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Multi-Terminal DC Fault Identification for MMC-HVDC Systems based on Modal Analysis - A Localized Protection Scheme

Vaibhav Nougain, Sukumar Mishra, *Senior Member, IEEE*, George S. Misyris, *Student Member, IEEE* and Spyros Chatzivasileiadis, *Senior Member, IEEE*

Abstract—For the purpose of DC fault identification in multi-terminal modular multilevel converter (MMC) high voltage DC (HVDC) systems, the proposed work addresses the issues of localized protection schemes. The proposed work is focused on selectivity issues such as differentiating between forward external and internal faults, and classification of type of fault contingency i.e., pole to pole (PTP) or pole to ground (PTG) in the system. The scheme uses equivalent network of multi-terminal MMC-HVDC systems for DC fault identification. Modal transformation is used to analyse line-mode and zero-mode voltage across the current limiting reactor (CLR) for different possible contingencies in the system. A maloperation region has been defined to address the issue of selectivity of internal HIFs and external low impedance faults (LIFs). Rate of change of DC voltage (dU_{dc}/dt) is used as the mitigation technique to differentiate a HIF as high as 1000Ω . Further, a sensitivity function is formulated which gives the variation of decisive parameters i.e., line-mode voltage and zero-mode voltage with respect to change in fault resistance and value of current limiting reactor. PSCAD/EMTDC based simulations are used to validate the performance of the proposed scheme. The scheme is validated in terms of detection time, robustness to WGN in measurement, security for AC faults, DC circuit breakers (DCCB) operation, power reversal (load transients).

Index Terms—MMC-HVDC, localized protection, fault identification, DC fault.

I. INTRODUCTION

THE idea of better scalability and very low harmonics has made modular multilevel converter (MMC) technology effectively applicable for HVDC systems with the objective of transmitting large offshore wind energy over long distances [1]-[3]. Multi-terminal MMC-HVDC configuration ensuring system reliability with continuous operation of power transfer even under DC faults has resulted in practical offshore wind projects like European "Super Grid" [3] and the four-terminal 3000 MW HVDC project in Zhangbei, China [13]. However, in case of a multi-terminal configuration, since there are numerous MMC terminals finding different paths (with different impedances) to contribute

to the fault current, the fault current is relatively higher compared to the conventional point to point HVDC system [4], which has a contribution from only two terminals. In order to mitigate the damage to the power electronic switches of MMC converters due to the fault current, direct current circuit breakers (DCCB) are used to isolate the faulty part of the network in time, ensuring continuous power transfer in the multi-terminal MMC-HVDC systems [5]. Therefore, a rapid and reliable fault identification scheme for DC faults is an indispensable requirement for such configurations.

Considering the fault identification schemes for multi-terminal MMC-HVDC systems in the literature, travelling wave (TW) based localized methods are effective and hence, popular. The authors in [6] employ rate of change of local current, synonym of ROCOC. The authors in [7] take the rate of change of voltage (ROCOV) of the current limiting reactor (CLR) to identify the fault upon inception. However, high impedance faults (HIFs) and the presence of white gaussian noise (WGN) jeopardize the reliability of the schemes in [6]-[7]. The rate of change of ROCOV of the CLR has been taken as the decisive parameter by authors in [8] working on the problem of maloperation due to WGN. However, the decision on minimum time window required for noise immunisation is a tricky affair for complex systems with multiple converters [9]. The authors in [10] take the transient energy ratio of DC Filter Link as the decisive parameter for fault identification whereas the authors in [11] employ the CLR Power. The authors in [12] propose a scheme integrating rate of transient voltages and communication based backup protection. The schemes in [10]-[12] work effectively for HIFs. However, the performance of such schemes is sensitive to fault type and fault resistance; at the same time the impact of noise [14] has also not been discussed in [10]-[12]. In addition, as pointed in [14], accurately distinguishing between external and internal faults is a problem unresolved with schemes proposed in [6]-[12].

Working on the aspect of selectivity for external and internal faults, the authors in [13] use frequency domain based ratio of transient voltages to distinguish between external and internal faults in the system. However, the scheme has weakness to WGN [14]. The authors in [14] employ phase-modal transformation to propose an elaborate analysis working on the effect of WGN and distinguishing between

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external and internal faults. The scheme proposed in [14] gives a good theoretical foundation to classify the faults based on line-mode and zero-mode voltage across the current limiting reactor. The scheme in [14] covers the broad analysis under forward external faults. However while distinguishing between internal HIFs and forward external low impedance faults (LIFs) using line-mode voltage, the scheme may have selectivity issues. This is a result of not considering the sensitivity of the decisive parameters with respect to fault resistance, R_f . The line mode and zero mode voltages used to analyse different fault contingencies in [14] are sensitive to fault resistance. As a result of which, they show similar characteristics for forward external LIFs and internal HIFs. This means that method proposed in [14] is prone to maloperation for internal HIFs and forward external LIFs. The contribution of the proposed work is inclusion of fault resistance in the mathematical analysis in order to classify forward external LIFs and internal HIFs. ROCOV (dU_{dc}/dt) with threshold, M_{set} is used to classify the similar ranging line-mode voltage of mentioned family of faults. This makes the mode voltage based classification implementable for HIFs up to 1000Ω . The proposed work defines a maloperation region analysis to classify between low impedance forward external and high impedance internal faults in a system. The proposed work formulates a sensitivity function to analyse the variation of decisive parameters in the proposed protection approach with respect to fault parameters i.e., fault resistance and value of current limiting reactor in the system.

The rest of the paper is organized as follows. Section II gives the test system configuration elaborating the MMC equivalent model, the overhead line (OHL) equivalent model and system equivalent network for different fault contingencies. Section III gives the fault analysis for different fault contingency in the system based on line-mode and zero-mode voltage. This is followed by the concept of maloperation region for internal HIFs and external LIFs and its mitigation. Section IV presents the proposed fault identification algorithm. Section V validates the scheme for different events. It also gives the sensitivity analysis of mode-voltages with respect to fault parameters. Finally, section VI concludes the paper.

Fig. 1: CIGRE 4-bus Multi-terminal benchmark Grid [17]

II. TEST SYSTEM CONFIGURATION

CIGRE 4-bus multi-terminal benchmark grid [17] is considered for the MMC-HVDC configuration as the test system

to validate the proposed fault identification scheme [refer to Fig. 1]. Current limiting reactors (L_{Tmn}) are employed to mitigate the rate of rise of current in case of a fault contingency in the system [18]. Fault F_1 shows a fault in line 1 at a specific location whereas fault F_2 shows a forward external fault and F_3 shows a backward external fault in the system. A bipolar line configuration with frequency-dependent transmission model (FDTL) for overhead lines (OHL) is considered for the system [24].

