Modular Multilevel Converters for heavy trucks

Abstract

This thesis examines alternative to power supply for a heavy truck application based on five different modular multilevel converter configurations that ultimately feed a 3-phase engine. Advantages and disadvantages of the different configurations are being discussed as well as other important factors that play a role in what configuration that is beneficial for the intended application. How half- or full-bridge submodules and battery cells relate to each other to achieve a desired voltage are being explained and calculated. Power losses of the converter submodules are being calculated as well as how a specific battery capacity, with increasing average power consumption, performs uphill according to set requirements. It turns out the be the double-armed modular multilevel converter configurations that has the best performance when it comes to utility, energy storage and the lowest power losses.

Content

1   Introduction

With today's growing awareness of the global environment and establishment of new laws and goals set by organizations such as the European Union and countries' governments worldwide, industries and vehicle manufacturers need to present innovative solutions to meet these goals for a better climate. Many vehicles manufacturers' answer to these goals are electro mobility or more commonly used: E-mobility. E-mobility is a term for the development or usage of an electric-powered drivetrains, with aim of shifting focus from vehicles that utilise fossil fuel [1]. In this thesis, a study and system design of a modular multilevel converter (MMC) with integrated battery modules is proposed.

1.1   Motivation

Nowadays the solution for electrical based vehicles is a VSC-controller. This solution is mostly used for applications for medium power requirements. An MMC can provide high power and is therefore more suitable for heavy truck application where the electrical engine needs to manage larger loads.

1.2   Purpose

Several papers have been done in the area of this thesis, but none have yet designed a system which consists of an MMC topology with integrated battery modules as a dc source instead of a capacitor as in a traditional MMC configuration. The purpose of this thesis is therefore to compare different MMC configurations to find the most appropriate solution, when it comes to performance and costs, and lastly simulate this system design.

1.3   Delimitations

Since the time of this thesis is limited the focus will be on what MMC configuration and system design is the most suitable for a heavy truck application and a small amount of time will be spent on the battery modules themselves.

1.4   Research questions

The future of E-mobility with long lasting and healthy batteries is possibly a system based on an MMC with integrated battery modules. MMC modules can be configured in many various ways to achieve different characteristics. The MMC modules configurations that are of main interest are: half- and full bridge, furthermore these converters are possible to connect as a star connection, double star connection and delta connection. The research questions are as follows:

- Which MMC module configuration *gives* the best performance at affordable cost?
- How should the battery modules be designed to achieve the most advantageous system design for a heavy truck application?

1.5   Related work

The high-power MMC topology was invented in year 2001 [2] and has ever since been popular and plenty of related conference papers, journal articles and research has been made on the subject. The MMC has been used in various areas such as HVDC transmissions [3] and STATCOMs [4] with great success. There have been studies on MMC topologies with capacitors as voltage source but not with integrated battery modules instead of capacitors.

2 Theory

This chapter will explain crucial parts of the thesis as well as theoretical information on methodologies that were used later.

2.1 Voltage Source Converter

Nowadays the most used converter for automotive drive system applications is the two-level Voltage Source Converter (VSC). However, this converter does not come without drawbacks. Firstly, power losses that depends on high switching frequency, higher than around *1 kHz*, typically of insulated gate bipolar transistors (IGBTs), these losses occur on the ac side owing to significant harmonic components, although, the power losses in the IGTBs are more significant. Secondly, the semiconductors that are used in VSCs for blocking voltages can only handle a couple of kilovolts. Therefore, in high-voltage applications to acquire desired behaviour and requirements a series connection of semiconductors must be utilised. Lastly, as mentioned above, the switching frequency must be high since the phase voltage is constantly switched between the dc rails of a two-level converter. Large direct voltages could lead to damages on the insulation of any equipment connected to the ac terminal. These disadvantages are significantly improved with topologies of multilevel converters. [5]
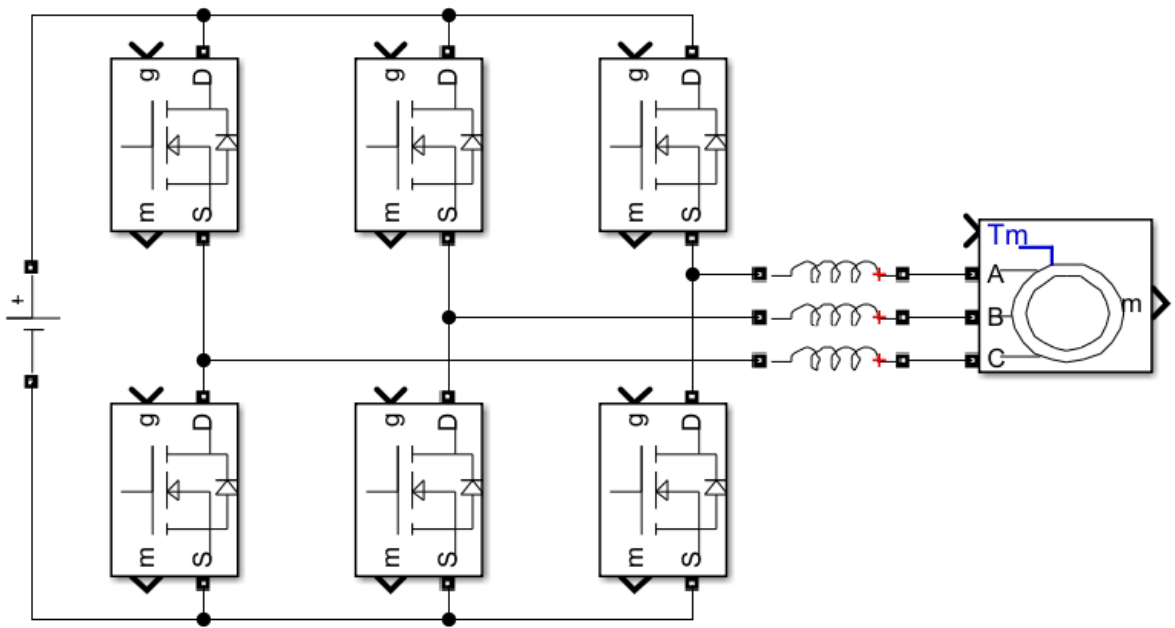

Figure 1 A 2-level 3-phase inverter as a reference design.

