Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications

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Abstract — **For demanding future applications in power transmission – like grid connection of large off-shore wind parks, solar thermic power generation or power supply of mega cities – there is a global need for advanced power electronic systems. The novel concept of Modular Multilevel Converter (M2C) offers superior characteristics for these applications. Its operations for HVDC-systems is explained and investigated with respect to new requirements – including failure management in Multi-terminal-HVDC-Networks.**

Index Terms — **High Voltage Direct Current (HVDC) transmission, Modular Multilevel Converters, Voltage Source Converter (VSC).**

I. INTRODUCTION

Advanced Voltage Source Converters (VSC) are a key component of future HVDC-transmission systems [1], [2], [3]. While bulk power transmission remains to be well suitable for line commutated thyristor converters, the most important future application fields share demanding requirements, which are best met by self-commutated converters. Examples of these applications are the integration of large solar thermic- and wind farms into the grid, the upgrading of the power supply for mega cities and the stabilization of existing AC-networks.

Main requirements are fast and independent control of active and reactive power flow, operation without bulky passive filters, black start capability and the option of extending the DC-network to more than two stations (multi-terminal). Severe fault conditions and disturbances – including short circuits at the DC-side – must be managed fast and safely.

II. DRAWBACKS OF CONVENTIONAL VOLTAGE SOURCE CONVERTERS (VSC)

A Two Level Converter with a high number ($n > 100$) of direct series connected IGBT-devices represents a well known technical solution [1], [5].

Known Three-Level- or Multilevel Converters would enable a better reduction of unwanted line side harmonics, but need a very complex construction – hampering industrial series application and leading to a limited low number of voltage levels [4], [5]. Mainly because of the stringent industrial and economical needs for modular construction, conventional Multilevel Converters did not succeed in these demanding HV-applications. In addition, they share some very essential drawbacks with other known VSCs:

- The very high slope (di/dt) of the arm currents (i_a) generates unwanted EMI-disturbances and imposes severe constraints to the physical arrangement and construction of these large converters.
- The stored energy of the concentrated DC-capacitor (C_d) at the DC-Bus (P_0, N_0) results in extremely high surge currents and subsequent damage if short circuits at the DC-Bus cannot be excluded [4].

In addition to the required bulky passive filters at the AC-side and the high switching losses of the semiconductors [5], these are very essential drawbacks.

III. MODULAR MULTILEVEL CONVERTER

This new topology has been introduced in order to avoid the severe drawbacks of conventional VSC in HV-applications [3], [6], [7]. The whole converter (Fig. 1) consists of a freely chosen number of identical submodules (SM, Fig. 2). In principle a converter arm, which consists of n submodules, represents a controllable voltage source. Essentially, Fig. 1 represents a voltage source converter, which is able to control the AC-voltages (multilevel) and the DC-Bus-voltage (V_d) fast and simultaneously via the switching states of the submodules. In contrast to known VSCs (including the multilevel converters) the internal arm currents (i_a) feature low di/dt and can be controlled, too. At first glance, when being compared to conventional VSC or multilevel VSC, the new topology offers several features, which are quite different and seem strange. Therefore, the main points are summarized in the following [4], [5], [6]:

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- The internal arm currents are **not** chopped; they are flowing continuously. The arm currents can be controlled by the converter control. Half the AC-current is flowing in each arm (see Fig. 3).
- Protection chokes (L_a, Fig. 1) can be inserted into the arms. They do **not** disturb operation or generate overvoltage for the semiconductors (see first point). The protection chokes (L_a) limit the AC-current, whenever the DC-Bus is short circuited (fault condition).
- The submodules (SM) are **two terminal** devices. There is no need to supply the DC-side-storage-capacitor (C_0) with energy ⇒ **no** isolated, floating DC-supplies. This is true for real power or reactive power transmission of the converter in any direction or combination.
- Voltage balancing (of the submodules) is **not** critical with respect to the timing of the pulses or the semiconductor switching times. It is assured by the converter control on a noncritical, larger time scale [4], [6].
- The DC-link voltage of the converter (V_d, Fig. 1) can be controlled by the converter, too (Fast control via the switching states). **No DC-link capacitors** or filters are connected at the DC-Bus. The DC-Bus current (i_d) and voltage are smooth and can be controlled by the converter, dynamically.

