrated in Figure 8. The curved edges of the characteristic curves are due to the current limiting function of the PROFET which increase the thermal losses for a given current. The tripping characteristic curve may be moved to allow longer periods of overcurrent if additional cooling of the device is employed, e.g. a heat sink. The characteristics does however also mean that the device is sensitive to ambient temperature. If the device is placed in a warm environment, it will trip for much shorter periods and lower levels of overcurrent than it would in a cold environment. The characteristics may also vary somewhat with manufacturing differences.

The PROFET has built in undervoltage protection, which is meant as a short circuit protection that instantly turns off the internal MOSFET if the voltage drops below a certain level. Although this is intended as a protective feature, it may also cause problems in a circuit where the wiring between voltage source and PROFET is somewhat resistive and multiple PROFETs are used to fuse different loads. If one PROFET is short circuited on its load side, a voltage drop will occur for all PROFETs which will trigger the undervoltage protection for all devices even though the fault is located on the load side of only one PROFET. Using a software based sequential reset of the PROFETs may isolate the fault from the other load circuits, but it is a slow procedure relative to the breaking time of the PROFET and relies on the function of e.g. a microcontroller. Also, if the other loads are of critical nature, e.g. ABS system, this behaviour may cause hazardous situations.

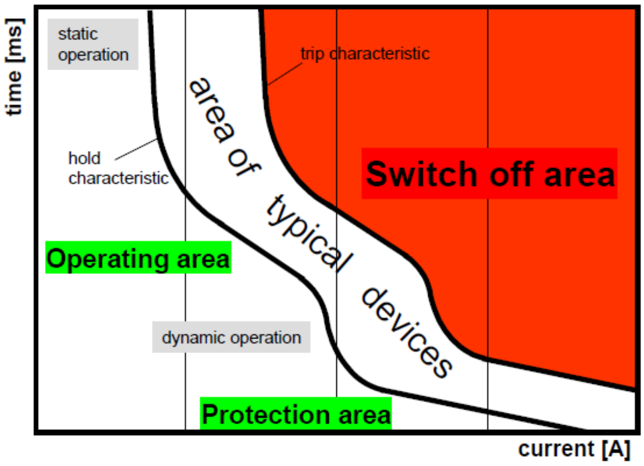


Figure 8: Internal tripping characteristic for a PROFET [22]

Since the PROFET uses a MOSFET as circuit breaker, additional protective circuitry is required when fusing inductive loads. [22]

5 Cable characteristics

From previous sections it is clear that inductances pose a problem for semiconductor circuit breakers. Apart from in electrical loads, there are inductances to be found in the wiring harness of the vehicle. In order to dimension a solid-state fuse correctly, it is therefore necessary to understand in which magnitude these inductances are. The measurements described in this chapter are however performed outside of the actual vehicle, wherefore increased inductance due to the iron in the chassis frame is not measured. In addition, wiring configurations vary from vehicle to vehicle, which result in a varied inductance. The measurements presented here should therefore only be considered as an estimate and the SSF be dimensioned with extra margins.

5.1 Theoretical model

One common model for a short range cable is the one found in Figure 9. As can be seen it is constituted simply by an inductive complex impedance in between the two ends. One way of obtaining the components of the impedance is to feed the cable with a sinusoidal measurement signal and measure attenuation and phase-shift. The model is however approximate and the circuit could be more accurately represented by the model shown in Figure 10. Parameters for this model is however more difficult to obtain by measurements, but it illustrates that the frequency of a measurement signal affects the result.

Parameters affecting the electrical properties of a cable are mainly the length of the cable and the distance between the conductors. [23]

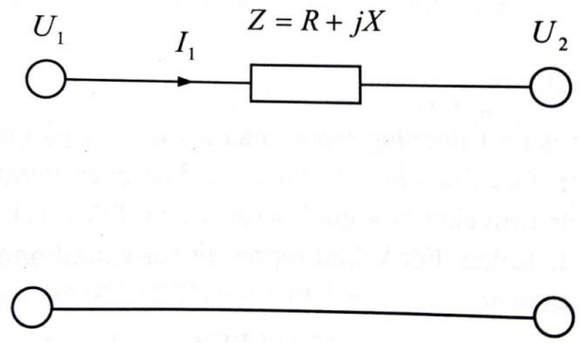


Figure 9: Short length cable model [23]

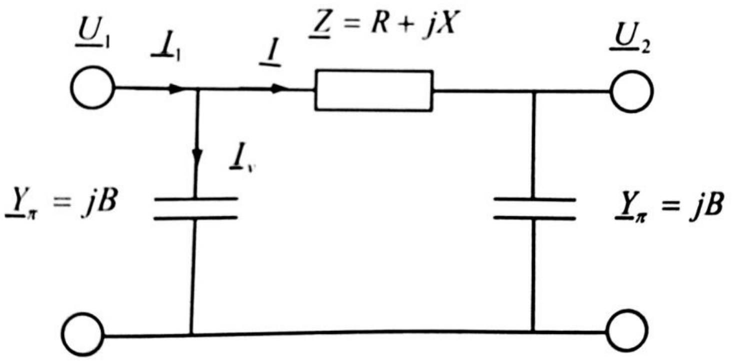


Figure 10: Medium length cable model [23]

5.2 Empirically obtained parameters

Since the electrical properties vary with cable length and distance between its conductors, it was decided that experiments were to be conducted. These aimed to find values of the properties that would represent a number of cables used in Scania's vehicles.

The measurements were made using an RCL-meter and a four-wire multimeter. When results had been obtained, they were fitted to the short cable model found in Figure 9. Measurements were performed on a wiring harness identical to the main harness of a truck. From the harness, seven different circuits where selected for measurements. All of the conductors used were designated for load power supply.

In Table 3 the measured DC-resistances can be found for the different conductors. The resistance per meter value is taken as one meter outgoing current path plus one meter return path. Table 4 presents the average of the measured inductances and inductance per meter circuit.

Table 3: Measured DC-resistances

Connector 1	Connector 2	DC-resistance $[m\Omega]$	Resistance per meter circuit (2-way) $[m\Omega/m]$
C37	C101	197	40
C107	C101	232	47
L101	C100	436	45
C1624	C1622	361	45
S40	C103	664	60
V4	C101	159	50
C427	C100	45	26

Table 4: Average values of measured inductances

Circuit	Average series inductance $[\mu H]$	Inductance per meter circuit (2-way) $[\mu H/m]$
C37-C101	3.06	0.62
C107-C101	3.16	0.64
C427-C100	2.77	1.63
C1624-C1622	4.91	0.60

L101-C100	8.44	0.87
S40-C103	11.1	1.01
V4-C101	2.20	0.69

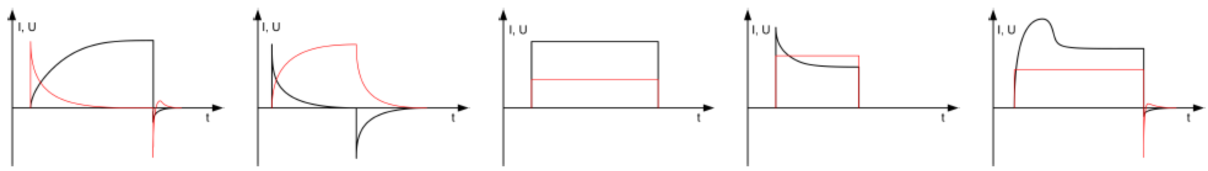
In general it may be said that the resistance stays below $1\,\Omega$ and in some cases is as low as less than $50\,m\Omega$. The inductances measure up to slightly above $11\,\mu H$. The measurements were however made in a laboratory environment with a wiring harness loose on the floor. When installed on a truck, inductances as well as capacitances may be larger since the chassis framework consists of iron. The iron provides a better path for a magnetic field than air and inductances may therefore increase. It is also connected to system ground, wherefore an electric field may be created between supply conductor and chassis frame. This effect would be equivalent to that of a large capacitor. [23]

6 Load characteristics

To fully understand how to design a solid-state fuse, it is important to know what currents it should allow without tripping. Therefore a load characterization was made.

6.1 Ideal and traditional loads

Traditionally loads have been of resistive, inductive, capacitive, light-bulb or motor-type. They were often controlled using relays that were closed when the load was to be activated and opened when it was to be deactivated. When closing the relay, a voltage transient occurred on the supply side of the cable feeding the load. This resulted in a somewhat different transient behaviour on the load side. The principal behaviour of the loads is illustrated in Figure 11. As can be seen the inductive load is current sluggish, whereas the capacitive load is voltage sluggish. The resistive load yields a step response. Looking at the lamp, it has an inrush current that decays when the filament is heated. The motor has a similar behaviour, but has a slower current rise-time since it is mainly inductive. When it speeds up, the back-EMF reduces the current. [2] [23]



(a) Inductive. (b) Capacitive. (c) Resistive. (d) Lamp. (e) Motor.

Figure 11: Principal transient behaviour of ideal loads [2]

6.2 Loads in practice

Loads of today are not simply resistive or resistive-inductive, but often have more complex transient behaviour, which may be repeated during its entire time of activation. For instance a headlight has a low resistance during the first milliseconds, before heated, and therefore initially draws a large current. But as soon as the headlight is warm, resistance decrease and current settles at normal level. Switched loads are also appearing very frequently; in almost every fan and motor, there is power electronics which control the current. These power electronics give rise to transients in the supply current, sometimes of significant amplitude. In addition, the load connected to a fuse is not always constituted by a single unit, but may be multiple units, all with switched power electronics. [6]

The load characteristics give rise to a series of challenges; to distinguish between a fault and a load, to break a regenerative current and to break inductive currents caused by loads. In order to better understand what currents to expect from loads, measurements on some loads were made. The loads were selected to be representative for a truck and were

- CUV (Light control unit)
- Chair heating
- EBS (Electric Brake System)
- VGT (Variable turbo geometry)
- Microwave oven
- EMS (Engine Management System)

- SMS (Suspension Management System)

Below, each load will be analysed somewhat more in detail in order to give the reader understanding for the challenges of designing a solid-state fuse. It has been attempted to take measurements on the loads during operation similar to that of normal use.

6.2.1 Chair heating

Measurements of the voltage and current to the chair heat at its fusing location yielded the results shown in Figure 12. During the measurements one chair was activated alternating between high heat and low heat. As can be seen from the figure, the load appears purely resistive. Looking closer at the switching instant, some contact bounces are found, but no significant effect in voltage or current is noted.

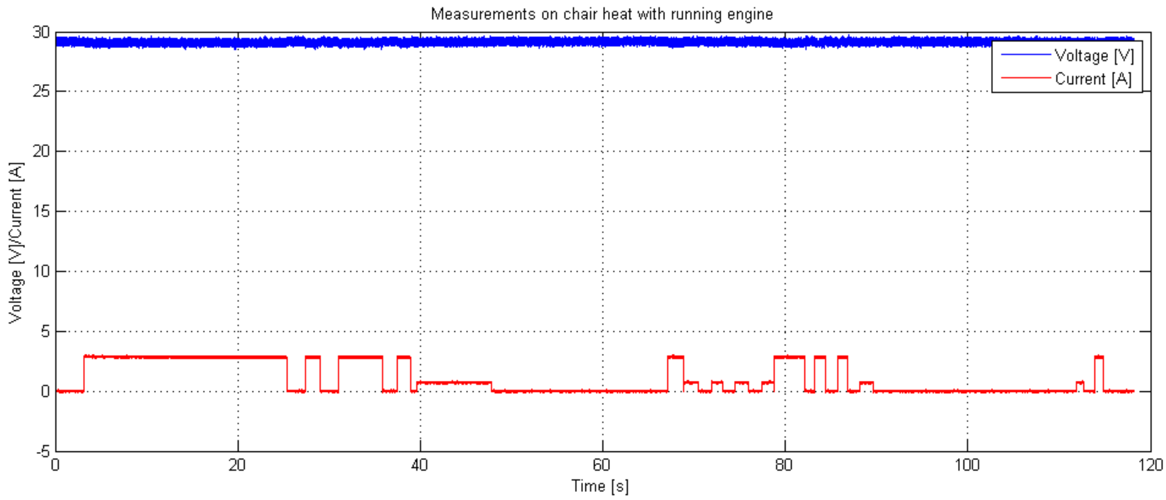


Figure 12: Voltage and current measured at the chair heating fuse

6.2.2 Microwave oven

Measurements on the microwave oven were performed at its point of connection and resulted in the values illustrated by Figure 13. The first half was measured with the engine stopped, then the engine was started, which corresponds to the voltage drop in the middle, and the measurements were repeated. During the measurements, the microwave was run in open-hatch mode, then started at maximum power, decreased in power incrementally and then increased again, thereafter it was stopped. As may be seen from the figure, it acts mainly as an inductive load. When the engine was started some superimposed sinusoidal current ripple occurred with amplitude of approximately $3\ A$.

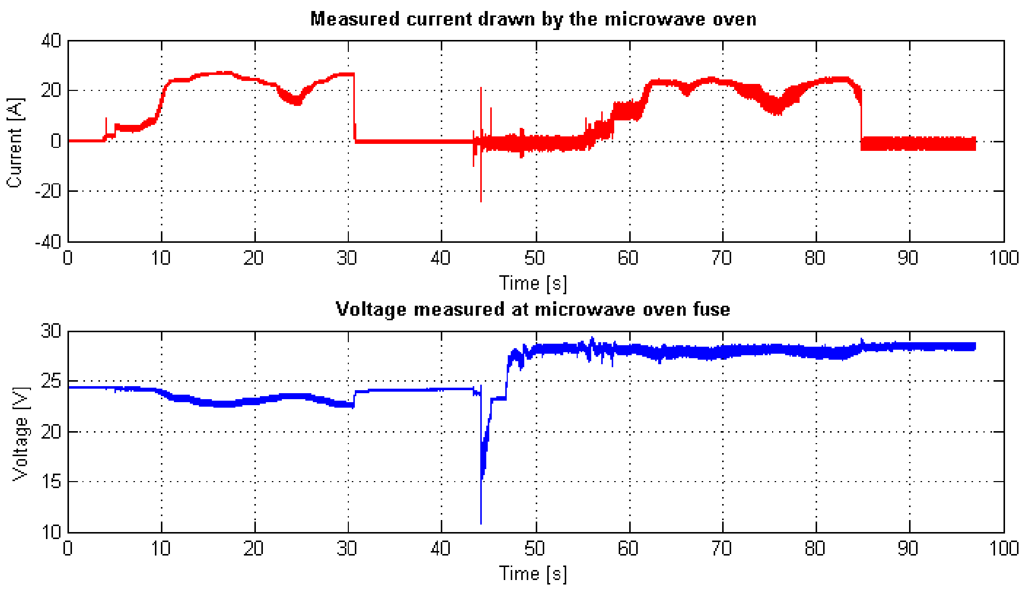


Figure 13: Current and voltage measured at the microwave-oven's point of connection

6.2.3 Light control unit

The light control unit controls and drives several light armatures. When measuring, the measurements were taken at its point of connection. The procedure was to first switch on the parking lights, then the dipped beam and finally the main beam. Current and voltage for one such measurement is shown in Figure 14. As seen from the figure, the light armatures are more or less ideal when considering a slower time scale. The inrush current to the main beam is very high, but the characteristics are almost ideal. Looking closer at the main beam turn-on however, it is found that the inrush current peak actually consist of three peaks following each other in time and that the dipped beam turn-on include significant amounts of ripple caused by power electronics.