2.2 The modular multilevel converter

As seen in Fig. 1 each phase leg consists of series connected converter modules which creates a phase arm. These phase arms are connected between the ac terminal and the dc terminal. The benefits of the MMC technology is its ability to convert a nearly ideal sinusoidal shape waveform on the ac-side, which eliminates the need of low order filter for harmonics [4]. What is worth to mention is that there will be no dc terminal in this thesis and furthermore, the capacitors of each submodule (SM) be replaced by battery cells. SMs and the converters will be connected solely to the ac terminal.
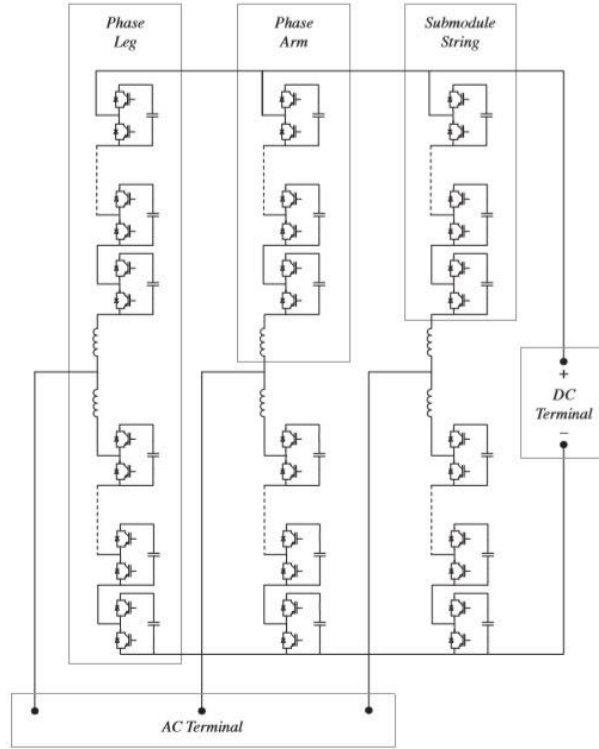
Figure 2 An example of a star-connected three-phase MMC topology with half-bridge SMs. [5]

The MMC modules can be connected in multiple different ways and a part of this thesis is to study and evaluate these connections to determine which configuration achieves the requirements at an affordable cost.

2.3   MOSFETs: structure and functionality

As recently mentioned, there are various ways to configure an MMC module, this depends mostly on what application that is considered. To begin with, the basic setup of the half-bridge submodule (HBSM) and full-bridge submodule (FBSM) will be presented.
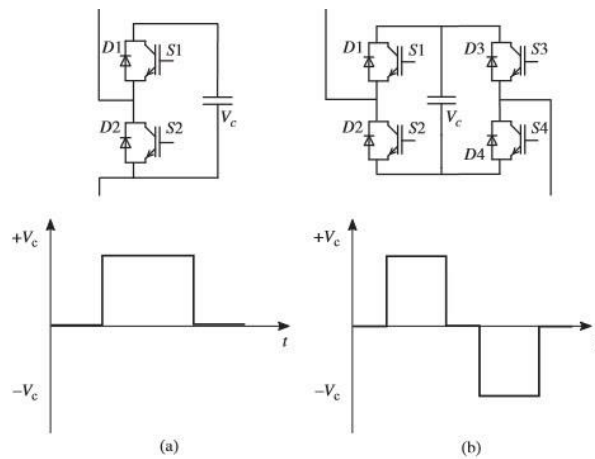

Figure 3 The two SM topologies that are studied, (a) half-bridge and (b) full-bridge, with respective voltages of one cycle. [5]

As seen in Fig. 2 the HBSM can only provide a unipolar voltage which makes the only suitable configuration for this SM is the double-star connection. The basic expressions for the HBSMs are presented in [4] and furthermore in [6] are as follows:

$$V_{ac} = V_{a1} + V_{a2}$$

$$2V_{dc} = V_{a1} - V_{a2}$$

Where U_{ac} is the ac output voltage of the MMC and V_{a1} and V_{a2} is the upper and lower voltage of phase A respectively. This is assumed that the voltage-drop across the arm inductance seen in Fig. 2 is zero. The resulting ac-voltage is the sum of all SMs of arm, defined in Fig 1.

The HBSM and FBSM can furthermore be cascaded to increase the voltage levels of operation where a string of N numbers of SMs can provide voltages between $-NV_c$ and $+NV_c$ which gives the total of $2N + 1$ levels [5], this applies for the HBSM if connected as a double-star connection as mentioned above since a bipolar voltage can be provided.

The output voltage of the HBSM and FBSM is either equal to the capacitor voltage, or in this case the nominal voltage of the BC, or zero, depending on the switching states of the IGTBs. Since the components of a FBSM is doubled compared to a HBSM, the power losses and the costs for a FBSM based MMC is significantly higher than a HBSM based MMC. [7]

Generally, the HBSM is cheaper and has the lowest losses because of less components. Although, this SM configuration is most dominating for HVDC applications [5]. The main drawback of a HBSM is the occurrence of a fault. A FBSM can provide a counter voltage to prevent short-circuit currents flowing from the ac-side to the fault on the dc-side. In comparison the FBSM converter is twice as expensive and increases the losses by about 80 % [5] compared to the HBSM.

2.4   MMC topology configurations

For the double-star configuration there is 6 arms with equal amount of SMs divided over all arms. One set of an upper and a lower arm form a phase leg including an arm inductor for the purpose of limiting the short-circuit current through the leg.

FBSMs will give double output voltage magnitude for the same module capacitor voltage or battery voltage. This means that for a half-bridge configuration the battery modules must consist of double number of cascaded connected battery modules than a full-bridge configuration to reach the same output voltage magnitude.

When it comes to a desire to match a specific voltage at the ac terminals of the SMs, [5] states that a star connected configuration is more beneficial were using the least number of SMs is of interest. The use of half-bridges makes it difficult to handle dc-side faults, that is one benefit of using full-bridges. With a full-bridge configuration the voltage is bipolar, this is advantageous since it enables the converter to control the current of both ac- and dc-side even in the case of a short-circuit of the stiff dc-side. Although this seems problematic this is mostly applicable, and needs to be considered, in HVDC applications. For this thesis application a fault will most likely occur on the ac-side of the modules and can therefore be handled since the MOSFETs can be turned off and prevent fault currents to enter the battery modules.

