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# Analysis of Modular Multilevel Converters with DC Short Circuit Fault Blocking Capability in Bipolar HVDC Transmission Systems

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## Keywords

«Modular multilevel converter», «bipolar hvdc transmission», «DC fault blocking».

## Abstract

This paper analyzes the station-internal phase-to-ground fault in bipolar HVDC transmission systems. An overvoltage problem due to the existence of the bipolar cells in the modular multilevel converter (MMC) arms closer to the grounding pole are presented. Consequently, a new hybrid arm MMC is proposed to overcome the overvoltage problem while providing the benefits of: a lower number of cells, fewer switching devices and lower conduction losses. Guidelines are developed and confirmed by simulation results to determine the required number of cells to block the DC side fault.

## Introduction

Voltage source concreters (VSCs) offer the most attractive solutions in the HVDC transmission development toward increasing renewable sources integration and increasing power transferring capability. For the bulk power transmission over land, the most frequent transmission connections are overhead lines or mixed over headline and cables. The point-to-point HVDC overhead line is normally a bipolar system and consists of two monopole asymmetric converters connected in series between two conductors with the different polarity. A bipolar HVDC transmission system based on VSC topologies is shown in Fig 1. Bipolar HVDC transmission systems also offer a higher availability compared to the monopole systems [1].

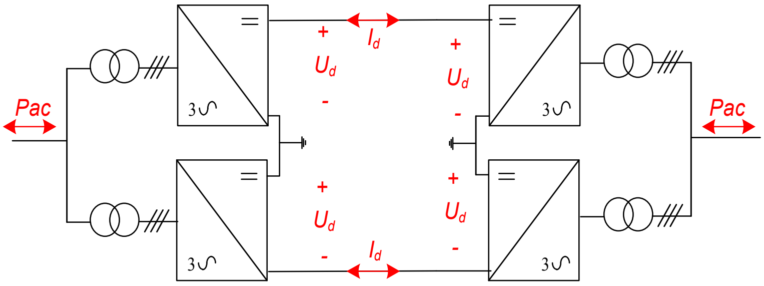


Fig.1: Bipolar HVDC transmission system

Among today's trendy VSC topologies, modular multilevel converter (MMC) [2] is one of the optimal VSC topologies according to the HVDC main performance criteria such as losses, modularity and active and reactive power controllability. However, one of the main problems of half-bridge (HB) MMC VSC, similar to all VSCs, is the DC fault blocking capability in which the AC source is feeding the fault on the DC side through the diodes of HB cells. In the applications which are vulnerable to the temporary DC faults, such as DC link with overhead lines, a fast HVDC line fault interruption is required. A straightforward way to interrupt the DC fault current is by means of a switch (either semiconductor or hybrid) which dissipate the energy into the passive elements. A hybrid HVDC breaker offers a negligible conduction losses, while preserving a fast current interruption capability [3-

4]. The fast fault handling would also enable the converter stations to operate as a stand-alone static compensation unit to stabilize voltage and increase transmission capacity in the AC grid during fault clearance. The HB MMC with the hybrid breaker at the DC pole is shown in Fig. 2. In addition, HB MMC together with the DC breaker provides the DC fault isolating which is one of the crucial requirements to secure the DC grids [4].

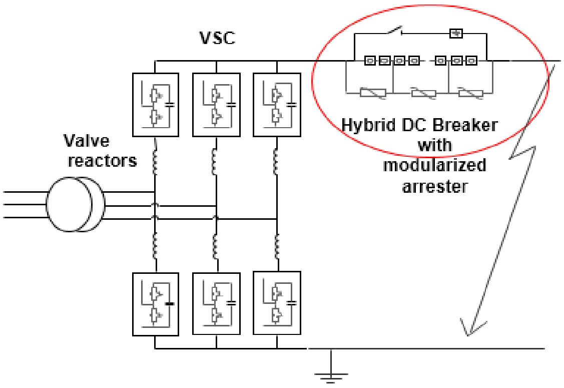


Fig.2: MMC with half-bridge cells using the fast hybrid breaker at the DC link

Employing bipolar cells instead of unipolar cells in the MMC is an alternative solution for the DC fault handling at the cost of a higher number of devices and higher semiconductor losses. The bipolar cells can be charged in both current directions, therefore, the capacitors can be inserted into the arms with either polarities [5]. Fig. 3 (a-b) shows the MMC arms formed by the bipolar cells such as full-bridge (FB) cells, or Cross connected (CC) cells [6], respectively. When the converter switches are blocked (uncontrolled) during the DC fault, a voltage with an opposite polarity of the AC voltage is inserted into the converter arms by the natural commutation of diodes. If the cell voltages are sufficiently high, the DC fault current can be blocked. As shown in [5], at least 50% of the arm voltage must be reversible to fully block the DC fault current in the steady states. Therefore, a mixed-cell MMC arm including either an arbitrary percentage of unipolar and bipolar cells (Fig. 3 (c)) or 100% semi-full-bridge (Fig. 3 (d)) cells [7], can potentially reduce the cost and loss penalties compared to the 100% bipolar cell arms. In addition to the DC fault limitation capability, using the bipolar type cells in the normal (controlled) switch operation, results in decoupled and independent control of AC and DC side voltages. This gives an extra freedom of controlling the maximum AC voltage regardless of the available DC voltage. However, if the bipolar operation is not required during the normal operation (controlled mode), an asymmetric configuration (three-quadrant cell) of all abovementioned bipolar cells can be used by removing an active switch (e.g., IGBT) from their structure as shown in Fig.3 (e)-(h) [8, 10].