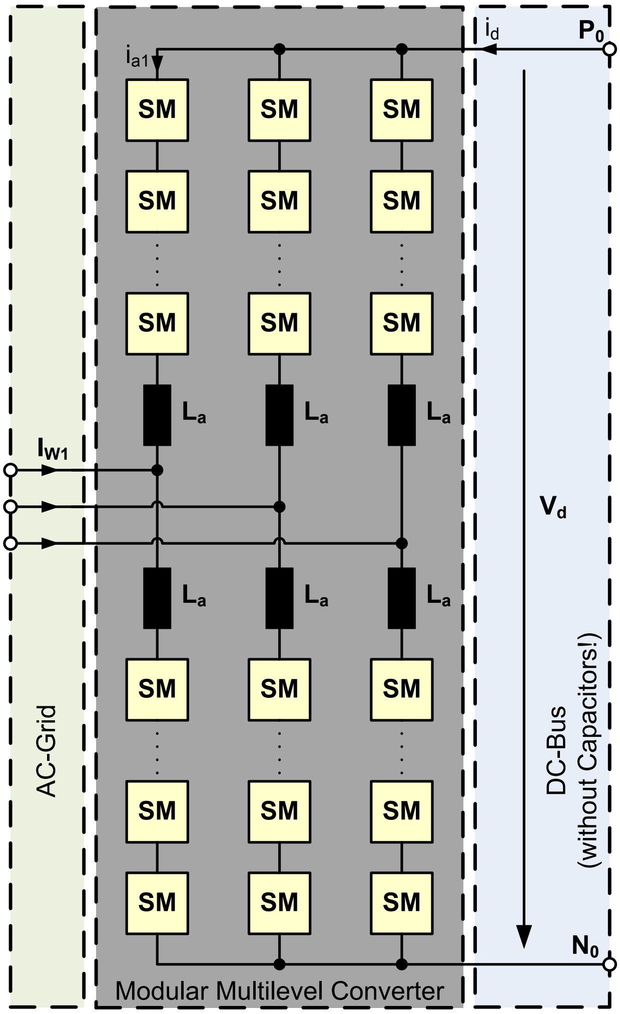

Fig. 1: HVDC-Station using Modular Multilevel Converter

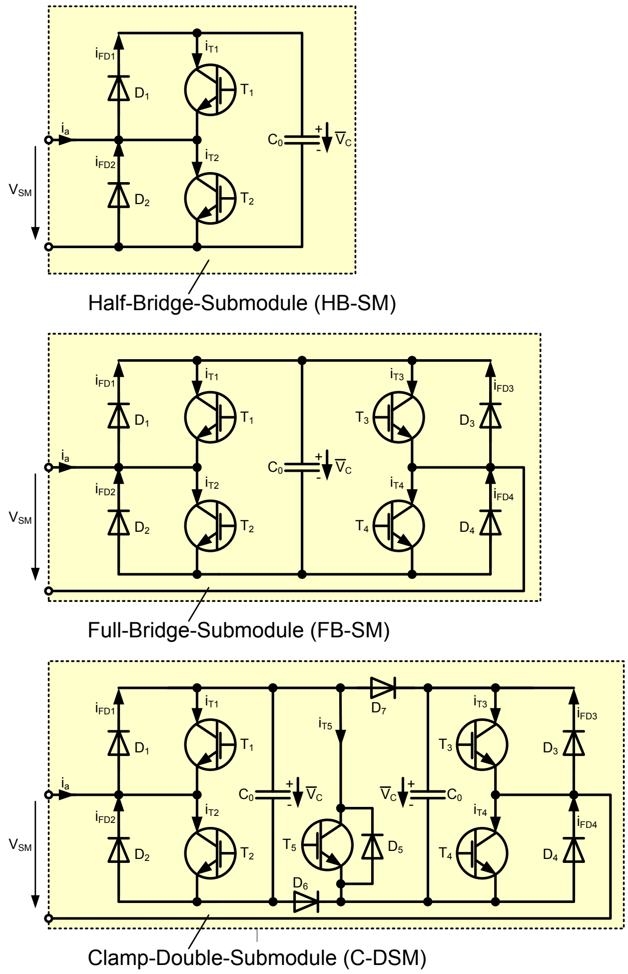

Fig. 2: Internal structure of appropriate submodules (SM)

IV. Dimensioning of the M2C-Converter

The power losses of a M2C-Converter compare in a favourable manner to conventional VSC. The main reason of this important advantage are the very low switching losses of the semiconductors [5], [6].

At first glance, the higher number of transistor functions – compared to the Two-Level Converter – seems to be a disadvantage. Taking into account the established status of control electronics, however, this point turns out to enable new valuable degrees of freedom of the converter control.

When comparing the expense for the power semiconductors and the power losses, the total required silicon chip area (not the number of transistor functions) for a given power rating of the converter has to be considered and kept constant.

