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Design and construction of a mobile unit for testing of electrical loading in vehicles

Konstruktion av en bärbar enhet för testning av elektrisk förbrukning i fordon

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Sammanfattning

Elkraftförsörjningen i lastbilen är idag en av de viktigaste frågorna för Volvo Lastvagnar. Kvaliteten på kraftförsörjningen är viktig bland annat för elektroniken som blir allt vanligare i bilarna. En noggrann kvalitetssäkring av elsystemet är i framtiden nödvändig och att belasta systemet med effektkrävande laster är en del av detta.

För att testa detta krävs en bärbar enhet som kan förbruka 200-300 A och har en noggrannhet under 5 A.

En sådan enhet har utvecklats och konstruerats. Enheten består av ett effektförbrukande system och ett styr- och reglersystem.

Det effektförbrukande systemet består av flera mindre effektförbrukande kretsar vilka i sin tur består av en MOSFET och en (i tre fall två) effektmotstånd samt kondensatorer för att släta ut eventuella spänningstransienter orsakade av induktansen i kablar och komponenter, vilka uppkommer på grund av styr- och reglersystemets switchfrekvens.

Styr- och reglersystemet är uppbyggt kring en A/D omvandlare. En analog insignal fås genom att jämföra inställt börvärde med aktuellt strömvärde för att hålla strömförbrukningen konstant oavsett spänning. Den analoga insignalen transformeras i A/D omvandlaren till 8 digitala signaler vilka styr MOSFETarna i det effektförbrukande systemet.

För att enheten skall betraktas som bärbar har den maximala vikten satts till 30 kg, men det visade sig att för att förbruka den önskade strömmen skulle vikten på kylflänsar och övriga komponenter överstiga 30 kg med mycket bred marginal. En modulerad lösning med tre stycken ihopkopplingsbara enheter konstruerades därför. De kan användas var för sig eller tillsammans. Enhet 1 består av styr- och reglersystem och två stycken kylflänsar och dess maximala strömförbrukning är 28 A. Enhet 2 består av tre stycken kylflänsar och kan kopplas till enhet 1. De har tillsammans en maximal strömförbrukning på 113 A. Enhet 3 består även den av tre stycken kylflänsar och kan kopplas till enhet 1 och 2. En maximal strömförbrukning på 198 A kan då uppnås.

Abstract

The supply of electrical power is an important issue for Volvo trucks. To reach high accuracy in the quality assurance of the electrical power system in the future is vital and to see how the electrical power system reacts when loading of power demanding loads is an important issue.

To test this a mobile unit for electrical loading is needed. The unit should have a maximum current consumption of 200-300 A and have an accuracy below 5 A.

Such a unit has been designed and constructed. The unit consists of one power consumption system and one electronic control system.

The power consumption system consists of one MOSFET, one, or in three cases two, power resistors and smoothing capacitors to eliminate voltage peaks caused by inductances in cables and components due to switching.

The control system is based on an A/D converter. An analogue input signal is obtained by comparing a reference value with the actual current value to get constant current consumption during system voltage variations. The A/D converter transforms the analogue input signal to 8 digital signals which control the MOSFETs in the power consumption system.

For the unit to be mobile a maximum weight of 30 kg seemed reasonable. However, it is not possible to consume the desired current and keep the weight below 30 kg, mainly because of the weight of the heatsinks. Therefore a modular design with 3 connectable units was considered. The units can be used separately or together. Unit 1 consists of the control system and 2 heatsinks and its total current consumption is 28 A. Unit 2 consists of three heatsinks and has together with unit 1 a maximum current consumption of 113 A. Unit 3 also consists of three heatsinks and together with unit 1 and 2 their maximum current consumption is 198 A.

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1 Introduction

1.1 Background and aim of the work

The supply of electrical power is an important issue for Volvo trucks and the quality of the electrical power is vital for electronics, among others, which has increased considerably in the vehicles during the recent years.
It is therefore of much interest to reach high accuracy in the quality assurance of the electrical power system in the future. One important issue is how the electrical system reacts when high-power demanding loads are connected to the system.
The topic for this thesis is therefore to design and construct an electronically controlled mobile unit for testing of electrical loading to see how the electrical system reacts on different high-power loading. Loads between a few A and approximately 200-300 A are desired to simulate with an accuracy below 5 A.
The unit should be used for field purposes, this means it has to be portable and its weight should not exceed 30 kg, which is seen as a reasonable limit for mobility.
About ten years ago components for constructing a unit for testing of electrical loading were purchased. The unit was never built and the components where left in a repository. Among these components are 21 semiconductors from Siemens, 12 current modules and 9 heatsinks with unknown characteristics and fans mounted. As many as possible of these components are to be used in the construction.
An important phase of the work is therefore to test the available components, in some cases because their characteristics are not known, and in general to verify their status with respect to aging.
It will be seen that in many cases it is not possible to use the existing components. It will also be seen that the mobility requirement poses very strict limits on the design of the unit and therefore a modular design will be considered.

1.2 Outline of the thesis

This report describes the design and construction of the testing unit.
In chapter 2 the design of the power consumption system is discussed. An important issue, which is treated in chapter 3, is the cooling of the components since the consumed power is converted into heat. Chapter 4 handles the other important issue of mobility, i.e. weight of the unit. In chapter 5 the design of the control system is presented. The different parts of the unit are supplied with different voltage levels, which is discussed in chapter 6. Construction of the unit is the subject of chapter 7. After constructing the unit, it was tested and the results of the tests are reported in chapter 8. Finally, conclusions are drawn in chapter 9.

2 Power consumption system

In this chapter the design of the power consumption system consisting of power resistors, power MOSFETs and smoothing capacitors will be discussed. It will become clear later in this report that three different units have been built instead of one. However, the design of the power consumption system is basically the same for all three units.

2.1 Set up of power consumption system

The power consumption system consists of several power consuming circuits. These circuits consists of one power MOSFET and one or, in three cases, two power resistors. Figure 2.1 illustrates an overview of the power consumption system. The system voltage, V_{system}, provided by the battery is 24 V.

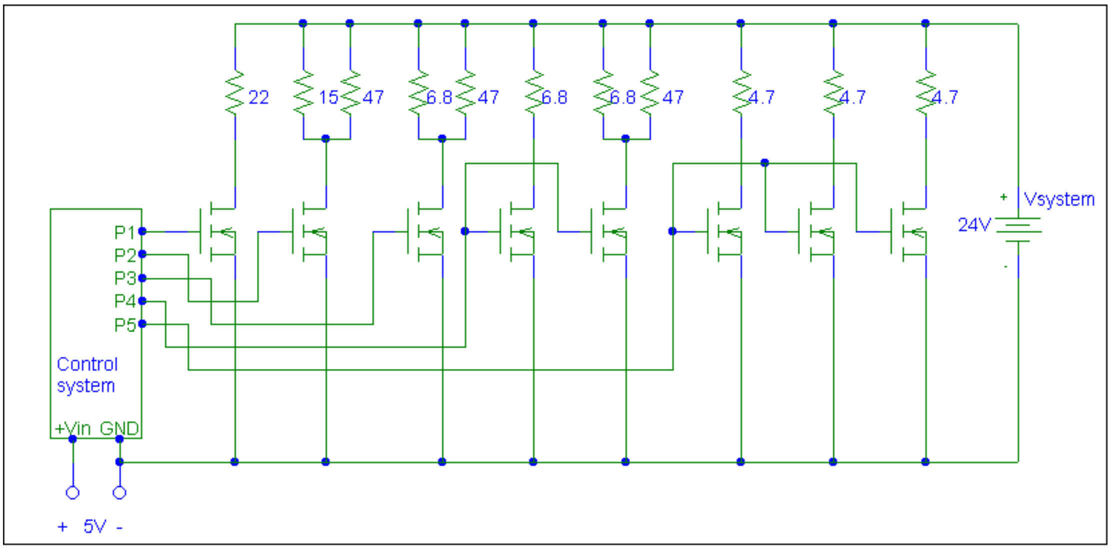

Figure 2.1. Power consumption system for unit one. Resistance values are explained in chapter 5.4.1.

2.2 Power resistors

2.2.1 Power dissipation

To decide the power dissipation limit of the power resistors was one of the most complex issues in the project. Both physical size and maximum power dissipation were decisive.

The limiting factor, concerning both physical size and power dissipation, is the available heatsink. It has a certain size in which the resistors must be mounted and its thermal resistance must be sufficient for dissipating the heat.
On top of the heatsinks there are two grooves, which were neglected and resistors mounted across these. If the grooves were to be considered the total number of resistors that can be mounted on each heatsink would decrease with between 20 to 50 % and so also the power dissipation. To compensate for the increased thermal resistance for mounting the resistors across the grooves the thermal resistance for the heatsink was increased.

Table 2.1 illustrates the results of the calculations of total power dissipation and total price on eight heatsinks and price per power with different power resistors (resistors of 6.8 Ω able to dissipate different amout of power are considered here).

Maximum power (W)	Total quantity on 8 heatsinks	Total power (W)	Price for 1 6,8 Ω resistor (SEK)	Total price (SEK)	Price / Power (SEK / W)
300	16	4800	277.00	4432.00	0.923
200	16	3200	192.00	3072.00	0.960
150	48	7200	96.03	4609.44	0.640
100	48	4800	73.40	3523.20	0.734
75	48	3600	54.56	2618.88	0.727
50	96	4800	25.00	2400.00	0.500

Table 2.1. Total power and price for different resistors mounted on heatsink.

The requirements of the project were to consume 200-300 A which corresponds to a power of 4800-7200 W at the system voltage of 24 V. Using the 150 W power resistors seems to be a good solution for both technical and economical reasons.

2.2.2 Resistance

The system voltage of 24 V results in a maximum current through the resistors at $P_{max} = 150$ W of

$$I = \frac{P}{U} = \frac{150}{24} = 6.25 \text{ A} \qquad (2.1)$$

which requires a resistance of

$$R = \frac{U}{I} = \frac{24}{6.25} = 3.84 \ \Omega \qquad (2.2)$$

However, the system voltage can vary between 12 and 29.5 V. Resistors from the E6 series are available and besides the resistors of 6.8 Ω considered in Table 2.1, also 3.3 and 4.7 Ω resistors are considered. Figure 2.2 illustrates the power dissipation in the 150 W resistors at considered resistances when the voltage varies between 10 and 35 V.

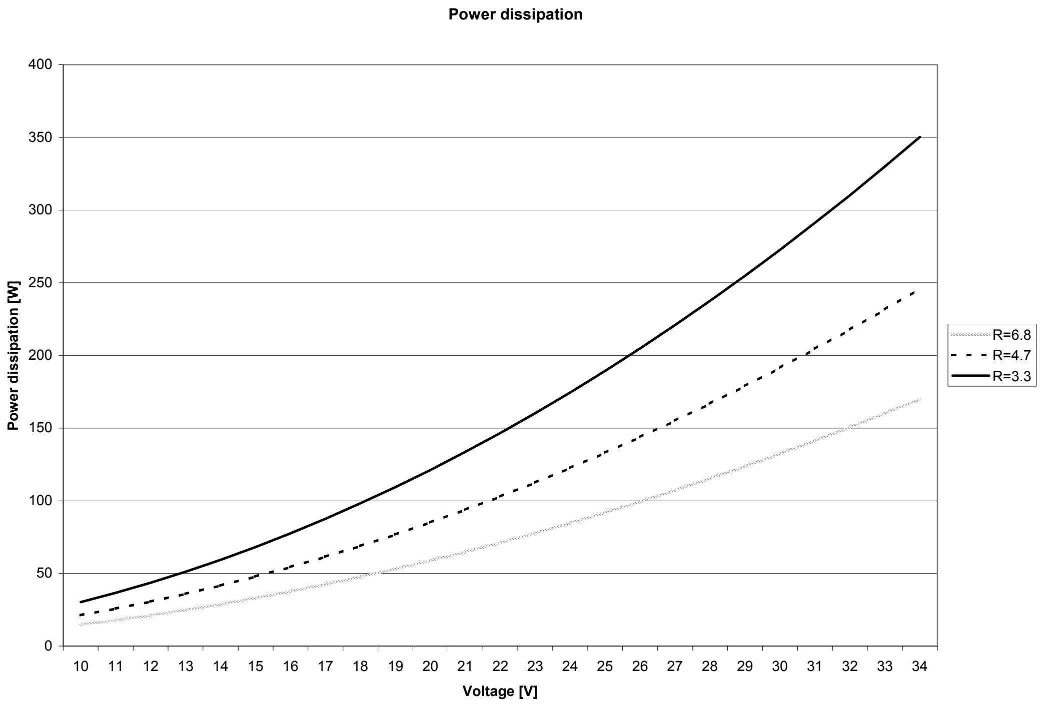

Figure 2.2. Power dissipation in W at considered resistances from the E6 series when the voltage varies between 10 and 35 V (R=3.3, 4.7, 6.8 Ω).