Although the solution based on bipolar and asymmetric cells offers the DC fault blocking capability, this results in fairly high cost and loss penalties as shown in Fig.4 [4]. In addition to the steady state rating, HVDC converters are normally designed in order to withstand the sever transients due to the importance of the system reliability and availability. One of the most critical failures that needs to be taken into account is the station internal AC faults. One example of this type of faults is the wall bushing insulation failure which causing an internal single-phase-to-ground fault between the converter AC terminal and the converter transformer. Authors in [11] addressed approximately 100% over-rating of the upper arms of the healthy phases in this case is caused by different converter arm characteristic of the FB MMCs. Therefore, in order to avoid the resulting overvoltage on semiconductor devices, the upper arms should be over-rated which results in extra cost and loss penalties.

In this paper, the internal phase-to-ground fault in the bipolar cell MMCs for asymmetric monopole and bipolar HVDC stations is analyzed in details. The overvoltage problem in the uncontrolled operation mode of the converter arms is theoretically investigated. Consequently, a new hybrid arm MMC is proposed to overcome the over-rating problem while providing the benefits of: a lower number of cells, fewer switching devices and lower conduction losses. Guidelines are developed and confirmed by simulation results to determine the required number of cells to block the DC side fault.

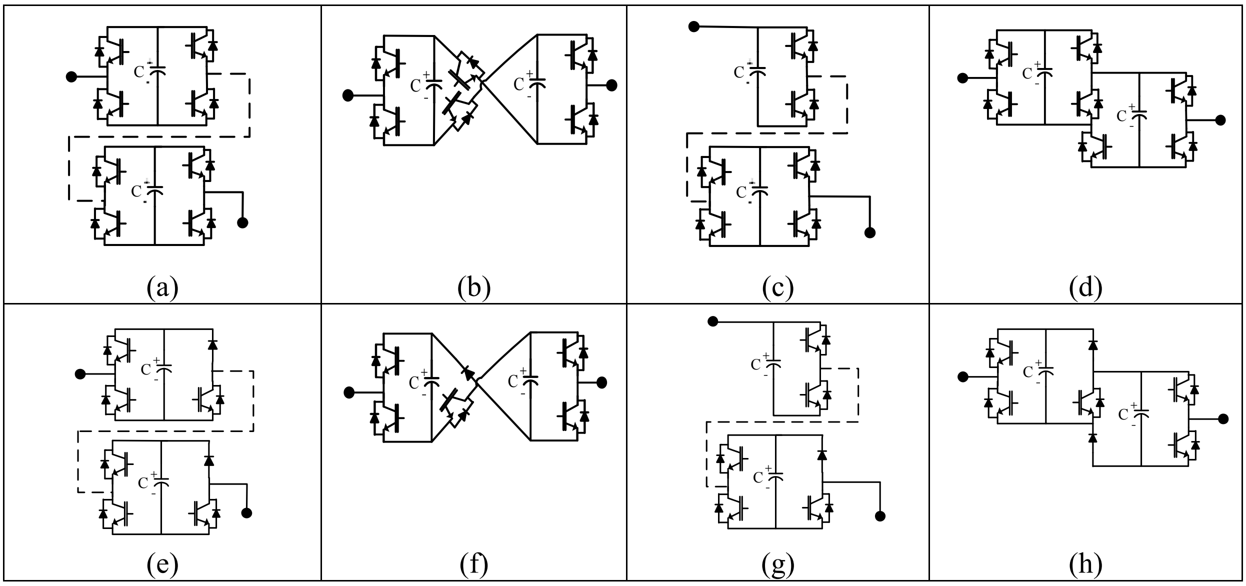


Fig.3: Bipolar cells: (a) Full-bridge, (b) Cross-connected (c) Mixed-cell, (d) Semi-Full-bridge, Asymmetric cells: (e) Full-bridge, (f) Cross-connected, (g) Mixed-cell, (h) Clamped-double-cell

