RTDS Tutorial

Intelligent Electrical Power Grids, TU Delft

Fault Location in MMC-HVDC Grids

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Introduction:

Once the fault is identified, accurately locating the fault helps in the rapid restoration of the isolated line back into the system. Generally, HVDC systems have long lines for the transmission of power. Using double-terminal methods is suitable for fault location for systems with long transmission lines. This comes with the additional problem of communication delay, which needs consideration.

The idea is to use simple R-L representation for long transmission lines and underground cables along with measured terminal currents and voltages related together by Kirchhoff's Voltage Law (KVL). In this tutorial, we will introduce the concept of time-domain-based fault location 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 identifying the type of fault and hence, locating the fault point in the faulty cable or line segment

In order to follow the tutorial, you should:

- Be able to do basic simulations in RSCAD
- Have a basic knowledge of Kirchhoff's Voltage Law (KVL) and its application in a circuit.
- Pre-requisite knowledge of Fault Identification in MMC-HVDC

Overview of Test System:

A 5-bus multi-terminal grid (±525kV) is considered the MMC-HVDC configuration as shown in Fig. 1. With our previous knowledge of fault identification, the fault, F_1 is identified at cable 1. The process of locating the fault can be carried out online (before the isolation of the faulty segment) or offline (after the isolation of the faulty segment). The online method has the intuitive advantage of being fast and not needing any external fault location module. The discussed algorithm is a time-domain-based online fault location method that locates the fault point in less than 1 ms after fault inception.

In the mathematical analysis explained ahead, the long cables are analyzed using their simplified R-L representation. The calculated fault distance using RTDS is found to closely follow the fault distance in the actual distributed frequency-dependent cable modeled in RSCAD. The reasons for this are a combination of different factors such as:

- The grounding capacitance for underground cable (UGC) is within $0.5\ \mu F/km$ whereas the equivalent DC link capacitor for an HVDC system is as high as 10^2-$10^3 \mu F$. Hence, the fault contribution from the grounding capacitance of cables and lines can be ignored in comparison to the DC capacitance contribution.
- The use of low-pass filters in the data processing eliminates the high-frequency contributions of grounding capacitance of UGC.

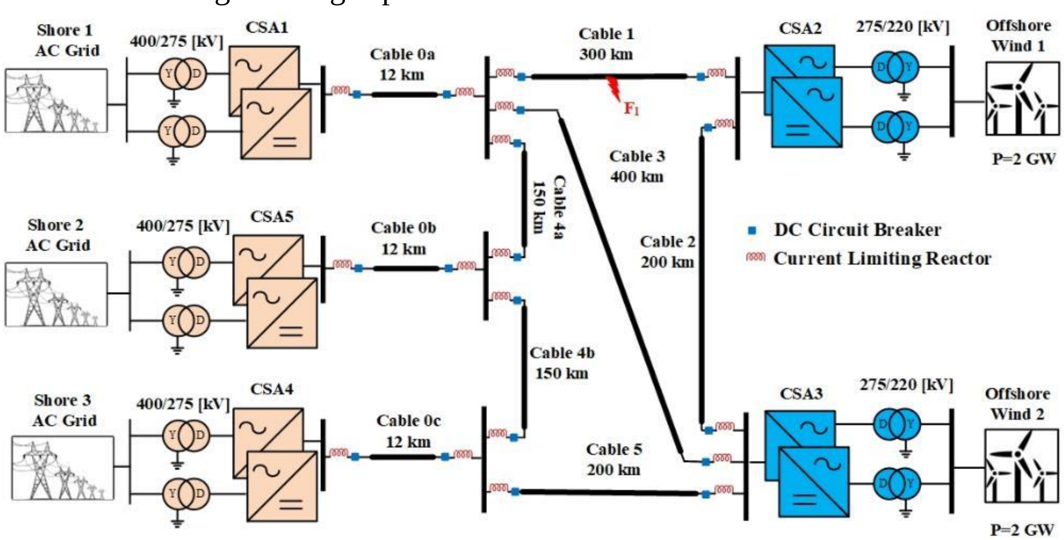


Figure 1: MMC-HVDC Test System

Understanding the parameters of a cable:

The location of the fault using time-domain methods requires information on resistance per unit length (r_o) and inductance per unit length (l_o) of the cable subjected to a fault. While simulating any fault location test, these values can be obtained by looking into their *cablename_out.text*. Fig. 3 shows one such *.out* file for cable *Scab525kV200KM_out* used in the tutorial cases. Using basic mathematics on series impedance at 0.001Hz, $r_o=0.009\Omega/km$ & $l_o=0.0028H/km$.

```
  Line Constants (.out ) output file.
  This file is over-written whenever the T-Line
  constants program is executed for this T-Line.
    T-Line Constants Version = RTDS_1.0.4
================================================
------------------------------------------------
 Phase Domain Quantities at 0.001000 Hertz.
------------------------------------------------
MATRICES INCLUDING ALL SIMULATED CONDUCTORS
MATRIX DIMENSION = 3

   SERIES IMPEDANCE  (Z) matrix in Ohms/meter
 9.001249208e-006 +j  1.764595835e-008   9.983928658e-010 +j  1.518754118e-008   9.983874798e-010 +j  1.518737008e-008
 9.983928658e-010 +j  1.518754118e-008   9.001249207e-006 +j  1.764595836e-008   9.983873653e-010 +j  1.518693312e-008
 9.983874798e-010 +j  1.518737008e-008   9.983873653e-010 +j  1.518693312e-008   9.001249197e-006 +j  1.764596908e-008

   SHUNT  ADMITTANCE (Y) matrix in Siemens/meter
 1.000000000e-010 +j  1.328820588e-012   0.000000000e+000 +j  0.000000000e+000   0.000000000e+000 +j  0.000000000e+000
 0.000000000e+000 +j  0.000000000e+000   1.000000000e-010 +j  1.328820588e-012   0.000000000e+000 +j  0.000000000e+000
 0.000000000e+000 +j  0.000000000e+000   0.000000000e+000 +j  0.000000000e+000   1.000000000e-010 +j  1.328820588e-012

   LONG-LINE CORRECTED SERIES IMPEDANCE MATRIX in Ohms
 2.700411220e+000 +j  5.294458673e-003   2.995239680e-004 +j  4.556385524e-003   2.995223511e-004 +j  4.556290494e-003
 2.995239680e-004 +j  4.556385524e-003   2.700411220e+000 +j  5.294371280e-003   2.995223189e-004 +j  4.556246799e-003
 2.995223511e-004 +j  4.556290494e-003   2.995223189e-004 +j  4.556246799e-003   2.700411217e+000 +j  5.294418193e-003

   LONG-LINE CORRECTED SHUNT ADMITTANCE MATRIX in Siemens
 2.999979752e-005 +j  3.986403971e-007  -1.337806184e-014 +j -3.422507962e-013  -1.337813487e-014 +j -3.422436668e-013
-1.337806184e-014 +j -3.422507962e-013   2.999979752e-005 +j  3.986403971e-007  -1.337822311e-014 +j -3.422403920e-013
-1.337813487e-014 +j -3.422436668e-013  -1.337822311e-014 +j -3.422403920e-013   2.999979752e-005 +j  3.986403971e-007
```

Figure 2: *.out* file of faulty cable

Fault Location Algorithm:

Identification of fault helps in detecting the faulty cable and additionally, classifying the fault into its type i.e., PTP, P-PTG, and N-PTG. In case the fault is permanent, the underground cable (UGC) needs isolation and restoration of the fault. Fig. 3 shows the equivalent 2 terminal circuits for (a) PTP, and (b) P-PTG faults. The analysis can be extrapolated for an N-PTG fault as well.

In Fig. 3(a), $v_1(t)$ and $v_2(t)$ are the terminal DC bus voltages, $i_1(t)$ and $i_2(t)$ are the current through CLRs at each terminal while $v_{dc1}(t)$ and $v_{dc2}(t)$ are voltage after CLRs, L_{m1} and L_{m2}. D_o is the total length of the cable whereas x_o is defined as the fault location.