Furthermore, a difference between the HBSM and FBSM is in terms of the sum of the capacitor voltage, V_c^Σ, in each arm. V_c^Σ is the sum of the capacitor voltage of the SMs, however in place of these capacitors' batteries will be added as a voltage source. In the region where $V_d < V_c^\Sigma$, a full-bridge converter can provide an ac-side electromotive force (emf) that is larger than half of the direct voltage V_d, which means that $\hat{u}_s > V_{d2}$, where $\hat{u}_s$ is the ac-side inner emf. [5]

One major drawback of a delta connected topology is the energy-storage elements that are distributed in the converter phases, which exposes them in different power pulsations, imposed by the existence of negative-sequence currents. If not treated this effect will result in a permanent divergence of the energy stored in the different branches, which leads to that a phase leg may be overcharged, while another may end up with a zero-voltage capability. To deal with this effect a zero-sequence current needs to be controlled inside the delta configuration, with a suitable amplitude and phase to redistribute the charge among the capacitors/batteries in different phase legs to restore the balance. This is solved with a battery management system.

A difference between a star- and a delta-connection is how the voltage and current are defined. For a star-connection the voltage over a leg of an MMC is equal to the phase voltage and the current that flows out of one leg is the line current. When calculating the active power, the line-line voltage and line current is used. When measuring the voltage of a star-connection the line-line voltage is obtained, therefore the voltage is needed to be divided by the square root of 3. When it comes to a delta-connection the voltage that is measured over a leg is the line-line voltage but, in this case, the current through one leg is the phase current, which is thereby divided by the square root of 3 to obtain the line current, hence the active power for both star- and delta-connections are equivalent. [8]

$$P_{3-phase} = \sqrt{3} \cdot U_H \cdot I_L \cdot \cos\varphi$$

Equation 3

There are 5 different topologies that were to be calculated. This topology has in total six arms whereof three upper arms create the positive voltage and the three lower arms create the negative voltage of the 3-phase supply to the engine. The upper or the lower set of arms needs to be capable of supplying the engine with the rated voltage for each configuration. In other words, the sum of the voltage of one arm must be equal to the line-line rms voltage U_H. The current I_d the flows through each arm is equally divided between all upper and lower arms, this current sums up to the ac-current to the engine I_L. This means that the current I_L in each arm will be lower for six arm configurations compared to three arm configurations.

2.4.1   Double-star configuration

The double double-star configuration can be configured with either half- or full-bridges. In Fig. 3 a configuration which consist of full-bridges, connected to a 3-phase engine, is shown. Two SMs are connected in series together with a string of three BCs, this ratio is for illustration purposes only since the voltage supply that this setup would result in would be to low for the intended application.
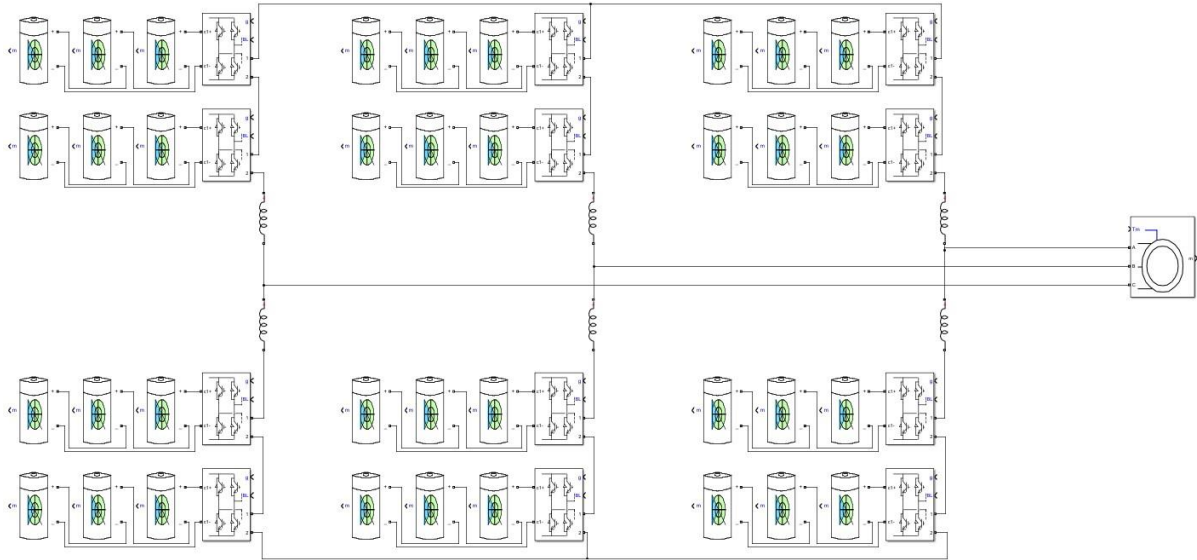

Figure 4 Double-star full-bridge configuration.

The MMC topology is highly customizable and may be configured in various ways for different behaviour. It is possible to add BCs in series for increased voltage per SM as well as connect BCs in parallel for increased battery capacity. It is as also possible to add more SMs in every arm for increased

2.4.2 Single-star configuration

The same circumstances yield for Fig. 4, the ratio between SMs and BCs are to low for the application of this thesis. The single-star configuration may consist of either half- or full-bridges.
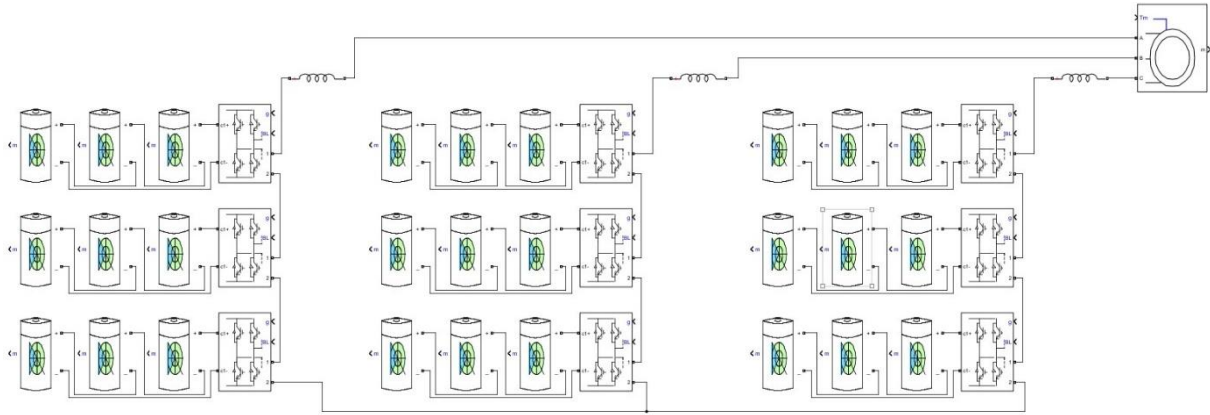

Figure 5 Single-star full-bridge.

