# Full-Bridge Modular Multilevel Converter for the Four-Quadrant Supply of High Power Magnets in Particle Accelerators


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## Keywords

≪Modular Multilevel Converters (MMC)≫, ≪Medium voltage converter≫, ≪Converter Control≫,≪Particle accelerators≫.



## Abstract

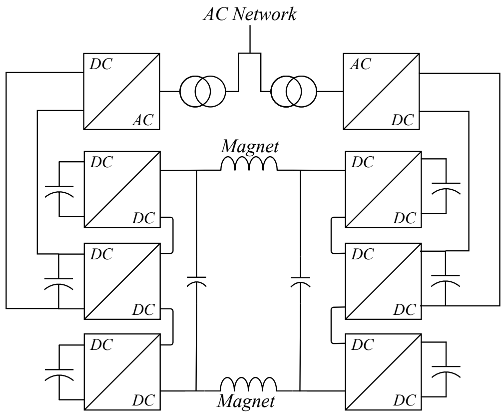
Many particle accelerators require to supply chains of magnets with high quality, high magnitude, cycling currents. To do this, the power converters need to provide high output voltages, reaching in some cases tens of kilovolts. Additionally, converters are required to store the magnet energy during de-magnitasion cycles. For such application, Full-bridge Modular Multilevel Converters (FB-MMC) could be used given their capacity to store energy, their inherent reliability and their good harmonic performance. This paper studies how this converter topology could be used for this application, proposing a method to recover and store the energy of the magnet using the converter submodules.


## Introduction

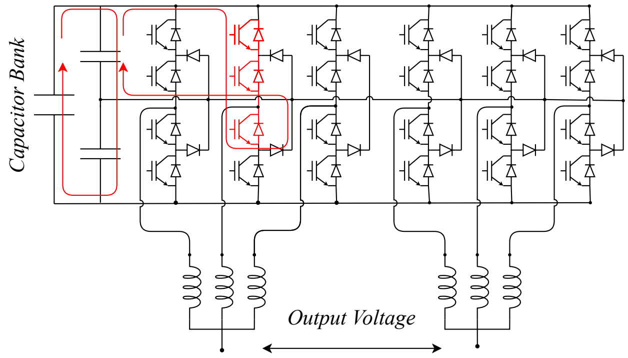
In particle accelerators, it is desired to precisely regulate the magnetic field generated by a set of magnets to control particle trajectories. However, the magnetic field is not always constant: it is small at the beginning of the cycle, when particles are injected into the machine, it increases during acceleration, remains constant during extraction and is brought back to the initial value at the end of the cycle. In some machines, this cycle happens every few seconds, leading to fast variations of the magnetic field and thus, of the current required to generate it.

In some machines, high currents, in the order of kA, are required for bending the trajectory of particles. This is the case of the CERN's Proton Synchrotron accelerator, where switch-mode power converters are used to supply the main dipole magnets [1]. This system generates high-quality pulses of current, up to 6 kA, every few seconds. To this avail, the converter must generate a voltage across the magnet of $\pm 10$ kV. In total, the system is dimensioned to handle an output power of 60 MW.

The design of such a powering system had to cope with several technical issues. The first concerns the rating of the semiconductors: the high current demanded by the application requires to connect several switches in parallel to form a basic commutation cell, which is then connected in series with others to meet the high voltage requirement. The second concerns the high power demand. Although the converters are connected to a strong distribution network, the large power fluctuations are enough to cause power quality issues. To avoid these quality issues, large DC capacitors banks are installed to store the magnetic energy and shave the peak power absorbed from the network.




(a) Simplified circuit diagram.




(b) A semiconductor failure can cause the discharge of the capacitor bank (red).

Fig. 1: Architecture of the powering system for the Proton Synchrotron at CERN [1].