Moreover, Figure 2.3 shows the loading of the considered power resistors as a percentage of the maximum power (150 W) for the three resistances considered when the voltage varies between 10 and 35 V. Table 2.2 shows the values of the percent loading for specific values of the applied voltage, namely 20, 24 and 28 V.

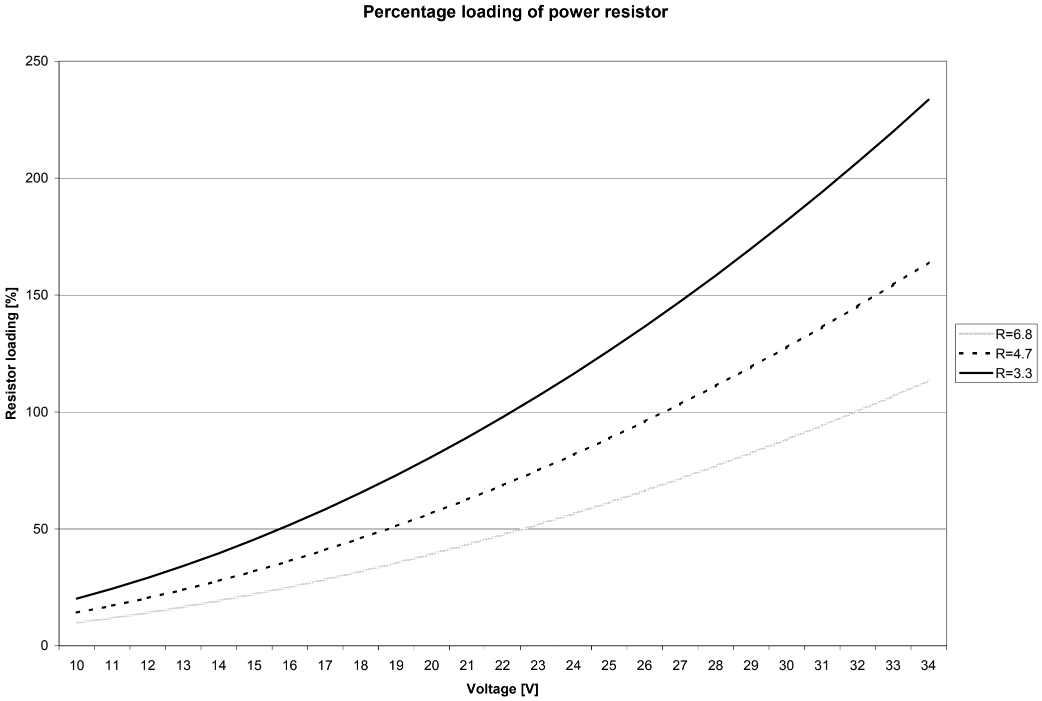

Figure 2.3. Resistor loading in [%] when the voltage varies between 10 and 35 V for different values of resistance (R=3.3, 4.7, 6.8 Ω).

Resistance (Ω)	Resistor loading (%) at 20 V	Resistor loading (%) at 24 V	Resistor loading (%) at 28 V
3.3	81	116	158
4.7	57	82	111
6.8	39	56	77

Table 2.2. Percent loading at pertinent voltage levels.

The resistance that maximises the use of the 150 W power resistor is 4.7 Ω. At 28 V there is a power dissipation of almost 167 W but an overload of 11% is acceptable for a short period of time. At 24 V the total power dissipation is 123 W (corresponding to 82 %).

2.3 Power MOSFET

2.3.1 Dimensioning criteria

When dimensioning the MOSFETs several different aspects were considered:

- Maximum power dissipation
- Maximum current
- Maximum voltage
- On-state resistance, R_{DSon}
- Switching losses
- Price

The maximum voltage has to be 100 V or above since voltage peaks can occur in the system. The absolute maximum current flowing through the MOSFET is approximately 7 A (obtained with the maximum system voltage of 30 V applied to the 4.7 Ω resistor, resulting in a current of 6.4 A), but an increase in temperature will decrease the maximum current tolerance for the MOSFET, therefore it is wise to have a wide margin. R_{DSon} should be as low as possible to minimise conduction losses (see 2.3.3). The rise time and fall time should be as short as possible to minimise switching losses (see 2.3.3).
The price of the component should also be relatively low, this is not a critical parameter, but of certain importance.

On the basis of these criteria the MOSFET IRF540 is chosen. From the manufacturer's datasheet [1], the most significant technical data have been reported in Table 2.3, where P_{tot} is the maximum power dissipation in the component, V_{DS} is the drain to source breakdown voltage, I_D is the maximum drain current, $V_{GS(TH)}$ is the threshold value of the gate to source voltage, R_{DSon} is the on-state resistance.

P_{tot} (W)	V_{DS} (V)	I_D (A)	$V_{GS(TH)}$ (V)	R_{DSon} (Ω)
120	100	28	2..4	0.06

Table 2.3. Significant data for IRF540 (from [1]).

2.3.2 Gate – source voltage

It is desirable to use the same voltage of the gate-source voltage at MOSFET as of the electronic control system so the same voltage source can be used. As shown in the characteristics reported in Figure 2.4, with V_{GS} = 5 V the MOSFET can conduct approximately 10 A at $V_{system} = 24$ V, which should be enough during all conditions in this construction.

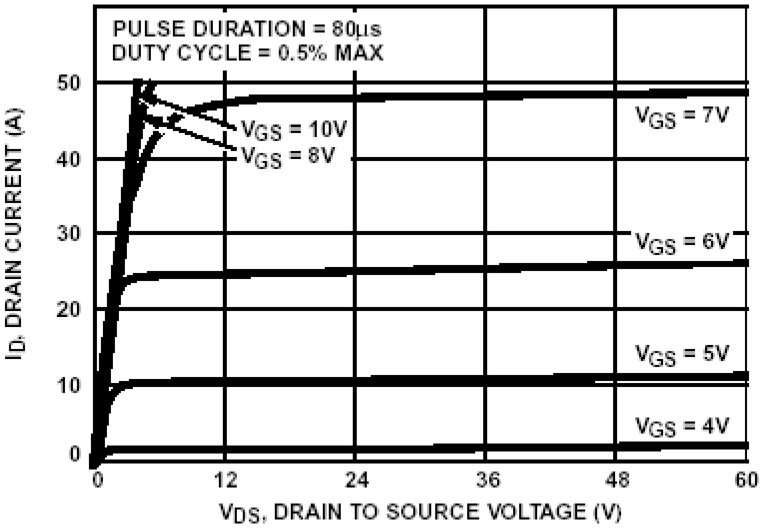

Figure 2.4. IRF540 output characteristics: drain current I_D as a function of drain-to-source voltage V_{DS} for different values of gate-to-source voltage V_{GS} (from [1]).

2.3.3 Power dissipation in MOSFET

As all power electronic components, the MOSFET IRF540 is characterised by both conduction losses and switching losses.

Conduction losses are due to the voltage drop over the MOSFET is not zero when conducting. The conduction losses, P_{cond}, depend on the on-state resistance, R_{DSon}, and the current flowing through the device, I_D, as

$$P_{cond} = I_D^2 \cdot R_{DSon} \qquad (2.3)$$

A typical value of 0.06 Ω is given for R_{DSon} in the datasheet [1]. With a voltage of 24 V and a resistor of 4.7 Ω, the steady-state current is U/R = 5.11 A and the conduction losses from Equation(2.3) are 1.56 W.

When switching, the current goes from zero to I_D and the voltage at the same time switches from V_{system} to V_{cond}. During this short period of time there are both current and voltage in the MOSFET at the same time, which causes switching losses.

Figure 2.5 shows the waveform and switching times for the drain-to-source voltage, V_{DS} and the gate-to-source voltage, V_{GS}.

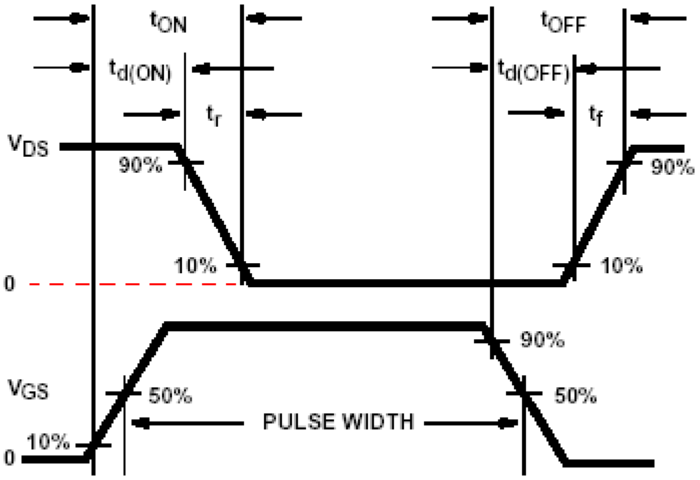

Figure 2.5. Waveforms of drain-to-source voltage V_{DS} and gate-to-source voltage V_{GS} during switching (from [1]).

The switching losses can be calculated as [2]

$$P_{switching-losses} = P_{on} + P_{off} = W_{on} \cdot f_s + W_{off} \cdot f_s \qquad (2.4)$$

where P_{on} is the losses when switching on, P_{off} is the losses when switching off, W_{on} is the energy when switching on and W_{off} is the energy when switching off and f_s the switching frequency. The energies W_{on} and W_{off} can be calculated as [2]

$$W_{on} = \int_0^{t_r} \Delta V_s \cdot \left(1 - \frac{t}{t_r}\right) \cdot I_D \cdot \frac{t}{t_r} \; dt = \frac{\Delta V_s \cdot I_D \cdot t_r}{6} \qquad (2.5)$$

where t_r is the rise time, illustrated in Figure 2.5 and ΔV_S is the voltage difference between conduction and blocking, and

$$W_{off} = \int_0^{t_f} \Delta V_s \cdot \frac{t}{t_f} \cdot I_D \cdot \left(1 - \frac{t}{t_f}\right) \; dt = \frac{\Delta V_s \cdot I_D \cdot t_f}{6} \qquad (2.6)$$

where t_f is the fall time, illustrated in Figure 2.5. The total switching losses from Equation(2.4) result as

$$P_{switching-losses} = \frac{\Delta V_s \cdot I_D}{6} \cdot \left(t_r + t_f\right) \cdot f_s \qquad (2.7)$$

Rise time and fall time for IRF540 are known and ΔV_s and I_D are also known parameters. The frequency though is not known. Figure 2.6 shows switching losses at different frequencies.