2.4.3 Single-delta full-bridge configuration

Only full-bridges were intended to be used for the single-delta configuration. The configuration can be seen in Fig. 5 and as previously mentioned for Fig. 3 and Fig. 4 the ratios between SMs and BCs are not reasonable.
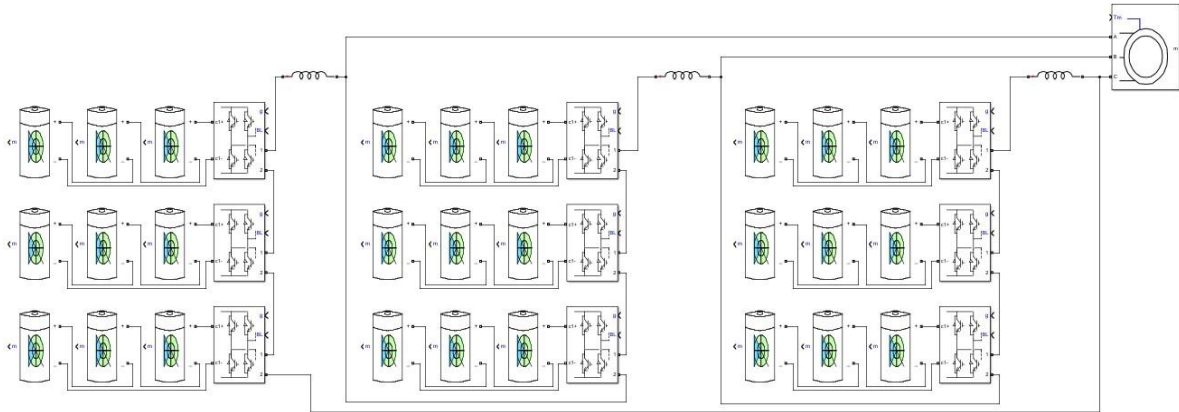

Figure 6 Single-delta full-bridge.

2.5   Lithium-ion batteries

The most widely used battery type for mobile units' applications is the lithium-ion battery. The lithium-ion battery has a high energy per mass ratio and provides high power and good efficiency. The batteries are often used with a dept-of-discharge (DoD) percentage to ensure good battery health, the employer required a *65 % DoD*. The DoD limits the withdrawal of energy from the battery to keep the stored energy within certain levels. The nominal voltage (U_{cN}) of the battery cells of this thesis were *4.2 V*.

Where the W is the stored energy of the batteries, U_{cN} is the nominal voltage of one battery cell, DoD is the depth-of-discharge which is the percentage of the battery capacity that may be discharged i.e. the useful energy of the battery.

2.6   Ampere hours

The ampere hours of the batteries are determined by their characteristics and which materials the batteries are made up of. However, this factor may be altered by placing battery cells in parallel strings in each SM, this solution may be considered for system designs with few battery cells in each SM.

2.7   Heavy truck application specifications

The thesis aims to work towards certain specifications that were requested of the employer. The MMC system design is intended to supply a 3-phase engine for a heavy truck with a total weight of approximately 40 tons. The average power consumption for this application is estimated to be *100 kW* on average when driving without incline. A request of an increase of *100 kW* per percent of incline in power supply when driving uphill, this criterion will be explained further in section 3.3.

A battery capacity of *1000 kWh* is requested to be the total stored energy of the battery cells. This value is linked to an driving law established in the EU where one driving session is limited to 4.5 hours at the time [9].

The employer has fully developed technology in electronic highways and therefore wants the MMC configurations along with the BCs to be compatible with the these. The proposed solutions of the thesis should be able to charge the BCs at the same time as driving. This criterion is also followed by the requirement of the system to support a high current for situations that requires a rapid increase in speed and being able to charge the BCs quickly.

3   Method

This chapter will contain strategies and methodologies to achieve the following results as well as how the work was performed.

3.1   Software

The software that was used to accomplish the results was MATLAB. The computations were easy to implement in MATLAB which is the cause for the selection of the computation tool. Other software that could have performed the same results is, for example, Microsoft Excel.

3.2   Methods for calculating the ratio between SMs and battery cells

The calculations were based on multiple data based on values that were required of the employer. This data was mostly based on for how long a heavy truck must be supported by the electrical drivetrain, what ac-voltage that was needed for the induction motor to work properly, furthermore the MMC along with the battery pack was needed to perform a large current at a limited amount of time for critical situations were a large power output is needed.

The calculations started off from a 2-level 3-phase inverter system design with a desired dc-side voltage, U_d, of *800 V* with one large battery pack with battery cells (BCs) in series and parallel to achieve *800 V*.

The value of U_d was an estimation of what was needed to supply the engine. This value was used to examine what ac-voltage and ac-current this would result in since the average power is the same for both the ac- and dc-side.

$$U_H = \frac{\sqrt{3} \cdot m_a \cdot U_d}{\sqrt{2} \cdot 2}$$

Equation 4

Where the 3-phase line-line ac-voltage U_H is the rms value of the voltage supplying the engine. A factor of $\sqrt{3}$, since it is a 3-phase system, is multiplied with the modulation index, *ma*, as well as the dc-voltage, U_d, the denominator of the equation represents the fact that half of the voltage is distributed over each leg of the MMC and the factor of $\sqrt{2}$ for rms value of the ac-voltage U_H.

With the ac-voltage and the required average 3-phase power of *100 kW* the ac-current can be calculated with the following formula.

$$I_L = \frac{P_{avg}}{\sqrt{3} \cdot U_H \cdot cos\varphi}$$

Equation 5

The average power requirement is an estimation of what active power the 3-phase engine may need for a loaded heavy truck application. A unity power factor was considered in this thesis although, there will be some reactive power consumption of the engine.

As previously mentioned, there are some differences between the star- and delta-connections when it comes to the ac-voltage and ac-current. The line-line ac-voltage of a star-connection, U_{Hy}, is the ac-voltage, U_H, divided by $\sqrt{3}$ whereas the ac-voltage of a delta connection, U_{Hd}, is the same as U_H define in Eq. 4. The ac-currents for the star- and delta-connections are calculated with the following formula.

$$I_{Lx} = \frac{P_{avg}}{3 \cdot U_{Hx} \cdot cos\varphi}$$

Equation 6

The only difference in Eq. 6 for star- or delta-connection is the voltage that is used in the denominator. U_{Hx} and I_{Lx}, with emphasis on the x, is used for both star- and delta-connections in these equations since the calculations are the same, with only the ac-voltage or ac-current as the changing factor in this and in future equations.

