

Per-Phase Controller for Medium Voltage Full-Bridge Modular Multilevel Converters

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Keywords: Modular Multilevel Converter, AC fault ride through, VSC-MVDC.

Abstract

This work proposes a per-phase control architecture for a full-bridge modular multilevel converter (FB-MMC) intended for medium voltage applications, such as MVDC multi-terminal distribution networks in off-shore wind farms or MVDC networks in industrial plants. The converter under study operates with 20kV on the DC side and is connected to an 11kV AC grid through a Δ -Y transformer. The response to a single line to ground (SLG) AC fault of the converter controlled with the proposed per-phase control architecture is compared with the conventional MMC using dq control. Simulation results in Matlab-Plecs prove that the proposed control approach has better response to a SLG fault compared with the conventional one, while maintaining a simple structure.

1 Introduction

MVDC is under consideration as an alternative to HVAC and HVDC to transfer power from offshore wind turbines to the mainland using multiple submarine DC cables and eliminating the need for expensive offshore platforms. MVDC has shown a good potential due to the reduced capital cost and the improved availability, even for transmission distances where typically HVDC is adopted [1]. It is expected that in the near future there will be a considerable development in wind turbine generation. Voltage Source Converters (VSCs) are the most commonly used types of converter for MVDC systems [2]. VSCs are better than the traditional Line Commutated Converters (LCCs) especially for offshore applications for the following reasons: VSCs do not require a strong AC system, they have smaller size compared to LCCs, and in order to reverse the power flow, in VSCs the current is reversed whereas in LCCs the direction of power flow depends on the polarity of the voltage, which increases the cost because of higher cable insulation requirements [3].

To reduce the losses of the converter, compared to 2-level VSC solutions [4], the use of Modular Multilevel Converter (MMC) became the preferred choice since 2010 [5].

In general, the advantages of a Modular Multilevel Converter over other VSC topologies are [6]:

- 1) High modularity and flexibility from low to high power rating.
- 2) High quality voltage waveforms with no need for filters.
- 3) Limited losses because of the low switching frequency of the cells.

- 4) High reliability and low maintenance required.
- 5) Robust system, low rate of change of currents during faults.

It is worth pointing out that 1) and 2) are the most relevant advantages with respect to LCC converters. Loss in a multilevel VSC are lower than the 2-level counterpart but larger than an LCC. Another advantage of the MMC is that the converter and the controller have higher flexibility when dealing with severe unbalance conditions like phase to ground fault. Several contributions in the literature have investigated the MMC control and operation under unbalance conditions [7]. One of the challenges regarding the MMC operation is the ability to remain connected to the grid after the AC fault, i.e. AC fault ride through capability [8]. AC faults can have serious impact on the networks, because of the large voltage transients involved [9]. Moreover, if the converter is not capable of AC fault ride through, the active power of the DC network will not be balanced by the AC side during a fault, and this can cause the network to collapse [10].

The MMC could be built with half-bridge cells or full-bridge cells. The optimal choice between half and full bridges depends on reliability, security, and the economic factor. The motivation for using the full-bridge connection is the fault blocking capability when dealing with DC faults [11]. The drawbacks of a full-bridge solution are the higher cost and the higher loss due to the increase number of devices. However, the benefits in terms of DC fault blocking capability can, in some applications, compensate for the additional complexity. For the sake of generality, this paper considers a full-bridge MMC as case study. However, the proposed per-phase control concept can be directly applied also to a half-bridge MMC or to a hybrid cell arrangement.

2 MMC operation principle

The Modular Multilevel Converter (MMC) topology is based on the series connection of cells, called submodules. Each submodule has a capacitor, representing the distributed energy storage of the converter. If the capacitor voltages are controlled, each chain of submodules can generate a controllable voltage, referred to as arm voltage. In each of the three phases of the converter, two arms, an upper arm and a lower arm, are connected together through two arm inductors. With a large number of submodules, the MMC can generate a staircase voltage similar to a sinusoidal waveform and therefore it minimises voltage harmonic distortion, which is one of the major advantages of this topology, which can be connected to the AC grid without bulky AC filters typical of 2-level VSCs or LCCs.

