RTDS Tutorial

Intelligent Electrical Power Grids, TU Delft

Fault Identification in MMC-HVDC Grids

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Introduction:

DC fault protection is different in behavior compared to its AC counterpart. As a result, a delay of a few milliseconds to identify and isolate the fault can lead to system collapse in DC grids. Considering a complex multi-terminal half-bridge modular multilevel converter- high voltage DC (MMC-HVDC) grid, it is important to narrow down the section of a bigger system (multi-terminal MMC-HVDC grid) to realize the accurate fault behavior with ease and logic.

In this tutorial, we will introduce the concept of time-domain-based fault identification of benchmark CIGRE MMC-HVDC grids using a real-time digital simulator (RTDS). At the end of this tutorial, you should be able to:

- Develop an understanding of marking the relevant section in a system to realize the behavior upon a fault inception
- Identify different types of faults i.e., pole-to-pole (PTP), positive pole-to-ground (P-PTG), and negative pole-to-ground (N-PTG) based on the pattern of time-domain-based parameters

In order to follow the tutorial, you should:

- Be able to do basic simulations in RSCAD
- Have the basic knowledge of multi-terminal DC grids

Overview of Test System:

A 5-bus multi-terminal grid (±525kV) is considered as the MMC-HVDC configuration as shown in Fig. 1. For a system as big as the HVDC grid, power transmitting underground cables are most likely to experience a fault contingency. A DC fault contingency prompts a very high rate of rise in current which can prove to be detrimental to the system's stability if the fault is not identified and isolated in time (limited to a few milliseconds). DC faults are unique in comparison to their AC counterpart because:

- Practically implemented half-bridge MMCs are defenseless against DC faults as the freewheeling diodes act as uncontrolled rectifier bridges upon fault inception.
- As DC faults are low-frequency transients (< 1 kHz), a low impedance is offered by the DC cables which further increases the fault current magnitude.

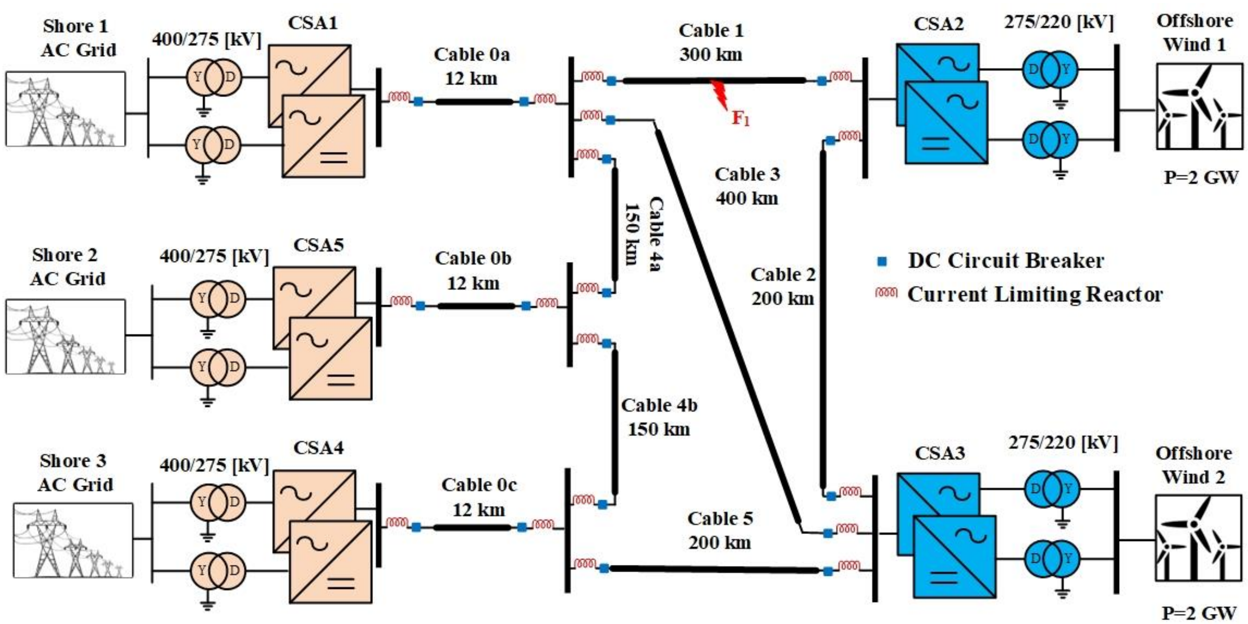

Figure 1: MMC-HVDC Test System

Understanding DC Fault behavior:

The externally placed CLRs not only help in limiting the rate of rise of fault current but also act as unique fault differentiators. The presence of CLRs prevents the instantaneous rise of current, where CLRs accumulate very high energy during the initial fault transients.