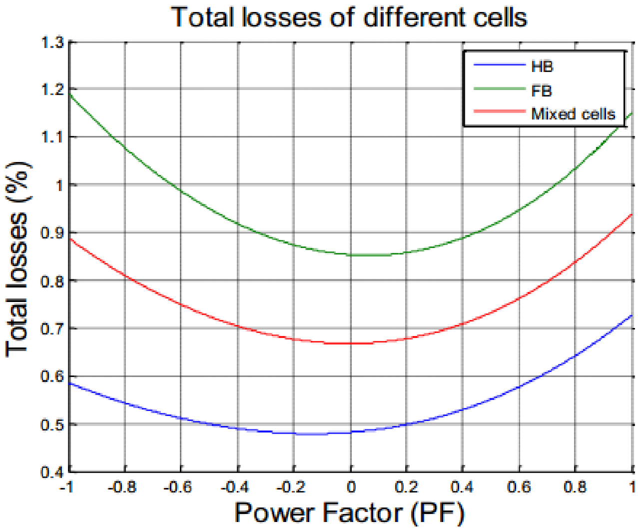


Fig 4. Total loss comparison of HB, FB, and Mixed cells

## Cell overvoltage due to station internal AC faults

During a station-internal phase-to-ground fault, the equivalent circuits of the grid and converter transformer, the converter cells, and the converter station are first presented. The overvoltage during such a fault is then explained in this section.

### Station internal phase-to-ground AC fault

For high voltage transmission, the grid side of the converter transformer is typically grounded at the neutral point, while the converter side of the converter transformer is typically ungrounded to allow for higher modulation index by third harmonics voltage injection. When a phase-A-to-ground fault occurs, the phase B and C voltages to ground become the line-to-line voltage due to the converter transformers, as shown in Fig. 5. The open-circuit AC source peak voltages (phase to ground) become:

$$V_{a\ peak} = 0,\quad V_{b\ peak} = 1.732\ U_d,\quad V_{c\ peak} = 1.732\ U_d \tag{1}$$

where $U_d$ is the grid side single phase peak voltage and it is also the pole to ground voltage in the bipolar HVDC system. The equivalent circuit for the AC source during an internal phase-ground fault is shown in the right graph of Fig. 5, where $L_{src}$ is the equivalent source inductance, including the transformer leakage and grid impedance.

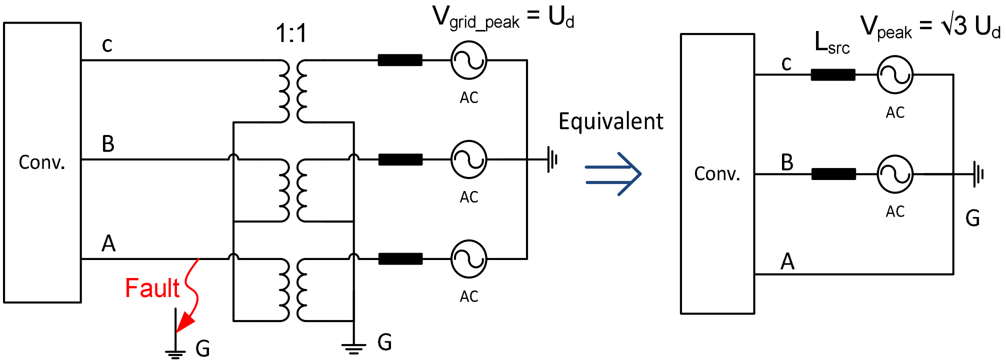
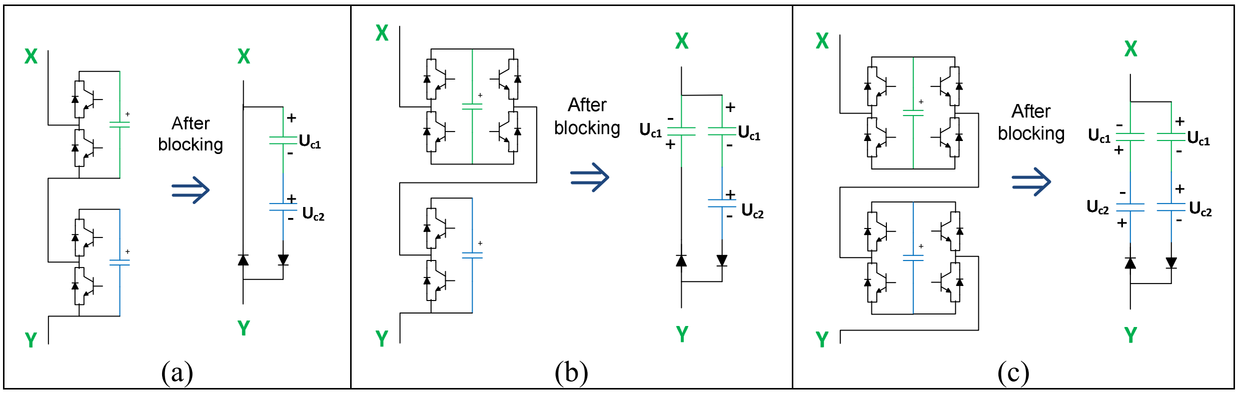


