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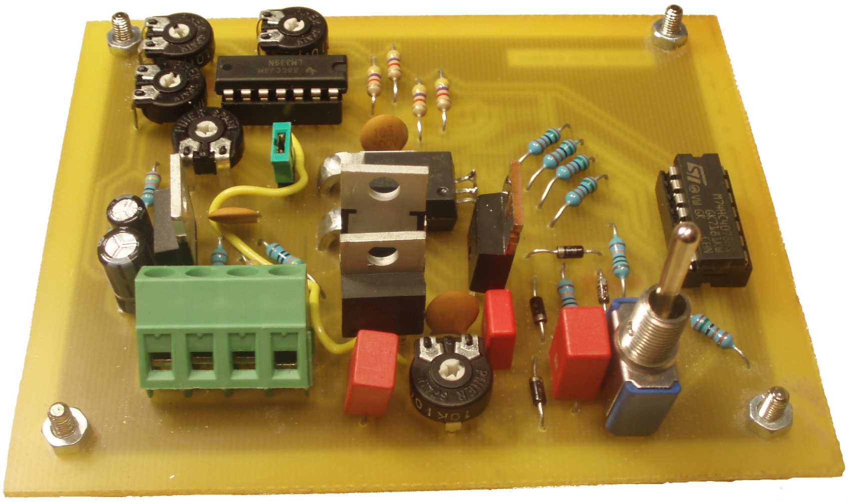

Active Fuse System

Improvements on the fuse system in commercial vehicles

Master of Science Thesis in Electric Power Engineering

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Göteborg, Sweden, 2008

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Cover:
A prototype of an active fuse unit, described in Section 3.3.
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Abstract

In this master thesis work the possibilities with an active fuse system has been investigated, with the background in the increased number of electric loads in commercial vehicles. Different design possibilities have be considered together with implementation alternatives. A prototype was built for testing turn-off times of an analogue switch circuit design. Experiments were also carried out on a power distribution unit, constructed by Volvo 3P in 2003 hereinafter referred to as the PDU, which utilizes a digital switch circuit design.

The results shows that a analogue switch design is to prefer for best protection, with turn-off times down to 0,5μs. The digital switch design was slower in all tests. The power losses for a traditional blow out fuse were compared to the prototype showing an equal power loss up to 10A and a greater power loss in the prototype afterward.

A mix of an analogue and digital circuitry design was thought as the best alternative. This design will have rapid response times and flexible fuse levels together with diagnostic features. The implementation of the active fuse system in a commercial vehicle has to be evaluated with respect to case specific needs.

Keyword: Active fuse system, SPS, MOSFET, Blow out fuse, PROFET.

Summary

The electric system in heavy vehicles has seen a great expansion to meet the increasing demands on emissions, fuel economy and comfort. An electric control system is more efficient than a mechanical system. The increase of comfort electric auxiliaries e.g window lifts, GPS and servos has contributed to the expansion of the electric control system.

The expansion of the electric system increases the demand on the fusing system to be safe and reliable. The traditional fuse system has disadvantages in low accuracy and inability to protect from different faults that could occur in a commercial vehicle such as over-voltage and transient. The traditional fuse system also has difficulties in fusing loads with high inrush currents in a flexible way.

This report will discuss how an active fuse system could be implemented in a vehicle, how to gain most of the system and how the system can be designed.

An active fuse system continuously measures the current, voltage and temperature to know when to turn off the circuit. By using a microcontroller several advantages are gained, e.g. diagnostic features and the possibility of real time dependent fusing levels.

The integration of an active fuse system could be done in several ways. Most advantages are gained if the system is integrated in the Electronic Control Units (ECUs). To use active fuses in every ECU are not likely. Instead the active fuses could be introduced in ECUs that today already uses semiconductors to turn on/off the loads to minimize the number of components. By using active fuses for ECUs that controls sensitive loads or for loads where faults often occur, the increased diagnostic feature and level of safety can overcome the increased cost. Another solution is introduction of a central active fuse unit that fuses several loads. By communicating with the ECUs the existing switches could be used to increase the fault isolation. From an economical point of view this solution is preferred but has its drawback in less diagnostic ability. A central active fuse unit can be combined with specific active fuses for sensitive loads where measurements are vital.

A prototype of an active fuse unit was constructed and evaluated to verify the functionality. The prototype was built by analogue components to achieve fast turn-off response time. This prototype was then compared to a software based system, that was constructed by VOLVO 3P in 2003, and is hereinafter referred to as the PDU (Power Distribution Unit).

The prototype has significantly shorter response time compared to both the PDU and a blow out fuse. To avoid damage of cables and sensitive loads hardware based switching is preferred. To gain all advantages with an active fuse system, diagnostic features are required. The architecture design of the active fuse system will depend on how it is integrated in the vehicle.

Acknowledgments

We like to thank our examiner, Assoc. Prof. Torbjörn Thyringer at Chalmers University of Technology and our supervisors Anna Larsson and Henrik Hallberg at Volvo Technology for their guidance and support with this master thesis. We also like to thank Hans Westerlind for his help and knowledge of the PDU.

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List of Abbreviations

Symbols

C_{GD}	Gate-Drain Capacitance
C_{GS}	Gate-Source Capacitance
I_{DS}	Drain-Source Current
$R_{\mathrm{DS(on)}}$	Drain-Source on-state resistance
R_{fuse}	Blow out fuse Resistance
V_{DS}	Drain-Source Voltage
V_{GS}	Gate-Source Voltage

Acronyms

A/D Converter	Analog to Digital Converter
BJT	Bipolar Junction Transistor
CAN	Control Area Network
CE	Construction Equipment
ECU	Electronic Control Unit
GPS	Global Positioning System
IGBT	Insulated Gate Bipolar Transistor
LCM	Light Control Module
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MTBF	Mean Time Between failure
NTC	Negative Temperature Coefficient
PDU	Power Distribution Unit
PPTC	Polymeric Positive Temperature Coefficient Device
PWM	Pulse Width Modulation
SoC	State of Charge
SoH	State of Health
SPS	Smart Power Switch
TVS	Transient Voltage Suppressors
VDC	Voltage Direct Current

1 Introduction

1.1 Background

The blow out fuse was invented in the 19th century and has been used in vehicles since the beginning of the automotive industry. The fuse consists of two connection plates connected with a fuse element. The fuse element can withstand a certain current level and if this level is exceeded, the element melts and opens the circuit. Depending on the characteristics of the fuse element it will withstand different current levels. The main objectives of the fuse is to protect the cable harness from over-current, which can lead to overheated cables, and secondly to protect the load. In figure 1 a blade fuse, commonly used in vehicles, is shown.

Figure 1: A blade fuse.

Once the fuse has blown it has to be replaced with a new fuse. This need of replacement limits the possible locations where the fuse can be placed since it needs to be accessible. The electric system in a vehicle contains many fuses; in a modern truck there are usually more than 80 fuses. They are arranged in different fusing levels to minimize the number of loads that are turned off when a fault occurs, but also to minimize the cable dimensions.

Even though the traditional fuse system works, there are some improvements that could be done. Besides the need of replacement, the blow out fuse turns off the circuit in case of failure without giving any information on why. It also lacks in protecting from other faults than over-current, such as over-voltages and reversed polarity faults.

A more sophisticated system where the safety is higher and the troubleshooting is easier is desired. This can be achieved by an active fuse system. An active fuse system can be realized in different ways but the fundamental idea is to monitor changes in the circuit and switch off the circuit when a fault occurs. In this way a more accurate fuse system can be achieved with the possibility of better diagnostic features. The information of the changes can be used to analyze the fault. The system can restart itself after a while to see if the fault was temporary or not. When the fault is corrected the circuit can switch on again without replacing the fuse.

The need for electric power in commercial vehicles is increasing continuously, increasing the possibility of electric faults. As a consequence this puts higher demand on the protection system. The traditional fuse system is based on an old technique that has several shortcomings, see Section 2.3, and improvements are desired.

1.2 Purpose/Aim

The aim of this project is to investigate how an active fuse system could be implemented in a commercial vehicle, replacing the traditional blow out fuse. Different active fuse system configurations is to be analyzed. A prototype utilizing analogue switching is to be constructed. Tests is to be carried out, both on the prototype and on a Power Distribution Unit (PDU), utilizing digital switching. Comparison between the PDU, prototype and blow out fuses is to be analyzed. The PDU is also to be used to investigate the diagnostic possibilities of an active fuse system.

1.3 Limitations

The electrical system in a commercial vehicle is complex and consists of many different subsystems. To analyze all subsystems and all types of loads is a time consuming work. Many subsystems can be fused in the same manner, therefore the electric loads and subsystems will be treated in general.

Another limitation is testing of the hardware configuration and the active fuse system architecture. To implement diagnostic features in the prototype, a microcontroller is needed, together with working software. Therefore these features are only handled in theory and not tested more than in the PDU.

1.4 Disposition

The report is divided into four different chapters. Chapter 1 presents the background, aim and limitations. In Chapter 2 the theory behind this thesis is presented and different fuse types and systems are explained. Chapter 3 describes the experimental set-up and how the experiments was carried out, together with the results. Chapter 4 contains the discussion and conclusion of the results and further work.

2 Theory

This chapter will give an insight in the electric system of a vehicle and different ways of protecting the system.

2.1 The electric system in commercial vehicles

The electric system in commercial vehicles has seen a great expansion to meet the increasing demands on emissions and fuel economy. It is the control and adjustments on the different processes, previously done in a mechanical manner that is now carried out with electronics. Increasing comfort through electric auxiliaries e.g. GPS and window lifts has put demand on the electric control and power supply. Also loads, previously supplied through mechanical power transfer are replaced with electric supply for higher energy efficiency. The advantage with an electronic control system is that the system easily can be adapted to variations and changed conditions. The accuracy of the electronic control system also has a key role for the evolution. The electric system is divided into subsystems, where each subsystem is designed for a specific need, e.g. supplying power to electric equipment, start up system and instrument utility. By using an electronic control system not only the efficiency is increased, but also diagnostic features are introduced. Another gain with an electric control system is the simplicity in customizing vehicles for specific needs, e.g. changing motor adjustments.

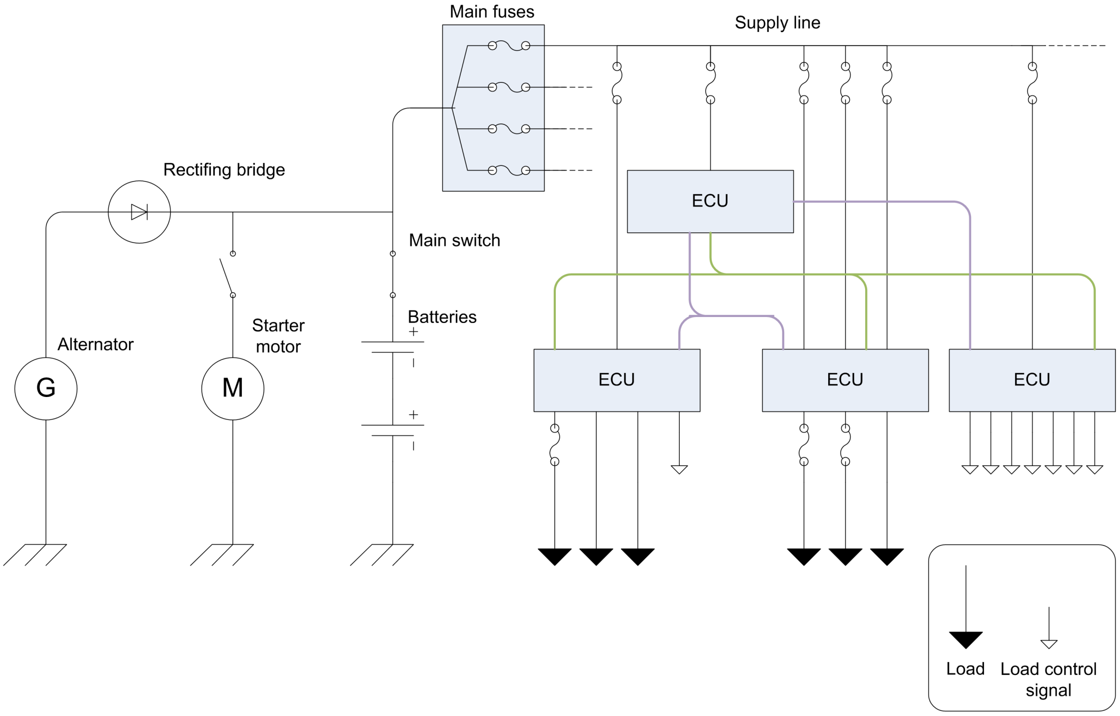


Figure 2: Overview of the electric system in a vehicle.

On the European market the electric system in commercial vehicles is supplied with two 12VDC batteries configured in series for a 24VDC voltage level. The batteries are charged through a rectifying bridge from the alternator, as can be seen in Figure 2. The starter motor is supplied from the same power bus as the alternator. This power bus is not protected with any fuse because of the high inrush current to the starter motor, see

Section 2.2.1. Toward the rest of the vehicle loads, the network is divided into several power buses. Each bus is dimensioned with respect to the total load and protected with the appropriate fuse to secure the cable. Between the power bus and the loads, electronic control units (ECUs) are placed. Each main component in the vehicle is controlled by its own ECU. Depending on the specific use of each ECU, it is supplied through one or more fuses. The ECUs can for example be used to distribute and control power throughput or for parameter regulation. The ECUs are connected to two communication networks, one control parameter network, represented as purple in Figure 2, for fast communication between one or a few ECUs, and one slower information network, represented as green in Figure 2, connecting all ECUs. The information network is also used as a backup for the control parameter network in case of failure. To prevent the electric system from discharging the batteries, when the vehicle is not in use, a main switch is used to break the circuit.

The placements of the loads in respect to the ECUs are visualized in Figure 3. The distance between fuse and load is notably long for, especially loads located in the rear, as the ECUs are located around the cabin. To repair damaged cable harness is difficult due to the distance and routing inside cable channels. For this reason it is of great importance that the cables are properly protected. For loads with high inrush current it is complicated to fuse the cables, the inrush current demand a higher fuse level which will lead to a larger cable diameter.

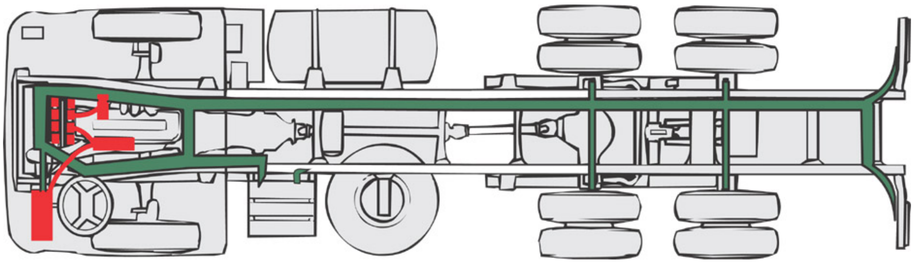


Figure 3: Cable stem in a truck.

There are large differences in the electric system of commercial vehicles. Due to legal regulations, the efficiency has been more important for trucks and buses, than for construction equipments, CE. Due to these regulations, the transition toward a more accurate and thereby more efficient, electronic control system has been faster for trucks than for CE. The production level is also higher for trucks than for CE which reduces the cost per unit of implementing new technology in the vehicle. A halting factor of improving the electric control system in trucks is its cost sensitivity. [10]

2.1.1 Load characteristics

In general, electric loads can be divided into inductive, capacitive and resistive. The current characteristics of these loads during turn-on and turn-off can be seen in Figure 4. The inductive load current characteristics can be explained with

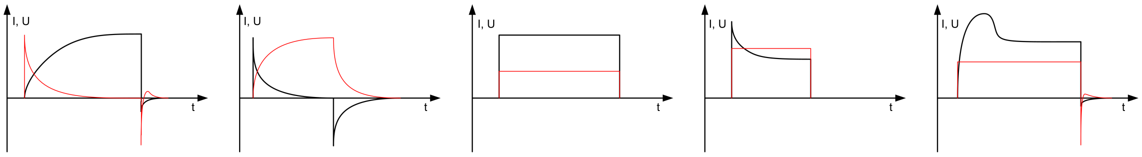
$$v_L = -L\frac{di_L}{dt}. \tag{1}$$

A rapid current change through the inductive load will result in a large voltage demand, i.e the inductor wants to continue driving the same current at every time instant. This will result in voltage transients during turn-on and turn-off. This current and voltage behavior of the inductive load is characterizing the current stiff property of the inductor as seen in Figure 4(a). The current and voltage characteristics of a capacitive load are on the other hand voltage stiff, leading to current transients as seen in Figure 4(b). It will in the same manner as the inductive load, according to

$$i_C = \frac{1}{C}\frac{dv_C}{dt}, \tag{2}$$

generate current transients during charging and discharging. Capacitive current and voltage characteristics are most seen in power electronics such as voltage regulators etc. In a vehicle some ECUs has a capacitive load characteristic.

A pure resistive load, as seen in Figure 4(c), does not create transients unless its characteristics is changed with thermal properties, such as a lamp, Figure 4(d), then high in-rush currents are generated. The thermal properties of a lamp results in increasing resistance with increasing temperature. The initial low resistance of the lamp will allow a high current to flow. The current heats the lamp rapidly with increasing resistance and a lower current flow as result. Motor load characteristics as seen in Figure 4(e) has a rotating inertia demanding high and rapid current changes during speed changes. The electrical motor can affect the system with an instant disconnect due to the inductive and capacitive characteristics as well as the stored mechanical energy. In vehicles inductive and resistive loads are most common.



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

Figure 4: Current (black) and voltage (red) characteristics for different loads.

2.1.2 Different electrical faults

In an electric system different faults can occur. A short description of the different types and how they can arise in a vehicle is presented in this section. The different faults are:

- Over-current.
- Over-voltage.
- Under-voltage.
- Transient.
- Reverse polarity.

