HIGH VOLTAGE SUPPLY FOR PARTICLE ACCELERATORS BASED ON MODULAR MULTILEVEL CONVERTERS

P. Asimakopoulos, K. D. Papastergiou, CERN, Geneva, Switzerland

Abstract

Modular Multilevel Converters brought a paradigm shift in very high voltage and high power applications with the replacement of high voltage valves by multiple series-connected, low-voltage modules that can be bypassed in case of fault. The reliability and precision in output waveform generation make it a potential candidate in accelerator power conversion. This work demonstrates operation of MMC-based high voltage magnet supply for a transfer line application. The output current regulation precision and the total power losses are examined. Finally, the challenge of the control optimization combined with the passive components dimensioning is highlighted.

INTRODUCTION

Modular multilevel converters (MMC) [1], [2] have become mainstream in the field of high power and high voltage conversion (static variable compensators, high voltage direct current transmission). This is mainly thanks to topological features that allow low switching frequency, use of low voltage semiconductors and the ability to bypass a fault without interruption of the supply.

This work aims to investigate the potential of MMC in high voltage and continuous current applications in particle accelerators. This could be, for example, a fast operating transfer line that requires high voltage at the magnet with simultaneous recovery of the magnet energy into capacitors and increased current regulation precision at the same time. Figure 1 illustrates typical fast magnetic cycling in accelerator transfer lines.

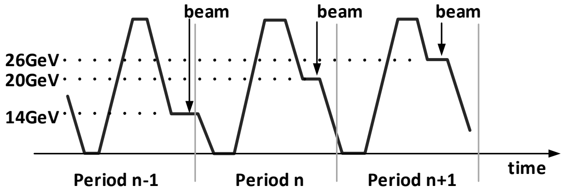

Figure 1: Example of magnetic cycles in transfer lines.

The MMC can be used in different components of the power magnet supply chain, see Fig. 2. At the three-phase configuration, it can successfully operate as an Active-Front End [3] substituting the Front-End converter in Fig. 2. In this work, the potential of the topology as a DC-current power supply is examined. The topology that is currently used as a power supply is the typical two-level H-bridge. At the single-phase configuration, the MMC comprises of two arms or half-legs, each of them having a number N of half-bridge or full-bridge modules connected in series with an inductor, see Fig. 3. Each module is connected in parallel with a capacitor. Additionally, Fig. 3 illustrates the magnet voltage and current during a period. For instance, in order to deliver a voltage equal to Vdc/2, the MMC inserts all the lower-arm modules and by-passes the upper-arm ones.

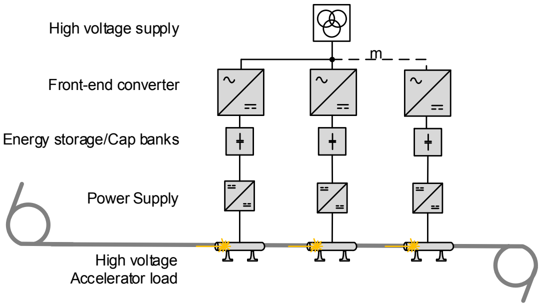

Figure 2: Power magnet supply chain.

The average module capacitor voltage in steady state is calculated

$$V_c = \frac{V_{DC}}{N} \qquad (1)$$

where V_{dc} is the DC-link voltage. The features of the MMC that are interesting for a high-power and high-voltage magnet supply application are:

The redundancy due to the modular nature of the power converter; a faulty module can be by-passed and a spare one can be inserted without interruption of the operation. In the faulty module replacement procedure, the service time and effort can, potentially, be reduced because only an MMC module has to be changed without affecting the other parts of the converter.

The scalability of the power converter that can offer a high output switching frequency with low individual module switching frequency. This is achieved by increasing the number of modules per arm without adding complexity to the mechanical implementation.

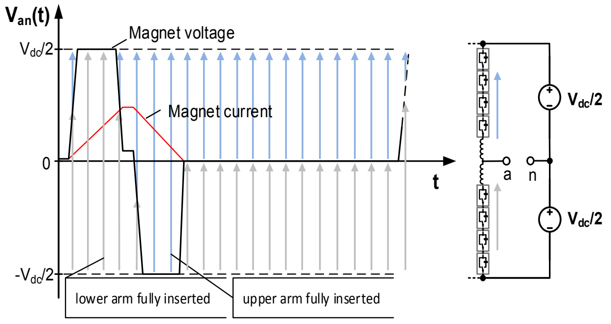

Figure 3: Magnet voltage and current profile built with the MMC.

CASE SET-UP

The modular multilevel arm discussed in this paper consists of six half-bridge modules built with two Infineon FF600R07ME4_B11, IGBT switches each with an anti-parallel diode. The DC-link voltage is 2200V (1100V per arm). The MMC main characteristics are provided in Table 1.