With values of the required ac-voltage and ac-current the ratio between the number of converters in relation to the number of battery cells can be calculated. This can be done by representing number of battery cells in series as a vector of integers from 1 to 20, more than 20 battery cells are not considered practical. To calculate the number of SMs per arm that are needed to achieve required voltage, several different factors need to be taken into account such as the nominal voltage of the battery, modulation index and what MOSFET typology that is used i.e. a half-bridge or a full-bridge typology.

$$N_{SMs} = \frac{\sqrt{2} \cdot U_{Hx}}{m_a \cdot U_{cN} \cdot N_{cells}}$$

Equation 7

Since there are 20 cases of different ratios between SMs and number of battery cells the resulting variable N_{SMs} is a 1 by 20 matrix containing the number of SMs used for a specific number of battery cells in series to achieve desired voltage of one converter.

3.3   Battery capacity

Another requirement of the employer was the performance on incline slopes. It was desired that the average output power of the MMC scales with every percent of incline. The slope is in percent where each percentage unit corresponds to *1 cm* rise per meter. *1 cm* rise translates to *0.57* degrees of incline.

$$P_{Slope} = P_{avg} + P_{Slope} \cdot Incline(\%)$$

Equation 8

The power consumption for increasing slope incline is calculated with Eq. 8. P_{avg} is the same average power as previously mentioned. The P_{Slope} is an increment of *100 kW* for every integer of slope incline.

The ampere hours of the MMC configurations are different depending on if the configuration is single or double and if HBSMs or FBSMs are used.

$$C_N = \frac{W}{U_{cN} \cdot DoD \cdot N_{arms} \cdot N_{SMs} \cdot N_{cells}}$$

Equation 9

Where the W is the total energy demand by the vehicle, U_{cN}, is the nominal voltage of one battery cell, DoD is the depth-of-discharge which is the percentage of the battery capacity that may be discharged i.e. the useful energy of the battery, N_{SMs} is the number of SMs of one leg and N_{cells} is the number of cascaded batteries for one SMs. The resulting C_N are the ampere hours of the different configurations.

3.4   Power losses

The employer had a requirement of a maximum value of the power losses of *1 %* for the MMC configurations, which is the reason for the investigation of the different configurations.

Power losses occur in the resistances of the MOSFETs and are calculated with the following formula.

$$P_{loss} = I_{vx}^2 \cdot R_{DS(on)} \cdot N_{arms} \cdot N_{SMs} \cdot N_{cells}$$

Equation 10

As previously mentioned, the ac-current is different depending on if a star- or a delta-connection is used. In Eq. 10, $R_{DS(on)}$ is the drain-source resistance of the MOSFETs. For FBSMs the value of $R_{DS(on)}$ is doubled since the current flows through two different MOSFETs which means that the power losses for FBSMs are twice as large compared to HBSMs. But because of bipolar voltage that the FBSM can provide, the power losses even out between the HBSM and the FBSM.

Furthermore, the differences between a DS-HB, DS-FB, SS-HB, SS-FB and a SD-FB are that the DS-HB and DS-FB has double the number of arms of SMs and therefore twice as many battery cells and SMs, although the current I_{Ly} is halved because it is divided into twice as many arms.

4 Results

This chapter will present the results of the investigated MMC configurations given above as well as answering the research questions.

4.1 Calculations of SMs and battery cells for different configurations

The results from the different configurations are shown in Fig. 3 and Fig. 4. These results are mainly based on Eq. 4 and Eq. 7 where the ac-voltage needed to supply the engine is based on a dc-voltage of *800 V* and then calculated with Eq. 4 to receive the corresponding ac-voltage for either a star- or a delta-connection. A phase-phase ac-voltage of approximately *490 V$_{rms}$* was calculated for the engine supply, this was the voltage that the SMs together with the battery cells needed to perform.
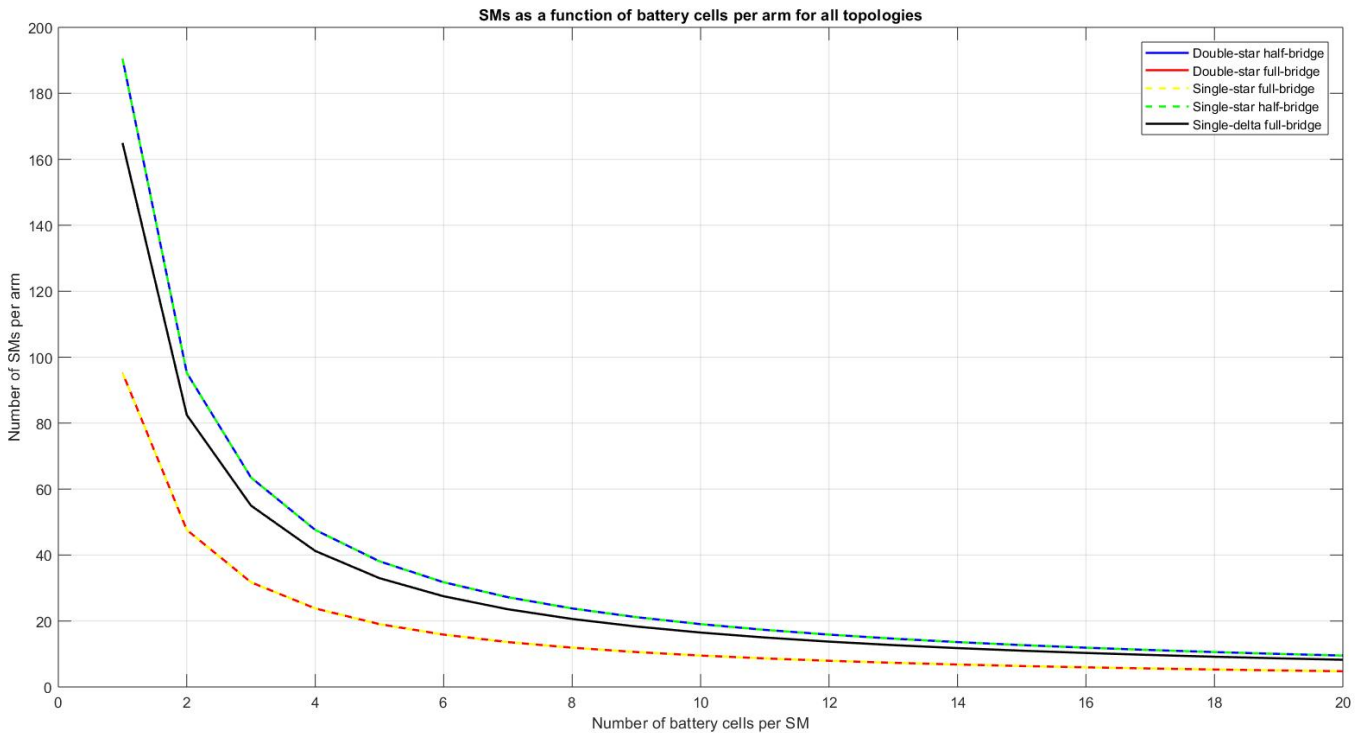

Figure 7 SMs and battery cells needed per arm.