Fig 5. Station internal single-phase-to-ground fault

## Equivalent circuit of converter cells after IGBT blocking

After the detection of a station internal fault, all of the converter IGBTs are blocked immediately (uncontrolled mode). The equivalent circuits of the typical HB cells, mixed HB-FB cells, and, FB cells after IGBT blocking are shown in Fig. 6. It is clear that in the uncontrolled mode, if a current is flowing from the X terminal to the Y terminal, all three types of cell structures insert the same reverse voltage in the current loop and all cell capacitors are charged by this current. However, if the current is flowing from the Y terminal to the X terminal, the HB cells are bypassed by the diodes, and the FB cells (or other bipolar cells) insert a reverse voltage in the current loop and are charged by this current. These cell equivalent circuits will be used to analyze the converter behavior during a station-internal AC fault.



(a) (b) (c)

Fig 6. Converter cell equivalent circuits after IGBT blocking: (a) all HB cells, (b) mixed HB-FB cells, (c) all FB cells.

## Analysis of cell overvoltage due to internal AC faults

Using the equivalent circuits in Fig. 5 and Fig. 6, the bipolar arm MMC HVDC station during a station-internal phase-to-ground fault can be represented by circuits in Fig. 7 (showing only the faulted pole in uncontrolled mode). It will become clear that all FB MMC and mixed-cell MMC behave the same in terms of cell overvoltage. Thus, only the HB MMC and the mixed-cell MMC equivalent circuits are shown in Fig. 7.

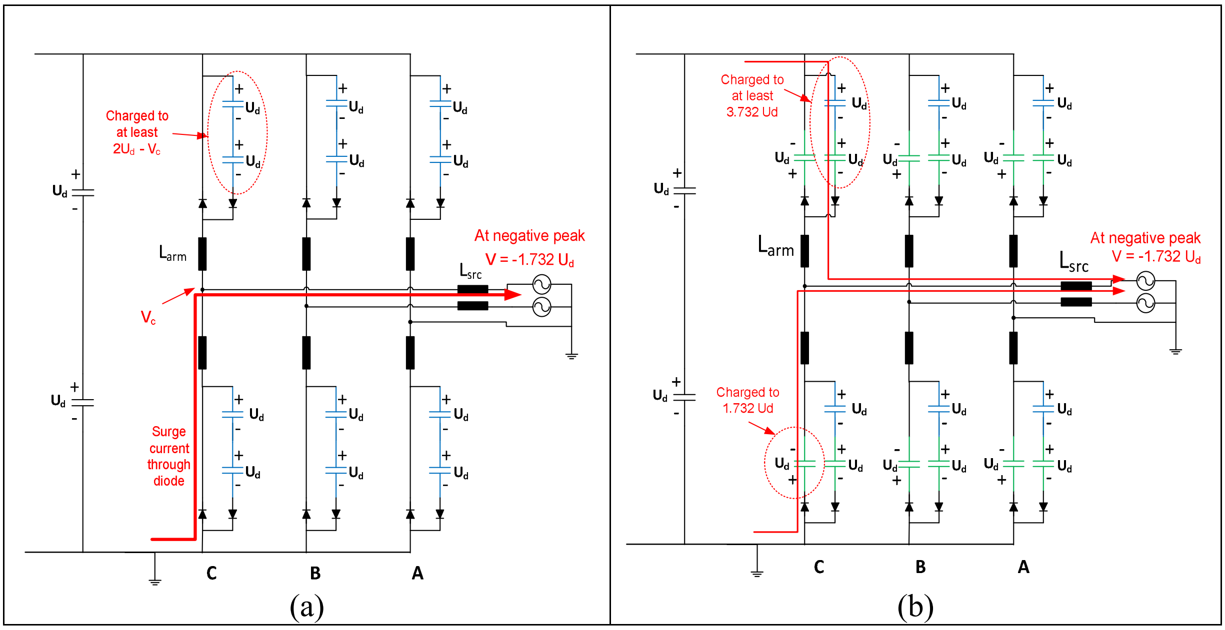


Fig. 7: Equivalent MMC circuit during an internal AC fault after IGBT blocking: (a) HB MMC, (b) Mixed-cell MMC

1) For the HB MMC, after IGBT blocking, the lower arm diode conducts a large current during the negative peak of the AC source voltage. This large current limits the phase terminal voltage according to the impedance of the circuit. A rough estimate of the phase terminal voltage can be found approximately by:

$$V_c = V_{src} * L_{arm} / (L_{arm} + L_{src}) < 0 \tag{2}$$

The upper arm voltage that is driven by the AC side negative voltage is given by

$$V_{arm\_upper} = 2U_d - V_c \tag{3}$$

According to equations (2) and (3), when the arm inductance is significantly smaller than the equivalent source impedance, the converter terminal voltage is clamped to a negative value close to the ground potential. Thus, selecting a smaller arm inductor will reduce the upper arm overvoltage during AC internal faults. However, for the HB MMC, the arm inductor must also be large enough to limit the DC fault current rise.

