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Usage of Power Solid-state Components in the Battery Disconnection Unit

Master's thesis in Sustainable electric power engineering and electromobility

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

Master's thesis 2022

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Master's Thesis 2022
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Abstract

In the development of electric vehicles, the need for long operation ranges and high power output, puts an extraordinaire demand on the size of the battery. Due to this there is a direct need to keep all components related to the battery as small and effective as possible. This master thesis explores the possibilities of replacing the large mechanical switches in the battery disconnection unit with solid-state switches in form of MOSFETs. Different set-ups of mechanical contactors and MOSFET relays are simulated in Matlab Simulink with the goal to evaluate if the solid-state relay could do the same task as the mechanical one. Component temperature and power loss is the deciding factor for the evaluation of the components. A smaller literature study is also done to investigate the different advantages and disadvantages of the two technologies. It is found that the MOSFET relay structures could preform the same and more operations as the mechanical contactors with significantly less space needed but at a much higher financial cost.

Acknowledgements

My special thanks goes out to Filipe Ribeiro Magalhães at Volvo Car Corporation for all the resources he helped me find and our technical discussions throughout our many meetings during the making of this thesis. I also would like to thank my examiner Torbjörn Thiringer for his lightning speed responses seven days a week to any and all technical or administrative questions I had during the course of the project.

Martin Ferm, Gothenburg, Aug 2022

List of Acronyms

BDU	Battery Disconnection Unit
PWM	Pulse-width Modulation
BEV	Battery electric vehicle

Contents

1
Introduction

1.1 Background

As the average individual grows more aware of the tremendous environmental challenges that humanity stands in front of due to its usage of fossil based power sources during the last century, the demand for more sustainable solutions increases as well. Since the need for cars as personal transport does not seem to decrease considerably in the foreseeable future, there is a direct and urgent need for a more environmentally friendly type of car. The electric car have been the costumers and manufacturers choice for this due to its higher energy density and a lower cost than other fossil free alternatives, this makes battery electric vehicles competitive and affordable for a wide range of customers. Many companies are moving more and more of their effort into the development of electric vehicles over combustion engine vehicles. Volvo Cars for instance stopped releasing new fossil base cars in 2019 and is focusing only on vehicles with electric motors with a goal to have at least 50% of thier sales be electric vehicles in 2025 [1]. The rapid transformation of the automotive market towards electrification is to a great extent driven by the technological improvements in the battery area. To keep improving there is a need to dive deeper in several fields of battery development, from how to charge the batteries faster to how minimize the environmental footprint. There is a need to introduce new ideas and innovate in order to coupe with new demands and competitiveness of the business. A big part of the challenges encountered in the automotive industry is the lack of space for placement of components which might lead to design changes or not design intended changes due to those restrictions. Downsizing components or replacing components with others that can preform the same task more efficiently is therefore crucial for the development of new vehicle platforms.

1.2 Aim

Today all high power switching in electric cars is made with mechanical contactors. The objective of this thesis is to investigate the battery disconnection unit between a car battery and the electric motor and to look into the advantages and disadvantages of replacing parts inside it with solid-state components. The main mechanical contactor on the positive side of the battery will be the main focus of this, as well as the contactor used in the pre-charge circuit connected in parallel to the main circuit. The reason for fixating on those two components in particular is that replacing them with solid-state relays could come with a lot of upsides, such as lower volume and higher performance. When examining if it is feasible to replace all or some of those parts, the areas of extra interest are,

- Power losses compared to the mechanical counterparts.
- How the new solid-state components handle the high DC fast charging currents and the cooling needed to operate these components.
- How the introduction of a solid-state relay could change the over all design choices for the battery disconnection unit.

To investigate these properties, calculations and simulations will be made using MATLAB Simulink. A simplified model will be made of the battery disconnection unit to evaluate the power losses and temperate of all relevant components during use. For the solid-state relays, many different kinds of semiconductors could be used, however high power MOSFETs best fit the voltage and current rages of the BEV, so all the models are built with MOSFET relays.

1.2.1 Volvo Cars

This masters thesis is done in collaboration with Volvo Cars Corporation and the research and testing done is made to be as relevant as possible to what Volvo is looking into at the moment. The choice of voltage levels that is tested is based on this with 450 V being the main focus as that is the one used today in Volvo's cars and 850 V systems are also examined as that voltage level is the likely future of their cars. Many other parameters used in the models are also based on Volvo's cars, like stray capacitance, choice of start-up times and the currents in the fast charge profile.

2
Theory

In many cases the word contactor, relay and switch is used interchangeably as they mean the same thing. There is no strict technical definition for any differences between them but usually the word used is dependent on size. In this text the electromagnetically controlled mechanical switches will be referred to as contactor or mechanical contactors, while the solid-state switches will be referred to as relays.

2.1 Mechanical contactor

The electric contactor is a device that is used open and close a circuits. Depending on design, the contactor can break both high and low currents with a much smaller control current very reliably [2] The larger the current the bigger then contactor needs to be. A common design for a contactor can be seen in figure 2.1.

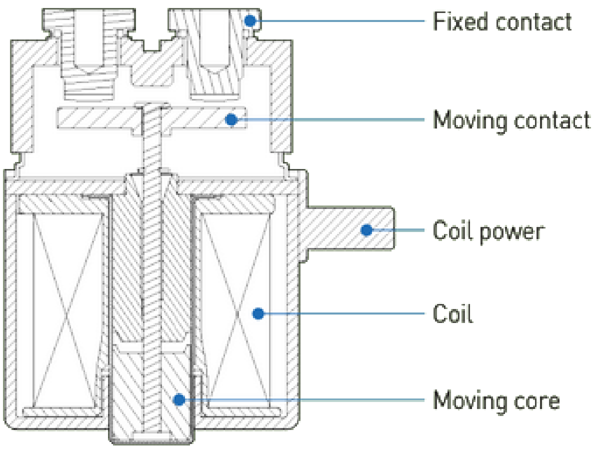

Figure 2.1: Sketch of a mechanical contactor. From LSIS cataloge [2].

On the contactor there is two main contacts, one positive and one negative. Beneath the the main contacts there is a connector plate. All these three components are completely electrically isolated from each other and as long as the contactor is in open mode there is no current flow. Mounted to the bottom of the connector plate is a magnetic core which is surrounded by a coil. When a current flows through the coil a magnetic field is created that forces the core up or down depending on the direction of the current in the coil. When the core and connector plate is moved into contact with the main contacts, current flows through the circuit. The current through the coil is called the control current and is usually much smaller than the currents through the main circuit.

2.2 MOSFET solid-state relay

The *Metal Oxide Semiconductor Field Effect Transistor* or MOSFET, is a relay without any moving parts, it is a so called solid-state relay. The MOSFET is made out of a solid piece of semiconductor material, generally silicon. Some parts of the semiconductor is treated with different processes to create impurities in the crystal with the electrical properties desired. Depending on how an area of the semiconductor is treated it is either of n-type with electrons as majority charge carrier or of p-type with holes (absence of electron) as a majority charge carrier. If n-type and p-type is next to each other a depletion layer is formed that prevents current completely. The MOSFETs used for the simulations in this thesis are so called n-channel MOSFETs and consists of a large volume of p-type with two areas of n-type embedded in the semiconductor. The two areas of n-type is referred to as the drain and the source. See figure 2.2

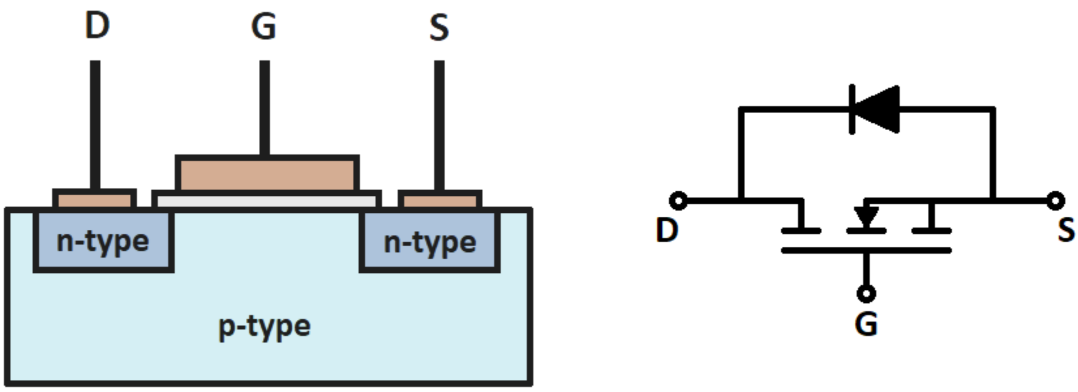

Figure 2.2: Simplified sketch of a n-channel MOSFET (left). Circuit representation (right).

To the drain and the source, contact plates are attached that acts as positive and negative terminals of the switch. Between them there is the gate terminal, this is what controls the MOSFET. There is a thin isolating layer between the gate and the semiconductor causing it to function as a capacitor. If a voltage is applied to the gate it generates an electric field that attracts electrons and pushes away holes, this changes the properties of the p-type semiconductor closest to the gate into n-type, which allows for current to flow as long as the gate is charged.

2.2.1 Back-to-back MOSFET

To operate as a switch in the BDU, the relay needs to be able to block and conduct current in both directions. The reason for this is simply that the battery needs to be charged as well as used to power the system. A regular MOSFET does not have these capabilities. However, if two MOSFETs are connected in series with source connected to source (a so called back-to-back configuration), then this is possible.

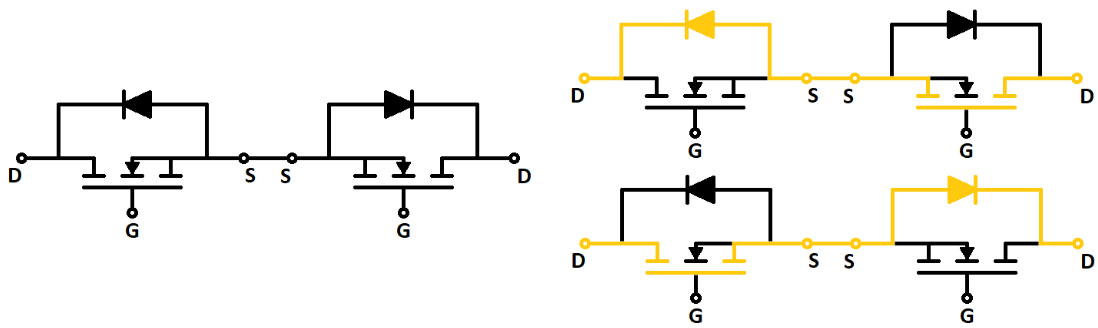

Figure 2.3: N-channel back-to-back MOSFET configuration and current flow.

Instead of one gate with just on and off, the back-to-back configuration have two gates with four different modes of operation.

- ON/ON: conducts current in both directions.
- ON/OFF or OFF/ON: Blocks current in one direction and conducts in the other. Direction depends on what gate is on and off.
- OFF/OFF: Blocks current in both directions.