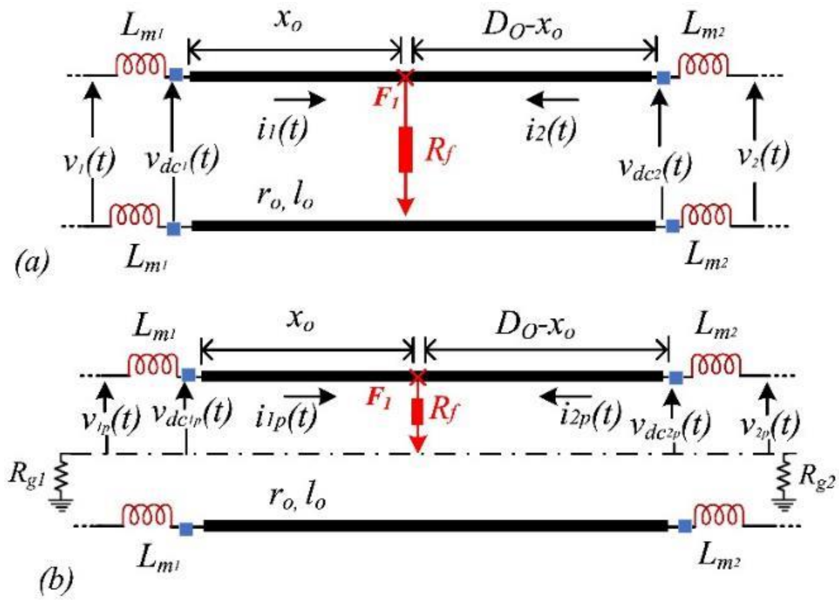


Figure 3: Equivalent 2T circuit for (a) PTP, (b) P-PTG fault

In Fig. 3(b), $v_{1p}(t)$ and $v_{2p}(t)$ are the positive pole terminal DC bus voltages, $v_{dc1p}(t)$ and $v_{dc2p}(t)$ are the positive pole voltages after CLRs, $i_{1p}(t)$ and $i_{2p}(t)$ are the positive pole currents across CLRs. R_{g1} and R_{g2} are the grounding resistances of respective terminals.

The fault location algorithm is explained in detail for a PTP fault using double-terminal time-domain method. Considering a PTP fault, F_1 at cable 1 as shown in Fig. 3(a), we can apply KVL considering both terminals to obtain eq. (1)-(2):

$$2r_o x_o i_1(t) + 2l_o x_o \frac{di_1(t)}{dt} + R_f[i_1(t) + i_2(t)] = v_{dc_1}(t)$$

$$2r_o(D_o - x_o)i_2(t) + 2l_o(D_o - x_o)\frac{di_2(t)}{dt} + R_f[i_1(t) + i_2(t)] = v_{dc_2}(t)$$

The current derivative terms ($\frac{di_n(t)}{dt}$) can be replaced by the drop in voltage across the CLR at bus *n*, avoiding substitution errors due to differential calculations as shown in eq. (3):

$$\frac{di_1(t)}{dt} = \frac{v_1(t)-v_{dc_1}(t)}{2L_{m1}} = \frac{u_1(t)}{2L_{m1}}; \frac{di_2(t)}{dt} = \frac{v_2(t)-v_{dc_2}(t)}{2L_{m2}} = \frac{u_2(t)}{2L_{m2}}$$

Subtracting eq. (1)-(2) negates the dependence of fault location on fault resistance (R_f). This means that the fault location method shows the same accuracy for low resistance and high resistance faults.

Further, if we incorporate eq. (3) and rearrange the expression, the fault location (x_o) for a PTP fault can be given as eq. (4).

$$x_o = \frac{\left[v_{dc_1}(t) - v_{dc_2}(t)\right] + 2r_o D_o i_2(t) + \frac{l_o D_o}{L_{m2}} u_2(t)}{2r_o[i_1(t) + i_2(t)] + \frac{l_o u_1(t)}{L_{m1}} + \frac{l_o u_2(t)}{L_{m2}}}$$

If the fault identified is P-PTG fault, the fault location (x_o) can be given as eq. (5).