The system described in [1], has been under operation since 2011, and constists of three-phase, three-level Neutral-Point Clamped converters as the basic switching cell. Two of these cells form a DC/DC converter, and there are six DC/DC converters connected in series with the magnets. To store the magnetic energy, each of the DC/DC converters is connected to a large capacitor bank. The losses on the converter and on the magnets are provided by two basic switching cells used as Active Front Ends, which are connected to two of the capacitor banks. To balance the rest of capacitors, a energy balancing strategy that distributes the energy is implemented. Fig. 1a shows the simplified circuit diagram of the system whereas Fig. 1b shows the diagram of one of the DC/DC converters.

One of the main disadvantages of this system is the lack of modularity. In particular, if a device fails, the affected DC/DC converter and, thus, the whole system needs to be stopped for repairing or moved to a degraded operation mode. Moreover, if the device fails into a short-circuit, then there is risk that a significant part of the stored energy discharges through the faulty converter leg (see Fig. 1b). Considering the large size of the capacitor banks, such a failure could cause considerable damage to the equipment concerned, leading to a long unavailability period. Another disadvantage concerns the high ratings required for the semiconductors. Since the commercial availability of high-voltage, high-current components is limited, there is little room for the optimization of the switching cells.

Therefore, in the framework of the studies for the construction of a new accelerator at CERN [2], this paper proposes to use Modular Multilevel Converters based on Full-Bridge submodules [3] (FB-MMC) as an alternative to the existing technology when high output voltages and energy storage are required. A system based on the FB-MMC can achieve high output voltages employing conventional low voltage semiconductors, allowing a better optimization of the converter. Besides, reliability can be significantly improved since the high modularity of the MMC allows to bypass a cell in case of failure without significantly impacting the operation of the converter [4]. Additionally, by using the submodules to store the energy from the magnets, the safety of the system can be increased by reducing the energy that can be potentially discharged in the case of a fault, which would be only a fraction of the total, and whose damage would be limited to a single cell, easily replaceable. Besides these features, there are other well-known advantages of using MMCs, as their high efficiency [5] and their low harmonic distortion [6], which would allow to reduce the size and cost of the filters.

Accordingly, the following sections describe the implementation of a particle accelerator powering system using MMCs. It explains how the submodules need to be dimensioned to store the magnet energy and how the control needs to be modified to incorporate this new feature. Then, the concepts developed are validated by simulation.

## Magnet Powering System using Full-Bridge MMCs

The architecture of a magnet powering system based on Full-bridge MMCs is shown in Fig. 2. The system is composed of two conventional MMC AC/DC converters in back-to-back configuration, with the magnet chain, which is split in two, connected between the positive and negative terminals. To control the current, each one of the MMCs produces an output voltage across its terminals, which is similar to the one produced by the other converter but with opposite polarity. By doing this, the voltage that the stations need to produce is only half the voltage required by the magnets and the maximum voltage to ground the magnets see is significantly reduced (to one quarter of the total voltage in this case).