Over-current occurs due to a decrease in the resistance in the circuit. The largest over-current occurs when the circuit is shorted to ground; the resistance is then only dependent on cable resistance and location. The current can rise to a considerable magnitude, a short circuit. When a load is degraded or damaged, its resistance can decrease and thereby cause an over-current situation. Over-current will mainly affect the cables in the vehicle and it is necessary to protect from this fault to avoid overheating.

Over-voltage can have different fault sources, e.g. failure in the voltage regulator or user related fault as jump start with a larger battery or charging with an incompatible charger. Over-voltage could affect many loads but electronics are most sensitive to over-voltage. Current or voltage spikes are called transients and can occur when an inductive or a capacitive load is switched on or off. The duration of a transient is in the range of some 100μs. The most severe transient occurs when the battery is disconnected from the alternator while it is charging, a so called load dump. Electronic loads, e.g. ECUs, are the most sensitive loads against over-voltage and voltage transient. If an ECU is damaged the loads connected to it can be affected. Reverse polarity faults will affect the electric system in the same manner as a voltage transient and are often user related. For instance the battery can be reversely connected after service maintenance. [14]

The most common fault in a vehicle is short circuit in the cables which can lead to over-current.

2.2 Different fuse types

Traditionally there have only been blow out fuses in the automotive industry but today there are some alternatives. This section will give an insight in three different types, the traditional blow out fuse, the Polymeric Positive Temperature Coefficient Device (PPTC) and the Smart Power Switch (SPS).

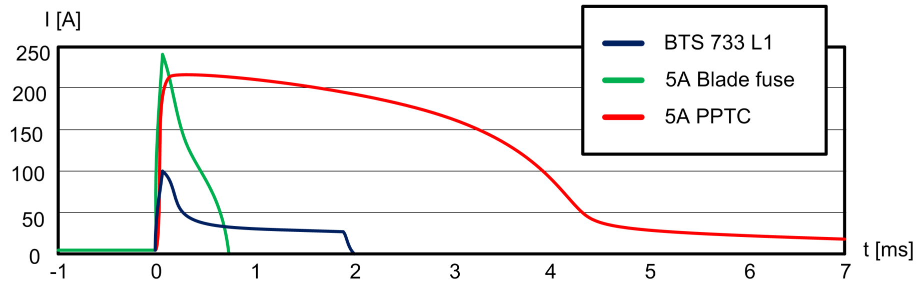


Figure 5: Turn-off characteristics for a 5A blow out fuse, a BTS733 (SPS) and a 5A PPTC at a short circuit event. [10]

2.2.1 Blow out fuse

A traditional fuse system is using temperature sensitive blow out fuses to protect the cables from overheating in the electric system. By placing the fuse between the power source and the load, a protection against over-current is achieved. Under normal conditions the temperature stays at a steady level, below the melting point of the fuse. When a short circuit occurs the current flow increases in the circuit. The current increase will cause thermal energy to be dissipated in the fuse due to the resistive losses. If the temperature exceeds the melting point of the fuse, the fuse melts and the circuit opens. Once the fuse is blown, it needs to be replaced to close the circuit again. The turn-off characteristics in Figure 5 shows a rapid response time for the blow out fuse, but with a high current peak. This is due to the fuse characteristics shown in Figure 7 where the tripping limit is drawn. The fuse will sustain a high current for a short time interval allowing the large current peak mentioned. [10]

Table 1: Opening times with respect to over-current for ATO® FKS-32 fuse. [6]

% of Ampere rating	**Opening time**	
	Min	Max
110%	100h	
135%	750ms	1800s
200%	150ms	5s
350%	40ms	500ms
600%	20ms	100ms

Automotive fuses

For automotive application a so called blade fuse is commonly used, see Figure 1. It is designed for the low voltage electric system used in automotive vehicles. Its dimensions, see Figure 6, are small making a compact installation possible. The nominal cold series resistance, $R_{fuse,nominal}$, varies from 108mΩ for a 1A rated fuse to 1,35mΩ for a 40A rated fuse[6]. The power dissipated in the fuse will vary between the different rated fuses, according to $P=I^2R_{fuse}$. With an increased current the fuse will be heated by the power dissipated in the fuse. The thermal capacitance of the fuse will decide on how much thermal energy that will be transferred to the surrounding before the fuse is activated.

The thermal capacitance varies between the different rated fuses and determine also if a fuse is slow acting, large thermal capacitance, or fast acting, small thermal capacitance.[11] The minimal thermal capacitance of a fuse is ranging from $1A^2s$ for a 1A rated fuse to $2000A^2s$ for a 40A rated fuse [6]. The fuse characteristics can in this way be presented in a time-current diagram seen in Figure 7. The maximum thermal capacitance for ATO fuses is presented in Table 1 in the form of a minimum opening time in respect to over-current. The thermal capacitance is varying between unit samples, this variation is the interval between maximum and minimum opening times for each over current.

Selecting an appropriate fuse is of great importance. To avoid nuisance openings the fuse must be chosen to operate at 75% in 25°C of its rated value. The variation of rated fuse level due to ambient temperature is from about +7% to -9% at a temperature interval from -40°C to 125°C as seen in Figure 8. The fuse is chosen according to

$$I_{catalog-fuse-rating} = \frac{I_{nominal-operation}}{0,75 \times I_{variation}}, \tag{3}$$

where $I_{variation}$ is the correction factor of the fuse as a result of temperature changes, see Figure 8. According to

$$Safetymargin = 1 - \frac{I_{nominal-operation} I_{catalog-fuse-rating}}{}. \tag{4}$$

At 125°C, $P_{temp-margin}$=0,91, the safety margin is calculated to 31,75%, to assure interruption free operation throughout the whole temperature range. The temperature dependence is mostly affecting slow characteristic fuses due to the lower melt temperature compared to the faster fuses. [5] Even with accurate selection of the blow out fuse the MTBF (Mean Time Between Failure) rate of blow out fuses is, according to Bell Communications Research, 67×10^6 hours. [12]

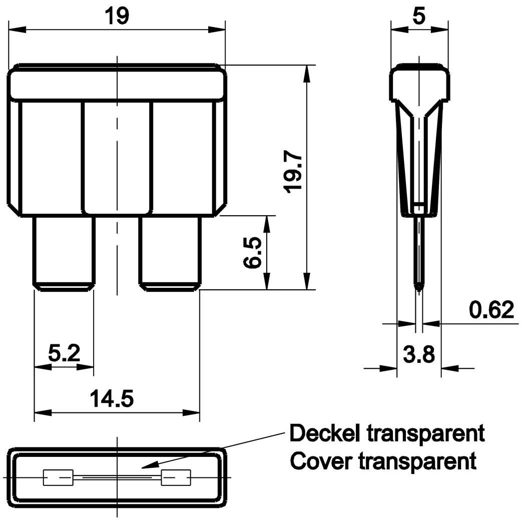


Figure 6: Reference dimensions of an ATO® FKS-32 fuse. [6]

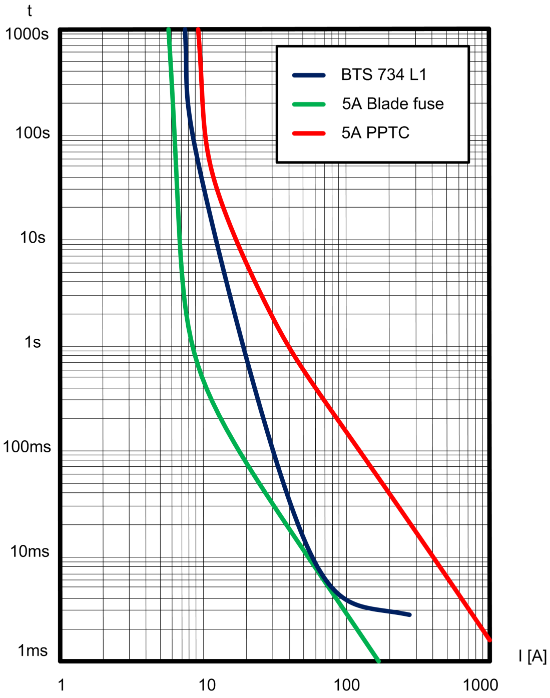


Figure 7: I-t curves for the blow-out fuse, the PPTC and the SPS (BTS734). [10]

2.2.2 Polymeric Positive Temperature Coefficient Device (PPTC)

Another type of temperature sensitive fuse is the PPTC. It consists of semi-crystalline polymer and conducting particles. As the blow out fuse the PPTC reacts on the change of temperature when a fault occurs. Under normal circumstances the polymer operates as a low resistance and when the temperature increases, the volume of the crystals in the polymer increases. This leads to a lower concentration of the conducting particles and the resistance will increase. A higher resistance will accordingly lead to a lower current to the load but it will still conduct. When the circuit is disconnected, by the main switch, the fault can be corrected. As the temperature drops the polymer will decrease in volume and the resistance in the PPTC will decrease, visualized in Figure 5, the PPTC will not have to be replaced.

Because of the temperature sensitivity, a change in the ambient temperature also change the energy required to trip the device. Figure 8 presents the changes in trip current for different temperatures. [11]

2.2.3 Smart Power Switch (SPS)

An SPS can be used in an active fuse system and consists of a Metal Oxide Semiconductor Field Effect Transistor (MOSFET), drive and logic circuit enclosed in one device. The MOSFET is operated by the logic and drive circuit. The majority of the SPSs have additional features such as; current and temperature sensing, protection against short-circuit, over-voltage and over-temperature. The transistor can also be switched manually by a signal to the drive circuit and can thereby also function as a relay. The SPS design and the structural design of the MOSFET will increase the on-state resistance with increasing

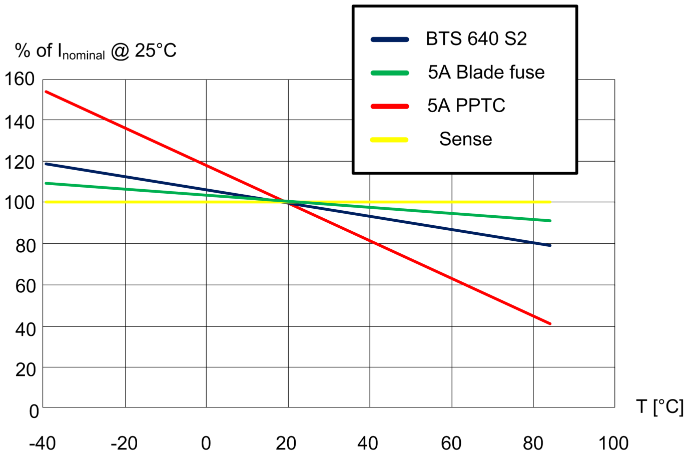
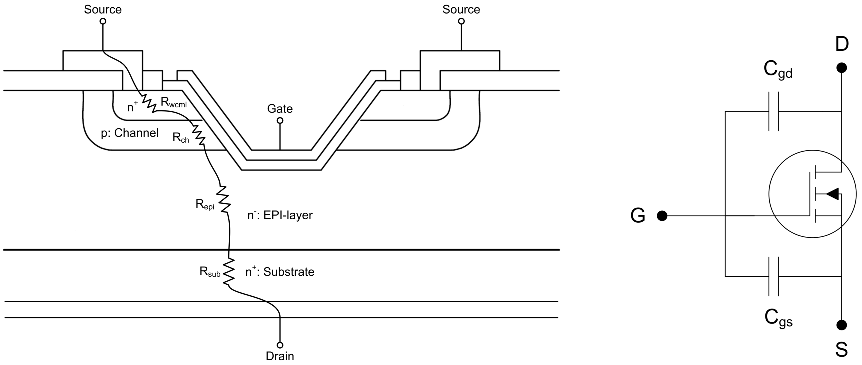


Figure 8: Thermal characteristics for different fuse types. [11]

current and temperature. This is the current limiting ability of the SPS and will limit high current peaks, shown in Figure 5. During current limitation the power is dissipated in the SPS as heat and has to be cooled to not break. With insufficient cooling the fusing level of the SPS is changed, see Figure 8 (BTS 640 S2).

MOSFET properties

When using a MOSFET as a switch in a fuse or SPS application the on-state resistance, $r_{DS(on)}$, and turn-off time are parameters of great interest. The on-state resistance varies from a couple of 100$\mu\Omega$'s to several 100mΩ's. The specific MOSFET designed to handle great power throughput is the power MOSFET. The power MOSFETs are manufactured with varying physical architecture designs depending on brand. Each design comes with both advantages and disadvantages in terms of manufacturing cost, cell density and performance. The structural design decides important parameters such as avalanche ruggedness, it also affects the size of the $r_{DS(on)}$ and the parasitic capacitances, seen in Figure 9(a) and Figure 9(b).



(a) $r_{DS(on)}$ dependency on the MOSFETs internal physical architecture.

(b) Simplified equivalent circuit of the MOSFET during turn-off.

Figure 9: MOSFET properties and equivalent circuit.

For low voltage devices the package, metallization and source resistance, R_{wcml}, together with the channel resistance, R_{ch}, constitute the majority of $r_{DS(on)}$. This makes the mounting of the device of great importance. For high voltage devices the epi-layer constitutes over 90 % of $r_{DS(on)}$. The on-state resistance has a positive temperature coefficient, i.e. the resistance will increase with the temperature. This effect is a result of the decrease of electron mobility with temperature. [13] [1]

To rapidly switch a MOSFET, the switch procedure of the device has to be understood. An equivalent model of a MOSFET during turn-off can be seen in Figure 9(b). The turn-off procedure can be divided into four time intervals shown in Figure 10. The total turn-off time is dependent on the parasitic capacitances values of the MOSFET, the voltage over the capacitances and the gate drive current available. During time interval one, the gate-source voltage, V_{GS}, drops to the Miller plateau. In the second time interval, the drain-source voltage, V_{DS}, increases to the supply voltage. During this time the gate-drain capacitance, C_{GD}, is supplied through the bypass capacitance from the drain-source current, I_{DS}, with its charging current, V_{GS} is therefore constant. During the third time interval, the gate-source C_{GS} is discharged to the threshold voltage and I_{DS} reduces to zero. During the fourth time interval, the rest of the energy in the parasitic capacitances of the MOSFET are discharged. [15] [7]

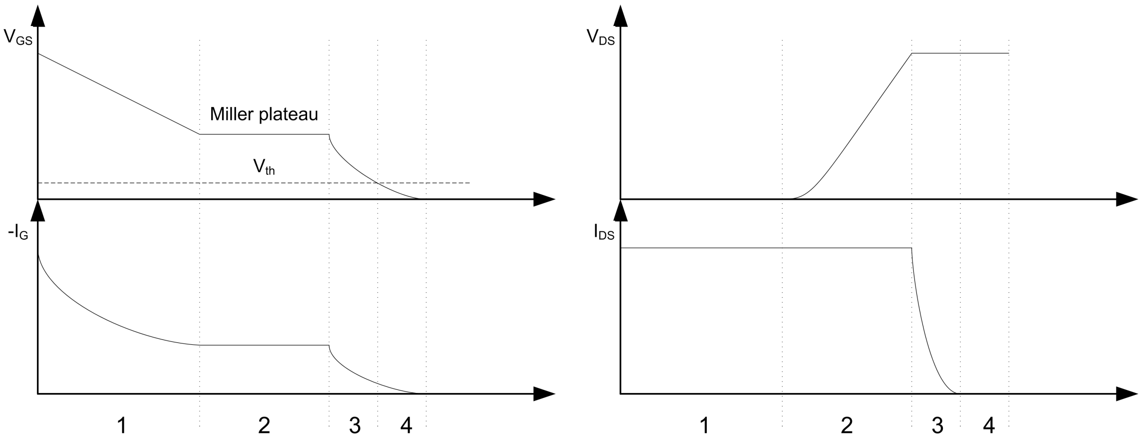


Figure 10: MOSFET turn-off switching waveforms. [16]

PROFET

The PROFET is a series of SPSs with varying properties; either thermal capacitance or active current sensing is used to detect overloads. All PROFETs have an input, a status, a drain and a source pin. The current sensing versions of the PROFET have an additional current output pin, which together with an external resistor will supply a voltage level proportional to the drain-source current. The PROFET has protection and measuring logic, a drive circuit and a power MOSFET. To enable diagnostics the status pin will indicate the failure cause when the PROFET is fused. The PROFET utilizes current limiting, that will be activated if the drain-source voltage exceeds a type-dependent value. The PROFET will limit the load current by decreasing the gate-source voltage, see Figure 11. The internal temperature protection has its limit set to 175°C, when this is exceeded the PROFET turns off the circuit until either satisfactory cooled or a new on-signal is applied to the input. The PROFET also contain an over-voltage protection and a short-circuit detection.

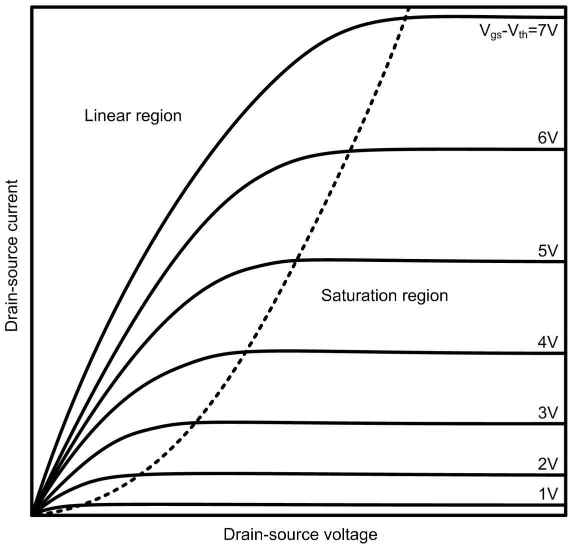


Figure 11: V_{DS} vs. I_{DS} at different V_{GS} levels.