A. MMC simplified equivalent model

The MMC configuration is represented with its simplified equivalent model [25] as shown in Fig. 2. The parameters in the simplified model are defined as, $R_{MMC} = \frac{2}{3}(R + \Sigma R_{on})$, $L_{MMC} = \frac{2}{3}L$, $C_{MMC} = 6\frac{C}{N}$. Here R is the arm resistance and ΣR_{on} is the sum of the on-state resistances of all IGBT modules [25]. L is the arm inductance, C is the sub-module (SM) capacitance and N gives the number of SMs per arm. L_{Tmn} is the CLR, whereas i_{s1p} and i_{s1n} are the source currents for the positive and negative pole. $U_{L12,p}$ and $U_{L12,n}$ are the positive and negative pole voltages across the CLR, whereas $i_{L12,p}$ and $i_{L12,n}$ are the positive and negative pole currents through the CLR.

Fig. 2: Equivalent model of MMC system

B. OHL equivalent model

Distributed parameter model of a bipolar OHL is shown in Fig. 3. C_{g0} and C_{p0} are defined as grounding capacitor and phase capacitor per unit length. L_{mn0} , R_{mn0} and M_{mn0} are defined as the self-inductance, resistance and mutual inductance of line mn per unit length [14].

Fig. 3: Distributed parameter model of bipolar OHL

Considering the parameters of multi-terminal MMC-HVDC configuration, the fault interruption needs to be within 3ms of fault inception [13]-[14]. This period sees fault current contribution from the DC capacitance of MMC and the grounding and phase capacitance of line. The equivalent DC capacitor of MMC is around 10^2 - $10^3 \mu F$ [21] while grounding capacitor and phase capacitor are within $0.01 \mu F/km$ [20]. Hence, the fault contribution from the grounding and phase capacitance of OHL can be ignored [22]. The grounding capacitor and phase capacitor for underground cables (UGC) can be as high as $0.5 \mu F/km$. Hence, the conclusion is valid for short to medium UGC as well.

Fig. 4: Equivalent network of MMC-HVDC system with bipolar OHL under P-PTG fault

C. Equivalent network during a fault contingency

Combining the MMC equivalent model and OHL equivalent model, Fig. 4 shows the equivalent network of MMC-HVDC system with bipolar OHL during (P-PTG) fault. The fault location d is the percentage of unit length with fault resistance R_f . In order to decouple the dependency of poles of transmission lines under pole to ground (PTG) faults, phase-modal transformation [14] is incorporated to the mentioned equivalent network. This phase-modal transformation for bipolar DC is analogous to symmetrical component transformation in 3ϕ AC. The phase-modal transformation is mathematically expressed as:

$$\begin{bmatrix} x_l \\ x_0 \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_p \\ x_n \end{bmatrix} \quad (1)$$

x_l and x_0 are defined as the line-mode and zero-mode variables whereas x_p and x_n are the positive-pole and negative-pole variables. The line-mode and the zero-mode equivalent network for fault F_1 in Fig. 1 is shown in Fig. 5 where C_{14} and C_{23} are the equivalent DC link terminal capacitances for line 14 and 23. Z_{14} and Z_{23} are the equivalent impedance for line 14 and 23 and are defined as:

$$\begin{cases} Z_{14}(j\omega) = j\omega(L_{41} + L_{T41}) + \frac{1}{2}L_{MMC4} + R_{41} + \frac{1}{2}R_{MMC4} & (2a) \\ Z_{23}(j\omega) = j\omega(L_{23} + L_{T32}) + \frac{1}{2}L_{MMC3} + R_{23} + \frac{1}{2}R_{MMC3} & (2b) \end{cases}$$

The mutual inductance of OHL is also transformed into L_{mn_l} and L_{mn_0} as:

$$\begin{cases} L_{mn_l} = L_{mn} - M_{mn} & (3a) \\ L_{mn_0} = L_{mn} + M_{mn} & (3b) \end{cases}$$

III. FAULT ANALYSIS FOR DIFFERENT FAULT CONTINGENCIES

A. Internal pole to ground (PTG) fault contingency

For an internal positive-pole to ground (P-PTG) fault contingency shown as F_1 in Fig. 1, $U_{f_p}(j\omega) = i_{f_p}(j\omega)R_f$ and $i_{f_n}(j\omega) = 0$. Using the phase-modal transformation, the conditions are transformed to the form:

$$\begin{cases} U_{f_l}(j\omega) + U_{f_0}(j\omega) = 2i_{f_l}(j\omega)R_f & (4a) \\ i_{f_l}(j\omega) = I_{f_0}(j\omega) & (4b) \end{cases}$$

Fig. 5: Simplified Equivalent network for (a) line-mode, (b) zero-mode

Considering equation 4, the combined equivalent mode network for an internal P-PTG is shown in Fig. 6. The idea is to derive the line-mode voltage ($U_{L12_l}(j\omega)$) and zero-mode voltage ($U_{L12_0}(j\omega)$) across the CLR (L_{Tmn}).

$$\begin{cases} U_{L12_0}(j\omega) = \frac{j\omega L_{T12} U_{dc}}{Z_1 + Z_2 \parallel [(Z_3 \parallel Z_4) + 2R_f]} \times \frac{Z_2 \parallel [(Z_3 \parallel Z_4) + 2R_f]}{Z_3} & (5a) \\ + \frac{j\omega L_{T12} U_{dc}}{Z_2 + Z_1 \parallel [(Z_3 \parallel Z_4) + 2R_f]} \times \frac{Z_1 \parallel [(Z_3 \parallel Z_4) + 2R_f]}{Z_3} \end{cases}$$

$$\begin{cases} U_{L12_l}(j\omega) = -\frac{j\omega L_{T12} U_{dc}}{Z_2 + Z_1 \parallel [(Z_3 \parallel Z_4) + 2R_f]} \times \frac{Z_1 \parallel [(Z_3 \parallel Z_4) + 2R_f]}{Z_1} & (5b) \\ + \frac{j\omega L_{T12} U_{dc}}{Z_1 + Z_2 \parallel [(Z_3 \parallel Z_4) + 2R_f]} \times \frac{Z_2 \parallel [(Z_3 \parallel Z_4) + 2R_f]}{Z_2} \end{cases}$$

where U_{dc} is pre-fault rated DC voltage of MMC-HVDC system. The impedances, Z_1 - Z_4 are frequency-dependent functions. Also, R_{MMCn} and R_{mn} are neglected in the calculation due to small magnitude for long transmission lines. For simplicity, impedances are written as Z_i and not $Z_i(j\omega)$