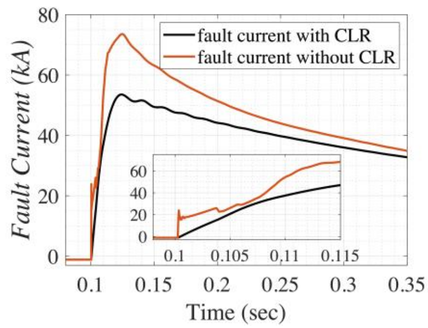

Figure 2: Fault Current (kA) upon fault inception

As a result, if the voltage across CLRs is measured, the fault shows a peculiar behavior and can be detected in less than 1 ms effectively. The characteristics are unlike:

- normal operational power transients
- transients during the restoration of the converter
- transients during (n-1) contingency

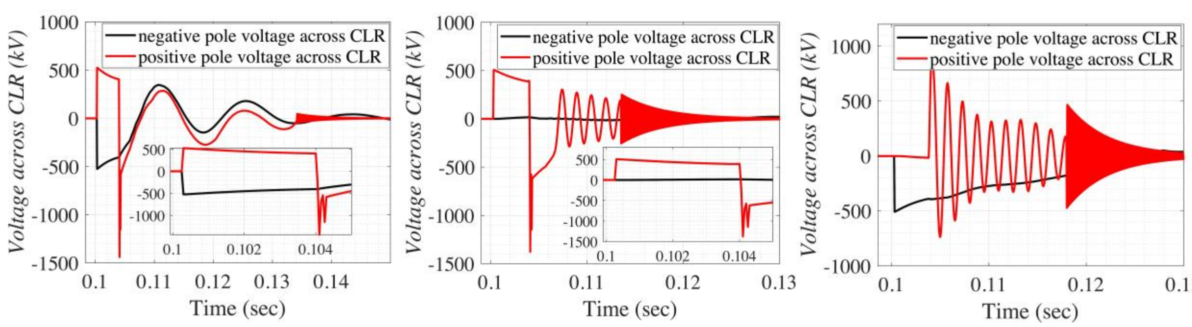

Figure 3: Voltage across CLR (kV) for (a) PTP, (b) P-PTG, and (c) N-PTG

Understanding types of DC Faults:

Understanding different types of DC faults in a bipolar cable configuration can help narrow down the affected area for isolation and restoration. A DC fault can be:

- pole-to-pole (PTP)
- positive pole-to-ground (P-PTG)
- negative pole-to-ground (N-PTG)

In order to decouple the dependency of poles of cables under PTG faults, phase-sequence transformation can be incorporated. This phase-sequence transformation for bipolar DC is analogous to symmetrical component transformation in *3Φ* AC. The transformation simplifies the classification of DC faults for intuitive understanding. The phase-sequence transformation is mathematically expressed as:

$$\begin{bmatrix} x_l \\ x_0 \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_P \\ x_n \end{bmatrix}$$

- x_l is defined as the line-mode (or balanced sequence) variable
- x_0 is defined as the zero-mode (or residual sequence) variable
- x_P is the positive-pole variable
- x_n is negative-pole variable

Classification of faults:

- *PTP* fault: For a *PTP* fault, $U_{f\_p}(t) - U_{f\_n}(t) = i_{f\_p}(t)R_f$ and $i_{f\_p}(t) + i_{f\_n}(t) = 0$. Applying phase-modal transformation, the conditions are transformed to the form:

$$U_{f\_l}(t) = i_{f\_l}(t)R_f$$
$$i_{f\_0}(t) = 0$$

  The following conclusions are true during the initial DC fault transients:

  1. Line-mode voltage $U_{L12\_l}(t)$ is positive
  2. Zero-mode voltage $U_{L12\_0}(t)$ is zero

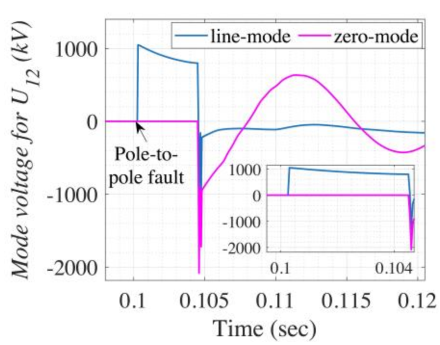

Figure 4: Mode voltage for PTP fault

MMC

- *P-PTG* fault: For a *P-PTG* fault, $U_{f\_p}(t) = i_{f\_p}(t)R_f$ and $i_{f\_n}(t) = 0$. Applying phase-modal transformation, the conditions are transformed to the form:

$$U_{f\_l}(\mathrm{t}) + U_{f\_0}(t) = 2i_{f\_l}(t)R_f$$
$$i_{f\_l}(t) = i_{f\_0}(t)$$

Using Fig. 4(a)-(b) in series as evident from the transformed conditions, the following conclusions are true during the initial DC fault transients:
1. Line-mode voltage $U_{L12\_l}(t)$ is positive
2. Zero-mode voltage $U_{L12\_0}(t)$ is positive

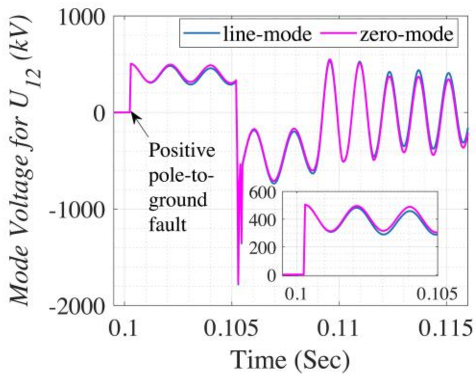

Figure 5: Mode voltage for P-PTG fault

- *N-PTG* fault: For an *N-PTG* fault, $U_{f\_n}(t) = i_{f\_n}(t)R_f$ and $i_{f\_p}(t) = 0$. Applying phase-modal transformation, the conditions are transformed to the form:

$$-U_{f\_l}(\mathrm{t}) + U_{f\_0}(t) = 2i_{f\_l}(t)R_f$$
$$i_{f\_l}(t) = -i_{f\_0}(t)$$

Using Fig. 4(a)-(b) with the transformed conditions, the following conclusions are true during the initial DC fault transients:
1. Line-mode voltage $U_{L12\_l}(t)$ is positive
2. Zero-mode voltage $U_{L12\_0}(t)$ is negative