For the variants of PROFETs with thermal short-circuit detection the minimum fusing current is decided on the package and cooling, as well as the type specific thermal characteristics of the device. The minimum fusing current is the border point at which the power absorbed and the power dissipation in the form of heat is balanced. Currents below the minimum fusing current are suitable for continuous operation. Loads resulting in a higher current are only recommended at short times. Using the PROFET at steady-state at the border of the minimum fusing current can result in unit temperatures up to 150°C. It is in this case important with a stable surrounding temperature environment to ensure full functionality.

For current sensing applications the internal current measuring is accurate to ±10% at a load current of 5A and ±50% at 0,5A. The current measurement is independent of temperature in the interval -40°C to 150°C and also independent of the voltage between 6,5V to 27V. If used in conjunction with a microcontroller to complete an active fuse unit, this accuracy is resulting in better precision of the fuse level compared to a conventional fuse. In the active fuse unit configuration, the PROFET will be temperature invariant. The PROFET can be configured in an over-current detection mode by applying a threshold voltage at the sense pin. The trip time will in such configuration be less then 100μs.

When choosing and designing the protection circuitry with a PROFET, the type of PROFET will decide on short term current-time characteristics. The short term current-time characteristics are dependent on fabrication choices, such as the use of different materials for packaging. For the steady-state operation, long term current-time characteristics, the maximum current is exclusively decided on what external cooling and heat sink is used.

2.3 Traditional fuse system

In automotive applications, fuses are mainly utilized to secure the cables from damage that could occur due to over-current. The fuse is chosen with respect to the load characteristics and thereafter the cable choice will be made. The cable will in most cases supply several loads each consuming power at different times. The dimensioning of the cable is done with respect to the maximum count of loads active at any given time. By fusing the system in different branches and fuse levels the amount and dimension of cables can be minimized. Figure 2 shows how the levels are utilized in a vehicle.

For every given load or group of loads, a fuse has to be chosen with respect to the load characteristics. Depending on continuous current load, inrush current and transient current characteristics of the load, a slow- or a fast-acting fuse is chosen. The fuse rating should be matched to the continuous current drawn by the load but it has to withstand higher load currents upon startup or variations in time that is normal characteristics for the load. This match is not always possible, resulting in the choice of a higher rated fuse compromising the safety and protection during normal operation. The choice of a higher rated fuse will allow continuous over-currents through the load without notice, which in the worst case will lead to damage of the load. Loads with very large inrush currents will lack the protection from a melt fuse because of the over dimensioning making it useless. As mentioned above the main task for the fuse is to protect the cables. When the fuse needs to be over dimensioned to suit the load, the cables also needs to be over dimensioned to keep the cables protected.

Regular melt fuses only protect against over-currents during enough time to make it blow. This mainly occurs during short circuits or larger over-currents over a longer time. The sensitivity against this kind of faults is dependent on if the fuse is slow or fast. Faults that are only time dependent will therefore be unnoticed. For example if a load that is meant to be active for a fixed time will lock in its active state, the fuse would not blow. The load can be of such a type that it will cause damage to its surrounding area if it is not turned off. The fuse will in this situation just notice the regular continuous current powering the load without blowing despite the damage that is being done to the environment of the load.

The sensitivity for current and voltage transients varies between different loads. Loads consisting of electronics, e.g. ECUs, are especially sensitive to changes in both current and voltage. These devices are often protected both with a fuse and with internal protections such as schottky diodes or TVS (Transient Voltage Suppressors). High power loads such as electrical motors are less sensitive and internal protection is often not needed. The protection of the load has to be adapted depending on the current and voltage characteristics of the load. The protection system must have load specific properties to ensure the functionality and protection. Once the melt fuse has blown it has to be replaced, meaning it has to be placed in such a way that it is accessible.

2.4 Active fuse system

Various applications require different protection specifications regarding fusing times and the complexity in the fusing structure. Loads also have various current characteristics at turn-on, on-state and turn-off that have to be matched with the proper fuse. An active fuse system can offer the possibility to change its properties to ensure a reliable protection during, and between, turn-on, turn-off and on-state. The system can consist of one or several active fuse units.

Besides the advantage of flexible fuse levels, it can also be resettable and provide protection against other stresses such as over-voltage and temperature. As described in Section 2.2.1 the power losses in a blow out fuse occur due to the inner resistance of the fuse element. An active fuse system has losses both in the switch and in the control circuit for the switch. For high currents, the power losses in the control circuit are small compared to the losses in the switch. With today's top of the line MOSFETs the on-state resistance is below $1\text{m}\Omega$. By choosing components with low power losses the losses can be in the same range as the blow out fuse.

2.4.1 Active fuse unit

The main properties of an active fuse unit is the ability to measure, compare the measurements with predefined limits and react by opening the circuit through a switch in case of a fault.

This functionality can be achieved by arranging the active fuse unit in different ways. Figure 12 is showing active fuse units all containing sensor, logic, drive and switch blocks but with different arrangements. The block scheme in Figure 12a is showing a fully integrated active fuse unit, a Smart Power Switch (SPS), which is produced by several manufacturers. It is a compact solution with all functionality integrated into a single unit making it cost effective. Despite the advantages, the SPS has drawbacks as temperature sensitivity and limited possibility to change the properties, see Section 2.2.3.

To avoid the temperature sensitivity the switch can be excluded from the block and placed separately, as in Figure 12c. The semiconductor manufacture NXP has newly released a product series called IPoC that uses this layout.

The opposite of a fully integrated unit is shown in Figure 12b. The containing blocks are separated and can be chosen more freely making it possible to adapt for application specific needs. Depending on the fuse architecture utilized, an active fuse unit can control several switches to achieve higher fault isolation. The power throughput can be easily adapted by adding more switch modules.

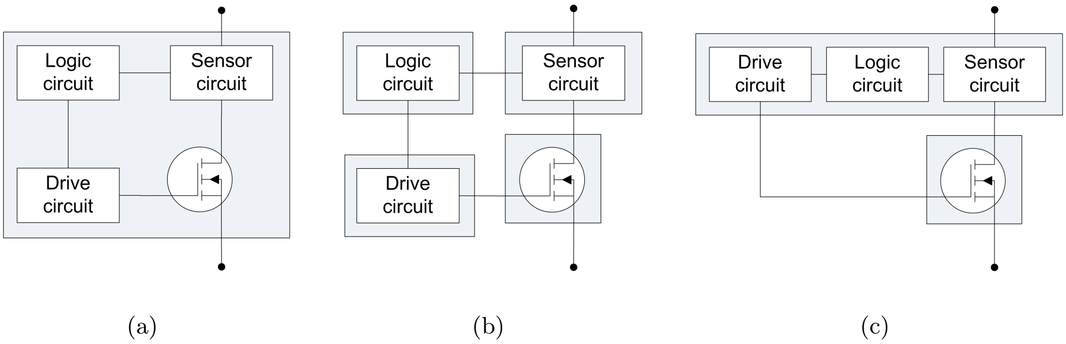


Figure 12: Various block schemes for active fuse systems arrangements.

Switch

The switch circuit handles the load power flow and is responsible for switching it on and off. This can be done by different switching components such as transistors and relays. The main properties of the switch are the turn-off time together with on-state losses and current limiting. Relays have the lowest on-state losses but they are slow and lack the ability to limit the current, this is the main reason why they are not suitable to use as a switch in a fuse application.

Another type of switch is the transistor. There are different types of transistors e.g. IGBT, BJT and MOSFET. Both the BJT and the IGBT has longer turn-off times than the MOSFET but have the possibility to switch higher voltages. For this application the most suitable transistor type is the MOSFET due to its current limiting effect, low forward voltage drop and short switching times compared to the other transistors.

To handle an increasing power demand the MOSFET can be put in parallel. MOSFETs are, compared to the BJTs, easy to configure in a parallel arrangement. The positive temperature coefficient of the on-state resistance will cause a decrease in current flow through the MOSFET with the highest current and the current will distribute evenly over all MOSFETs in the parallel arrangement. A slight difference in initial current is caused by production variations, i.e. $r_{DS(on)}$ will vary between the samples. This initial current difference will decrease with rising current throughput as a result of the positive temperature coefficient of $r_{DS(on)}$.

When connecting two MOSFETs in parallel, a symmetrical layout is preferred. Even the gate-source voltage is best kept the same to ensure equal gate currents when switching. The gate pins should not be connected together directly because of the present stray inductances that may cause high-frequency oscillations together with the gate capacitances. This is avoided by placing a damping resistance in series with each MOSFET gate. [15]

When paralleling the MOSFETs the gate capacitances will add together and result in an increase of the time constants τ_1 and τ_2, see Figure 10. A higher demand will be put on the drive circuit in terms of capability of sinking a higher current to compensate for the increased time constants.

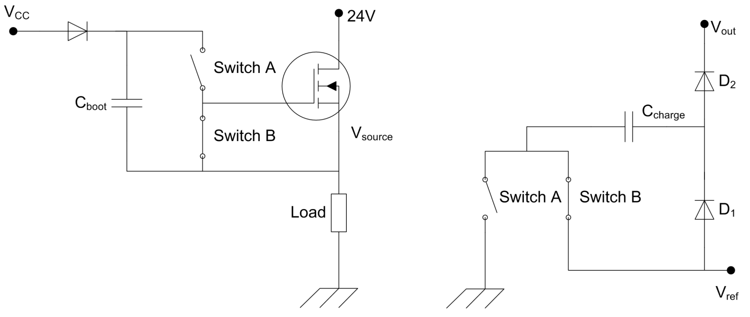
To achieve protection against reversed polarity, two MOSFETs connected in reverse direction to each other must be placed in series to be able to switch the reversed current. [14] Another solution is placing a diode in series with the MOSFET.

Drive circuit

The drive circuit should be able to control the switch in an effective and sufficient way e.g. the switch should not be limited by the drive circuit, nor should it have a significant contribution to the total power loss. The drive circuit is the link between the logic level signal and the switch and should be equipped with electric isolation if required. In a fuse application the switch has to cut the power on the high-side of the load. The load is then protected from faults in the rest of the circuit. A low-side placement of the switch will expose the load to faults in the circuit, even when switched off. The main difference between high-side and low-side drivers is the demand on pushing the gate-source voltage above supply voltage in a high-side application. The gate-source voltage has to be greater than the gate-source threshold voltage specific for the given MOSFET. This is usually achieved with a bootstrap circuit.

In Figure 13(a) the principle of a bootstrap circuit is presented. Switch A and B is controlled by the input signal to the gate. When switch B is closed, the bootstrap capacitor is charged by the supply voltage and the gate is connected to ground. When switch A is closed, the bootstrap capacitor is connected between the source and gate pin of the MOSFET which pushes the gate voltage to $V_s + V_{cc}$. Due to current leakage in the MOSFET, the energy in the capacitor will decrease with time. In an application, like fuse system, where the MOSFET mainly is on, the voltage, V_{GS}, will drop below V_{th} after a certain time and the MOSFET will enter its resistive region. Hence the bootstrap method alone is not suitable for this application. By adding a charge pump that charges C_{boot} when the MOSFET is conducting, a reliable system is achieved.

A charge pump work as a bootstrap circuit but uses an external oscillating circuit to charge/discharge a capacitor. Figure 13(b) presents the principles of a charge pump. When switch A is closed, the capacitor C_{charge} is charged by the reference voltage. When switch B is closed, the voltage over the capacitor pushes V_{out} to $2\times V_{ref}$. In a drive circuit application, V_{ref} is connected to V_s and V_{out} is connected to switch A of the bootstrap



(a) Bootstrap (b) Charge Pump

Figure 13: Bootstrap and charge pump designs.

circuit.

Sensor circuit

To control the load and to know when a fault occurs, current, voltage and temperature measurements are of great importance. A voltage measurement is usually done with a voltage divider and a temperature sensor e.g. an NTC can be used to monitor the temperature. The current can be measured in many different ways. The most obvious way is to measure the voltage drop over a shunt resistance. An alternative is to use a hall sensor that uses the Hall Effect to sense the current. Another alternative is using a MOSFET with internal current and temperature measurements. The internal current measurement measures a voltage over a small resistor, through which a small current proportional to drain-source current flows. The internal temperature measurement is done with a diode build into the MOSFET structure.

The accuracy of the measurements varies with the choice of components, if a high accuracy is needed a more accurate component is used.

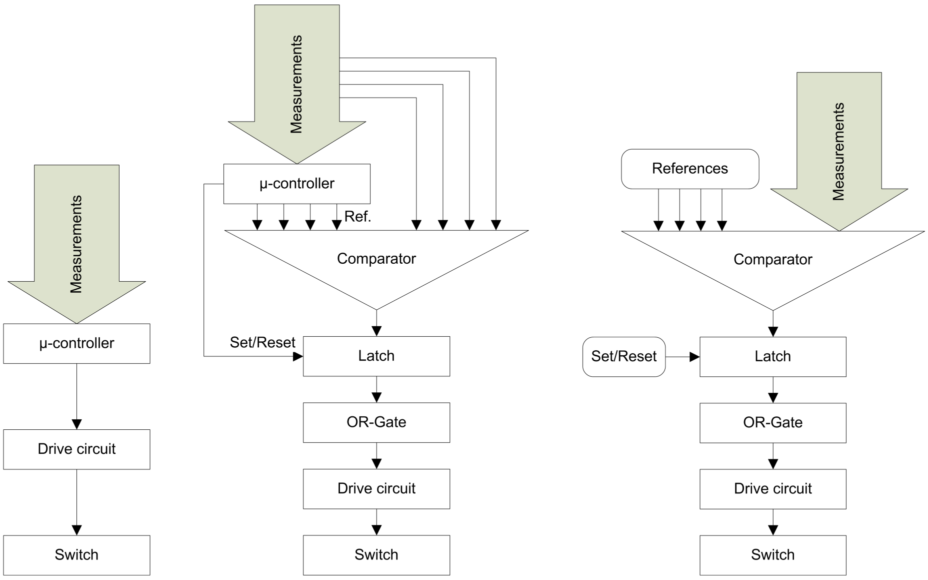
Logic circuit

To know when a fault has occurred and to be able to switch the transistor, the current, temperature and voltage conditions in the system need to be compared with preset limits continuously. This can be made either by hardware circuitry, as in Figure 14(c), or by software with a microcontroller, as in Figure 14(a). The hardware approach gives a faster detection and reaction times compared to a software based system. The software based system will on the other hand be more flexible and need fewer components to achieve the same functionality.

It is of great interest to change the switching limits with time. This will be less complicated with a software based system compared to a hardware based. A mixture of both methods is presented in Figure 14(b), in this way a fast reaction time can be achieved without violating the flexibility of the system.

Diagnostics

To achieve diagnostic features a microcontroller is needed. The most central feature is the recording and storing of fault measurements. It is desirable to detect both slowly



(a) Software

(b) Hardware and software

(c) Hardware

Figure 14: Three different logic-circuit configurations.

or rapid changes in current and voltage e.g. degraded components or a short circuit. The demand on high resolution sampling during rapid faults makes recording and storing for a long time difficult because of the data density. Slowly changing faults does not need high resolution sampling, instead it needs to be sampled over a long time to detect changes.

One solution is to have a short time buffer recording data with high resolution just containing the nearest time prior to the fault. Long term storage of data with lower resolution is acting as a complement to the short time buffer. This solution makes it possible to discover long term changing faults as well as instant faults.

2.4.2 Fuse network architecture

An active fuse system is more expensive than a traditional with blow out fuse but has, as mentioned, several advantages that might overcome the increase in cost. Compromises in cost and diagnostic features must be done when the architecture of an active fuse system is realized. This will effect the level of protection to the limit of what is needed.

The architecture of an active fuse system can be realized in several ways and open up for new ideas according to fusing architecture. As explained in Section 2.3 the traditional fuse system is designed in different fuse levels and branches to increase the level of protection and the fault isolation. Due to the higher accuracy and possibility to use switches that already exist in a vehicle, an active fuse system has the possibility to reduce the total number of fuses dramatically. The dimension and length of the cables can also be minimized due to a more flexible placement of the fuse unit and the higher accuracy.

To replace each blow out fuse with an active fuse unit will lead to a high protection level and diagnostic features but might be unnecessary expensive. Instead the active fuse unit can be combined with blow out fuses to achieve a more cost efficient system with high diagnostic features where it is needed.

A central active fuse unit

Many loads are, especially in a truck or a buss, controlled by a control unit, e.g. the lights are controlled by the Light Control Module (LCM). In the LCM, transistors are used to switch on/off the loads and are controlled by a signal from the CAN-bus.

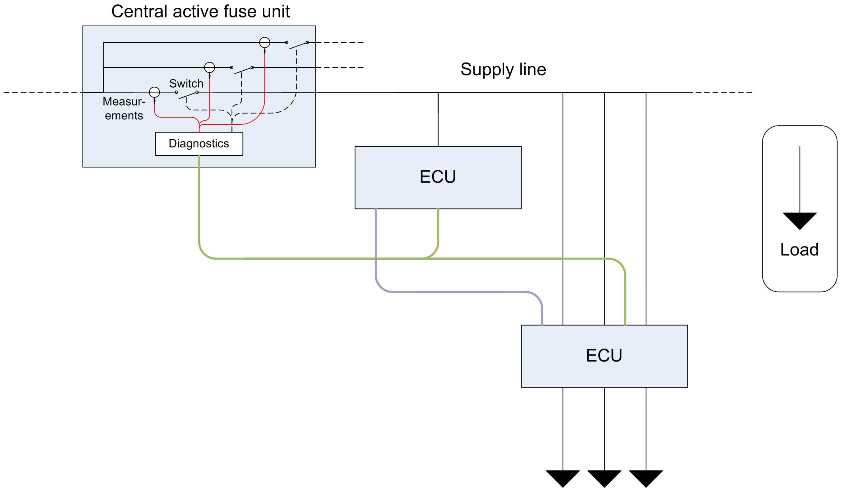


Figure 15: A central active fuse unit.