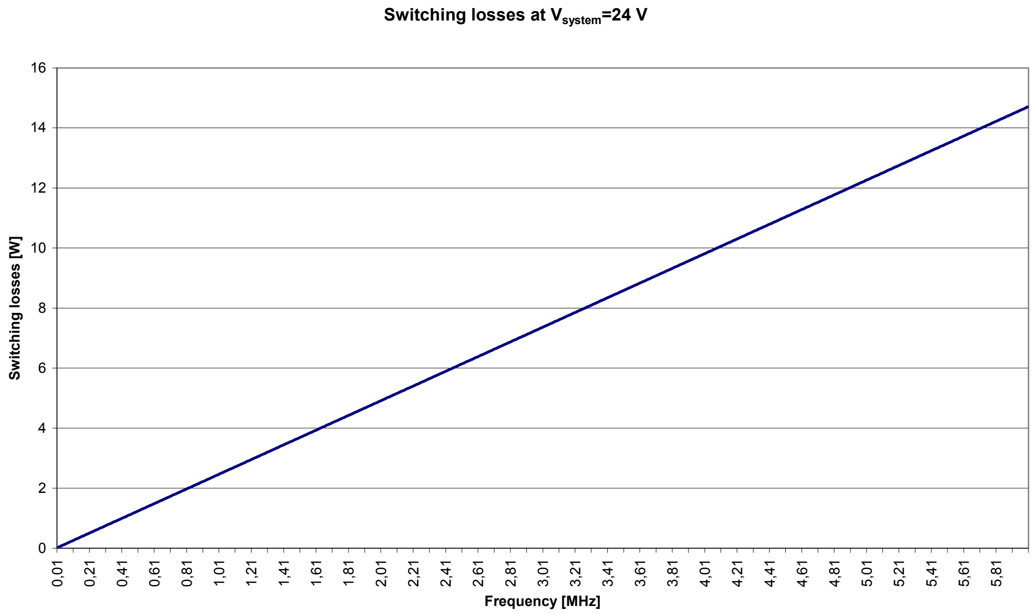

Figure 2.6. Switching losses in the MOSFET IRF540 at frequencies from 10 kHz to 6 MHz.

The maximum switching frequency f_{max} for the IRF540 is calculated as:

$$f_{max} = \frac{1}{t_{d(ON)} + t_r + t_{d(OFF)} + t_f} \qquad (2.8)$$

where $t_{d(ON)}$ is the delay between gate-source voltage and drain-source voltage response at turn on, illustrated in Figure 2.5 and $t_{d(OFF)}$ is the delay between gate-source voltage and drain-source voltage response at turn off, also illustrated in Figure 2.5.

Values from the datasheet [1] are substituted and the maximum switching frequency for IRF540 is calculated to 5.4 MHz. This frequency implies a total power dissipation, i.e. sum of conduction and switching losses, of 16.3 W.

2.3.4 Thermal limitations

The maximum temperature on the MOSFET heatsink is calculated based on analogy of voltage, current and resistance calculations [3], as shown later in Figure 3.5, with the following formulas:

$$\frac{T_{junction,max} - T_{heatsink}}{R_{th\text{-}junction\text{-}heatsink}} = P_{max} \qquad (2.10)$$

$$\frac{T_{heatsink} - T_{ambient}}{R_{th\text{-}heatsink\text{-}ambient}} = 18 \cdot P_{max} \qquad (2.11)$$

where $T_{junction,\ max}$ is the maximum junction temperature for the MOSFET, $T_{heatsink}$ is the temperature of the MOSFET's heatsink, $R_{th\text{-}junction\text{-}heatsink}$ is the thermal resistance between MOSFET's junction and heatsink and P_{max} is the maximum power dissipation from the MOSFET, $T_{ambient}$ is the ambient temperature, $R_{th\text{-}heatsink\text{-}ambient}$ is the thermal resistance between heatsink and ambience and 18 the number of MOSFETs on one heatsink.

By substituting from (2.10) into (2.11)

$$\begin{aligned} &\frac{T_{junction,\,max} - P_{max}\cdot R_{th\text{-}junction\text{-}heatsink} - T_{ambient}}{R_{th\text{-}heatsink\text{-}ambient}} = 18\cdot P_{max} \Leftrightarrow \\ &\Leftrightarrow P_{max} = \frac{T_{junction} - T_{ambient}}{18\cdot R_{th\text{-}heatsink\text{-}ambient} + R_{th\text{-}junction\text{-}heatsink}} \end{aligned} \qquad (2.12)$$

Substituting the values, $T_{junction,\ max}$ = 175 °C, $T_{ambient}$ = 25 °C, $R_{th\text{-}heatsink\text{-}ambient}$ = 1.1 °C/W, $R_{th\text{-}junction\text{-}heatsink}$ = 1.25 °C/W in Equation(2.12) gives P_{max} = 7.13 W. With conduction losses of 1.56 W, the maximum switching losses are 5.57 W. Equation(2.7) gives that a switching frequency of 2.27 MHz results in switching losses of 5.57 W.

The maximum switching frequency for the MOSFET with respect to heating concerns is thus 2.27 MHz.

2.4 Smoothing capacitor

The control system switching frequency of 24 kHz (see chapter 5.5.1) is together with induction in cables and components causing voltage and current peaks from the power source. The voltage peaks are between 100 and 150 V. This kind of voltage peaks will cause major problems and can severely damage the electrical system of the truck. The voltage peaks will also create losses in the MOSFET, which may be overheated, since the drain to source breakdown voltage is 100 V.

To eliminate the voltage and current peaks smoothing capacitors are connected in parallel with the power consumption system, as shown in figure 2.7.

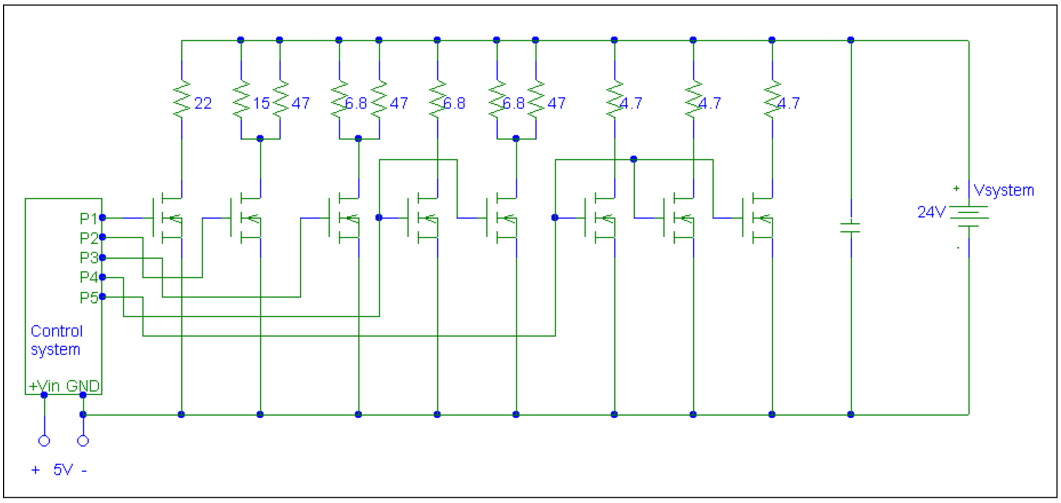

Figure 2.7. Smoothing capacitor connected in parallel with power consumption system.

The capacitance of the smoothing capacitor is chosen to 66 mF based on test results.

2.4.1 Operational life time of electrolyte capacitor

The operational life-time of an electrolyte capacitor may be a critical parameter.

The operational life of the capacitor (PEH200KD5220M) can be calculated with Equation(2.13) to Equation (2.15) [4].

$$P_{LOSS} = I_{RMS}^{2} \cdot ESR \qquad (2.13)$$

where P_{LOSS} are the power losses in the capacitor, I_{RMS}, the RMS current through the capacitor and ESR the ESR-value for the capacitor from [5].

$$T_h = T_a + R_{th} \cdot P_{LOSS} \qquad (2.14)$$

T_h is the winding hotspot temperature, T_a the ambient temperature and R_{th} the thermal losses in the capacitor from [5].

$$L_{OP} = A \cdot 2^{\frac{85-T_h}{C}} \qquad (2.15)$$

where L_{OP} is the operational life time, A is the expected life time at 85 °C hotspot temperature and C a constant from [4], equal to 12 for PEH200KD5220M.

I_{RMS} is very close to zero since the pulse is very short and the current through the capacitor is zero otherwise. $I_{RMS} \approx 0$ gives that T_h must be close to ambient temperature. T_h = 30 °C results in a operational life time of $479 \cdot 10^3$ hours, equal to 20000 days or almost 55 years, which should be enough.

3 Cooling

The cooling is of much interest in the design. Since the available heatsink had unknown characteristics it was tested and the results of the test are reported in this chapter. Other cooling issues will also be discussed.

3.1 Test of available heatsink

The heatsink thermal characteristics are of vital importance for the construction. Along with the available components are 10 heatsinks with unknown characteristics, displayed in Figure 3.1.

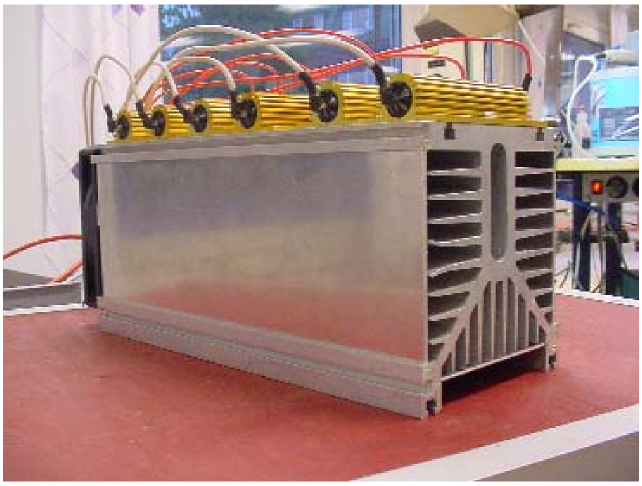

Figure 3.1. Available heatsink

3.1.1 Test setup and theory

The thermal resistance of the heatsink, $R_{th\text{-}heatsink\text{-}ambient}$ is one of the most critical parameters in the design since the power consumed is converted into heat which has to be cooled down. It can be calculated as [3]

$$R_{th-heatsink-ambient} = \frac{T_{heatsink} - T_{ambient}}{P} \quad (3.1)$$

where $T_{heatsink}$ is the heatsink temperature, $T_{ambient}$ is the ambient temperature and P the power dissipated on the heatsink.

In the test eight 50 W Arcol power resistors were used with a resistance of 15 Ω each, dissipating a total power between 200 and 400 W in steps of 50 W in the different test setups. The resistors are mounted next to each other on top of the heatsink and a fan with capacity 141 m^3/hour is attached to the side of the heatsink. Since the influence of the fan is difficult to calculate, the heatsinks thermal resistance is tested with the fan running and is really the heatsink-fan thermal resistance. The eight resistors were connected in parallel to a voltage source.

3.1.2 Measurements

The different levels of power specified in 3.1.1 were tested to get the average thermal resistance of the heatsink. Four temperature sensors were connected to the heatsink, two of them placed just underneath the resistors in bored grooves to get the maximum temperature in the sink, two sensors placed inside the sink, one near the attachment point of the resistors and one at the bottom. One additional sensor measured the ambient temperature. Figure 3.2 shows the temperature rise just underneath one of the resistors.

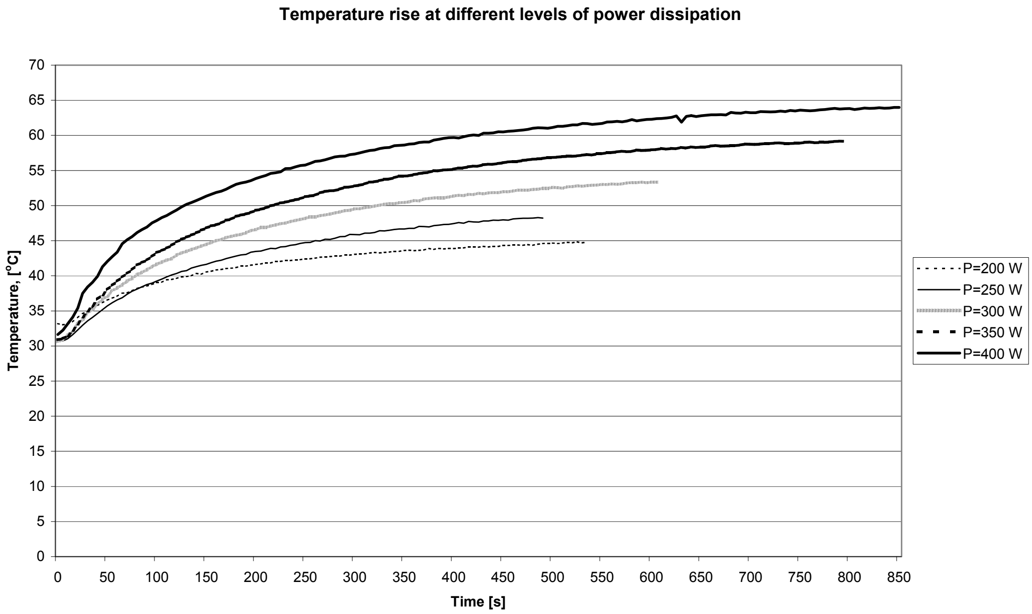

Figure 3.2. Heatsink temperature rise at different levels of power dissipation. P varying between 200 and 400 W in steps of 50 W.

