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Exploiting DC-DC Converters for DC fault protection in a DC Grid

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SUMMARY

The ability of DC-DC converters to block external fault current offers potential for application in DC grid protection applications, such as connecting separate protection zones. In addition, isolated DC-DC converters offer the ability to control the current during and after the fault, allowing better transients and monitoring during the fault, and possibility to restart the grid once the fault is cleared. This paper summarizes protection functions of both isolated and non-isolated converters to help designers to select the optimal converter for the functional requirements of the DC grid. Key benefits demonstrating fault current blocking, and controlled current during and after the fault are shown in simulation using the CIGRE benchmark DC grid. It is concluded that DC-DC can take DC Circuit Breaker function, but it generally introduces less disturbance than DC Circuit Breaker during fault current blocking.

KEYWORDS

DC-DC Converter, DC Grid, DC Fault Protection.

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1. INTRODUCTION

DC-DC converters may play an important role in large multiterminal DC grids in the future. They enable interconnection of grids operating at different voltages, with different grid configuration and grounding strategies [1]. They also offer different functionalities in DC grids such as significant protection functionalities, something that does not exist in AC transformers, which perform a similar voltage stepping role in AC grids [1, 2, 3].

Half-Bridge (HB) MMC converters need to be blocked under DC faults, but Full-Bridge (FB) MMC can operate and control DC current under DC fault conditions [4]. In addition, FB MMC can help with black start and post fault recovery of DC grids. This paper explores if DC-DC can potentially offer some of these functionalities.

The role of DC-DC in DC grid protection has been studied on very simple DC grids only, and primarily isolated DC-DC converter type [2, 3]. Building on the activities in CIGRE WG B4.76 [1], this paper evaluates key protection features of isolated and non-isolated DC-DC converters for DC Grid applications and examines protection benefits of DC-DC in a complex DC grid developed by CIGRE that includes two DC voltage levels and two DC-DC converters [5]. Section 2 discusses the control options with different DC-DC converter families and the impact of different faults and grid configurations. PSCAD/EMTDC benchmark DC-DC converter models developed as part of WG B4.76 (available in [1]) are integrated and simulated in CIGRE DC grid to highlight relevant differences.

1.1. Overview of DC Grid Protection

Multiterminal DC grid protection is a developing topic with more complete reviews on the subject found in [6, 7, 8, 9, 10]. While the main goals are the same as the design of an AC protection system, DC grid protection is especially affected by the cost of a DC breaker and the speed of operation including detection, selection and clearing the fault. Different zoning methods that have been proposed are discussed in detail in [6].

The ability of a DC-DC converter to block or control fault currents through the converter offer huge potential as the device facilitates not only interconnection of separate grids at different voltage levels, but also implementation of the protection of the adjacent zones, potentially without any additional DC circuit breaker.

This paper describes the control functions for DC-DC converters that can be used by a DC grid protection designer to take best advantage of the capability in these devices in achieving all functional requirements of the system.

2. DC-DC CONVERTERS RESPONSE TO DC FAULTS

DC-DC converters can be grouped into two main categories: isolated and non-isolated. Isolated converters offer galvanic isolation, simplify interconnection of different types of DC grids, offer wider voltage stepping, and control benefits. Non-isolated converters can offer cost savings in applications where galvanic isolation is not required and the stepping ratio is low.

Both isolated and non-isolated converters offer DC fault blocking through the converter. Their response, however, may differ depending on the topology and the implementation in DC grid. DC-DC converters may not respond exactly as DC circuit breakers and the advantages/disadvantages should be evaluated to achieve their optimal use. The main advantages of a DC-DC converter’s fault response are fast speed, minimal overcurrent and current control capability. The actual characteristics of the response depend on the type of converter and type of grid, and is analyzed in the following sections.

2.1. DC Fault Control Options with Isolated Converter

Isolated DC-DC converters comprise a wide range of topologies, but for HVDC applications, the state-of-the-art is based on front-to-front multilevel converters, with galvanic isolation achieved by connecting the AC sides via a transformer. During an external grid fault, the converter can block fault current by:

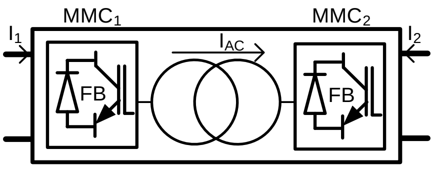
1. Blocking both bridges.
2. Only the bridge on the faulted side is blocked, while the bridge on the unfaulted side continues to operate and can provide DC fault current control.

