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DC Fault Protection of Multi-terminal HVDC Systems Using DC Network Partition and DC Circuit Breakers

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Abstract

This paper concentrates on using fast acting DC Circuit Breakers (DCCBs) at strategic locations to allow the entire Multi-terminal HVDC (MTDC) system to be operated interconnected but partitioned into islanded DC network zones following faults. This configuration uses least number of DCCBs in order to minimise the capital cost and power loss while retaining the benefit of system interconnection. The proposed concept has greater flexibility during normal operating condition and reduces the need for pre-fault partitioning of the system. During a DC fault, the DCCBs at the strategic cable connections that link the different DC network partitions are opened such that the faulty DC section is quickly isolated from the remaining of the MTDC system. Thus, the healthy DC network zone can recover and power transmission can be restored quickly. The faulty DC section can be protected using slow AC circuit breakers. MATLAB/SIMULINK simulations are presented to demonstrate satisfactory system behaviour during DC faults.

Keywords

HVDC, Multi-terminal HVDC system, DC fault, DC network partition, Modular Multilevel Converter (MMC), DC Circuit Breaker.

I. Introduction

Increased global energy demands and the utilization of renewable energy generation have raised new requirements for the future electricity grid connection. At present many countries are trying to reduce their energy dependence on fossil fuels, nuclear energy, etc. and to focus more on renewable energy sources to cover their energy needs. To accommodate the high penetration of renewable generation and increase the security of supply require large scale network integration and the need for longer distance power transmission. HVDC becomes a more preferable choice in terms of transmitting a bulky amount of power over a long distance and VSC technology has been the main focusing area of recent HVDC research due to its inherent advantages.

Multi-terminal HVDC system (MTDC) connects more than two converter stations at an HVDC transmission network. The most appropriate technology for multi-terminal applications are VSC based HVDC as line commutated converter (LCC) based HVDC is much more difficult to configure as MTDC due to the requirement to change the DC voltage polarity for power flow reversal. The VSC based HVDC technology has greater flexibility for large-scale offshore transmission network integration due to its ability for AC voltage support, independent control of active and reactive power and black–start capabilities [1-2].

Even though MTDC has great operational flexibility there are several technical challenges that need to be addressed, and in particular the protection of an MTDC system in the event of a fault at the DC side of the network including fault protection, fault location and isolation [1-3]. The protection system has to be designed in such a way that it can act fast, e.g. within few milliseconds, as the rate of rise of DC fault current is very high due to the low impedance of the DC network. An effective protection method needs to detect the fault and its location and isolate the faulty line in a selective manner allowing fast restoration of normal system operation following a DC fault [4-7].

There are several protection method have been proposed for MTDC system [4, 6-8]. A protection method of VSC based MTDC system was discussed in [9] in which a ‘Handshaking’ method using DC switchgear and AC circuit breakers were proposed. But the system recovery is slow which can pose significant operational problems for MTDC systems and connected AC networks due to the large loss of infeed. Fast and reliable fault detection is mandatory to clear the fault on time to avoid the shutdown of the entire systems. In that case, fast acting DCCB which is capable of operating within a few milliseconds have to be adopted to isolate the faulty cable such that the healthy part of the DC network can continue operating. But there are some drawbacks of using DCCBs which are as follows:

- High capital cost
- Large footprint
- High on state loss

In this paper, possible MTDC system configurations are analysed in terms of DC fault protection considering the minimal use of DCCBs for reduced cost and power loss. The proposed system configuration concentrates on using least number of fast acting DCCBs at strategic locations to allow the entire MTDC system to be operated interconnected but partitioned into islanded sections following faults. The rest of the paper is structured as follows: Section II describes the fault behaviour of an MMC based converter. DC network configuration and protection arrangement are outlined in section III and system configuration is described in section IV. The simulation studies of the proposed concept are presented in section V and section VI draws the conclusions.

II. DC Fault Behaviour

DC faults can cause serious consequences for VSC based HVDC systems due to the low impedance of the DC network and the existence of the freewheeling diodes in converters. DC faults can be caused by several reasons such as ship anchors for undersea cables or lightening strike in case of overhead lines, physical damage, electrical stress, cable aging and environmental stress [10]. When a DC fault occurs, the current increases significantly due to the discharge of the DC cable capacitor, AC side current feeding through the freewheeling diodes that can potentially damage the power electronic devices [11]. In case of a MTDC system, a single DC fault could potentially bring down the whole DC system and all converter stations connected to the common DC network would experience over-current leading to the complete system being shut down for prolonged period. Primarily, the DC faults that are possible in an HVDC system can be categorized as line-to-line fault and line-to-ground fault [12]. As line-to-line fault usually results in higher fault current, thus only the line-to-line fault response is considered in this paper.