3.1.3 Test results

The thermal resistance of the heatsink has been calculated from the measurements above according to Equation(3.1). The results obtained are reported in Table 3.1.

P (W)	$T_{heatsink}$ (°C)	$T_{ambient}$ (°C)	ΔT (°C)	$R_{th,heatsink\text{-}ambient}$ (°C / W)
400	64,0	28	36	0,090
350	59,2	28	31,2	0,089
300	53,3	29	24,3	0,081
250	48,2	29	19,2	0,077
200	44,8	29	15,8	0,079

Table 3.1. Thermal resistance for available heatsink.

The average thermal resistance for the heatsink is 0.083 °C/W, but since the temperature rise had not completely stagnated, the thermal resistance gets higher as more power is consumed and the grooves on top of the heatsinks have been neglected, the thermal resistance for the heatsink is set to 0.10 °C/W. The variation of heatsink temperature caused by the power dissipated for the thermal resistance of 0.10 °C/W is shown in Figure 3.3.

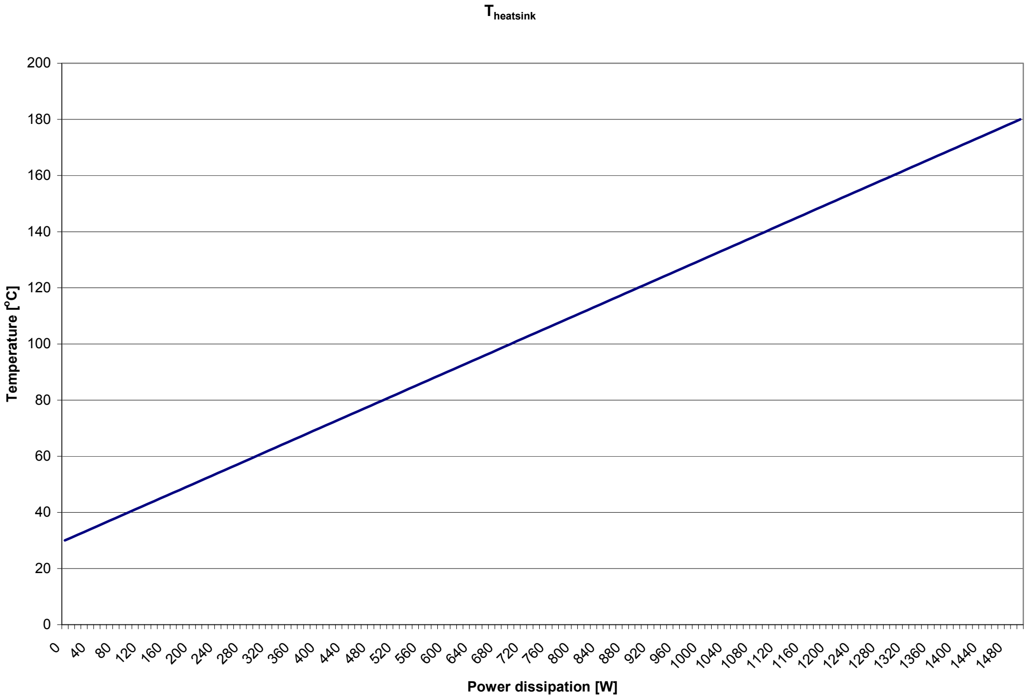

Figure 3.3. Heatsink temperature as a function of power dissipation with R_{th}=0.10 °C / W.

3.2 Fan

3.2.1 Available fan

The available fan had a power supply of 230 V AC. After considering the idea of a 24 / 230 V DC/AC converter proved to be too expensive the available fan was replaced with a 24 V DC fan. The fan characteristics can be seen in Table 3.2.

Capacity (m^3/h)	Noise level (dB)	Number of revolutions (rpm)	Power consumption (W)
141	41	2400	6

Table 3.2. Fan characteristics.

3.2.2 Cooling effect by fan

A fan can blow or suck air through the heatsink. Tests where performed with the fan sucking, blowing and without it. Results are presented in Figure 3.4. Tests showed that there was no apparent difference between using a blowing or sucking fan. A blowing fan has the advantage though of cooling itself when running, which increases its lifetime compared with using a sucking fan. When dissipating power without a fan the temperature in the heatsink never stagnated, so the test was aborted.

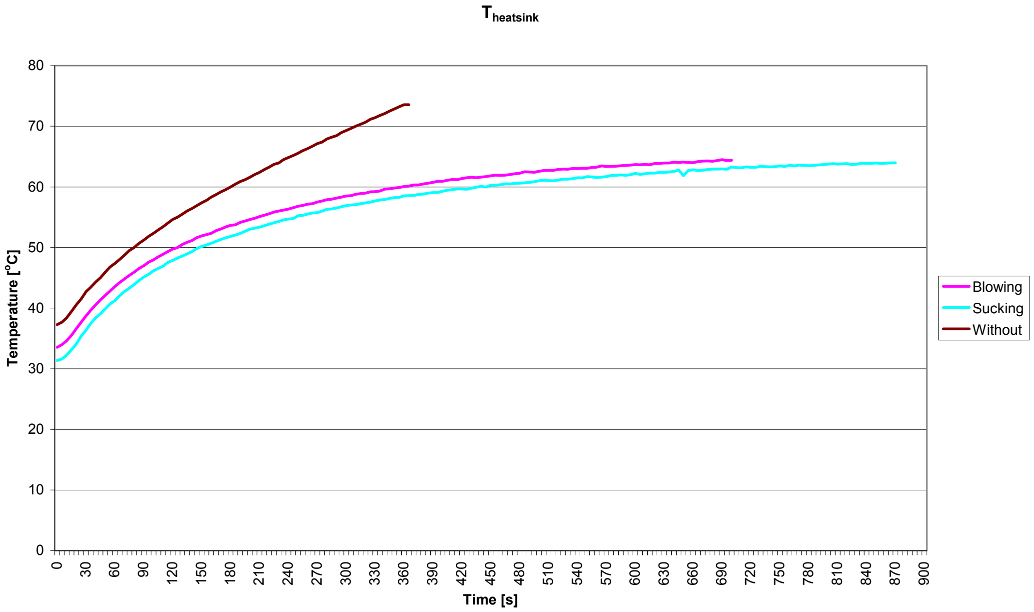

Figure 3.4. Temperature on heatsink with blowing, sucking and without fan.

3.3 Maximum power dissipation

The amount of power that can be dissipated by the heatsink can be calculated on the basis of analogy with calculations of voltage, current and resistance in an electrical circuit [3], as illustrated in Figure 3.5. In particular, there is an analogy between thermal and electrical resistance, whereas temperature corresponds to voltage and power dissipation to current.

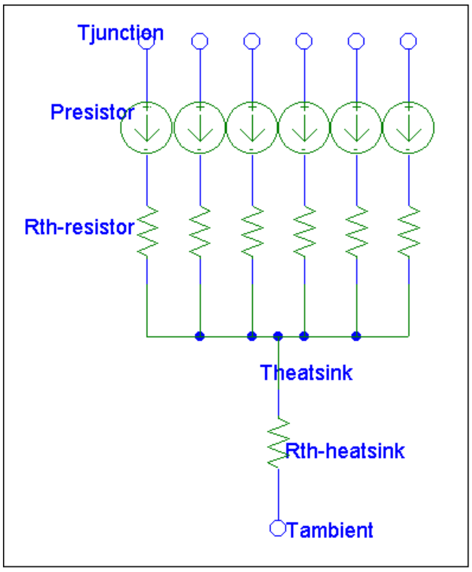

Figure 3.5. Circuit showing the analogy between thermal resistance and electrical resistance.

For the circuit of Figure 3.5, the following equations can be written:

$$\frac{T_{heatsink} - T_{ambient}}{R_{th-heatsink\text{-}ambient}} = 6 \cdot P_{resistor,\,max} \qquad (3.2)$$

$$\frac{T_{junction,\,max} - T_{heatsink}}{R_{th-resistor}} = P_{resistor,\,max} \Leftrightarrow T_{heatsink} = T_{junction,\,max} - P_{resistor,\,max} \cdot R_{th-resistor} \qquad (3.3)$$

By substituting from (3.3) into (3.2)

$$\begin{aligned} &\frac{T_{junction,\,max} - P_{resistor,\,max} \cdot R_{th-resistor} - T_{ambient}}{R_{th-heatsink\text{-}ambient}} = 6 \cdot P_{resistor,\,max} \Leftrightarrow \\ &\Leftrightarrow P_{resistor,\,max} = \frac{T_{junction,\,max} - T_{ambient}}{6 \cdot R_{th-heatsink\text{-}ambient} + R_{th-resistor}} \end{aligned} \qquad (3.4)$$

The maximum junction temperature, $T_{junction,\ max}$, is 220 °C [6], ambient temperature, $T_{ambient}$ = 25 °C. The thermal resistances are $R_{th\text{-}heatsink\text{-}ambient}$ = 0.10 °C/W, $R_{th\text{-}resistor}$ = 0.81 °C/W. This results in a maximum value of $P_{resistor,\ max}$ = 138 W.
The temperature of the heatsink, $T_{heatsink}$ at $P_{resistor,\ max}$ is 108 °C.

3.3.1 Protection from high temperatures in power resistor junction

If the power resistors maximum core temperature is exceeded, its lifetime will decrease considerably. It is therefore essential that the core temperature of 220 °C, which is the specified maximum core temperature in the datasheet, is not exceeded. To protect from exceeding the critical temperature, a thermoswitch on the heatsink is used, mounted between the power resistors as seen in Figure 3.7.

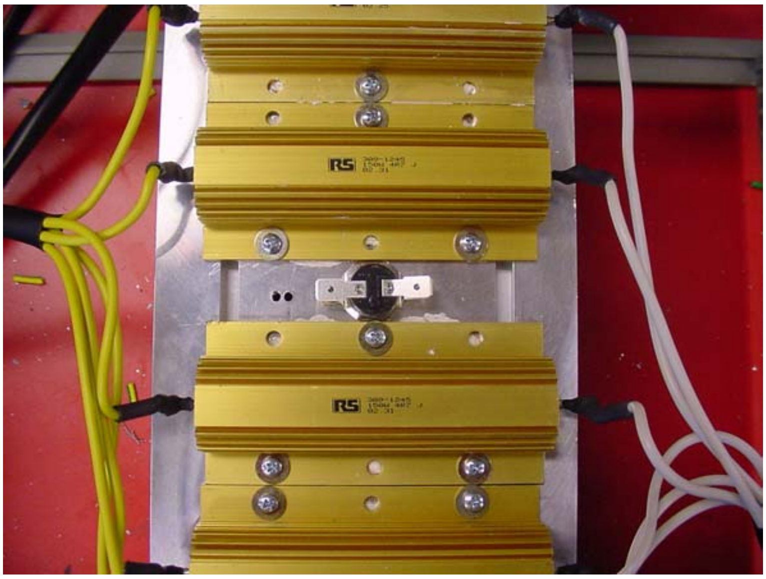

Figure 3.7. Thermoswitch mounted on heatsink to protect from over temperatures in junction of power resistors.

The core temperature for the resistors at heatsink 2-8 can be calculated as:

$$T_{junction} = P_{res}\left(6 \cdot R_{th-heatsink} + R_{th-resistor}\right) + T_{ambient} \qquad (3.5)$$

In Figure 3.8 the junction temperature is given when the power dissipation in the power resistor varies from zero to 170 W.