Fig. 6: Combined equivalent mode network for an internal PTG

and are mathematically defined as:

$$\begin{cases} Z_1 = [2(Z_{14} + j\omega L_{T14}) || j\omega L_{MMC1}] + 2j\omega(L_{T12} + dL_{12,1}) & (6a) \\ Z_2 = [2(Z_{23} + j\omega L_{T23}) || j\omega L_{MMC2}] + 2j\omega(L_{T21} + (1-d)L_{12,1}) & (6b) \\ Z_3 = [2(Z_{14} + j\omega L_{T14}) || j\omega L_{MMC1}] + 2j\omega(L_{T12} + dL_{12,0}) & (6c) \\ Z_4 = [2(Z_{23} + j\omega L_{T23}) || j\omega L_{MMC2}] + 2j\omega(L_{T21} + (1-d)L_{12,0}) & (6d) \end{cases}$$

Similarly, the line-mode voltage and zero-mode voltage for Negative-pole to ground (*N-PTG*) are defined as:

$$\begin{cases} U_{L12,0}(j\omega) = -\frac{j\omega L_{T12} U_{dc}}{Z_1 + Z_2 || [(Z_3 || Z_4) + 2R_f]} \times \frac{Z_2 || [(Z_3 || Z_4) + 2R_f]}{Z_3} & (7a) \\ U_{L12,1}(j\omega) = -\frac{j\omega L_{T12} U_{dc}}{Z_2 + Z_1 || [(Z_3 || Z_4) + 2R_f]} \times \frac{Z_1 || [(Z_3 || Z_4) + 2R_f]}{Z_3} & (7b) \end{cases}$$

B. External PTG fault contingency

1) *Backward External PTG fault contingency*: For a backward external PTG fault contingency, F_3 (see Fig. 1), the combined equivalent mode network is similar to Fig. 7 where the fault occurs behind L_{T12} instead of after L_{T12} (refer to Fig. 7). The line-mode voltage and zero-mode voltage for a backward external PTG fault are defined as:

$$\begin{cases} U_{L12,0}(j\omega) = -\frac{j\omega L_{T12} U_{dc}}{Z_5 + Z_6 || [(Z_6 || Z_7) + 2R_f]} \times \frac{Z_6 || [(Z_6 || Z_7) + 2R_f]}{Z_7} & (8a) \\ U_{L12,1}(j\omega) = -\frac{j\omega L_{T12} U_{dc}}{Z_6 + Z_5 || [(Z_6 || Z_7) + 2R_f]} \times \frac{Z_5 || [(Z_6 || Z_7) + 2R_f]}{Z_7} & (8b) \end{cases}$$

TABLE I: Polarity of line-mode and zero-mode voltages for different PTG faults

Fault Contingency	Polarity	
	$U_{L12,0}$	$U_{L12,1}$
<i>P-PTG</i>	Positive	Positive
<i>N-PTG</i>	Negative	Positive
<i>Backward External</i>	Negative	Negative
<i>Forward External</i>	Positive	Positive

where the impedances, Z_5 - Z_7 are defined as:

$$\begin{cases} Z_5 = [2(Z_{23} + j\omega L_{T23}) || j\omega L_{MMC2}] + 2j\omega(L_{T12} + L_{T21} + L_{12,1}) & (9a) \\ Z_6 = [2(Z_{14} + j\omega L_{T14}) || j\omega L_{MMC1}] & (9b) \\ Z_7 = [2(Z_{23} + j\omega L_{T23}) || j\omega L_{MMC2}] + 2j\omega(L_{T12} + L_{T21} + L_{12,0}) & (9c) \end{cases}$$

2) *Forward External PTG fault contingency*: For a forward external PTG fault contingency, F_2 (see Fig. 1), the combined equivalent mode network is shown in Fig. 7. The line-mode voltage and zero-mode voltage for a forward external PTG fault are defined as:

$$\begin{cases} U_{L12,0}(j\omega) = \frac{j\omega L_{T12} U_{dc}}{Z_8 + Z_9 || [(Z_9 || Z_{10}) + 2R_f]} \times \frac{Z_9 || [(Z_9 || Z_{10}) + 2R_f]}{Z_{10}} & (10a) \\ U_{L12,1}(j\omega) = -\frac{j\omega L_{T12} U_{dc}}{Z_9 + Z_8 || [(Z_9 || Z_{10}) + 2R_f]} \times \frac{Z_8 || [(Z_9 || Z_{10}) + 2R_f]}{Z_8} & (10b) \end{cases}$$

where the impedances, Z_8 - Z_{10} are defined as:

$$\begin{cases} Z_8 = [2(Z_{14} + j\omega L_{T14}) || j\omega L_{MMC1}] + 2j\omega(L_{T12} + L_{T21} + L_{12,1}) & (11a) \\ Z_9 = [2(Z_{23} + j\omega L_{T23}) || j\omega L_{MMC2}] & (11b) \\ Z_{10} = [2(Z_{14} + j\omega L_{T14}) || j\omega L_{MMC1}] + 2j\omega(L_{T12} + L_{T21} + L_{12,0}) & (11c) \end{cases}$$

Fig. 7: Combined equivalent mode network for a forward external PTG

TABLE II: Polarity of line-mode and zero-mode voltages for different *PTP* faults

Fault Contingency	Polarity	
	$U_{L12,0}$	$U_{L12,1}$
<i>PTP</i>	0	Positive
Backward External	0	Negative
Forward External	0	Positive

C. Internal *PTP* fault contingency

For a *PTP* fault contingency (F_1) in the system shown in Fig. 1, $U_{f-p}(j\omega) - U_{f-n}(j\omega) = i_{f-p}(j\omega)R_f$ and $i_{f-p}(j\omega) + i_{f-n}(j\omega) = 0$. Applying phase-modal transformation, the conditions are transformed to the form:

$$\begin{cases} U_{f-1}(j\omega) = i_{f-1}(j\omega)R_f \\ i_{f-0}(j\omega) = 0 \end{cases} \quad (12a)$$

$$\begin{cases} i_{f-0}(j\omega) = 0 \end{cases} \quad (12b)$$

Fig. 8: Combined equivalent mode network for an internal *PTP*

Considering equation 12, the equivalent mode network for an internal *PTP* fault is shown in Fig. 8. The line-mode voltage and the zero-mode voltage for internal *PTP* are defined as:

$$\begin{cases} U_{L12,0}(j\omega) = 0 \\ U_{L12,1}(j\omega) = \frac{j\omega L_{T12}U_{dc}}{Z_1 + Z_2||R_f} - \frac{j\omega L_{T12}U_{dc}}{Z_2 + Z_1||R_f} \times \frac{Z_1||R_f}{Z_1} \end{cases} \quad (13a)$$

$$\begin{cases} U_{L12,1}(j\omega) = \frac{j\omega L_{T12}U_{dc}}{Z_1 + Z_2||R_f} - \frac{j\omega L_{T12}U_{dc}}{Z_2 + Z_1||R_f} \times \frac{Z_1||R_f}{Z_1} \end{cases} \quad (13b)$$