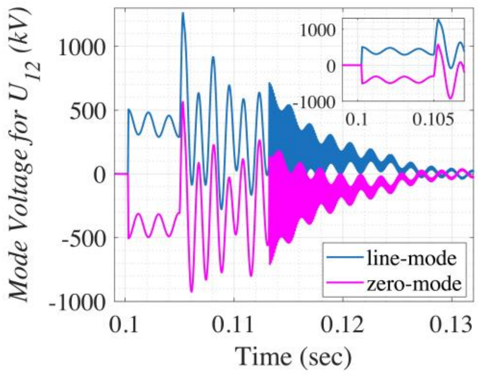

Figure 6: Mode voltage for N-PTG fault

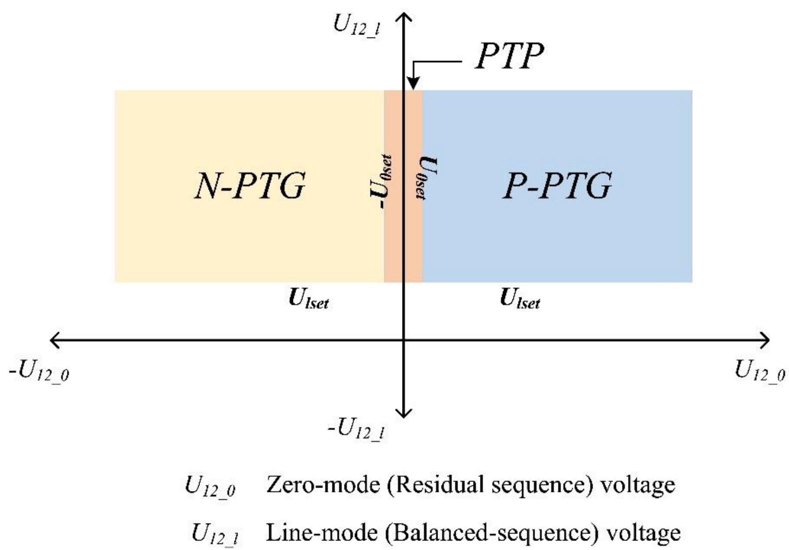

Figure 7: Classification of DC faults based on mode voltages

- U_{0set} is used as a static residual threshold for the practical implementation of the sequence transformation and its interpretation. It is set to be 10 kV for the simulated case.
- U_{lset} is used as a static balanced threshold to differentiate a fault with other events. It is set to be 100 kV for the simulated case.

Validation using RTDS:

Considering the draft file, the **A** region indicates the converter station and connection between *main* and *small timestep*. It also consists of control & protection., meter, and draft variables. In the mentioned network, we have five such stations.

The **B** region indicates the disconnector, which disconnects the converter station from the land and sea land cables. In the above network, we have five such disconnectors. The **C** region is a DMR (Dedicated Metallica Return) land cable with a length of 20 km. This cable connected the onshore converter to the sea cable. In the above network, we have three such land cables. The **D** region is submarine cable. Considering the mentioned network, we have six cables. The length of these cables can be found in the paper.

E region indicates the VARC DC CB. This region also consists of fault logic and the operating time of VARC. In all the models, the VARC is connected to a positive pole and placed at either end of the cable. Region **F** consists of Wind turbines and scaling transformers to mimic the wind power pack/wind farm. We have two such wind power packs. Region **G** has general meters and master controls.