Table 1: MMC Main Characteristics

Component type	Value
DC-link voltage	2200[V]
Maximum current	450[A]
Maximum output voltage	1100[V]
Arm inductance	0.001[H]
Module capacitance	0.25[F]
Capacitor voltage rating	450[V]
Capacitor reference voltage	366[V]
Number of modules per arm	6
IGBT power module ratings	650[V]/600[A]

The electro-magnet load assumed has an inductance of 0.1H and a resistance of 0.2Ohm. The current profile of the electromagnet is provided in Table 2.

Table 2: Electromagnet Current Cycle

Part of the profile	Duration(s)
Ramp-up	0.05
Flat-top	0.01
Ramp-down	0.05
Zero-load current	1

SIMULATION RESULTS

The described MMC is evaluated for the load current regulation precision as well as for the total semiconductor device power losses of an MMC are evaluated having as a reference the conventional H-bridge based DC-DC power supply with a DC-link of 1100V. The converter operation is simulated for a range of switching frequency levels per module from 400Hz to 2400Hz.

Operation

Figure 4 illustrates some key waveforms of the system's main operation variables. The magnet current (I_magnet) has the shape that is provided in Table 2. The unidirectional flow of the current during the ramp-up and flat-top stage forces the upper-arm current (Iarm_hi) to follow the output current and the lower-arm current (Iarm_lo) to stay around zero. Hence, during this phase, the stressing of the lower-arm semiconductor devices is small compared to the upper one. During the ramp-down stage a negative voltage is applied on average to the load that results to the reduction of the upper-arm current and to a negative lower-arm current. The sum of the upper and lower arm currents is the magnet current plus a small DC component for the semiconductors power losses. The bottom graph of Fig. 4 shows the instantaneous power losses for two modules, one belonging to the upper (Pmod_hi) and one to the lower-arm (Pmod_low). As expected, the waveforms correspond to the magnet and arm currents.

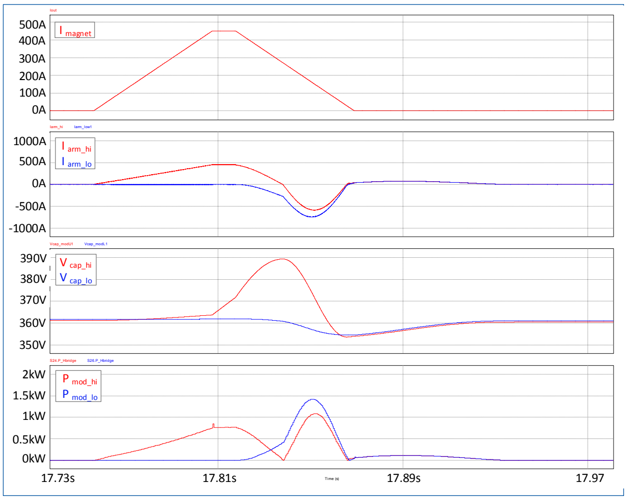

Figure 4: MMC operation as DC-DC high voltage supply. From top to bottom: Load current, upper (red) and lower (blue) arm current, upper module capacitor voltage (red) and lower module capacitor voltage (blue), instantaneous power losses for high (red) and low (blue) module

A primary requirement for this application is the power supply precision to produce the current profile that is set as a reference. The precision upper limit is set to 100 parts per million (ppm) and, in this investigation, it is measured at the flat-top of the current profile. Figure 5 demonstrates the relation between the output current precision and the switching frequency per module. The precision is improved significantly, as the switching frequency per module increases. The benefit is that a satisfactory precision can be achieved with a switching frequency of only around 1000Hz per module. In practice, the number of modules would be more than 30, leading to lower switching frequency per module. An increase of the number of modules per arm has a direct impact in the current precision figure since more modules result in a higher frequency output ripple due to the interleaving effect of the modules. The size of the arm inductance is also critical for this ripple, as it is shown in Eq. 2. The combined effect of the arm inductance and the switching frequency on the arm current ripple and, as an extension, on the output current, can be demonstrated

$$di_L = \frac{t_{con} * V_{DC}}{2 * L_{arm}} \qquad (2)$$

where di_L is the current change at an inductance L_{arm} during the conduction time t_{con} within a switching period of a module, under an applied voltage V_{DC}. The effective switching period in the case of the output current can be twelve times lower than the individual switching period of each module due to the the interleaving effect of the MMC modules.