For the BDU implementation, only ON/ON and OFF/OFF is needed, which means that the gates of both MOSFETs can be connected together since they should always receive the same signal.

2.2.2 Pulse-width modulation

One of the advantages of using solid-state relays is the access to pulse-width modulation (PWM). This is made possible by the high switching speed of the MOSFET that the mechanical contactor lacks. The basic idea of PWM is to let the current through in small pulses while blocking the current between pulses. This reduces the average current to $I = I_{on} \cdot t_{on}/t_{total}$. The length of t_{on} depends on the desired current, and can easily be changed over time according to a control preference or adjusted to fit other conditions in the circuit. This allows for a much higher level of control of the currents and voltages in the system. Figure 2.4 below demonstrates this by showing how PWM could smooth out the transition of voltage levels over a capacitor in a RC circuit.

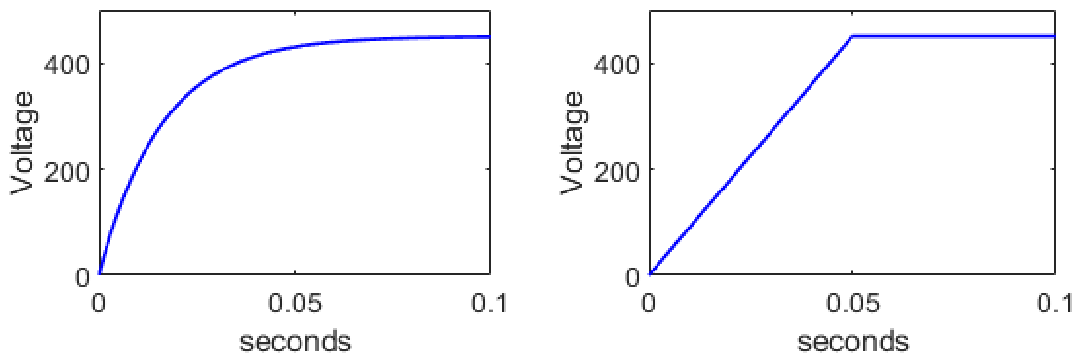

Figure 2.4: The graph to the left shows the voltage over a capacitor after a switching event. The graph to the right shows the same capacitor but with PWM switching implemented.

For the BDU, pulse-width modulation is not needed while driving or charging since during these times, other components in the car decides the current and the switches job is to just let through as much current as needed with as small losses as possible. During the pre-charge sequence however, PWM might be highly relevant, as it could reduce or remove the need for the pre-charge resistor.

2.2.3 Short circuit protection

In existing BEV systems today short circuit protection is generally done with electric fuses and/or detection systems connected directly to the mechanical contactor. Due to the moving parts of the contactor and the inexactness of the activation of the fuses, the response time of those systems ranges from a few milliseconds to hundreds of milliseconds depending on design. This is slow compared to that of the solid-state relay which can operate in the nanosecond range by itself. Although with fault detection included this brings the relays response time to a short into the microsecond rage. [3]. Because of the faster response to a fault, the short circuit current could be drastically lowered with the use of solid-state relays, and many fuses could be removed form the system as well as they become redundant.

2.3 Practical comparison of mechanical contactors and MOSFET relays

When comparing MOSFET relays and mechanical contactors in the context of a BEV, the areas of most interest are, size, weight, prize and losses during use. Any specific numbers that is used to compare the two in this section is gathered from the the mechanical contactor GRP-M400-A [2] and the MOSFET relay CAB760M12HM3 [4] but the comparison should hold between any contactor and MOSFET used for the same application. For the MOSFET relay to be able to preform the same tasks as the mechanical contactor the MOSFET needs cooling and be connected back-to-back, (this is explained in more detail in chapter 3). This additional set-up is therefore added to the volume, weight and cost for the MOSFET when analysing the advantages and disadvantages.

- **Size and weight:** The volume of the GRP-M400-A contactor is 574.2 cm^3 and its weight is 750 g. Which is much larger than the CAB760M12HM3 MOSFET with a volume of 87.2 cm^3 and weight of 179 g. When back-to-back configuration and cooling is considered as well the whole MOSFET relay set-up would have a volume and weight of roughly 400 cm^3 and 700 g. The nearly halving of the volume is an especially a big deal for the battery pack since space is a very limiting factor in that over all design. If Pule-width-modulation is used to reduce or eliminate the pre-charge circuit as well, the size difference can be even larger with the MOSFET configuration being only a quarter of the volume of the mechanical contactor.
- **Prize:** The cost of a component depends on many things that are hard to quantify in exact numbers, such as buying bulk or company connections and history. However the price of two high power MOSFETs with cooling is roughly in the rage of 50 to 100 times more expensive than that of a mechanical contactor. Even if introducing the MOSFET relay into the system would remove many of the fuses otherwise needed, the prize would still be many times higher then that of the contactor set-up used today.
- **Losses:** The losses of the mechanical contactor comes from two sources. First the small voltage drop over the contactor due to its contact resistance between the contactor and the connector cables (the internal resistance is negligible). And secondly the power needed to drive the control circuit with the coil, this is not strictly losses but since the currents in the coil is not used in the main system they are added to the losses as unproductive power usage. The GRP-M400-A contactor has a resistance of 0.2 mΩ and the control circuit needs 5 W to operate, this gives a total power loss of, $0.0002 \cdot 300^2 + 5 = 18 + 5 = 23W$ during 300 Ampere motor usage. For the MOSFET the power loss comes from the internal resistance of the MOSFET (the so called $R_{ds(on)}$). The power needed to activate the gate is negligible. The resistance over the CAB760M12HM3 MOSFET 1.33 mΩ. Giving it a power loss of $0.00133 \cdot 300^2 + 0 = 119.7W$ at the same power usage. For the 850 V system this represents an increase form 0.009% losses to 0.047% losses from the relay. If the MOSFET is used for PWM as well there is also switching losses to be considered during the start-up sequence.
- **Environmental impact:** One big difference between the two technologies is the materials they are made of and the manufacturing techniques involved. The mechanical contactor is made of commonly available materials, copper, plastic, iron among others, while the MOSFET relay is usually made out of doped silicone with a more complicated manufacturing process. If you look at the LCA (Life-cycle-analysis) of the MOSFET [5] compared to that of the mechanical contactor, you see a much higher environmental footprint. The manufacturing of the MOSFET is a very high energy intensive process, and it involves many hazardous materials, often including arsenic and fluorine. Their are a number of different greenhouse gasses (CF_3, NF_3, C_4F_8) that are

commonly associated with the MOSFET production as well [5]. The comparative energy consumption for the MOSFET production gets even worse if the upstream environmental effects of the chemicals used are considered as well, since the productions of those very high purity chemicals is in of themselves a energy intensive and hazardous process. Two other aspects that could be considered are also the worker safety and the end-of-life pollution of lead form lead-based soldering. But due to high levels of regulation and protocol, the workers are only at risk in case of catastrophic failure and the the presence of lead in soldering have become very rare since it is not allowed in the EU.

There are also other aspects that could be useful to consider. One of them is the superior switching speed of the MOSFET to the mechanical contactor. PWM and short circuit protection has been mentioned as possible uses of this, but they do not necessarily need to be the only once. Having a component with higher performance is always a good if there is no obvious drawback, because it opens up the possibility for further innovations and new design strategies. Another thing that need to be considered however is the availability of the components. Mechanical contactors are made out of common materials and and are readily available everywhere. This is not the case for semiconductor that are made of more specialised materials that are of high demand. This is can be seen in the price difference of the component. But price is not the only factor that is effected by the material, a more scarce resource is susceptible to shortages if the there is disturbances to the market environment or global supply chain.

3

Case set-up

3.1 Basic representation of BDU system

In its most basic form, a battery disconnection system consists of a battery, two main contactors, one on the positive side and one on the negative side, and a smaller pre-charge circuit. All this is connected to the electric motor, other smaller auxiliary systems as well as the charging contacts. The big advantage of having two main contactors is partly to completely isolate the battery and also to have redundancy in case of a fault. If the positive main contactor would get stuck in a closed position for instance, the circuit could still be broken by opening the negative contactor.
The pre-charge circuit consists of a secondary contactor with a resistance in series, all connected in parallel with the positive main contactor. Since contactors are designed with low resistance in mind to avoid unnecessary losses during use, the currents could get extremely high and damage the contactor at the moment of connecting. The purpose of the pre-charge circuit is to close before the positive main contactor to decrease the initial voltage difference to a level that the contactor could handle.

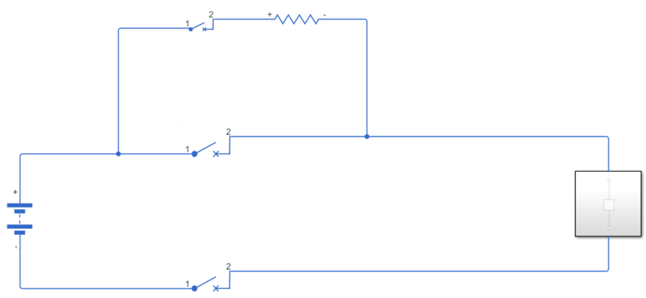

Figure 3.1: Simplified model of battery disconnection system.

To simulate the full behavior of the system and to analyse what voltages and currents the different components are experiencing at all times, some other properties must also be considered. The combined internal resistance and stray inductance of the system (busbar, fuses and so on), is very important to include to get accurate simulation results. A capacitance can be used to represent the passive effects of all connected loads on the system.

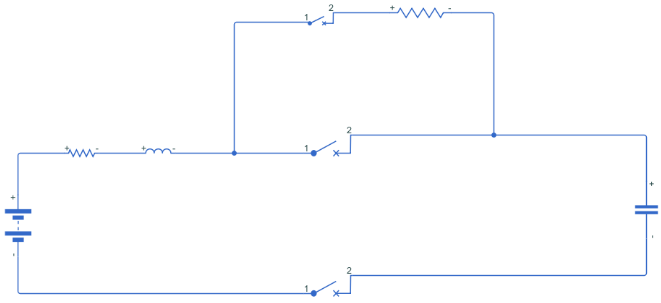

Figure 3.2: A more useful model of the system, including internal resistance and stray inductance.

For the battery and the contactors (both mechanical and solid-state), the necessary parameters needed to simulate the system can be found in data sheets for those components. However the internal resistance and stray inductance of the system is dependent on the over all design of the car, (contact resistances, resistance of busbar, internal resistance of battery, are some of the contributing factors to those parameters). Since the analysis will include some system designs that has not been implemented as of yet, these parameters needs to be estimated based on similar designs already in use. The same goes for the capacitance of the connected loads. The needed resistance placed in the pre-charge circuit is calculated based on the rest of the model and is chosen to fulfil the wanted behavior of that particular simulation. Since both 450V and 850V batteries will be simulated with both 50ms and 100ms startup times, four different pre-charge resistance values are needed. The parameters used in the simulations as well as a full model for the startup sequence can be found in the table and figure below as well as in Appendix A.