In order to investigate these figures for the M2C, a few general parameters have to be defined (Eq.: (1) ... (3)):

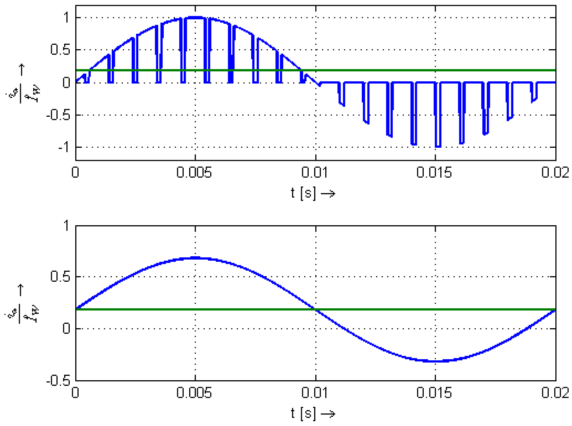

Fig. 3: Comparison of the arm currents of Two Level Converter and the M2C (lower plot)

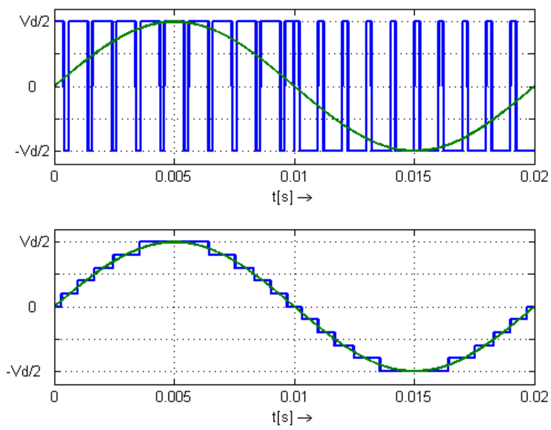

Fig. 4: Comparison of the AC-line voltages of the Two Level Converter and the M2C (lower plot)

The first parameter (m) describes the ratio of the AC-current ($|\bar{I}_W|$) to the DC-current ($\bar{I}_d$) in normalized form. Note that (m) has a sign (according to the sign of the DC-current ($\bar{I_d}$)). The next parameter (k) describes the relative amplitude of the AC-voltage controlled by the converter. ("modulation index") [2]. The third value (b) describes the relative amplitude of the DC-Bus-voltage (V_d) controlled by the converter. A typical nominal value of this "DC-side modulation index" is b = 0.5.