The y-axis represents the number of SMs, depending on topology, that is needed together with the number of BCs in series, on the x-axis, to achieve the ac-voltage that were calculated with Eq. 4.
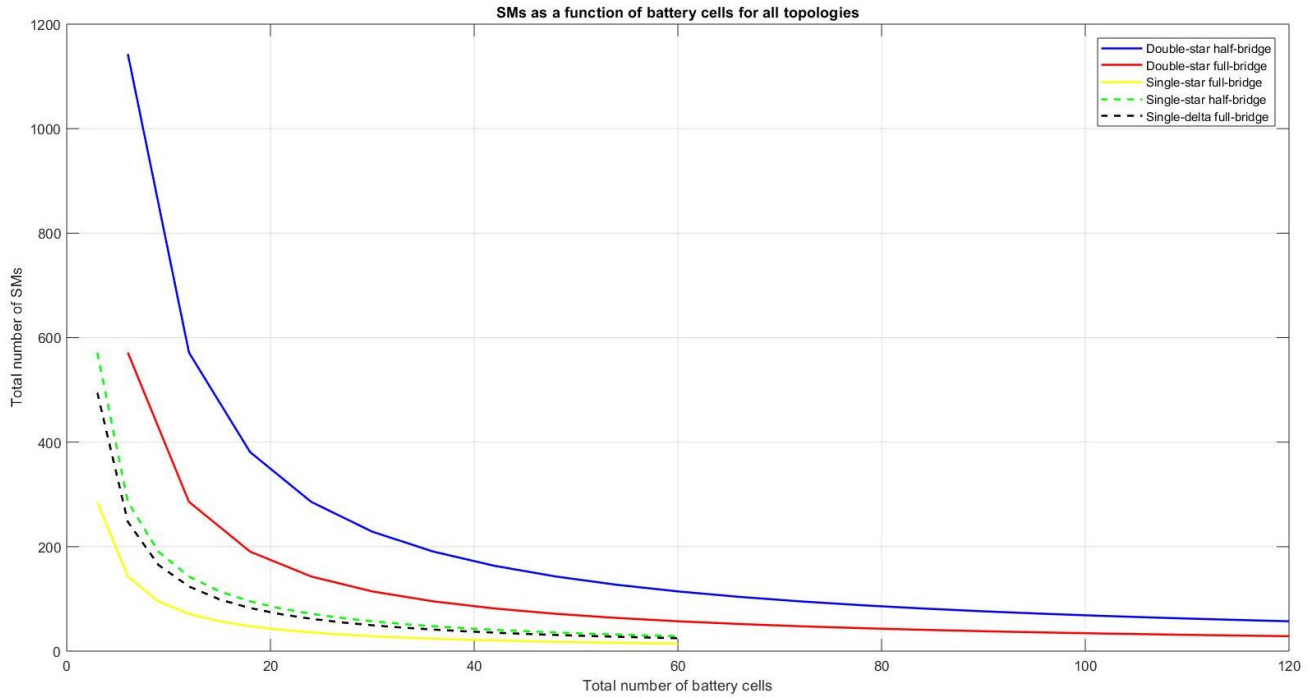
Figure 8 Graph of the total number of SMs and battery cells needed for all configurations.

For clarification and for a fairer comparison Fig. 7 shows the results of the calculations, for the ratios between SMs and battery cells, per arm. If it is only of interest to use as few components as possible for the final system design, the obvious choice of topology is either of the single-star or single-delta configurations.

Further, the DS-HB seems to require a much larger number of components compared with the rest of the configurations, but when it comes to the performance of ampere hours this configuration will have an advantage.

4.2   Battery cell capacity for all configurations

Calculations were made to investigate how the ampere hours differed for each configuration. The results are shown in Fig. 5. The bars represent the required amount of stored energy of the different topologies. The results were calculated with Eq. 9.
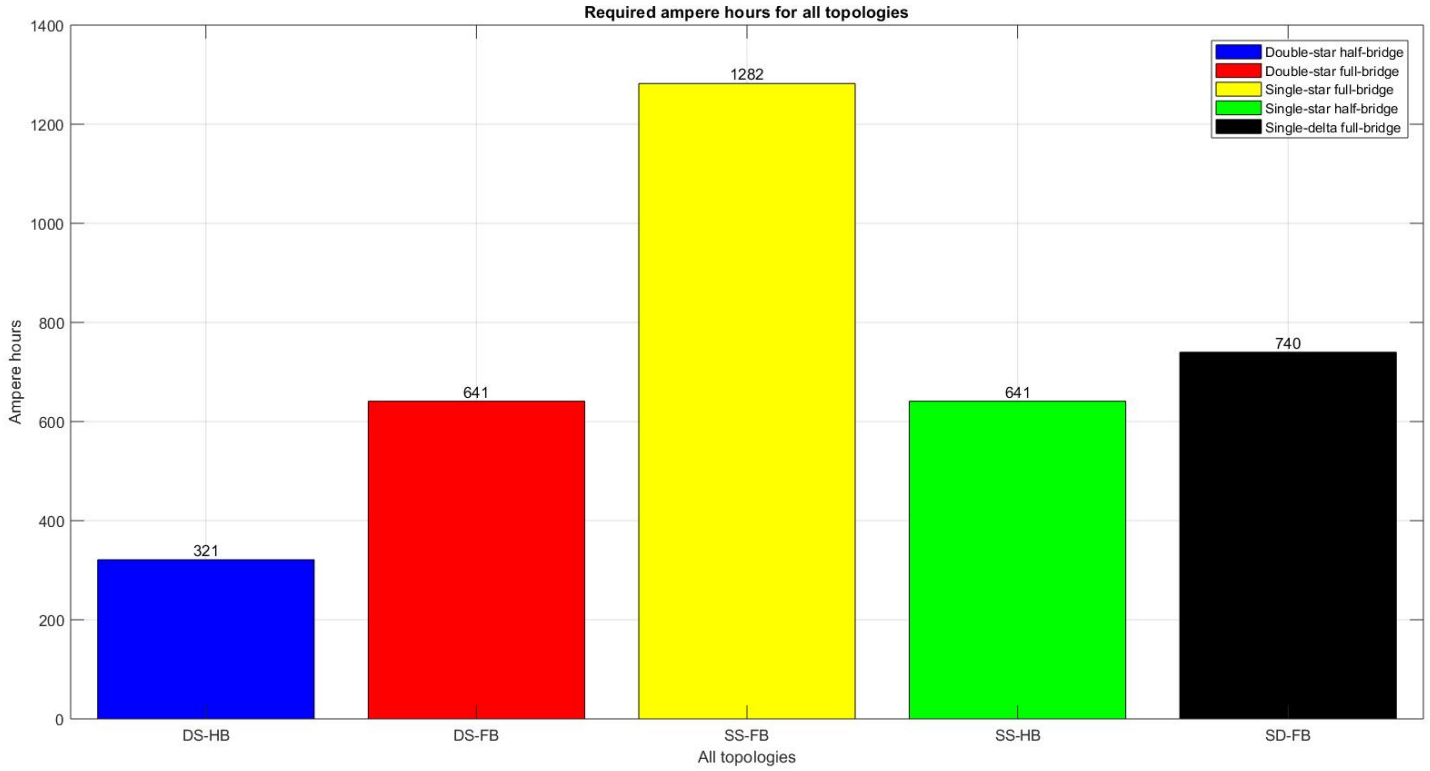