Table 3.1: Component parameters used in the simulations. **Calculations for pre-charge resistances can be found in section 3.1.1.*

Battery Internal resistance:	22	mΩ
Other system resistance:	10	mΩ
System stray inductance:	6	uH
Mechanical contactor resistance:	0.2	mΩ
Solid-state relay resistance (per MOSFET):	1.33	mΩ
Capasative reprenatation of loads	1700	uF
Traget ΔV:	20	V
Needed total resistance during pre-charge, 450V 50ms:	9.45	Ω
Needed total resistance during pre-charge, 450V 100ms:	18.89	Ω
Needed total resistance during pre-charge, 850V 50ms:	7.84	Ω
Needed total resistance during pre-charge, 850V 100ms:	15.69	Ω

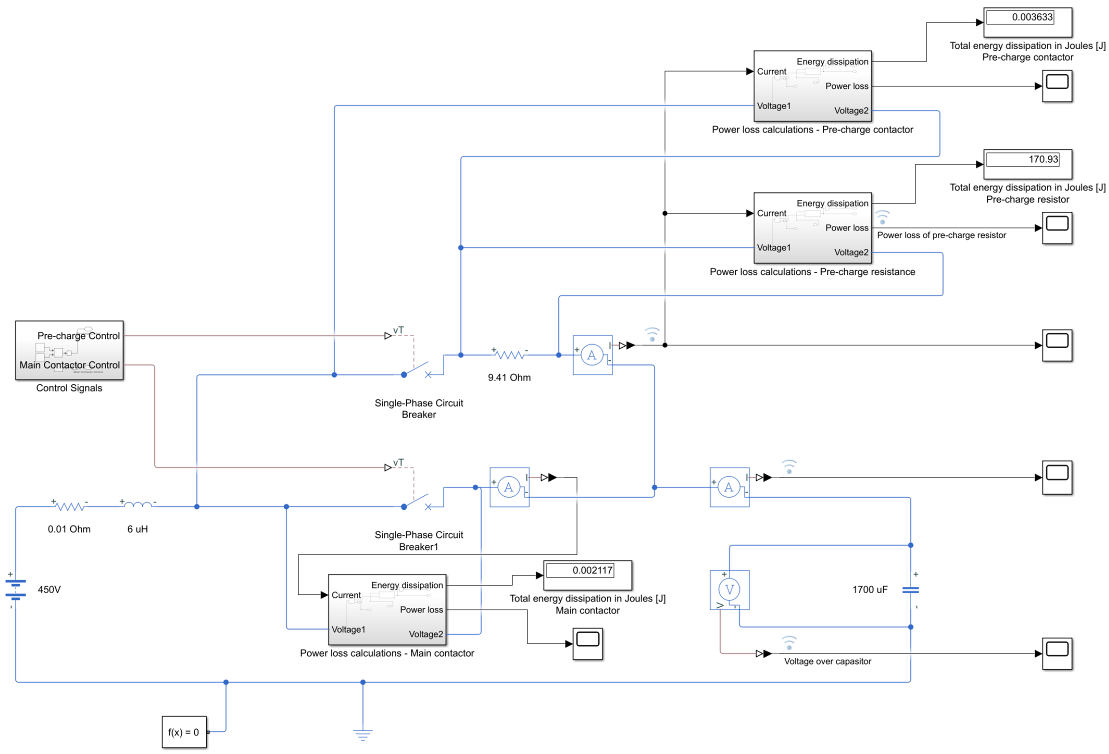

Figure 3.3: Full Simulink model for simulating startup sequence of "450 V, capacitor only" configuration.

Current and voltage sensors are added to the model to monitor the components. Voltage over the load capacitance as well as current through the pre-charge circuit is of special interest in this particular model. Power loss and total energy dissipation is measured and calculated for the positive main contactor, the pre-charge contactor and the pre-charge resistance. The total energy dissipation in a component is derived by integrating the power loss curve,

$$P_{loss}(t) = U_{meas} I_{meas} \tag{3.1}$$

$$E_{dissipated} = \int_0^\infty P_{loss}(t)\ dt \tag{3.2}$$

The contactors are controlled by a simple signal controller that tells the contactors, when to open and close. In figure 3.3 the pre-charge contactor closes at $t = 0.05$ and opens at $t = 0.12$, the positive main contactor closes at $t = 0.10$ and stay closed for the rest of simulation. A bit of overlap is good for redundansies but almost no current flows through the pre-charge circuit after the main contactor is closed. Note that the main contactor on the negative side is not included in the model. This is because is stays closed at all times during simulation. The internal resistance of that component is instead added to the total system internal resistance.

3.1.1 Pre-charge circuit calculations

For a 450 Volt battery with internal resistance of 22 mΩ and a contactor with 0.2 mΩ internal resistance, the initial current, (ignoring other factors) would be more than 20 kA. With all other parts factored in, this would of course be much smaller, but still thousands of amps. In that case, the risk for the contactor to simply be welded closed by the lightning arc would be substantial. The pre-charge circuit's role in the BDU is to lower the voltage difference over the main contactor to an acceptable level before it closes. This voltage difference is often simply referred to as ΔV, and in these simulation it is chosen to be 20 V.
The voltage over the load capacitor in the model after the pre-charge contactor closes can be described with,

$$U_c = U_b\Big(1 - e^{-t/RC}\Big) \tag{3.3}$$

where U_c is voltage over the capacitor, U_b is nominal battery voltage, R i total resistance and C is capacitance of the load capacitor. The stray inductance is not included in this equation since it is negligible in the cases this equation is used.
The same equation can be rearranged to describe the resistance needed to have a certain ΔV at a specific time (note that $U_b - \Delta V = U_c$)

$$R = \frac{-\,t}{Cln\Big(1 - \frac{U_b - \Delta V}{U_b}\Big)} = \frac{t}{Cln\Big(\frac{U_b}{\Delta V}\Big)} \tag{3.4}$$

Simulations will be made to study both a startup time of 50 ms and 100 ms. And since C and the preferred ΔV is known, the needed pre-charge resistance can be calculated for both the 450V and the 850V systems as

$$R = \frac{50 \cdot 10^{-3}}{1700 \cdot 10^{-6} \cdot ln\Big(\frac{450}{20}\Big)} = 9.45\ \Omega \quad , \quad \frac{100 \cdot 10^{-3}}{1700 \cdot 10^{-6} \cdot ln\Big(\frac{450}{20}\Big)} = 18.89\ \Omega \tag{3.5}$$

$$R = \frac{50 \cdot 10^{-3}}{1700 \cdot 10^{-6} \cdot ln\Big(\frac{850}{20}\Big)} = 7.84\ \Omega \quad , \quad \frac{100 \cdot 10^{-3}}{1700 \cdot 10^{-6} \cdot ln\Big(\frac{850}{20}\Big)} = 15.69\ \Omega \tag{3.6}$$

The correct pre-charge resistor R_{pc} for any given model is then, R subtracted by all other minor resistances in the system.

3.1.1.1 Choice of pre-charge resistor

When choosing a resistor to be used as the pre-charge resistor, the heat buildup during startup need to be considered. The total dissipated energy in the resistor can be derived just like for the contactors, by integrating the power loss curve over the time of interest. The power loss for the resistor is easiest calculated by $P = R_{pc} \cdot I_{pc}^2$, where I_{pc} is the current thought the pre-charge circuit,

$$I_{pc} = \frac{U_b}{R} e^{-t/RC} \tag{3.7}$$

$$E_{Rpc} = \int_0^{t_i} R_{pc} I_{pc}^2 \, dt = \int_0^{t_i} \frac{U_b^2}{R^2/R_{pc}} e^{-t/RC} \, dt \tag{3.8}$$

The integration parameter t_i is here eiter 50 or 100 ms. For a 450 V system with startup time of 50 ms and R_{pc} of 9.4 Ω, the total dissipated energy is roughly 170 Joules for every startup. This means that a pre-charge resistance with power rating of 30W could handle a startup every 5.7 seconds, (170/30 = 5.7). Or if, two consecutive startups within 30 seconds is a goal, the 9.4 Ω resistor needs to have a power rating of at least 12 Watt. For the 850 V system, the energy dissipation would instead be 612 Joules and a resistor with power rating of 41 Watt would be required for two consecutive start-ups within 30 seconds.

3.1.1.2 Inital power surge with pre-charge circuit

The initial power surge of the system after the pre-charge sequence is finished and the main contactor closes is still large, but not enough to damage the contactor. The simplest way to look at it is to divide ΔV by the combined resistance of the system, this would give a initial current of 660 A. However here the stray inductance and the capacitance of the load need to be considered as well. The current through that RLC circuit can be calculated by second-order linear differential equations, or just simulated in the model. In that case the maximum current the contactor experiences directly after contact is 234 A, which is well within what the main contactor can handle.

3.2 Solid-state relay model

The solid-state relays can be implemented in many different ways in the battery disconnection unit. To test what configurations is the most suited for this particular application three model setups will be simulated:

- MOSFET relay in pre-charge circuit only.
- MOSFET for both pre-charge and main contactor.
- Multiple MOSFET relays in parallel for temperature optimization.

All setups will be done with back-to-back MOSFETs and for both 450V and 850V. PWM (pulse-width modulation) will also be tested as an alternative method of doing the pre-charge sequence. Two different PWM set-ups will be tested, one where PWM is used to reduce the size of the pre-charge resistor. And one where the pre-charge sequence is done with PWM in the main relay instead, and does not use a pre-charge circuit at all.

3.2.1 Creation of PWM profile

To operate the pulse-width modulation, you either need a feedback loop or a predetermined pulse-profile. Since the startup will generally be under the same conditions every time, the more basic solution is preferable, using the same sequence of pulses every time it starts. A feedback loop is still very useful thou for creating the pulse-profile. The idea being that the model is first run with a feedback loop controlled PWM while also recording all control signals to the MOSFET. The feedback loop can then be removed and the pre-charge sequence can after that be run by using the saved control signal profile.

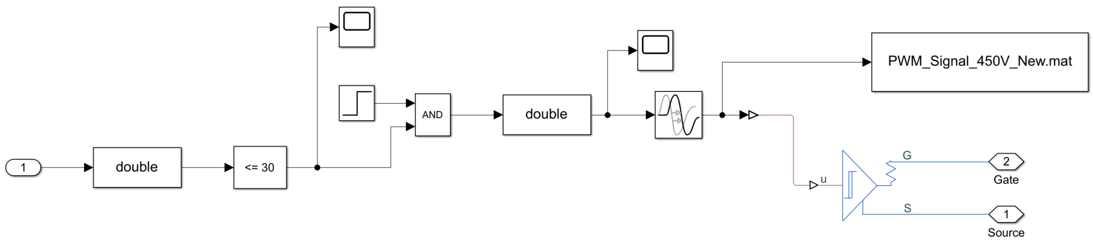

Figure 3.4: Simulink model created to control PWM and to export control signals used to a Matlab file for later use.