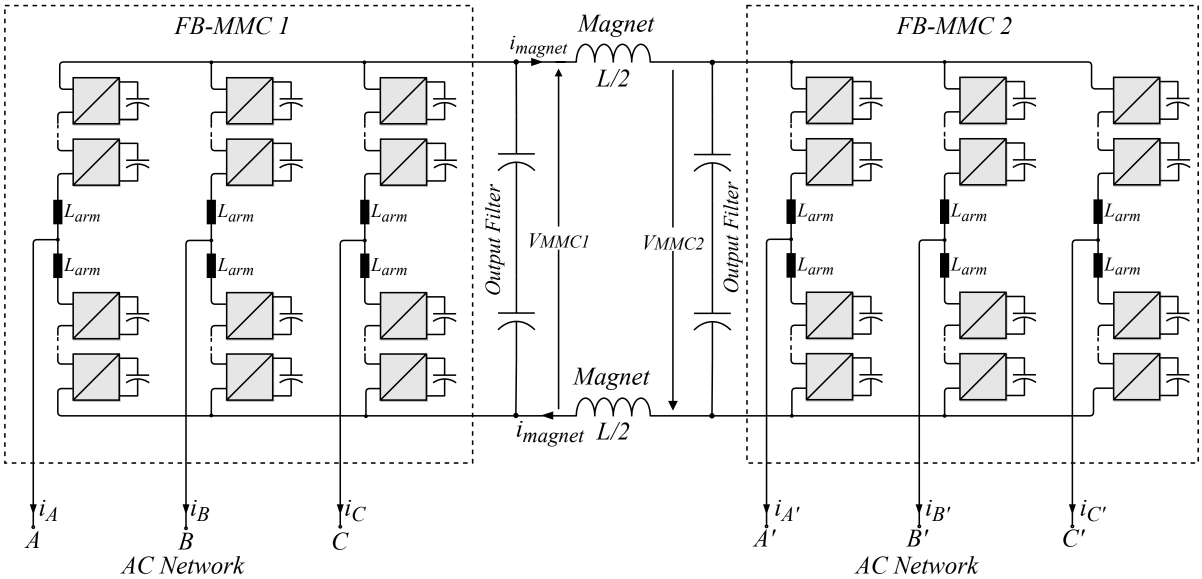



Fig. 2: Diagram of the proposed magnet power supply system based on Full-Bridge Modular Multilevel Converters.

A significant difference with the system described in [1] is that there are not dedicated converters working as Active Front Ends. Instead, the MMCs allow to manage directly the connection to the AC network while keeping the control of the output current and voltage [7]. On the other hand, contrary to conventional back-to-back systems, where power flows from one converter's network to the other [8], this application requires that both converters absorb power from the AC network. Absorbed power, which is a fraction of the total, is used to cover only the system losses. The energy required to create the magnetic field in the magnets comes exclusively from the MMC submodule capacitors. Therefore, and contrary to what happens in typical MMC applications, the voltages of the submodules are subjected to large voltage swings during the ramp-up and ramp-down of the magnets.

For this application, the large capacitor banks are replaced by a distributed storage using the MMC submodules. Converter design for this application requires a compromise between the number of submodules, their maximum and minimum voltages and the selection of the capacitors. Given the amount of energy to store, the converters must be able to generate the peak output voltage at the end of the ramp-up, where the charge, and thus the voltage of the submodule is minimal. On the other hand, a compromise between modularity and submodule voltage needs to be found: a high submodule voltage allows to reduce the number of semiconductors but requires higher ratings for IGBTs and would result in a poorer harmonic performance. Conversely, a high number of submodules would add extra complexity to the system and would result in excessive losses.

For the system under consideration, the converters must be able to generate an output voltage of 5 kV at the end of the ramp-up period. A rated submodule voltage of 1.2 kV offers a good compromise between number of cells and component availability. In fact, many commercially available MMCs employ similar voltages [9]. Finally, the total energy to be stored is 14 MJ, split between the two converters. With this

Table I: Main System Parameters

| Parameter | Value |
|---|---|
| Rated DC voltage | $\pm$5 kV |
| Rated AC voltage | 2.6 kV |
| Number of Submodules | 8 FB |
| Submodule Capacitance | 0.29 F |
| Rated submodule voltage | 1.2 kV |
| Minimum Submodule Voltage | 0.625 kV |

data, eight submodules per arm are selected, which results in a minimum submodule voltage of 625 V at the end of the ramp-up transient, enough to produce the 5 kV required by the magnets. A submodule capacitance of 0.29 F guarantees that the voltage does not drop below this value. Using these values, the rest of the converter parameters can be determined using some of the methods found in literature. Table I summarizes the main parameters of the converters.

## Converter Control

The final objective of the MMCs is the accurate control of the magnet current while managing the energy balance between the magnets and the internal storage. To control the converter, several cascaded loops are required. At the highest level, there is a current regulator, where the measured current is compared with the reference given by the accelerator operators to generate the voltage references for the converters. The required magnet voltage, $V_{magnet}$*, is divided by two and sent to the converters with opposite signs. The individual references, ($V_{MMC1}$* $V_{MMC2}$*), are passed directly to the low level control to generate the DC components of the arm voltages.