$$x_o = \frac{\left[v_{dc_{1p}}(t) - v_{dc_{2p}}(t)\right] + r_o D_o i_{2p}(t) + \frac{l_o D_o}{L_{m2}} u_{2p}(t)}{r_o\left[i_{1p}(t) + i_{2p}(t)\right] + \frac{l_o u_{1p}(t)}{L_{m1}} + \frac{l_o u_{2p}(t)}{L_{m2}}} + \frac{R_{g2} i_{2p}(t) - R_{g1} i_{1p}(t)}{r_o\left[i_{1p}(t) + i_{2p}(t)\right] + \frac{l_o u_{1p}(t)}{L_{m1}} + \frac{l_o u_{2p}(t)}{L_{m2}}}$$

If the terminals are solidly grounded i.e., $R_{g1}=R_{g2}=0\Omega$, the fault location (x_o) can be given as eq. (6).

$$x_o = \frac{\left[v_{dc_{1p}}(t) - v_{dc_{2p}}(t)\right] + r_o D_o i_{2p}(t) + \frac{l_o D_o}{L_{m2}} u_{2p}(t)}{r_o\left[i_{1p}(t) + i_{2p}(t)\right] + \frac{l_o u_{1p}(t)}{L_{m1}} + \frac{l_o u_{2p}(t)}{L_{m2}}}$$

Validation using RTDS:

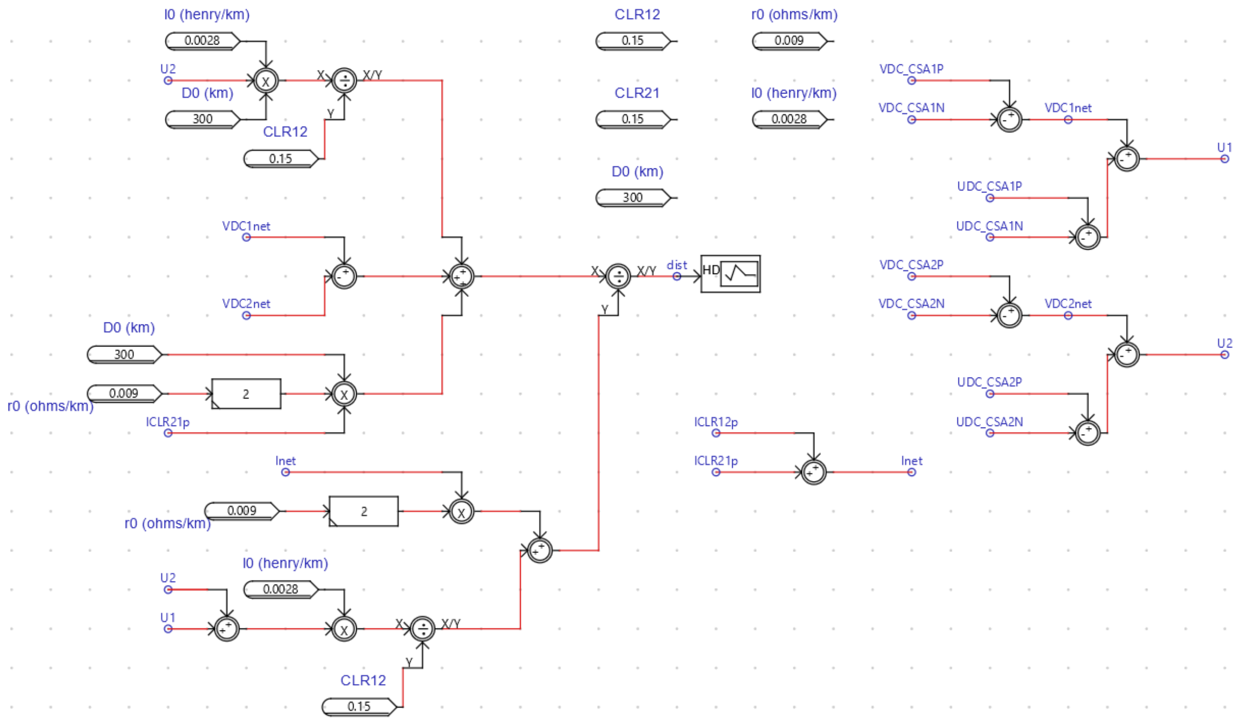


Figure 4: *Draft* file of fault location algorithm

1. Fault at bus 1 terminal: A PTP fault occurs at bus 1 terminal at t=0.1005s. Further, real-time voltage and current data is incorporated in the algorithm as shown in Fig. 4. The calculated fault location is shown as Fig. 5. The fault location behavior is reliable immediately after a fault has occurred as shown between t=0.1008 to t=0.102s.