In figure 3.4, the current through the MOSFET is compered to a fixed value. In this example it is 30 Ampere. If the value is lower than the reference current, and the general control signal for the MOSFET is in its ON-state, the current pulse continues. As soon as the current gets to high, the pulse ends and waits for the current to decrease. This control signal is put through a time delay equal to the maximum switching speed of the MOSFET, then sent to the MOSFET that acts as the relay in the circuit. The signal is also saved to a Matlab file for later use. This file can then be used as the control signal for the circuit.

3.2.2 Pre-charge only model

The MOSFET pre-charge model focuses on analysis of the pre-charge sequence and the effects of replacing the pre-charge contactor with a MOSFET relay. Both positive and negative main contactors are kept mechanical. The model is made in 12 different versions, (three different tests with four versions each). The tests are, normal pre-charge, PWM with resistor and PWM without resistor. The versions of each test are, 450V with 50ms start-up, 450V with 100ms start-up, 850V with 50ms start-up and 850V with 100ms start-up. All these tests are made with two Wolfspeed CAS175M12BM3 [6] connected back-to-back for multi-directionality. For tests run with cooling, a CP4009D6XJ [7] heat sink is used. The parameters can be found in appendix A. Figure 3.5 shows the setup.

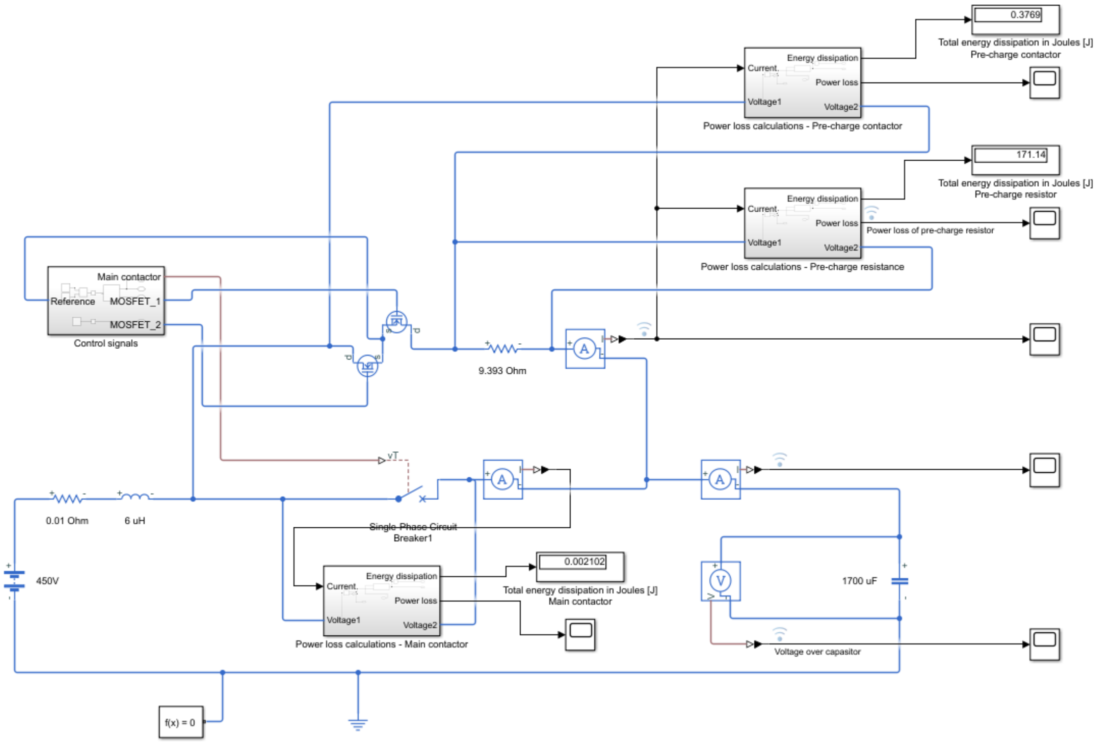

Figure 3.5: MOSFET pre-charge relay setup for 450V, 50ms system.

The model measures voltage and current over the pre-charege resistor, relay and capacitor and calculates the power loss and energy dissipation with those measurements according to (3.1) and (3.2). As described in *Section 3.1* the simulation is run for 0.15 ms and the MOSFET are run by a control signal that closes the pre-charge contactor at $t = 0.05$, then closes the main contactor at $t = 0.10$. Finally the pre-charge relay opens at $t = 0.12$. The pre-charge resistor is dimensioned to reduce the voltage difference over the main contactor to 20 V before it closes.

3.2.2.1 PWM tests

The PWM tests are made as modified versions of the normal MOSFET start-up model. The control signal for the relay is replaced and the pre-charge resistor is either removed or replaced with a smaller resistor *Figure 3.6*. The size of the replacement resistor depends on reference current during the PWM.

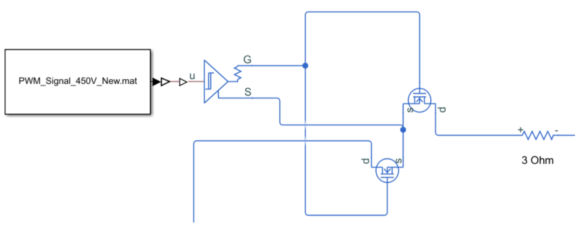

Figure 3.6: Control signal and replacement resistor for pulse-width modulation test model.

For the PWM tests, the control signal is made to limit the maximum current through the relay. According to the data sheet of Wolfspeed CAS175M12BM3 the maximum current is 175A, but a much lower current would be preferred to reduce the wear and to stretch out the relays lifetime.

3.2.3 Pre-charge and main contactor

The *MOSFET-only* model uses the same setup for the pre-charge circuit as the previous non-PWM model. The main contactor is replaced with two Wolfspeed CAB760M12HM3 connected back-to-back. When a heat sink is added to the relay, a CP3012-XP [8] liquid cooling heat sink is used. In this model the focus is to study the difference in losses between this model and the mechanical contactor model and to analyze the temperature in the relay. The set-up is shown below in Figure 3.7.

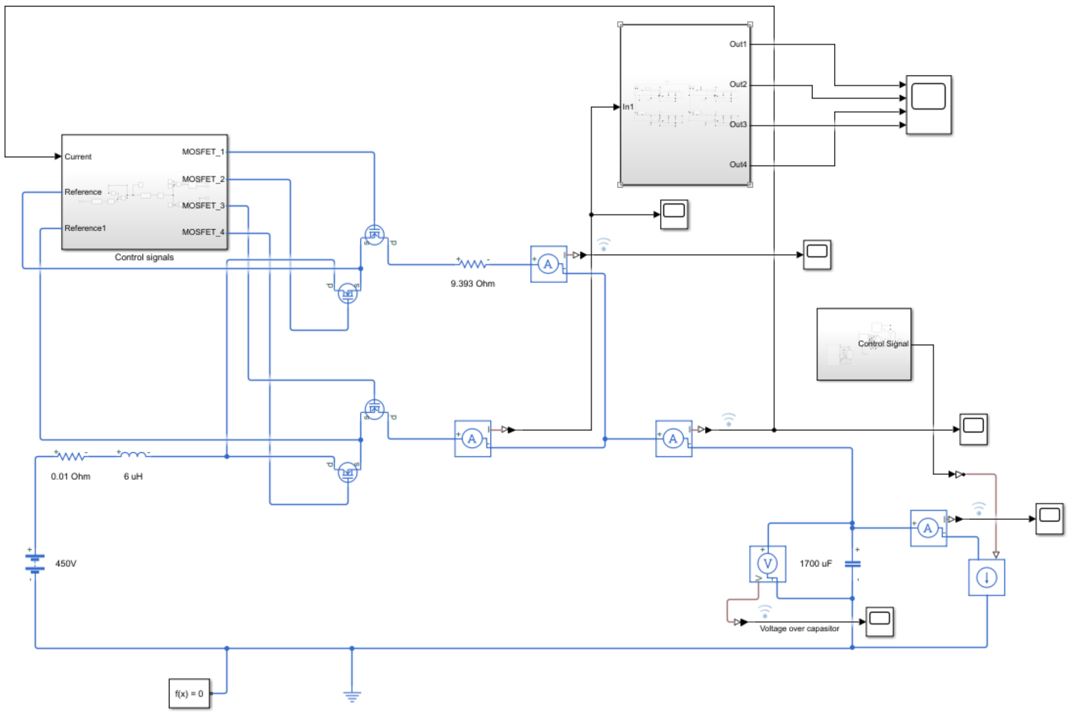

Figure 3.7: *MOSFET-only* configuration for 450V 50Ms

A big change for this simulation compared to earlier models is that the simulation length is extended to 54 minutes from 0.15 seconds. The longer time frame is needed to be able to study the effects of heat buildup in the MOSFET during drive or charge. To simulate the drive and charge conditions, a drive cycle current profile and a fast charge current profile is created and fed into a current source that is placed in parallel to the capacitor. The currents through the main MOSFET is fed into a thermal circuit the calculates the present temperature at all times.

3.2.4 Parallel MOSFET setup

One way to limit the temperature rise in the MOSFET to a level that is easier for the cooling to handle, is to decrease the current. The temperature in the MOS-

FET is highly current dependent. There is even a small positive feedback effect of temperature increase in the component. Since the internal resistance of the MOSFET increases with higher current as well as higher temperatures, a small change in current can make a big difference for the MOSFETs thermal behavior. A more detailed explanation of this phenomenon can be found in *Section 3.3*. In this model, two pairs of back-to-back MOSFETs (CAB450M12XM3 [9]) are placed in parallel to reduce individual current flow. The thermal behavior of those MOSFETs are then compared to the single MOSFET structure of the *MOSFET-only* model. The pre-charge relay still only consists of one back-to-back and is not the focus of this model since the short usage time makes the temperature buildup in that component less prevalent.