The simplified equivalent circuit of a half bridge MMC during a DC line-to-line fault is shown in Fig. 1 where the behaviour of a single SM when its capacitor switched in (T_1 is ON) is also shown in same figure. Unlike the two-level VSC, half bridge MMC does not have a large DC link capacitor at converter terminal though cable capacitor is still present. For MMC converter, the total DC voltage in each converter leg under normal operation equals the nominal DC link voltage. It indicates that approximately half of the SMs are connected to their internal DC capacitors.

To analyse the fault behaviour of the circuit shown in Fig. 1, a number of stages can be considered [13]. The first stage refers to the first sub-milliseconds after the fault initiation. During this stage, the converter remains operational until it is blocked due to over-current and/or DC under voltage. Both the cable capacitor and the capacitors within the SMs will discharge. Due to the short period the discharge of the SMs' DC capacitors are not significant. The second stage, all IGBTs will be blocked. The SMs are now equivalent to diodes meaning that converter will work as a bridge converter. The DC fault current is mainly provided by the discharging of the cable capacitance and the three-phase AC source through the AC side and arms inductors. This stage is the most serious in terms of fault. Due to the relatively small cable capacitance compare to the conventional 2-level VSCs, the maximum DC fault current is expected to be considerably lower for MMC based converter.

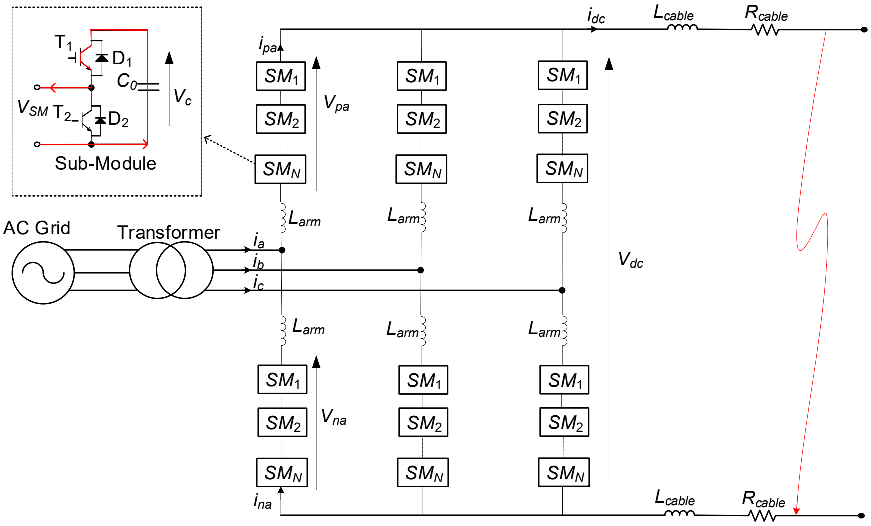


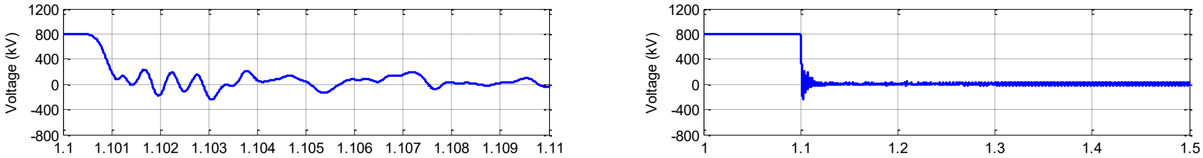
Fig. 1 Equivalent circuits of half bridge MMC during DC line-line fault

Table 1 Parameters of the simulated system

Item	MMC Station 1	MMC Station 2
Rated Apparent Power (S)	1000MVA	1000MVA
Rated Active Power (P)	±1000MW	±1000MW
Converter Nominal DC Voltage	800kV (±400kV)	800kV (±400kV)
AC Grid Voltage	400kV	400kV
Nominal Frequency	50Hz	50Hz
SCR	5	10
Transformer rated Power	1000MVA	1000MVA
Transformer Voltage ratio	400/400kV	400/400kV
Transformer Reactance	20%	20%
Arm Inductance	10%	10%

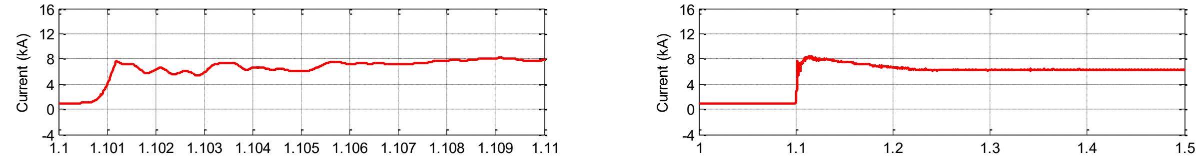
A typical back-to-back half-bridge MMC based converter has been considered for analysing the DC fault behaviour and the system parameter are shown in Table1. A permanent DC line-to-line fault is applied at 1.1s and the MMC based converter is blocked 1ms after the fault initiation. Fig. 2 shows the system response during the whole fault period. Short (Figs. 2(a)-(e)) and long (Figs. 2(f)-(j)) duration time-scale waveforms have been presented for ease of analysis.