In Figure 15 one way of designing the active fuse system is presented. The LCM is connected to a central fuse unit that measure and switch off the circuit in case of a fault. The fuse level is regulated according to the characteristic of the active loads. When a fault occurs, the fuse unit switch off the circuit and thereafter the transistors in the LCM. When the transistors in the LCM are switched off, the fuse unit switches on again and send a signal via the CAN-bus to switch on the transistors one by one to detect which load that failed and to isolate the fault. In this way all loads connected to the LCM can be protected by only one active fuse and still have good diagnostic feature and fault isolation.

The central fuse unit can replace each fuse in the main fuse box in the vehicle and in this way control and monitor the entire electric system. To gain most of this architecture each load needs to be able to be switched on/off by a signal from the CAN-bus and the characteristics of the load must be known. If a fault occur at a load that can not be switched off by the CAN-bus, this fault can not be isolated and could disrupt the entire branch. If the load characteristics are not known, the appropriate fuse level can not be set and the safety level of the system could be violated.

Another advantage is that the starter could be protected, which it is not today, due to the high inrush currents.

A disadvantage with this architecture is that the measurement only takes place at one place in each branch. If the branch consists of many loads, the risk that two loads degrade at the same time increases, which leads to difficulties in obtaining the health of each load. The time to obtain which load that failed would also increase due to that all loads has to be tested individually. Fault that occurs between loads in a branch can also be unnotice.

The time to connect the load will also be longer, since the signal need to pass through the active fuse unit, to set the current limit, before it can switch on the load. Even if this extra time is short it could violate the safety if the load needs to be switched on fast, e.g. the airbag, anti-brake lock or brake light. The speed of the CAN-bus is typically around 250kbit/s in a vehicle which lead to a transmission time of a few μs. The logic circuit in the fuse needs to calculate the appropriate current limit and has a large contribution to the total response time. If the different current limits are calculated in advance and only set by the logic circuit this time can be minimized.

Active fuses integrated in the ECUs

An active fuse unit integrated in an ECU is presented in Figure 16. By replacing the traditional fuses in branches where faults often occur or where better diagnostic feature is required the advantages of the new system can overcome the increased cost. This architecture works in the same manner as for the architecture described above but with the fuse unit placed inside the ECU. There is no longer any need for changing the fault levels depending on which loads that are active since each load is fused by its own active fuse. In this way a faster start up response can be gained. By replacing the drive circuit in the specified ECU with an integrated circuit where the drive circuit is combined with a measurement circuit and a microcontroller this can be achieved without violating the size of the ECU. If several loads are fused through one ECU, one microcontroller can be used for several active fuses. This architecture could of course be combined with a central fuse unit to achieve both high diagnostic feature for a specific load and an active protection over the entire system.

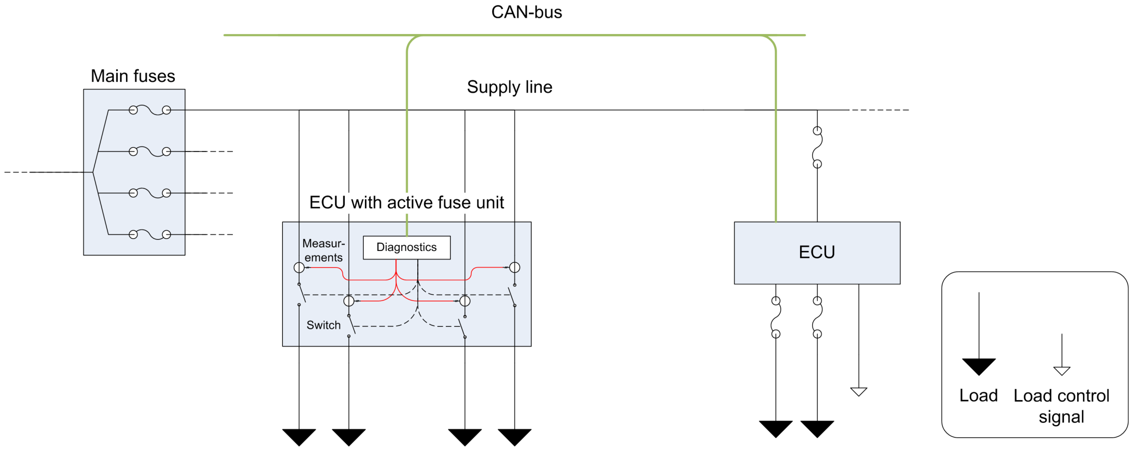


Figure 16: An active fuse unit integrated in an ECU.

Loads with different fault characteristics

If the load is not connected to an ECU, the load can be fused alone or together with a load that has a different fault characteristic to maintain some of the diagnostic features. By analyzing the fault current, the active fuse unit might be able to detect which load that has failed. The disadvantage of this method is that all loads in that group are switched off even if only one is failing. To increase the fault isolation several switches can be used together. Each switch would need its own drive and logic circuit, to be able to switch them individually, but the measurement could be concentrated to one place. The diagnostic features would be reduced, as for the central fuse unit, but also the cost.

2.4.3 Safety aspects

As stated prior, the traditional fuse system has some drawback and lacks protection for some faults that can arise in a vehicle. The main reason for a new system should not only be to achieve higher diagnostic features but also to improve the safety level. An active fuse system will improve the over-current protection with the ability to change the fuse level to allow high inrush currents and with a better accuracy of the fuse level. It could also include protection against over-voltage, over-temperature and time dependent faults.

An active fuse unit consists of many different components compared to the traditional fuse system which rely on one passive component, the blow out fuse. If one part fails in the active fuse unit it could lead to malfunction of the entire fuse unit. The active fuse unit should therefore be designed carefully to avoid risks of damage. By choosing quality components and keeping good margins to the device ratings these risks could be minimized.

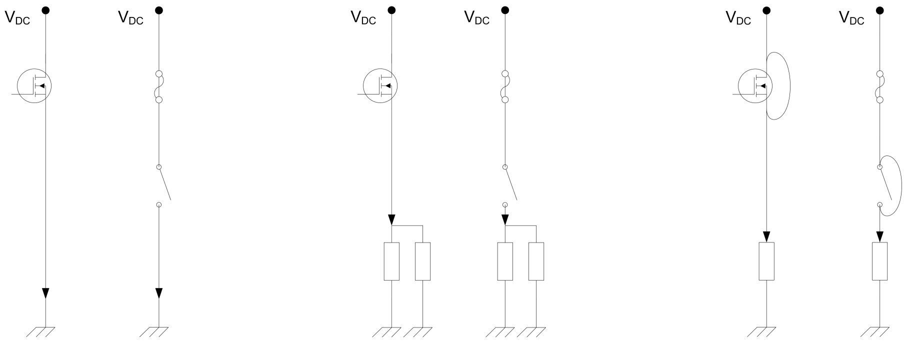
If the active fuse unit is damaged it is desired that the switch ends up in its off-state. Depending on which part that fails, this must be treated in different ways and is not always possible to achieve. If the sensor circuit is damage, it is most likely that the measurement drops to zero, by comparing the measurement with a hysteresis, instead of a maximum value, failure in the sensor circuit could be detected. Failure in the logic circuit or the drive circuit is more difficult to detect. If the switch has an internal protection it might switch off the circuit before any damage is caused. The most severe damage can be caused if the switch fails. With today's devices, the state in which the MOSFET end up in when destroyed can not be predicted. The reason for MOSFET destruction is that it has been exposed to too high temperature, current or drain-source voltage. With a fast and reliable control system most of these stresses could be avoided.

When choosing the switching component in the active fuse system, consideration to the failure rates has to be taken into account. The switching component is of greatest importance in the active fuse system due to that it is responsible for the power throughput. Figure 17 shows five different fault scenarios where a MOSFET based active fuse system is compared against a traditional blow out fuse together with a relay. A short circuit fault with the assumption that the fault is not damaging the MOSFET is shown in Figure 17(a). Both the blow out fuse and the active fuse system will handle this fault. The blow out fuse will have to be replaced before full functionality could be restored. The overload fault case in Figure 17(b) is treated in the same manner as for the short circuit but with the difference in tripping times for the blow out fuse will be longer. In the bypassed or defect switch fault in Figure 17(c) the blow out fuse is still intact and operational. The active fuse system is in this case inoperative.

The fault case in Figure 17(d) blow out fuse that is faild to a high resistance. Blow out fuse failure ending up in a low resistance state is shown in Figure 17(e). The blow out fuse has to be replaced for full functionality in both cases. Damage to the active fuse system resulting in high resistance will also result in a need for replacement.

The case of a short circuit in conjunction with over voltage is not likely to appear but will result in uncontrollable power flow and risk of hazardous temperatures for both the blow out fuse and the active fuse system, shown in Figure 17(f). Another fault is the possibility of arcing during replacement of the blow out fuse during load or short circuit conditions. The arcing can lead to hazardous local temperature rises. This will not affect the active fuse system. [11]

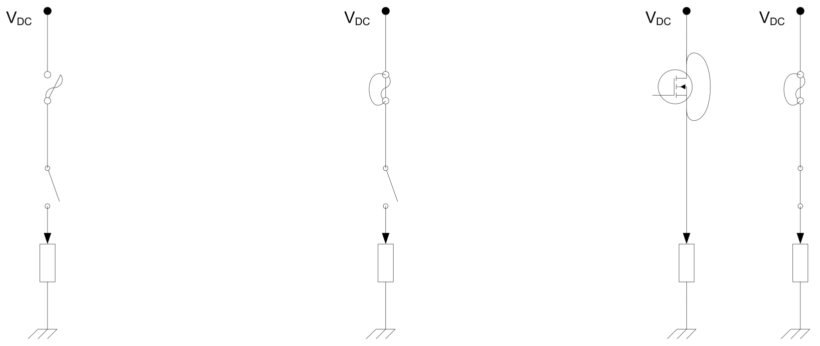
The MOSFET will meet the safety level of the blow out fuse together with a relay in all but one case, the one shown in Figure 17(c). The case described in Figure 17(f) is also hazardous but equally treated for both the MOSFET and the blow out fuse. Possible causes to these events are treated in the section below together with directions to possible solutions.



(a) Short circuit.

(b) Overload.

(c) Bypassed or defected switch.



(d) Blow out fuse damaged to high resistance.

(e) Blow out fuse damaged to low resistance.

(f) Short circuit and over voltage.

Figure 17: Possible faults for the active fuse system and the traditional blow out fuse. [11]

MOSFET failure

Different conditions in an electric circuit can lead to forced turn-ons that in return lead to internal destruction of the MOSFET. A rapid change in the drain-source voltage can lead to a forced current conducting mode if it exceeds the dv/dt capability of the device. There are two mechanisms activated by a to high drain-source voltage rise leading to forced current conducting. The first mechanism will be triggered by the increased voltage across the drain and source terminal resulting in a current flowing through the gate resistance, I_1 in Figure 18. When the voltage drop across the gate resistance, R_g, exceeds the threshold voltage, V_{th}, the device will enter conduction mode. The drain-source voltage rise capability is set by

$$\frac{dv}{dt} = \frac{V_{th}}{R_G C_{gd}}, \tag{5}$$

where C_{gd} is the gate-drain capacitance. To avoid this failure a higher V_{th} is preferred together with a carefully chosen gate circuit impedance. The negative temperature coefficient of V_{th} is to consider where high temperatures is expected. The second mechanism is caused by the parasitic BJT of the MOSFET. As can be seen in Figure 18, the drain-source voltage rise will drive a current, I_2, through the drain-base capacitance, C_{db}, and the base resistance, R_b, turning the BJT on if the voltage across R_b, V_{be}, exceeds about 0,7V. The resulting drain-source voltage capability limit can be calculated by

$$\frac{dv}{dt} = \frac{V_{be}}{R_b C_{db}}. \tag{6}$$

As for the first mechanism the limit will decrease with higher temperature because of the positive temperature coefficient of R_b, thus to increase this limit R_b has to be reduced. Both mechanisms will result in a forced turn-on if the dv/dt capability is exceeded, damaging the MOSFET. The major root cause of MOSFET failures and breakdowns is turn-on of the parasitic BJT transistor. [1] [18]

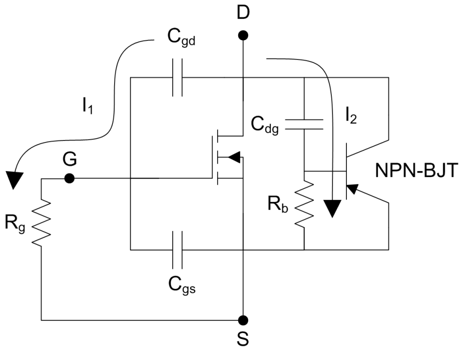


Figure 18: Equivalent circuit of a Power MOSFET with two mechanisms of dv/dt induced turn-on. [1]

Another source of failure is single-shot avalanche events that occur during inductive load turn-off. The inductive load will after turn-off continue to drive a drain-source current, I_d. This current will induce a voltage that will add to the supply voltage, V_s, and clamp the drain-source voltage at breakdown voltage of the MOSFET, V_{br}. The current flowing through the MOSFET prior to the turn-off will be the avalanche current, I_{as}. As the drain-source voltage is clamped to V_{br} and the current will decay from I_{as} according to the size of the inductance, L, energy is dissipated in the device. The energy dissipated, E_{as}, is according to

$$E_{as} = \frac{1}{2}\frac{V_{br}}{V_{br} - V_s} L I_{as}^2. \tag{7}$$

The energy will increase the junction temperature of the MOSFET to a temperature maximum dependent on the initial junction temperature, avalanche time and avalanche current. If the junction temperature increases beyond the maximum junction temperature rating of the MOSFET, critical damage to the device can occur. [3] [8]

Other causes to failure is single event burnout and single event gate rupture which both is a result of high energy particles passing through the MOSFET structure. The particles energize local hot spots of the MOSFET structure which causes destructive failure such as avalanche. Tests shows that failure rates, $P_{failurerate}$, can be predicted according to

$$P_{failurerate} = D_{offtime} \times 10^{0.19 \times V_{stress} - 14.3} [\frac{\%}{year \times cm^2}] \tag{8}$$

for the voltage stress of the MOSFET, V_{stress} in percentage, and per die size exposed. These sources of failure will vary with altitude but the failure rate is reduced with reduced operating voltage and/or increasing the rated voltage of the MOSFET. This faults appears during off-state, $D_{offtime}$, when the voltage over the MOSFET is high. These faults mostly affects high voltage devices because of their structural design. [9] [17]

The common solution to the reliability issue throughout the treated fault events is keeping temperatures as low as possible together with a secure margin to both the voltage and current ratings of the device. Considering all these aspects Bell Communications Research equals the safety level of a blow out fuse in a fuse holder to a low power transistor. [12]

2.5 Power Distribution Unit, PDU

In 2002 Volvo 3P started an Advanced Engineering project where a PDU was built and analyzed. In 2004 the project ended and since then, no further work on the PDU has been done. Foremost, the PDU replaces the main fuses in a truck but it also includes a fuse for the starter, which today is un-fused. The PDU works as an active fuse system where switch modules measure the temperature, voltage and current in each branch and switch off the circuit if a fault occur. The data is transmitted to a main controller that can communicate with a PC or cabin unit. The main controller and the switch modules are described more in detail in section 2.5.1 and 2.5.2. Figure 19 shows the fundamental principle of the PDU.

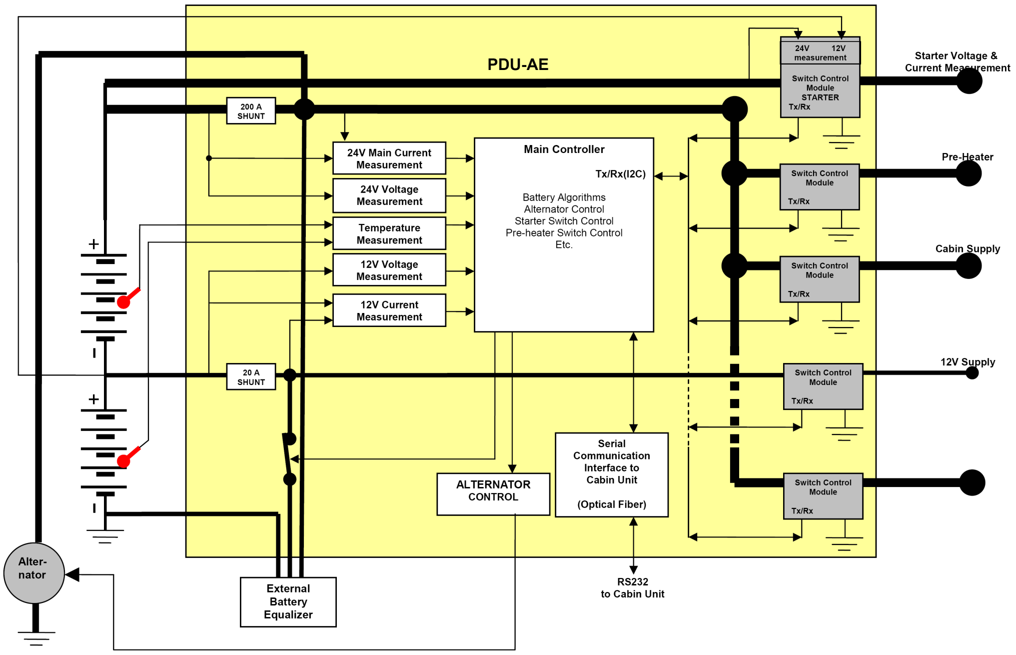


Figure 19: Overview of the PDU.

2.5.1 Switch modules

There are two different types of switch modules, one for high currents and one for lower currents. The main difference between them is the transistor. In the high current module, a special power MOSFET is used and in the low current module five SPS are used.