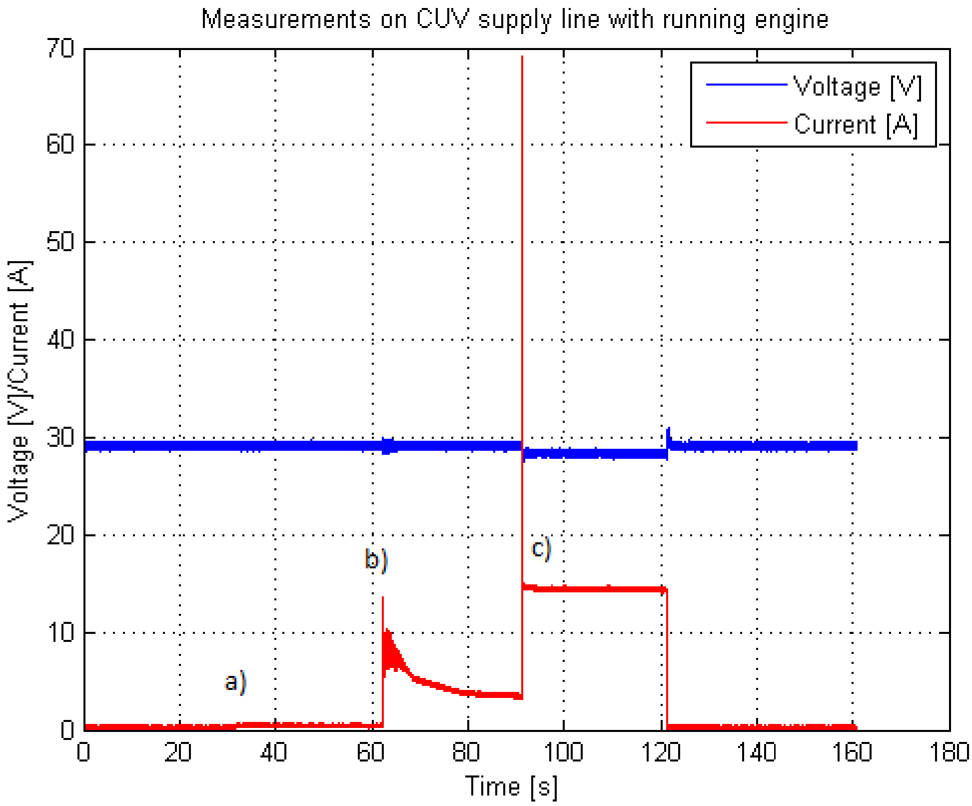


Figure 14: Voltage and current measured at CUV point of connection. Parking light switched on at a), dipped beam at b) and main beam at c)

6.2.4 Brake control unit

The brake control unit works during vehicle operation. Measurements were therefore made at the fuse location when driving in a varied way, including panic breaking and attempts at wheel spin. As may be seen from Figure 15, the unit works in intervals and when it does, significant current peaks occur. Looking closer at these peaks, they consist of a high current level with superimposed ripple of approximately $1\ A$ in amplitude. Each pulse lasts around a few seconds.

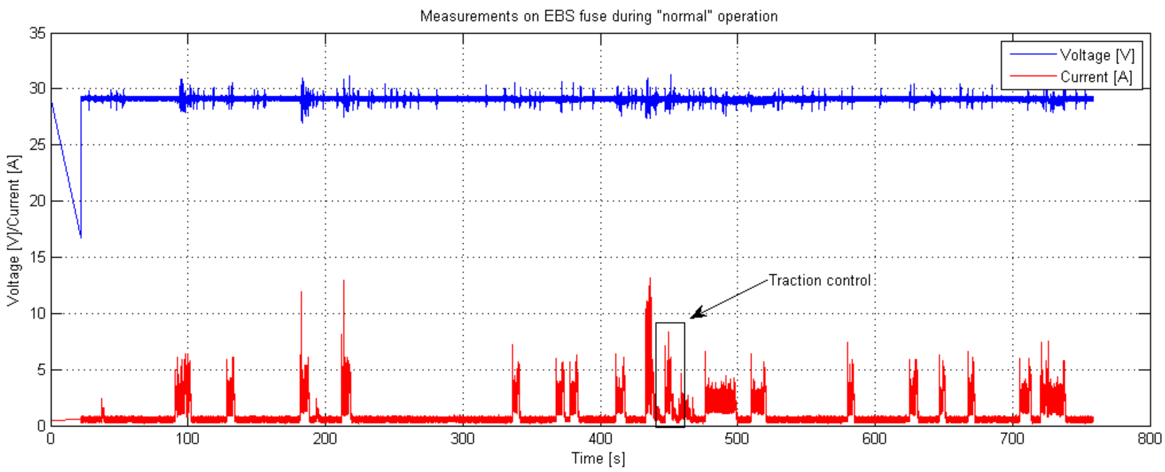


Figure 15: Voltage and current measured at EBS fuse

6.2.5 Air suspension system

The air suspension system works while driving and when requested to by the gate driver. Measurements were made at its fuse. Figure 16 show measured current and voltage when operating the system. In the beginning measurements are made while manually raising and lowering the suspension, then the engine is stopped and cranked again (corresponding to the large voltage drop). After that the truck was driven, first on country road and then on a bumpy test track. The passage on the test track is shown as large current peaks.

As is seen in the figure, manual operation corresponds to constant current with significant amplitudes of ripple. Driving on the bumps large current peaks occurred and these are almost square and last for approximately $6\,ms$ with irregular intervals.

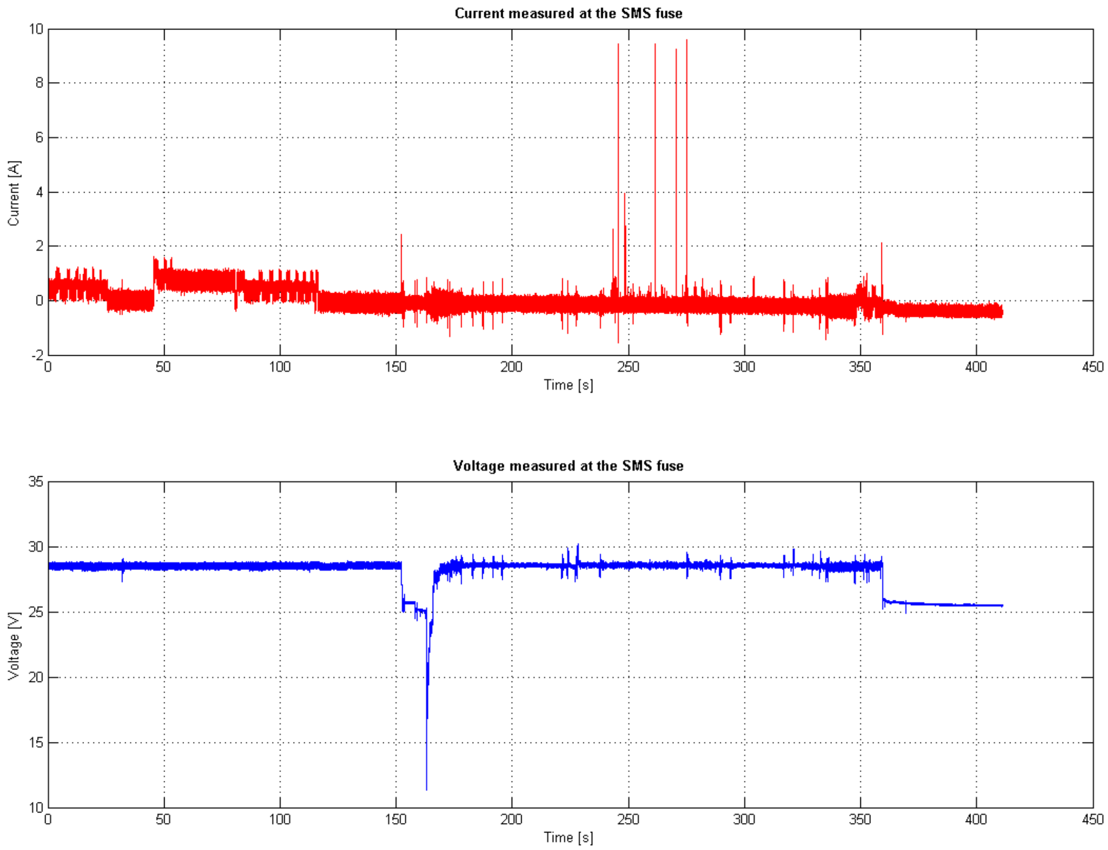


Figure 16: Current and voltage measured at the SMS fuse

6.2.6 Variable turbo geometry

The variable turbo geometry works during driving. Measurements were made at the unit's point of connection and the results presented in Figure 17. As may be seen, the VGT works in pulses, each pulse being a few milliseconds. The measurements were taken during varied driving; constant high rotational speed, accelerations, full throttle while using the retarder and more. In spite of this, the VGT kept pulsing current.

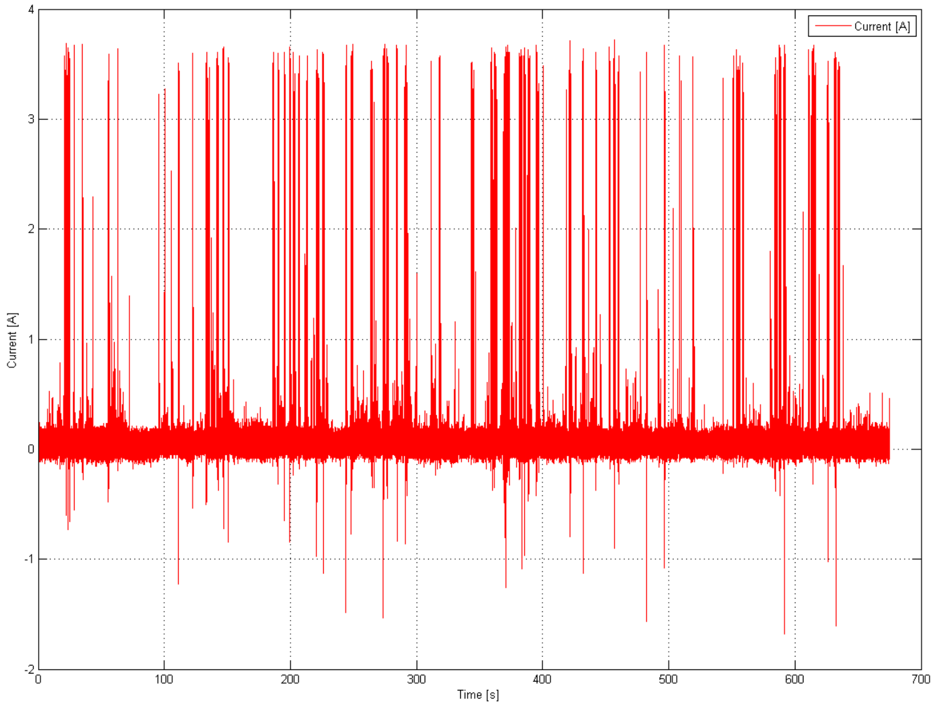


Figure 17: Current measured at the VGT

6.2.7 Engine control unit (EMS)

Measurements were taken at the EMS fuses but the results that are presented in Figure 18 represent the measurements taken on both fuses since they were very similar. As may be seen, there is no resolving of a current level when observing the measurements in the timescale used in the figure. Looking closer however, it is found that the EMS draws current in small pulses which have a reoccurrence frequency of approximately 800 Hz and large pulses with a frequency of 88 Hz. These pulses form the pattern shown in the figure. The pulses themselves are not rectangular but shaped as in Figure 19.