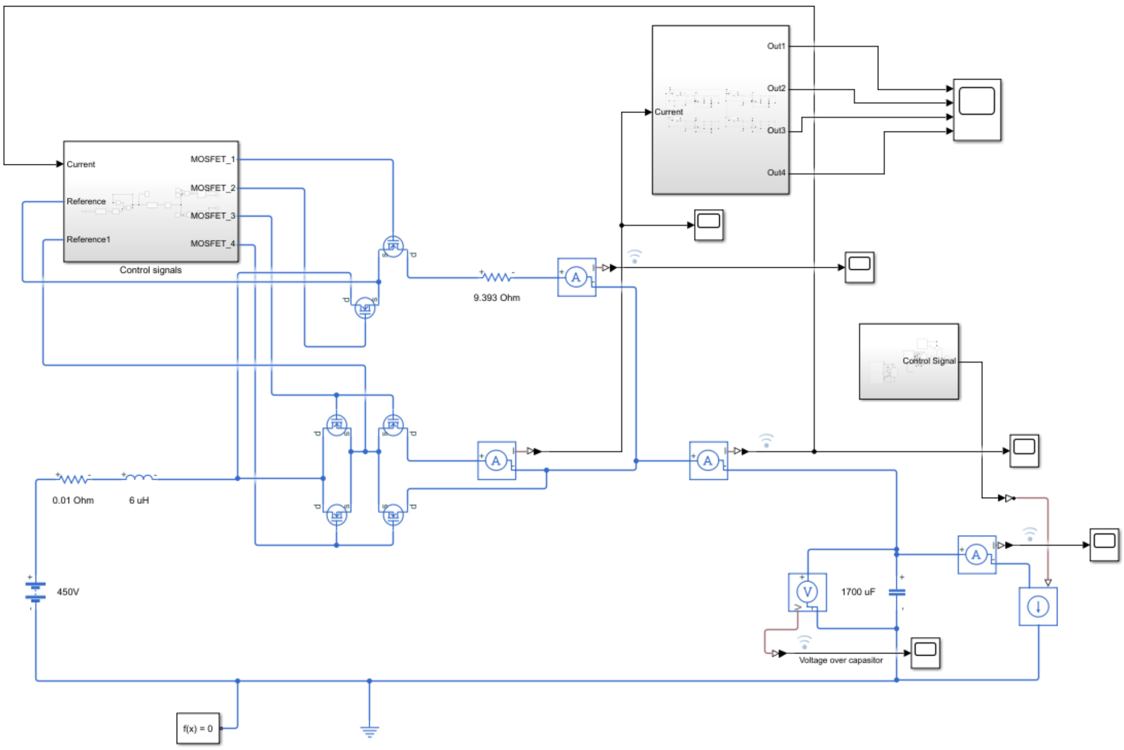

Figure 3.8: *Parallel-MOSFET* configuration for 450V 50Ms

3.3 Thermal model

To analyze the temperatures in the solid-state relays during use, a thermal model needs to be added to the simulation. The temperature rise in the component relates to the power loss and can be described as,

$$T = T_a + R_{th} P_{loss}(t) \tag{3.9}$$

where T is the final temperature in steady state, T_a is the ambient temperature which is assumed to be 25 C, and R_{th} is the thermal resistance och the component. The thermal resistance is a property that describes the the components resistance to heat flow and is measured in (K/W). A higher value of thermal resistance will result in a hotter component during use. In this model a cold plate heat sink will be connected to the MOSFET to reduce the total thermal resistance as much as possible. The power loss in (3.9) is calculated as,

$$P_{loss}(t) = R(T, I)I(t) \tag{3.10}$$

where $I(t)$ is the current through the component, and $R(T, I)$ is the internal resistance in the component which is both current and temperature dependent. An example on how the resistance varies can be seen in Figure 3.9.

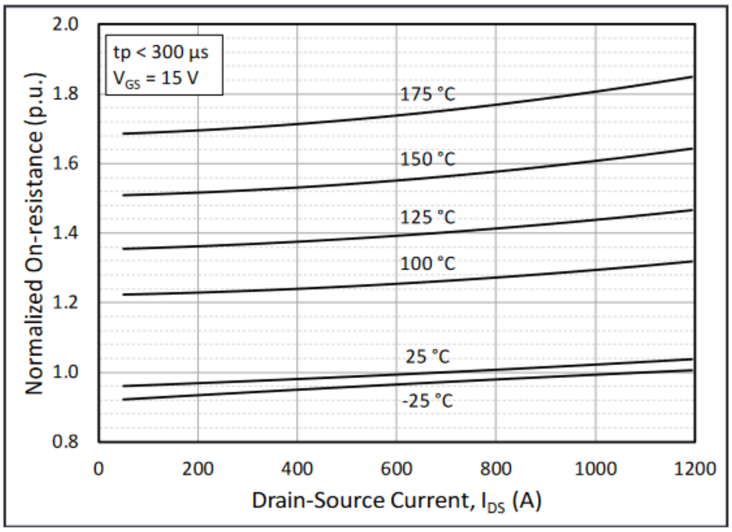

Figure 3.9: Relative resistance compared to base value, depending on temperature and current. Extracted from the CAB760M12HM3 data sheet [4]

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With the data in Figure 3.9 an array of resistance values can be made. During simulation, current and temperature can be used as input to this array to get the correct resistance at all times, and by multiplying this with $I(t)$ the power loss can be calculated. R_{th} is the sum of R_{th}-junction-to-case and R_{th}-case-to-ambient, values for which can be found in the MOSFET and heat sink data sheets respectively. (Note that adding a heat sink does not add to R_{th} but rather replaces an otherwise higher case-to-ambient thermal resistance value.)

3.3.1 Thermal circuit design

With the information in *Section 3.3* a steady-state temperature model can be made. That model would however not show the true temperature of the system but rather the temperature the component would reach if all other variables stayed the same for a long enough time. In the scenario of a solid-state relay used in a car this would not be the case very often. To account for a time varying current and the components inability to instantaneous change its temperature, a new element needs to be added to the model. Heat capacity or thermal capacitance is a property that describes how much heat must be supplied to a component to make it change its temperature. It also functions as a measure for how much heat the components stores while in use. A high heat capacity means it takes longer for the component to both heat up and cool down. To make a transient thermal model, both thermal resistance and thermal capacitance is needed for both junction-to-case and case-to-ambient. The relationship between power loss, temperature, thermal resistance and capacitance is the same as the relationship between current, voltage, electrical resistance and capacitance. This makes it possible to make an electric circuit model that is an analog to the thermal behavior of the component. Figure 3.10 shows the thermal circuit used to simulate the temperature in the MOSFET relay.

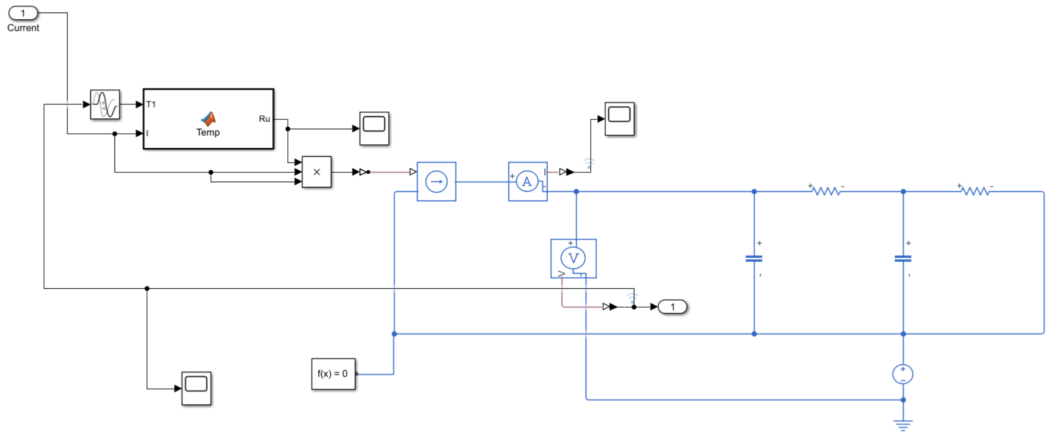

Figure 3.10: Thermal circuit used to calculate temperature of CAB760M12HM3 during use.

A variable current source is added to the thermal circuit with the same value as the current through the relay. R_{th1} and C_{th1} represents the cold plate heat sink and R_{th2} and C_{th2} represents the MOSFET. The voltage source represents the ambient temperature T_a. The transient temperature of the relay can then be measured as the voltage V_T. The temperature is then both used as the output for the simulation and fed back into the resistor array to keep the power loss calculations correctly updated. The thermal resistance of a component is often listed in the data sheet and is usually easy to obtain. The thermal capacitance however is less straightforward and needs to be extrapolated from a pulse response impedance cure. The equation used to calculate the value is,

$$C_{th} = \frac{4\tau}{R_{th}\pi} \tag{3.11}$$

where τ is the time for the impedance to hit steady state after a pulse. This value is only a approximation. To see how the capacitance effect the temperature, four thermal models with different capacitance values will be simulated simultaneously side by side and compered to see the effect of different heat capacities in the MOSFET. One of those capacitance values will be zero, to study the steady-state temperature of the relay as well.

4

Simulation result analysis

4.1 Start up and pre-charge simulations

This section presents the simulation results from the start-up sequence simulations. The parameters of high interest here are, current through pre-charge circuit, power loss in relay and pre-charge resistor, voltage over capacitor and power surge after main contactor close.

4.1.1 Mechanical contactor design

Figure 4.1 shows the current through the 450 V pre-charge circuit during a 50ms start-up. Maximum current is reached right after contactor closure and it is 48 A. After the main contactor closes, both current through, and voltage over the pre-charge contactor drops to zero. During the 50 ms start-up, the 9.41 Ω pre-charge resistor dissipates 171 Joules of energy, and the pre-charge contactor dissipates 0.0036 Joules.

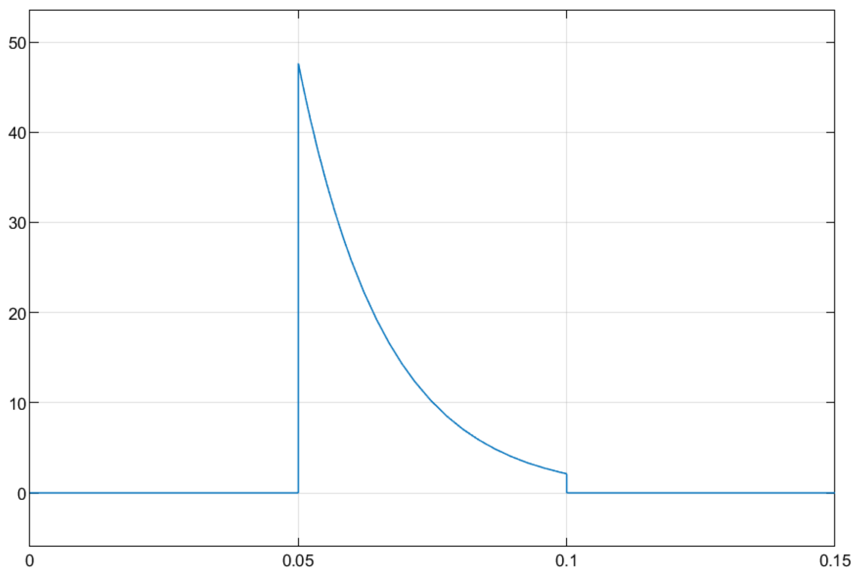

Figure 4.1: 450 V, 50 ms. Pre-charge circuit current.

Figure 4.2 shows the total current through the system. Between $t = 0.05$ and $t = 0.10$ we see the current that passes through the pre-charge circuit. After that there is a short but high power surge as the main contactor closes with a voltage difference of 20 V and very low impedance. The maximum current in the main capacitor is 234 A. The system stabilizes in about 1 ms.