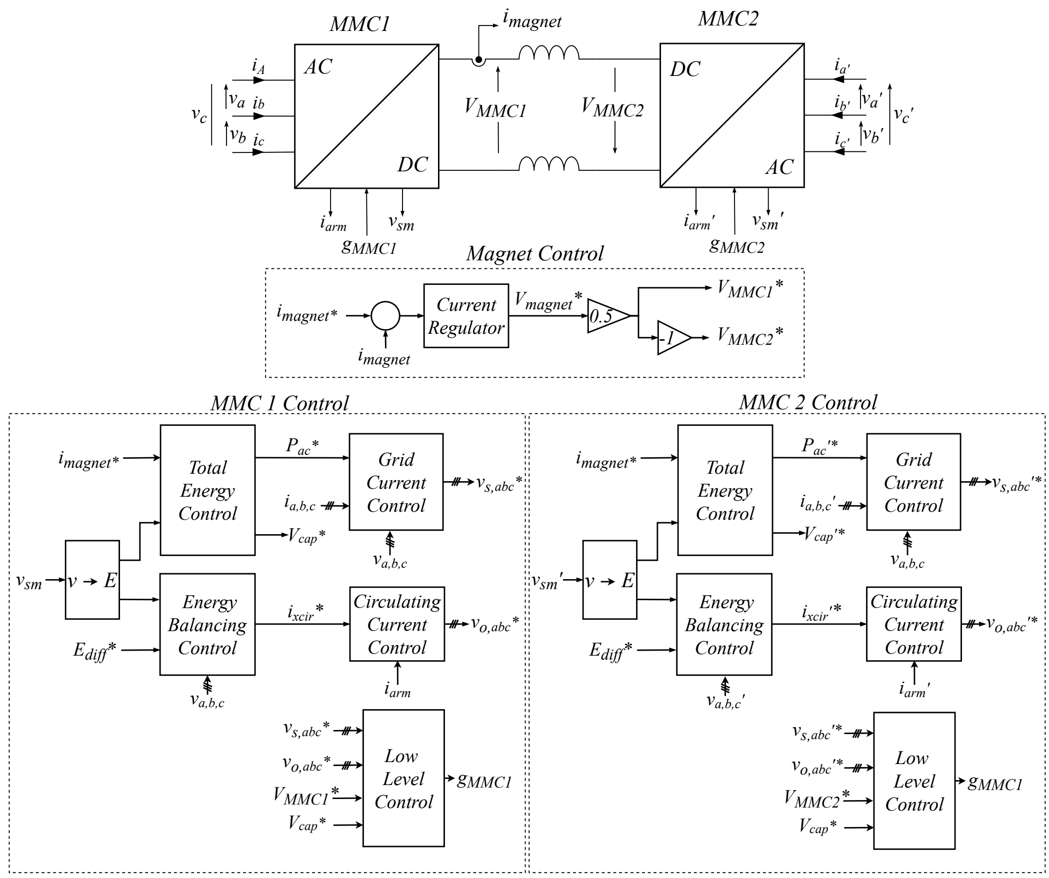



Fig. 3: Simplified diagram of the control of the system.

As previously explained, the control must ensure that the converter only absorbs from the AC grid the active power required to cover the converter and magnet losses. Hence, the magnetic energy needs to be provided exclusively from the submodule capacitors and has to be recovered at the end of each acceleration cycle. The relation between the converter energy ($E$), the AC ($P_{AC}$) and DC ($P_{DC}$) powers is:

$$\frac{dE}{dt} = P_{\text{in}} - P_{\text{out}} = P_{\text{AC}} - P_{\text{DC}} \tag{1}$$

where $P_{\text{out}}$ is the power demanded by the magnets and $P_{\text{in}}$ the power required form the AC grid to keep the MMC energy at its reference value. For the MMC energy control, $P_{\text{DC}}$ can be considered as a disturbance and the MMC energy is controlled by means of $P_{\text{AC}}$. Neglecting losses, if the power imported from the ac grid is zero, the magnet power have to be obtained from the MMC (cell capacitors) at the expense of reducing their stored energy.