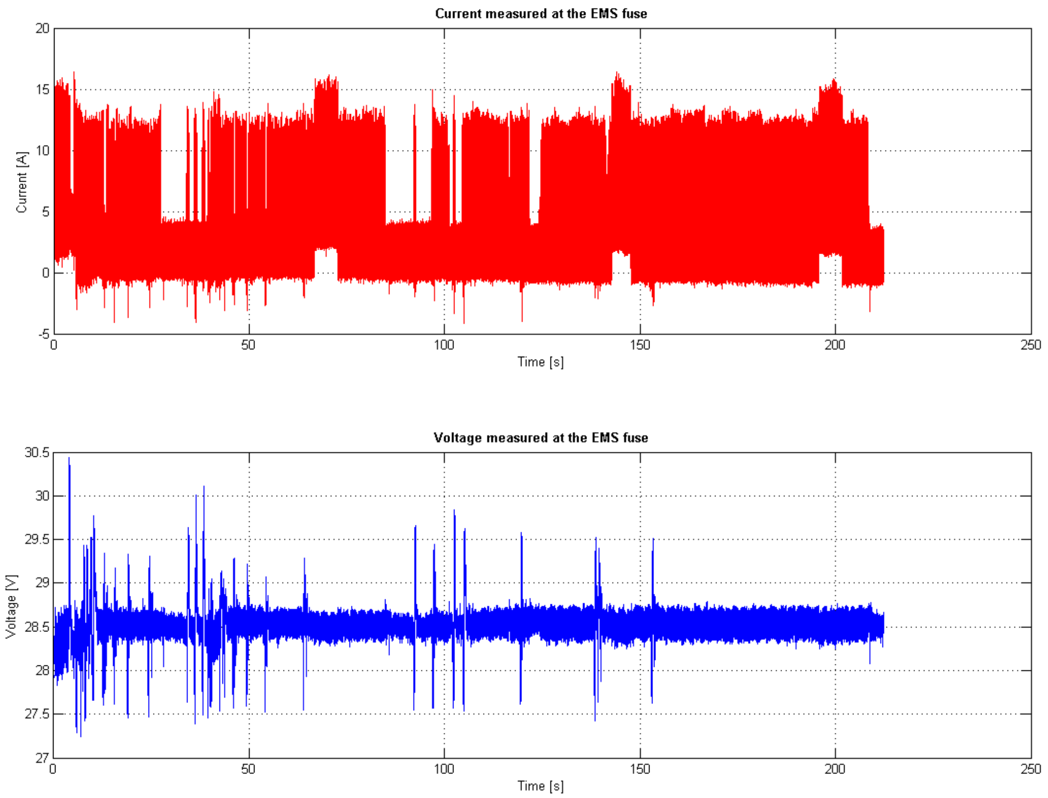


Figure 18: Current and voltage measured on one of the EMS fuses

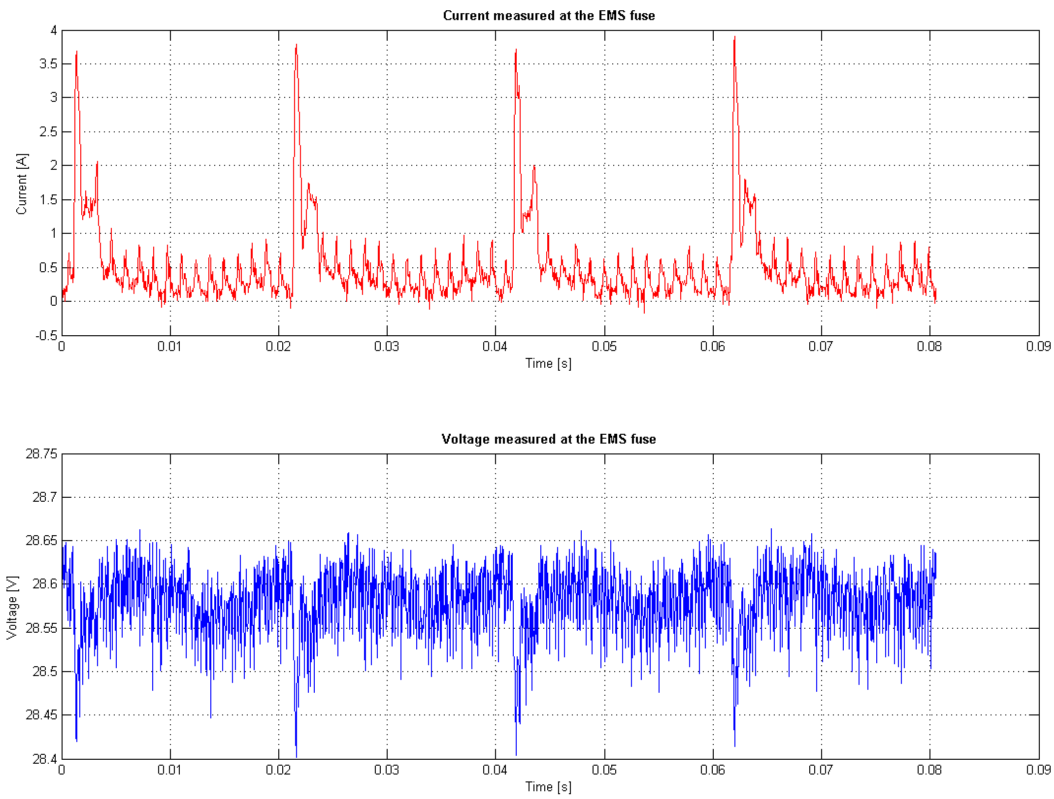


Figure 19: Current pulses from Figure 18

7 Fault characteristics

Fuses traditionally protect against overcurrents and short circuit currents. In a commercial vehicle this often occurs due to any of three reasons; incorrect connection of cable (solid short circuit), damage to cable causing a solid short circuit and fault in connected load. Most of these faults are manageable with a normal fuse since they bring a significant overcurrent. However, a non-solid short circuit may cause heat to be dissipated without tripping a blow-out fuse. This constitutes a risk of fire.

Another, more dangerous kind of fault is constituted by bad connections. Sometimes a screw terminal is not fastened enough or a solder breaks loose. These events give raise to a higher resistance across the interface and thus increased power dissipation when a constant current is drawn. For passive loads, the total current actually decreases with increased resistance, and therefore the fuse will not trip. But since power is dissipated where it is not meant to, overheating may eventually occur and there is a significant risk of fire. A traditional fuse will not trip, but a system that knows what normal currents look like could identify this as a fault and break the circuit. Because of this, it is of interest to study what characterizes a fault in terms of current and voltage. [24]

Experiments were made to find empirical data. During these experiments, a cable subject to a current of $2\ A$ was imposed external damage by means of squeezing, bending and cut with metallic object. The cable end-point was also dipped in salt-water. The cable was fed by two series connected $12\ V$-batteries connected in series with a $30\ A$ fuse.

7.1 Squeezing

Squeezed cables may be caused by a series of reasons. The result is a deformation of insulation and conductors which may cause short-circuits or bad contact. In order to obtain electrical characterization for this, cables of two types occurring in trucks were squeezed by hammering.

The result of squeezing these two cables where that the insulation broke and the conductors where exposed to each other and the environment as is exemplified in Figure 20. Since the squeezing was made using a metallic object, temporary short-circuits to ground by the object caused yellow sparks to fly. When the cable was lightly shaken by hand, light arcs appeared intermittently. A $30\ A$ fuse was used for personal protection, but it did not trip even though current peaks of more than $980\ A$ was measured.

Figure 20: Cable after squeezing, 1 of 14 samples

Electrically, squeezing of the cables generally appeared as current peaks followed by interrupted current or by current peaks followed by resumed normal current. This behaviour was repeated when the cable was lightly shaken. Only in 1 of 14 cases, the interruption was immediate and permanent. In 3 of 14 cases was a short-circuit to ground permanent since the short-circuited conductors melted away from each other. It was in these cases that the fuse tripped. A typical example of the electrical characteristics is illustrated in Figure 21.

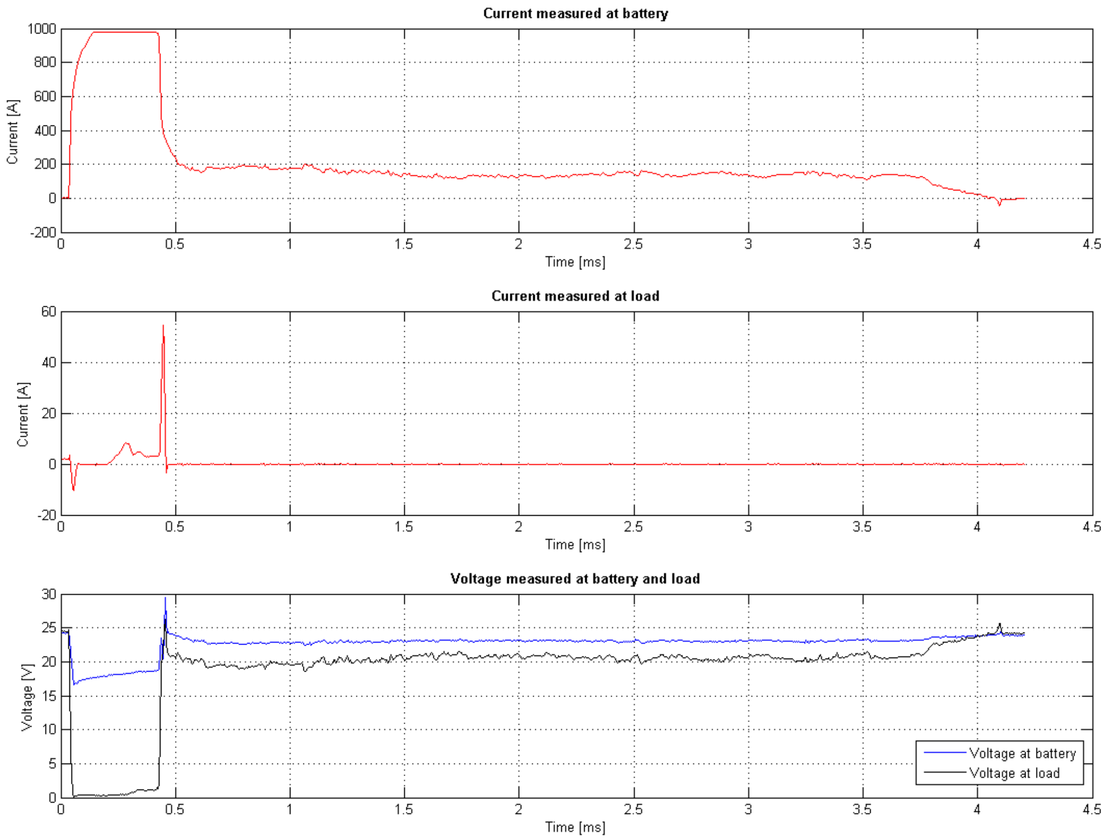


Figure 21: Currents and voltages typically appearing when squeezing a cable. The pattern was repeated when shaking the cable lightly. It corresponds to a short-circuit to ground during a limited time.

7.2 Bending

Faults from bending occur for example after long time of use. It was simulated by bending cables by hand until a fault occurred. One of five samples after test is shown in Figure 22. As can be seen, the damage is nearly not visible, whereas the conductors actually are entirely broken.

Figure 22: Cable after bending simulation, 1 of 5 samples

Electrically the bending was, in all five cases, characterized by direct interruptions followed by a brief current spike when the interruption ended and the constant current load regained power. The behaviour is typically illustrated by the measurements presented in Figure 23.

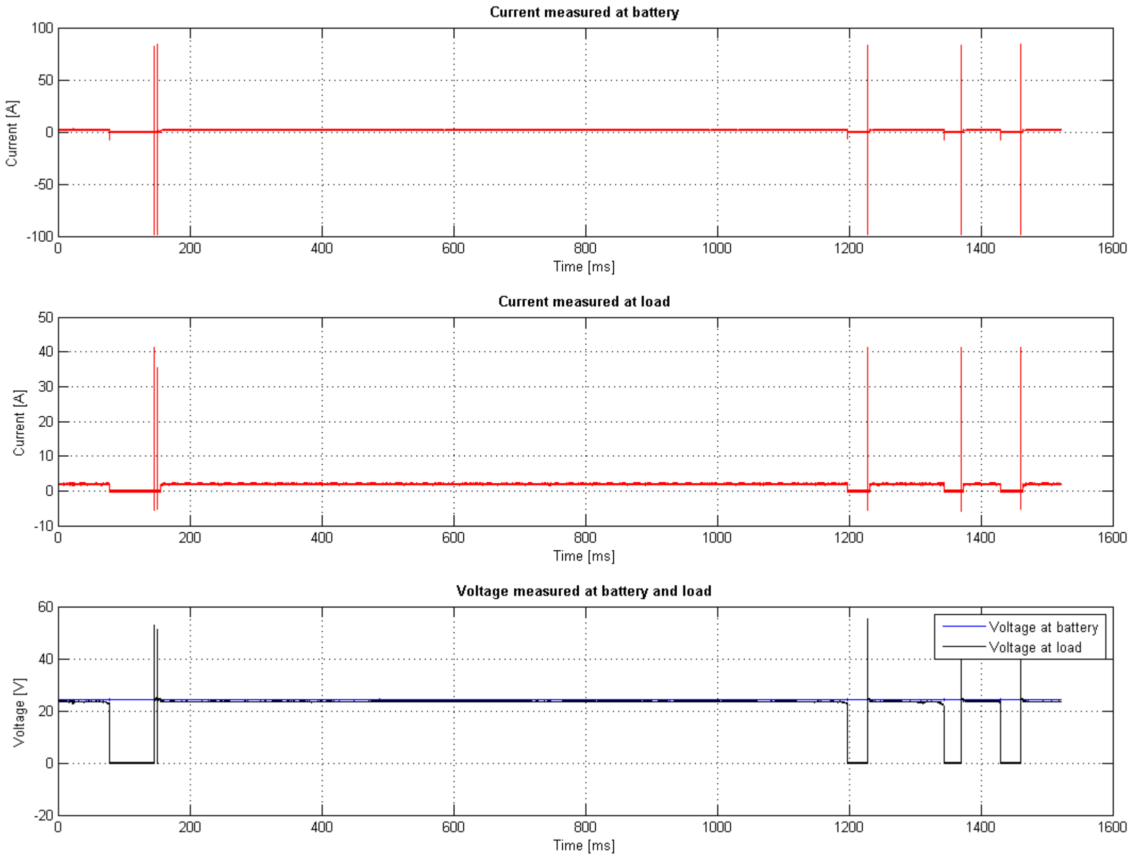


Figure 23: Currents and voltages measured when exposing a cable to bending

7.3 Cutting

Cutting may be caused for instance during service or as a consequence of incorrect service. In the experiments, it was simulated by the use of a hacksaw, which after the experiments looked as shown in Figure 24 a). Most of the damage was caused without the fuse tripping. A cable after the experiments were performed is shown in Figure 24 b). The cable was 1 of 5 samples. As can be seen, it is burnt, which also was true for the other samples.

a) b)

Figure 24: a) The hacksaw used in the cutting simulations after the experiments were performed and b) 1 of 5 cable samples used in the experiments after execution

During the experiments, sparks flew and short, intermittent arcing occurred. Electrically, the experiments yielded a large amount of current peaks on the supply side joined with voltage drop on the load side. Following the peaks were longer periods of high currents, in the order of $20\ ms$, during which the load drew nominal current, but had almost zero voltage. When the short-circuit ended, normal load voltage was generally restored, until the moment when the conductors had almost been entirely cut-off and resistance too high. Eventually, the cable stopped conducting. The behaviour is generally illustrated by Figure 25.

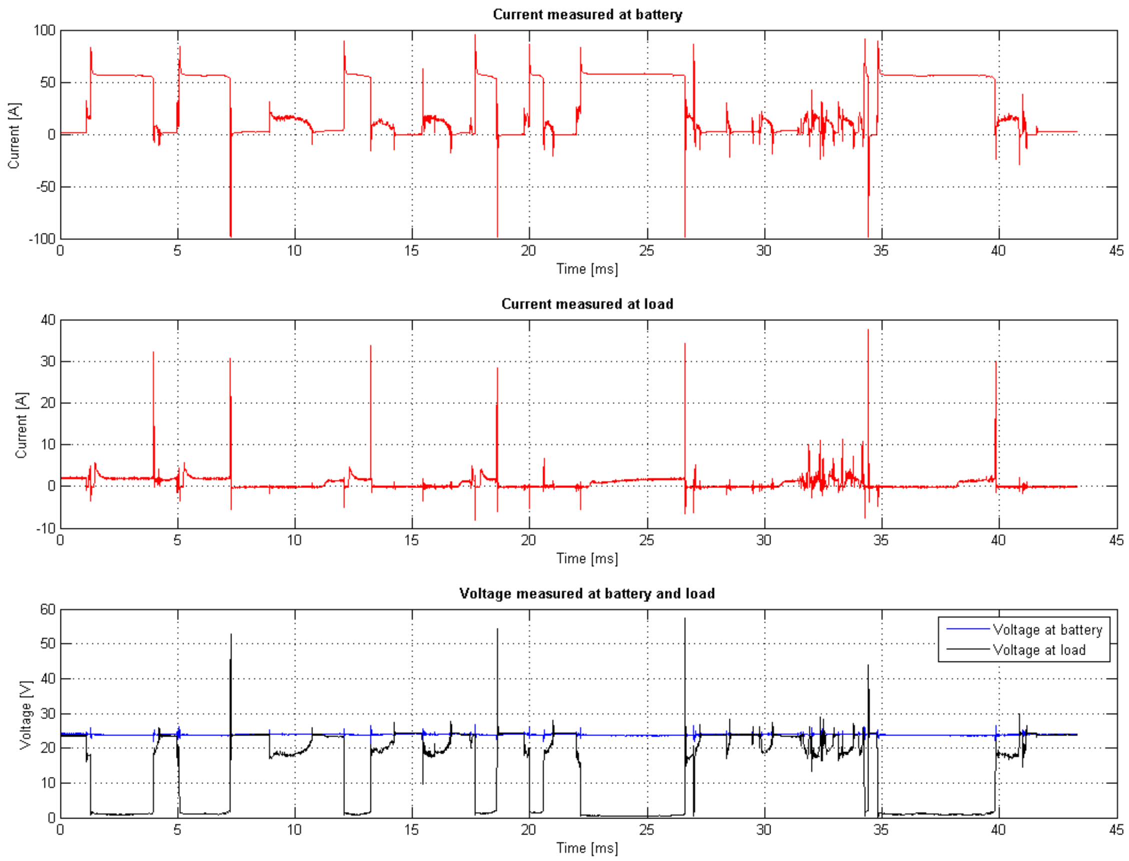


Figure 25: Currents and voltages measured during cutting-simulations

7.4 Salt water

Some cables are meant to be connected and disconnected by the truck driver when for instance attaching a trailer. When they are disconnected they are supposed to be placed so that the connector is oriented in any way but up, so that there is no risk of water ingress. Sometimes however, this happens anyways. When it does, soft short-circuits may occur, especially if the water contains salt, which may come from the road. In order to characterize a short-circuit due to salt-water ingress, powered cables with bare ends were dipped in various degrees of salt water. [24]

Driven by the series connected batteries, the cables where lowered into the salt water. During this time, a current was measured. The results are found in Table 5. As may be seen, the currents are of no significant magnitude, but still constitute power losses.