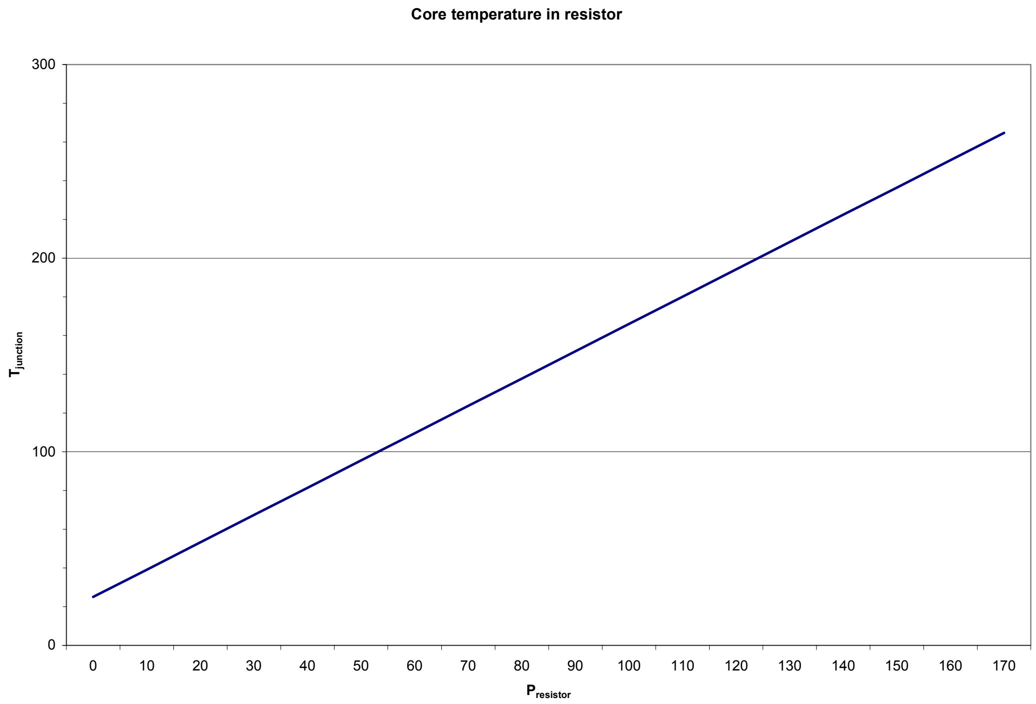

Figure 3.8. Core temperature in resistor when power dissipation in resistor varies.

In chapter 3.3 the maximum heatsink temperature was calculated to 108 °C. The thermoswitch, which protects the power resistor junction from overtemperatures, is therefore set to 100 °C.

At heatsink one there are power resistors with different maximum power dissipation mounted because of different power dissipation demand. This is further discussed in chapter 5.4.1 and Table 5.1. The calculation for heatsink one is also performed according to Equation(3.5) and the maximum heatsink temperature is 70 °C due to higher thermal resistances in the power resistors.

4 Mobility

This section will deal with the mobility of the unit, which is one of the most important criteria for the project.

4.1 Power consumption and mobility

To meet the criterion of mobility the weight is important. The maximum weight of the unit for one to be able to carry it is set to 30 kg which seems to be a reasonable value.
The heaviest component in the construction is the available heatsink. On each of those heatsinks a maximum of six 150 W power resistors can be mounted. With a resistance of 4.7 Ω per resistor and a current of 5.1 A at V_{system} = 24 V the total current on one heatsink is 30.6 A, equivalent to 734 W. The heatsink has a weight of 5 kg. To match the mobility criterion a maximum of 5 heatsinks can be used, resulting in a total current of 153 A equivalent to 3670 W and an accuracy of 5 A.
To match the current criterion at least seven heatsinks have to be used. This means a total weight of 35 kg for the heatsinks and a total weight between 50 and 60 kg.
To consider is also that to reach the desired accuracy it is not possible to consume 30.6 A on the first one or two heatsinks.
The desired current and power consumption can never be reached in a single mobile unit with a weight of maximum 30 kg. Table 4.1 shows maximum current consumption when using different numbers of heatsinks at V_{system} = 24 V.
To reach the desired total current and accuracy at least 8 heatsinks have to be used.
When using eight heatsinks the weight will be at least 50 – 60 kg and cannot be considered as mobile. The heatsinks are therefore divided into three units.

Number of heatsinks	Current consumption (A)	Power consumption (W)
1	30.6	734.4
2	61.2	1468.8
3	91.8	2203.2
4	122.4	2937.6
5	153.0	3672.0
6	183.6	4406.4
7	214.2	5140.8
8	244.8	5875.2

Table 4.1. Current and power consumption at heatsinks connected to V_{system} = 24 V.

4.2 Three connectable units

The first unit contains two heatsinks with power resistors consuming a total of 30 A at V_{system} = 24 V. It also contains the control system and connections for unit two and three.
The second and third unit consists of three heatsinks with power resistors and MOSFETs controlling the current flowing through the resistors. The total power dissipation is theoretically 2.2 kW, equivalent to 92 A at V_{system} = 24 V, for each unit.
The design of the power consumption circuits for unit 2 and 3 is analogous to unit 1, as presented in chapter 2.

Unit one can be used on its own or together with unit two or together with unit two and three depending on the power consumption demands. When used with unit two the total power consumption is 113 A, equivalent to 2.7 kW, and when all three units are used the total power consumption is 5.2 kW, equivalent to 215 A at $V_{system} = 24$ V.

5 Control System

To regulate and control the current consumption in the unit, a control system is designed, which is discussed in this chapter.

5.1 Use of control system

The voltage level in a Volvo Truck has a variation of 17.5 V in extreme cases. The unit should be able to consume constant current during reasonable variations of voltage.
From Ohm's law

$$U = R \cdot I \Leftrightarrow I = \frac{U}{R} \qquad (5.1)$$

it can be understood that if the voltage decreases the resistance has to decrease as well to keep the current constant and if the voltage increases, the resistance also has to increase.

5.2 Voltage variations

The voltage level can vary between approximately 12 and 29.5 V. With very high loading, i.e. cranking motor running, bad condition of battery and cold temperatures the battery voltage can be as low as 12 V. At extremely low temperatures the alternator, and so also the battery voltage, can reach 29.5 V.

5.2.1 Battery / alternator regulation system

The battery has a voltage level of 24 V. For charging the battery, the alternator uses a voltage of $V_{alternator}$ = 28 V at typical conditions. All loads up to the maximum output current of 85 A for the alternator are supplied by the alternator at $V_{alternator}$. When a load that consumes more than the maximum alternator output current is connected, the battery is used to supply the remaining current to the load. Therefore a load of e.g. 200 A cannot be supplied with $V_{alternator}$, but is supplied with the voltage of the battery. When the diesel engine is turned off, the alternator is taken out of function. The current to all loads is then supplied by the battery. Therefore, when the cranking motor is started, high currents, up to 1.5 kA, are consumed by the battery and the voltage may decrease down to 12 V at very low temperatures for a couple of seconds. An extreme starting event at –36 °C is shown in Figure 5.1. During normal starting conditions the system voltage decreases with between 3 and 6 V.

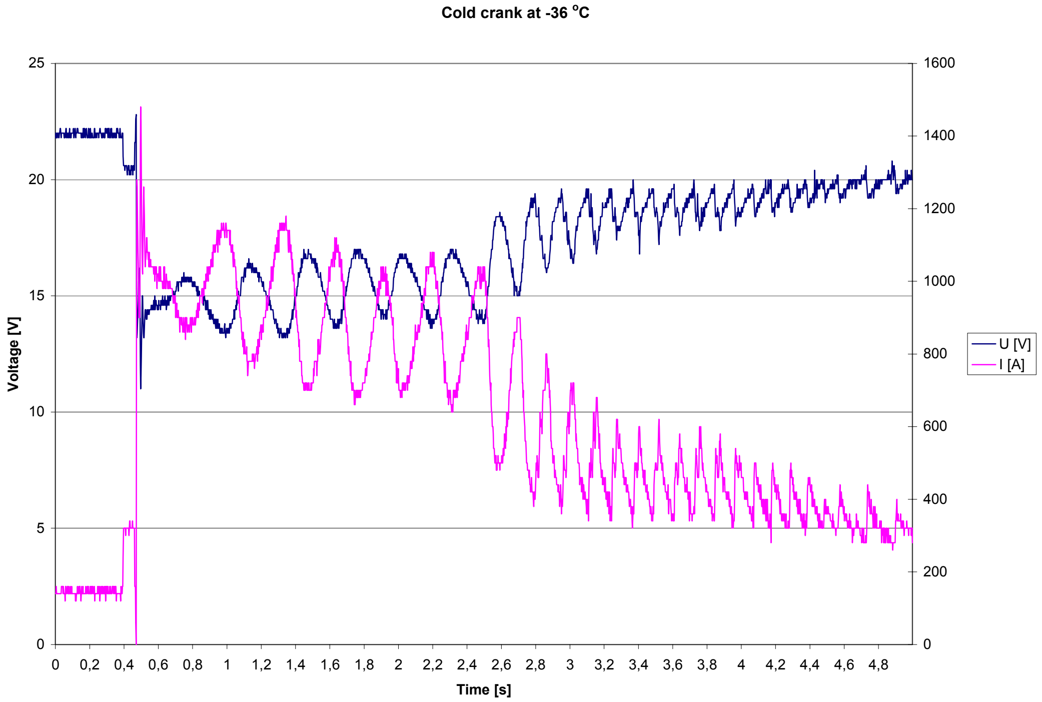

Figure 5.1. Battery voltage when cranking motor is running at ambient temperature –36 °C.

5.3 Considered control system ideas

Before the final solution was found, several different solutions were considered and tested, of which two are mentioned below.

5.3.1 Simopac

Among the available components was a semiconductor, SIMOPAC, shown in Figure 5.2.

Figure 5.2. SIMOPAC

The initial idea was to use SIMOPAC both as a semiconductor and as a power consumer. Several and repeated tests on SIMOPAC showed that it was not reliable. The gate-voltage shifted with several volts at different test occasions and at some occasions even conducting in the blocking mode. The same SIMOPAC could be non-linear in the morning and linear in the afternoon. Several different SIMOPAC modules were tested but none proved to have reliable characteristics.

5.3.2 Pulse width modulation

Another idea was to use pulse width modulation to control the current consumption. But since the load should be able to test how much current that can be consumed from a MOSFET output this idea was neglected.

If using pulse width modulation the MOSFET output would switch as well when the control system switches the current controlling MOSFETs, which not is desired.

5.4 Analogue to digital converter

The final solution was to use an 8-bit analogue to digital converter. The outputs control the gate voltage at the power MOSFETs. The accuracy of the system is designed to be at least 1 A, still with the ability to reach 200 A. The outputs on the A/D converter is designed to control as much current as the binary weight of that output at V_{system} = 24 V, i.e. output 1; 1 A, output 2; 2 A, output 3; 4 A, output 4; 8 A and so on. The 8-bit analogue to digital converter could then theoretically have a maximum current consumption of 255 A at 24 V.

To consume 200 A at 12 V the resistance must be 0.06 Ω (12 V / 200 A = 0.06 Ω). When all the outputs are conducting the total resistance, R_{tot}, in this design is 0.11 Ω and cannot be lower since the resistors are connected in parallel and the resistance therefore decreases the more outputs that are active.

Figure 5.3 shows the maximum output current at different voltage levels with R_{tot} = 0.11 Ω.