$$m = \frac{3 \cdot \pi \cdot |\bar{I}_W|}{4 \cdot \bar{I}_d}, \quad |m| > 2 \qquad (1)$$

$$k = 2/(m \cdot \cos\varphi), \quad 0 < k < 1 \qquad (2)$$

$$b = V_d/(2 \cdot n \cdot \bar{V}_C), \quad 0 < b < 1 \qquad (3)$$

Knowing these parameters, it becomes possible to compute all the relevant semiconductor currents in a submodule and the resulting on state losses (See [5]). All submodules are loaded equally, if the real power flow is divided equally between the three converter phases and the voltage distribution is balanced. These conditions are fulfilled by appropriate control of the converter [6]. In consequence, a DC-current component of ($I_d/3$) plus an AC-current component of ($I_{W1}/2$) is flowing in each converter arm under steady state conditions (see Fig. 3).

V. Power Losses of the Converter

Table 1 displays the semiconductor data. The data is based on typ. 4.5kV-devices. In order to assure an equal size of total chip area for a Two-Level Converter, the chips (T_1, D_1) and (T_2, D_2) of the M2C would have to be paralleled for the Two-Level Converter.

A significant advantage of the M2C is given by the fact, that well proven and high volume series semiconductors can be used. The pulse frequency of the semiconductors is typically $f_P = 3 \cdot f_1 = 150$Hz which is fully sufficient owing to the extremely fine steps of the multi level waveform. A Two-Level Converter would require at least a 10 to 15 times higher pulse frequency – in order to enable a reasonable compromise regarding the size and the losses of the passive filters at the AC-side. This fact is the main reason for the significantly lower losses of the Modular Multilevel Converter.

The chosen DC-voltage of V_d = 300kV results in a submodule voltage of V_C = 2.4kV. This incorporates enough margin for redundant operation with 5% of failed submodules per arm.

VI. Multi-terminal-HVDC-Networks

There is strong evidence, that the new requirements for

TABLE 1
Typical Power Semiconductor Data

		U_F [V]	r_T [mΩ]	W_{on} 1) [Ws]	W_{off} 1) [Ws]	W_{rec} 1) [Ws]	R_{thjc} [k/kW]
← M2C →	**T1**	**1.8**	**2.4**	**4.0**	**2.7**	**--**	**13.5**
	T_2	**1.8**	**1.6**	**4.0**	**2.7**	**--**	**9.0**
	D_1	**1.8**	**3.0**	**--**	**--**	**0.5**	**27**
	D_2	**1.8**	**2.0**	**--**	**--**	**0.5**	**18**

1) (Switching loss energy at V_{ref}= 2.25 kV, I_{ref}= 0.9kA)

extended HVDC-transmission will result in multi-terminal HVDC-Networks. In conjunction with the shift in power generation from fossil fuels to solar and windpower, power transmission in very large and extended HVDC-Networks will be the key enabling technology.

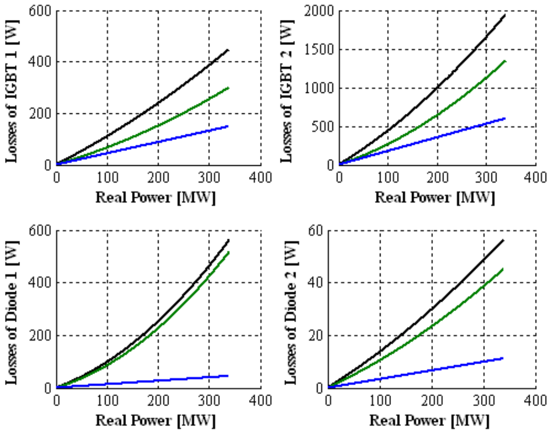

Fig. 5: Losses of the M2C-Semiconductors (cos φ = 0.88)