Table 5: Average of currents through tested cables when dipped in various degree of salt water

Volume percent	Peak current	Steady state current
0 %	0 A	0 A
2 %	0.15 A	0.1 A
3 %	0.5 A	0.2 A
5 %	1.15 A	0.25 A
10 %	1.9 A	0.35 A

7.5 Load faults

As was seen earlier, loads are not simply resistive, inductive or capacitive, but have behaviours that might even be considered stochastic if not a number of external circumstances are known. The complexity of the loads in terms of internal function and design also means that faults of very various kinds may appear. Internal malfunction is however something that the load should handle internally. The only load fault that concerns the fuse is when the fault entails currents that are harmful to the wiring harness. [25] Because of this, no further examination of load faults have been made.

7.6 Remarks regarding voltage drops

For all the studied faults, a majority of the experiments have resulted in a significant voltage drop at the load side, when the fault situation is present. It has either been caused by voltage division when there has been bad, or no, contact in the conductor, or it has been because of current division when a short-circuit have occurred.

8 Standards and requirements

In a great number of industrial applications, there are standards regulating how a certain product should function. In the case of fuses for vehicles, ISO 8820 regulates their function and the standard has been adopted in Sweden as SS-ISO 8820. In addition to the requirements set out in the standard, there are a number of requirements specified by Scania. These regulate for instance the temperature span for which the device should function, what levels of vibration it should withstand and for which voltage range it should work.

This section assumes a CEU that is to be located on the engine since this is a worst case scenario.

8.1 Environmental requirements

Looking at the requirements for components located around the engine it is internal documents specifying the environmental requirements, namely TB1900. This document specifies that the component should function during ambient temperatures of up to $150°C$ and down to $-40°C$ for a given amount of time. Storage should be possible for the entire specified interval and down to $-55°C$. The component should also withstand temperature cycling in the interval, splash of cold water, exposure to salt mist, dropping the device from $1\,m$, substantial amounts of vibration, forces caused at service, gravel bombardment, various chemicals, scratching and ageing. It should also fulfil IP6K9K and be fire-retardant. The last requirement is verified by FMEA.

8.2 Electrical requirements

The electrical requirements of a component are specified in internal documents, TB1901 for 24 V-components and TB1902 for 12 V-components. These specify operating voltage range, what voltages, externally imposed faults and transients it should withstand. They also specify EMC-requirements. However, they are not written for electrical components that act as a fuse and may need additional amendments.

8.3 Fuse-link requirements

ISO 8820 specifies requirements for fuse-links in road vehicles. It specifies a fuse-link as the

> *"interchangeable part of the fuse, consisting of an insulator and electrical conducting parts such as the terminals and the fuse element".*

Considering that one of the main advantages of using solid-state fuses is the reduced need for replacement, it is likely that the fuse-link itself will actually not be interchangeable. The ISO does however specify requirements, and test procedures, for the fusing function, which are applicable to solid-state fuses.

The applicable parts are specified in ISO 8820-1 as sections 5.2, 5.3, 5.5, 5.6 and 5.7. Since the work focuses on loads with a rated fusing current of less than $30\,A$, requirements for blade-fuses of ATO-type are used below.

8.3.1 Voltage drop (ISO 8820-1 section 5.2)

The ISO specifies that the voltage drop across a fuse-link at rated current should be less than a specific value. This is a way to regulate the energy losses, and thereby heat dissipation, caused by the fuse-link. Some voltage drops and corresponding resistances are shown in Table 6.

Table 6: Maximum voltage drop for some rated fusing currents

Rated fusing current $[A]$	Maximum voltage drop $[mV]$	Corresponding resistance $[m\Omega]$
5	175	35
10	140	14
30	120	4

8.3.2 Transient current cycling (ISO 8820-1 section 5.3)

Electrical loads of various kind draw transient currents in different modes of operation. The ISO specifies transients that the fuse should withstand without tripping. For a blade fuse, the transient pulse is illustrated by the excerpt from SS-ISO8820-3 found in Figure 26.

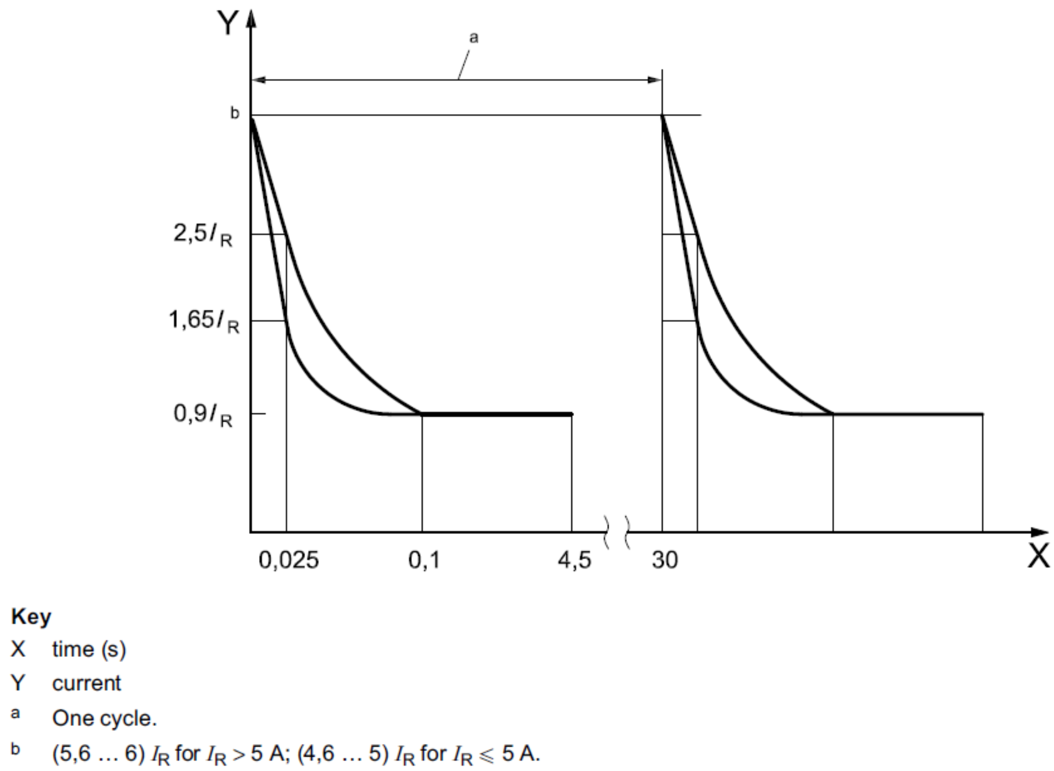


Figure 26: Transient cycling test pulse as specified by ISO 8820-1 (figure is an excerpt from SS-ISO 8820-1)

8.3.3 Operating time rating (ISO 8820-1 section 5.5)

The ISO section specifies how to verify the tripping time for a fuse-link at different factors of overcurrent. The required values are, for a blade fuse, specified in table 5 of ISO 8820-3. For an overcurrent of 10 % above the rated current, the fuse-link should not trip after less than 360 000 s for instance, whereas it must trip after less than 100 ms but more than 20 ms at 600 % overcurrent. The ISO section also specifies the maximum current through the fuse link after tripping.

8.3.4 Current steps (ISO 8820-1 section 5.6)

This ISO section specifies requirements on the fuse-link's ability to withstand heating due to low level of overcurrents. This requirement may be relevant to test during environmental testing according to internal documents since the semiconductor fuse is not able to withstand the same level of heat as the blow-out fuse. The ISO section also specifies the maximum current through the fuse link after tripping.

8.3.5 Breaking capacity (ISO 8820-1 section 5.7)

The requirement concerns the fuse-links ability to break a fault current and specifies a test circuit for which the fuse-link should be able to break the current. The test circuit consist of a series LR-circuit connected to a voltage supply. The ISO section also specifies the maximum current through the fuse link after tripping.

9 Fault detection

Solid-state fuses open up for a whole new range of features; they may be reset, remote controlled, diagnosed, but also have custom fault detection schemes. In section 8.3 the tripping requirements for a fuse-link were mentioned. These are specified by a standard, but solid-state fuses do not have to conform to this standard. Instead the new possibilities that are brought by using semiconductor technology could be used to improve fault detection and tripping so that detection accuracy and speed are increased.

There are several methods of fault detection, ranging from instant current measurements to statistical analysis. In the following a few methods are discussed and compared to the experiment results presented in sections 6.2 and 7.

9.1 Instant current measurements

One method of fault detection is instant current measurements in the sense that the instant current is observed and when it reaches a certain level, the fuse trips. Provided that the semiconductor circuit breaker is fast, as in the case of a MOSFET, this method allows for very short lead time between the fault occurs and the current is interrupted. It is also simple to implement using analogue electronics and could therefore be made to be a robust solution.

Looking at the loads on which measurements were performed it can easily be seen that this approach require a quite high tripping level since a number of the loads draw current peaks from time to time. A high tripping level means that the cable needs to be able of conducting currents of this level continuously and still not overheat. This is equivalent to over-dimensioning the cable and therefore also introducing unnecessary costs and weight. The solution could however be useful in the case of chair heating since it is almost purely resistive and do not include any current peaks when considering only the heating elements. A slight disturbance caused by, for instance, a load dump would however trip the fuse, effectively making it an ineffective solution.

An example of a disturbance causing problems using this kind of detection may be seen in Figure 27. In this case it is the inrush current that is causing a problem, since the fusing level was set to only $14\,A$. The inrush current only appears when enabling the fuse in this case and should thereafter stabilize at approximately $2\,A$.

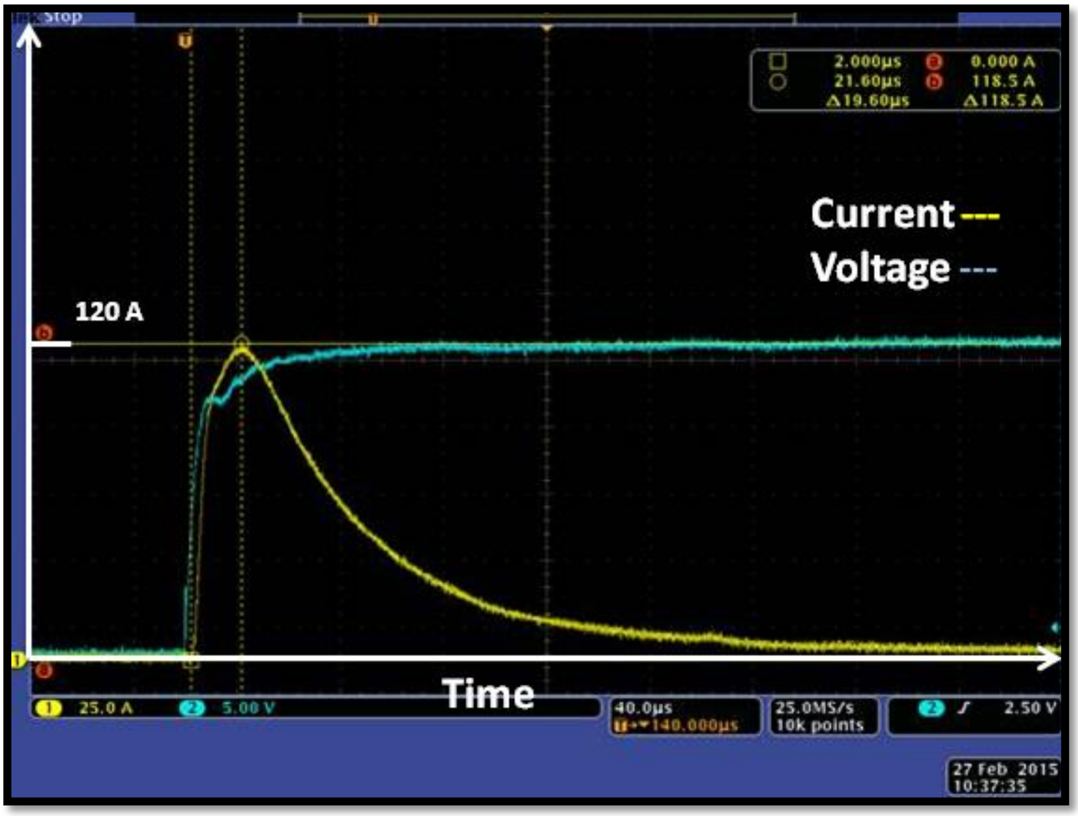


Figure 27: Current and voltage measurement performed on a component with severe inrush current and bypassed fuse

9.2 Imitation of blow out fuse

As described in section 2.1, the blow-out fuse trips when it is overheated. This occurs when the power dissipation for a certain time is too high. From this it can be found that a solid-state fuse can be made to imitate this by integrating the square of the passing current over time and reduce the integral value with a forgetting factor corresponding to heat dissipated to the surrounding air. This method is similar to the thermal estimation described in section 9.3, but considerably more simplified.

Implementation may be made either in a microcontroller, by using an analogue integrator with a discharge resistance or as a hybrid between the two. Comparing the solution to measurements made on actual loads shows that the nominal fusing current in most cases may be lower than if the instant current measurement method was used.

A major advantage in using this approach is that there are already defined tests and requirements in ISO 8820.

9.3 Thermal estimation

Another possibility is to use thermal estimation. The purpose of using fuses is to protect the wiring harness, primarily from damage caused by overheating as a consequence of overcurrents. Instead of only studying the current, it is possible to estimate the conductor core temperature using an observer, e.g. a Kalman-filter, with current and ambient temperature as inputs. The general concept is described in [26]. This technique allow for optimization of cable dimensions since only a moving average of the power consumption is relevant for the fusing action and a very varied load pattern is accepted. Even if the load from time to time draws very high currents, the fuse will not trip unless the cable is close to overheating.

The method require some kind of processing unit to be involved since the calculations to be made are quite complex. Since a control unit is anyways required to obtain most of the advantages using solid-state fuses, this constitutes no direct extra costs. It does however add some additional risks because the processing unit is alone responsible for tripping.