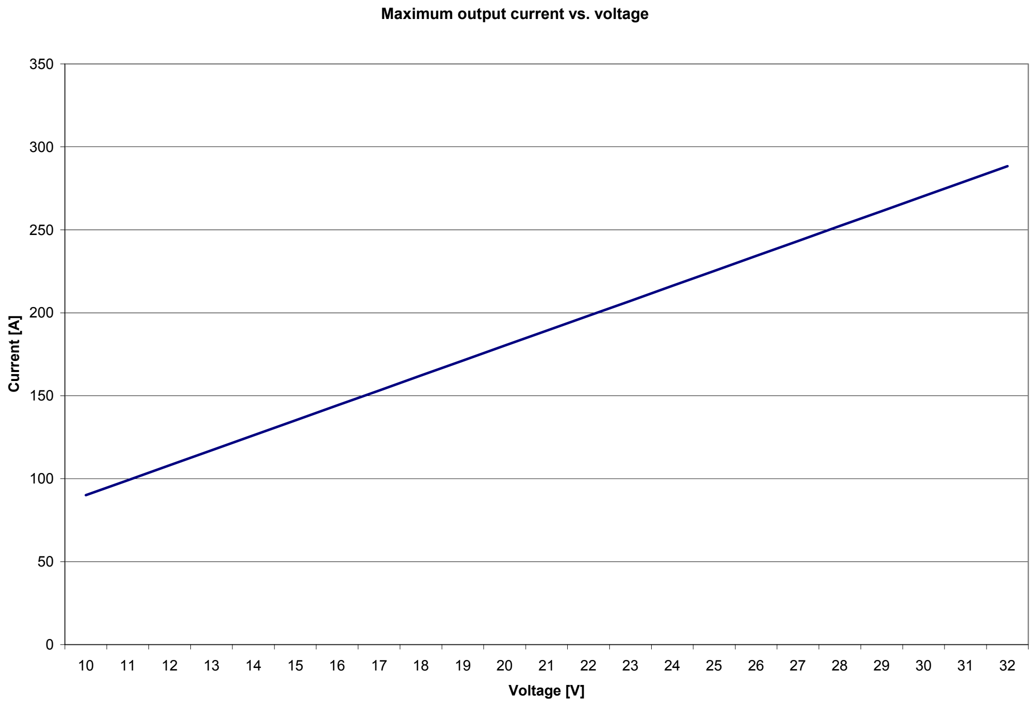

Figure 5.3. Maximum output current at different voltage levels with R_{tot} = 0.11 Ω.

The total power consumption is split up on several different resistors, illustrated in Table 5.1.

A/D binary output weight	Resistor				Current at $V_{system} = 24$ V (A)	Heatsink number
	Power limitation (W)	Resistance (Ω)	Number	Total resistance (Ω)		
1	100	22	1	22.00	1.1	1
2	100	15	1	11.4	2.1	1
	50	47	1			
4	150	6.8	1	5.9	4.0	1
	50	47	1			
8	150	6.8	2	3.2	7.6	2
	50	47	1			
16	150	4.7	3	1.57	15.3	2
32	150	4.7	6	0.78	30.6	3
64	150	4.7	12	0.39	61.2	4, 5
128	150	4.7	18	0.26	91.8	6, 7, 8

Table 5.1. Total power consumption split up.

To get better accuracy resistances are connected in parallel at the typical current values of 2, 4 and 8 A. At higher currents the effective use of power resistors and heatsinks are more important than accuracy since low current outputs will adjust the accuracy to the desired output current. The output for a theoretical consumption of 128 A at V_{system} = 24 V can only consume 92 A at V_{system} = 24 V since there is only room for 18 resistors on heatsink 6, 7 and 8.

5.5 Gate control system

The main component in the gate control system is the A/D converter. Surrounding this are several other components as shown in Figure 5.4.

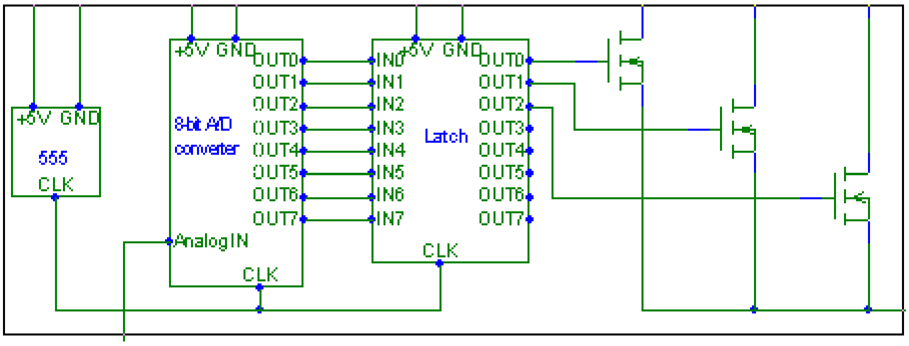

Figure 5.4. Gate control system.

The 555 supplies the A/D converter and latch with a clock pulse, which they need in order to operate. For the MOSFET gate voltage to be stable at 5 V a latch is used after the output from the A/D converter. The outputs from the latch go to the gate input of the MOSFET.

5.5.1 Set up of 555 and associated components

The frequency generated by the 555 is calculated as [7]

$$f = \frac{1.49}{(R_A + 2 \cdot R_B) \cdot C} \qquad (5.2)$$

where f is the frequency, R_A is the resistance labelled RA in Figure 5.5, R_B is the resistance labelled RB and C the capacitance labelled C.

Substituting values in Equation(5.2) with the ones given in Figure 5.5 gives an oscillating frequency of 24 kHz. This frequency is desired since it lets the A/D, latch and MOSFET-gate change their outputs before another value is valid and causes less inductive currents in the cables and components than using higher frequencies.

The square wave is connected to the A/D converter and the latch.

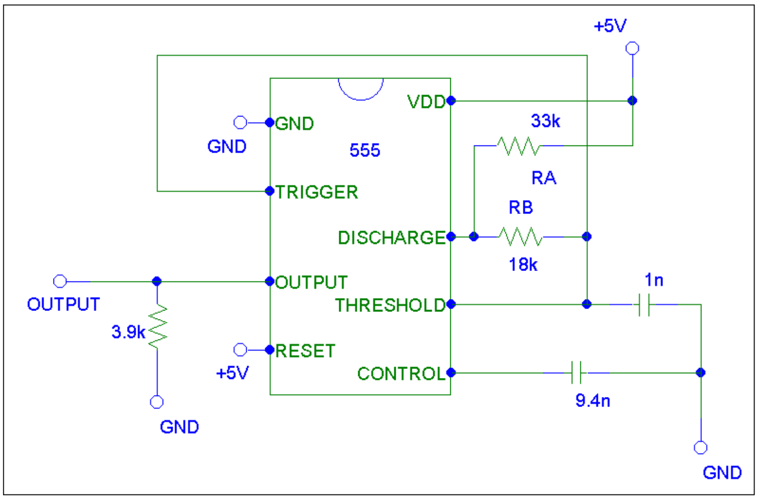

Figure 5.5. 555 connections.

5.5.2 Set up of A/D converter and associated components

Figure 5.6 shows the setup of the A/D converter. When A0 and A1 are grounded, the analogue input from IN1 is transformed into digital signals.

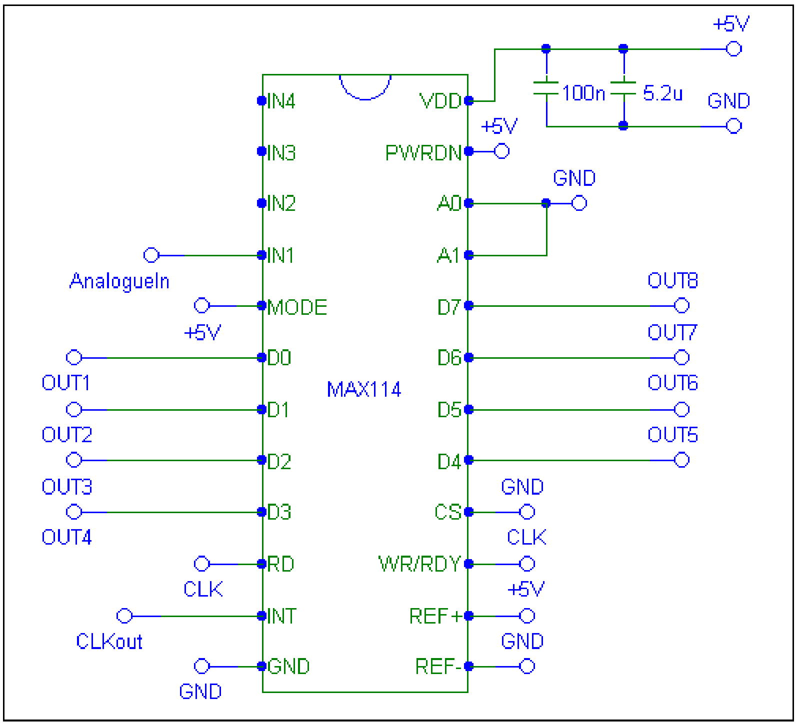

Figure 5.6. A/D converter connections.

5.5.3 Set up of latch and associated components

The set up of the latch is illustrated in Figure 5.7. To get a stable gate-output and to ground the output when there is no output from the latch a 12 kΩ resistor is connected between output and ground.

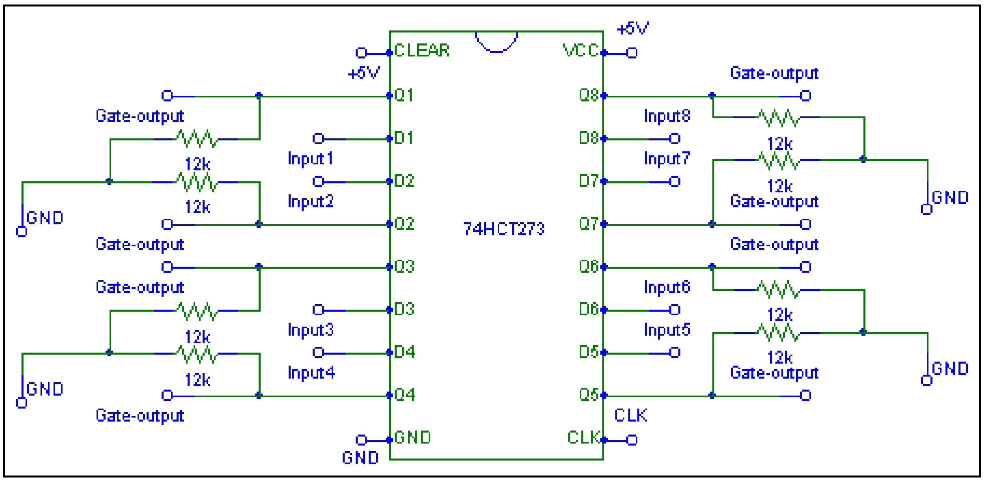

Figure 5.7. Latch connections.

5.6 Analogue input signal

A LEM current module measures the total current from the supplying source. This gives a rated current of 1:2000 of the consumed current. Via a precision resistor of 50 ± 0.05 Ω the measurement signal from the current module is grounded. The voltage drop over the precision resistor, V_{LEM}, implies that a total current of 200 A is equivalent to 5 V.

The reference voltage, V_{ref}, is controlled via a potentiometer with a maximum reference voltage of 5 V. In Figure 5.8 the analogue input signal can be followed. The voltage levels from the current module and reference potentiometer can easily be differentiated. The difference between these signals is added to the reference voltage and then the sum is inverted.

The reference voltage is fixed to a certain current value: 5 V is equivalent to 200 A.

5.7 Protection systems

5.7.1 Start-up

To be sure that no MOSFET is conducting at start-up the control system is connected separately. After connecting this and ensuring that no MOSFETs are conducting the power consumption system is connected.

5.7.2 Overtemperature

If the maximum temperature is exceeded in any of the heatsinks, the corresponding thermoswitch will switch off. The thermoswitches are connected in series so overtemperature at one heatsink will break the current for the entire unit. If unit 2 or 3 is disconnected, a switch is used to bypass the thermoswitches on the disconnected unit.

When the heatsink temperature is exceeded all the MOSFETs should stop conducting and wait for the temperature to decrease. This is done by the CLEAR-input on the latch by the connections in Figure 5.9.

