Control and Protection of the HVDC/AC electrical grids

Assignment 3: MTDC Protection

By: Dr. Vaibhav Nougain, TU Delft

The material for this assignment is adapted from the paper:

1) **V. Nougain**, S. Mishra and S. S. Jena, "Resilient Protection of Medium Voltage DC Microgrids Against Cyber Intrusion," in IEEE Transactions on Power Delivery, vol. 37, no. 2, pp. 960-971, April 2022, doi: 10.1109/TPWRD.2021.3074879.
2) **V. Nougain**, S. Mishra, S. S. Nag and A. Lekić, "Fault Location Algorithm for Multi-Terminal Radial Medium Voltage DC Microgrid," in IEEE Transactions on Power Delivery, vol. 38, no. 6, pp. 4476-4488, Dec. 2023, doi: 10.1109/TPWRD.2023.3318689.
3) **V. Nougain**, S. Mishra, J.M. Rodriguez-Bernuz, A. Junyent-Ferré, A. Shekhar and A. Lekić, "Adaptive Single-Terminal Fault Location for DC Microgrids" (Under Review).

System Description:

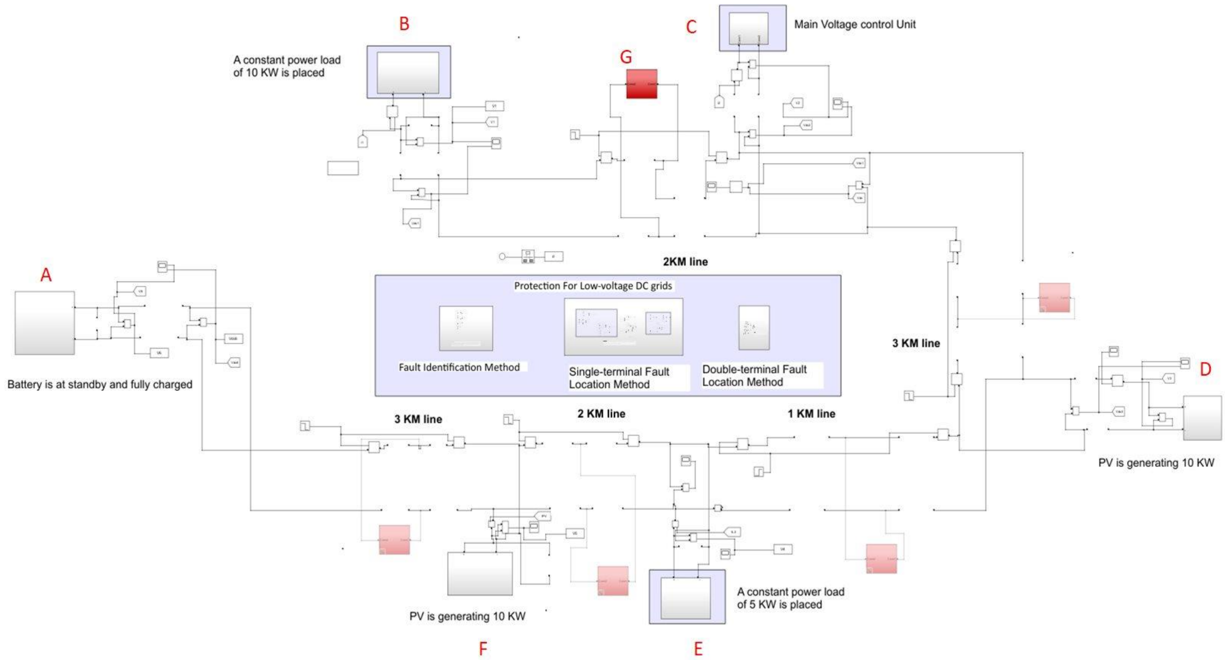

Fig. 1. The low voltage MTDC system under study in MATLAB/Simulink.

A low voltage (700V DC) monopolar grid is shown in Fig. 1. A is a Nickel-Metal-Hydride type battery with nominal voltage of 300V and rated capacity of 200Ah interfaced with a bi-directional converter to allow charging and discharging of the battery. The control objective of A is to operate in power reference mode in the presence of Main Voltage Control Unit (C) and in voltage control mode in the absence of C. B is a constant power load which is a combination of buck converter and two parallel resistive loads of 11.52Ω each. The buck converter in B is used to main the output voltage at 240V. This makes the behaviour of the load to be constant power always extracting $240^2/(11.52/2)$=10kW. Main voltage control unit (C) is a combination of 3 arm universal bridge (IGBT/Diodes) connected to a three-phase programmable voltage source through source impedance, transformers and LC filters. This acts as the power grid where the universal bridge has the control objective of maintaining the DC voltage of the system. D is a mathematically modelled photovoltaic (PV) system modelled as controlled current source with a boost converter. The boost converter is responsible to extract the maximum power point of the PV system for varying irradiation and temperature. The maximum power point tracking gives 10kW of PV generation. E is a constant power load of 5kW similar to B. F is a PV system generating maximum power of 10kW similar to D. Finally, G (red box) shows the fault inception. If similar faults are to be simulated in the system, the other uncommented red-boxes can be commented. Various monopolar distribution lines are used to distribute the generated power amongst the loads in the system. They are represented by lumped RL parameters with resistance per unit length to be 0.3293Ω/km and inductance per unit length to be 0.522mH/km. Additionally, externally placed current limiting reactors with value of 1mH are put at each terminal of all the lines.