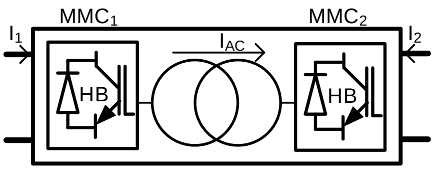
The advantages of maintaining converter operation during a DC fault and providing control of fault current have been studied with FB MMC [4] and only key benefits are presented:

1. The fault circuit is kept alive, enabling continuous monitoring of line voltage.
2. Full current control can be used to restart the grid, ramping up the current in a controlled way to minimize the grid disturbance and allow fast restart when a fault has cleared.
3. The transient overvoltages and overcurrents during the fault are better controlled.

The ability to restart the grid offers similar capability compared to FB AC-DC MMC converters [4]. This can be fully implemented with a DC-DC converter using HB cells.

Isolated DC-DC converters can be implemented with FB cells to provide an additional benefit of allowing the fault current in the faulted system to be reduced by control action. However, in the HB design, it is only possible to block additional energy into the fault, but high current can continue to freewheel through the converter even if it is fully blocked. Characteristics for isolated converters are summarized in Table 1.

<table>
<tr><th rowspan="4">Control Response</th><th></th><th colspan="2">Converter Type</th></tr>
<tr><th></th><th>FB / FB


MMC1 is full bridge
MMC 2 is full bridge</th><th>HB / HB


MMC1 is half bridge
MMC 2 is half bridge</th></tr>
<tr><td>Cell Blocking</td><td>Fault current is reduced immediately and energy is absorbed in the FB cell capacitors (on both sides).</td><td><u>Faulted side</u>: Line DC fault current continues to circulate through reverse diodes until energy is dissipated.
<u>Unfaulted side</u>: Not normally blocked, but if blocked then energy flowing into the converter will charge cell capacitors</td></tr>
<tr><td>Current Control</td><td>It is possible to control I_1, I_2 and I_{ac}. Gradually reduce fault current through the converter by control. Energy is partially absorbed in the FB cell capacitors depending on the degree of control and can be shared on both sides.</td><td><u>Faulted Side</u>: No DC current control but AC component I_{ac} is regulated from unfaulted side. Can be blocked to prevent discharge of cell capacitors.
<u>Unfaulted side</u>: Gradually reduce fault current I_{ac} through the converter by controlling the internal AC voltage. DC current gradually reduces.</td></tr>
</table>

Table 1: Characteristics of fault current control for isolated DC-DC converters.

2.2. DC Fault Control Options with Non-Isolated converter

The non-isolated DC-DC can also be implemented with various HB/FB topology combinations on its upper/lower arms. In general, this topology offers less control flexibility for DC fault current regulation compared with isolated DC-DC. Table 2 summarizes characteristics of non-isolated converters.

One of the simplest configurations of the non-isolated DC-DC, which uses HB on upper and lower arms, is that it is not able to block current in the case of faults on the HV side. Therefore, it requires operation of external protection devices to clear the fault [1]. This DC-DC configuration might be interesting in applications such as power flow control or unidirectional power flow, but due to the limited protection features, it is not evaluated in this paper.

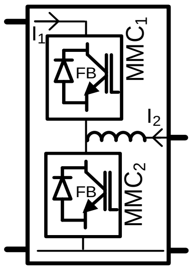
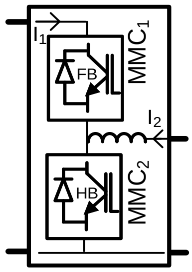
<table>
<tr><th colspan="4">Converter Type</th></tr>
<tr><td rowspan="6">Control Response</td><td></td><td>FB /FB

MMC1 is full bridge
MMC2 is full bridge</td><td>FB / HB

MMC1 is full bridge
MMC2 is half bridge</td></tr>
<tr><td rowspan="2">Cell Blocking</td><td rowspan="2">Fault current is reduced immediately and remnant energy is absorbed by cell capacitors (on both sides).</td><td><u>HV Fault</u>: Remnant fault current energy will be absorbed the FB/HB cells.</td></tr>
<tr><td><u>LV Fault</u>: Circulating fault current will flow through freewheeling diodes of the HB cells. Current from the HV side will be blocked.</td></tr>
<tr><td rowspan="2">Current Control</td><td rowspan="2">Fault current is fully controllable and can be maintained or reduced (with energy absorbed by the cells). Capacitor energy sharing can be controlled internally.</td><td><u>HV Fault</u>: Full control similar to FB/FB design.</td></tr>
<tr><td><u>LV Fault</u>: Full control similar to FB/FB design, although circulating fault current cannot be immediately forced to zero (since it can always circulate through the freewheeling diodes)</td></tr>
</table>