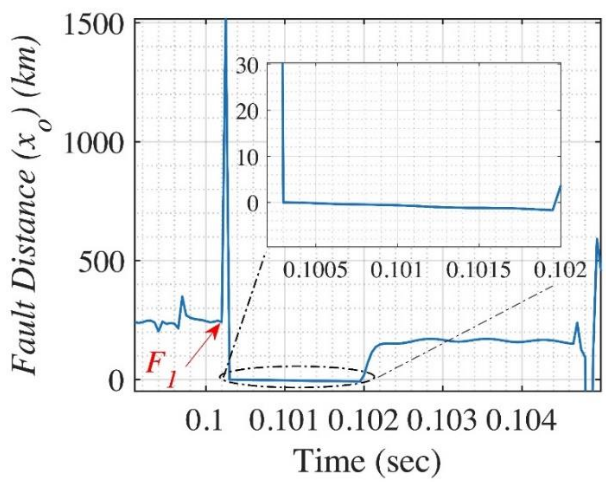


Figure 5: Fault distance for fault at 0% length

2. Fault at 50% length: A P-PTG fault occurs at 50% distance of a 300km cable. Fig. 6 shows the calculated fault distance. The fault location plot moves around 150km with nearly 97% accuracy as seen in Fig. 6.

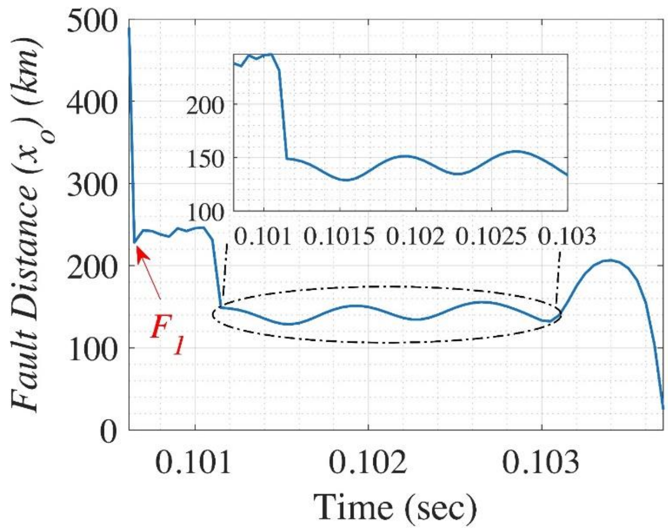


Figure 6: Fault distance for fault at 50% length

3. Fault at 100% length: An N-PTG fault occurs at 100% distance of the 300km cable. Fig. 7 shows the calculated fault distance. The fault location plot moves around 300km with nearly 95% accuracy as seen in Fig. 6.

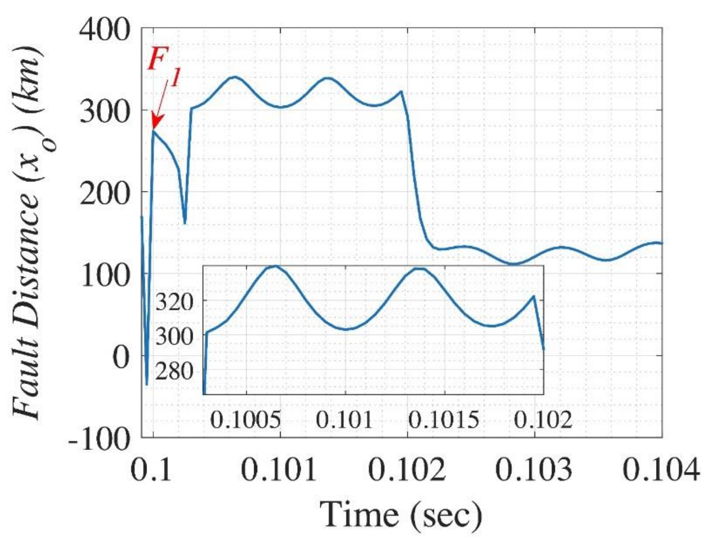


Figure 7: Fault distance for fault at 100% length

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.