D. External *PTP* fault contingency

Similar to the previous subsection, the line-mode voltage and the zero-mode voltage for a backward external *PTP* fault are defined as:

$$\begin{cases} U_{L12,0}(j\omega) = 0 \\ U_{L12,1}(j\omega) = -\frac{j\omega L_{T12}U_{dc}}{Z_5 + Z_6||R_f} + \frac{j\omega L_{T12}U_{dc}}{Z_6 + Z_5||R_f} \times \frac{Z_5||R_f}{Z_5} \end{cases} \quad (14a)$$

$$\begin{cases} U_{L12,1}(j\omega) = -\frac{j\omega L_{T12}U_{dc}}{Z_5 + Z_6||R_f} + \frac{j\omega L_{T12}U_{dc}}{Z_6 + Z_5||R_f} \times \frac{Z_5||R_f}{Z_5} \end{cases} \quad (14b)$$

Also, the line-mode voltage and the zero-mode voltage for a forward external *PTP* fault are defined as:

$$\begin{cases} U_{L12,0}(j\omega) = 0 \\ U_{L12,1}(j\omega) = \frac{j\omega L_{T12}U_{dc}}{Z_8 + Z_9||R_f} - \frac{j\omega L_{T12}U_{dc}}{Z_9 + Z_8||R_f} \times \frac{Z_8||R_f}{Z_8} \end{cases} \quad (15a)$$

$$\begin{cases} U_{L12,1}(j\omega) = \frac{j\omega L_{T12}U_{dc}}{Z_8 + Z_9||R_f} - \frac{j\omega L_{T12}U_{dc}}{Z_9 + Z_8||R_f} \times \frac{Z_8||R_f}{Z_8} \end{cases} \quad (15b)$$

Fig. 9: Classification of different fault contingencies based on $U_{Lmn,1}$ and $U_{Lmn,0}$

The line-mode and zero-mode voltages are evaluated for different fault contingencies. *PTP* fault is classified on the basis of polarity of $U_{L12,1}$ and $U_{L12,0}$ in Table I whereas *PTP* is classified in Table II. The combined classification of *PTP* and *PTG* fault contingency is shown in Fig. 9. The zero-mode voltage threshold is set to be U_{0set} in order to distinguish between *PTP* and *PTG* fault. Similar range of line mode voltage for forward external LIFs and internal HIFs is shown as *PTG* maloperation region and *PTP* maloperation region in Fig. 9. The maloperation region is defined by the area between U_{iset0} and U_{iset1} . Fig. 10 shows line mode voltage ($U_{L12,1}$) for forward external LIFs and internal HIFs (detailed in Table VI). It is evident that there exists fault region where an external fault can lead to relay tripping. Hence, jeopardizing the selectivity. The maloperation region shown in Fig. 10 consists of two types of faults i.e., external LIFs and internal HIFs. The parameter, $|dU_{dc}/dt|$ can be effectively used to differentiate a LIF and HIF as shown in Table VI. The analysis considers the maximum possible value of $|dU_{dc}/dt|$ for internal HIFs along OHL fault location. Addressing the issue of HIFs, the scheme hence can detect a fault as high as 1000Ω.

IV. PROPOSED FAULT IDENTIFICATION ALGORITHM

The fault identification algorithm employs rate of change of DC voltage (dU_{dc}/dt) as the trigger signal. If the absolute slope is greater than the threshold, D [refer section VI(A)], the algorithm evaluates $U_{L12,0}$ and $U_{L12,1}$. The decision on D is discussed in Section VI(A). The first classification is based on the analysis of zero-mode voltage, $U_{L12,0}$ where *PTP* and *PTG* family of faults are differentiated. The property of zero-mode voltage, $|U_{L12,0}| < U_{0set}$ for *PTP* family of faults (refer to Table II) is used for this purpose. The threshold, U_{0set} is defined 1kV for the practical implementation of the scheme. Once the *PTP* and *PTG* family of faults is classified, we refer to Table I and Table II to check the conditions for further classification of fault. As evident from the tables, the polarity of line-mode and zero-mode voltages differentiate the backward external faults from the other faults (forward external and internal). However, the classification

TABLE III: Parameters implemented

Symbol	Quantity	Range
$R_{MMC1}/L_{MMC1}/C_{MMC1}$	Parameters- MMC_1	192.4m Ω /60mH/300 μ F
$R_{MMC2}/L_{MMC2}/C_{MMC2}$	Parameters- MMC_2	243.2m Ω /77.3mH/375 μ F
$R_{MMC3}/L_{MMC3}/C_{MMC3}$	Parameters- MMC_3	684.8m Ω /96mH/240 μ F
$R_{MMC4}/L_{MMC4}/C_{MMC4}$	Parameters- MMC_4	371.2m Ω /72mH/450 μ F
C_{g0}, C_{p0}	Grounding and phase Capacitor per unit length	0.0078 μ F/km, 0.0085 μ F/km
L_{mn0}, L_{Tmn}	Self-inductance per unit length, Current Limiting reactor	1.82mH/km, 90mH-150mH
R_{mn0}	Line Resistance per unit length	102m Ω /km
$OHL_1/OHL_2/OHL_3/OHL_4$	DC overhead line length	300km/240km/150km/380km
D, U_{0set}	Threshold for $ dU_{dc}/dt $, Threshold for zero-mode voltage	100kV/ms, 1kV
U_{Iset1}, U_{Iset2}	Threshold 1 and 2 for line-mode voltage	PTP- 170kV, PTG- 85kV, PTP- 300kV, PTG- 150kV
M_{set}	Threshold of dU_{dc}/dt to mitigate maloperation region	PTP- 3000kV/ms, PTG- 1500kV/ms,

Fig. 10: Simulation validation for maloperation region for Line Mode Voltage (kV) with Time (sec) for (a) Forward External (0.01 Ω), PTP (480 Ω), (b) Forward External (0.35 Ω), PTP (500 Ω), (c) Forward External (3.1 Ω), PTP (1000 Ω)

of forward external and PTP internal or forward external and PTG internal have a maloperation region where the differentiation between the internal and forward external fault is not possible looking into the line-mode voltage alone. Thresholds, U_{Iset1} and U_{Iset2} are defined to identify the maloperation region. If $U_{Iset1} < U_{L12,l} < U_{Iset2}$ is satisfied, the decision on internal or external fault is taken using $|dU_{dc}/dt| > M_{set}$. Here M_{set} is the threshold to mitigate the maloperation. The flowchart shown in Fig. 11 shows the proposed protection scheme.