Table 2: Characteristics of fault current control for non-isolated DC-DC converters

2.3. Characteristics of Faults for different DC Grids

The effects of an external short circuit fault on the DC-DC converter will depend on:
a. Converter type and fault current limitation ability.
b. Grid configuration type (in HV applications these are typically bipole or symmetrical monopole).
c. Short circuit fault type.
d. Grounding impedance.

Pole-to-pole faults (and double-pole-to-ground faults) will typically generate the highest fault currents and the fault current magnitude may be independent of the type of grounding or grid.

The effect of pole-to-ground faults can vary, depending on the earthing. In bipole systems, the fault current is high and similar to a pole-to-pole fault. In symmetrical monopole systems, this can lead to a lasting overvoltage on the unfaulted pole, depending on the control and grounding. In the case of the isolated DC-DC converter, the earthing on the different sides is independent; whereas in the non-isolated DC-DC converter, the neutrals are linked through the converter. This will affect the DC grid protection strategy, especially in the case of pole-to-ground faults. A systematic analysis of each case is beyond the scope of this paper but is performed in the B4.76 WG brochure [1].

3. TEST SYSTEM

To understand the impact of the protection capabilities, the models of both isolated and non-isolated converters developed in [1] are integrated in the DC Grid Test System, developed by CIGRE WG B4.57/58 [5]. Figure 1 shows the test circuit with two DC fault locations studied.

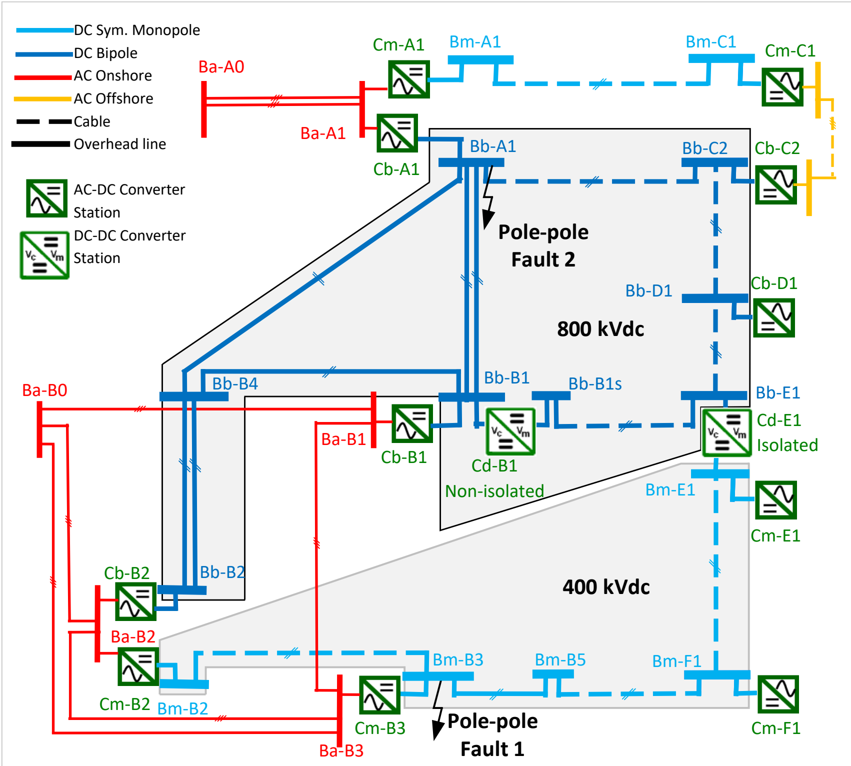


Figure 1: CIGRE DC Grid Test System

4. SIMULATION RESULTS

The following DC-DC operating modes are tested to demonstrate the protection functionality:

1. Isolated DC-DC converter during a pole-to-pole fault and applying cell blocking control.
2. Isolated DC-DC converter during a pole-to-pole fault and applying active current control.
3. Non-isolated DC-DC converter during a pole-to-pole fault with cell blocking control.