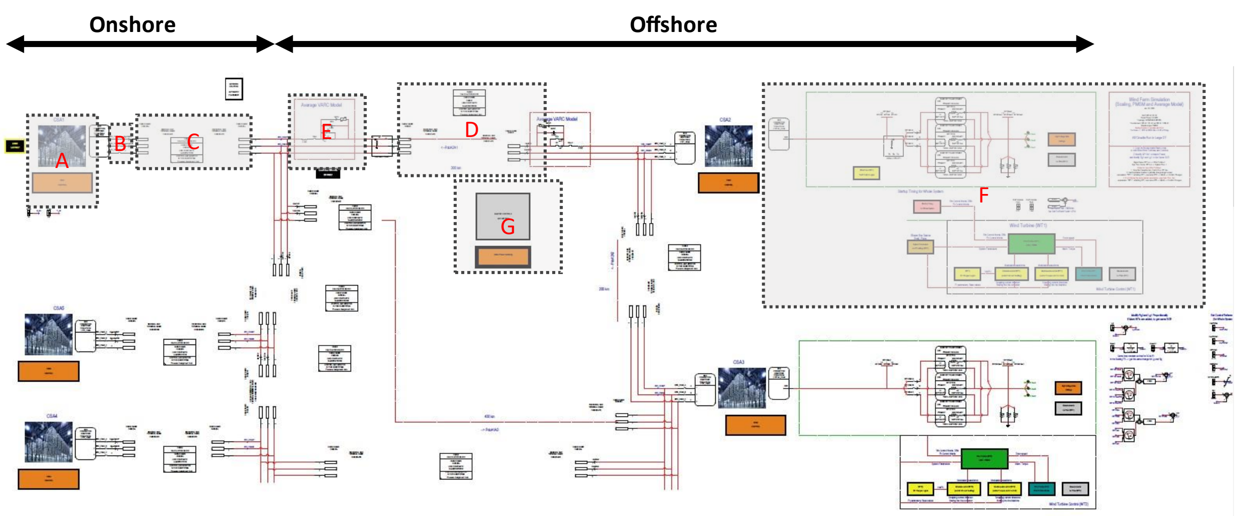


Figure 4: *Draft* file of 5 Terminal MMC-HVDC system

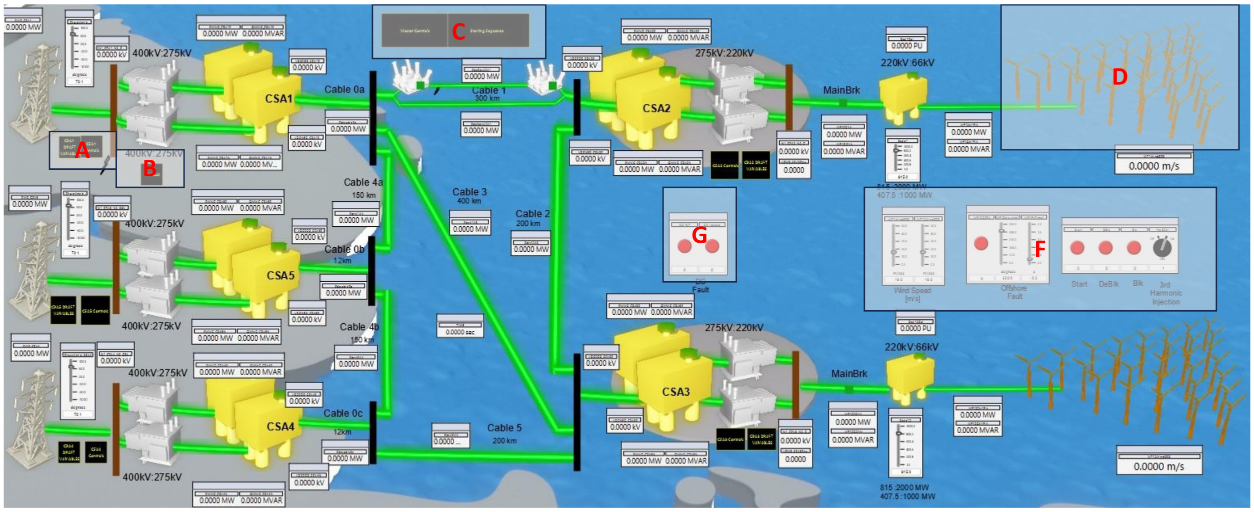


Figure 5: *Runtime* file of 5 Terminal MMC-HVDC system

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 confirm if the distance algorithm works for different following cases:
   - PTP, R_f=0 ohms, d=50%
   - P-PTG, R_f=10 ohms, d=100%
   - N-PTG, R_f=50 ohms, d=0%

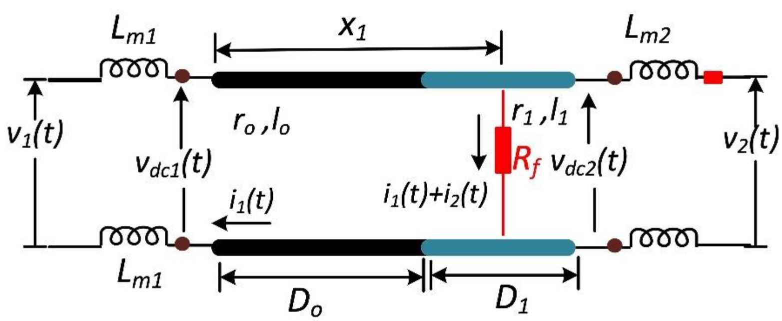
What is the effect of increasing fault resistance (if any) and different fault types (if any) on the performance of the algorithm?

2. Pick the right option:
    I. Using a double-terminal method for fault location, the accuracy of fault location for a fault resistance, R_f=0.001Ω is 98%. For a similar fault with R_f=100Ω, the accuracy would <u>(better/worse/same).</u>

    II. A PTP fault is located at 70% of the cable length from terminal 1. Assuming same pre-fault voltage for terminal 1 and terminal 2, current from terminal 2 would be <u>(greater/lesser/same)</u> in comparison to current from terminal 1.