Figs. 2(a) and (f) show the collapse of the converter DC link voltage with oscillations immediately after the DC line-to-line fault initiation. Due to the arm reactance the DC link voltage can go to negative. Figs. 2(b) and (g) represent the converter DC currents showing slow increase due to the presence of the converter transformer leakage inductance and arms reactance. Figs. 2(c), (h) and (d), (i) show the upper and lower arm currents respectively where the arm currents of the converter tend to be negative which confirms that the in-feed currents from the AC to DC sides during DC fault are flowing through the anti-parallel diodes. Figs. 2(e) and (j) show large AC currents feeding from the AC networks during the fault period.



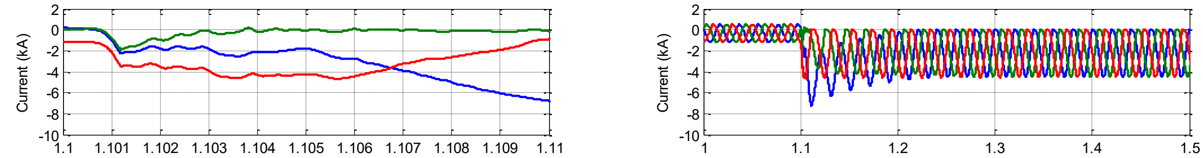
(a) DC Link Voltage

(f) DC Link Voltage



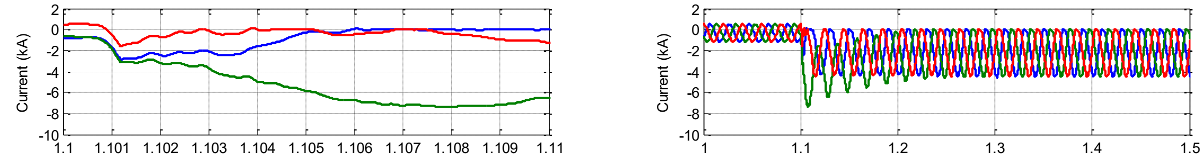
(b) DC Link Current

(g) DC Link Current



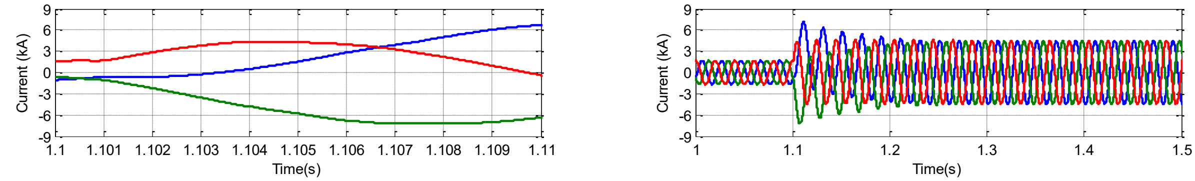
(c) Upper Arm Current

(h) Upper Arm Current



(d) Lower Arm Current

(i) Lower Arm Current



(e) Converterside Current

(j) Converterside Current

Fig. 2 Response from a half bridge MMC converter during DC line-to-line fault

III. DC Network Configuration and Protection Arrangement

A. DC Network Configuration

The infrequency of DC fault events and the inconsistency of power generation from wind farms, the expected cost of losing access to that energy may not be sufficient to justify investment in multiple DCCBs. In that case, the DC grid should be configured in a number of partitions where a fault anywhere on a particular partition would result in the entire partition being isolated by clearance from “slow” DC switches and circuit breakers on the AC side. The partitioning should be such that the power being supplied from any partition to any AC system to which it is connected is less than the limit for a permanent ‘loss of infeed’ limit of that AC system. However, such partitioning reduces the operational flexibility of the DC grid. Fast acting DCCBs located at strategic locations connecting different DC network partitions may allow the full DC grid to be operated interconnected pre-fault but partitioned into islanded sections following faults. A typical DC network configuration is shown in Fig. 3 where only limited numbers of DCCBs are used to reduce the cost of the entire MTDC system. In case of any fault event within one DC partition at least two of the DC network zones can continue operating.