For cases 1 and 2, the fault is applied at the bus Bm-B3 in the 400 kV system, which is remote from DC-DC and enables study of the impact of the grid parasitics on the transient voltage and current at the converter. Similarly, for the non-isolated converter, the fault is applied at bus Bb-A1. All MMC AC-DC converters block and open AC CBs when local DC voltage drops below 0.8 pu. They deblock when local DC voltage recovers above 0.8 pu.

4.1. Fault on 400kV DC Grid with Isolated DC-DC blocked

A permanent DC fault is applied at 400 kV bus Bm-B3. The 400kV DC grid is a single protection zone and has no DC Circuit Breakers. In case of a DC fault:

1. Four AC-DC MMC converters (Cm-B2, Cm-B3, Cm-F1 and Cm-E1) are blocked and their AC CBs is opened after 30 ms.
2. Isolated DC-DC Cm-E1 is blocked (both bridges).

At around 500 ms DC fault current on all converters is reduced to zero and fault is assumed cleared. Since there is no power infeed to 400 kV DC grid, DC voltage is not rising and no MMC is deblocked. The simulation results are shown in Figure 2.

- Graphs (b), (d) and (f) show variables on the faulted 400 kV DC system. It is seen that DC fault currents are large and peak values are over 30 kA.
- Graphs (a), (c) and (e) show 800 kV DC grid variables. This grid experiences only a small disturbance, related to load disconnection of DC-DC. DC-DC effectively shields 800 kV system from faults on 400 kV grid. The DC currents through MMC converters are shown.
- Graphs (g)-(n) show internal variables for the isolated DC-DC. It is seen that all variables are within the design limits.