V. RESULTS AND VALIDATION

Fig. 1 shows the four-terminal MMC-HVDC system with DC voltage of ± 200 kV. MMC at bus 1 operates in DC voltage control and constant reactive power control [23]. MMCs at bus 2-4 operate in constant active and reactive power control. The parameters employed for different MMCs are shown in Table III.

TABLE IV: Parameters implemented for different MMCs

	MMC ₁	MMC ₂	MMC ₃	MMC ₄
Capacity (MW)	800	1200	1600	2000
Rated DC Voltage (kV)	± 200	± 200	± 200	± 200
Rated Current (kA)	0.8	1.2	1.6	2
No. of SMs per arm	200	200	200	200

The different parameters employed in the overall scheme are shown in Table IV. The sampling frequency (f_s) of the proposed scheme is 20 kHz. For the wavelet transform is set as 1-level and the corresponding frequency is 5 kHz-10 kHz [13]. The mother wavelet is selected as sym8 [15]. Frequency

Fig. 11: Flowchart of proposed protection scheme

dependent (phase) model is used to model overhead transmission line (OHL) with DC correction (refer Appendix). The test system is simulated employing PSCAD/EMTDC based electromagnetic transient simulations.

A. Evaluating trigger event threshold, D

The absolute rate of change of DC voltage, $|dU_{dc}/dt|$ is used as the trigger event for the evaluation of decisive parameters, $U_{L12,0}$ and $U_{L12,1}$. The threshold for the trigger event, D is defined for a DC fault contingency in the system with the objective that normal system transients should not be identified as a fault. The decision for D is taken considering different type of fault contingencies, *PTP* and *PTG*, with varying fault location in the OHL and for varying fault resistance, R_f . As shown in Fig. 12, the magnitude of $|dU_{dc}/dt|$ decreases with the increase in fault resistance, R_f and the increase in the fault location percentage in a line. Based on the results shown in Fig. 12, D is taken to be 100kV/ms keeping a considerable safety margin and timely triggering to avoid delays.

Fig. 12: dU_{dc}/dt (kV/ms) vs fault resistance, R_f (Ω)

B. Sensitivity Analysis

The decision of other thresholds (U_{0set} , U_{L1set1} and U_{L1set2}) is made using the logarithmic partial derivative based sensitivity analysis [27]. The function $G(j\omega)$ is the mode-voltage, whereas the variables p_i are the critical parameters (R_f , L_{Tmn}). The sensitivity of function $G(j\omega)$ for a small variation in p_i is defined as:

$$S_{p_i}^{G(j\omega)} \triangleq \frac{\partial \ln G(j\omega)}{\partial \ln p_i} \bigg|_{p_{i0}} = \frac{\frac{\partial \ln G(j\omega)}{G(j\omega)}}{\frac{\partial \ln p_i}{p_i}} \bigg|_{p_{i0}} = \frac{\partial G(j\omega)}{\partial p_i} \bigg|_{p_{i0}} \frac{p_{i0}}{G_0(j\omega)} \quad (16)$$

where p_{i0} represents nominal value of the i th parameters and $G_0(j\omega)$ represents the nominal value of mode-voltage with p_{i0} parameter. For a small change (Δp_i), the mode-voltage function is evaluated as:

$$G(j\omega, p_i) = G(j\omega, p_{i0}) + \frac{\Delta p_i}{p_{i0}} S_{p_i}^{G(j\omega)} \quad (17)$$

$$\text{where } \Delta p_i = p_i - p_{i0} \text{ and for } i=1, \sum_{i=1}^n S_{p_i}^{G(j\omega)} = S_{p_1}^{G(j\omega)}.$$

1) Sensitivity with fault resistance, R_f : *PTP* line-mode voltage is considered as the sensitivity function ($U_{L12,1}$). The sensitivity of line-mode voltage with fault resistance is defined as:

$$S_{R_f}^{U_{L12,1}(j\omega)} = \frac{\partial \ln U_N}{\partial \ln R_f} \bigg|_{R_{f0}} - \frac{\partial \ln U_D}{\partial \ln R_f} \bigg|_{R_{f0}} \quad (18)$$

$$S_{R_f}^{U_{L12,1}(j\omega)} = -\frac{\gamma R_{f0}}{Z_1 + \gamma R_{f0}} \quad (19)$$

where $U_{L12,1} = \frac{U_N}{U_D}$ and $1 + \frac{Z_1}{Z_2} = \gamma$. For a small change (ΔR_f), the line-mode voltage, $U_{L12,1}$ is evaluated as:

$$U_{L12,1}(j\omega, R_f) = U_{L12,1}(j\omega, R_{f0}) - \frac{\gamma \Delta R_f}{Z_1 + \gamma R_{f0}} \quad (20)$$

where $\Delta R_f = R_f - R_{f0}$. Fig. 16 shows the variation of $U_{L12,1}$ with R_f . With increasing R_f , the signal damping is increasing.

Fig. 13: U_{Tmn} (kV) vs R_f (Ω) for (a) PTP, (b) PTG faults

Fig. 13 shows the variation of mode voltages with fault resistance for different fault contingencies used to define maloperation region. Mode voltage variation with fault resistance follows an inverse relation. This means that when fault resistance increases, mode voltages decrease [refer eq. (20)]. If the thresholds for mode voltages are lower, the scheme may detect higher impedance faults. However, the selectivity can be jeopardised in case of low impedance forward external faults (refer to Fig. 10). The proposed work uses a lower threshold setting keeping in mind the idea to differentiate between a forward external LIF with internal HIF. This makes the proposed scheme sensitive to HIFs up to 1000Ω .