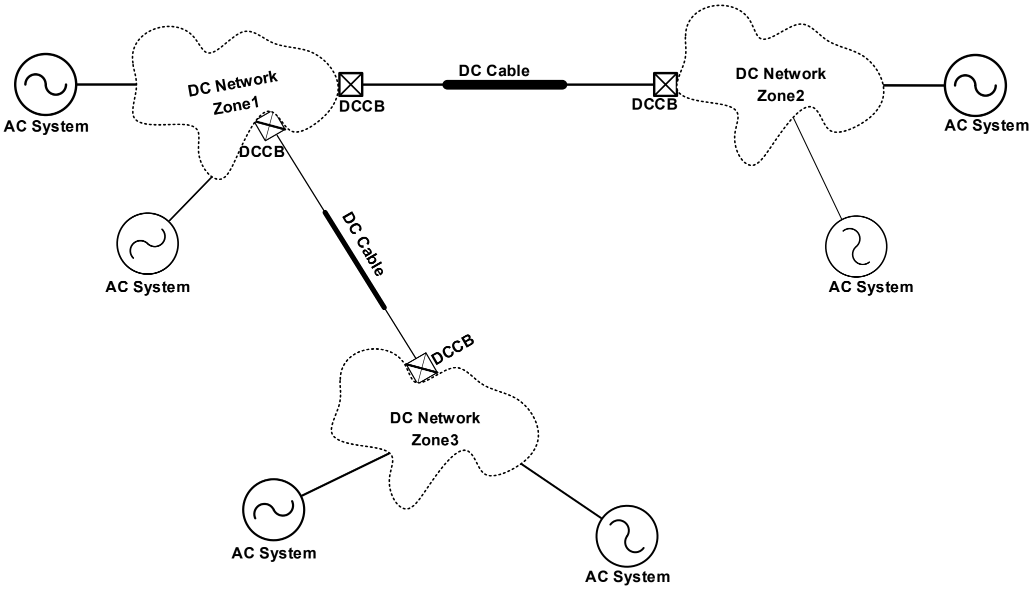


Fig. 3 Possible DC network configuration using DC partition and least number of DCCBs

B. Protection Arrangement

There are a few possible ways to clear the DC side faults without causing a large loss of infeed. Different protection strategies for MTDC system have been described and analysed in [4, 7-9, 14, 15]. The main purpose of this work, in case of any fault event in one DC zone, the healthy zone will achieve normal operation after isolating the connection cables using the equipped DCCBs. The faulty DC section can be protected using slow AC circuit breakers and DC switches. The following steps have been taken for the proposed system to clear a DC fault.

Step 1: Using local current measurement approach to detect the fault current which is flowing through DCCBs and converter arms.

Step 2: If the fault current goes above pre-determined set value the DCCBs will be set to open with a 10ms delay for this study. In addition, a converter will be blocked if its arm current reaches its threshold protective level.

Step 3: After isolating the faulty zone the system will restart for the normal operation

Step 4: By opening the ACCBs of the faulty zone can be protected.

IV. System Configuration

Different types of configurations can be arranged for MTDC systems which result in different requirements for the system model, control, protection scheme, etc. For example, the optimal configuration of the MTDC system based on offshore and onshore wind farms connections largely depend on their locations. Fig. 4 shows the five-terminal MTDC system considered in the paper consisting of MMC based converter connected to AC systems. More terminals can be added easily to the system, once the control and operation have been dealt with. The system contains two DC zones which are interconnected by DC cables equipped with DCCBs. No DCCBs are used within each DC zone so as to minimise the cost and power loss.

In this proposed system 100mH limiting reactors are connected between the DC line on both positive and negative pole as shown Fig. 4. The main purpose of using DC reactors is to decrease the rate of increase in current so as to allow the system more time to detect and isolate the fault before the rest of the network experiences over currents.