Comparing the method to the measurements performed on actual loads, it can be seen that there is a clear potential for obtaining a suitable and efficient solution by using the method.

9.4 Statistical methods

Apart from performing direct analysis of the current or ambient temperature, these may be analysed from a statistical point of view. By calculating, for instance, expected value and standard deviation and comparing to values calculated during normal operation, it might be possible to detect faults. This is however not further investigated in this thesis.

9.5 Hybrid detection

If a microcontroller is used in the system, this may be used to combine several of the methods described, or others. One possibility is for instance to use the blow-out imitation method and combine it with a current ceiling so that it acts as a blow-out fuse as long as the current reaches levels which it should never reach during normal operation. If it does, it should trip instantly.

9.6 Voltage based detection

Another possibility that is not found in literature is to measure the voltage drop between fuse and load. As was found when simulating faults, a voltage drop occurred in most cases, even when no disruption or abnormality in current was measured. This could lead to the conclusion that a reliable method for fault detection is to monitor the voltage at fuse and load.

In practice this would be solved by having the load determine when its supply voltage is considered too low. When this is the case, it would send a signal over the vehicle network to the fuse. If the fuse finds its internal voltage measurement to be normal when receiving this signal, it is an indication that a fault has occurred. If then a predetermined subsequent number of signals arrive, the fuse consider a fault to be present and trips.

The method has some drawbacks. One is that the fault may not be only in the supply conductors, but also in the vehicle network conductors. In this case, no error message will arrive to the fuse. The load may also be powerless before any message has been sent. This is however avoided if parallel buffer capacitors of enough capacity are used within the load. All in all, it can be said that voltage based detection appears to be an accurate method of detection. However, it should be combined with other means of fault detection since there is risk of malfunction.

10 Simulations

Before implementing algorithms for detection in practice, it is useful to simulate them beforehand in order to find whether they do their job or not. A simulation model is also a good tool to find whether the algorithms work with new kinds of equipment before the equipment is even manufactured.

In the work made for this thesis, a simulation model was developed which built on the data measured during the experiments described in sections 6 and 7.

10.1 The model

The simulation model used is found in Figure 28. It was built using Simulink and based on some assumptions;

1. The fault current (current that does not pass through the load) is independent of the connected load
2. The current that passes through the load during a fault is proportional to the normal load current.

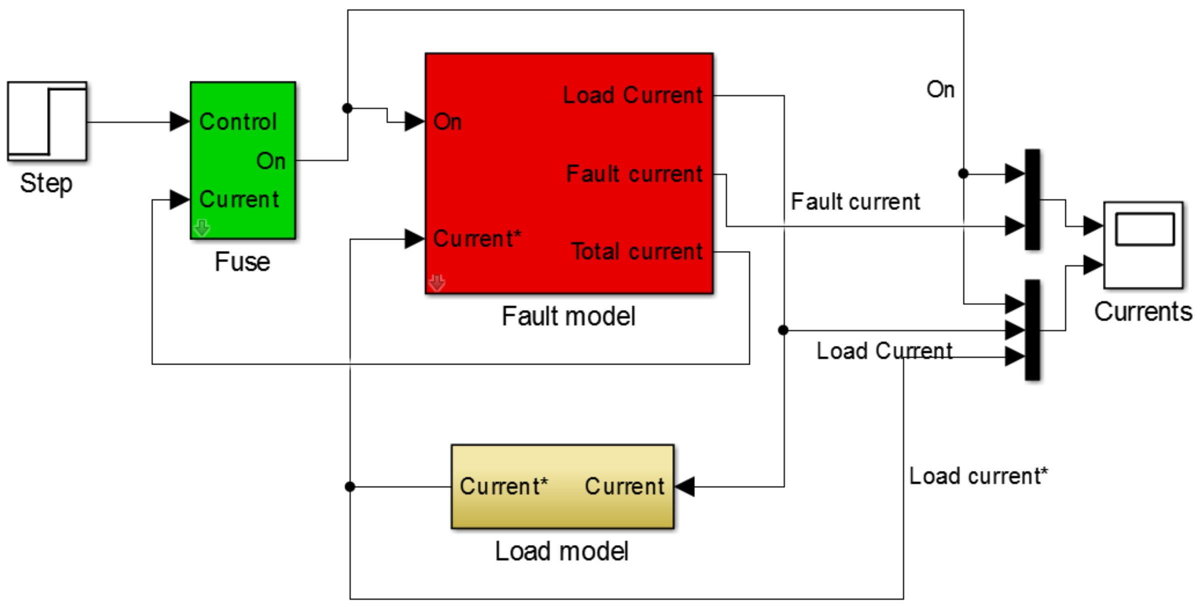


Figure 28: Simulation model

These two assumptions make it possible to extrapolate the measured data from previously described experiments. The load model simply consists of the measured current data series from a load of the user's choice. This value is then outputted to a fault model as a requested value. Within the fault model, the current that the load actually receives is calculated based on measurements performed when simulating faults. Within the fault model, a fault current is calculated. This current is the same as measured during the simulation of faults when the current that passed the actual load is subtracted. The fuse module contains logic for detecting a fault. It takes calculated total current from the fault model and a control input and outputs a logical signal which indicates whether the fuse has "tripped" or not.

The consequence of making the assumptions is that the model is not a perfect model of reality. For instance, the second assumption only holds for a constant current load, whereas a constant power or resistive load would consume more or less current respectively during a fault. It does however give a quite good approximation of how a load acts during a fault, and in particular, it use real measured data to obtain these values.

10.2 Fault detection using the model

Since time was limited it was decided to only perform simulations and develop a detection algorithm according to ISO 8820. The goal was to find a transform that would allow only a single threshold value to be used in combination with an integrator.

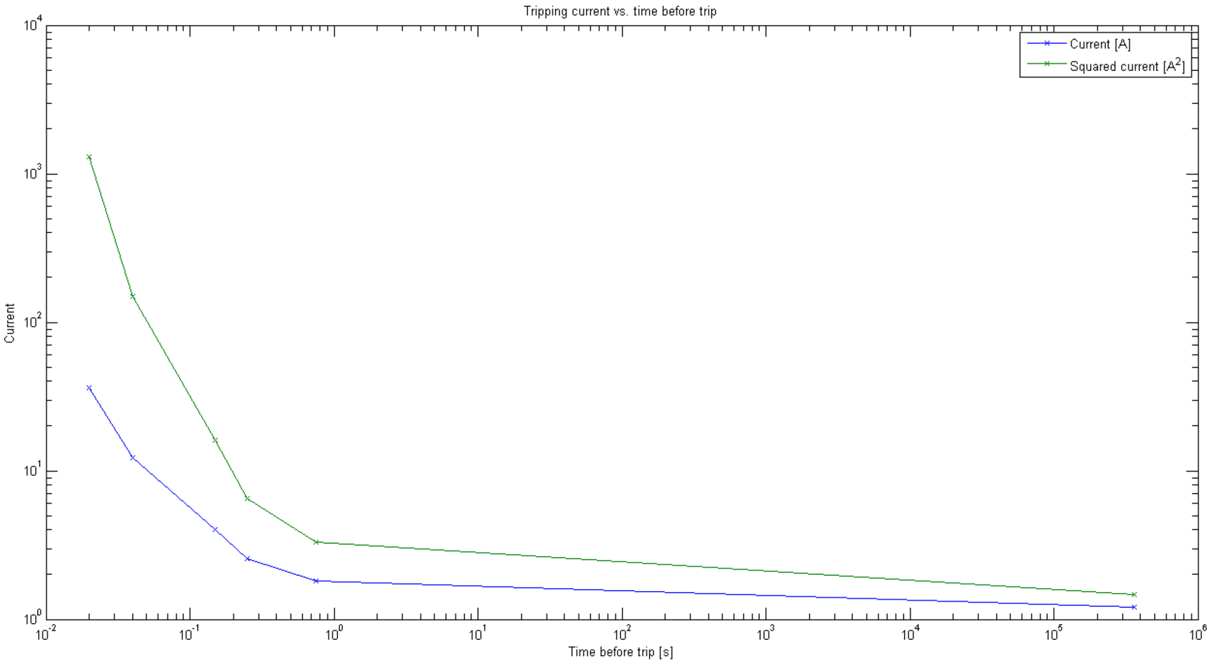


Figure 29: Current vs. tripping time

By graphical inspection of the squared current plotted against tripping time according to the ISO, a somewhat exponential relation could be seen, see Figure 29. Using the values and allowing Matlab to identify an inverse function yielded a multiple term exponential function, which is omitted here due to it not being used. Instead, the Simulink model was used with a sequence of pulses corresponding to the values specified in the ISO for a blade fuse. A transform was then developed by reasoning that the inverse of an exponential function is a logarithmic function, inserting it into the model together with an integrator and varying coefficients until acceptable results were generated. The experiment model is shown in Figure 30.

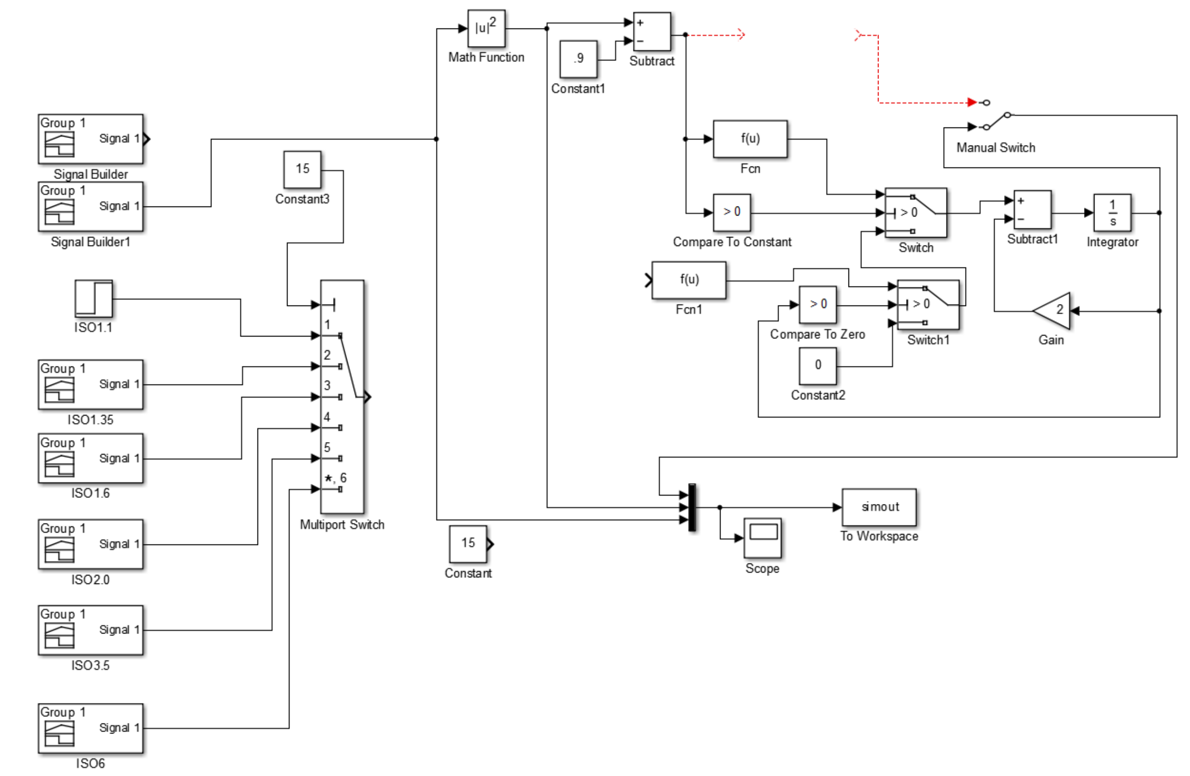


Figure 30: Experiment model for imitating the tripping scheme outlined in ISO 8820-3

When applying pulses corresponding to the tripping criteria specified in the ISO, the model tripped at every pulse within the specified interval. That is, not faster or slower. It also did not trip for the pulse train specified in the ISO as allowed current pulses. The transform while applying test pulses is shown in Figure 31.

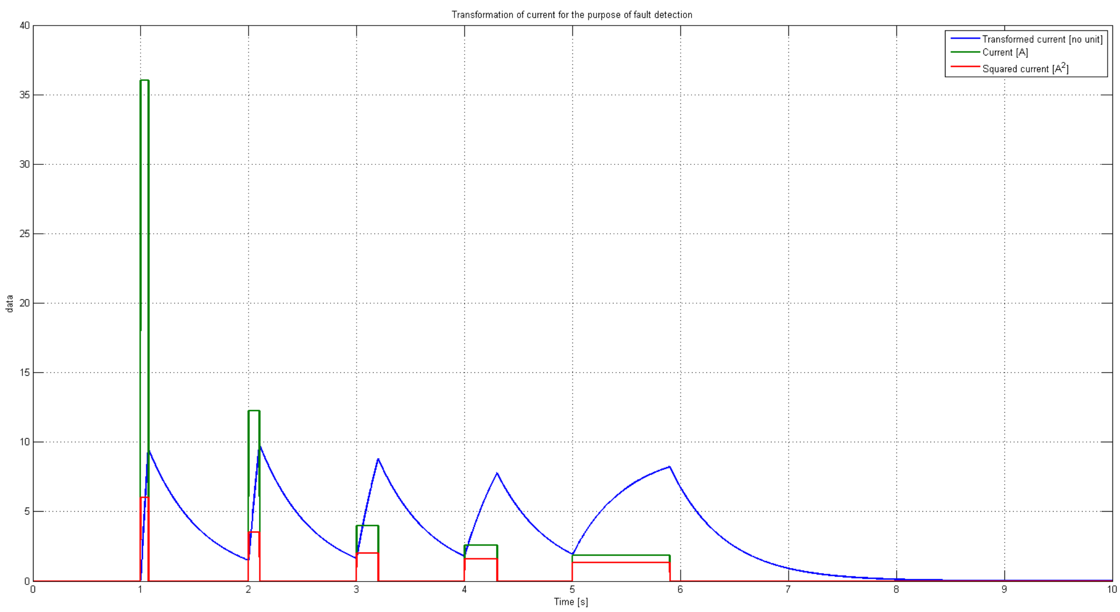


Figure 31: Transform of current test pulses according to ISO 8820-3

11 Demonstrator and practical experiments

In order to better demonstrate the concept, a series of demonstrators and prototype boards were built. First, components were tested, then parts of the full system, and finally a board containing four “fuses” controlled by a microcontroller.

11.1 Stand-alone evaluation of BTS555

The BTS555 is an Infineon SPS. The device is rated for $165\ A$ continuous current and has an analogue current sense feedback. At currents above $520\ A$ it shuts down and remains turned off until its input is pulled high and then low again. It also features an overtemperature shut-down which triggers at $150°C$ and will also latch the SPS in shut down until re-enabled. The device’s product summary may be found in Figure 32.