- **Black line: Total Losses**
- **Blue line: Switching Losses**
- **Green line: On State Losses**

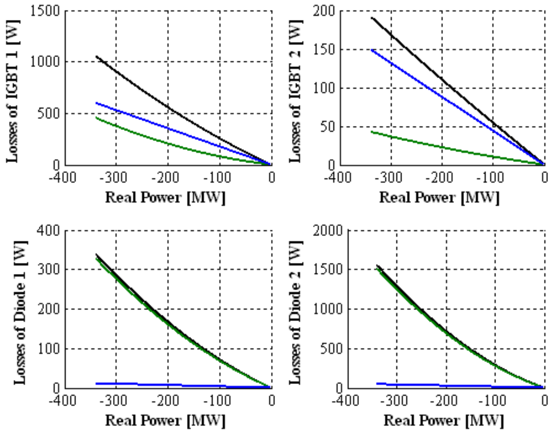

Fig. 6: Losses of the M2C-Semiconductors (cos φ = -0.88)

- **Black line: Total Losses**
- **Blue line: Switching Losses**
- **Green line: On State Losses**

With respect to failure management, no appropriate technical regulations or complete standards are existing up to now for these large DC-Networks. Therefore, some essential aspects – which are of major influence on converter design – shall be discussed in the following. The investigations will focus on management of DC-short circuits, because this represents a key point, see Fig. 7.

When a DC-failure occurs in any branch of the DC-Networks, power transmission in all associated stations and AC-grids is no more feasible. Therefore, the faulty branch must be disconnected from the DC-Network in order to continue power transmission in the other branches, at least. It is very desirable to affect the other AC-Networks and stations as little as possible and to restart power transmission in the other branches as quickly as possible.

For the purpose of disconnecting the faulty branch, the following means are possible:

1. Limiting the DC-fault currents by the arms reactors of the M2C (plus the AC-reactors) and turning off all AC-switches.
2. Limiting the DC-fault currents by fast acting DC-switches (mechanical or semiconductors switches).
3. Limiting the DC-fault currents by the (fast action) of the M2C-Converters, electronically.

The first method is now "state of the art" in the first industrial applications [6]. It works well and reliable, because – in contrast to conventional VSC – there is no surge current from discharging of capacitors and the arm reactors can be sized in a useful manner. Main drawbacks are the long switching times of the AC-switch gear and the consequence, that all the AC-switches of all stations have to be tripped. Finally, mechanical disconnect switches have to isolate the faulty branch.

The second method seems to be preferable at the first glance, but – owing to basic physical reasons – the DC-switches would be very hard to realize. They do need forced arc extinction and very high energy absorption. It is reasonable to assume, that their switching times are similar to the AC-switch gears, at least. In consequence, no advantage – compared to the first method – would result.

Electronic switches – as an alternative realization – could realize the desirable switching times below 1ms. In such a time span, the AC-sides can remain almost unaffected and the AC-switch gears must not be tripped. This is very desirable, because solely the faulty branch would require a longer interruption time (deionization, testing,…). Unfortunately, the expense and the drawbacks of appropriate electronic DC-switches are quite considerable. They must be designed for safe voltage blocking using numerous series connected devices, water cooling of the considerable on state losses and high energy absorption at turn off [6]. In conjunction with the mechanical construction and associated control electronics its expense comes close to one half of a complete converter station. From an economical point of view, the added on state losses in normal operation, represent a severe disadvantage, too.

VII. FAULT CURRENT INTERRUPTION

Owing to the above reasons, there is strong evidence to consider the third method – which means limitation of the DC-fault currents by electronic switching of the converters, themselves. Besides the very desirable fast switching, the existing overall infrastructure of the converter (construction, HV-isolation, cooling, control electronics) can be used. In addition, the inherent reliability – owing to the redundant series connection of submodules – can be preserved, too, if the desired functionality is implemented in the submodules. Appropriate structures of submodules are given in Fig. 2.