As discussed above, to control the output voltage, the voltages of the submodule capacitors have to be controlled to ensure that all store the same energy. Consider an MMC with number of submodules per arm equal to N . Each submodule could be a half-bridge or full-bridge cell. Assume that each submodule capacitor acts as a voltage source or energy buffer. Under these assumptions, the voltage generated by each arm – and therefore the AC and the DC voltages of the converter – can be controlled by employing a multilevel modulation technique, e.g. staircase, PD (Phase Disposition), PS (Phase Shift) etc. [12]. In this paper, the gate signals for the submodules have been generated using a Phase Shifted Carrier modulation (PSC-PWM). By controlling the switches, the number of submodules to be inserted or bypassed during each sampling period can be decided making sure that 1) the voltage across the capacitors are balanced and 2) the desired sinusoidal voltage is generated by each phase of the converter. The number of output voltage steps depends on the number of series connected submodules in each arm [13].

As mentioned before, a PSC-PWM technique is used for generating the switching signal to the full-bridge submodules and the number of triangular carriers for each arm is equal to $2N$, where N is the number of the submodules in each arm. Each submodule has two modulation signals phase shifted by 180 degree one for each of the two half-bridge legs. The switching pulses of each submodule are generated by comparing the triangular carrier wave with the modulation signals. To achieve a staircase multilevel output waveform, the phase shift between the carriers should be equal to $(\pi/2N)$ [4]. The capacitors voltage balancing is achieved using a sorting algorithm based on the direction of the current of the arm. For example, if the current is charging the inserted capacitors then the sorting will be ascending, i.e. the capacitors with the lower energy will be inserted first. Instead, if the current has opposite sign the sorting will be descending. Fig. 1 presents the block diagram of this algorithm, which makes sure none of the submodules capacitors will discharge to zero or overcharge. This enables correct operation of the converter that can control output AC and DC voltages at the reference value.

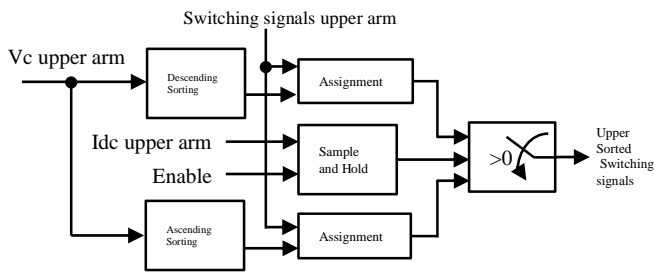


Fig. 1 Capacitors Sorting Algorithm

Another approach to balance the submodules voltages is by adding a balancing component to the modulation index of each submodule [14]. This algorithm has the disadvantages of generating harmonics in the output voltage and of increasing the complexity of the control architecture.

3 Control structure of MMC

To explain the basic principles of MMC control, the simplified model in Fig.2, can be used. If the total energy of the arm is E_{tot} , where N is the number of submodules for each arm and E_c is the energy of each submodule, then $E_{tot}=E_c*N$. If the ripple across is capacitor is small, a basic approximation is to consider the capacitors as DC voltage sources, and the arm as a controllable voltage source. The cell capacitor size must be calculated based on the desired voltage ripple.

The DC component in the circulating current i_{circ} multiplies with the DC link voltage v_{DC} to balance the power delivered to the AC side with the losses across the arm inductor and the submodules. The function of the arm inductor is to reduce the transients in the circulated and fault currents.

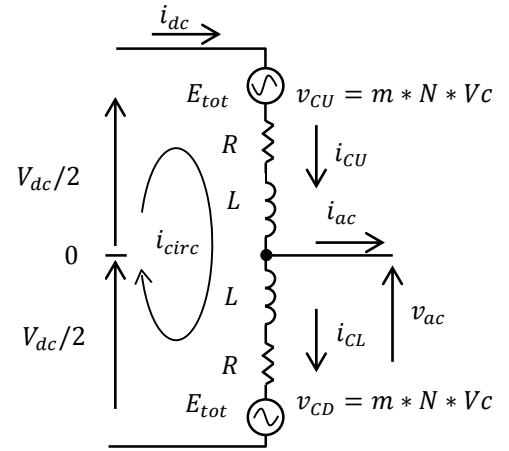


Fig.2 MMC Equivalent Circuit – 1 phase.