Fig. 14: Simulation results for P-PTG fault at $t=1s$ for (a) Voltages at bus 1 (kV) vs Time (sec), (b) Voltages at bus 2 (kV) vs Time (sec), (c) Voltages at bus 3 (kV) vs Time (sec), (d) dU_{dc}/dt (kV/ms) vs Time (sec), (e) Mode voltages at Bus 1 (kV) vs Time (sec), (f) Mode voltages at Bus 2 (kV) vs Time (sec), (g) Mode voltages at Bus 3 (kV) vs Time (sec), (h) Mode voltages at Bus 4 (kV) vs Time (sec)

Fig. 15: Simulation results for N-PTG fault at $t=1s$ for (a) Voltage at bus 1 (kV) vs Time (sec), (b) Voltages at bus 2 (kV) vs Time (sec), (c) Voltage at bus 3 (kV) vs Time (sec), (d) dU_{dc}/dt (kV/ms) vs Time (sec), (e) Mode Voltage at Bus 1 (kV) vs Time (sec), (f) Mode Voltages at Bus 2 (kV) vs Time (sec), (g) Mode Voltage at Bus 3 (kV) vs Time (sec), (h) Mode Voltage at Bus 4 (kV) vs Time (sec)

2) *Sensitivity with current limiting reactor, L_{Tmn}* : The sensitivity of line-mode voltage with current limiting reactor is defined as:

$$S_{L_{T12}}^{U_{L12,1}} = \left. \frac{\partial \ln U_N}{\partial \ln L_{T12}} \right|_{L_{T120}} - \left. \frac{\partial \ln U_D}{\partial \ln L_{T12}} \right|_{L_{T120}} \quad (21)$$

The sensitivity function is simplified to:

$$S_{L_{T12}}^{U_{L12,1}} = 1 - 2j\omega \frac{(1 + \beta^2)L_{T120}}{Z_1 + \gamma R_f} \quad (22)$$

where $\beta = \frac{L_{MMC}}{2L_{T12} + L_{MMC}}$. For a small change (ΔL_{T12}), the line-mode voltage, $U_{L12,1}$ is evaluated as:

$$U_{L12,1}(j\omega, L_{T12}) = U_{L12,1}(j\omega, L_{T120}) - \Delta L_{T12} \left(\frac{1}{L_{T120}} - \frac{2j\omega(1 + \beta^2)}{Z_1 + \gamma R_f} \right) \quad (23)$$

where $\Delta L_{T12} = L_{T12} - L_{T120}$. Fig. 16 shows the variation of mode voltages with value of CLR.

C. Scheme validation for different faults

1) *Validation for P-PTG faults*: A metallic P-PTG fault (F_1 in Fig. 1) occurs at $t=1s$ at a distance of 50% in Line 1. The decisive parameters are analysed in Fig. 14. Fig. 14(a) shows DC link voltage at bus 1 (U_{dc1}), positive pole voltage (U_{1p}) and negative pole voltage (U_{1n}). Fig. 14(b) shows U_{dc2} , U_{2p} and U_{2n} and Fig. 14(c) shows U_{dc3} , U_{3p} and U_{3n} .

TABLE V: Variation of mode voltages at different CLR with variation of fault location (*internal- F_1 , external- F_2*) and fault resistance

		$R = 0.01\Omega$								$R = 0.35\Omega$								$R = 3.1\Omega$							
		$U_{L12}(kV)$		$U_{L21}(kV)$		$U_{L14}(kV)$		$U_{L23}(kV)$		$U_{L12}(kV)$		$U_{L21}(kV)$		$U_{L14}(kV)$		$U_{L23}(kV)$		$U_{L12}(kV)$		$U_{L21}(kV)$		$U_{L14}(kV)$		$U_{L23}(kV)$	
		Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line
P-PTG																									
10%		227.3	180.3	190.4	172.4	43.2	38.4	-42.2	-38.7	220.4	173.5	182.2	163.4	41.2	35.6	-39.8	-36.8	115.6	108.6	110.4	166.6	28.7	26.5	-26.4	-23.4
30%		234.2	204.2	198.2	176.5	47.2	41.2	-45.2	-39.4	227.8	196.8	190.4	168.8	42.6	39.8	-41.6	-34.6	116.6	98.4	99.4	94.5	32.4	29.8	-29.8	-28.8
50%		221.6	188.8	176.2	164.2	44.4	40.2	-38.2	-36.7	214.5	180.2	169.8	158.5	41.4	38.7	-34.5	-34.1	110.6	99.6	104.6	97.8	28.4	23.5	-27.3	-22.4
70%		232.4	198.5	188.4	162.4	47.8	43.2	-42.5	-40.1	222.4	201.2	192.4	173.5	42.5	38.6	-34.1	-29.8	124.4	112.2	114.8	104.6	35.6	30.6	-33.4	-28.8
90%		245.2	212.2	198.2	178.2	45.6	39.8	-38.1	-32.8	237.4	202.4	190.2	173.4	41.5	35.6	-31.2	-27.8	138.6	120.4	106.4	96.4	32.4	26.8	-36.8	-30.2
External		144.2	120.3	-212.1	-202.2	142.6	120.8	-207.6	-212.4	137.2	115.1	-201.6	-192.3	136.8	113.4	-198.8	-201.2	90.2	82.4	-80.2	-76.2	90.4	88.6	-84.2	-78.6
N-PTG																									
10%		-227.3	180.1	-190.4	172.3	43.2	38.4	-42.2	-38.7	-220.4	173.5	-182.2	163.4	41.2	35.6	-39.8	-36.8	-115.6	108.6	-110.4	166.6	28.7	26.5	-26.4	-23.4
30%		-234.2	204.2	-198.2	176.5	47.2	41.2	-45.2	-39.4	-227.8	196.8	-190.4	168.8	42.6	39.8	-41.6	-34.6	-116.6	98.4	-99.4	94.5	32.4	29.8	-29.8	-28.8
50%		-221.6	188.8	-176.2	164.2	44.4	40.2	-38.2	-36.7	-214.5	180.2	-169.8	158.5	41.4	38.7	-34.5	-34.1	-110.6	99.6	-104.6	97.8	28.4	23.5	-27.3	-22.4
70%		-232.4	198.5	-188.4	162.4	47.8	43.2	-42.5	-40.1	-222.4	201.2	-192.4	173.5	42.5	38.6	-34.1	-29.8	-124.4	112.2	-114.8	104.6	35.6	30.6	-33.4	-28.8
90%		-245.2	212.2	-198.2	178.2	45.6	39.8	-38.1	-32.8	-237.4	202.4	-190.2	173.4	41.5	35.6	-31.2	-27.8	-138.6	120.4	-106.4	96.4	32.4	26.8	-36.8	-30.2
External		-144.2	120.3	-212.1	-202.2	-142.6	120.8	-207.6	-212.4	-137.2	115.1	-201.6	-192.3	-136.8	113.4	-198.8	-201.2	-90.2	82.4	-80.2	-76.2	-90.4	88.6	-84.2	-78.6
PTP																									
10%		0.1	482.2	0.2	441.4	0.2	80.4	-0.2	-76.7	0.2	473.2	0.1	432.6	0.2	75.6	-0.4	-70.8	0.6	378.6	0.2	326.8	0.3	42.3	-0.3	-34.2
30%		0.2	462.4	0.3	446.4	0.3	82.4	-0.3	-74.2	0.3	456.8	0.4	440.6	0.2	77.8	-0.4	-74.3	0.7	346.6	0.4	332.4	0.3	52.6	-0.5	-46.8
50%		0.2	446.5	0.2	427.4	0.3	74.2	-0.2	-71.2	0.2	440.2	0.3	420.6	0.1	70.2	-0.3	-66.6	0.1	336.6	0.3	312.6	0.2	47.2	-0.4	-45.2
70%		0.3	461.4	0.1	433.6	0.1	87.6	-0.1	-78.2	0.1	453.6	0.3	423.7	0.3	81.5	-0.2	-72.2	0.3	348.6	0.3	318.2	0.4	54.6	-0.4	-45.7
90%		0.1	472.6	0.2	439.8	0.2	88.2	-0.3	-80.2	0.4	465.6	0.3	428.4	0.1	83.2	-0.2	-74.3	0.1	368	0.2	354.4	0.2	52.6	-0.3	-48.6
External		0.1	287.8	-0.3	-305	0.2	288.4	-0.2	-327	0.1	280.3	-0.2	-293.2	0.2	282.4	-0.4	-275.4	0.2	178.1	-0.2	-214	-0.3	179.2	-0.2	-234.5