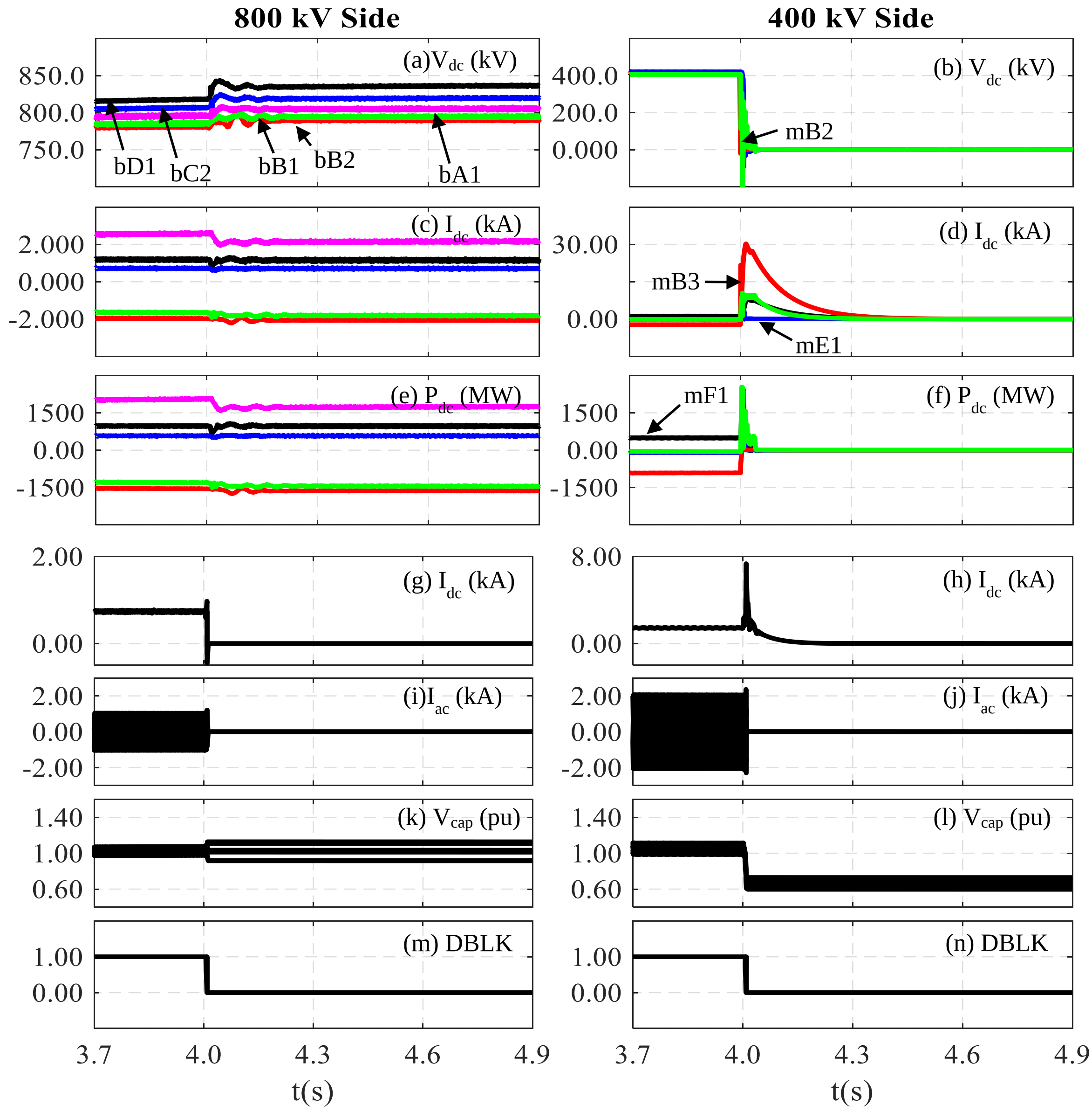


Figure 2: DC grid and Isolated DC-DC converter response during a 300 ms pole-to-pole fault on the Bm-B3 bus of 400 kV system, assuming DC-DC blocking.

A direct comparison with a DC Circuit Breaker is not possible since DC-DC also offers voltage stepping function in this test case. However, the DC-DC fault current shows desirable waveform since it reduces gradually and has no overcurrents. A DC circuit breaker includes 3-10 ms opening delay [10], and peak value can be around 15-30 kA similar as with MMC currents in Figure 2d.

4.2. Fault on 400kV DC Grid with Isolated DC-DC controlling current

The same permanent DC fault is applied at 400 kV bus Bm-B3, but in this case, DC-DC controls fault current. The bridge on the faulted side is blocked but the bridge on the unfaulted side can regulate current at any reference value during the fault. The simulation results are shown in Figure 3, which are similar as in Figure 2, with the following key differences:

- The disturbance on 800 kV system is marginally better, since load of DC-DC rejection is gradual.
- The fault current from DC-DC is controlled at 300A (shown in Figure 3h).
- The internal DC-DC variables are within design limits while current is running through DC-DC and 400 kV DC grid has very low DC voltage.