A standard vector control structure is used in this study. The control structure is based on proportional-integral (PI) regulators. The active power PI regulator is responsible for the generation of the desired direct current component (I_d), while the AC voltage PI regulator generates the quadrature current reference (I_q). The two PI current controllers (I_d and I_q) are used to generate the modulating signals for the Pulse Width Modulation (PWM) as shown in Fig.3. For the conventional MMC, a standard three-phase PLL can be used to create the synchronization angle (θ) which is used to transform between the stationary and rotating reference frames [6].

If the standard three phase vector control is used for a grid connected MMC, it requires in general three controllers for the positive, negative and zero sequence to enable operation during unbalanced conditions. This study proposes a different way of dealing with unbalanced conditions and faults, by implementing three independent per-phase controllers so that decomposition and control of the sequence components is not needed. One of the difficulties in designing a controller for single phase of the MMC is the lack of natural rotating frame. While for conventional three phase systems it is easy to generate the phase angle, frequency and the amplitude from the Phase Lock Loop (PLL) to transform from the stationary frame to the rotating one, for single phase systems a fictitious three phase system must be recreated to perform the transformation. The rationale for this is that when designing a new control

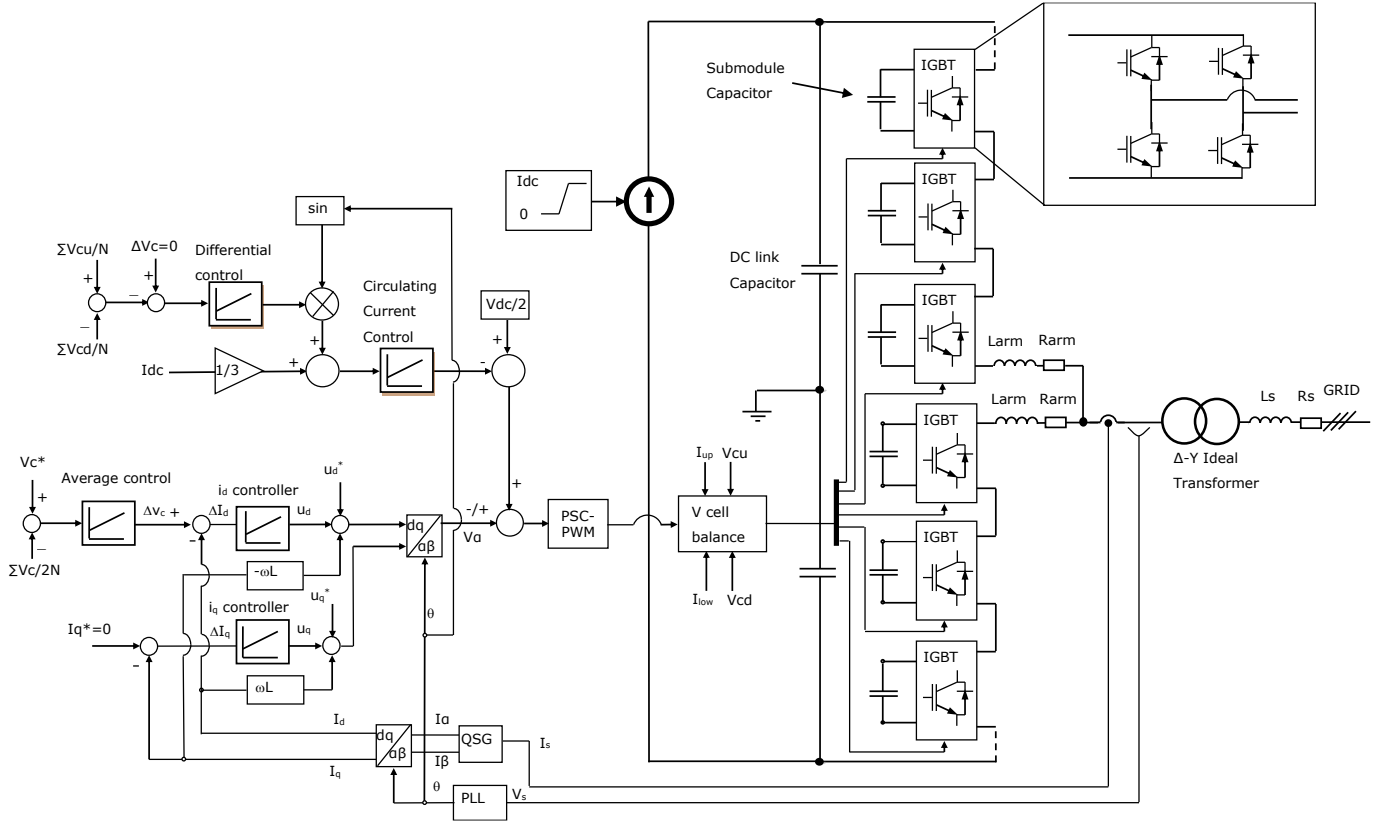


Fig. 3. Overall Control Structure for each phase of MMC.