    III. For a dedicated metallic return (solidly grounded) system, the expressions for fault location for pole to pole and pole to ground faults are the same. <u>(True/False)</u>

Bonus Question:



A two-segmented cable with resistance & inductance per unit length of segment 1: *ro*, *lo* & segment 2: r_1, l_1 is shown in Fig. 7. A pole-to-pole fault occurs at segment 2. Assuming that the joint resistance of segment 1 and segment 2 is 0, derive the expression of fault location, x_1 using double terminal time-domain method.

<u>Answer</u>: $x_1 = D_o + \frac{[v_{dc_1}(t) - v_{dc_2}(t)] + 2(r_o D_o + r_1 D_1) i_2(t) + \frac{l_o D_o + l_1 D_1}{L_{m2}} u_2(t)}{2 r_1 [i_1(t) + i_2(t)] + \frac{l_1 u_1(t)}{L_{m1}} + \frac{l_1 u_2(t)}{L_{m2}}} - \frac{2 r_o D_o [i_1(t) + i_2(t)] + \frac{l_o D_o}{L_{m1}} [u_1(t) + u_2(t)]}{2 r_1 [i_1(t) + i_2(t)] + \frac{l_1 u_1(t)}{L_{m1}} + \frac{l_1 u_2(t)}{L_{m2}}}$

<u>Hint:</u> V. Nougain and S. Mishra, "Current-Limiting Reactors Based Time-Domain Fault Location for High-Voltage DC Systems With Hybrid Transmission Corridors," *in IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1-10, 2023, Art no. 3507010, doi: 10.1109/TIM.2022.3227610.