Figure 9 Required ampere hours for all configurations. The numbers above the bars represents the amount of ampere hours.

The low requirement of ampere hours for the DS-HB is because of its number of arms and the fact that half-bridges are used. The unipolar property of the half-bridge contributes to the low result of required ampere hours because the DS-HB consist of more battery cells in series, as previously discussed in chapter 2.2. The DS-FB and SS-HB configurations requires the same amount of ampere hours although their topologies are different. This is explained by the number of arms and if the configurations consist of half- or full-bridges.

The SS-FB configuration requires a lot of ampere hours compared to the other configurations. The fact that the star-connections require a larger amount of stored energy is because the ac-voltage U_{Hy} is smaller than the voltage U_{Hd}, which leads to a larger ac-current, I_{Ly}, according to Eq. 6.

4.3   Slope incline performance with determined battery capacity

These calculations were made to see how the power consumption change with increasing slope incline. As seen in Fig. 6 to the left, the required power of the MMC is increasing linearly. This behaviour was expected and wanted by the employer. The result was based on Eq. 8.
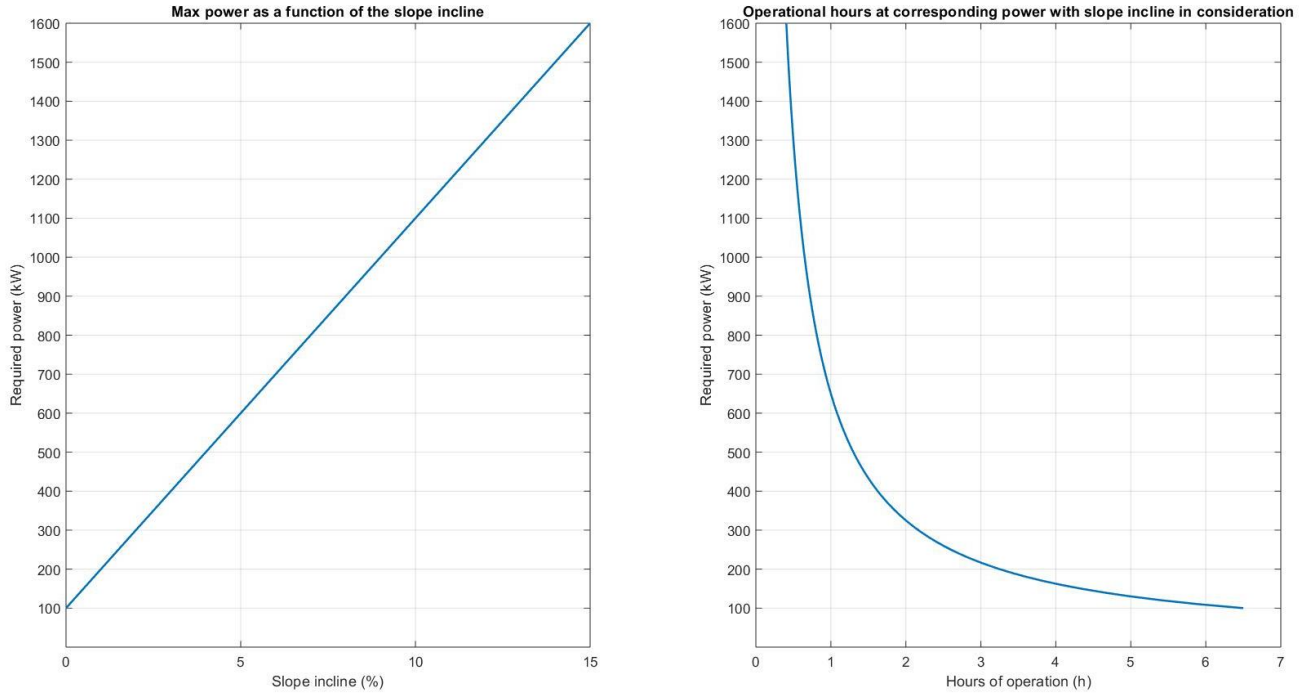

Figure 10 (Left) The required power output of the MMC considering slope incline. (Right) The resulting hours of operation with the battery capacity of 1000 kWh considering the slope incline.

To the right in Fig. 6 is the hours of operation with increasing slope incline with the battery capacity of *1000 kWh*. It is worth to mention that the *DoD* of *65 %* of the total battery capacity has been considered, i.e. only *650 kWh*.

4.4   Results of the power losses

As previously mentioned, the power losses mainly depend on the $R_{DS(on)}$ of the MOSFETs that are used. For system designs with fewer battery cells per SM, the drain-source breakdown voltage, (V_{ds}), attribute of a MOSFET may be decreased since the V_{ds} will be lower compared to a system design with a larger number of battery cells. Since the focus of the calculations were mainly the power losses, the MOSFETs were chosen by the lowest $R_{DS(on)}$ that could handle said transients. The MOSFETs that were used in this thesis is shown in Table 1.

Table 1 List of studied MOSFETs.