architecture based on per-phase controllers, it would be desirable to be able to exploit the standard dq control structure, rather than changing the control to resonant solutions that, even if equivalent to the dq one in principle, have a more challenging implementation. In a single phase system, in order to emulate the behaviour of a three phase one, a quadrature axis should be first created by making a phase shift of 90 degrees of the phase voltage, thus building an α and β system. To do so, different methods can be used such as: Inverse Park, Hilbert Transformer, and Transport Delay. The operation of these methods is discussed and tested in [15]. Below are some of the methods used in this work:

- Transport Delay: using phase shift by 90° ($T/4$). This method has high sensitivity to frequency deviations and harmonic distortion since each frequency components is delayed by $1/4$ of the fundamental period.
- Inverse Park Transform: using Low Pass Filter LPF as in equation (1) to attenuate the oscillations resulting from the Direct Park transformation.

$$LPF = \frac{w_f}{S + w_f}, \text{ where } w_f = 2\pi * f_c \quad (1)$$

The inverse park transform method can be used to generate the quadrature axis from a single phase input signal by introducing a filter in a loop consisting of direct and inverse park transformation as shown in Fig.4.

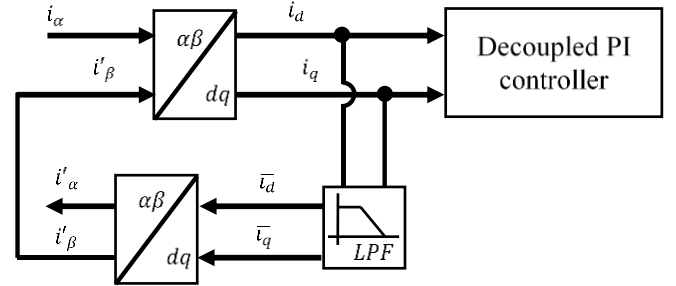


Fig.4 Inverse Park Transform Scheme.

The MMC control embodiment proposed in this paper provides an independent control for each phase and improves the converter operation during low impedance single line to ground (SLG) fault on the AC side, without the need for negative sequence controllers.

In this paper, the Inverse Park Transform (IPT) method has been used to generate an imaginary axis from the actual one, with a LPF to attenuate the oscillations resulting from the Direct Park transformation. This filter is introduced in a loop consisting of Direct and Inverse Park transformation. Fig.3 illustrates the proposed control structure for one of the three phases of MMC, and the quadrature axis generator is indicated as QSG. The other two phases have the same control structure.