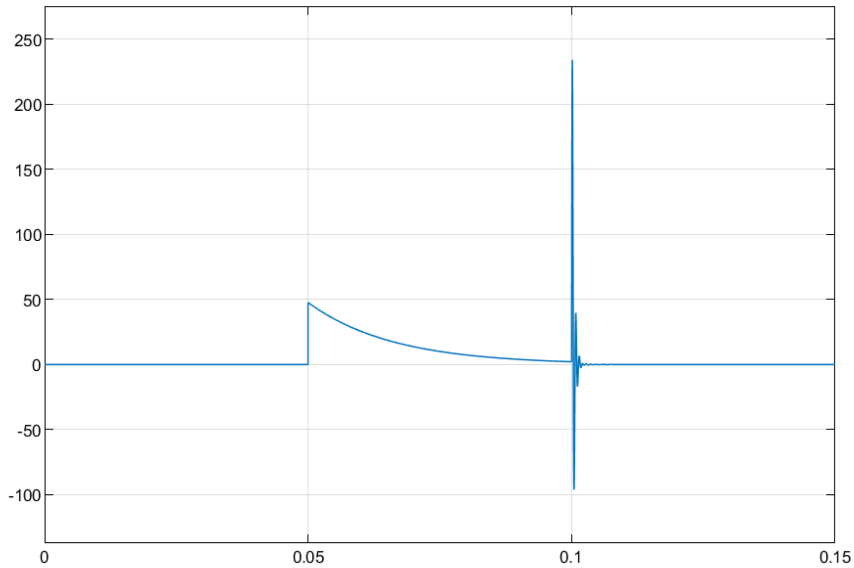

Figure 4.2: 450 V, 50 ms. Total current to capacitor.

For the 850 V system the power surge at $t = 0.10$ would look identical since the conditions are the same, (uses the same ΔV). The pre-charge would however have a higher current with a maximum value of 108 A. The energy dissipation in the 7.81 Ω pre-charge resistor in that system is 611 J, and in the contactor it is 0.016 J.

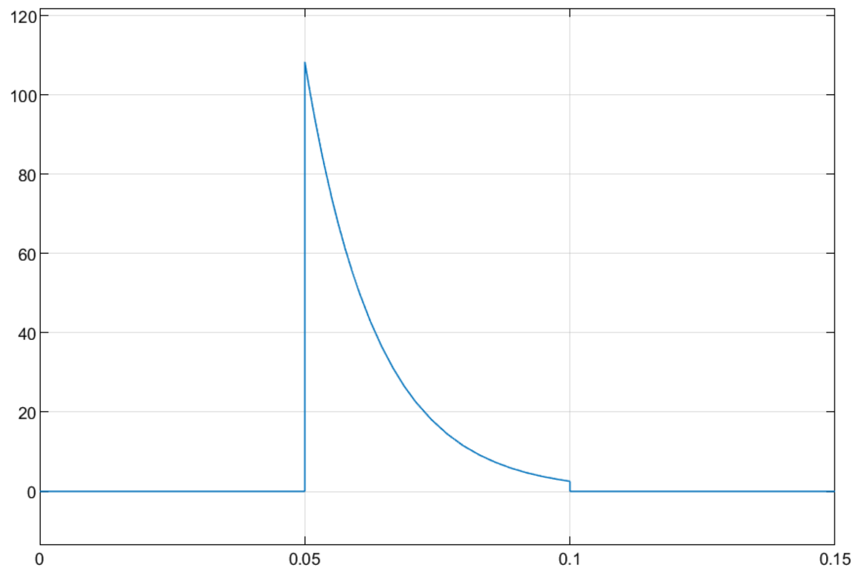

Figure 4.3: 850 V, 50 ms. Pre-charge circuit current.

The voltage over the capacitor for a 450 V, 50 ms model is shown in Figure 4.4. Between $t = 0.05$ and $t = 0.10$, the voltage rises from 0 to 430 V. When the main contactor closes the voltage increases to 450 with some small oscillations that subsides in 1 ms. The absolute maximum voltage over the capacitor is 458 V.

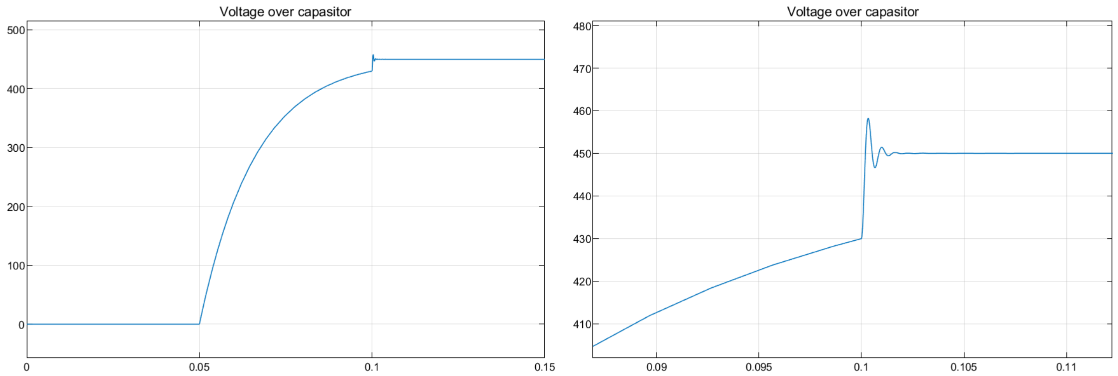

Figure 4.4: 450 V, 50 ms. Voltage over capacitor (left). Close up of main contactor closure at t = 0.10 form the same graph. (right).

For the 850 V, 50 ms model the voltage curves would have the same shape but with an increase from 0 to 830 V instead. The over-voltage at $t = 0.10$ would however be 8 V for the 850 system as well as the closing conditions for the main contactors are the same, giving that system a maximum voltage of 858 V. For the 100 ms start-up the power losses are very similar. 171 J and 612 J dissipated energy for 450V and 850 V system respectively. The closing of the main contactor produces the same response from the system with a maximum current of 234 A and a short over-voltage of 8 V for both 450 V and 850 V. The current is lower however since the pre-charge is more outdrawn. The maximum current through the 100 ms pre-charge circuit is 24 A and 54 A for the 450 V and 850 V models.

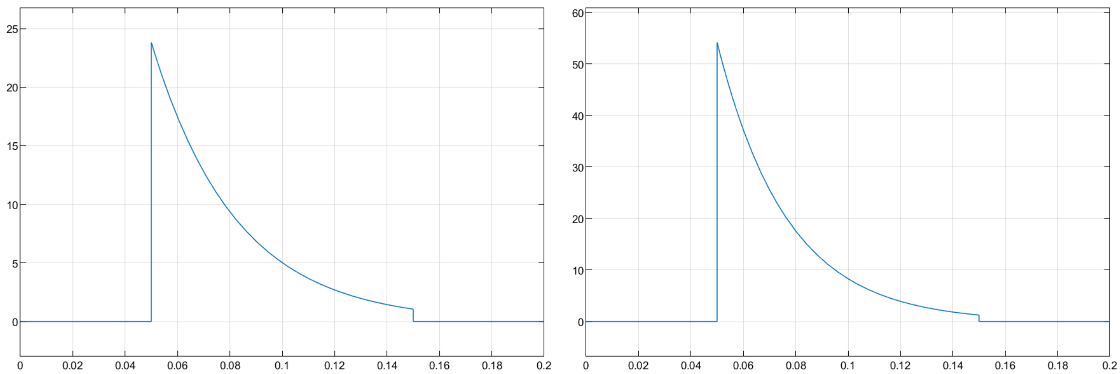

Figure 4.5: 100 ms pre-charge current for 450 V (left) and 850 V (right).

4.1.2 Solid-state relay design

Figure 4.6 shows the pre-charge currents of the *Pre-charge only* model for both 450V and 850V. It is very similar to the mechanical contactor design with only the difference in internal resistance and switching speed separating them. Since the pre-charge resistance is lowered to compensate for the higher resistance in the MOSFET the maximum reached currents are the same, 48 A and 108 A respectively. The total dissipated energy in the relay is 0.38 Joule (per relay) for the 450V model and 1.62 Joule for 850 v model.

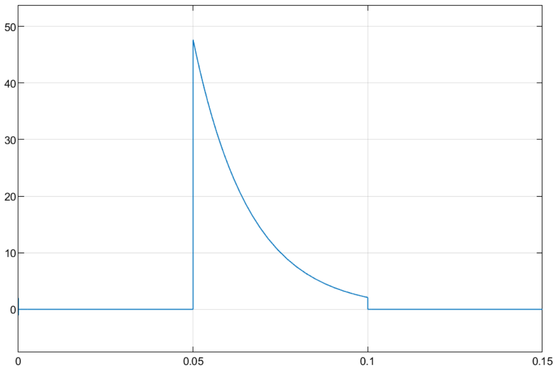

Figure 4.6: 50ms MOSFET relay pre-charge currents for 450V system (left) and 850V system (right).

The left image in Figure 4.6 is near identical to figure 4.1, this shows that the MOSFET relay is capable of preforming the same switching tasks as the mechanical contactor which is as expected. This is only true as long as the MOSFET is operation within its temperature range, therefore the power loss needs to be examined as well. Since the time frame of the start-up is in the millisecond range, a simplified temperature estimate for the MOSFET relay could be made with the average power loss during the pre-charge as,

$$P_{loss(avg)} = \frac{E_{dissipated}}{t} \tag{4.1}$$

Generally in this situation the preferred temperature of the MOSFET is known, and the amount of cooling needed is what is relevant to find out. This can be calculated with (3.9) and (3.10) and the power loss simplification as follows,

$$R_{th,min} = \frac{T_{max} - T_a}{P_{loss(avg)}} \tag{4.2}$$

where $R_{th,min}$ is how low the thermal resistance needs to be made to not exceed the preferred temperature. Inserting the values form the 50ms simulations gives,

$$R_{th,min} = \frac{150 - 25}{(0.38/2)/0.05} = 32.9 \quad , \quad \frac{150 - 25}{(1.62/2)/0.05} = 7.7 \tag{4.3}$$

here the dissipated energy values are divided by 2 since the relay consists of two back-to-back MOSFETs. The temperature value is chosen to be the highers possible value the CAS175M12BM3 MOSFET could handle. Equation (4.3) indicates that, for the relay to function, every CAS175M12BM3 need cooling that reduces the thermal resistance to 32.9 or lower (7.7 for 850V system). The case-to-ambient thermal resistance of the CAS175M12BM3 MOSFET without cooling is highly dependent of the positioning within the system but a very rough estimate would place it in the 40 to 70 R_{th}-rage. This means the that for a 50ms start-up the 850V system definitely needs cooling and the 450V system very likely needs it. When looking at the for the 100 ms set-up, the current is substantially lower than the 50 ms version. The maximum current for the 450 V system is 24 A and the dissipated energy in the relay is 0.18 Joule. For the 850V, 100 ms system, the maximum current is 54 A and the dissipated energy is 0.81 Joule. Using (4.2), the cooling needs of the 100 ms systems is calculated to be 138.9 R_{th} and 30.9 R_{th} (or less) for 450V and 850V. This means that the 450V, 100 ms system can run without cooling and the even the 850V system is fairly close to be able to do so as well.