2) For the mixed–cell or FB MMC, after IGBT blocking, the lower arm blocks any current flow during the negative peak of the AC source voltage. Thus the phase terminal voltage will be equal to the AC source voltage, i.e., -1.732 $U_d$. This voltage will then charge the upper arm (both HB and FB cells) to at least $2U_d$ - ($-1.732U_d$) = 3.732 $U_d$, i.e., 87% overvoltage. Again, the energy associated with the upper arm inductor will further charge the upper arm capacitor until the upper arm current drops to zero.
Therefore, an overvoltage protection device such as arrestors might be designed in order to avoid too high voltage rating in semiconductor components above 70% of the nominal voltage rating. This will results in around 2.7 p.u. semiconductor rating for the FB MMCs and around 2 p.u. semiconductor rating for the mixed-cell MMCs, where the conventional HB MMC is assumed to have 1 p.u. semiconductor rating. The excessive overvoltage during a station-internal phase–to-ground fault is thus caused by the bipolar cells in the arms that are connected to the grounding pole.

One may notice that in the above analysis, the DC side voltage is assumed to be stiff, which is not true, especially for long overhead DC lines. Substantial magnetic energy is trapped in long overhead DC lines. These magnetic energy must be absorbed by the converter cell capacitors after the IGBT blocking, which will also cause cell overvoltage.

In summary, during a station internal AC fault, there are two main contributors to the cell overvoltage in the upper arms: 1) the negative voltage from AC grid side, which can be assume an infinite energy source, and one must limit the negative voltage by some form of voltage clamping to avoid cell overvoltage; 2) magnetic energy associated with the DC current, which is a finite energy source, and one can size the arm capacitance accordingly to avoid cell overvoltage.

Based on this analysis, this paper proposes a new mixed-cell MMC topology for DC fault blocking, and the extensive overvoltage can be avoided in the case of AC internal fault in Asymmetric monopole or bipolar system configurations.

## Proposed bipole HVDC system based on mixed-cell MMCs

A new hybrid arm MMC topology is proposed with 100% unipolar cells in the arms that are connected to the grounding pole, and with 100 % bipolar cells in the arms that are away from the grounding pole. The basic converter configuration based on FB and HB cells is presented in Fig. 8. With 100% FB cells at the upper arms (lower arm) in the upper pole (lower pole), the proposed converter can block DC faults in asymmetric monopole and bipolar system configurations. According to the above analysis, the 100% HB cells at the arms that are closer to the ground potential reduces the cell overvoltage to the same level as a normal HB MMC during an internal phase-to-ground fault.

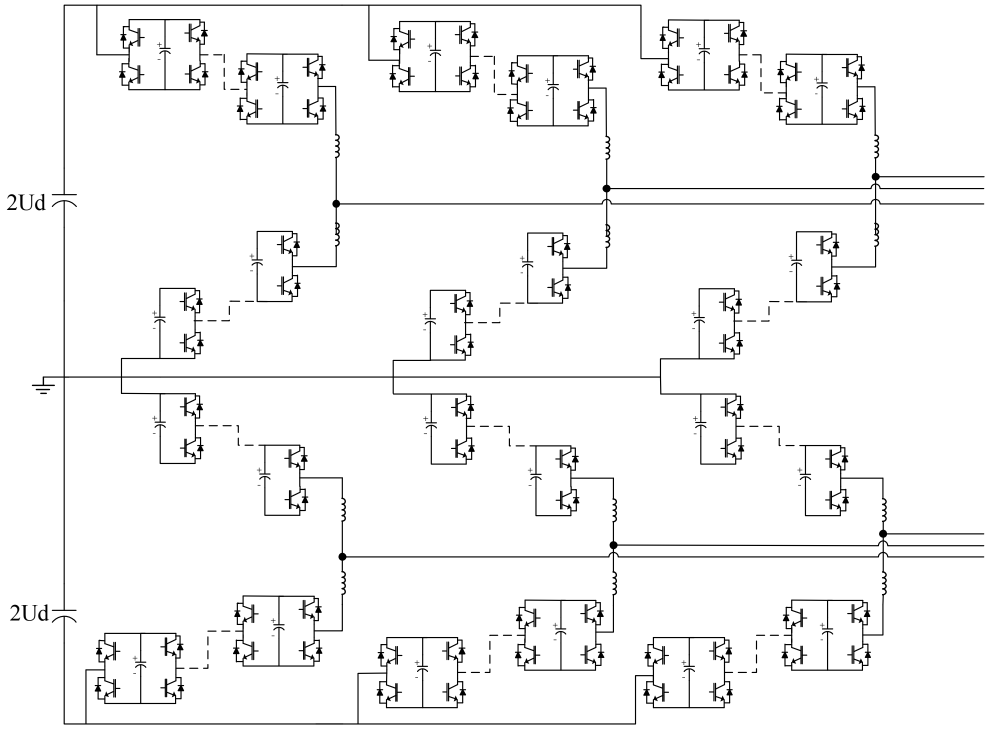


Fig. 8: Proposed MMC with positive arm 100%FB and negative arm 100%HB for asymmetric monopole and bipolar HVDC systems