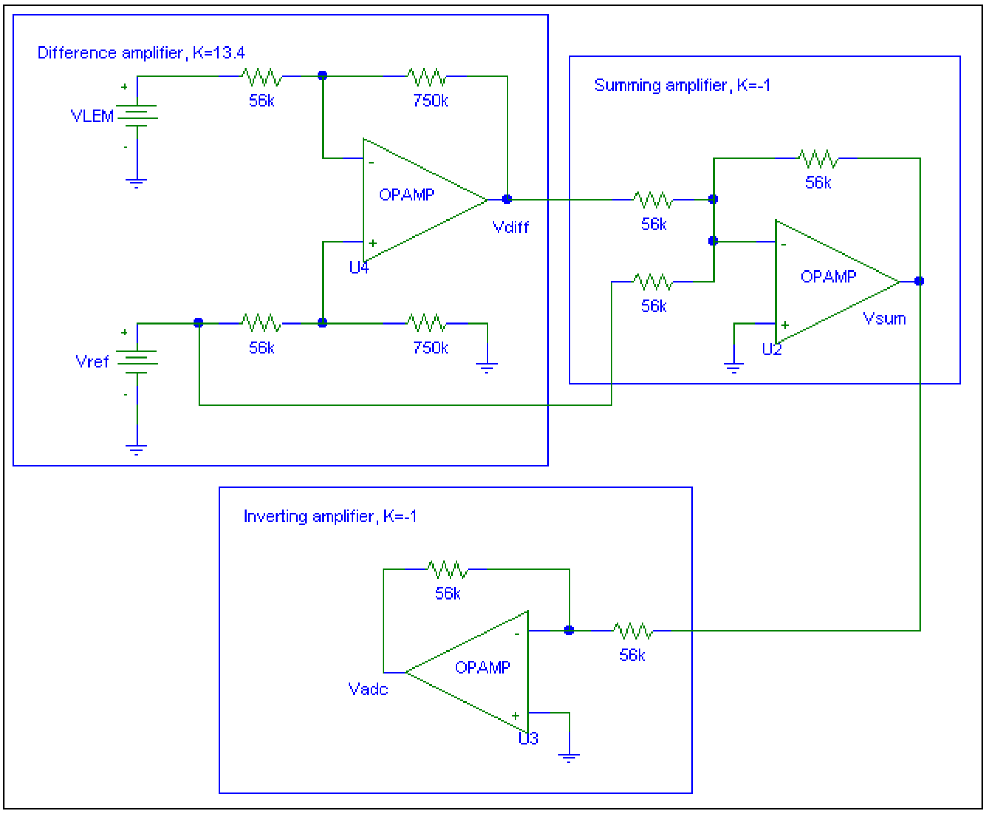

Figure 5.8. To achieve the analogue input voltage V_{LEM} and V_{ref} is differentiated in the difference amplifier, then the difference is added to the reference voltage, V_{ref}, which is inverted to the input signal on the A/D converter, V_{adc}.

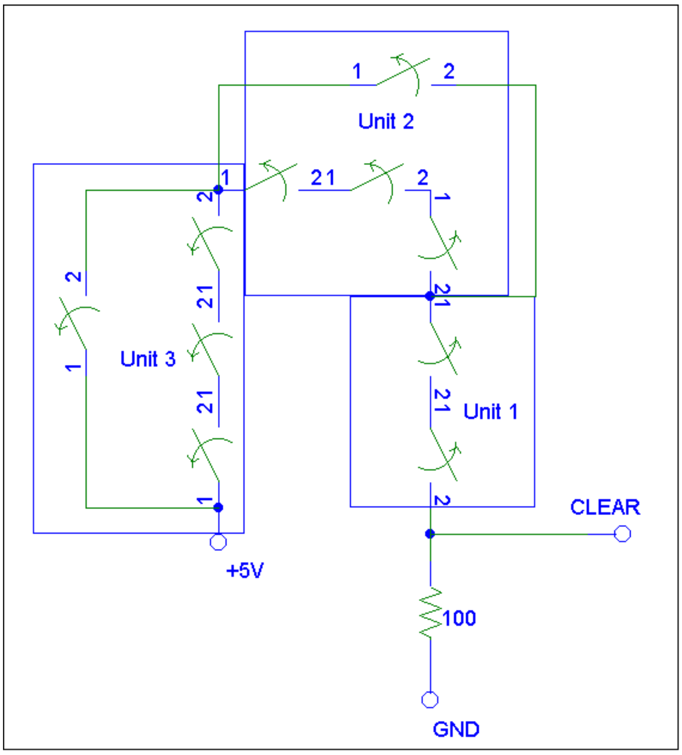

Figure 5.9. Overtemperature protection system. At normal temperatures the switches are closed and the CLEAR-input is at +5 V. When the maximum temperature is exceeded anywhere, that switch is opened and the CLEAR-input is grounded. When unit 2 or 3 is disconnected a switch is used to bypass the thermoswitches.

5.7.3 Protection of A/D converters analogue input

To protect the A/D converters analogue input from high voltages or negative voltages two diodes are connected to the input signal, as illustrated in Figure 5.10.

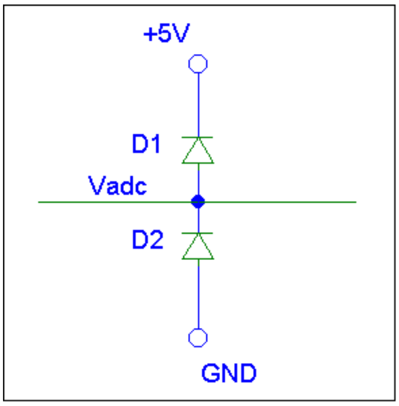

Figure 5.10. Protection of analogue input on A/D converter.

When V_{adc} exceeds 5V plus the diode breakdown voltage, V_{diode}, the diode D1 starts conducting and the A/D analogue input is protected from over voltages. When V_{adc} is below GND – V_{diode} the diode D2 starts conducting and protects the input from negative voltages.

5.8 Current display

A voltage display is connected via resistances to measure the current from LEM current module as shown in Figure 5.11. This is to facilitate the manual adjustment of the desired current value, but is meant to be used just as an indication, not an accurate measurement.

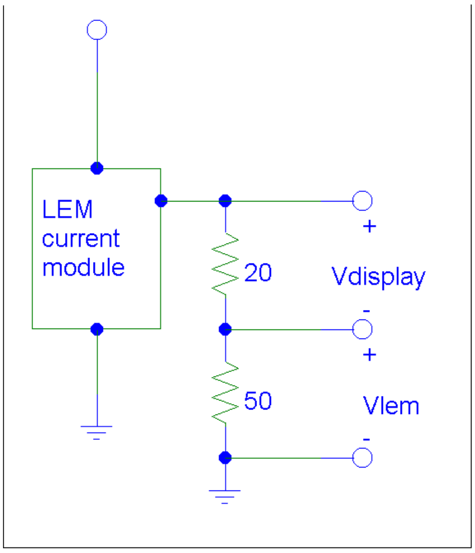

Figure 5.11. Voltage display connected to LEM current module signal.

6 Power supply

Converters require space, dissipate heat and are rather expensive. If components can be supplied with battery voltage, space is saved, extra temperature rise prevented and the cost is reduced. The aim is therefore to run as many components as possible on the system voltage, 18 - 32 V. However, electronic equipment and the available current modules cannot be supplied with 24 VDC. In this chapter, the different voltage levels used are presented.

6.1 Voltage level of the vehicle's electrical system

In chapter 5.2 the voltage variations in the electrical system of the vehicle were described. As the voltage is between 18 and 32 V except for a short period of time, the components supplied with the vehicle system voltage are those that can be supplied with voltages between 18 and 32 V.

Components supplied with vehicle system voltage:

- Power resistors
- 120 mm ∅ fans
- 5 VDC converter
- ±15 VDC converter

6.2 5 VDC

The 5 V DC power supply is constituted of a TRACO DC-DC converter with a maximum output power of 15 W. This component converts the vehicle system voltage to 5 VDC within supply variations between 18 and 32 VDC.

Components supplied with 5 VDC:

- Control electronics
- MOSFET gate
- 50 mm ∅ fans

Since 24 V fans with a diameter of 50 mm are less effecient and more expensive, fans with 5 V power supply are used.

6.3 15 VDC

The ±15 VDC power supply is a TRACO converter, with 5 W maximum output power which converts a source voltage between 18 and 32 VDC to ±15 VDC.

Components supplied by ±15 VDC:

- LEM – Current module
- Control electronics – operational amplifiers

7 Construction

Some specific considerations concerning the construction of the units are discussed in this chapter.

7.1 Cable dimensioning

The cables from the current connections in each unit to the resistors have a diameter of 1.5 mm^2. The maximum current through these cables is about 20 A depending on the ambient temperature.

The MOSFET gate cable has a diameter of 0.75 mm^2, since the currents to the gate are very small, in order of µA.

All cable dimensions have a wide margin, to protect from overheating since cables are placed above the power resistors.

7.2 Component placement

The heatsinks with the power resistors are placed at the right side of the case. To the left of them there are about 5 centimetres left where MOSFETs, MOSFETs heatsinks and connections are fitted. The heatsink is placed at the front to enhance cooling of MOSFETs and its heatsink.

7.3 Cable run

The cables are run to a screw tap which works as a cable bracket across the case to protect the cables from the heat from the resistors and to make it easier to survey the construction. The cable run is shown in Figure 7.1.

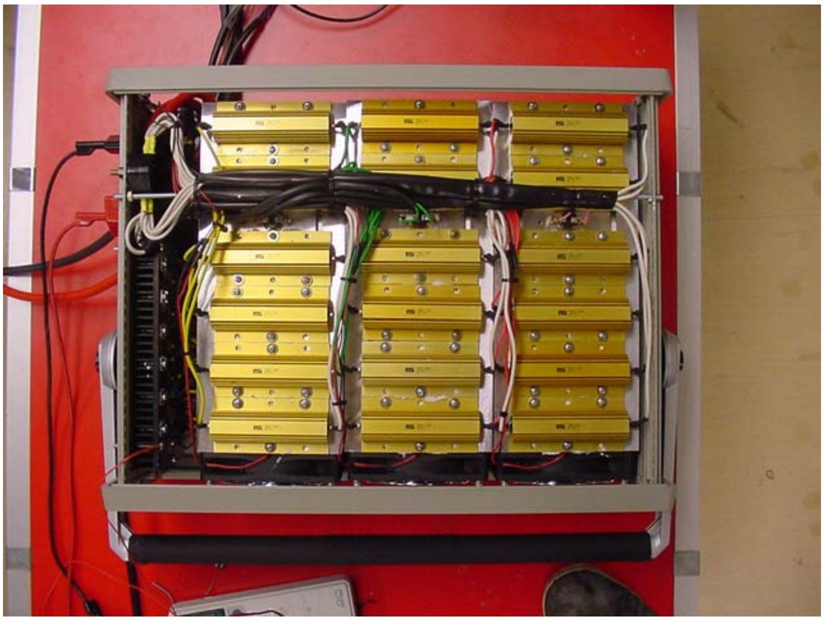

Figure 7.1. Cable run in unit 2, 3.

7.4 Connections

Figure 7.2 shows the connections inside unit two and three. The external connections are of screw type and connections can be screwed on to the unit, as shown in Figure 7.3.

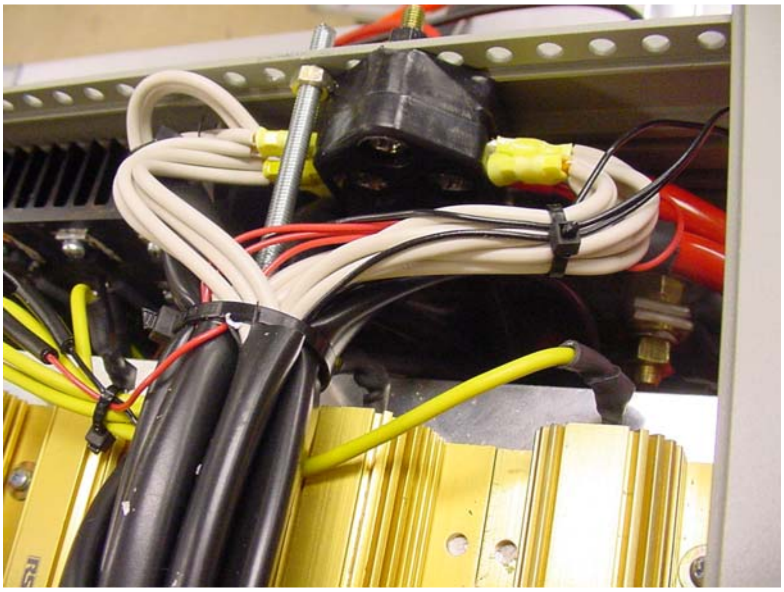

Figure 7.2. Connections inside unit 2, 3.