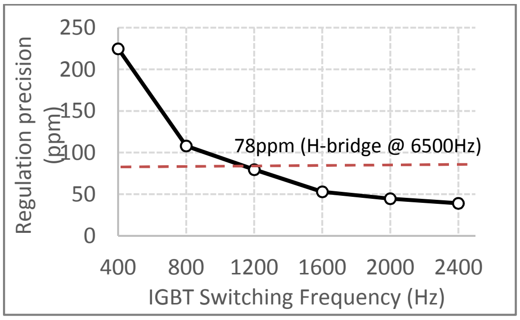

Figure 5: Regulation precision for different switching frequency levels.

Power Losses of Semiconductor Devices

The relation of the average total semiconductor losses per cycle as a function of the switching frequency per module appears in Fig.6. The power losses of a conventional 2-level (H-bridge) magnet supply switching at 6500Hz are also included and considered as a baseline for the design. The total power losses generated by the converter decrease rapidly as the switching frequency drops to as low as 400Hz which would be a typical frequency with a reasonable number of modules. It is remarkable that even with a switching frequency of 2400Hz per module, that corresponds to a precision of approximately 40ppm, the power losses are kept to almost 500W that is quite lower than the 831W of the H-bridge at a switching frequency of 6500Hz (1700V/1600A IGBT power module).

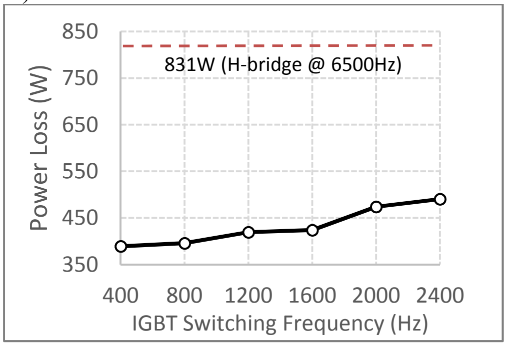

Figure 6: Semiconductor devices power losses for the MMC for different switching frequency levels

Figure 7 illustrates the distributed power losses per semiconductor type for an upper-arm module, as a function of the switching frequency. The switching frequency losses increase almost linearly with the switching frequency, but the greatest part of the losses is caused during the conduction. The reason is that the switching frequency is very low and does not have a high contribution to the losses. On the contrary, the increased number of switches in-series conducting the full arm current leads to the rise of the conduction losses.

Figure 8 shows the losses distribution for a lower-arm module and for a range of switching frequency levels. The greatest part of the losses comes from the diodes conduction losses. It is observed that the IGBT conduction losses of the lower-arm modules are decreased compared to the upper-arm modules in Fig. 7.

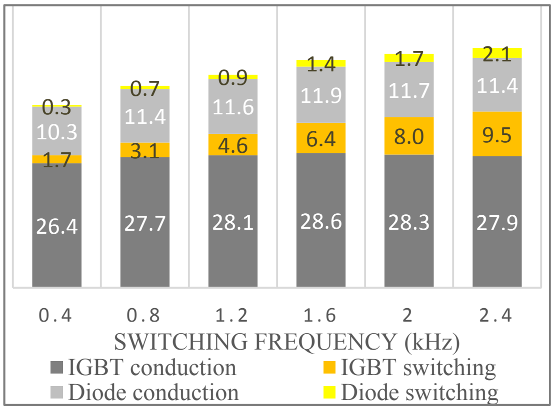

Figure 7: Switching and conduction power losses distributed per device type, i.e. IGBT and diode, for upper-arm module and for different switching frequency levels

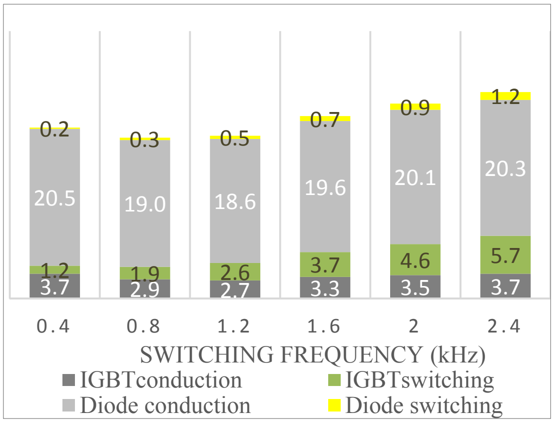

Figure 8: Switching and conduction power losses distributed per device type, i.e. IGBT and diode, for lower-arm module and for different switching frequency levels

CONCLUSIONS

This work demonstrated that generating a high precision output current for an accelerator electromagnet application is possible with an MMC based converter. Despite the remarkably low switching losses and the output precision, some concerns regarding the increased number of semiconductors and the control complexity are naturally raised. The system requirements such as total power and voltage level will eventually determine the potential (financial, technical) for replacing conventional high voltage semiconductor valves by MMC arms.

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