$$\frac{dE}{dt} = -P_{\text{DC}} \tag{2}$$

Therefore, in order to fed the magnets using the MMCs energy, the stored energy needs to be modify according to the magnet energization and de-energization cycle, that is, the cell capacitor voltages have to be reduced as the magnets current increases and vice versa. For this purpose, the following relation between the magnets and the MMC energy can be written:

$$\frac{1}{2} \cdot L \cdot i_{\text{magnet}}(t)^2 = \frac{1}{2} \cdot 6 \cdot C \cdot N \cdot ({V_{\text{o,cap}}}^2 - V_{\text{cap}}(t)^2) \tag{3}$$

where $L$ is the magnet inductance, $C$ is the submodule capacitance, $N$ is the number of cells per arm, $V_{o,cap}$ is the initial capacitor voltage, $i_{magnet}(t)$ is the instantaneous magnet current and $V_{cap}(t)$ is the instantaneous cell capacitor voltage. Given that the magnets inductance and current waveform are known, the following cell voltage reference can be defined:

$$V_{\text{cap}}(t) = \sqrt{{V_{\text{o,cap}}}^2 - \frac{L}{6 \cdot C \cdot N} \cdot i_{\text{magnet}}(t)^2} \tag{4}$$

Using (4), the desired trajectory for the total energy of the MMC is constructed. Since the capacitor voltage measurements are available, it is possible to obtain the instantaneous energy stored by the converter and to compare it with the desired trajectory. The error is passed to the total energy controller, which regulates the power that needs to be absorbed by setting the d-axis AC current reference.

Horizontal and vertical balancing of leg and arm energies is achieved by controlling the circulating currents flowing through the arms. The horizontal balancing, or the difference between the legs energies, is controlled by setting a DC component on the circulating current reference. On the other hand, vertical balancing, or the difference between the upper and lower arms energy, is controlled by injecting AC components to the circulating currents. These components are of positive sequence to balance the common energy differences between upper an lower arms and of negative sequence to balance the differential energy differences between them. The current references generated by the three energy balancing controllers are passed to the circulating current control, which ensures their proper tracking by means of proportional-resonant regulators.

Finally, for the generation of the switching signals, a phase-shifted PWM modulation strategy is used considering the low number of submodules employed. To guarantee the individual balancing of the submodules, additional components are added to the modulation signal sent to each submodule to modify the connection/disconnection times and, subsequently, the charge of the capacitor. Additionally, the phase-shifts between the legs and arms PWMs are selected to maximize the harmonic performance of the converter. The simplified diagram of the control is shown in Fig. 3.

## Simulation Results

A simulation model of the system has been developed in MATLAB/Simulink to verify the proper behavior of the proposed strategy. The model consists of two Full-Bridge MMC converters connected as proposed across a magnet chain of inductance L=0.9 H and resistance R=0.16 Ohms.The models for the converters include a detailed representation of the submodules, which allows to verify the proper behaviour of the balancing loops and the low-level controller. The modulation strategy used is the phase-shifted PWM, with a carrier frequency of Fc=250 Hz. To filter the output voltage ripple, second order output filter formed by the arm reactors and an output capacitor is added to the output terminals of the two stations. On the AC side, the converters are supplied by two wye/delta transformers with the delta on the secondary to allow the injection of third order harmonics. The supply voltage is 2.6 kV. The rest of parameters are collected in Table I.