		$R = 480\Omega$								$R = 500\Omega$								$R = 1000\Omega$							
		$U_{L12}(kV)$		$U_{L21}(kV)$		$U_{L14}(kV)$		$U_{L23}(kV)$		$U_{L12}(kV)$		$U_{L21}(kV)$		$U_{L14}(kV)$		$U_{L23}(kV)$		$U_{L12}(kV)$		$U_{L21}(kV)$		$U_{L14}(kV)$		$U_{L23}(kV)$	
		Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line	Zero	Line
P-PTG																									
10%		143.2	120.5	138.8	114.6	20.2	18.6	-19.8	-18.7	135.2	133.5	142.2	133.4	36.6	33.3	-33.8	-31.8	90.2	84.4	91.4	86.6	10.7	10.5	-12.4	-11.4
30%		142.2	126.2	140.2	96.5	25.2	24.6	-22.2	-18.8	139.6	134.6	142.4	138.8	22.5	19.9	-21.6	-18.7	91.4	82.2	92.4	87.3	12.4	9.8	-9.8	-8.8
50%		141.6	128.8	146.6	124.8	23.4	20.6	-18.8	-16.7	137.5	130.2	139.8	128.5	36.4	36.7	-32.5	-31.1	89.6	81.3	90.1	86.2	10.4	10.5	-12.3	-10.4
70%		144.8	138.6	142.4	122.4	22.8	20.2	-20.5	-18.1	136.4	131.2	142.4	128.5	25.5	22.6	-28.1	-21.8	90.4	82.2	91.2	87.6	11.6	10.6	-13.4	-11.8
90%		145.5	132.2	148.2	128.2	26.6	19.8	-21.1	-18.8	138.6	132.4	138.2	123.4	41.5	35.6	-31.2	-27.8	91.4	84.4	92.4	89.1	12.2	11.8	-12.8	-11.2
External		70.6	66.4	-104.2	-93.2	72.6	68.8	-107.4	-102.4	67.2	60.1	-110.6	-98.4	74.2	67.5	-118.8	-101.5	12.1	10.4	-11.2	-10.2	13.4	12.6	-12.2	-11.6
N-PTG																									
10%		-143.2	120.5	-138.8	114.6	20.2	18.6	-19.8	-18.7	-135.2	133.5	-142.2	133.4	36.6	33.3	-33.8	-31.8	-90.2	84.4	-91.4	86.6	10.7	10.5	-12.4	-11.4
30%		-142.2	126.2	-140.2	96.5	25.2	24.6	-22.2	-18.8	-139.6	134.6	-142.4	138.8	22.5	19.9	-21.6	-18.7	-91.4	82.2	-92.4	87.3	12.4	9.8	-9.8	-8.8
50%		-141.6	128.8	-146.6	124.8	23.4	20.6	-18.8	-16.7	-137.5	130.2	-139.8	128.5	36.4	36.7	-32.5	-31.1	-89.6	81.3	-90.1	86.2	10.4	10.5	-12.3	-10.4
70%		-144.8	138.6	-142.4	122.4	22.8	20.2	-20.5	-18.1	-136.4	131.2	-142.4	128.5	25.5	22.6	-28.1	-21.8	-90.4	82.2	-91.2	87.6	11.6	10.6	-13.4	-11.8
90%		-145.5	132.2	-148.2	128.2	26.6	19.8	-21.1	-18.8	-138.6	132.4	-138.2	123.4	41.5	35.6	-31.2	-27.8	-91.4	84.4	-92.4	89.1	12.2	11.8	-12.8	-11.2
External		-70.6	66.4	-104.2	-93.2	72.6	68.8	-107.4	-102.4	-67.2	60.1	-110.6	-98.4	74.2	67.5	-118.8	-101.5	-12.1	10.4	-11.2	-10.2	-13.4	12.6	-12.2	-11.6
PTP																									
10%		0.1	285.8	0.2	292.2	0.2	42.4	-0.2	-46.7	0.3	278.5	0.2	283.2	0.6	38.2	-0.2	-40.8	0.4	176.6	0.3	177.8	0.3	18.3	-0.2	-14.3
30%		0.3	287.8	0.2	290.4	0.3	42.2	-0.3	-44.2	0.3	279.6	0.2	285.2	0.8	37.2	-0.3	-39.2	0.2	177.4	0.3	179.2	0.6	16.3	-0.8	-18.5
50%		0.4	286.2	0.3	287.8	0.2	41.5	-0.2	-40.3	0.2	278.8	0.3	281.6	0.2	37.2	-0.6	-38.4	0.3	176.2	0.3	177.1	0.2	17.6	-0.2	-15.2
70%		0.5	289.5	0.2	288.8	0.1	45.6	-0.2	-39.1	0.2	281.2	0.4	280.4	0.5	41.5	-0.2	-36.4	0.3	179.1	0.3	177.2	0.6	14.2	-0.2	-15.2
90%		0.1	292.2	0.3	288.2	0.2	41.2	-0.2	-42.3	0.2	284.2	0.4	282.4	0.2	41.1	-0.3	-39.4	0.3	178.9	0.3	179.3	0.6	18.2	-0.6	-18.3
External		0.3	132.8	-0.5	-162	0.4	132.4	-0.2	-162	0.2	125.2	-0.4	-128.2	0.3	127.4	-0.4	-122.4	0.1	38.1	-0.2	24.7	0.3	29.2	-0.2	-35.4

Fig. 16: U_{Tmn} (kV) vs L_{Tmn} (mH)

Fig. 14(d) shows that $|dU_{dc}/dt| > D$ for bus 1-3. This triggers the evaluation of U_{Lmn_I} and U_{Lmn_O} . Since $|U_{Lmn_O}| > U_{0set}$, the fault is identified as PTG family of faults. For bus 1-2, $U_{L12_I} > U_{Iset2}$, the fault is identified as internal as shown in Fig. 14(e), (f). For bus 3, the fault is identified as backward external P-PTG while for bus 4, the fault is identified as forward external P-PTG as shown in Fig. 14(g), (h).