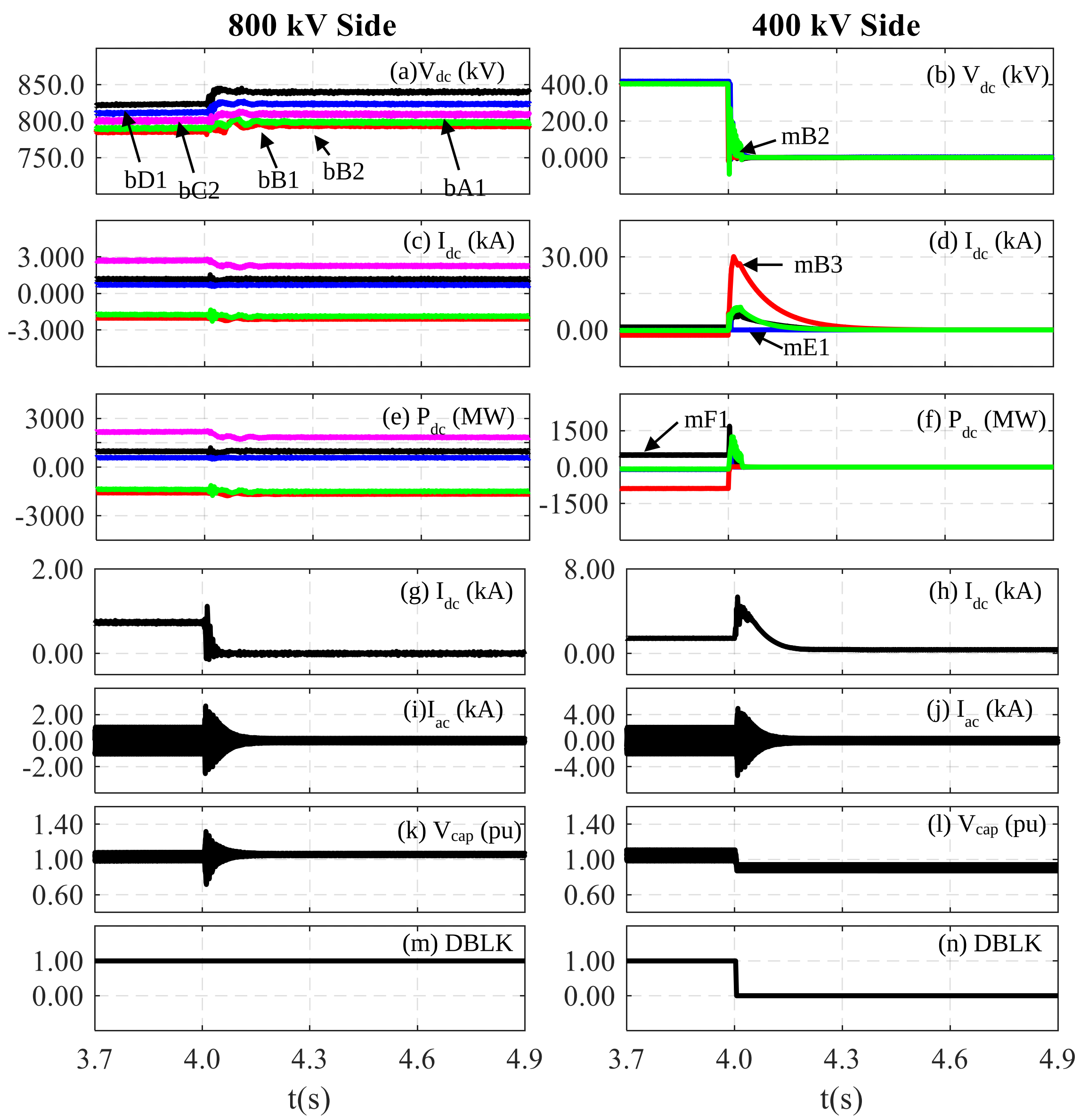


Figure 3: DC grid and Isolated DC-DC converter response during a 300 ms pole-to-pole fault on the Bm-B3 bus of 400 kV system, assuming DC-DC current control.

4.3. Fault on 800 kV DC Grid with non-Isolated DC-DC blocked

A permanent DC fault is applied at 800 kV bus Bb-A1. The 800 kV DC grid is a single protection zone and has no DC Circuit Breakers. In case of DC fault:

1. Five AC-DC MMC converters (Cb-A1, Cb-B2, Cb-B1, Cb-C2 and Cb-D1) are blocked and their AC CBs is opened after 30 ms.
2. Isolated DC-DC Cd-E1 is blocked (both bridges).
3. Non-Isolated DC-DC Cd-B1 is blocked (both bridges).

The simulation results are shown in Figure 4.

- Graphs (b), (d) and (f) show variables on the faulted 400 kV DC system. This grid experiences only a small disturbance, related to load disconnection of DC-DC. DC-DC effectively shields 400 kV system from faults on 800 kV grid.
- Graphs (a), (c) and (e) show 800 kV DC grid variables. It is seen that DC fault currents are large and peak values are over 30 kA

- Graphs (g)-(l) show internal variables for Non-Isolated DC-DC Cd-B1. It is seen that all variables are within the design limits.