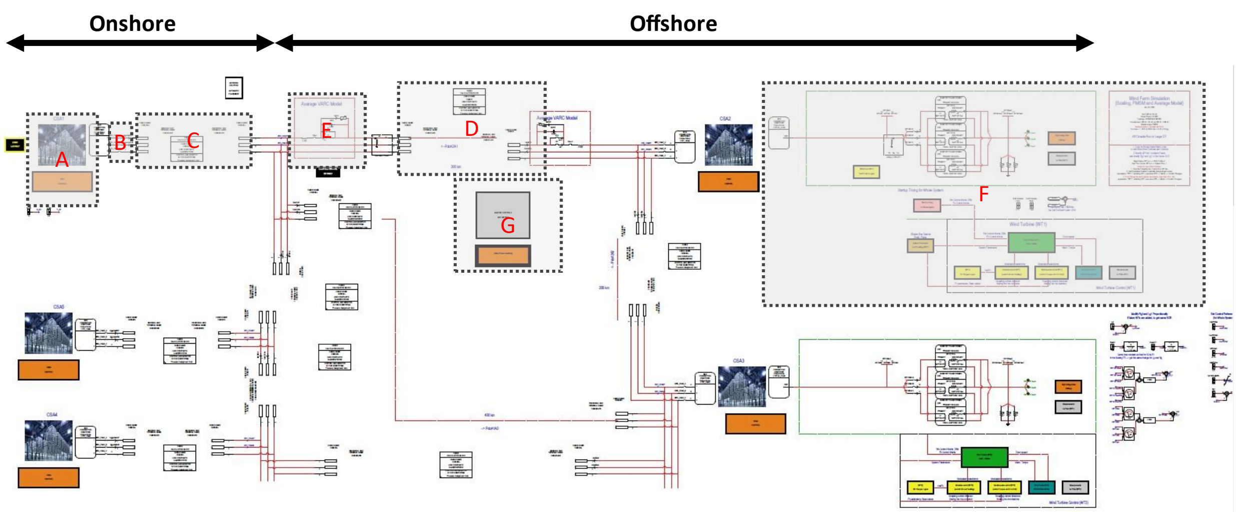

Figure 8: *Draft* file of 5 Terminal MMC-HVDC system

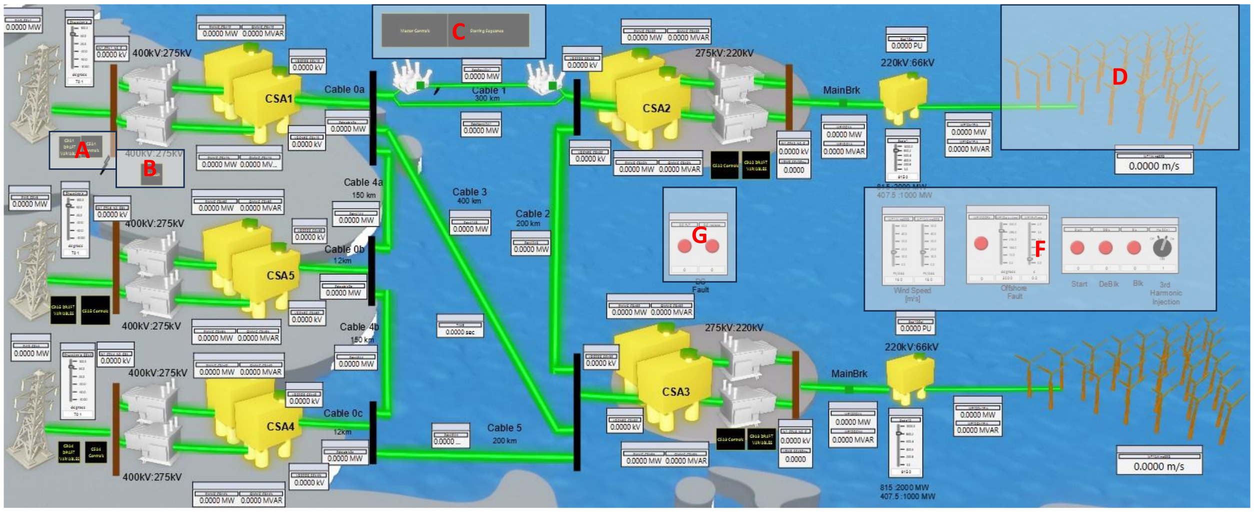

Figure 9: *Runtime* file of 5 Terminal MMC-HVDC system

In the *runtime*, we have six regions, Region **A** indicates the control functions & setpoints, and Draft variables. These two blocks in this region remain the same for all the converters. Furthermore, region **B** indicates AC fault duration, fault button, and re-set signal near the *CSA1* converter. Region **C** has two hierarchy boxes, namely *Master control* and *Starting sequence.* As the name indicates, the *Master control* has all necessary global setpoints and control functions. Similarly, *Starting sequence* has control switches that give the breaker close command and de-block signal to the converter station.

Region **D** consists of wind turbine controls, draft variables, and setpoints. Furthermore, region **F** consists of a wind speed control slider, offshore faut & fault duration, and Energisation buttons of the wind turbine. Region **G** consists of DC fault and reclose command for DC breakers.

Tutorial Questions:

1. Simulate the following DC faults and observe the residual and balanced sequence voltage:
    a. PTP, R_f= 0 ohms
    b. P-PTG, R_f= 100 ohms
    c. N-PTG, R_f=200 ohms

    Extend the study for different fault resistances. What is the effect of increasing fault resistance (if any)?

2. For a transient, comment on the type of fault for the following reported real-time values:
    a. Residual-sequence voltage= 160kV, Balanced-sequence voltage= 172kV
    b. Residual-sequence voltage= 2kV, Balanced-sequence voltage= 172kV
    c. Negative pole voltage= 5kV, Balanced-sequence voltage= 250kV
    d. Negative pole voltage= -300kV, Balanced-sequence voltage= 600kV

3. A researcher was simulating fault behaviour using RTDS. She forgot to record the balanced-sequence voltage but recorded the given values for residual-sequence voltage. Is the data enough to comment on the type of fault?

Time (s)	Residual-sequence voltage (kV)
1	-2.15kV
1.0005	-12kV
1.001	-325kV
1.0015	-338.4kV
1.002	-318.2kV
1.0025	-326.5kV
1.003	-341.5kV

4. Comment on the type of fault for the following observations:
    a. The residual sequence current is reported to be 0 kA while the balanced sequence voltage is 400kV.
    b. The residual sequence current and the balanced sequence current are reported to be 12 kA.
    c. The positive pole current is 0 kA while the balanced sequence voltage is 400kV.