For the simplicity, an asymmetrical monopole for point-to-point transmission is considered for the further analysis. For the proposed converter, during the station internal phase-to-ground fault, after blocking of all IGBTs, the equivalent circuit is shown in Fig. 9. At the negative peak of source voltage (-1.732 $U_d$), the low arm diode conducts with a high surge current. The surge current creates voltage drops across the source and arm impedances. This is the same case as a normal HB MMC. Assuming $L_{src} \approx 2L_{arm}$, the upper arm capacitors will be charged from $2U_d$ to at least $2.577U_d$, i.e., the same overvoltage level as a normal HB MMC. This overvoltage can be further reduced if the arm inductance is even lower. The same principle can be applied to a bipolar system configuration. The proposed solution can be generalized by having all kind of bipolar cells in the positive arm and unipolar cells in the negative arm of the converter.

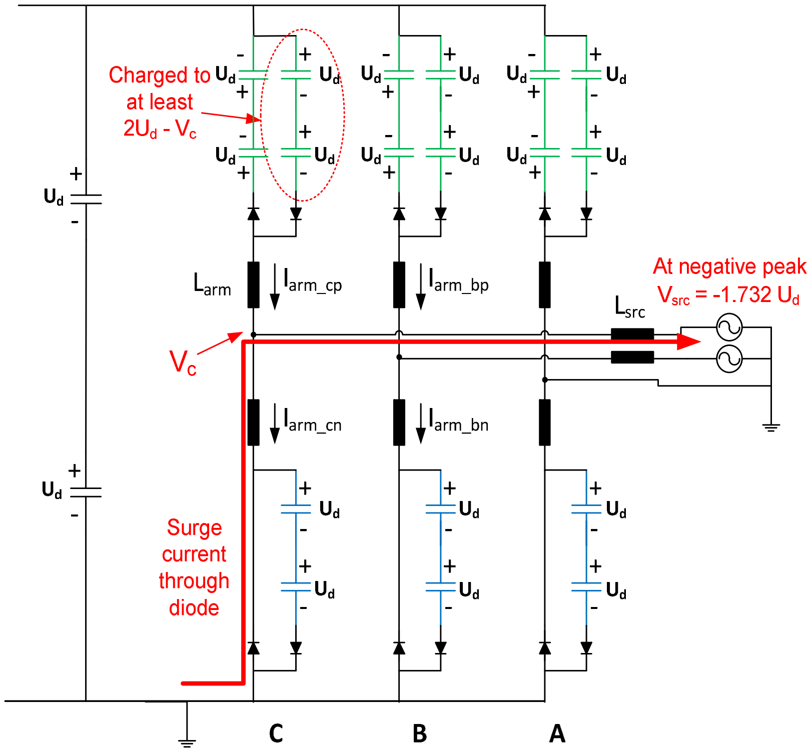


Fig. 9: Equivalent circuit of proposed MMC with bipolar cells after IGBT blocking

## Simulation results

A detailed switch-level converter (+/- 600 kV DC and 1.2 GW) simulation is set up to verify the proposed converter cell overvoltage during the station internal AC phase-to-ground fault. Both the grid impedance and the converter transformer leakage inductance are assumed to be 0.12 pu, while the converter arm inductance is assumed to be 0.06 pu.

Two types of faults are simulated: the station internal phase-to-ground fault, and the DC pole-to-ground fault. Converter IGBTs are blocked 1 ms after a fault occurs. To find the worst case overvoltage, 20 fault cases are applied at 1 ms increment for one fundamental cycle at different PQ operating points.

### Station internal phase-A-to-ground fault simulation results

The worst-case station-internal AC fault overvoltage happens in the inverter mode. The DC load current charges the converter arms, which results in a higher cell overvoltage. Results for this worst case are shown in Fig. 10.

Larger surge current is observed at phase B and phase C, and clamps the negative AC voltage to less than -100 kV. Therefore, the overvoltage problem due to the AC side grid is to a large extend avoided. However, in this fault case, the cell overvoltage is mainly triggered by the DC current magnetic energy, not the AC side negative voltage. As shown, the DC current decays to zero in about 12 ms after the fault, charging the phase A and phase C upper arms to about 35% overvoltage.

Therefore, regardless of the cell type (bipolar or unipolar cells), some overvoltage is required for the upper arms due to the magnetic energy trapped in long overhead DC lines. As mentioned, one can size the arm capacitance accordingly to avoid this cell overvoltage.