Product Summary

Overvoltage protection	$V_{bb(AZ)}$	62	V
Output clamp	$V_{ON(CL)}$	44	V
Operating voltage	$V_{bb(on)}$	5.0 ... 34	V
On-state resistance	R_{ON}	2.5	mΩ
Load current (ISO)	$I_{L(ISO)}$	165	A
Short circuit current limitation	$I_{L(SCp)}$	520	A
Current sense ratio	$I_L : I_{IS}$	30 000	

Figure 32: Product summary for Infineon's BTS555 [27]

In order to find whether the device fulfil the requirements set out by Scania, testing according to internal document, TB1901, was carried out.

11.1.1 Test setup

The test setup may be found in Figure 33. The BTS was connected so that its tab was coupled to a 15 A $30\ A$ blade fuse which in turn was coupled to a switch mode power supply. The output pins of the BTS were coupled to an electronic load. On the load’s secondary side was a $1.417\ m\Omega$ series shunt for current measurements. The shunt was connected to supply ground.

On the BTS sense pin, a $1\ k\Omega$ resistance was connected to ground. Both the sense signal and shunt measurements were acquired using an oscilloscope with $50\ \Omega$ internal termination in order to avoid noise.

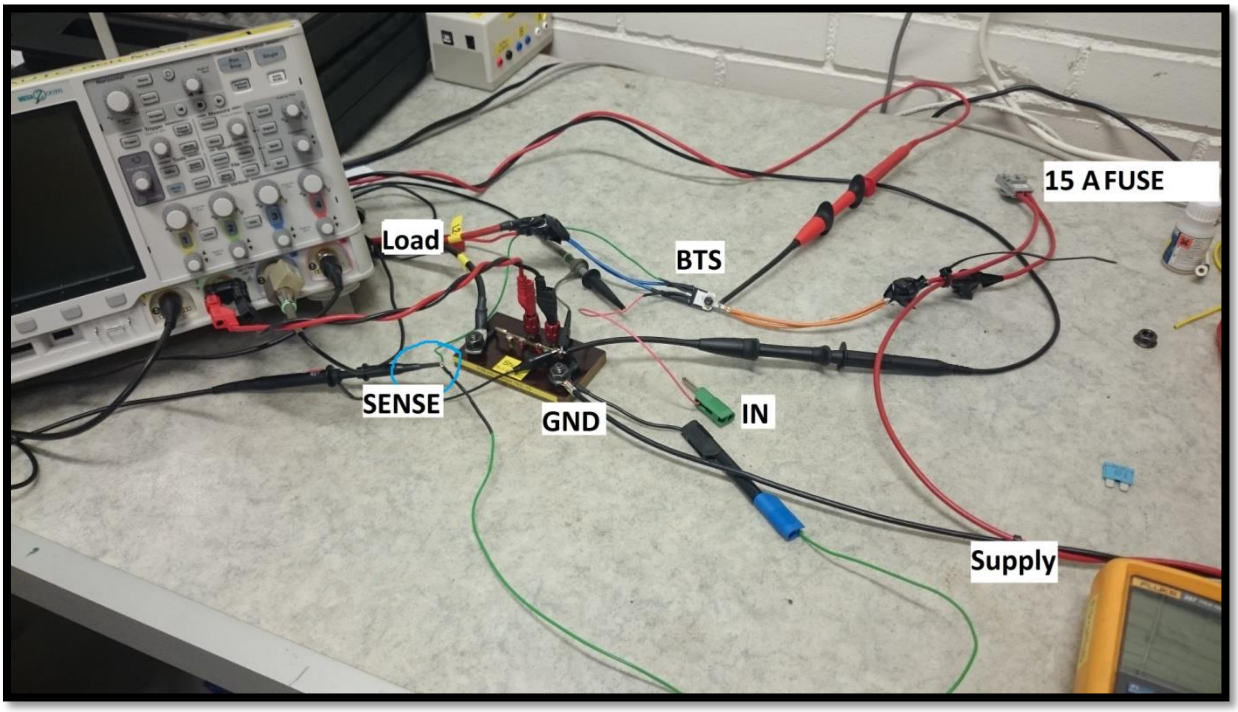


Figure 33: Setup for evaluating the BTS555

11.1.2 Testing

The BTS was tested for “normal operation”, meaning the electronic load was set to 20 A and a hard short circuit to ground was introduced at the output of the BTS. Out of 8 attempts, the BTS automatically interrupted the current in between 130 and $150\ \mu s$ for all attempts. This time was too short for the blow-out fuse to trip. No noticeable heating of the BTS occurred during any part of this test. While testing its function with high ambient temperature, T_{amb}, the internal protective functionality shut the component down at $T_{amb} = 90^{\circ}C$ and $I = 20\ A$.

Testing was performed during lowering of the supply voltage, leading to a shut-down of the BTS at $3.7\ V$. Operation was resumed as soon as voltage was above this level. At an increase in voltage up to 50 V, no changes to the operation were noted.

When disabling the device by disconnecting the control pin, a quiescent current of $24.4\ \mu A$ was measured. This is a level accepted by ISO 8820-3 where it is stated that a tripped blade fuse may only conduct $0.5\ mA$.

Increasing the supply voltage to 38 V during an hour did not affect the function of the BTS in any noticeable way. Removing one or several connections to the BTS did not affect it either. While applying a reverse voltage however, the device was extensively heated and eventually broke down. This was however most probably caused by there not being a current limitation on the input connection in the test setup.

Reversing supply and output on the BTS yielded that it would conduct current as normal when the supply voltage was higher than 3.7 V. Otherwise, only the diode would conduct current, and heating occur.

Applying a short circuit to ground on the device’s output generated a current peak of up to $1\ kA$ before the device turned itself off. Turn-off occurred within approximately $230\ \mu s$ from introduction of the short-circuit. Short circuit behaviour is shown in Figure 34. The figure shows measured current through the BTS and voltage measured between BTS output and ground. The voltage drops distinctly when the fault is introduced, and the current measured by the shunt starts to increase, whereas the current studied through the BTS sense signal initially decreases but then starts to increase.

Studying the current measured at the shunt, it may be seen that it does not instantly reach its peak value, but has a rise time. This rise time is caused by inductances in the circuit. The current obtained from the sense output does not respond instantly to the increased current measured at the shunt. It does however increase rapidly after approximately $50\ \mu s$ after the fault has occurred and saturates at approximately $100\ A$. This is due to internal limitations of the BTS.

The negative current measured at the shunt coincides with the occurrence of a positive voltage, and it is likely, but not certain, that this is caused by internal capacitances in the BTS.

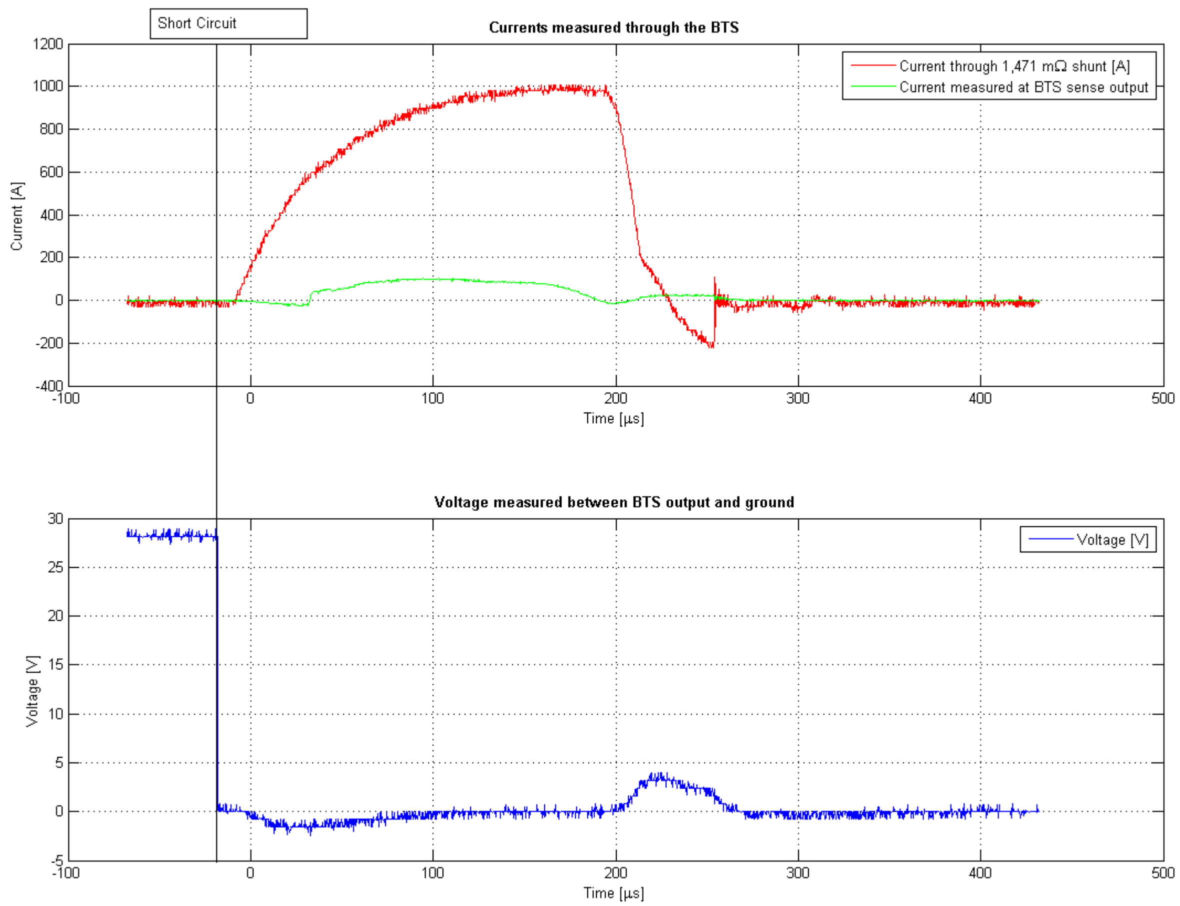


Figure 34: Short circuit testing of BTS555

In addition to the testing described above, the BTS was also subjected to ESD of up to $8\ kV$.

11.1.3 Concluding remarks

From the performed tests it could be concluded that the BTS555, on its own, fulfil several of the requirements set out by Scania for 24 V electrical devices in TB1901. Testing with transient pulses could however not be performed due to heavy use of the testing equipment.

11.2 Concept evaluation of anti-serial MOSFETs

As was described in section 4.5, one way of breaking regenerative currents is to connect two MOSFETs anti-serial. In order to make this work, a drive circuit need to be used. The drive circuit's purpose is to generate a potential relative to the MOSFET's source terminal in order to bias the gate enough so that the MOSFET starts to conduct.

One option is to use the circuit depicted in Figure 35. In this setup, the MOSFETs' source terminals are coupled together and connected to the IN-pin of an LM5050 OR-ing driver. The LM5050 is specifically designed to act as an "ideal diode rectifier", meaning that it controls the voltage drop of a MOSFET by biasing the gate until a certain voltage drop is achieved. For further information about the circuit, it is advised to have a look at the component's datasheet. [28]

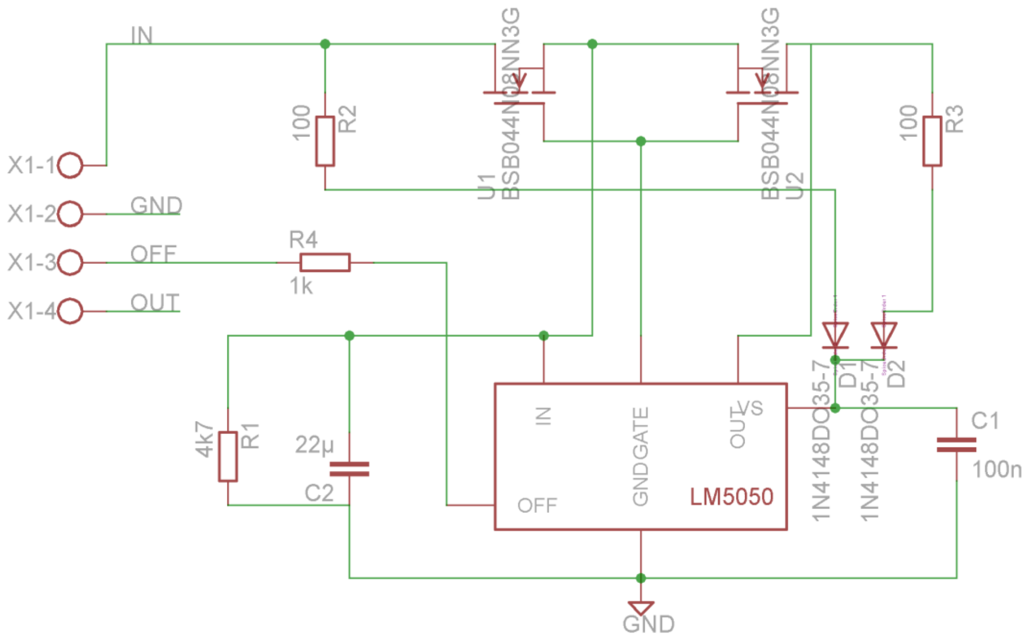


Figure 35: Anti-serial MOSFETs with LM5050 drive circuit. A solution proposed by Jan Hellgren, RECU.

The proposed circuit draws its power from either drain-side of the two MOSFETs, depending on which one have the higher voltage. The power is drawn through a $100\,\Omega$ resistor and a rectifying diode. In the circuit, connected between IN-pin and ground is a $4.7\,k\Omega$ resistor in parallel with a $22\mu F$ capacitor. These are for making the LM5050 start its internal charge pump. For controlling the MOSFETs, there is an OFF-pin, which disables the LM5050 if pulled high. The implemented circuit is shown in Figure 36.

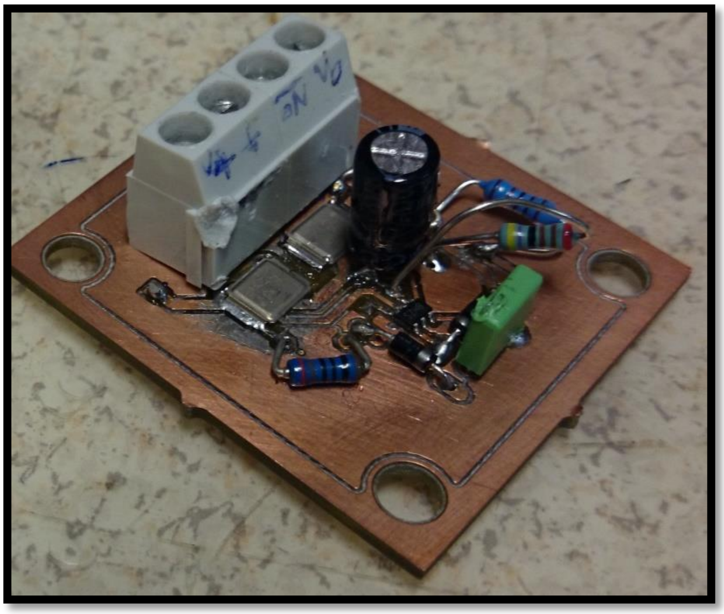


Figure 36: Circuit for evaluating anti-serial MOSFETs

As might be understood from the description above, the LM5050 is only designed to allow a forward current to pass the MOSFETs. In other words, if reverse biased, the LM5050 will turn off the MOSFETs.