High current switch module

The PDU include five high current switch modules. The MOSFETs are designed by Intra with very low on-state losses, $R_{DS(on)}$ is 0,4mΩ. It can withstand continuous currents up to 200A and peak currents up to 2000A. The design features large contact areas for both source and drain, making additional cooling unnecessary. The MOSFET has a built in NTC sensor that measure the temperature. The current is measured using the on-state resistance and the voltage is measured using a voltage divider. The measured values are sent to a microcontroller that compares the value with a preset limit. Due to the ability to switch currents up to 2000A the A/D-converter of the microcontroller converts the current measurement to 9,76A/bit. It will switch the circuit if the temperature exceeds a preset limit. The switch modules also include a gate driver with a charge pump to drive the MOSFET. For the switch module that is controlling the starter motor, two MOSFETs are used in parallel to withstand higher current.

Low current switch module

The low current switch module is based on five SPS from Infineon, the BTS660P. The SPS have a built in temperature-, voltage- and current-protection as well as a MOSFET driver and a logic circuit that will switch the SPS in case of a fault. The internal limits, current limitation of 90A, voltage limitation of 70V and temperature limitation of 150°C are mostly used to protect the SPS. The on-state resistance, $R_{DS(on)}$, is 9mΩ and the turn-off time is between 30 and 110μs. A more detailed explanation of the PROFET is found in Section 2.2.3

The only output from the SPS is the current, and an external voltage divider is used to measure the voltage. A microcontroller with a built in A/D-converter is used to collect the measured values. The settling time for the current measurement is maximum 500μs.

2.5.2 Main controller

The main controller can communicate both with the switch modules and with a PC or a cabin unit via an RS232 connection. It measures the current, voltage and temperature of the batteries. This data is used to calculate the state of charge (SoC) and state of health (SoH) for the batteries. The microcontroller forwards the measured information from the different switch modules to the cabin unit or to a PC.

3 Experiment & Result

The experiment was divided into three different parts, first the different loads were tested to obtain the characteristics, secondly a prototype was built to achieve better understanding of an active fuse system and to turn off the circuit using hardware instead of software. Thereafter, tests were done both on the prototype, the blow out fuse and the PDU to see the difference in flexibility, time response and to get ideas on improvements.

3.1 Test Equipment

The test equipment used in this experiment is presented in table 2 below. The power supply is used to simulate the batteries in a vehicle. In a battery the current is only limited by the temperature and the current peaks can be over 2000A. The power supply SM6020 has a current limitation of 20A.

Table 2: Test Equipment.

Instrument	**Manufacture**	**Name**	**Spec.**
Power Supply	Delta Electronics	SM6020	0-30V/0-20A
Current Probe	Fluke	80i-110s	20kHz Bandwidth
Current Probe	PEM UK ltd.	CWT ultra mini	20MHz Bandwidth
Oscilloscope	LeCroy	Wavesurfer 454	350MHz Bandwidth

Both a Rogowski coil (CWT) and a Fluke current probe where used. The reason for using two different current probes is to see both the fast transients and the steady state levels. The CWT has a high bandwidth of 20MHz which is enough to perceive most current changes in the circuit. For longer pulses (over 1ms) the measured value starts to decline from the real value due to the phase displacement[2]. The current probe Fluke 80i-110s has the ability to measure the steady state current level accurate but has a bandwidth of 20kHz which is smaller than the rise time of the power supply which will lead to a declination of the actual value for fast transients.

The oscilloscope has a bandwidth of 350MHz with four different channels and will not affect the measurements.

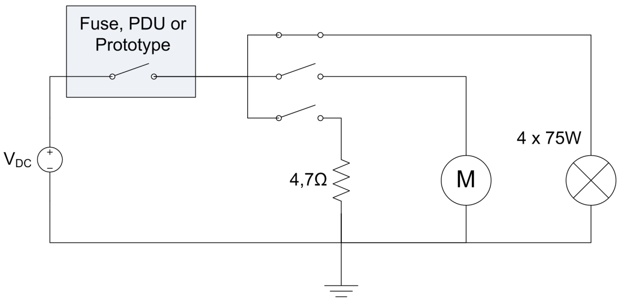


Figure 20: Test circuit setup with three different loads and the fusing system.

3.2 Load characteristic

In a heavy vehicle many different loads are used. As described in Section 2.1.1 there are main differences between the loads, for instance they can be inductive, capacitive or resistive. To be able to set proper fusing limits it is of great importance to know the current characteristics of each load. Three different loads are used during testing, a 4,7Ω resistance, a 75W headlight and a DC-motor. To verify the characteristics of the loads, turn-on and turn-off tests where performed. In Figure 20 the test setup of loads together with the fuse system of choice is presented.

The power supply was set to 24V for each load and the result for the resistor is presented in Figure 21, for the lamp in Figure 22 and for the DC-motor in Figure 23. The load characteristics can be compared to the theoretical load characteristics in Figure 4.

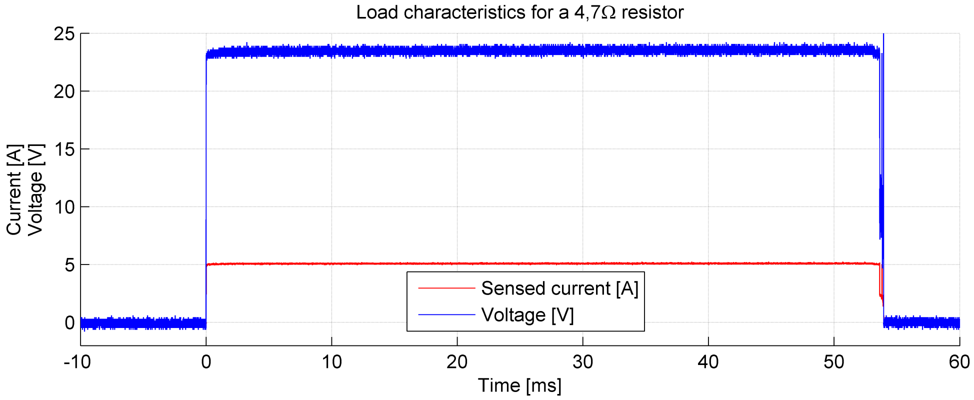


Figure 21: Load characteristics for a 4,7Ω resistor.

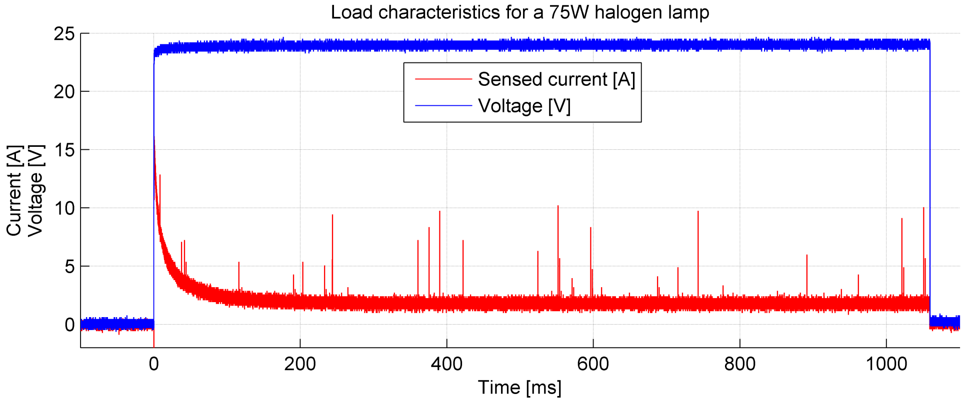
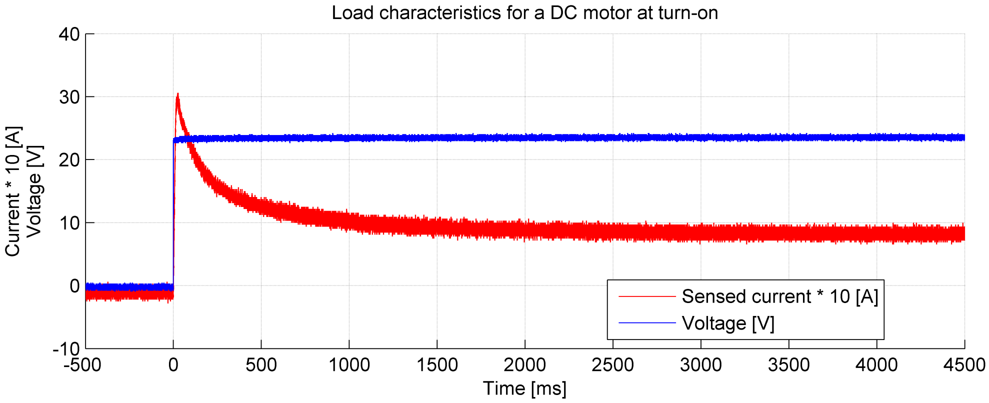
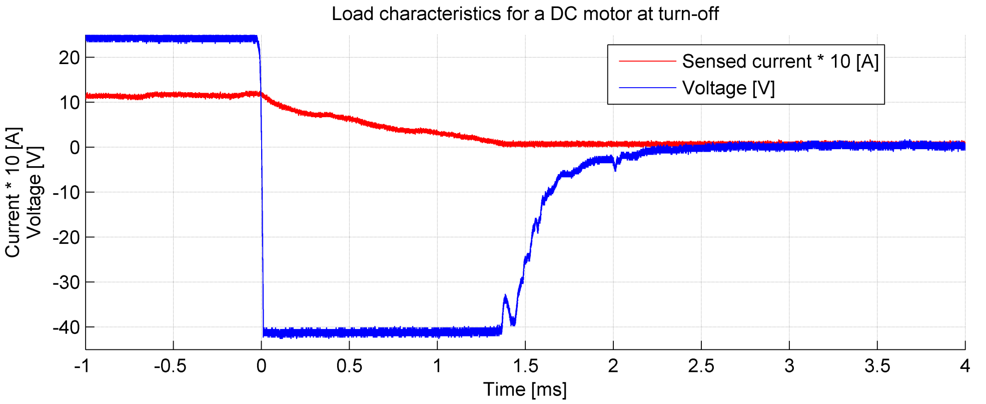


Figure 22: Load characteristics for a 75W lamp.



(a) Turn-on.



(b) Turn-off.

Figure 23: Load characteristics for a DC-motor.

3.3 The prototype

The prototype was constructed for the purpose of testing turn-off times on a hardware based active fuse system. Tests where carried out on the loads described in Section 3.2, the test setup is displayed in Figure 20.

3.3.1 Prototype circuit layout

The prototype was built with the different sub-circuit separated, as in Figure 12a, to decrease the temperature sensitivity and to allow changes more easily, see Section 2.4. The circuit is presented in Figure 24. By using hardware switching, the functionality could be tested without using a microcontroller. A disadvantage is that the diagnostic features are lost, but at a later stage a microcontroller could be included with small changes. An advantage is that a faster response is achieved compared to the PDU which uses software based switching, see Section 2.5.

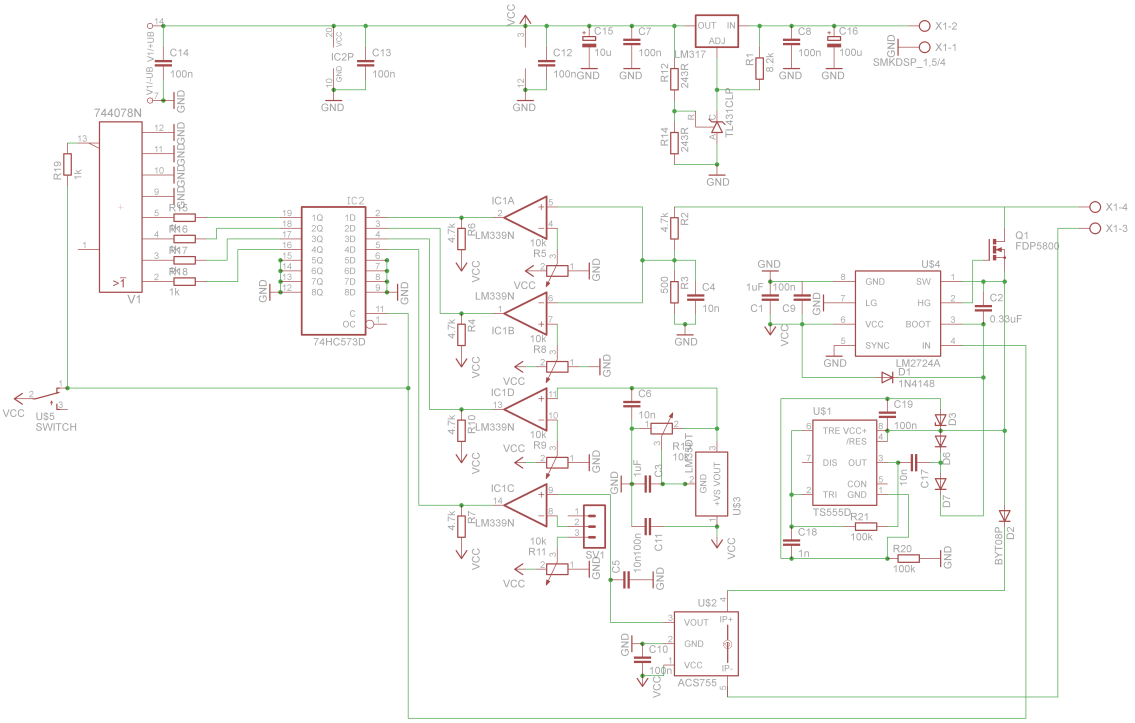


Figure 24: Schematic of the prototype.

In an automotive application the parts have requirements in voltage, current and temperature. The voltage level in a heavy vehicle is 24V and to protect against overvoltage, specifications for the prototype were chosen to 48V. In a heavy vehicle the current peaks can be up to 2000A. The prototype is aimed for securing and controlling smaller loads resulting in the choice of 50A continues current specification limit. The temperature requirement is between -40°C and 125°C in an automotive application [10]. This prototype was built for experiment purpose and the temperature requirement was not considered when the components were selected.

Introducing active fuses instead of passive can lead to higher losses, see Section 3.6.1. When choosing components, part selection where made to minimize the losses. In Table 3 the different components used are presented.

Table 3: Part list.

Part	**Art. no.**	**Farnell no.**	**Price (SEK)**
Drive IC	LM2724AM	8181357	25,89
Timer IC	TS555CDT	1263129	3,85
MOSFET	FDP5800	1495237	18,97
OR/NOR gate	M74HC4078B1R	9755527	3,26
Latch	M74HC573M1R	1094307	1,39
Voltage comparator	LM339N	2293821	1,67
Trim resistor	T18 10K 10%	1141462	16,19
Temperature sensor	LM35DT	1469235	21,44
Current sensor	ACS755LCB-050-PFF	1521724	57,08
Voltage regulator	LM317T	1523842	6,25
Voltage reference	TL431CLP	1106038	0,96

Logic circuit

The main task of the logic circuit is to compare the measured values with a predefined limit and send a signal to the drive circuit. As seen in Figure 24 this circuit consists of one voltage comparator, one latch and one OR-gate. Four different comparators are needed to be able to compare the fuse limits against measurements (over-voltage, under-voltage, over-current and over-temperature). Instead of using four single comparators a quad-comparator was used. The latch is used to store the fault so the circuit is open until the fault is corrected by the user. This unit also needs four different inputs to be able to latch for each fault. If the OR-gate was placed before the latch it would only need to be a single latch but then the information on the fault reason would be lost. The OR-gate is used to give a signal to the drive circuit regardless of which limit that has been exceeded. As for the latch, the OR-gate needs four inputs. The chosen components are listed in Table 3. Trim resistors were used to set the reference signals to the comparator between 0-5V.

Each component needs time to perform its operation, for the voltage comparator the time is 0,3μs, for the latch around 0,4μs and for the OR-gate the time is around 0,4μs. All signals need to go through these components before they can turn off the transistor and the total delay time for the logical circuit is then typically around 1,1μs.

Switch

In this prototype the switch circuit consists of a MOSFET transistor. The transistor needs to be able to handle currents up to 50A and voltages up to 48V, see Section 3.3.1. To ensure that the MOSFET does not operate near its limits the choice fell on a FDP5800 which can handle drain-source voltages up to 60V, continues current up to 80A and a peak current up to 320A. The on-state resistance is typically 5,6mΩ. The turn-on time is 37ns and the turn-off time is 64ns. With these ratings the specifications of the prototype is within good margins.

Drive circuit

The drive circuit could either be bought as a part or be built from scratch. To save time the first option was used. As described in Section 2.4 there are some considerations that have to be taken into account when choosing a drive circuit e.g. losses and turn-on time. How fast the MOSFET can be turned on and off depends not only on the MOSFET itself but also on how fast the drive circuit could charge/discharge the gate capacitance [4]. This relationship is expressed as

$$dT = \frac{dV \times C}{I} \Rightarrow [Q = V \times C] \Rightarrow I = \frac{Q}{dT}, \tag{9}$$

where
dT = Turn-on/turn-off time,
dV = Gate voltage,
C = Gate capacitance (from gate charge value),
I = Peak drive current (for the given voltage value),
Q = Total gate charge.

From the data sheet of the MOSFET the total gate charge, Q, is 58nC at 5V and the turn-on time is 37ns, this gives a peak current of 1,57A. The chosen MOSFET driver, LM2724, can drive a peak current of 3A at a supply voltage of 5V and will thereby not limit the MOSFET.

The driver can use a bootstrap circuit to achieve a gate voltage above the threshold voltage. As described in section 2.4.1 this method is unable to keep the MOSFET on for a long time due to current leakage in the MOSFET and a charge pump was built to support the drive circuit and keep the transistor conducting. The charge pump consists of a timer circuit, TS555D, which oscillate the output voltage to charge and discharge the capacitors, see Figure 24.