The Full-Bridge-Submodule (FB-SM) is well known and is applicable for the desired function. It can cut off arms currents of any direction by impressing the appropriate polarity of terminal voltages in the arm. This can be assured by turning off all the IGBTs – in the simple manner. The additional switching states, however – compared to the simpler HB-Submodule – are not very useful in normal operation, because a reverse voltage polarity at the DC-Bus is not required for HVDC-applications. Therefore, using double the number of semiconductors and doubling the semiconductor losses in normal operation represents a severe drawback.

Owing to these reasons, alternative topologies have been introduced, which enable the desired cut off and voltage clamping functionality. An advantageous realization is given by the shown Clamp-Double-Submodules in Fig. 2. In normal operation it represents an equivalent of two Half-Bridge-Submodules. The total expense for the semiconductors and the resulting losses are only slightly increased, owing to the addition of T5, which is normally on. In order to cut off fault currents T5 is turned off, resulting in voltage clamping and energy absorption. During voltage clamping, both capacitors are in parallel, ensuring minimized overvoltage. Employing this new type of submodule, the following investigations of DC-fault currents in a multi-terminal HVDC-Network have been done.

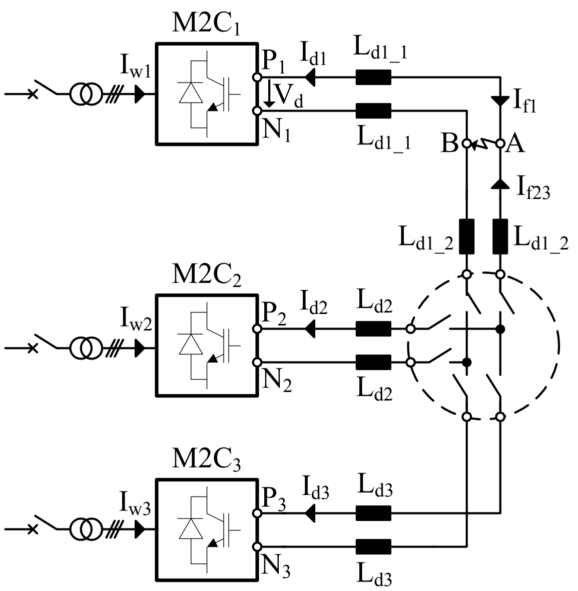

Fig. 7: Example of a Multi-terminal-Network with 3 branches

VIII. Simulation Results

The basic multi-terminal HVDC topology according to Fig. 7 will be considered. Three converters are linking three asynchronous 50Hz grids over a 300kV multi-terminal HVDC connection. The corresponding DC lines are joint at a DC switchyard (dashed circle), which is operated under zero current switching conditions (Pure disconnect switches, for instance: Vacuum tube switches).

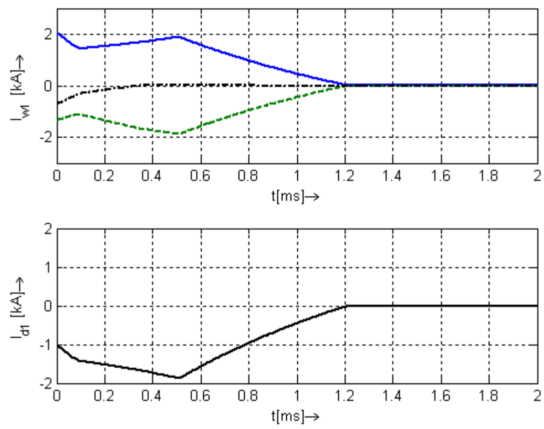

Fig. 8: Station 1 (M2C$_1$)