3.1 AC side equations

The total energy stored in each arm should be controlled to the required reference value throughout the outer voltage control. From Fig.2, if the voltage across the arm inductor is negligible, the voltage across the upper arm can be represented by equation (2):

$$v_{CU} = \frac{1}{2}V_{DC} - m \sum_{x=1}^N V_{cx} \quad (2)$$

Where m is the modulation index. The voltage equations for upper and lower arm are:

$$V_{DC}/2 = v_{CU} + L \frac{di_{CU}}{dt} + Ri_{CU} + v_{ac} \quad (3)$$

$$V_{DC}/2 = v_{CL} + L \frac{di_{CL}}{dt} + Ri_{CL} - v_{ac} \quad (4)$$

Subtracting (4) from (3),

$$(v_{CL} - v_{CU}) - 2v_{ac} = L \left(\frac{di_{CU}}{dt} - \frac{di_{CL}}{dt} \right) + R(i_{CU} - i_{CL}) \quad (5)$$

Defining v_{diff} as:

$$v_{diff} = \frac{(v_{CU} - v_{CL})}{2} \quad (6)$$

and observing that:

$$i_{ac} = i_{CU} - i_{CL} \quad (7)$$

Substituting the two equations (6) and (7) into (5) gives,

$$v_{ac} = v_{diff} + \frac{L}{2} \left(\frac{di_{ac}}{dt} \right) + \frac{R}{2} (i_{ac}) \quad (8)$$

The above equation (8) shows that the AC current can be controlled by controlling v_{diff} [16].

3.2 DC side equations

As mentioned before in the analysis of the AC side, v_{diff} represents half of the difference between of the upper and lower arm voltages and is the AC side control variable. Instead, to write the DC side equation, the average voltage v_{avg} can be defined as:

$$v_{avg} = \frac{(v_{CU} + v_{CL})}{2} \quad (10)$$

Defining the circulating current i_{circ} as:

$$i_{circ} = \frac{(i_{CU} + i_{CL})}{2} \quad (11)$$

Adding equation (3) and (4) gives:

$$V_{DC} - (v_{CL} + v_{CU}) = L \left(\frac{di_{CU}}{dt} + \frac{di_{CL}}{dt} \right) + R(i_{CU} + i_{CL}) \quad (12)$$

And substituting equations (10) and (11) into (12), gives the final DC side equation:

$$V_{DC} = 2v_{avg} + 2L \left(\frac{di_{circ}}{dt} \right) + 2R(i_{circ}) \quad (13)$$

From equation (13), the circulating current can be controlled by controlling v_{avg} .

3.3 Total Phase Energy Control

The total capacitor energy in each phase is defined as:

$$\sum E_C = \sum E_{CU} + \sum E_{CL} \quad (14)$$

Where,

$$\frac{d\sum E_{CU}}{dt} = i_{CU} * v_{CU} \quad (15)$$

$$\frac{d\sum E_{CU}}{dt} = i_{CU} * \left(\frac{v_{DC}}{2} - v_{ac} - L \frac{di_{CU}}{dt} - Ri_{CU} \right)$$

$$\frac{d\sum E_{CL}}{dt} = i_{CL} * v_{CL} \quad (16)$$

$$\frac{d\sum E_{CL}}{dt} = i_{CL} * \left(\frac{v_{DC}}{2} + v_{ac} - L \frac{di_{CL}}{dt} - Ri_{CL} \right)$$

Substitute (15) and (16) into (14),

$$\frac{d\sum E_C}{dt} = V_{DC} i_{circ} - v_{ac} i_{ac} - \left(L \frac{d(i_{CU} + i_{CL})}{dt} + R(i_{CU} + i_{CL}) \right) \quad (17)$$

Equation (17) represents the total instantaneous power absorbed by the upper and lower arms. To guarantee controlled energy storage, in steady state the average value of (17) must be equal to zero. That is, if R is neglected for simplicity, the DC side power ($V_{DC} i_{circ}$) and the AC side average power $v_{ac} i_{ac}$ are equal. Therefore, to control the energy stored in the phase, there are two possible options: either the AC power is imposed and the DC power is used as control variable for the energy or the opposite [17]. In the case study in Fig. 3, the DC power is imposed by imposing the desired DC voltage and controlling the circulating current. Instead, the AC power reference is driven by the phase energy control.