Sense circuit

Apart from the effect of the temperature environment, which is not considered for this prototype, the measurement circuit needs to be accurate and fast. The output voltages need to stay under 5V since this is the maximum amplitude of the reference signal.

To measure the voltage, two resistors were used as a voltage divider, see Section 2.4.1. This gives an instantaneous voltage measurement and the accuracy is specified by the tolerance of the resistor used and the temperature coefficient, which is ±5%. A more precise resistor could be used to achieve a more reliable voltage measurement but with an accurate measurement of the resistor before use, the value could be defined more precise. The temperature was measured using a temperature sensor with an accuracy of maximum 1,5% for its operational temperature range.

For the current measurement two different devices were considered, one current sensor using the hall effect to measure the current and one current monitor that measures the voltage drop over a shunt resistor in the circuit. The shunt method introduces an extra resistor in the load circuit which increases the total losses, the bigger resistance, the higher the losses are. Apart from the losses a higher resistance increases the accuracy of measuring lower currents due to that the offset voltage of the device gets less significant. The losses in a hall sensor are very small, around $100\mu\Omega$ and the accuracy is maximum ±2,8%. The hall sensor has a temperature dependency, if a microcontroller was used the measurement from the temperature sensor could be used to recalculate the sensed current and would thereby not affect the accuracy. However, this prototype is designed to operate in 25°C

Table 4: Response time and losses for each component.

Part	**Time**	**Losses**
Voltage comparator	1,3μs	10mW
Latch	118ns	0,4mW
OR/NOR gate	43ns	0,1mW
Total logic circuit	1,46μs	10,5mW
Drive IC	39ns	1mW
Timer IC	n/a	0,55mW
MOSFET	138ns	5,6m$\Omega\times$I$_{ds}$
Total switch circuit	177ns	1,55mW + 5,6m$\Omega\times$I$_{ds}$
Current sensor	4μs + 0,5μs/A	50mW + 0,1m$\Omega\times$I$_{ds}$
Voltage measurement	-	110mW
Temperature sensor	-	0.3mW
Total sense circuit	4μs + 0,5μs/A	160,3mW + 0,1m$\Omega\times$I$_{ds}$
Total	5,64μs + 0,5μs/A	172,35mW + 5,7m$\Omega\times$I$_{ds}$

and the temperature dependence is thereby ignored. Due to the lower losses in the hall sensor this method was used to measure the current.

The rise time for the hall sensor is 20μs for the total current range, which is 50A. This leads to a rise time of 0,4μs/A ($\frac{20\mu s}{50A}$ = 0,4μs/A). Due to inductance in the hall sensor a propagation time of 4μs is also needed.

3.3.2 Price

In Table 3 the component costs for the prototype were stated. The total price is 156,95 SEK, which only includes the component costs from Farnell. The actual component cost will be significantly lower when manufactured, but production costs will be added. It can be stated that the price for an active fuse unit will be higher then for a traditional blow out fuse arrangement with a blow out fuse and fuse holder.

3.3.3 Construction

The prototype was first built on a project board where changes easily could be applied to improve the performance and correct possible errors. To allow high currents, the load was placed outside the board connected with wires. When the functionality was verified a PCB board was constructed to minimize the inductance in the wires which could cause undesired oscillation.

3.3.4 Test

To verify the basic functionality of the prototype the reference levels where adjusted manually during operation to break the load circuit. Thereafter the functionality of the different measurement circuits was verified by increasing the load voltage and load current. The responses were analyzed in an oscilloscope (LeCroy Wavesurfer 454). When the basic functionality was verified three different tests were done on the circuit, a short circuit test and an over- and under-voltage test. The temperature was not further tested, this due to difficulties in finding a fast thermometer that could be used to compare the sensed temperature with. The current was measured using a current probe (CWT 015b).

Short circuit test

To study the functionality of the over-current protection a short circuit test with a pure resistive load of 4,7Ω was done. The voltage was set to 24V. To decrease the short circuit current, a 2,2Ω resistance was used as a short circuit. The current limit of the prototype was set to 10A. The results are presented in Figure 25. As shown the time from that the current exceeds the reference to that it starts to decline is approximately 7μs. The calculated response time is 5,64μs + 0,5×5 = 8,14μs. As seen the current sensor has the longest response time.

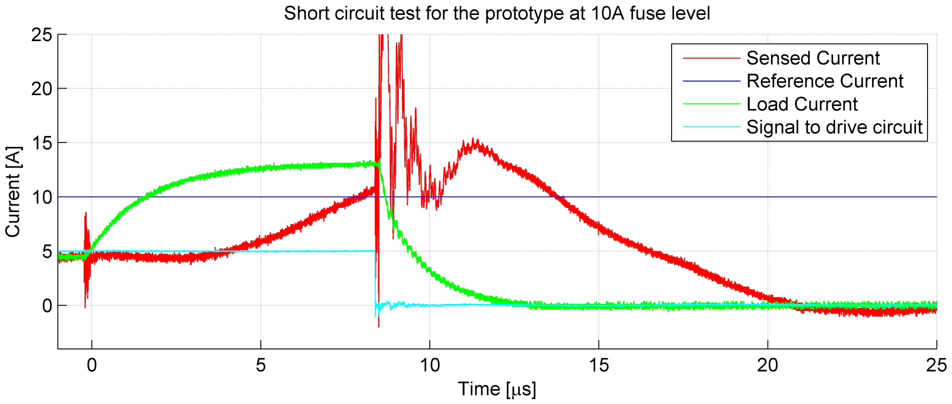


Figure 25: Short circuit test for the prototype at 10A fuse level.

A further test was carried out with the current limit set to 1A. As seen in Figure 26 the turn-off time is around 3μs shorter than for the test with 10A limit. This is due to that a smaller increase in the sensed current is needed to turn-off the circuit. For both tests a blanking time is needed to allow the sensed current to decline before the circuit can be turned on again.

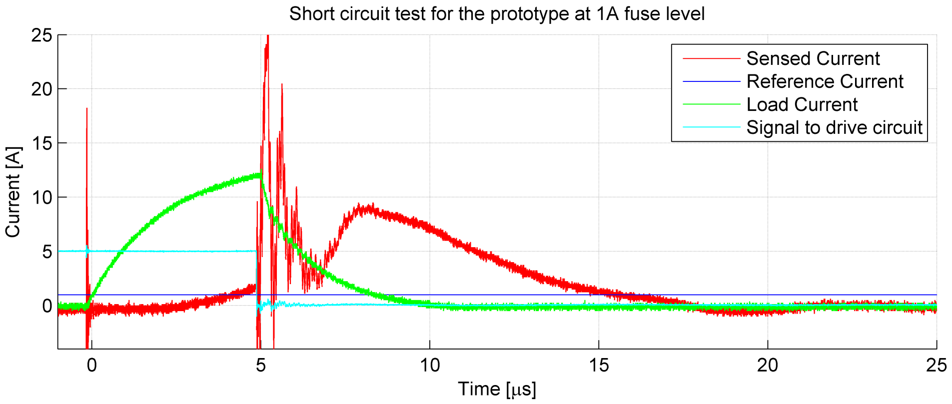


Figure 26: Short circuit test for the prototype at 1A fuse level.

Over- and under-voltage test

The over- and under-voltage protection was tested by increasing/decreasing the voltage level over the load. The test circuit for both over- and under-voltage protection is shown in Figure 27. The setup is shown in Figure 27.

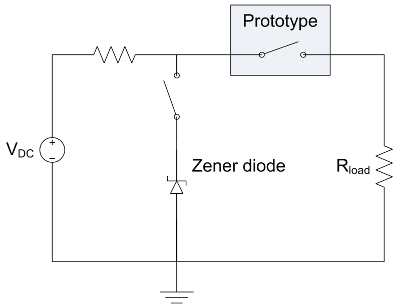


Figure 27: Setup for the over- and under-voltage test.

For the over-voltage test a zener diode with a breakdown voltage of 24V was used. The voltage from the power supply was set to 26V and the over-voltage limit was set to 25V. The result is presented in Figure 28. At time 0 the switch is opened and the voltage increases. As seen the drive signal turns off after around 0,5μs which is much shorter than for the short circuit test. This is due to the longer rise and propagation time for the current sensor. The response time for the logic ICs are a third of the calculated response time of 1,46μs.

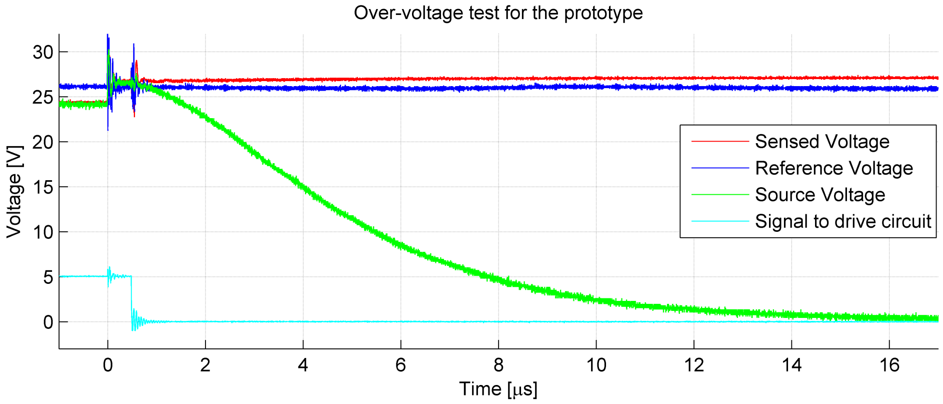


Figure 28: Over-voltage test for the prototype.

The under-voltage test was done in a similar manner but with a supply voltage of 24V and a zener diode with a breakdown voltage of 15V. While the switch is open the voltage over the load will stay at 24V and when the switch is closed it decreases rapidly to 15V. The voltage limit was set to 18V and as seen in figure 29 the response time is in the same range as for the over-voltage test.

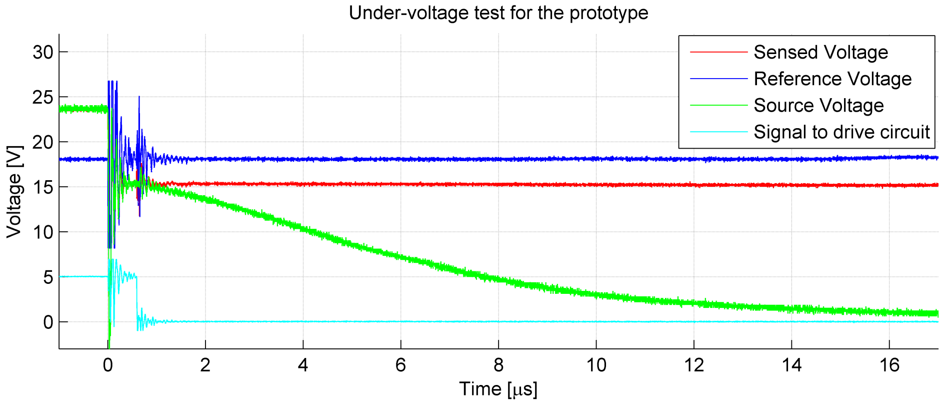


Figure 29: Under-voltage test for the prototype.

3.4 Blow out fuse

To verify the opening times for the blow out fuse in Table 1 a short-circuit test was done on a 10A blow out fuse. A resistive load of 4,7Ω was connected to the power supply at 24V, which yield a current of 5,1A. Due to shortage of a more powerful power supply a resistor of 2,2Ω was used to short circuit the load. The short circuit current was then limited to 16A, 160% of 10A. The theoretical response time for the 200% over-current case is between 150ms and 5s for the blow out fuse. As presented in Figure 30 the response time for the fuse is 1,1s which is within the theoretical value stated in Table 1.

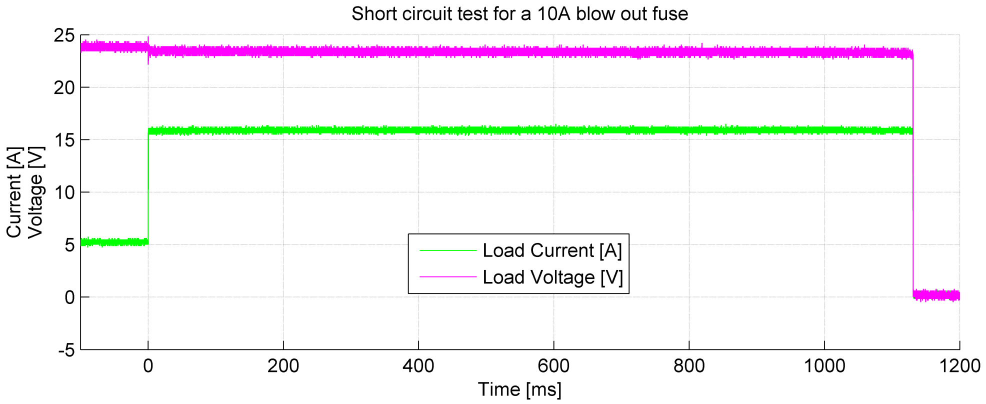


Figure 30: Short-circuit test for a 10A blow out fuse.

Due to the characteristic of the blow out fuse the response time depend on the over current. A test was done on a 1A blow out fuse to see the response rime for a large over current. A 4,7 and a 2,2 Ω resistors was connected in parallel to a 24V power supply which yield a current of 16A, 1600% of 1A. The results are presented in Figure 31 and the time response is 3ms.

3.5 PDU

The PDU works, as described in section 2.5, as an active fuse system. The MOSFET is switched off by a microcontroller when the measured values exceed the preset limit. By using a microcontroller the data of the measurement can be stored and analyzed at a later stage. Due to lack of documentation, especially on the software design, a large effort was

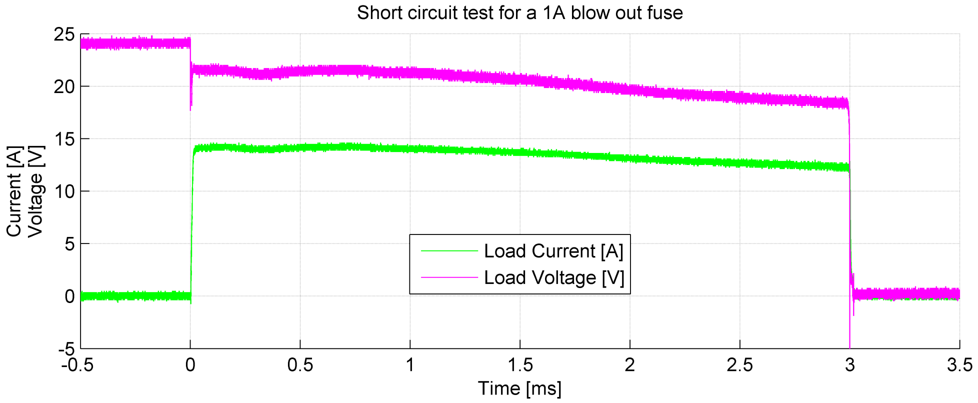


Figure 31: Short-circuit test for a 1A blow out fuse.

taken to understand the working principle of the software which is described in Section 3.5.1. Thereafter a test was done in order to check the response time.

3.5.1 Software

The PDU consist of different sub circuits, described in Section 2.5, each containing a microcontroller. The main task for the microcontroller of the main controller is to communicate both with a PC or the cabin unit and with the switch modules. It should also calculate the state of charge (SoC) and state of health (SoH) of the batteries.

For the microcontroller in the switch modules, the main task is to transmit the measured data to the main controller and to give a signal to the drive circuit when a fault has occurred. It is not obvious which microcontroller that compares the measured values with the limits. The most probable way is to make the comparison in the switch module to achieve a faster response time. As seen in Figure 35 and 36 the turn off times is in the range of 2-12ms which is a considerable long time to perform this task.

If the PDU is connected to a PC the data can be displayed in the program PC Tool. In PC Tool the different current limits could be changed, there are three different fuse levels to allow high inrush currents. The first current limit starts first after 10ms which means that the first 10ms are unprotected. Changes could also be applied to the temperature limit and a function that automatically shut down the circuit after a certain time could be used. The voltage limit could not be changed by the user and no further tests were done on the over-voltage function. According to the technical specification, the PDU should switch off after 2h if the voltage exceeds 36V, after 2 minutes if it exceeds 48V and after 300ms if it exceeds 58V. It should also switch off the circuit after 8ms if the voltage is below 8V and after 20s if it is below 12V. The measured data could be stored in the PC with a resolution of 6 samples/min and could be used to study long term changes in the behavior of the loads.

3.5.2 Test

Due to the low resolution of the current measurement and the higher current throughput, compared to the prototype, in the high current switch module these switches were not tested and all measurements and tests were done on the low power switches. First the PDU was connected to a PC to test the functionality. Three different current limits could be applied at different times to allow high inrush currents. Figure 32 presents how the

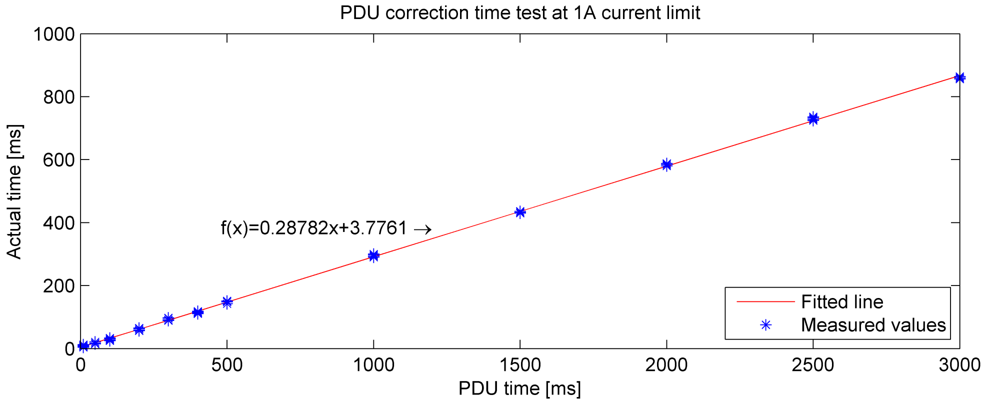


Figure 32: The time difference between the PC tool and the PDU.

trip time varies with the time set in the program. Tests where carried out with a current of 2,5A applied through a 4,7 Ω load and the current limit was set to 1A. When the power where switched on the time until turn-off where recorded. Several tests where performed on each set time. As seen, there is a linear correlation between the set time and the actual time, therefore a recalculation must be done to set the desired time. The actual time is given by

$$t_{actual}(x) = 0,28782 \times t_{set} + 3,7761. \tag{10}$$

The deviation of the samples at each set time in Figure 32 is presented in Figure 33. As seen the maximum deviation from the fitted approximation is 12.67ms. This time is supposed to be due to that the microcontroller compares not only the current limit but also the temperature and the voltage limits. Depending on where in the loop the fault happens, the turn-off time varies. This large variation can also be a result of interruption due to communications and transmissions between the switch circuit and the main circuit. The first limit was set to 10ms, which according to 10, will result in a turn-off time of 6,65ms. The maximum deviation from the expected turn-off time is 90,2%, deviation of 6ms seen in Figure 33.