4.1.3 Pulse-width modulation start-up

Using PWM in the start-up to regulate a semi constant current through the pre-charge circuit gives the start-up currents and voltage a more controlled transition. Figure 4.7 and 4.8 shows the the difference of PWM and no PWM.

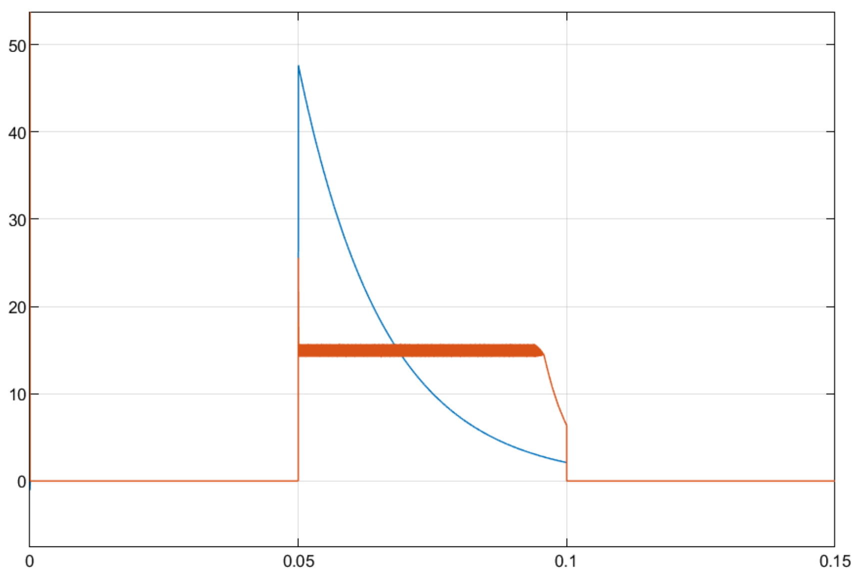

Figure 4.7: 450 V, 50 ms. Pre-charge circuit current. Brown is with PWM control and blue is without PWM.

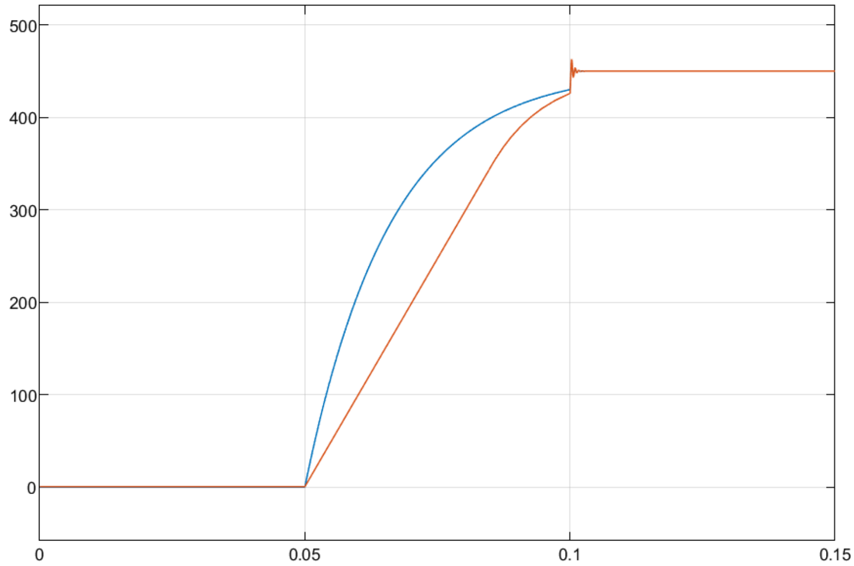

Figure 4.8: 450 V, 50 ms. Voltage over capacitor during pre-charge. Brown is with PWM control and blue is without PWM.

In figure 4.7 and 4.8 the PWM curve is form a circuit with a 6 Ω pre-charge resistor. The lower resistor is needed to be able to complete the start-up in 50 ms with PWM. The switching speeds used are close to ideal for the implementation (1 μs rise time) wish is not unreachable for a MOSFET built for this application. Figure 4.9 shows what might be a more realistic version of the same setup. There the average current is close to that of figure 4.7 but the current deviates more form the average due to slower switching.

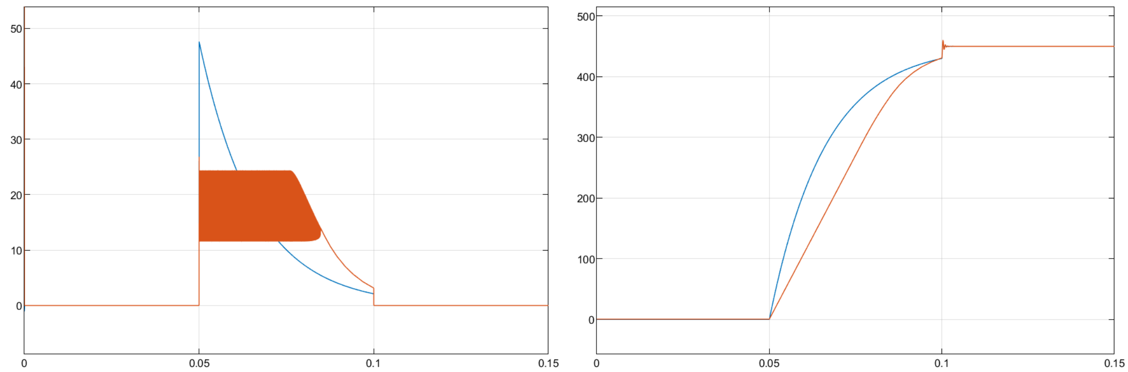

Figure 4.9: 450 V, 50 ms. PWM comparison of current (left) and voltage (right), with slower switching speed. (10μs rise time)

For the PWM in figure 4.9 the losses in the 6 Ω resistor is 76 J and the losses in the relays are 95 J. This is roughly the same total losses as was seen in the 9.4 Ω resistor with no PWM setup. The same is true if the pre-charge resistor is 3 Ω or 0.01 Ω. When the resistance is lowered however, the switching speed and the cooling needs to increase. In theory the pre-charge circuit could be removed completely and the pre-charge sequence could be handled by a the main circuits MOSFET relay if the cooling is good enough. Using the simplified equations (4.1) and (4.2) with the datasheet for the MOSFET CAS175M12BM3 [?] and the heat sink CP4009D6XJ [7] gives an approximation on how small the pre-charge resistor could be made. The maximum energy dissipated in the whole relay is the given by,

$$E_{max} = 2t\frac{T_{max} - T_a}{R_{th}} = 2 \cdot 0.05 \cdot \frac{125}{0.135} = 92.6 \tag{4.4}$$

this is a bit lower than the 95 J from the 6 Ω test, which means that the resistor need to be a at higher than 6 Ω for that specific setup.
Using the same equation for the MOSFET and heat sinks used in the main relay tests and the parallel main relay tests gives the indication that, for the pre-charge circuit to be removed multiple MOSFETS needs to be connected in both parallel and series to divide the power loss. If the start-up is 100 ms however the CAB760M12HM3 MOSFET used for the main relay could handle the pre-charge without a pre-charge circuit using PWM, reaching a temperature of 73 C above ambient. However for the for this to work the PWM must operate at a frequency in the 100 kHz range.

4.2 Temperature analysis of drive and fast charge

This section presents the the simulation results of the temperature analysis of the main MOSFET relays in the *MOSFET only* models. Both a single back-to-back configuration and a parallel configuration is tested for fast charge and normal drive. The 54 minutes long fast charge profile used for the tests is shown in figure 4.10.

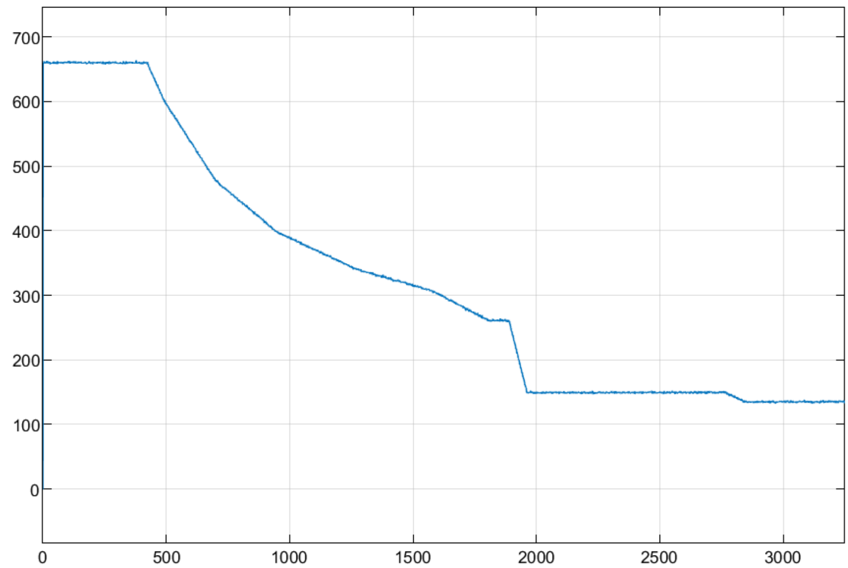

Figure 4.10: Current of fast charge profile used for temperature tests.

Figure 4.11 shows the temperature in one of the the CAB760M12HM3 MOSFETs during a fast charge. The blue curve represents the the steady-state temperature (with no heat capacity), and the others curves shows the effects of gradually higher thermal capacitance. On the time scale of one hour with a slow changing current the differences are very small between the cures. The maximum temperature is reached at the start of the charging during the 660 Ampere period and it reaches 114 C at its highest peak.

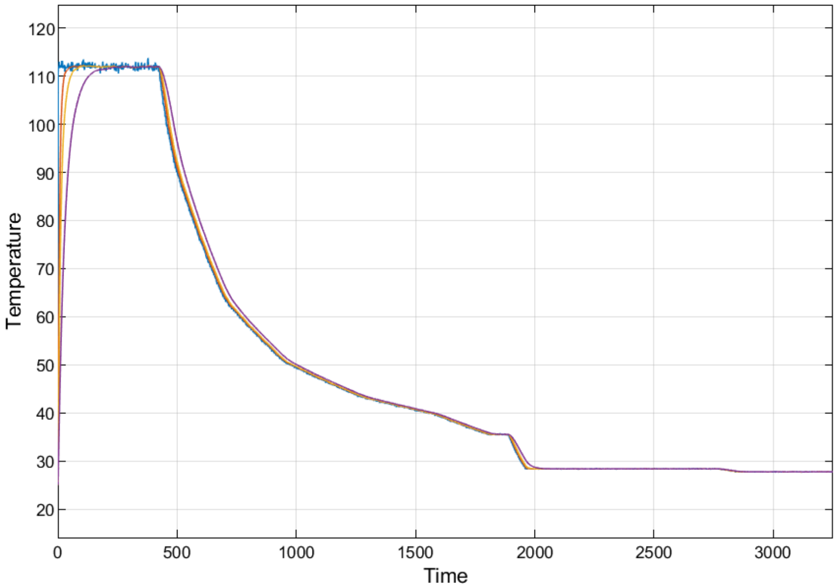

Figure 4.11: Temperature in CAB760M12HM3 relay during fast charge.