3.4 Differential Energy Control in Each Phase

If an ideally symmetric converter is considered, controlling the total phase energy guarantees individual control of the upper and lower arm energies. In practical system, where asymmetries are present, upper and lower energies must be actively controlled. To this purpose, the energy unbalance between the upper and lower arm is defined as:

$$\Delta E_C = \sum E_{CU} - \sum E_{CL} \quad (18)$$

Assuming that the converter is operating in a condition where the two energies are different, i.e. $\Delta E_C \neq 0$, the only way of rebalancing the arms is to identify a control variable that provides an average power contribution that is equal and opposite in upper and lower arm, so that the energy difference can be driven to zero without affecting the total energy stored in the phase. This can be achieved by observing that upper and lower arms have equal and opposite AC voltages, but the circulating current has the same direction. Thus, by adding to the circulating current reference an AC component in phase with the AC voltages and controlling its amplitude with the differential energy controller, the desired balancing effect can be achieved, as shown in Fig. 3 [18].

3 Simulation results

The three phase with independent control for each phase shown in Fig.3 has been tested for an AC single phase to ground fault SLG on the grid side with a fault resistance equal to 0.1Ω at 1sec., to verify the performance of the model. One of the two terminals of the DC transmission line replaced by a DC current source for simplicity and faster running simulation using PLECS.

The MMC is responsible for controlling the active and reactive power and has the ability to work as a rectifier/inverter, so it can control the power flow and regulate the DC link voltage with a Δ -Y transformer used on the AC side.

In a conventional MMC control system, during unbalance conditions the reference voltage normally contains positive, negative and zero sequence components (depending on the structure of the transformer), and additional controllers for the different sequences are needed. This can be achieved also by controlling each phase independently to inherently include the effect of the sequence components. It can be seen from the simulation results in Fig. 5 that in the conventional three phase positive sequence controller, the current is distorted with a dominant third harmonic component, while for the proposed MMC controller in Fig.6 the three phase AC current waveforms are not distorted during the fault. Fig.7 (a) and (b) show the FFT of the three phase current for the proposed control and the conventional one (positive sequence only) respectively.

From the simulation, it is clear that the proposed MMC control can ride through the fault without the need for additional sequence controllers, thus providing a simple control architecture that is effective under unbalanced and faulty AC networks.

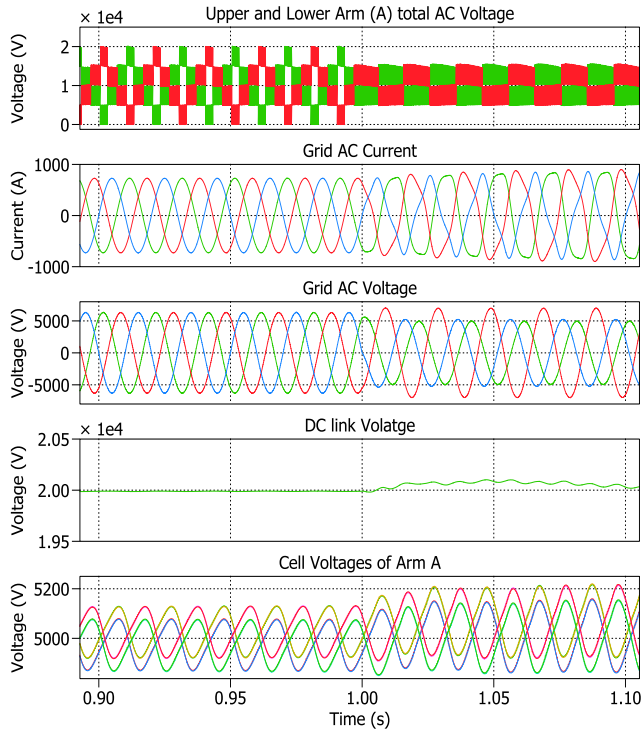


Fig.5 Conventional MMC operation before and after the SLG fault at 1sec.