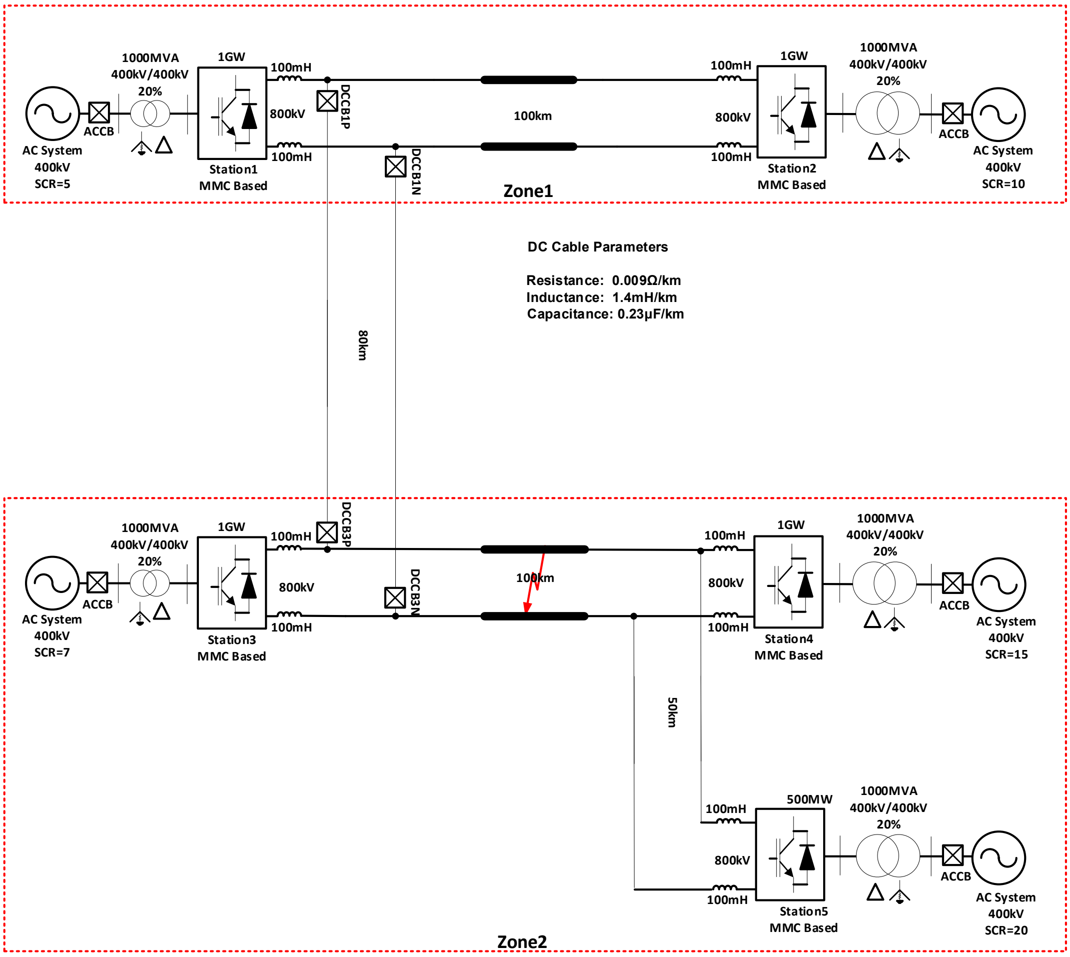
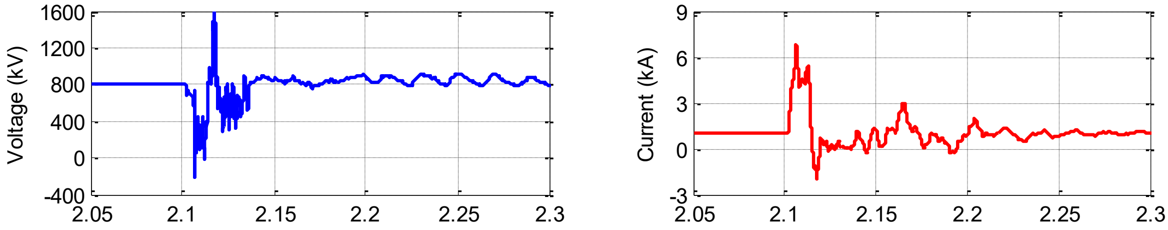


Fig. 3 Block diagram of a proposed five terminal MMC based MTDC system

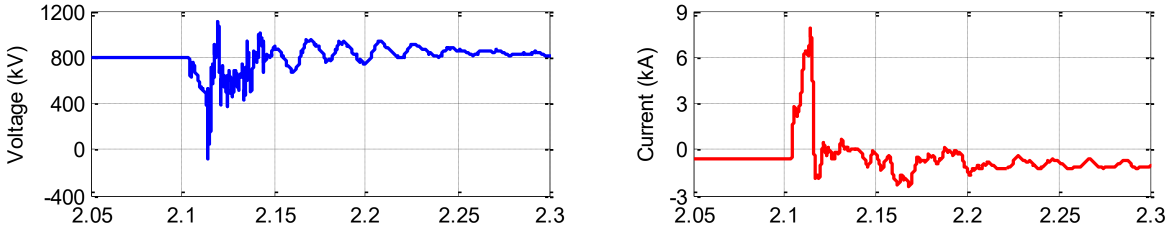
V. Simulation Studies

The proposed protection method is applied to the MTDC system shown in Fig. 4 and verified in MATLAB-SIMULINK environment Modelling an MMC converter in detail switching mode requires large computational efforts, thus, average models with controllable voltage and current sources are used, and additional semiconductor devices are added to ensure that the model accurately replicates all possible current paths in a real converter during DC faults. On this configuration Pi model of the cable is used.