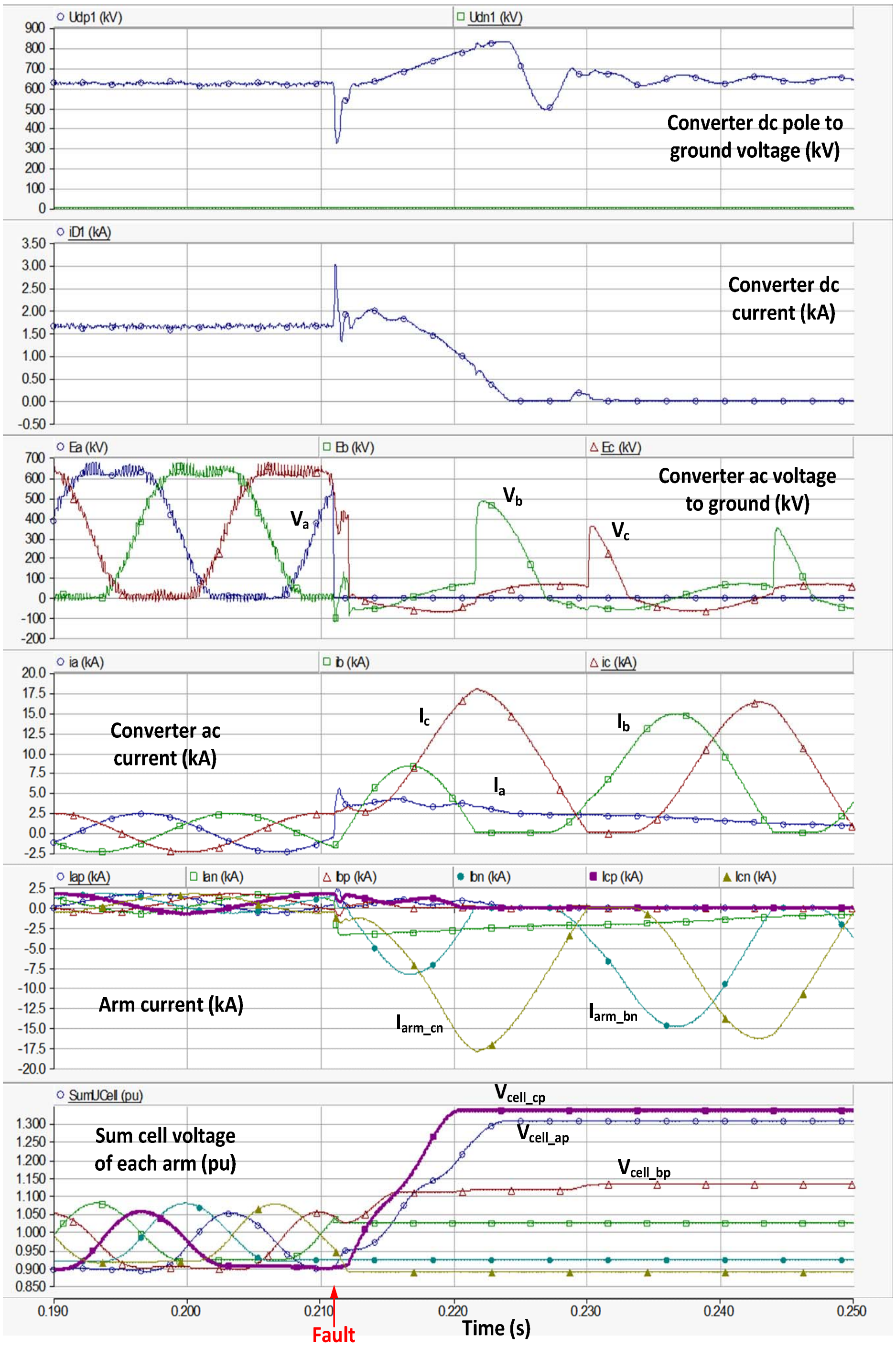


Fig. 10: Worst-case cell overvoltage during an station-internal AC phase-to-ground fault (MMC IGBTs blocked 1ms after the fault)

## DC pole-to-ground fault simulation results

A close-by DC fault is applied (only part of the DC overhead lines are in the fault current loop). The worst-case cell overvoltage from DC pole-ground faults happens in the rectifier mode. The magnetic energy associated with both the initial DC load current and the DC fault current must be observed by the FB upper arms. Results for this worst case are shown in Fig. 11. In this worst case, most of the DC side magnetic energy is absorbed by one FB arm (phase C), causing it to result in 25% overvoltage.