11.2.1 Results

The circuit was connected to a 28 V switched mode power supply and a resistive load connected to the output of the circuit. Initially, the OFF-pin was connected to a 5 V supply, but when pulled low, the circuit started conducting. The current rise time was however in the order of $1\ ms$. Pulling the OFF pin high once again, current was interrupted but the fall-time in the order of $100\ \mu s$. In addition, the LM5050 regulates the gate-voltage so that the voltage across the MOSFETs is $22\ mV$ even if it is possible to achieve smaller losses.

11.2.2 Remarks

The LM5050 is not perfect for fusing applications since it is not designed to allow reverse currents and because of the voltage drop. However, it is useful for demonstration purposes where a reverse current is not wanted. If reverse action is required it is recommended to use another drive circuit. Note that the drive circuit needs to have an internal or external charge pump in order to continuously provide a high potential to the MOSFETs. I.e. A bootstrap circuit will not suffice.

11.3 Testing of two anti-serial connected SPS

Another solution using the same method is to have two SPS connected anti-serial to each other. Since the SPS have built in drive circuits, these do not need any additional external drive circuit. For testing the concept, two modules each consisting of an International Rectifier AUIPS7125 smart power switch along with a pull-down transistor and current sense resistor were built. The schematic of one module is shown in Figure 37.

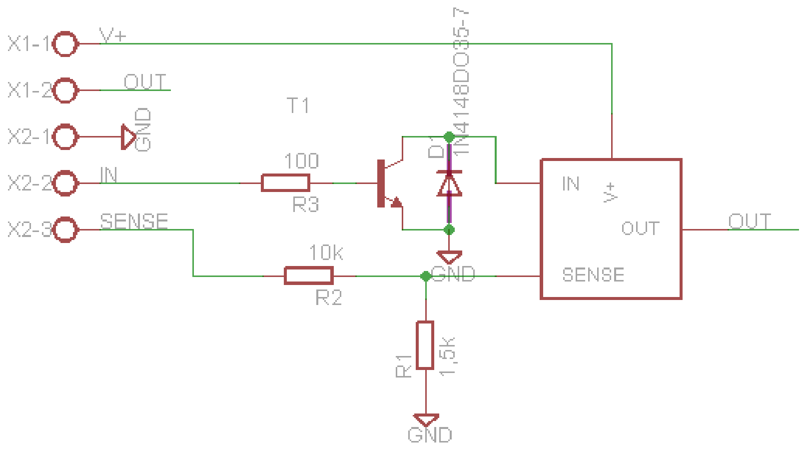


Figure 37: Schematic for an AUIPS7125 test board

When testing, the output terminals of the two boards were coupled together. The V+-terminal of one module was connected to 28 V supply and the other to a resistive load. Pulling the IN-pin of both the SPS low by pulling the transistor base high resulted in a current through the load, and when pulling the IN-pin high again, the current was interrupted. Repeating the procedure when reversing the current gave the same result. Reversing the supply so that 28 V is connected to the circuit's GND and ground to the V+ would for the described configuration however result in a current flowing and potential over-heating as a result. If however the diodes of both circuits are rearranged so that they are located between IN-pin and the transistor collector, and another diode is added in series with the Sense-pin, no current would flow. The present layout is necessary for reverse battery protection if only one SPS is used.

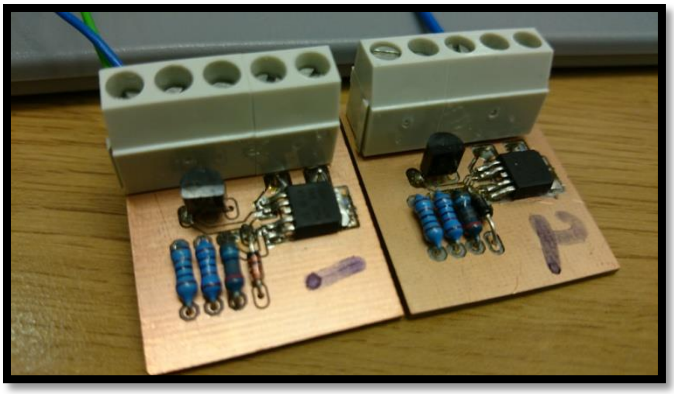


Figure 38: Two modules for evaluating the AUIPS7125RTRL SPS

11.3.1 Concluding remarks

Using two anti-serially connected SPS provide a method to break regenerative currents without an excessive need of additional components. This solution is advised to study further.

11.4 Full fuse demonstrator

For testing the concept of Solid State Fuses, a full feathered demonstrator was designed and built based on the theory discussed above and the prototype circuits built. The demonstrator comprised of four fuse modules, controlled by an AVR type microcontroller. Each channel employed different solutions for breaking the current. They were

1. A single BTS555 smart power switch
2. A single AUIPS7125RTRL smart power switch
3. Two anti-serially connected AUIPS7125RTRL smart power switches
4. Two anti-serially connected AUIRFR3607 MOSFETs

each equipped with necessary control and drive circuitry. For current measurement, a $5\ m\Omega$ shunt resistance was connected at the output of each circuit breaker. The two terminals of the resistance were connected to an INA122U instrument amplifier, which gain had been set to 20x. The amplifier was then connected to the AT90CAN64 AVR MCU.

On the board were also an RS232 transceiver and D-sub9 connector, a CAN transceiver and screw terminals, as well as a 5 V positive voltage regulator. The full schematic is found in Appendix A and the board may be seen in Figure 39. **.**

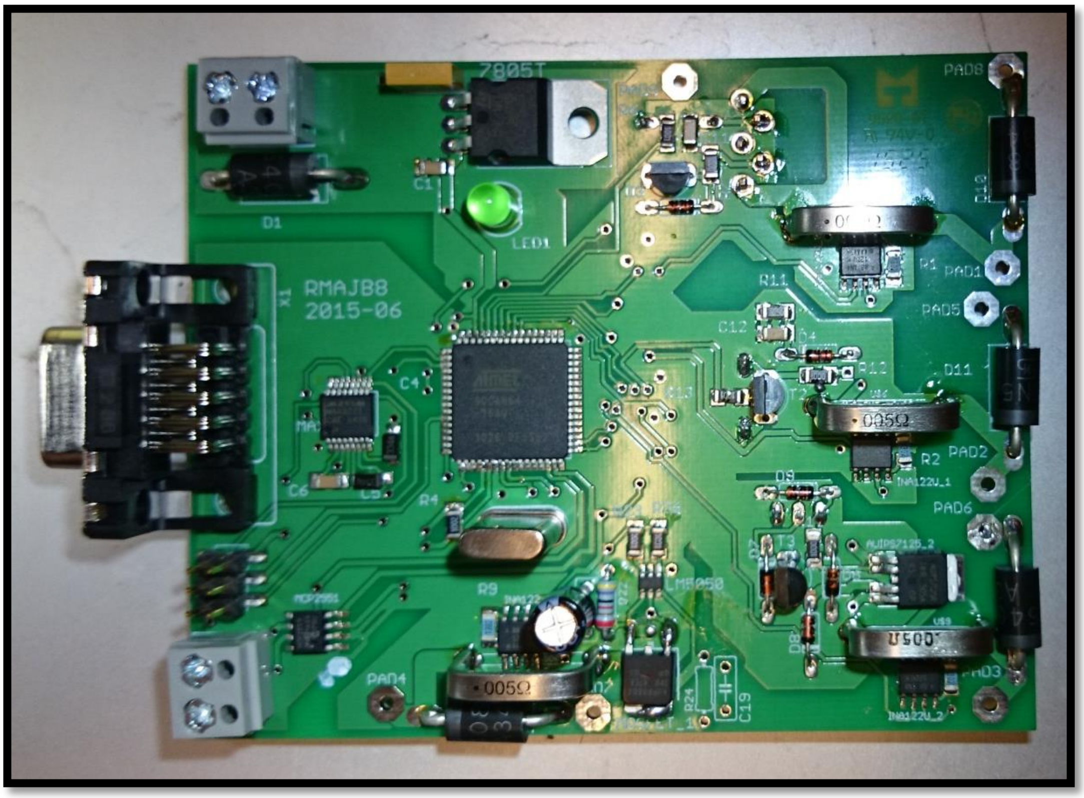


Figure 39: The demonstrator

11.4.1 Evaluation

As was found in chapter 4, inductive loads pose a challenge for semiconductor breakers, therefore one of the more inductive loads of a truck was chosen for evaluating the demonstrator; a window motor. The motor is a permanent magnetized brushed DC-motor, which also yield transients upon commutation. Hence, it is one of the "dirtier" loads of a truck in the sense that it generates distortions and electrical noise.

The tests run using the demonstrator aimed to illustrate the function of SSFs. Therefore only channel 2, equipped with a single AUIPS7125RTRL smart power switch was used and the

MCU configured so that the SPS sense feedback was used for current measurement. Implemented in the MCU was a simple detection scheme using fixed levels for detection. The first second had a limit of 11 A, and thereafter 1.1 A was used as limit. The code is found in Appendix B.

If overcurrent was detected, the MCU disabled the breaker. After one second, the MCU re-enabled the breaker. This process would be repeated three times, and the fourth time the MCU would disable the breaker indefinitely.

11.4.2 Concluding remarks

The demonstrator board functioned almost as intended. The measurement amplifiers had to be changed to a model that handled voltages up to 36 V. Apart from that and not having had time to test the communication ports, the demonstrator may be used as a base for further examination of the concept of Solid State Fuses.

11.5 Overall conclusions from prototypes

The prototypes that have been built show that it is possible to break regenerative currents using MOSFETs, that SPS provide a simple way of including high-side MOSFETs in a circuit, and that it is possible to implement a fuse for an inductive load using an SPS and a MCU. They also show that the BTS555 fulfil a great number of requirements that Scania put on electrical components.

12 Summary

The work that has been made has been separated into three phases; literature study, measurements and prototyping.

During the literature study, it was found that existing solutions include the blow-out fuse and PPTCs. Volkswagen has conducted some research within the area of temperature estimation and Volvo experimented with SSFs in 2008 and before. The study then focused on the semiconductor circuit breaker and in particular the MOSFET and IGBT. It was found that these have limitations when it comes to heat and breaking inductive currents. In addition it was found that the MOSFET has lower losses up to a certain current which depend on the MOSFET's on-state resistance.

Another device that was studied was the Smart Power Switch (SPS). This device consists of a MOSFET with integrated drive circuitry and a number of protective functions. Later on in the thesis, important sections of Scania's requirements on electrical components as well as relevant standards were discussed. It was found that the standard ISO 8820 outline one method for fault detection and states what level of inductive currents a fuse should be able to break.

The measurement phase consisted of characterising cable impedances, loads and faults. Regarding cable inductances it was found that when not fitted to a vehicle, the greatest inductance measured was $11\ \mu H$. Resistances were in the range of less than $1\ \Omega$. Looking at load characteristics, these did not correspond to traditional and theoretical loads. Instead they could more or less be interpreted as stochastic unless outer circumstances were known. The loads drew currents of varying amplitude and which included significant amounts of transient behaviour.

Fault measurements were also performed. These were concluded to either generate current spikes or plain interruptions. Spikes or interruptions could be repeated several times during a fault. Regardless of how the fault manifested itself in current, it was found that a significant voltage drop could be noted between supply and load in all fault cases. It was also noted that the $30\ A$ fuse used for personal protection did not trip in a majority of the fault cases.

Moving on to the prototyping phase, four prototypes, or experiments, were made. First, a SPS was evaluated in relation to Scania's requirements on electrical components, were it was found to meet a most of the requirements it was tested for. Second, a prototype for evaluating a concept of anti-serial MOSFETs was built. The prototype proved that the concept would work for breaking regenerative currents. It was however found that the LM5050 drive circuit used in the prototype only allows currents in the forward direction.

A prototype for testing the concept of anti-serial MOSFETs using SPS was built and it was found that using two anti-serial SPS is a method for breaking regenerative currents that require few additional components. Finally, a full fuse demonstrator was built consisting of four breakers and four measurement modules. A micro processing unit (MCU) was used for detecting faults. As a load, a window motor was used. When evaluating the demonstrator, it was found to work as expected with the mentioned load.

Apart from the above mentioned phases, a brief description of how a Solid State Fuse system may be implemented into a commercial vehicle with regard to information flow was made. It was found that three levels of integration could be chosen; Non-communicating, communicating by dedicated wires and integration with the on-board vehicle network i.e. CAN-bus.

13 Analysis and discussion

In the following, an analysis of the concept of Solid State Fuses will be discussed in relation to the use in heavy vehicles.

13.1 Possibilities of the Solid State Fuse

First, it should be mentioned that the results from experiments and literature studies presented above indicates that the technology is mature for Solid State Fuses. More precisely, the voltage drop is low enough to meet the requirements set out in applicable standards, tripping times are in an accepted range and the current when tripped is low enough. Using additional circuitry, also the demands on breaking inductive currents may be handled.

In theory there is a lot to gain from using SSFs over blow-out fuses. The most significant advantage being that they are virtually access free since they may be reset by software. Because of this, they need not be located accessibly to the user or even have a removable lid. Instead, the SSF unit may be sealed, and installed where convenient from a technical point of view. Thus reducing cable lengths, i.e. material cost, weight and inductances.

Being flexible in its detection scheme, the SSF may freely be adjusted to fit its intended load with regard to permitted currents. Therefore, it is possible to optimize the wiring harness in ways that are not possible with a blow-out fuse due to e.g. tolerances in manufacturing and standards.

Another important aspect of using SSFs is that they offer diagnostic feedback and automatic reset. Using these features could theoretically provide an early warning that a cable is about to malfunction or that a load is not behaving as expected depending on how the SSF is implemented. As an extension, the driver may be alerted and a workshop appointment automatically arranged so that unnecessary vehicle off road (VOR) is avoided.

For the driver, this means no more having to look for a tripped fuse in the weak light from a cell phone by the side of a heavy trafficked road. Instead, the fuse resets itself until it is certain that maintenance is required.

13.2 Limitations of the Solid State Fuse

First and foremost, heat constitutes a major challenge. As could be seen from the testing of the BTS555, its internal protective functionality tripped at $T_{amb} = 90°C$ and $I = 20\ A$. Requirements state that an ambient temperature of $T_{amb} = 125°C$ should be handled if the SSF is to be installed near the powertrain. Apparently, a certain amount of cooling is necessary if it is installed there. One option is to use water cooling, in which case even the harsh environment of the powertrain may be endurable. It is however advised that further studies be made in the area.

The second limitation is the initial cost. This question will be addressed in section 13.6. It should however be mentioned here that the initial cost must be looked at from a wider perspective.

Other challenges are vibrations, breaking of inductive and regenerative currents as well as over voltage. Since there are already a great number of electronic components on a commercial vehicle, it is bound to be concluded that the challenge of vibrations is possible to overcome. Regarding the three other mentioned challenges, these may be overcome by adding external circuitry to the semiconductor circuit breaker.

Measurement of current requires some care when designing the circuit, but this question was addressed in section 3.1.