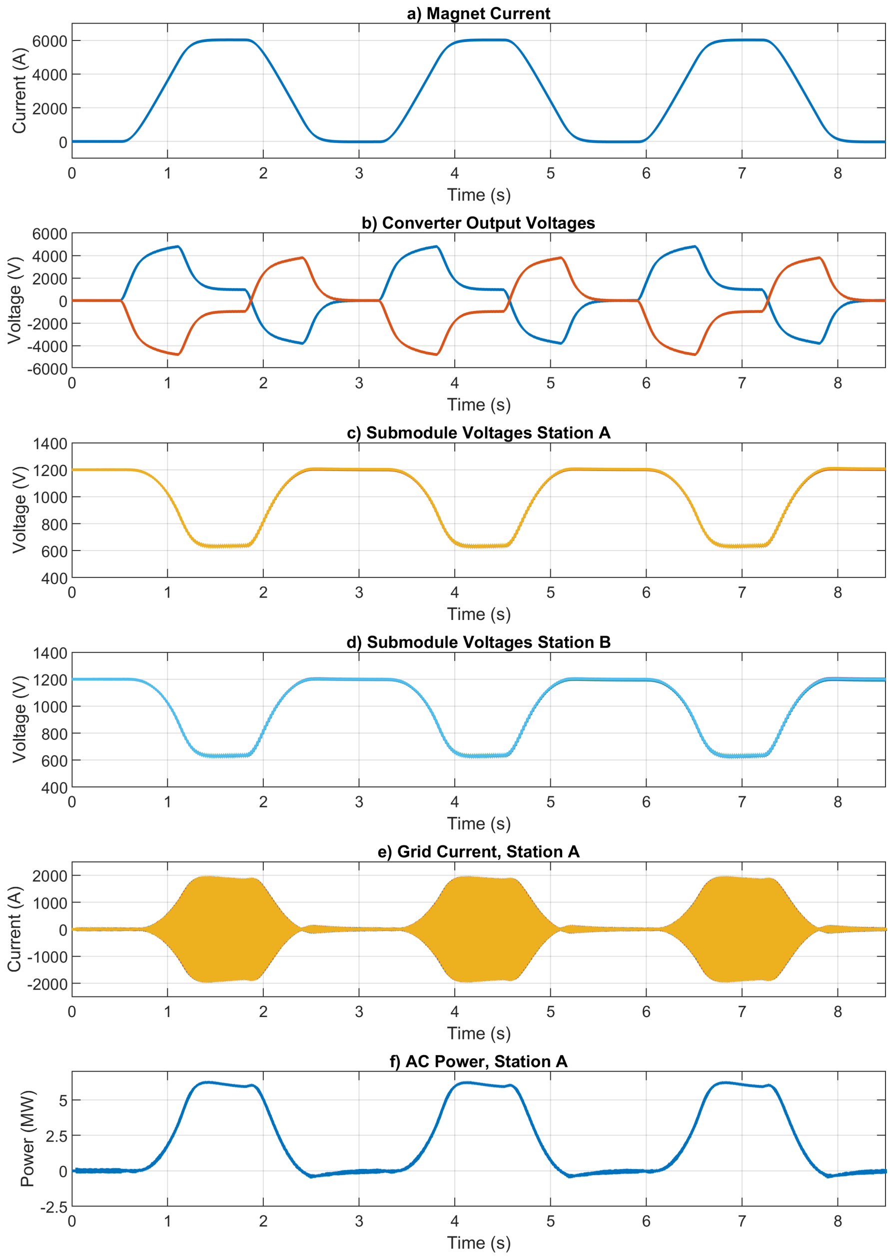



Fig. 4: Main operation curves of the power converter. a) Magnet current. b) Converter output voltages. c) Submodule Voltages of station 1. d) Submodule Voltages of station 2. e) AC current absorbed by the converter 1. d) AC power absorbed by converter 1.