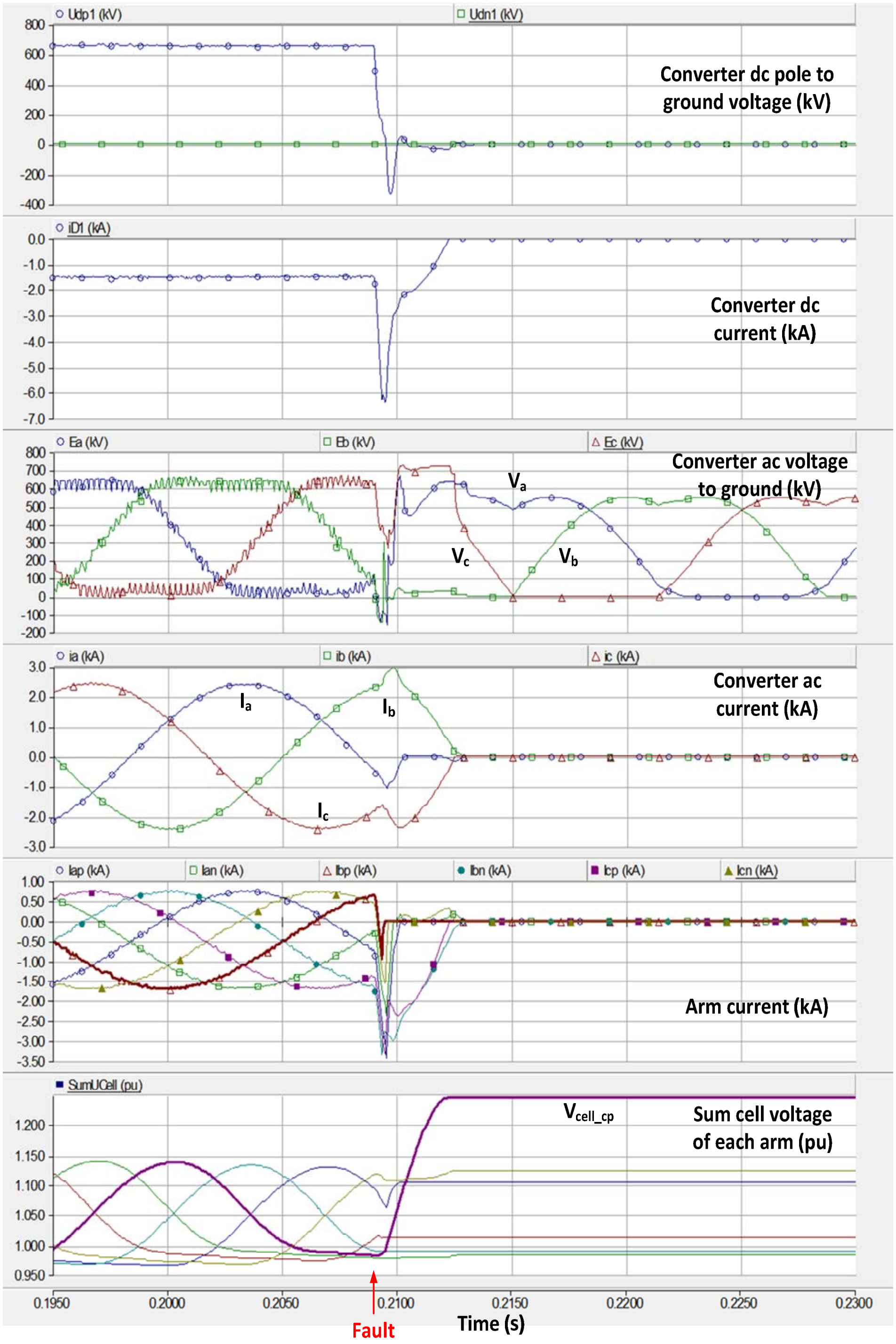


Fig. 11: cell overvoltage during a dc pole-to-ground fault
(MMC IGBTs blocked 1ms after the fault)

The maximum cell overvoltage is 35% and 25% respectively for each case. This result agrees with theoretical analysis. This over-rating is not significant and thus overvoltage protection may not be required.

Therefore, the proposed hybrid arm MMC converter arms offers the DC fault blocking capability similar to the DC breaker while both the required semiconductor rating and loss penalties are reduced compared to the conventional MMC with 100% bipolar or mixed-cell arms. This has been achieved by creating a voltage clamping through using unipolar cells in the arms closer to the grounding potential in the asymmetric monopole or bipolar HVDC stations.

## Conclusion

In this paper, the overvoltage on the upper arms of the bipolar cell MMCs in bipole HVDC stations in case of the internal AC single-phase fault to ground was theoretically explored. The analysis of the overvoltage issue shows that over-rating is mainly caused by the AC grid side due to the uncontrolled characteristics of the bipolar cells in the arms closer to the grounding pole. In order to solve the over-rating problem, a new asymmetric monopole hybrid arm MMC topology has been proposed. Finally, to find the worst case overvoltage, two types of faults have been simulated: the station internal phase-to-ground fault, and the DC pole-to-ground fault. The proposed hybrid arm MMC provides the DC short circuit fault blocking capability in both bipolar and asymmetric monopole HVDC stations with the benefits of: lower number of cells, fewer switching devices and lower conduction losses compared to other cell based alternative solutions.

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