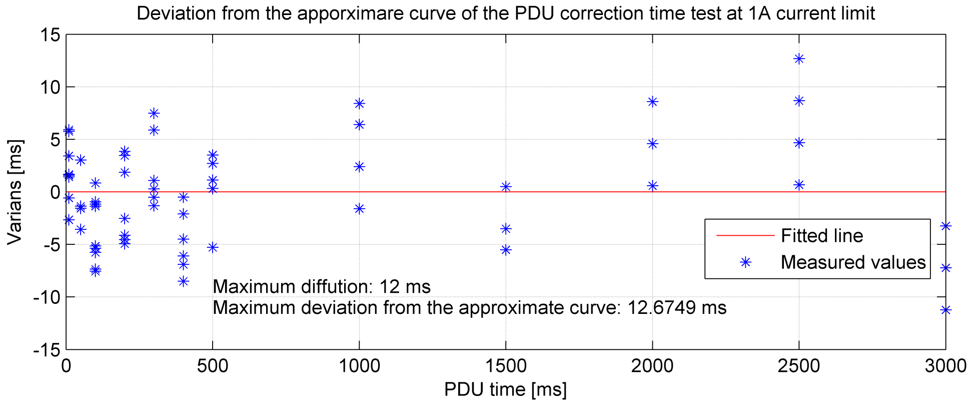


Figure 33: The turn-off time deviation for the PDU.

Another characteristic that was investigated was the tripping time at different overcurrents. The PDU time was set to 500ms and a current of 12A was applied through the load. The current limit was varied between 1A-11A. In figure 34 the result is presented.

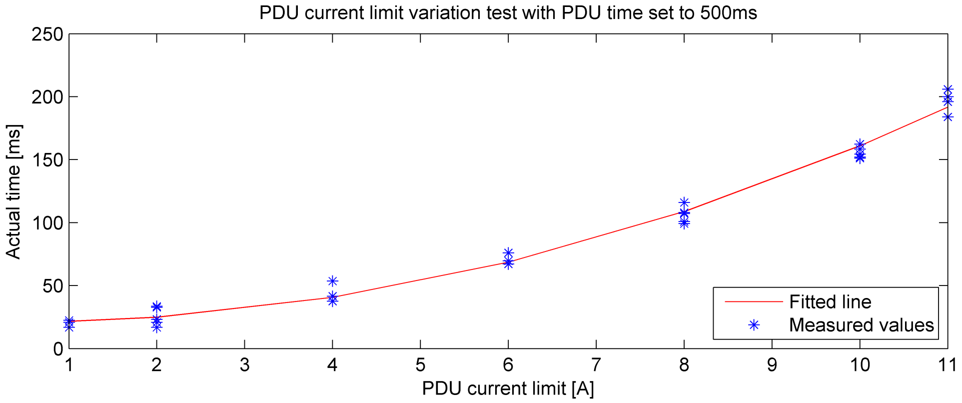


Figure 34: The time variation for different current limits.

The turn-off time increases with lower over-current in respect to the limit. The reason of this behavior was not found.

Short-circuit test

As for the short-circuit test for the blow out fuse and the prototype a 2.2Ω resistance was parallel connected with a 4,7Ω resistance to achieve a higher current. The current limit was set to 10A and the response time for the PDU is presented in Figure 35 and 36. As shown, the time differs from occasion to occasion. This is, as explained in 3.5.2, depending on where in the control loop the fault appears. The current sensor is only active while the SPS has a gate signal as can be seen in Figure 36.

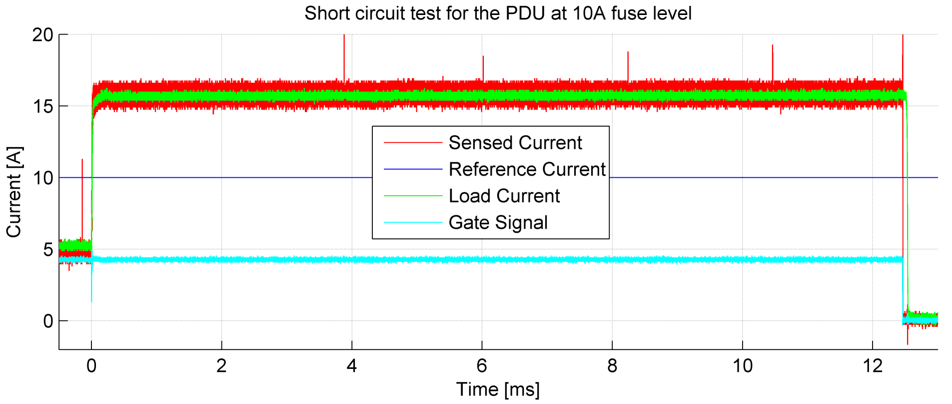


Figure 35: Short-circuit test for the PDU at 10A fuse level.

A test with the fuse level set to 1A was done to see if the turn-off time differed from the 10A test. In Figure 37 the result is presented. As seen the turn-off time is approximately 6,8ms, which is in the same range as for the 10A test.

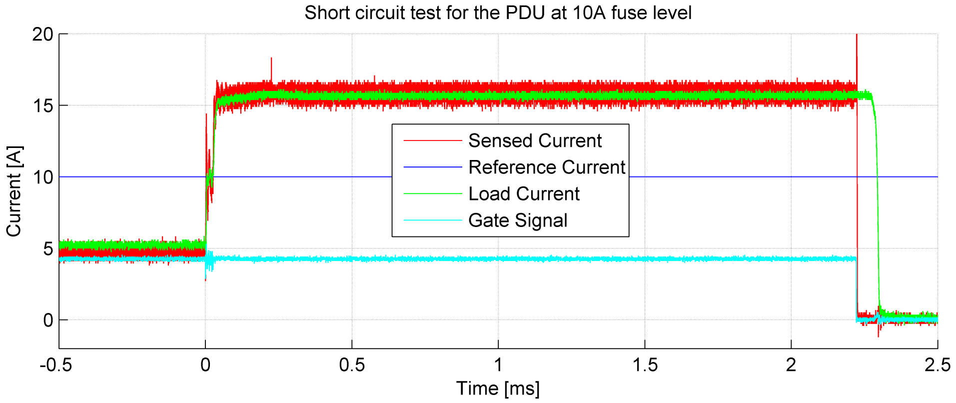


Figure 36: Short-circuit test for the PDU at 10A fuse level.

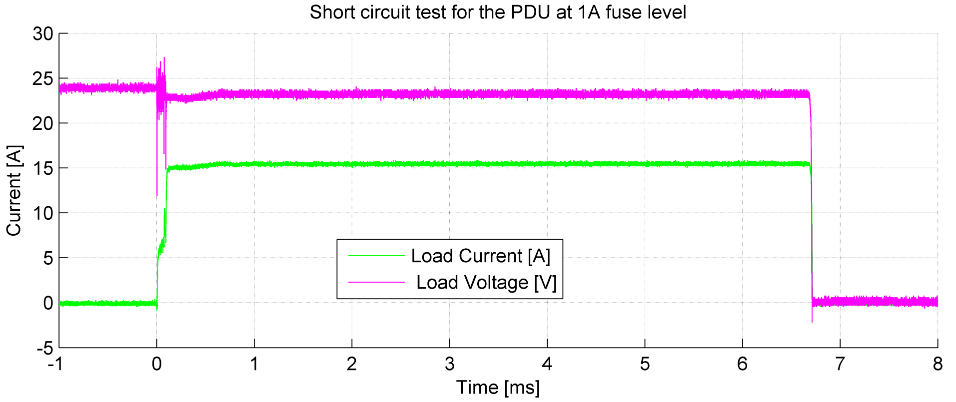


Figure 37: Short-circuit test for the PDU at 1A fuse level.

High inrush-current

A further test was done to test the possibility to switch loads with high inrush current. A 75W halogen lamp were used as a load. After the start up sequence a 10Ω resistor was connected in parallel with the lamp. In Figure 38 the load characteristic is presented together with the different current limits. The limits were set to 25A for 20ms, 8A between 21 and 120ms and thereafter 4A. At time 325 the resistor was connected and the current increase. The PDU starts the sequence with different current limits when the current changes to allow current peaks. The PDU was supposed to turn-off the circuit when the last current limit of 4A was reached, after 120ms, but the PDU turn-off the circuit first after 240ms. The reason for the long turn-off time was supposed to be due to that the linear approximation varies between different levels of over-currents.

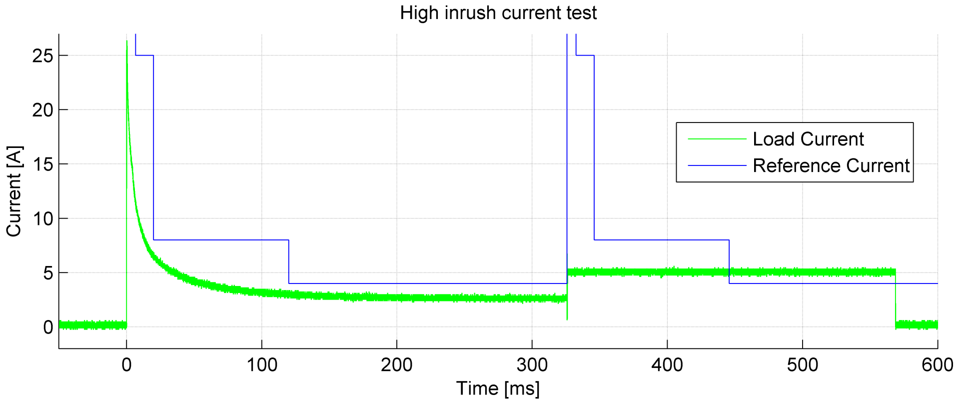


Figure 38: Short-circuit test when allowing high inrush current.

3.6 Comparison

Figure 39 presents the turn-off times for the different fuse units when an over-current occurs. As seen the turn-off times is shorter for both the prototype and the PDU than for the blow out fuse.

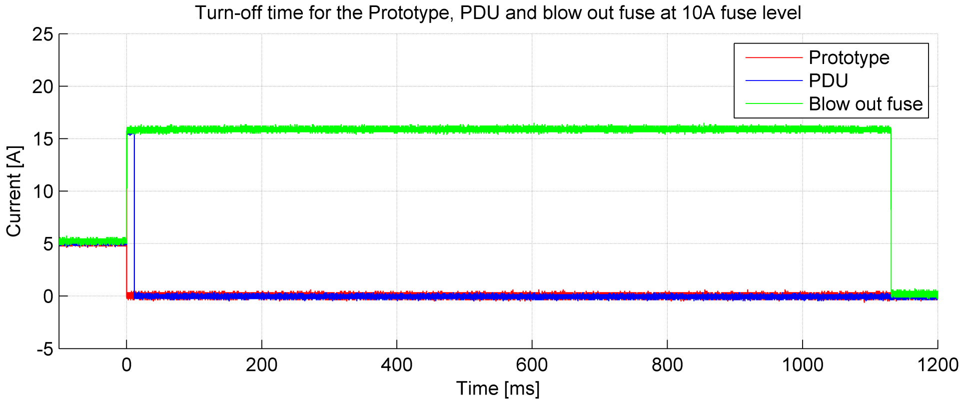


Figure 39: Switch off sequence for Prototype, PDU and Blow out fuse at 10A fuse level.

A higher over-current would lead to a shorter turn-off time for the blow out fuse. As seen in Figure 40 the turn-off time for a 1A blow out fuse is 3ms when an over-current of 16A is applied. For the PDU the turn-off time is 6,5ms and for the prototype it is in the μs range. The fastest turn-off time for the PDU varies between 0-12ms independent of the over-current. If a delay time is applied the turn-off time will vary depending on the over-current. As seen the turn-off time for the prototype is still faster than for both the blow out fuse and the PDU.

3.6.1 Power losses

Each component causes losses which have to be included when considering an active fuse system. For the traditional blow out fuses the losses are caused by the internal resistance that varies from a couple of mΩ to several hundred mΩ depending on the current rating, see Section 2.2.1. In an active fuse system the losses occur both in the switch, sense and logic circuit. In Table 4 the losses for each component are presented. In Figure 41 the power losses for the blow out fuse, the prototype and the PDU are compared. The power

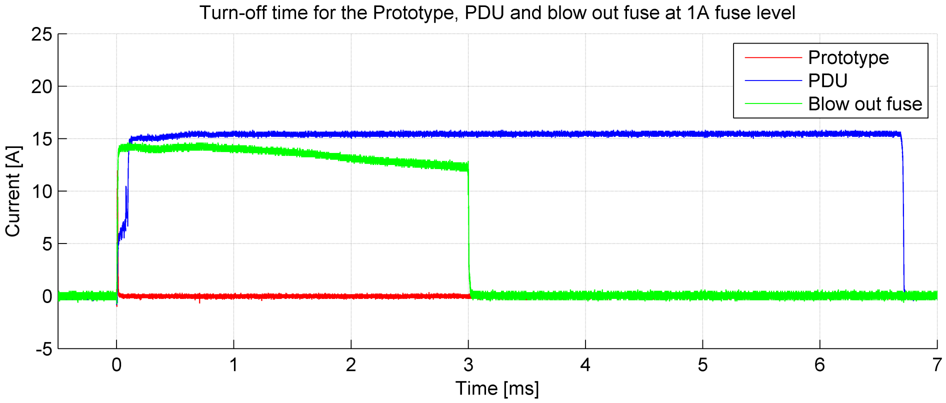


Figure 40: Switch off sequence for Prototype, PDU and Blow out fuse at 1A fuse level.

losses in the PDU is including the power loss in the switch and the microcontroller. For small currents the power losses is in the same range for both the prototype and the PDU as for a blow out fuse but for higher currents the power losses increases dramatically, mainly due to the on-state resistance of the MOSFET. By choosing a MOSFET with lower on-state resistance, these losses could be reduced.

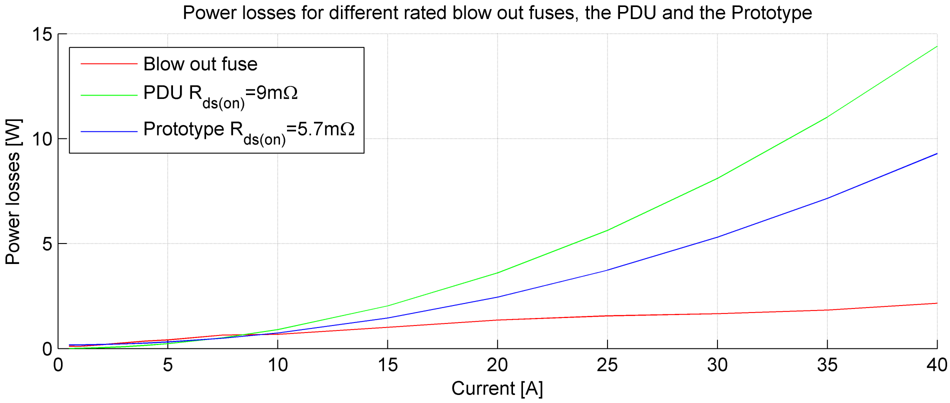


Figure 41: Power losses for the prototype and blow out fuses.

The nominal cold resistance is used to calculate the power losses for the blow out fuse. In reality the resistance changes with the temperature, as for the MOSFET. The power loss in the MOSFET was calculated with the assumption that the on-state resistance is constant. The resistance chosen was rated at 80A and 25°C, this resistance will be lower for lower currents. Even if these losses are small, consideration must be taken when choosing components.

4 Discussion

The aim of this report has been to investigate how an active fuse system could be designed and implemented. Two different active fuse systems have been tested and compared with the traditional blow out fuse. In this section the active fuse unit design, architecture and benefits of an active fuse system are discussed.

4.1 Active fuse unit design

Three different system designs have been analyzed and tests have been carried out on two of them, the prototype and the PDU. The main difference is in the way the fuse level is compared, either analogue or digital. The PDU gives a more flexible system with possibility to change the fusing level continuous during time. The drawback is longer turn-off time compared to the prototype. A short turn-off time is desired. It will lower the demand on the internal protection in electronic devices e.g. ECUs. A shorter turn-off time will decrease the energy dissipated in the power MOSFETs, reducing the maximum ratings needed. The most frequent electric fault in vehicles is short circuits in cables, see Section 2.1.2. To prevent damaged cables due to over temperatures shorter turn-off times is essential. At the same time a flexible system is desired to increase the safety level when fusing loads with high inrush current. A flexible active fuse unit is also to prefer when it is to be installed in an application. The same unit design can be used in many different applications with minor changes, reducing the cost.