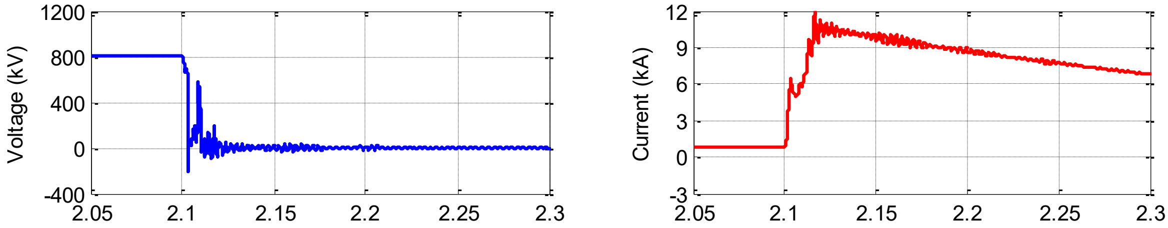
The Station 1 and 3 are assigned to transmit 800MW and 600MW power to the DC grid, respectively. Station 5 transmits 400MW power to the AC grid whereas Station 2 and 4 regulate the DC link voltage (800KV) of the entire MTDC grid using DC droop control to ensure effective active power sharing between the two. For simplicity, each converter operates at unity power factor. A DC line-to-line fault is applied at the time instant of 2.1s. In this case, the fault is placed at the midpoint of the transmission line between station 3 and 4 which is 50 km away from both stations. DCCBs are enabled and operated in accordance with automatic fault detection including 10ms time delay for the breaker to activate.



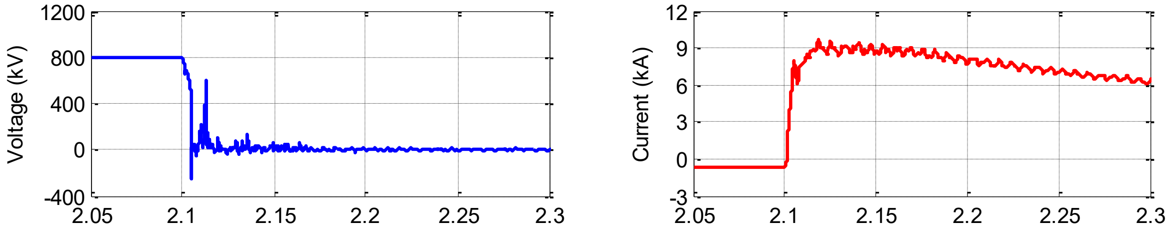
(a) DC Link Voltage Station1 (f) DC Link Current Station1



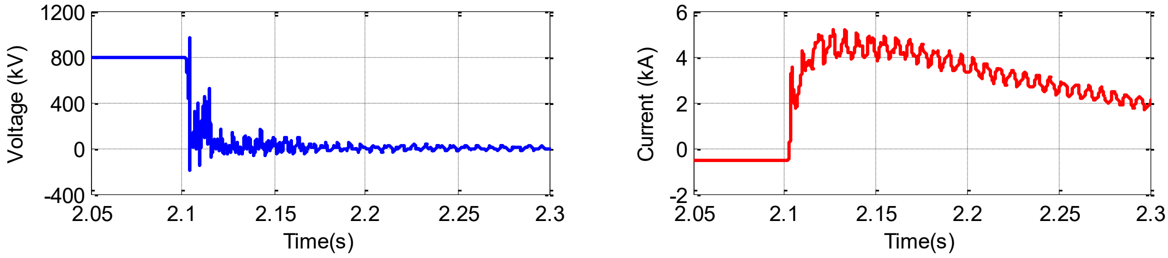
(b) DC Link Voltage Station2 (g) DC Link Current Station2