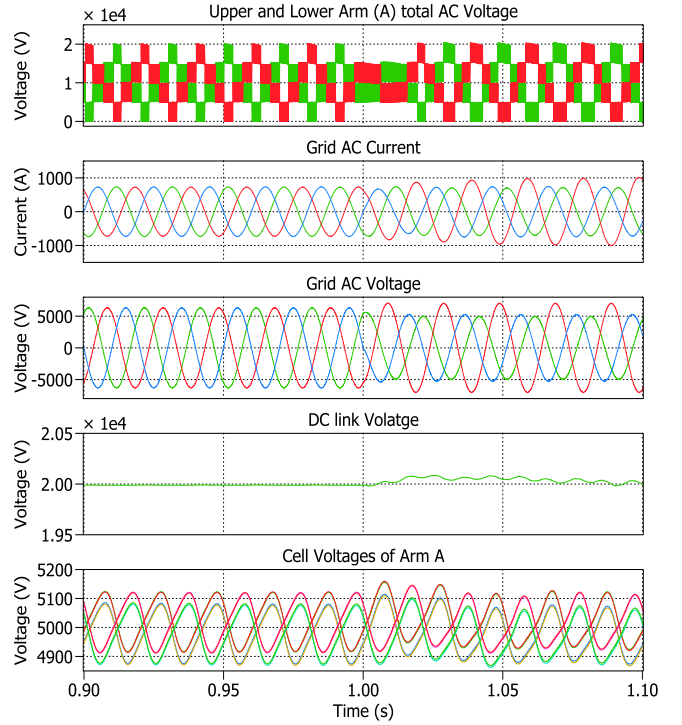


Fig.6 Proposed MMC operation before and after the SLG fault at 1sec.

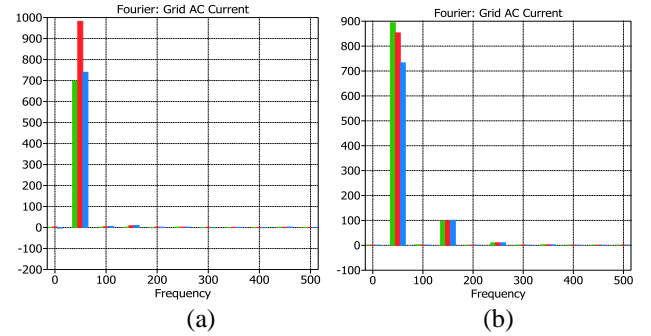


Fig.7 FFT analysis of the three phase AC current after the fault for (a) Proposed MMC. (b) Conventional MMC.

Table 1. Shows the parameters used in this MMC model with the medium line pi section transmission line model.

Table 1. Parameters of the MMC used for the simulation.

| MMC converter | |
|----------------------------------|--------------------|
| Number of Full Bridge submodules | 4 |
| Submodule capacitor voltage | 5 kV |
| Arm Inductance | 25 mH |
| Arm Resistance | 25 m Ω |
| Switching frequency | 1.2 kHz |
| Submodule capacitor | 5 mF |
| Grid side Parameters | |
| Source Inductance | 0.5 mH |
| Source Resistance | 0.5 m Ω |
| MVDC transmission line | |
| Line inductance | 0.24 mH/Km |
| Line resistance | 0.042 Ω /Km |
| Line capacitance | 0.045 μ F/Km |

4 Conclusion

The proposed control arrangement is characterised by simple implementation, using the same design for each individual phase controller and thus turning also the control system into a modular structure, whose hardware and software can be optimised. Instead, to deal with asymmetrical disturbances such as the SLG fault, the conventional three phase controller needs additional controllers for the negative sequence current to improve the performance of the converter during the asymmetrical disturbance, thus increasing the complexity of the algorithm. Simulation results show that the proposed per-phase control scheme can provide good performances during AC faults, providing high quality AC currents and maintaining the correct balancing of the submodules capacitors.

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