Fig. 4 shows the simulation results of the system supplying the magnets with trapezoidal currents. Fig 4a shows the current flowing through the magnets, which reaches 6000 Amps at the end of the acceleration cycle. To achieve the desired current increasing and decreasing rates, the converters apply voltages with opposite polarity (Fig 4b). The peak voltage is produced at the end of the ramp-up, where the drop across the magnet resistance and the voltage caused by the $L \cdot di/dt$ add up, reaching the expected peak value of 5 kV on both converter outputs. The discharge and charge of the submodule capacitors is shown in Fig 4c and Fig 4d, where a selection of several submodule capacitor voltages has been done for simplicity. The proper dimensioning of the submodule capacitors together with a suitable control action guarantees that these do not discharge below the 625 V, allowing the generation of the required output voltage at the end of the ramp-up. Since the submodule capacitance is high, the voltage fluctuations due to the connection/bypass of the cells are small, playing a little role for the dimensioning of the cells, which, as explained, is based mainly on the voltage generation capabilities of the converter. Additionally, these figures also show the proper behaviour of the individual capacitor balancing algorithm: no deviations between the submodule voltages are observed.

On the other hand, Fig 4e shows the current absorbed by one of the stations whereas Fig 4f shows the resulting power. As explained, the total energy balancing loop requires to absorb only the power dissipated by resistive elements. The proper behavior of the current loop allows to follow the current reference given by the total energy controller. As it can be seen, the burden on the AC network is significantly reduced: the power supplied to the magnets can reach values as high as 60 MW whereas the power absorbed from the AC network, summing the contribution of the two stations, remains below 13 MW.

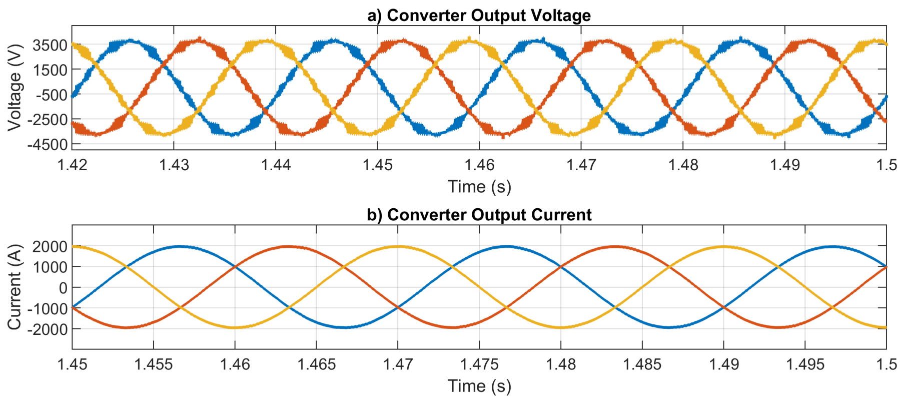



Fig. 5: Output MMC AC voltages and currents during current flat-top.

Finally, Fig. 5, shows the MMC AC voltages. During the flat-top, where the current is at its maximum level, the MMCs can synthesize high quality output waveforms with eight voltage levels. In this sense, the harmonic performance of the MMCs is better than that of the 3-Level converters used in [1]. Note that, during the phase of the cycle where the submodule capacitors are fully-charged, and thus fewer levels are used, the currents absorbed are small. Therefore, the impact on AC network quality is minimal.

## Discussion and Conclusion

This paper demonstrates the feasibility of using Full-Bridge MMCs for providing the pulsed currents required by the magnet chains of a particle accelerator. By using this converter topology, it is possible to shave the peak power absorbed from the AC grid by allowing the exchange of energy between magnets and the submodule capacitors. Compared with the existing solution, using MMCs would improve the reliability of the system by distributing the energy storage among a large number of cells. Besides, the high modularity of the solution would allow to bypass a faulty module, improving the availability of the machine. On the other hand, the lower voltage ratings required for the semiconductors would allow a better optimization of the cells and, thus, of the converter performance. In this sense, it has been showed that the MMC can obtain the required output current using a low switching frequency. However, the reduction of the switching frequency might not result in a reduction of the losses compared with the existing solution considering that more semiconductors are needed.

## Acknowledgements

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