Protection Strategy:

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. Therefore, a fast fault identification scheme is required to timely identify the fault so that the process of fault isolation can be executed for the faulty segment. To complement it, a fault location scheme can be implemented to determine the distance of fault in the faulty segment. This would help in rapid restoration of the system by clearing the fault (in case of a permanent fault). The MATLAB model presents a fault identification scheme along with two fault location schemes: (a) Single-terminal fault location for the cases when communication is not available in the system and (b) Double-terminal fault location for the cases when communication is available in the system.

1) Fault Identification Scheme:

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. As a result, if the voltage across CLRs is measured, the fault shows a peculiar behavior and can be detected almost instantaneously. The voltage across current limiting reactors at each terminal is locally measured and compared to a static threshold which is determined by the voltage level and the system parameters like line or cable length.

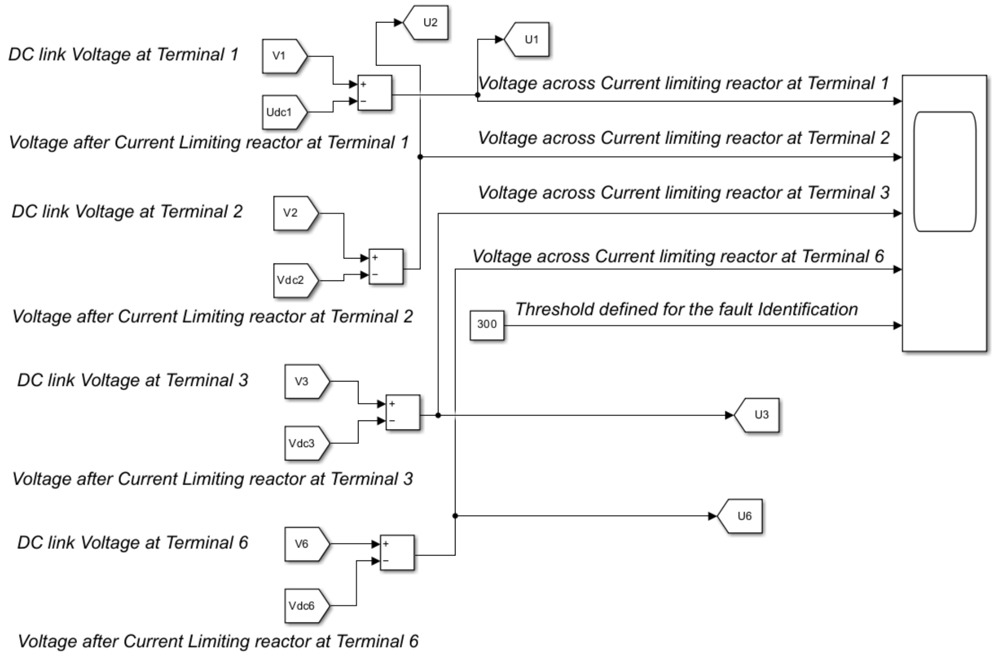

Fig. 2. Fault Identification Scheme in MATLAB/Simulink.

If a terminal voltage violates the threshold then we can know for sure that that terminal is directly related to the fault. The algorithm is fast, dependable (which means in case of a fault, the fault is indeed detected), secure (it can differentiate between a normal system transient and a fault transient) and selective (it indicates a fault only for internal contingencies in the zone of the fault and not for external DC faults). The method and its adaptation (for bipolar and homopolar line configuration) has found widespread use in DC power grids. The method is local, simple and effective to identify the position of the fault in a complex multi-terminal system.

2) Fault Location Scheme:

Accurately locating the fault helps in the rapid restoration of the isolated line back into the system. This saves a lot of time and manual labour in locating and then fixing the fault, restoring normal DC power grid operation. Depending on the communication infrastructure of the low voltage system, either a single-terminal location scheme or a double-terminal location scheme can be implemented. Single-terminal location schemes (the ones without communication in the system) have inherent dependence on the fault resistance value. As a result, for high resistance faults, the accuracy of the method may be limited. Double-terminal location schemes (the ones with communication in the system) mathematically eliminate the dependence of fault resistance from fault location accuracy. As a result, the method is robust for high resistance faults as well.