Figure 4.12 shows a close up of the start of the fast charge and how the temperature is effected if the relay is already at a higher temperature at the start of the fast charge. Which is a common scenario since fast-charging often is done with driving both before and after. (Note that the maximum temperature does not change unless the starting temperature is higher then the maximum charge temperature).

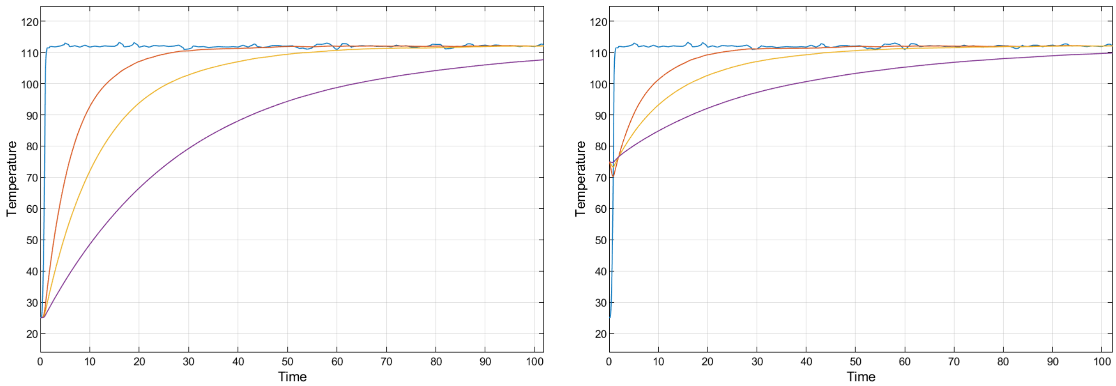

Figure 4.12: Temperature during fast charge. Starting temperature of 25 C (left) and 75 C (right)

In figure 4.13 the same fast charge is used but with the parallel set-up of two CAB450M12XM3 back-to-back relays. Here the maximum temperature is 47 C.

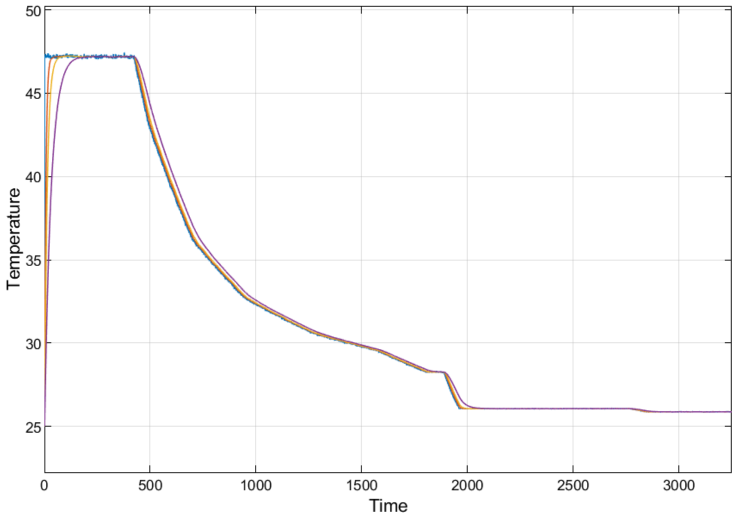

Figure 4.13: Temperature in parallel connected CAB450M12XM3 relay during fast charge.

A closer look of the effects of different heat capacities can be seen in figure 4.14. There the temperature is shown during a very aggressive 10 minutes driving. Due to the constantly changing currents, a steady state temperature is never reached. The difference between the red curve which represents the thermal capacitance that was calculated with (3.11) and the steady state temperature is often 10 ^{o}C or more. In the case of the yellow and purple curve which has thermal capacitance that is 2 and 5 times higher, the the first estimation the temperature difference is even higher.

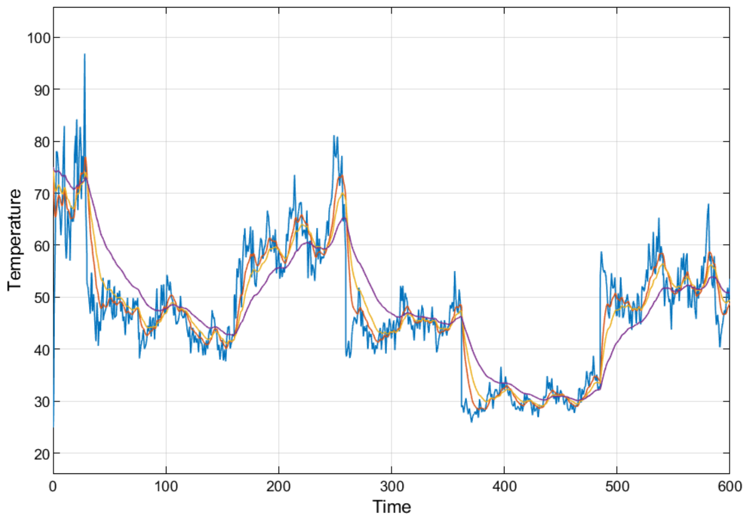

Figure 4.14: Temperature during 10 minutes of driving. Currents range between 150 A to 600 A.

5
Conclusion

5.1 Discussion

When testing the high power MOSFET relays, it immediately becomes clear that they, at least in theory, easy could function as the switches both for the pre-charge circuit and the main one. Whether it is a superior alternative to the existing contactors however is a harder question to answer. The trade off between them is basically a higher prize tag for a smaller volume. How much of a larger prize and size difference is of course very case to case dependent. For the pre-charge relay, start-up time was a very deciding factor in how large and expensive the MOSFET needed to be. The start-up times tested in the models was 50 and 100 milliseconds. If the start-up time was allowed to be even longer, the demand on the relay would decrease lineally with the time used. The results in section 4.1.2 shows that if the start-up time is long enough the pre-charge relay tested did not need any extra cooling at all which would increase the volume savings drastically. When it comes to the the increase in voltage from 450 to 850 V, the implications for the main relay is very good since it reduces the current and therefore the power losses. However the effect on the pre-charge relay is that the cooling demands increase exponentially with the voltage increase. The same goes for the main relay in the test case where the main relay was used for the start-up. The tests showed that in the currently used 450 V systems it was possible to optimize away the whole pre-charge circuit with the use of MOSFETs with PWM-control. However as the system voltage increases this possibility becomes less and less optimal to a point where it would be more space effective to keep the pre-charge circuit than to have many multiples of parallel MOSFET relays to divide the energy dissipation of the start-up. This could be counteracted with longer start-up times, but since it only lowers the currents lineally with time while the energy dissipation increases exponentially with the higher voltage this would be fairly ineffective way to compensate for this if the voltages would increase even more in the future.

5.2 Future work

On top of the trade off between prize for volume decrease, there is another factor that could be very important for the evaluation of the MOSFET relay, and that is availability. If the component is not possible to get hold of in large enough quantities then the whole discussion of advantages and disadvantages between the technologies becomes just theoretical. It is easy to determine that the supply has been lowered due to supply-chain disruptions that was accelerated during the time of the covid pandemic, but to what extent and if the trend is reversing or if the supply shortage will get worse is harder to say without a more extensive deep dive in to that subject. Another subject that could be more thoroughly examined is the actual maximum temperatures of the MOSFETs. The maximum temperature used in this thesis is based on the data sheets for those MOSFETs but in the case of the start-up sequense the time frame might be so short that the MOSFET might be able to handle much higher temperatures.

Bibliography

[1] Volvo Cars Coperation, "Taking the lead: embracing a cleaner mobility, The Future is Electric", https://group.volvocars.com/company/innovation/electrification, (accessed Aug. 18, 2022).

[2] LS electric co., "Catalog-LSIS-GPR-High-Voltage-DC-contactors", GPR-series catalog, Aug. 18, 2022.

[3] R. Rodrigues, Y. Du, A. Antoniazzi and P. Cairoli, "A Review of Solid-State Circuit Breakers," in IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 364-377, Jan. 2021, doi: 10.1109/TPEL.2020.3003358.

[4] Wolfspeed, CAB760M12HM3, datasheet, 2020, https://assets.wolfspeed.com/uploads/2020/12/CAB760M12HM3.pdf

[5] Boyd. Sarah B, *Life-cycle assessment of semiconductors*, Springer Science & Business Media, 2011.

[6] Wolfspeed, CAS175M12BM3, datasheet, 2022, https://assets.wolfspeed.com/uploads/dlm_uploads/2022/06/wolfspeed_CAS175M12BM3_data_sheet.pdf

[7] Wieland Microcool, CP4009D6XJ, 2021, https://www.microcooling.com/wp-content/uploads/2021/03/CP4009D-data-sheet.pdf

[8] Wieland Microcool, CP3012-XP, 2019, https://www.richardsonrfpd.com/docs/rfpd/CP3012.pdf

[9] Wolfspeed, CAB450M12XM3, datasheet, 2020, https://assets.wolfspeed.com/uploads/2020/12/CAB450M12XM3.pdf

A

Table of Simulation Parameters

Table A.1: Component parameters used in the simulations.

Battery Internal resistance:	22	mΩ
Other system resistance:	10	mΩ
System stray inductance:	6	uH
Mechanical contactor resistance:	0.2	mΩ
Resistance CAS175M12BM3 :	10.4	mΩ
Resistance CAB760M12HM3 :	1.73	mΩ
Resistance CAB450M12XM3 :	3.7	mΩ
Capasative reprenatation of loads	1700	uF
Traget ΔV:	20	V
Needed total resistance during pre-charge, 450V 50ms:	9.45	Ω
Needed total resistance during pre-charge, 450V 100ms:	18.89	Ω
Needed total resistance during pre-charge, 850V 50ms:	7.84	Ω
Needed total resistance during pre-charge, 850V 100ms:	15.69	Ω
Total Thermal resistance (pre-charge set-up)	0.135	K/W
Total Thermal resistance (full MOSFET set-up)	0.114	K/W
Total Thermal resistance (parallel MOSFET set-up)	0.145	K/W
Total Thermal capacitance (full MOSFET set-up)	7.5 + 37.5	J/K
Total Thermal capacitance (parallel MOSFET set-up)	3.75 + 18.75	J/K

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
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