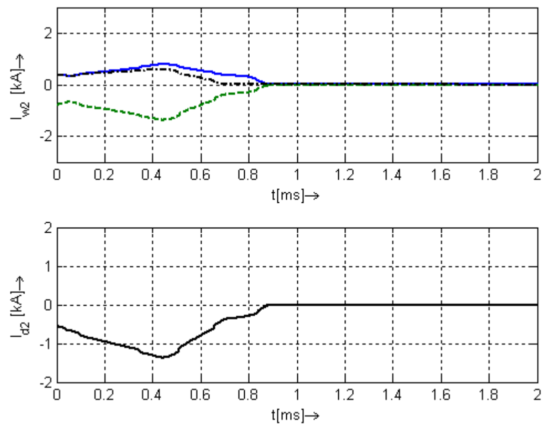

Fig. 9: Station 2 (M2C$_2$)

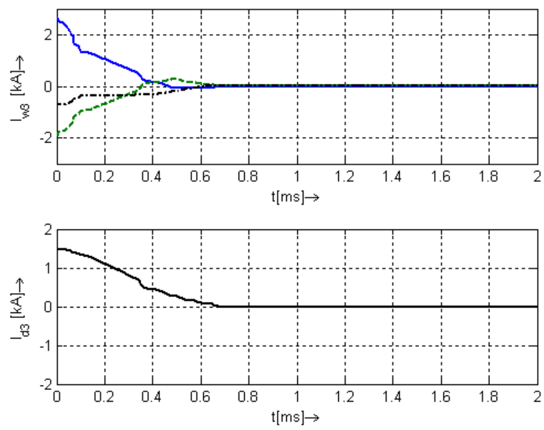

Fig. 10: Station 3 (M2C$_3$)

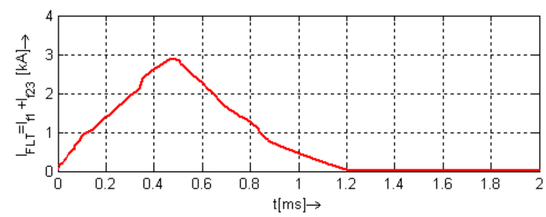

Fig. 11: Failure current

A line-to-line fault between terminals A and B in the DC System is occurring at t=0. The one-way distances between converter and said fault location are defined to be 40km for converter $M2C_1$, 30km for $M2C_2$ and 160km for $M2C_3$. A line inductance of 1mH per km is assumed, which holds approx. for an overhead line. Grid- and transformer-impedances result in u_K = 14%. The converter arm-inductances are L_a= 22mH per arm. Before the fault, $M2C_1$ is operating as rectifier at 300MW real and 225MW reactive power, $M2C_2$ as rectifier at 150MW real power, and $M2C_3$ in inverter at 450MW real and 220MW reactive power flow, respectively. In order to take into account some delay for fault recognition and communication, the clamping action is triggered 0.5ms after the fault.

The AC- and DC-currents for each converter, as well as the resulting fault current supplied by the converters are shown in Fig.8-11. As expected, the DC currents rise steeply until clamping state is triggered. As soon as clamping action starts, all currents are decreasing to zero in approximately one millisecond.

All converter submodule capacitor voltages are only slightly increasing during this action (approx. 3% … 6%) while absorbing the energy caused by the faulty loop. Therefore, all the converters remain fully operable for immediate restarting. In all the converter stations, none of the associated AC-switches have to be tripped.

Assuming a sufficiently fast mechanical switching action at the switchyard, power transmission may restart immediately after the faulty branch is disconnected from the network. The associated converter of the the disconnected, faulty branch may wait for line deionization and can manage the clearing of the fault, independently. A high repetition rate for testing and restarting is possible. After successful clearing of the fault, closing of the disconnect switches without any surge currents can be accomplished.

IX. Conclusions

The topology of Modular Multilevel Converter is well adopted to the requirements of advanced HVDC-transmission systems. In comparison to other VSC concept it offers superior characteristics, especially with respect to operational power losses, industrial scalability, EMC and failure management under severe fault conditions.

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