(c) DC Link Voltage Station3 (h) DC Link Current Station3



(d) DC Link Voltage Station4 (i) DC Link Current Station4

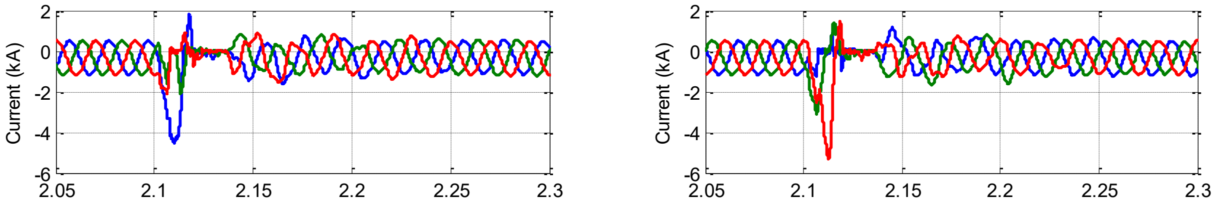


(e) DC Link Voltage Station5 (j) DC Link Current Station5

Fig. 4 System behaviour on the DC side during a DC fault at 2.1s

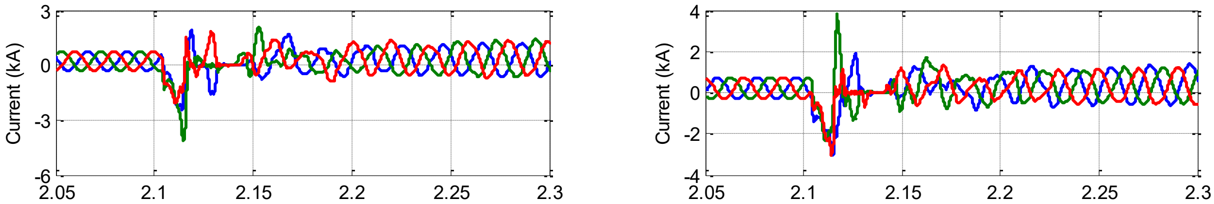
The obtained results representing the system's behaviour are presented in Figs. 5(a)-(e), where the responses of the DC voltage magnitudes (as recorded on the DC Link voltage of each converter) to the fault are shown. It is evident from Fig. 5, that the existence of the DC fault line will have severe impacts on the entire system which lead to DC voltages collapse and increase in DC link current. The DC link voltages on each side of the faulty line decrease faster than the other DC link voltages. From Figs. 5(a)-(e) it can be seen that the DC link voltage decays to approximately zero-negative value once the local converter station is blocked. The DC link Voltage of Stations 1 and 2 take longer to fall to zero compare to other stations as they are further away from the fault. Figs. 5(f)-(j) demonstrate the DC link current during the fault. It can be seen that the fault peak current is higher in station 3 and 4 compare to others due to the distance of the fault location.

Fig. 6 represents the upper and lower arm currents respectively. In this proposed system as soon as a fault occurs all the converters have been blocked in a selective manner using automatic detection and blocking method. In this simulation study station 1-5 are blocked their converters at 6ms, 14ms, 3ms, 5ms and 4ms respectively after the fault initiation. After blocking the converter, the AC current continue increasing (see Fig. 7) through the freewheeling diodes.