Manufacturer	$R_{DS(on)}$	V_{ds}
Infineon	1.5 mΩ	60 V
Infineon	1.2 mΩ	80 V
Infineon	1.5 mΩ	100 V

The results in Fig. 7 shows how the power losses vary, depending on variables mentioned in Eq. 10. Hence the increasing of the voltage V_{ds} different MOSFETs listed in Table 1 were used for the calculations to obtain the most truthful result of the power losses.
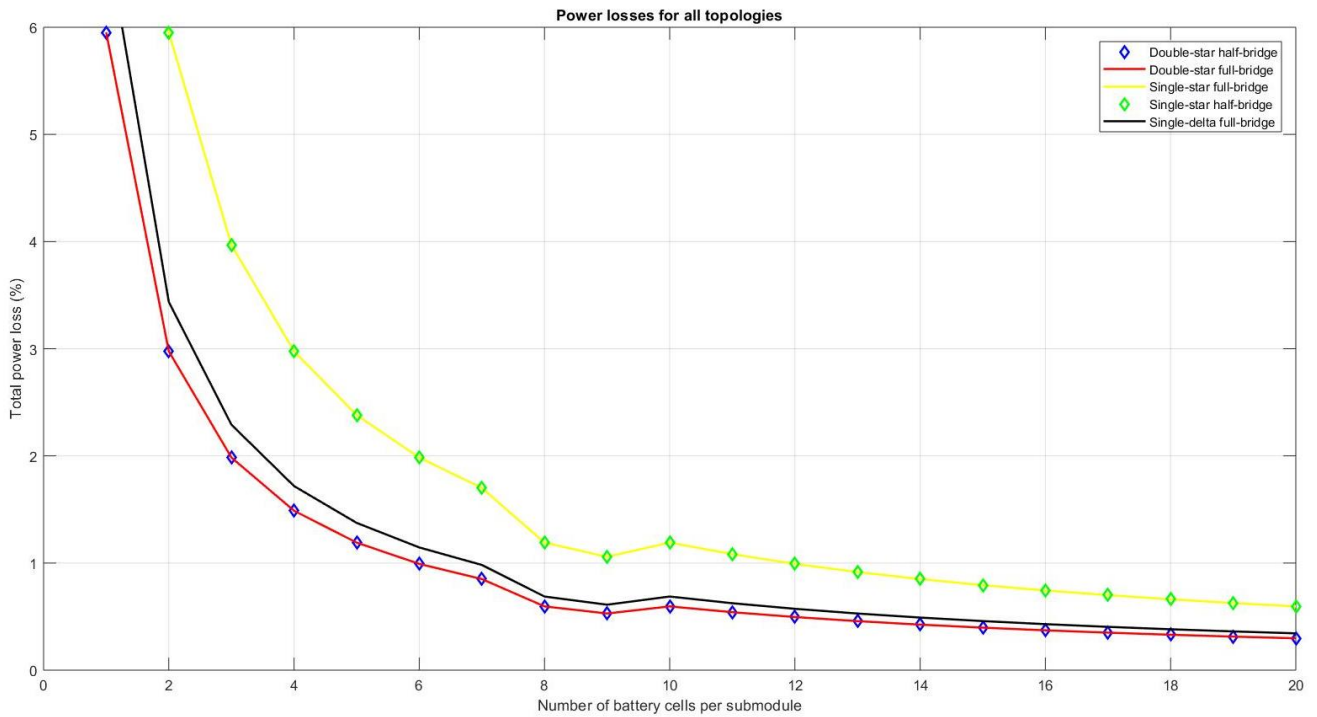

Figure 11 The results of the power losses for specific MOSFETs with different value of $R_{DS(on)}$.

The differences between the studied MOSFETs were what voltage rating the MOSFETs had. The voltage ratings of the MOSFETs was selected to manage twice of the rated voltage to withstand eventual transients in the circuit.

5 Discussion

This chapter contains discussions of the results and the methodology of the thesis. Since this thesis is solely theoretical there will be no discussion of tests that went wrong or complications along the way since most of the faults that occurred were bugs in the MATLAB scripts or misconceptions of the theory.

5.1 Method

As mentioned in the beginning of section 3.2, the groundwork of the thesis was the system design where an MMC configuration was connected to one large battery bank. Since the voltage and current, of the different MMC configurations, were defined in different ways, it was logical to use this is a starting point for the different configurations to have the same starting conditions.

5.2 Results

The obtained results agree with what was theoretically expected from the theory in section 2. Although, some results did surprise, and some configurations did perform more poorly or different than expected. The difference in needed components for half- and full-bridges agrees what was mentioned in the theory section.

5.2.1 Performance comparison of the configurations

When examining the ratios of the different configurations for one arm specifically, differences in the results are not that great. But when the single- and double-arm configurations are considered, it is easier to distinguish advantages and disadvantages. It may seem like the double-star configurations require the greatest number of components but when compared to the other results that is, storage capacity requirement and power losses, the double-arm topologies are the configurations that has the most attractive performance and lowest power losses. The results of the required ampere hours were rational although, the result of the SS-FB configuration marked with a yellow colour in Fig. 5, was surprisingly high compared to the other configurations.

5.2.2 Slope incline calculations

These calculations were based on a specific already decided battery capacity and thus have not a direct connection to the examined MMC configurations. Although, the result gives a measure of what can be expected with the determined size of the battery capacity.

6   Conclusions

The conclusion is that the double-arm configurations are the most beneficial system design for a heavy truck application. The double-arm configurations can provide both a reasonable ratio between SMs and BCs as well as performing well on the power loss calculations. As mentioned in section 2.7, a request of being able to charge the BCs at the same time as driving, the double-arm configurations are the easiest applicable methods to achieve this request.

The most effective way of distributing the battery cells is up to what application that the MMC topology is being used in. It also depends on the performance of the battery cells that are intended to be used. However, an MMC topology makes it easy to implement battery cells in series as well as to connect them in parallel, depending on application.

As described in section 2.7, the employer requested a solution which were able to drive and charge the BCs at the same time. The most appropriate solution is the double-armed configurations since the circuits are symmetric which facilitates the charging of the battery cells.

6.1   Future work

The work that has been made in this thesis is a groundwork for what may be a common solution for high power battery-based applications. Since the double-arm configurations seems to be the most beneficial solution for this application, a further investigation on half- and full-bridges performances in complete systems may be of interest. Although, it seems as there is no general answer to which configurations are the most effective when it comes to costs and performance since it is highly dependent of what area the MMC topology is used within. It would have been interesting to study the configurations in reality and see how the performance is on a real application.

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Appendix