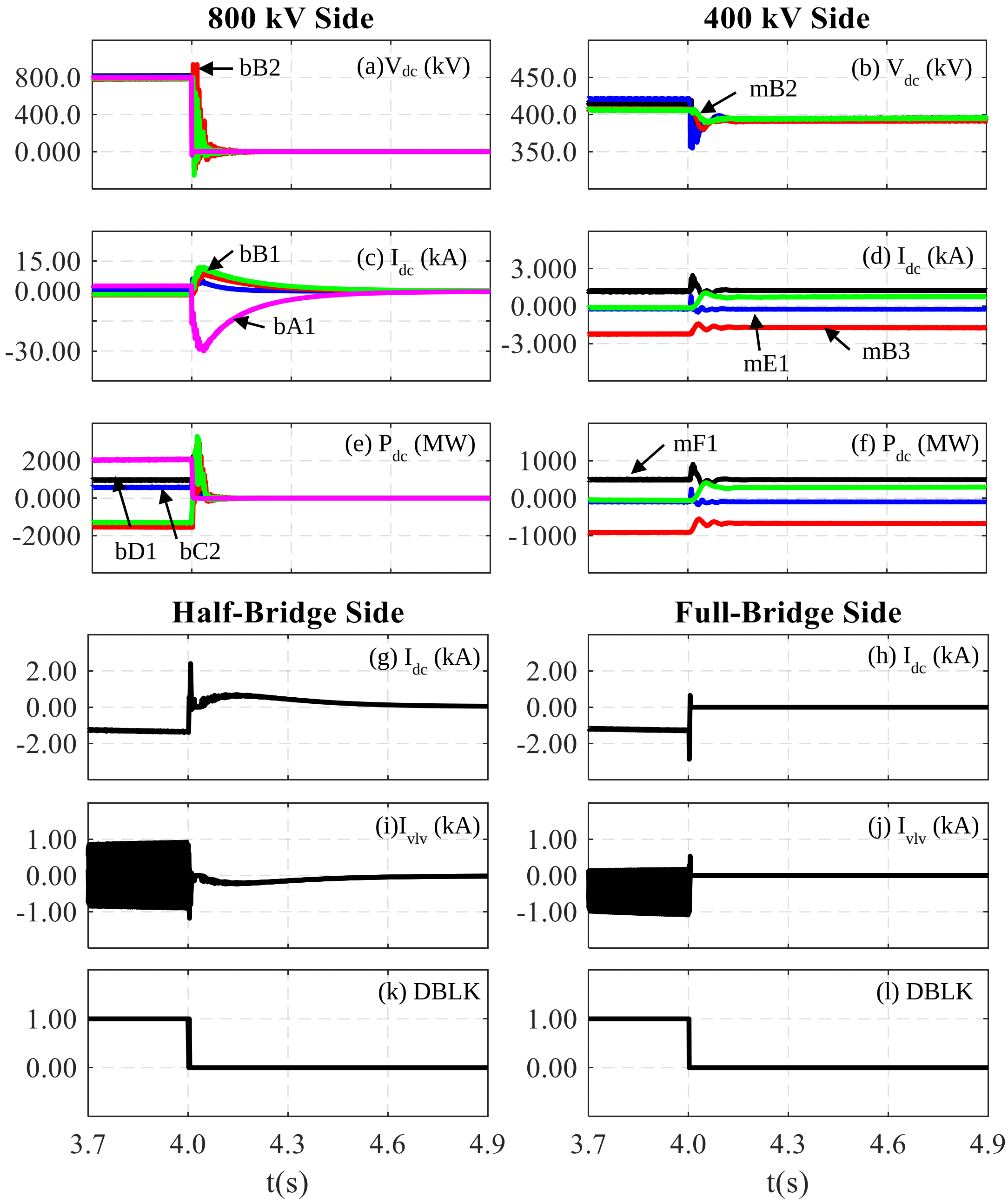


Figure 4: DC grid and Non-Isolated DC-DC converter response for a permanent pole-to-pole fault on the Bb-A1 bus of 800 kV system; assuming DC-DC is blocked.

5. CONCLUSIONS

The ability of a DC-DC converter to control or block fault currents to allow application as protection devices in DC grid is demonstrated. Similar to DC breakers, external faults do not propagate through the converter and the converter can be safely restarted when the fault is cleared. However, DC-DC fault current blocking introduces less disturbance since there is no overcurrent that is normally seen with DC Circuit Breaker operation. In addition, DC-DC fault current can be limited and/or reduced to zero.

DC-DC converters have an additional feature allowing continuous control of the current at a reference value (including zero current) into the fault. It has been demonstrated that the DC-DC current is successfully controlled to 300 A during the fault. The possible benefits of this ability are:

1. The fault circuit is kept alive which enables continuous monitoring of line voltage. This could be used to more quickly detect when the fault is cleared and safely reclose.
2. The controlled current allows controlled recovery of the grid after the fault has cleared (not studied in this paper).
3. The transient overvoltages and overcurrents are better controlled. This is visible comparing Figure 2a-d with that controlled case in Figure 3a-d.

It should be noted that the benefits in these examples are not all significant in the simulated cases for this paper, but this is highly dependent on the DC grid and the protection coordination within the grid. Achieving optimal use of the additional protection capability in different applications and DC-DC role in post-fault recovery are topics for further research.

6. REFERENCES

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