Talking about low voltage systems, it is more likely that a low resistance fault occurs than a high resistance faults so a single-terminal location scheme can be suitable for such a setup. However, both the schemes are implemented and discussed ahead.

a. Single-terminal location scheme

Once the fault is identified, an equivalent 2T circuit of the faulty network as shown in Fig. 3 is used to implement the single-terminal fault location method. Here $v_{dc1}(t)$ and $\hat{v}_{dc2}(t)$ are the terminal voltages at each side of the line, $i_{dc1}(t)$ and $\hat{\imath}_{dc2}(t)$ are the currents fed into the fault by the terminals on each side. *r* and *l* are the unit resistance and inductance of the line. L_n is defined as the value of the CLR and R_f is defined as the fault resistance. *D* is the cable length whereas *d* is the fault distance from bus terminal.

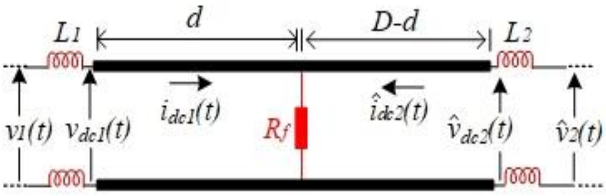

Figure 3: Equivalent 2T circuit of the faulty network

Applying KVL from terminal 1, we get the following equation:

$$v_{dc1}(t) = 2rdi_{dc1}(t) + 2ld\frac{di_{dc1}(t)}{dt} + R_f[i_{dc1}(t) + \hat{\imath}_{dc2}(t)]$$

With some mathematical manipulations [3], the other terminal (directly related to the fault) current is derived in terms of the localised value of current as:

$$\hat{\imath}_{dc2}(t) = \frac{d}{D-d} i_{dc1}(t)$$

Substituting the above equation in the KVL equation, we can re-define $v_{dc1}(t)$ as:

$$v_{dc1}(t) = d\left(ri_{dc1}(t) + l\frac{di_{dc1}(t)}{dt}\right) + R_f\frac{D}{D-d}i_{dc1}(t)$$

Rearranging for the calculated fault location (*d*), we can write the following quadratic polynomial:

$$d^2\left[r + \frac{l}{L_m}\frac{u_1(t_1)}{i_1(t_1)}\right] - d\left[\frac{v_{dc_1}(t_1)}{i_1(t_1)} + rD + \frac{lD}{L_m}\frac{u_1(t_1)}{i_1(t_1)}\right] + D\frac{v_{dc_1}(t_1)}{i_1(t_1)} = DR_f$$

Evaluating the quadratic polynomial at $t=t_2$ can give us another equation with the constant DR_f on the RHS. Subtracting the two equations would give us the final quadratic expression:

$$d^2\frac{l}{L_m}\alpha(t_1,t_2) - d\left[\beta(t_1,t_2) + \frac{lD}{L_m}\alpha(t_1,t_2)\right] + D\beta(t_1,t_2) = 0$$

Here $\alpha(t_1, t_2) = [u_1(t_1)i_1(t_2) - u_1(t_2)i_1(t_1)]$, $\beta(t_1, t_2) = [v_{dc1}(t_1)i_1(t_2) - v_{dc1}(t_2)i_1(t_1)]$. Fig. 4 shows the implementation of the single-terminal fault location scheme in MATLAB/Simulink. There are different wonderful methods to determine the fault distance in the literature. The tutorial shows validation of one of the novel single-terminal methods. Firstly, $\alpha(t_1, t_2)$ and $\beta(t_1, t_2)$ are defined with a window of 7 samples. A window with fewer samples gives a triangular distance behavior (instead of a trapezoidal behavior) solution, while a window of abruptly high samples, such as 20 samples, gives an erroneous fault distance solution. A window of 3-10 samples is recommended to implement consecutive sample manipulation. Further, the coefficients of the quadratic polynomial are defined and finally the roots of the quadratic polynomial are solved. One of the solutions is negative for the most part and is defined as the invalid distance while the other solution gives accurate fault distance for nearly 4μs.