2) *Validation for N-PTG faults:* Similar to previous subsection (P-PTG), Fig. 15 shows the fault identification for a N-PTG metallic fault at $t=1s$ at a distance of 50%.

TABLE VI: Analysis of Maloperation region

$\frac{dU_{dc}}{dt}$ (kV/ms)	Fault Resistance (Ω)					
	Forward External			High Impedance Internal		
PTP	0.01 Ω	0.35 Ω	3.1 Ω	480 Ω	500 Ω	1000 Ω
$\frac{dU_{dc1}}{dt}$	-4962	-4896	-4688	-2022	-1988	-212
$\frac{dU_{dc2}}{dt}$	-5024	-5054	-4921	-1968	-1937	-184
PTG	0.01 Ω	0.35 Ω	3.1 Ω	480 Ω	500 Ω	1000 Ω
$\frac{dU_{dc1}}{dt}$	-2464	-2412	-2310	-1267	-1212	-122
$\frac{dU_{dc2}}{dt}$	-2668	-2611	-2516	-1313	-1245	-118

Fig. 10 shows the zoomed propagation time of the waves for 2 fault scenarios. One at 10%, other at 100% (forward external). This is the case with maximum propagation delay in the analysis. The proposed fault identification scheme considers HIF up to 1000 Ω which delays $|dU_{dc}/dt| > D$. As a result of which the maximum delay encountered or the maximum detection time of the proposed scheme is 2.37ms.

TABLE VII: Fault Detection Time for the proposed scheme

Maximum Propagation time of travelling wave	1.12ms
Delay for HIF (1000 Ω) to violate triggering event	1.13ms
Delay due to 1-level wavelet transform	0.12ms
Maximum delay encountered	2.37ms

F. Response to AC faults

To check the response of AC faults on the proposed scheme, a 3 ϕ metallic AC fault is simulated on the AC side of MMC₁. The decisive parameters are shown in Fig. 17. $|dU_{dc}/dt| > D$ is violated for both bus 1-2. However, mode voltages point to no fault zone ($U_{L12_I} = -324$ kV, $U_{L12_0} = 186$ kV; $U_{L21_I} = -86$ kV, $U_{L21_0} = 0.3$ kV) as can be seen in Fig. 9.

Fig. 17: Simulation results for AC fault behind MMC₁ for (a) Voltage at Bus 1 (kV) vs Time (sec), (b) Voltage at Bus 2 (kV) vs Time (sec), (c) dU_{dc}/dt (kV/ms), (d) Mode Voltages at Bus 1 (kV) vs Time (sec), (e) Mode Voltages at Bus 2 (kV) vs Time (sec)

G. Response to power reversal

To check the performance of the scheme under system transients, the P_{ref} command at each bus is changed at $t=0.75$ s (P_1 from 0 to +368MW, P_2 from +374MW to +214MW, P_3 from +178MW to -198MW). As evident from Fig. 18, $|dU_{dc}/dt| < D$. Since the trigger event is not violated, the performance of the scheme is intact for power reversal and system transients. Following the event of power reversal, a PTP fault is applied at $t=1$ s. As evident from Fig. 18, $|dU_{dc}/dt| > D$ within $t=1.001$ s. The mode voltage analysis identifies a PTP fault.

Fig. 18: Simulation results for transient operation in the system (a) Real Power (P) (MW) vs Time (sec), (b) Voltage at Bus 1 (kV) vs Time (sec), (c) Voltage at Bus 3 (kV) vs Time (sec), (d) dU_{dc}/dt (kV/ms), (e) Mode Voltage at Bus 1 (kV) vs Time (sec), (f) Mode voltages at Bus 3 (kV) vs Time (sec)

H. Response to DCCB operation

The scheme operation is analysed for a fault F_1 (Fig. 1). Once, the fault is identified, DCCB operation isolate Line 1. The external mode voltages are analysed for the DCCB operation at $t=1.003$ ms in Fig. 19. It is seen that the external mode voltages do not violate U_{lset1} .

I. Effect of White Gaussian Noise (WGN)

White Gaussian Noise (WGN) in the measurement induces high frequency components in the measured data of current and voltage. This can cause inaccuracy in the results for the fault identification of the proposed scheme. As a result, a rolling mean filter (RMT) is employed with a moving window of 50 sample steps [16]. WGN is random in nature with the property of zero mean [14]. Hence, the filter eliminates the effect of WGN to a great extent without

Fig. 19: (a) U_{L23_l} (kV) vs T (sec), (b) U_{L14_l} (kV) vs T (sec)

affecting the accuracy of the proposed fault identification scheme. Fig. 20(a) shows U_{dc1} with 30dB WGN and also with RMT. Fig. 20(b) shows dU_{dc1}/dt obtained through the filtered voltage, U_{dc1} .

Fig. 20: U_{dc1} vs T (sec), (b) dU_{dc1}/dt (kV/ms) vs T (sec)

J. Comparison to relevant literature

The authors in [14] propose a fast and simple scheme which works up to a fault resistance of 200Ω. Table V shows the existence of maloperation region as the fault resistance increases further. It means scheme in [14] maloperates as fault resistance increases beyond 200Ω. The proposed work studies the effect of fault resistance in the mathematical analysis to increase the reliability of the scheme for HIFs as high as 1000Ω.

The detection time of the proposed scheme is higher than that of in [14]. This is a result of delay due to HIF to violate the triggering event and the delay due to 1-level wavelet transform.

VI. CONCLUSION

The contribution of the proposed work has been to improve the selectivity (distinguishability between external and internal faults) of localised protection for DC fault identification in multi-terminal MMC-HVDC systems. Based on the findings of the proposed work, it can be concluded that:

- Considering fault resistance in the modal analysis points out the issue of maloperation region for internal high impedance faults (HIFs) and forward external low impedance faults (LIFs).
- Mitigating the region helps the scheme to detect HIF as high as 1000Ω.
- A sensitivity analysis is proposed which formulates the variation of decisive parameters i.e., line-mode and zero-mode voltages with respect to critical parameters like fault resistance and current limiting reactor. This analysis is used to decide system thresholds (U_{0set} , U_{1set1} and U_{1set2}).
- The proposed scheme works well for HIFs, in the presence of WGN up to 30dB. The scheme is rapid due to localised nature and can identify fault well within 2.4ms. It is secure for AC faults, DCCB operation, power reversal (load variations).

APPENDIX

Fig. 21: Implemented overhead Line (OHL) Configuration

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