As seen in Section 3.6 the prototype is clearly the fastest. The software based PDU suffers from an insufficient control loop resulting in long turn-off times compared to 100μs stated for the PROFET, see Section 2.2.3. The diffusion of the turn-off times is up to 12 ms resulting in a deviation of 90,2% at 10μs, the shortest turn-off time possible in the PC Tool, see Section 3.5.2. A faster control loop is desired for making use of the PDUs hardware performance, which could be achieved with new software. With new software the PDU could also gain better diagnostic features, e.g. a short term buffer for fault analyze and more reliable timings for the different current levels. Due to that the comparison must be done in the microcontroller, the PDU would still be slower than the hardware approach even with new software.

A interesting result of the turn-off time tests and comparison between the prototyp, the PDU and the blow out fuse is that the digital switched PDU is slower then the blow out fuse when fusing a 1600% over-current, see Section 3.6. The analougue switched prototype is still the fastest. Because of the greater risk of damage from a 1600% over-current then from a 100% over-current this over-current is of great intrest to fuse as quickly as possible. An analouge switching design is thereby prefered.

The prototype shows fast turn-off times but lacks the possibility of changing the fusing levels in time. This could be solved by having a microcontroller setting the levels through a DA-converter. This solution would add flexibility to the prototype without compromising the performance. The tests show that the performance of the prototype could be increased further by improvements. The current sensor for example stands for the majority of the turn-off time and could be improved.

A combination between the PDU and the prototype was thought as the best solution. By using software to set the fusing levels and using hardware to compare the measured values to the fuse levels, this solution will gain both the performance of the prototype and the flexibility of the PDU. The possibility of failure is decreased with analogue comparison of the fuse levels.

To minimize the size of the active fuse system an integrated circuit including drive, logic and measurement is desired. By placing the MOSFET apart from the drive circuit the temperature dependency is minimized without violating the size of the unit. The unit could be adapted to various loads more freely by just changing MOSFETs. This is important because the different fault situations varies with different loads, see Section 2.4.3.

4.2 The active fuse system architecture

Both a central fuse unit architecture and an architecture with a fuse unit in required subsystems, described in Section 2.4.2, are possible solutions. The central active fuse unit architecture gains its most advantages where switches and communications are already available in the electric system. A central fuse unit can offer protection and supervision over the entire electric system of the vehicle with few fuses. Due to the use of preexisting switches and utilizing fewer measuring points the cost is lower then for the local active fuse unit architecture.

Implementation of a local active fuse unit architecture can either be done as a complement to a central fuse unit, in a stand alone configuration or in an electric system that lacks condition to use a central fuse unit. The subsystem controlled by a local active fuse unit, will due to the higher amount of measuring points, have more accurate diagnostic features then the central active fuse unit architecture.

Both systems can be implemented together with a traditional fuse system. For gradual implementation of an active fuse system the choice of implementing active fuse units in subsystems is to prefer. In this way only loads that will gain on greater diagnostic features can be protected and the rest of the traditional fuse system can be left untouched. A central active fuse system can replace one or several of the main fuses in a vehicle. If the loads are controlled by a switch they can be used to increase the fault isolation and in this way reduce the total number of fuses for that branch. In fact, a central active fuse unit can replace every blow out fuse in a branch. A disadvantage with this architecture is that even if the fault isolation is high a fault will disrupt every load for a short time to investigate which load that failed. Other disadvantages with a central active fuse unit is that faults within the branch will be unnoticed and the accuracy in fuse level will be reduced.

4.3 Advantages

The most obvious advantages of an active fuse unit are the reset ability and better diagnostic features. The reset ability makes other fuse placements possible. The placement does not have to be easily accessible, as for the blow out fuse. This results in the possibility of shorter cables, which reduces the risk of cable faults e.g. glitches. The minimized cable length will also result in lowered costs and total weight. The diagnostic feature is increased due to the increased number of measurement points throughout the electric system. By analyzing the measurements, degraded components in the circuit could be found. The component can then be replaced before it is defected out and starts affecting other components. In this way vehicle service could be scheduled for maximized availability as the result. In case of faults, e.g. short circuits or abnormal temperatures, the measurements can be used for better understanding in investigating the fault scenario. The current limiting can keep the electric system active during transients, which will lower the number of disrupts.

Another advantage is the accuracy of the active fuse system is greater then for the traditional fuse system. The accuracy together with the over-voltage protection and increased fusing speeds will reduce the need of internal protection of the electronics, e.g. ECUs. The higher accuracy of the active fuse system compared to the traditional fuse system will also make reduced cable dimensions possible.

An advantage with the active fuse system is the possibility of current limiting. This will also improve the reliability of the electric system, e.g. a large over-current will be suppressed and the magnitude of the resulting voltage transient will be reduced.

An active fuse system also enables fusing of loads that today are not possible to fuse, e.g. the starter motor.

4.4 Disadvantages

When introducing a new technology, unexpected problems may occur. Due to the importance of the fuse system the reliability of the new system must be carefully investigated. As mentioned there are a number of reasons for an active system to malfunction. The MOSFET is exposed to the load power, therefore adequate safety margins has to be chosen. By designing a fast and accurate control system stresses leading to faults in the MOSFET could be avoided. The drawback of the MOSFET compared to a blow out fuse is the uncertainty of which state it will take in the case off fault. Therefore the worst case always has to be treated. The possible fault scenarios of the MOSFET compared to a switch secured with a blow out fuse is shown in Figure 17. As seen the single scenario where the MOSFET lacks the security of the switch and fuse is when the MOSFET and switch is bypassed, Figure 17(c). The probability of the event to occur has to be investigated. With proper dimensioning of the MOSFET, the ability to reset and the gained performance and diagnostic features is enough favourable to apply an active fuse system.

5 Conclusion

Implementing new technologies will always invoke problems to overcome. With today's technology it is possible to implement an active fuse system. The major advantages are the diagnostic features and higher level of protection. A lowered demand on the internal protection in ECUs can be achieved together with decreased cable lengths and dimensions.

The architecture of the system can be realized in several ways and the most appropriate layout must be chosen individually. Implementing active fuse units where the largest advantages are gained would be a smooth transition path toward an active fuse system.

The hardware based prototype was, as expected, faster than the digital based PDU. For low over-currents both active systems were faster than the blow out fuse. During high over-currents the PDU is the slowest while the prototype is still the fastest. A analogue switching design is to prefer for uncompromised protection.

The flexibility were, as expected, better for the PDU than the prototype even though the PDU did not work as accurate and fast as expected.

For high currents the power losses were higher for the PDU and the prototype than for the blow out fuse. By using MOSFETs with lower on-state resistance these losses can be minimized.

With proper dimensioning of the active fuse system, the ability to reset and the gained performance and diagnostic features is too great of an advantage for not investing in the higher initial cost required.

6 Further work

To implement an active fuse system into a vehicle further research must be done, both on construction, architecture and safety. A flexible and fast circuit with a hardware controlled MOSFET and a microcontroller that sets the fuse levels was thought as the best solution.

To gain most advantages the active fuse system needs to use microcontroller and communicate with other units via the CAN bus. Problems that can occur when using microcontroller has only been mentioned in this master thesis and further analysis must be done.

To decide on where to implement active fuses it is important to know where fault occur most frequently. Investigation on where the amount of cable can be minimized most and a closer investigation of the ECU can also have impact on where to implement active fuses.

Further research needs to be done on the reliability of using semiconductor in the fuse system. Self heating could cause problem when using the transistor as a current limiter or switching off high current, a thermal analysis should be done to ensure the safety of the system, especially if implemented in system affecting the vehicle safety as airbag or ABS (Anti Break System).

In this thesis the different loads have been tested individually. In reality different fault can affect other loads in the circuit. Simulations over a large system must be done to see how a fault can propagate in the system. The load characteristics at different fault situation must be further analyzed to achieve good diagnostic features as well.

In further development of the prototype fuse levels comparing the energy density of the faults could be added. This would minimize the unwanted disrupts caused by non harmful transients.

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A Appendix

```
%**************************
% Power losses prototype vs blow out fuse
%**************************

fuse_resistance = [450 108 47.2 30.5 22.5 16.5 11.5 6.80 4.50 3.40 2.50...
    1.85 1.50 1.35]*10^-3;
fuse_current = [0.5 1 2 3 4 5 7.5 10 15 20 25 30 35 40];
AFS=0.17235 + 0.0057*(fuse_current.^2);                 % Prototype losses.
PDU=0.0016*5 +  0.009*(fuse_current.^2) + 15*24*10^-6;  % PDU losses.

figure('Name','Power losses','NumberTitle','off','Position',...
    [1 scrsz(4)/3 800 280])
hold on; grid on;
plot(fuse_current,fuse_resistance.*(fuse_current.^2),'r')
plot(fuse_current,PDU,'g')
plot(fuse_current,AFS,'b')
legend('Blow out fuse','PDU R_{ds(on)}=9m\Omega',...
    'Prototype R_{ds(on)}=5.7m\Omega',0)
xlabel('Current [A]'), ylabel('Power losses [W]')
title('Power losses for different rated blow out fuses,
the PDU and the Prototype')

%*********************************
% Time correction PDU
%******************************

time = [10:10:3000];
% All measurements in millisecounds.

% Time set for the front AUX switch in the PDU.
PDU_time_front_AUX=   [ 10 10 10 10 10 10 10 10 10 10
                        50 50 50 50 50 50 50 50 50 50
                        100 100 100 100 100 100 100 100 100 100
                        200 200 200 200 200 200 200 200 200 200
                        300 300 300 300 300 300 300 300 300 300
                        400 400 400 400 400 400 400 400 400 400
                        500 500 500 500 500 500 500 500 500 500
                        1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
                        1500 1500 1500 1500 1500 1500 1500 1500 1500 1500
                        2000 2000 2000 2000 2000 2000 2000 2000 2000 2000
                        2500 2500 2500 2500 2500 2500 2500 2500 2500 2500
                        3000 3000 3000 3000 3000 3000 3000 3000 3000 3000
                        ];

% Measured time from tests done on the front AUX switch.
Actual_time_front_AUX=[   8.32   6.08  10.08  12.40   6.08  12.56   8.24...
                          8.24   8.08   4.00
```

```
                         14.60  16.80  16.60  16.80  21.20  14.60  16.80...
                         14.60  14.60  16.60
                         31.20  25.00  31.40  27.20  26.80  25.20  27.40...
                         31.60  33.40  25.00
                         64.80  64.80  56.80  56.40  63.20  58.80  64.80...
                         65.20  65.20  57.20
                         90.40  96.00  89.60  91.20  97.60  96.00  97.60...
                         91.20  91.20  88.80
                        114.40 116.80 116.80 118.40 112.80 118.40 116.80...
                        110.40 112.00 110.40
                        148.80 142.40 148.80 150.40 148.80 148.00 148.00...
                        151.20 148.80 142.40
                        300.00 298.00 298.00 294.00 298.00 300.00 300.00...
                        300.00 298.00 290.00
                        432.00 430.00 432.00 432.00 436.00 432.00 432.00...
                        432.00 432.00 436.00
                        584.00 584.00 584.00 580.00 588.00 580.00 580.00...
                        580.00 588.00 584.00
                        728.00 728.00 732.00 728.00 728.00 728.00 736.00...
                        728.00 728.00 724.00
                        860.00 856.00 864.00 860.00 864.00 856.00 864.00...
                        856.00 864.00 856.00
                        ];

% A fitted linear line of the measurements.
fit=polyfit(PDU_time_front_AUX,Actual_time_front_AUX,1);
f=polyval(fit,PDU_time_front_AUX);

figure('Name','PDU correction time test','NumberTitle','on','Position',...
    [scrsz(3)/4 scrsz(4)/6 800 280])
hold on; grid on;
plot(PDU_time_front_AUX(:,1),f(:,1),'r-')
plot(PDU_time_front_AUX,Actual_time_front_AUX,'b*')
xlabel('PDU time [ms]'), ylabel('Actual time [ms]')
title('PDU correction time test at 1A current limit')
legend('Fitted line','Measured values',4)
text(1200,1200*fit(1,1)+fit(1,2),['f(x)=',num2str(fit(1,1)),'x+',...
    num2str(fit(1,2)),' \rightarrow'],'FontSize',10,...
    'HorizontalAlignment','right','VerticalAlignment','bottom')

% Calculate the diffusion in every test point.
diff=zeros(12,1);
for n = 1:12
   diff(n)=max(Actual_time_front_AUX(n,:))-min(Actual_time_front_AUX(n,:));
end

figure('Name','The deviation from the approximated curve of the PDU
correction time test','NumberTitle','on','Position',...
    [scrsz(3)/4 350+scrsz(4)/6 800 280])
```

```
plot([0:1:3000],zeros(1,3001),'r-')
hold on; grid on;
plot(PDU_time_front_AUX,Actual_time_front_AUX-...
    (PDU_time_front_AUX*fit(1,1)+fit(1,2)),'b*')
axis([0 3000 -15 15])
xlabel('PDU time [ms]'), ylabel('Varians [ms]')
title('Deviation from the apporximare curve of the PDU correction
time test at 1A current limit')
legend('Fitted line','Measured values',4)
text(500,-10,['Maximum deviation from the approximate curve: ',...
    num2str(max(max(abs(Actual_time_front_AUX-...
    (PDU_time_front_AUX*fit(1,1)+fit(1,2)))))),' ms'],...
    'FontSize',10,'HorizontalAlignment','left','VerticalAlignment','top')
text(500,-8, ['Maximum diffution: ',num2str(max(diff)),' ms'],...
    'FontSize',10,'HorizontalAlignment','left','VerticalAlignment','top')



% PDU time set to 500 ms, voltage 12V, resistance 1ohm and a current of
% 12A. The tests where done for different current limits.

% Current limit in the PDU.
PDU_current_front_AUX=    [ 1  1  1  1  1
                            2  2  2  2  2
                            4  4  4  4  4
                            6  6  6  6  6
                            8  8  8  8  8
                            10 10 10 10 10
                            11 11 11 11 11
                            ];

% Measured time from tests done on the front AUX switch.
Actual_time_front_AUX_current=    [ 20.80  20.80  20.80  16.80  22.40
                                    32.80  16.80  23.20  33.60  20.80
                                    37.60  37.60  53.60  37.60  41.60
                                    67.20  69.60  76.00  69.60  76.00
                                    116.00 108.00 107.20 99.20  100.80
                                    162.40 154.40 152.00 158.40 151.20
                                    184.00 200.00 206.00 196.00 196.00
                                    ];

% A fitted linear line of the measurements.
fit_current=polyfit(PDU_current_front_AUX,Actual_time_front_AUX_current,2);
f_current=polyval(fit_current,PDU_current_front_AUX);

figure('Name','PDU current limit variation','NumberTitle','on',...
    'Position',[scrsz(3)/4 scrsz(4)/6 800 280])
hold on; grid on;
plot(PDU_current_front_AUX(:,1),f_current(:,1),'r-')
```

```
plot(PDU_current_front_AUX,Actual_time_front_AUX_current,'b*')
xlabel('PDU current limit [A]'), ylabel('Actual time [ms]')
title('PDU current limit variation test with PDU time set to 500ms')
legend('Fitted line','Measured values',4)
```

B Appendix

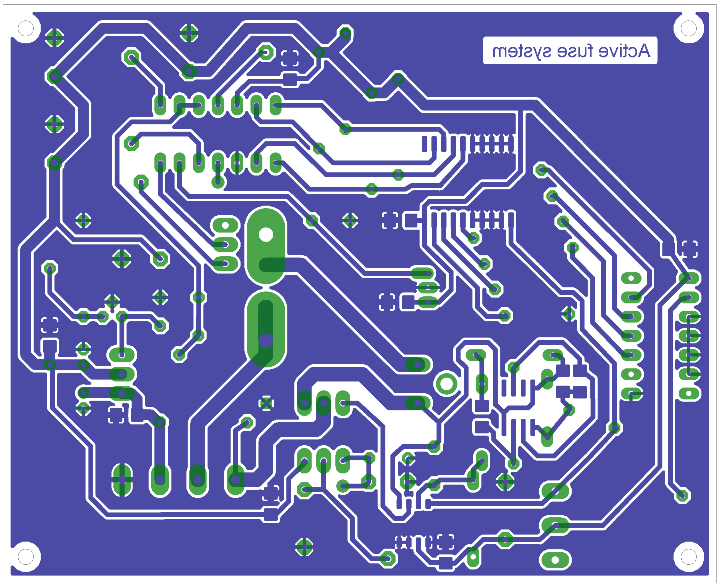

Figure 42: PCB layout for the prototype.

C Appendix

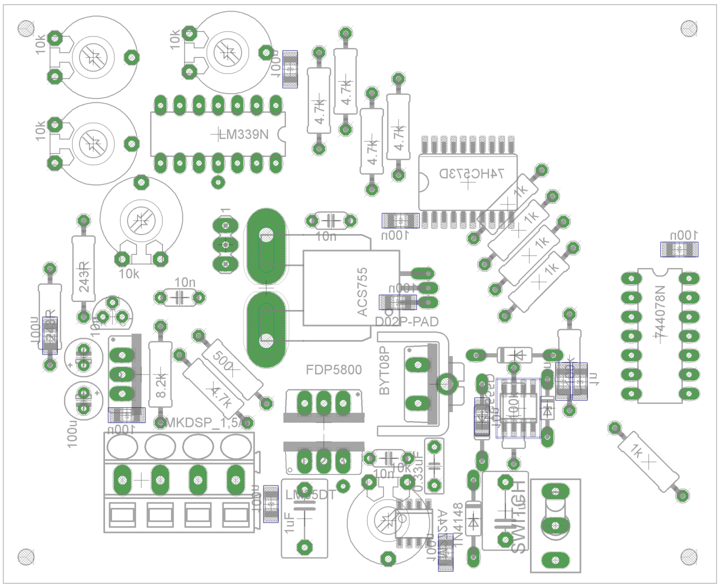

Figure 43: Component placement on the PCB.