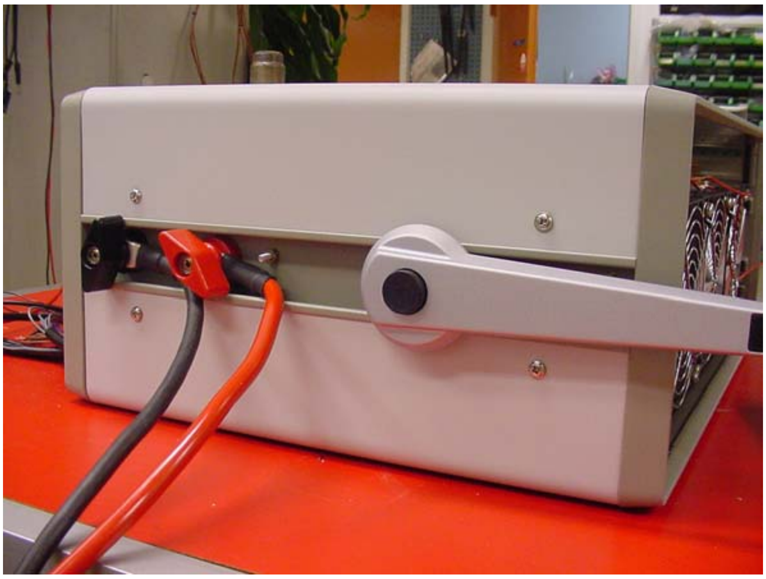

Figure 7.3. External connections on unit 2, 3.

8 Testing results

Testing has been done with three units, the results are reported below.

8.1 Current range and total resistance

The total current range is 0 to 198 A at V_{system} = 24 V. Unit one can consume 28 A, unit two 85 A and unit three 85 A. Unit one can be used alone, with a total current consumption between 0 and 28 A at V_{system} = 24 V, equivalent to a power consumption between 0 and 670 W. Unit one has a total resistance of 0.86 Ω.
When unit two is connected to unit one the total current consumption can vary between 0 and 113 A at V_{system} = 24 V, equivalent to a total power consumption up to 2.71 kW. Unit one and two together have a total resistance of 0.212 Ω.
When unit two and three are connected to unit one, the total current consumption is between 0 and 198 A, which is equivalent to a total power consumption between 0 and 4.75 kW at V_{system} = 24 V. The units have together a total resistance of 0.121 Ω. Figure 8.1 shows the maximum current consumption for unit 1, unit 1+2 and unit 1+2+3 at different voltage levels.

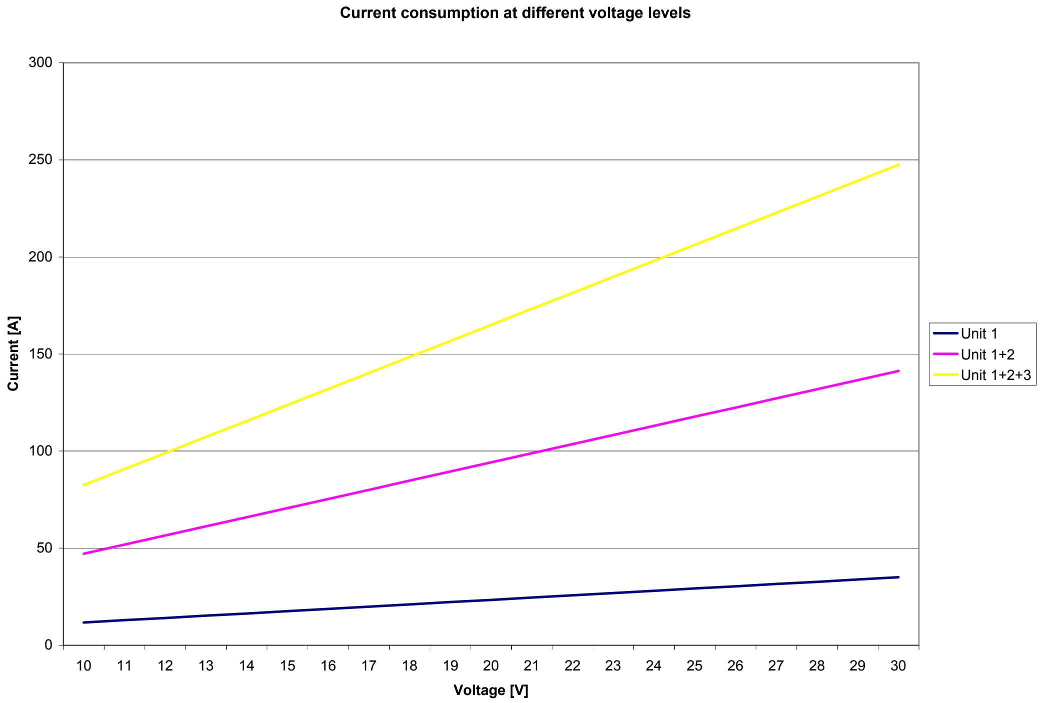

Figure 8.1. Maximum current consumption at different voltage levels when using unit 1, unit 1+2 and unit 1+2+3.

8.2 Current accuracy

The current accuracy was tested with unit 1, unit 1+2 and unit 1+2+3.
To test the current accuracy, current values between 0 and 28 for unit 1, 0 and 113 for unit 1+2 and 0 and 198 for unit 1+2+3 where set with an instrument giving 1 A accuracy. The current accuracy for the units were with this instrument measured to 1

A, which is the lowest resolution on the instrument. The accuracy of the units must therefore be at least 1 A.

8.3 Current stability

To test current stability the current was set to 7 different levels and then the current variations observed during voltage variations were recorded. Results are reported in Table 8.1 and also plotted in Figure 8.2. The current was set to reference value at V_{system} = 24 V. Current deviation in percent of reference value are reported in Table 8.2.

24 V (A)	12 V (A)	16 V (A)	20 V (A)	22 V (A)	23 V (A)	23.5 V (A)	26 V (A)	28 V (A)
10	9	10	10	10	10	10	10	10
40	35	38	39	40	40	40	40	42
70	56	59	73	70	70	70	71	73
110	98*	116	113	108	110	110	116	120
140	-	132*	147	141	140	140	140	139
170	-	-	164*	170	170	170	166	163
200	-	-	-	180*	189*	193*	200	200

*) Maximum current consumption for voltage level.

Table 8.1. Current stability.

24 V (A)	12 V (%)	16 V (%)	20 V (%)	22 V (%)	23 V (%)	23.5 V (%)	26 V (%)	28 V (%)
10	10	0	0	0	0	0	0	0
40	13	5	2	0	0	0	0	5
70	20	16	4	0	0	0	1	4
110	11	5	3	2	0	0	5	9
140	-	6	5	1	0	0	0	1
170	-	-	4	0	0	0	2	4
200	-	-	-	10	6	4	0	0

Table 8.2. Current deviation in percent of reference value.

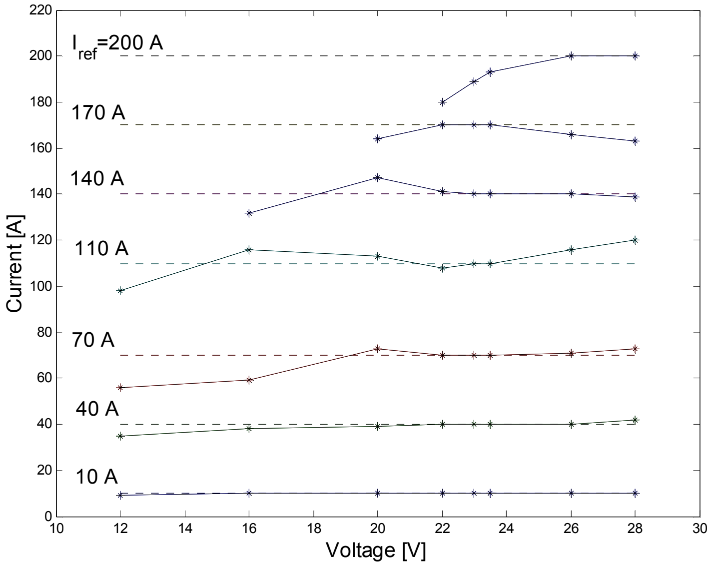

Figure 8.2 Current stability.

When the system is running in a truck the voltage is either about 28 V or 24 V most of the time. When the voltage is within these ranges the current is rather constant with almost no deviation at all from the desired values.

8.4 Heatsink temperature

8.4.1 Temperature of the power resistor

The power resistors and power resistor heatsinks is at acceptable values during the test. During a 45-minute test with unit 1+2+3 with power consumption over the maximum rating for the unit, 215 A at V_{system} = 26.0 V equivalent to 5.59 kW, the maximum power in the heatsink, just underneath one of the power resistor, stagnated at 90 °C and 120 °C on the aluminium housing of the power resistors.

8.4.2 MOSFET

The maximum value that the MOSFET heatsink temperature stagnated at was 55 °C at a number of different test.
At constant voltage level the MOSFET temperature stagnates at levels between 30 and 45 °C.

8.5 Weight

It was pointed out in chapter 4 that the weight of the unit is of utmost importance because the unit is supposed to be used in the field and therefore it must be portable. For this reason, after the units were built, it was verified that the weight of each unit was lower then 30 kg (considered as a reasonable limit for mobility). The contribution of the different components to the weight of the unit is reported in Table 8.3 for unit 1 and in Table 8.4 for unit 2 or 3.

Component	Approximate weight (kg)
Power resistor heatsinks	10.0
MOSFET heatsink	0.5
Power resistors	1.40
COMPAC case, handle, wiring, MOSFET, connections, control system	9.15
Total	21.05

Table 8.3 Weight of unit 1.

Component	Approximate weight (kg)
Power resistor heatsinks	15.0
MOSFET heatsink	0.5
Power resistors	3.15
COMPAC case, handle, wiring, MOSFET, connections	7.15
Total	25.8

Table 8.4. Weight of unit 2 and 3.

9 Conclusions

The purpose of this work was to design a unit that could consume between 200 and 300 A. A unit which can consume a maximum of 198 A, equivalent to almost 4750 W at V_{system} = 24 V has been designed and constructed.

The unit consists of power consumption systems and a control system.

The power consumption system consists of 44 power consuming circuits, which consist of one or in three cases three power resistors and one power MOSFET. The control system controls the gate-voltage on the MOSFET, measures the consumed current and compares it with the reference value to decide how many power consumption circuits should be active.

To meet the mobility criteria i.e. that the unit should have maximum weight of 30 kg in order to be portable, it was decided to split the unit into three. Therefore three units were constructed. Unit one consists of the control and regulating system and 2 heatsinks with a total current consumption of 28 A equivalent to 670 W at V_{system} = 24 V. Unit two and three consist of 3 heatsinks each with a total current consumption of 85 A equivalent to a power consumption of 2.0 kW.

Unit one can be used on its own, with a total current consumption of 28 A at V_{system} = 24 V. Unit one can also be used with unit two, then consuming a maximum of 113 A, equivalent to 2.71 kW at V_{system} = 24 V, or together with unit two and unit three, consuming a total of 198 A, equivalent to a power of 4.75 kW at V_{system} = 24 V.

The current stability of the unit is very accurate. Varying the system voltage between 18 and 28 V, the current is nearly constant at all voltages for desired current consumption.

The accuracy was desired to be below 5 A. The accuracy is at least 1 A.

The units can be used for field-testing, unit one has a weight of 19 kg, and unit two and three have a weight of 25.8 kg each.

Protection system circuits have been designed to protect the units against overtemperatures and undefined start-up outputs. The protection system also protects the inputs to the A/D converter from over-voltages and negative voltages.

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