13.3 Remarks regarding detection

As could be seen from chapter 9, there is a variety of possible detection schemes when using SSFs. The traditional ISO 8820-based scheme has, by practical experiments and gathered experience from Scania, proven to be insufficient. Using SSFs, this scheme could be replaced by more sophisticated methods, able of detecting even a bad connection and intermittent faults. Which of the schemes that is most suited to replace the ISO-based one is however not sufficiently investigated within this thesis. Instead it is proposed that another thesis should be written solely on the subject of detecting a fault.

Worth noting is that Scania has submitted a patent application regarding fault detection using voltage measurements.

13.4 Implementation and technology

When implementing a SSF system intended for a commercial vehicle it is advised to use MOSFET-technology. This is because of the lower losses it brings compared to the IGBT. As could be seen in section 4.2.5, the IGBT have a voltage drop of approximately $2\ V$ whereas the MOSFET has an on-state resistance of a few milliohms. The latter means that several hundred Ampère needs to be drawn by the load in order for the IGBT to be more efficient than the MOSFET.

The IGBT has a higher tolerance to high voltage, but since these high voltages only occur for very short periods of time in a commercial vehicle, a MOSFET may be used with a few additional components for over voltage protection.

Using semiconductor circuit breakers require considerations to be made with regard to

1. Inductive currents (snubber circuit)
2. Regenerative currents (anti-serial breakers)
3. Over voltage (current limited zener diode or grounding transistor)
4. Voltage transients (RC-snubber between breaker terminal and ground)
5. Heat dissipation (heat sinks)

where the proposed remedy is found in parenthesis.

A gate driver circuit is required for controlling the MOSFET. One option is to use an SPS where gate driver and MOSFET are integrated into one device. From the results of evaluating the BTS555 it may even be considered a preferred solution to use SPS as breaking device. In particular, it is advised to use two anti-serial breakers in order to prevent regenerative currents from flowing when the fuse is in its tripped state.

Whereas the SPS often provide an analogue sense feedback, this only provides limited information and the use of an additional measurement device is suggested. This may be constituted by a measurement resistance and a measurement amplifier as described in section 3.1.

For detection, there are several hardware options to use as described in section 3.2. Starting from a vehicle point of view it is not advisable to have a non-communicating SSF system. Not having this kind of system limits the hardware to at least a hybrid system since some logic is required for the communication. Having communication is a requirement for having an access free system, which is one of the greatest advantages of installing an SSF system, which is why a communicating system is strongly recommended.

A hybrid system enables the use of more advanced detection schemes backed up by a crude analogue detection system. One option is that the fall back is the over-current protection function of a SPS which was found to have a fast reaction to solid short circuits in section 11.1.2. If a micro processing unit (MCU) is used as hardware for the detection system, the possibilities to use different detection schemes are virtually unlimited. This is probably desirable when developing an SSF system, but once an adequate detection scheme has been found, it may be implemented in a faster device, for instance a Field Programmable Gate Array (FPGA).

Hardware-wise special care should be taken to EMC-aspects. Since loads have been found to draw transient currents, the SSF system is inevitably going to be exposed to electromagnetic interference. The effect of which is limited by separating the power parts from the detection parts and keeping current loops short.

13.5 Detection

From the performed measurements, it could be concluded that fault detection is a complex question. The simple approach would be to imitate a blow-out fuse, which most likely is easily implemented in software running on an MCU. For this solution, standards already exist and present methods for testing could probably be applied with only minor changes. It was however noted that the $30\ A$ fuse used for personal protection during the fault measurements did not trip in a majority of the fault situations. Therefore it is here advised that further studies should be made on alternative methods of fault detection. A number of alternative methods are proposed in chapter 9. The one that at a first glance appears to have the greatest potential is the voltage based detection scheme. This statement is made based on the fact that for every studied fault situation, a significant voltage drop was noted.

When studying ISO 8820 it is found that tripping should not be instant, as opposed to how Sjöberg and Steen's Active Fuse System and the demonstrator presented in this thesis operate. The purpose of non-instant tripping is to allow loads to have inrush currents, but another reason is likely because blow-out fuses of nature are sluggish. Because of the inrush currents the SSF system need not be infinitely fast, but may instead work in the timescale specified in the ISO. If it is necessary to work faster because an alternative detection scheme is used, this might be solved by using for instance an external analogue envelope filter with a higher bandwidth.

13.6 Economical consideration

The blow-out fuse is cheap and the initial cost of the SSF will inevitably be higher in comparison. Instead, one should study the vehicle level. As was mentioned above, the flexibility of SSFs brings potential for optimization of wiring both with regard to length and cross sectional area, thus reducing wiring costs. If the system in addition can provide early warnings that a cable is beginning to malfunction or a load is misbehaving, there is possibility for increasing the vehicle's up-time, hence lower losses for the transport companies.

Since every SSF in addition to fuse function provide relay functionality, there is weight and size reduction potential also for the system itself.

14 Conclusion

From the work performed in this thesis, it can be seen that the technology is in place for developing Solid State Fuses. No dedicated solution have however been found on the present market during the work. A Solid State Fuse may consist of a semiconductor circuit breaker, a measurement module, a detection module and a gate driver circuit. For breaking the current, a MOSFET solution is advised due to the low voltage drop and thereby low losses. Special care needs to be taken when designing the breaker in order to avoid problems caused by inductive currents, regenerative currents, over voltage and voltage transients. Also heat dissipation needs to be addressed.

From measurements it was found that detection is a complex matter which it is recommended that further studies be made in. The straightforward solution is however to implement the detection scheme outlined in ISO 8820 in a micro processing unit. An accurate method for fault detection was however found to be voltage based detection, where the voltage difference between SSF and load is monitored.

The greatest challenge of making the transition to Solid State Fuses was found to be ambient temperature in combination with heat dissipation. Apart from this challenge, all the studied challenges may be solved by proposed additional circuitry. This includes effects from cable impedances.

A simple simulation model was developed and the ISO 8820 detection scheme was tested with satisfactory results.

A demonstrator was built, showing that an inductive load could be fused using a microprocessor unit based hardware solution with MOSFET circuit breakers. The demonstrator could be used for further studies of Solid State Fuses.

15 Future work

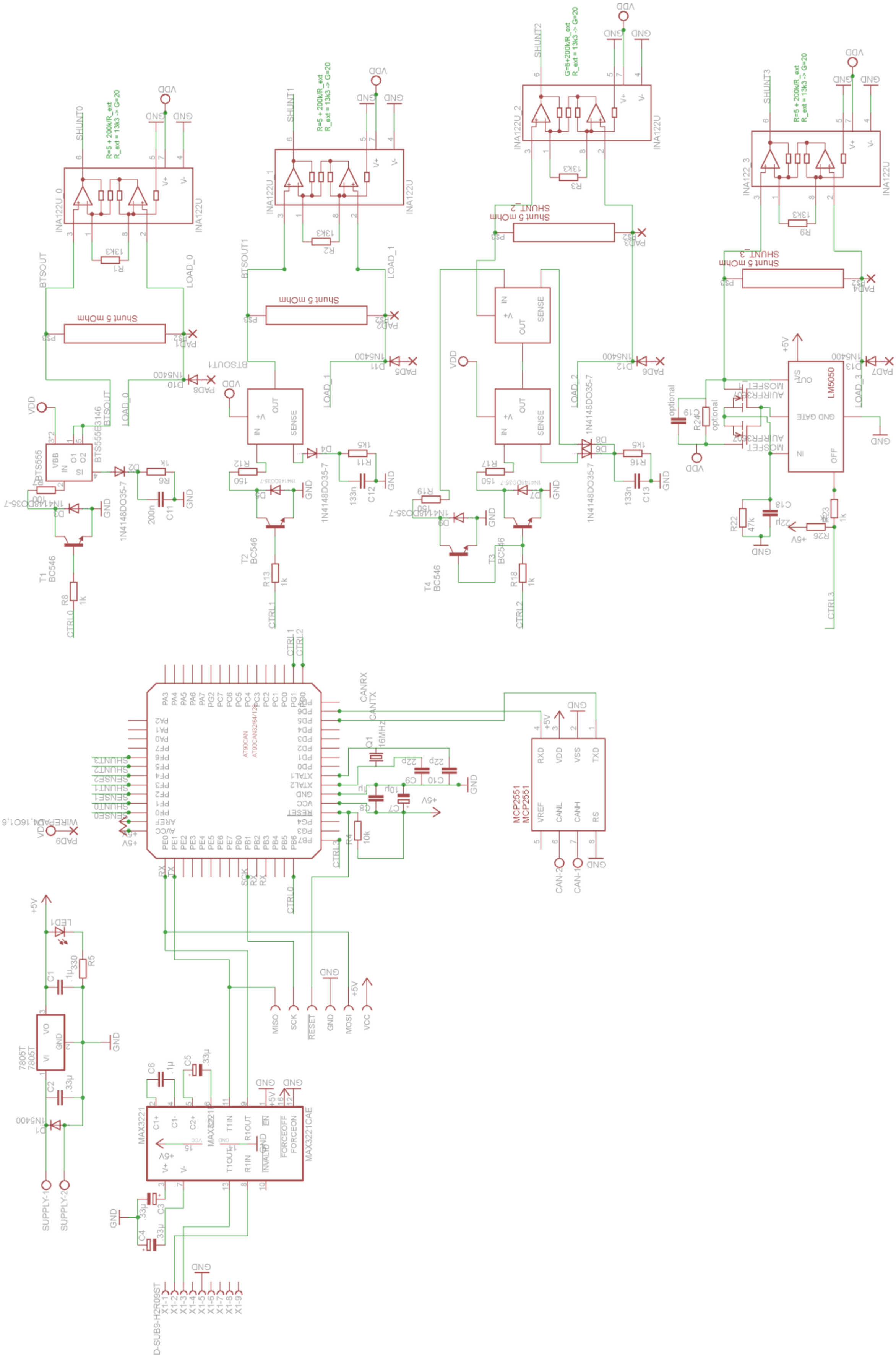
In general there are three tracks for future work on the topic of Solid State Fuses. The first track is an in-depth study of schemes for fault detection. For this track, the demonstrator hardware developed in this thesis could be used since it is based on an AVR microprocessor.

A second track is to further develop hardware in order to meet requirements set out in standards, legal documents and internal requirements. For this track, it is recommended to implement a simple detection scheme and focus on the hardware requirements being met. One area of focus could be to be able to install a SSF system in the powertrain environment.

The third proposed track is vehicle integration. Here it is proposed to investigate which level of communication the SSF system should meet as well as investigating how data from the SSF system may be used in order to provide benefits for the entire vehicle, transport companies and manufacturer.

Another area of work is investigating how to write requirements specifications for Solid State Fuses. It needs to be specified how they should function and how their function should be tested and verified.

Appendix A. Schematic for the demonstrator board



Appendix B. Code run on the demonstrator board

```
/*
 * demo0.c
 *
 * Created: 2015-06-10 13:05:01
 *  Author: rmajb8
 */

/* Include necessary libraries */
#include <avr/io.h>
#include <avr/interrupt.h>

/* Define constants */


#define SENSE0 0
#define SENSE1 2
#define SENSE2 4

#define LIMIT_IDLE 10
#define LIMIT_STARTUP 400
#define LIMIT_STEADYSTATE 40
#define RETRY_LIMIT 3
#define IDLE_STATE 0
#define STARTUP_STATE 1
#define STEADY_STATE 2
#define TRIPPED_STATE 3
#define LATCHED_STATE 4
#define INIT_STATE 5

#define CTCVAL 20
#define STARTUP_TIME 12500
#define INIT_DELAY 12500

#define TRIP0 PORTB = PORTB & ~(1<<PINB6)
#define TRIP1 PORTG = PORTG & ~(1<<PING1)
#define TRIP2 PORTG = PORTG & ~(1<<PING0)
#define CLOSE0 PORTB |= (1<<PINB6);
#define CLOSE1 PORTG |= (1<<PING1);
#define CLOSE2 PORTG |= (1>>PING0);

/* Declare global variables */
uint16_t current_state;
uint8_t limit_state;
uint8_t retries;
uint16_t cnt;

/* Function for reading ADC channel ch.
Return is a 10-bit unsigned integer where 1023 corresponds to µC's
AREF */
uint16_t read_current(uint8_t ch) {
      ADMUX = ch;
```

```
      ADCSRA |= 1<<ADSC;
      while(ADCSRA & (1<<ADSC));
      return ADC;
}

/* Function for updating states. Currently working as an exponential
filter as:
y_n = (x_n + x_(n-1))/2 */
uint16_t update_state(uint16_t new, uint16_t old) {
      uint32_t inter = new + old;      //Perform summation (since
both inputs are uint16, there is a risk of overflow/truncation if
uint32 is not used for the intermediate result.)
      return (uint16_t)(inter>>1);     //Divide by 2 (Bitwise right-
shift 1 position and result is less than 2^16)
}

int main(void)
{
      /* Initialize global variables */
      cnt = 0;
      limit_state = INIT_STATE;

      /* Set data direction registers */
      DDRB |= (1<<PINB6) | (1<<PINB7);
      DDRG |= (1<<PING0) | (1<<PING1);

      /* Initialize ADC */
      ADCSRA |= (1<<ADEN) | (1<<ADPS0) | (1<<ADPS1) | (1<<ADPS2);

      /* Initialize timer */
      TCCR0A |= (1<<WGM01) | (1<<CS00) | (1<<CS01);
      OCR0A = 50;
      TIMSK0 |= (1<<OCIE0A);

      sei();

    while(1)
    {
        //TODO:: Please write your application code
    }
}

/* Timer0 compare match interrupt handler */
ISR(TIMER0_COMP_vect) {
      cli();     //Disable interrupts
      current_state = read_current(SENSE1); // Read ADC and filter
the value
      /* Event handler */
      switch(limit_state) {
            /* Load is idling */
            case IDLE_STATE:
            if (current_state>LIMIT_IDLE)
            {
                  limit_state = STARTUP_STATE;
                  cnt = 0;
            }
```

```
        break;
        /* Load is starting up */
        case STARTUP_STATE: if (cnt >= STARTUP_TIME)
        {
              limit_state = STEADY_STATE;
        }
        else if(current_state > LIMIT_STARTUP)
        {
              TRIP1;
              limit_state = TRIPPED_STATE;
              retries++;
              cnt = 0;
        } else {
        cnt++;
        }
        break;
        /* Load is in steady state */
        case STEADY_STATE: if (current_state>LIMIT_STEADYSTATE)
        {
              TRIP1;
              PORTG = 0;
              limit_state = TRIPPED_STATE;
              retries++;
              cnt = 0;
        }
        break;
        /* Fuse has tripped */
        case TRIPPED_STATE: if(retries > RETRY_LIMIT) {
              limit_state = LATCHED_STATE;
              PORTB = PORTB & ~(1<<PINB7);
        } else if (cnt>=STARTUP_TIME)
        {
              limit_state = IDLE_STATE;
              CLOSE1;
              cnt = 0;
        } else {
              cnt++;
        }
        break;
        /* Fuse is starting up */
        case INIT_STATE: if (cnt>=INIT_DELAY)
        {
              cnt = 0;
              limit_state = IDLE_STATE;
              CLOSE1;
        } else {
              cnt++;
        }
        break;
    }


    sei();      //Re-enable interrupts
}
```

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