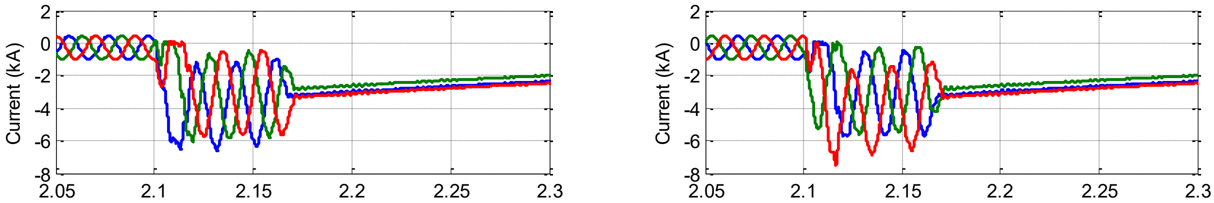
(a) Upper Arm Current Station1

(f) Lower Arm Current Station1



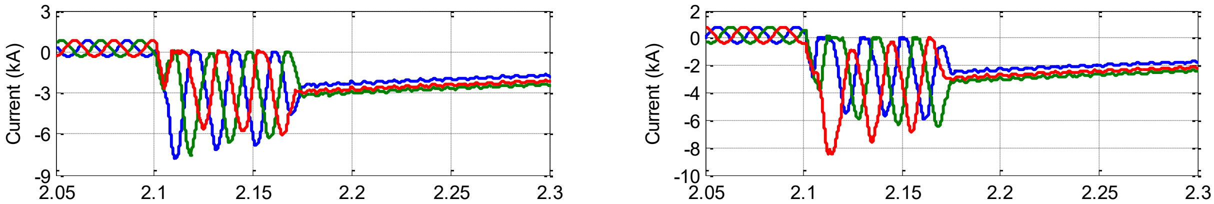
(b) Upper Arm Current Station2

(g) Lower Arm Current Station2



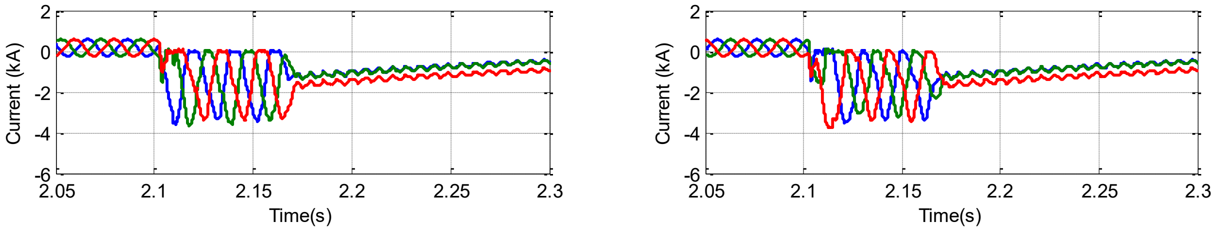
(c) Upper Arm Current Station3

(h) Lower Arm Current Station3



(d) Upper Arm Current Station4

(i) Lower Arm Current Station4

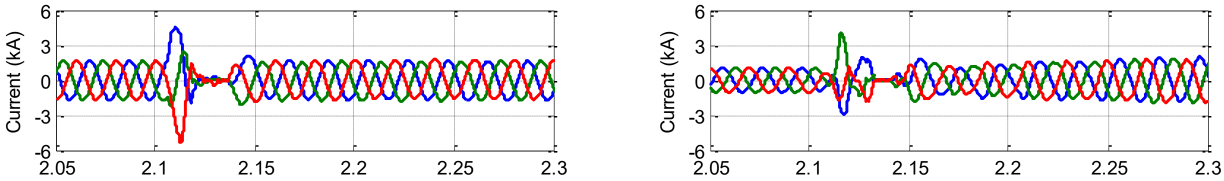


(e) Upper Arm Current Station5

(j) Lower Arm Current Station5

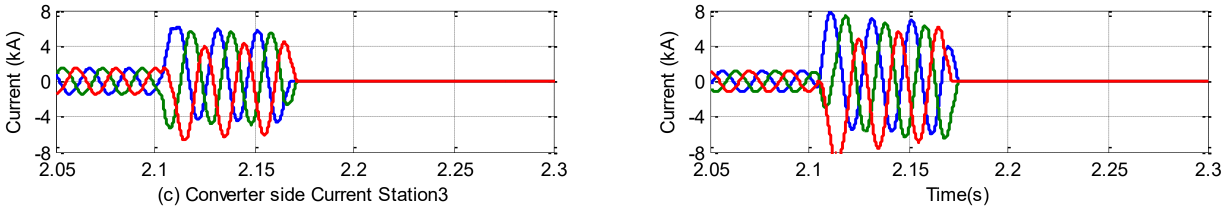
Fig. 6 Arm currents during a DC fault at 2.1 s

In this simulation DCCB1P and DCCB1N are opened 13ms after fault initiation (including detection time) whereas for DCCB3P and DCCB3N, it is 12ms. After the opening of the DCCBs, the MTDC system is split into two isolated DC zones. The AC current, the arm current and the DC currents in the healthy zone (i.e. Zone 1) will decay to zero. Therefore, the DC voltage quickly rises to their steady-state level (see Figs. 5-7) and the system can be restarted for normal operation.



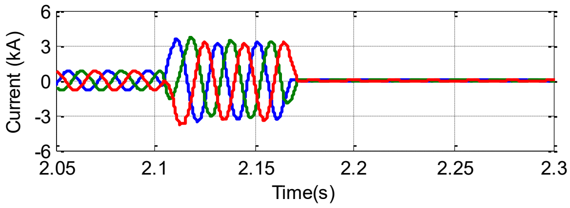
(a) Converter side Current Station1

(b) Converter side Current Station2



(c) Converter side Current Station3

(d) Converter side Current Station4



(e) Converter side Current Station5

Fig. 5 Converter side AC currents during a DC fault at 2.1 s

System recovery process is the key factor for the healthy part of the MTDC system. In this case after disconnection of the cable between station1 and 2 where the DCCBs are located, the healthy zone (Zone 1 in the example) needs to be restarted for the normal operation. Thus, Station 1 and 2 are restarted at 36ms and 44ms respectively after the fault initiation with station 2 controlling the DC link voltage and Station 1 regulating active power. The healthy zone is reached in steady state within 300-400ms after the recovery process. On the other hand the faulty zone (i.e. Zone 2) is protected using "slow" AC circuit breakers. In this simulation study AC circuit breakers in Station 3, 4, and 5 are opened at 63ms, 65ms and 64ms respectively after the fault initiation.

Another important observation is that the loss of a transmission line due to fault results in a reduction in overall power capacity of the MTDC system. This has a direct consequence on the remaining healthy lines of the MTDC system and proper power rescheduling will be required to ensure stable system operation.

VI. Conclusions

DC fault protection of an MTDC system has emerged as the critical issue at present due to the low impedance of DC networks. DC network partition with minimum use of DCCBs at strategic locations are proposed and studied in this paper. In this case the faulty DC section is isolated using DCCBs allowing the healthy DC section to recover and restore quickly while the faulty zone is protected by AC circuit breakers which are already installed on the AC sides. The simulation results corresponding to DC fault protection have been presented give a satisfactory result. The proposed concept based on a five terminal MTDC system have been studied here, can be extended to different terminal numbers and DC network partitioned which could be cost effective.

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