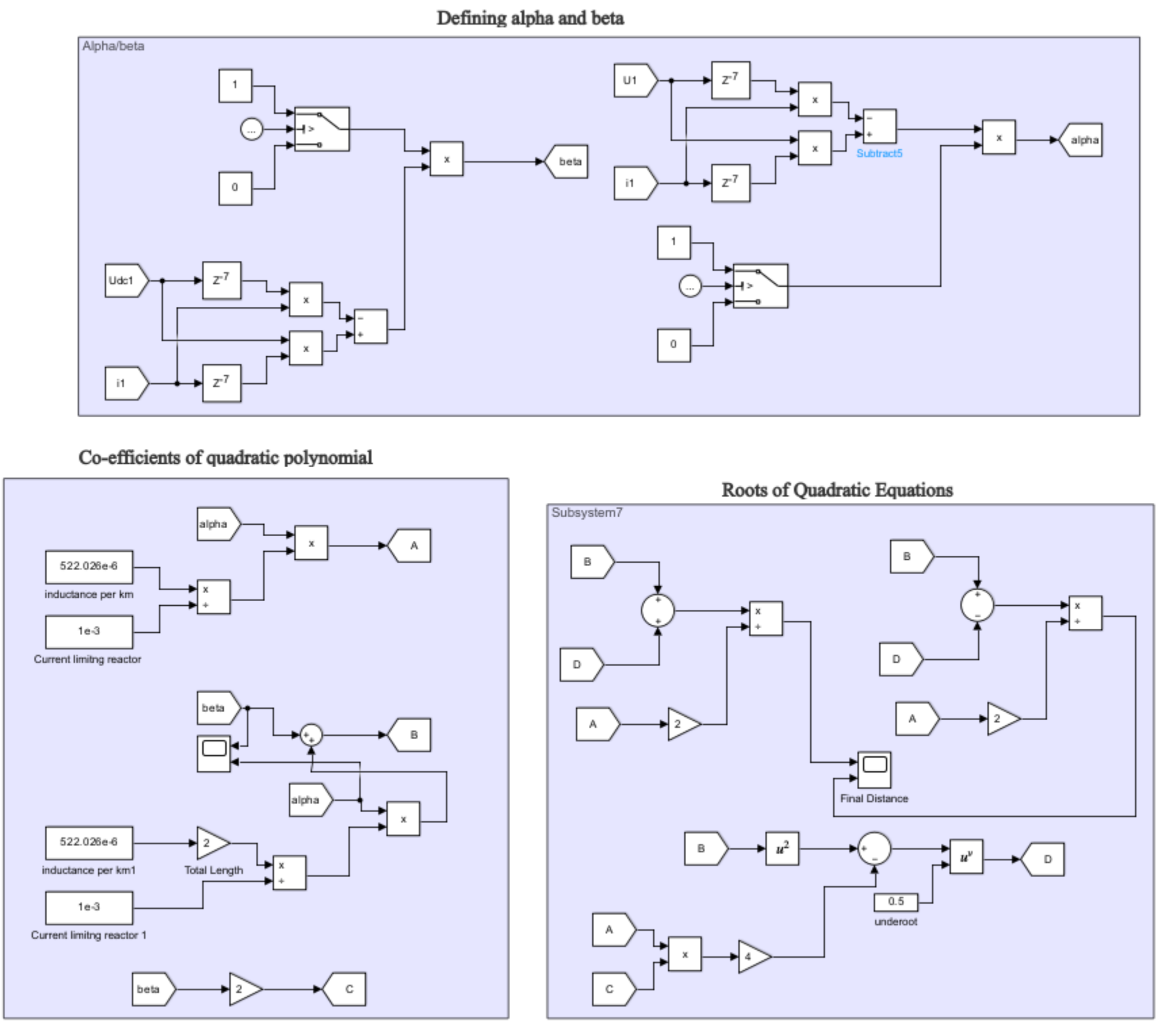

Figure 4: Single-terminal fault location scheme in MATLAB/Simulink

b. Double-terminal location scheme

Similar to the previous case, once the fault is identified, an equivalent 2T circuit of the faulty network as shown in Fig. 5 is used to implement the double-terminal fault location method. In Fig. 5, $v_1(t)$ 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.

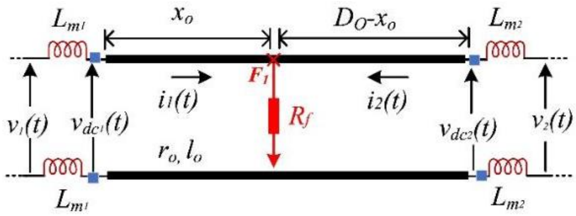

Figure 5: Equivalent 2T circuit of the faulty network

The fault location algorithm is explained in detail using double-terminal time-domain method. Considering the fault, F_1 at cable 1 as shown in Fig. 5, we can apply KVL considering both terminals to obtain the following equations:

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

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

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 below:

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

Subtracting the two KVL equations 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 the current derivative term and rearrange the expression, the fault location (x_o) can be defined as:

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

The implementation of the double-terminal fault location in MATLAB/Simulink is shown in Fig. 6. The method is simple and accurate for different DC faults in the system.

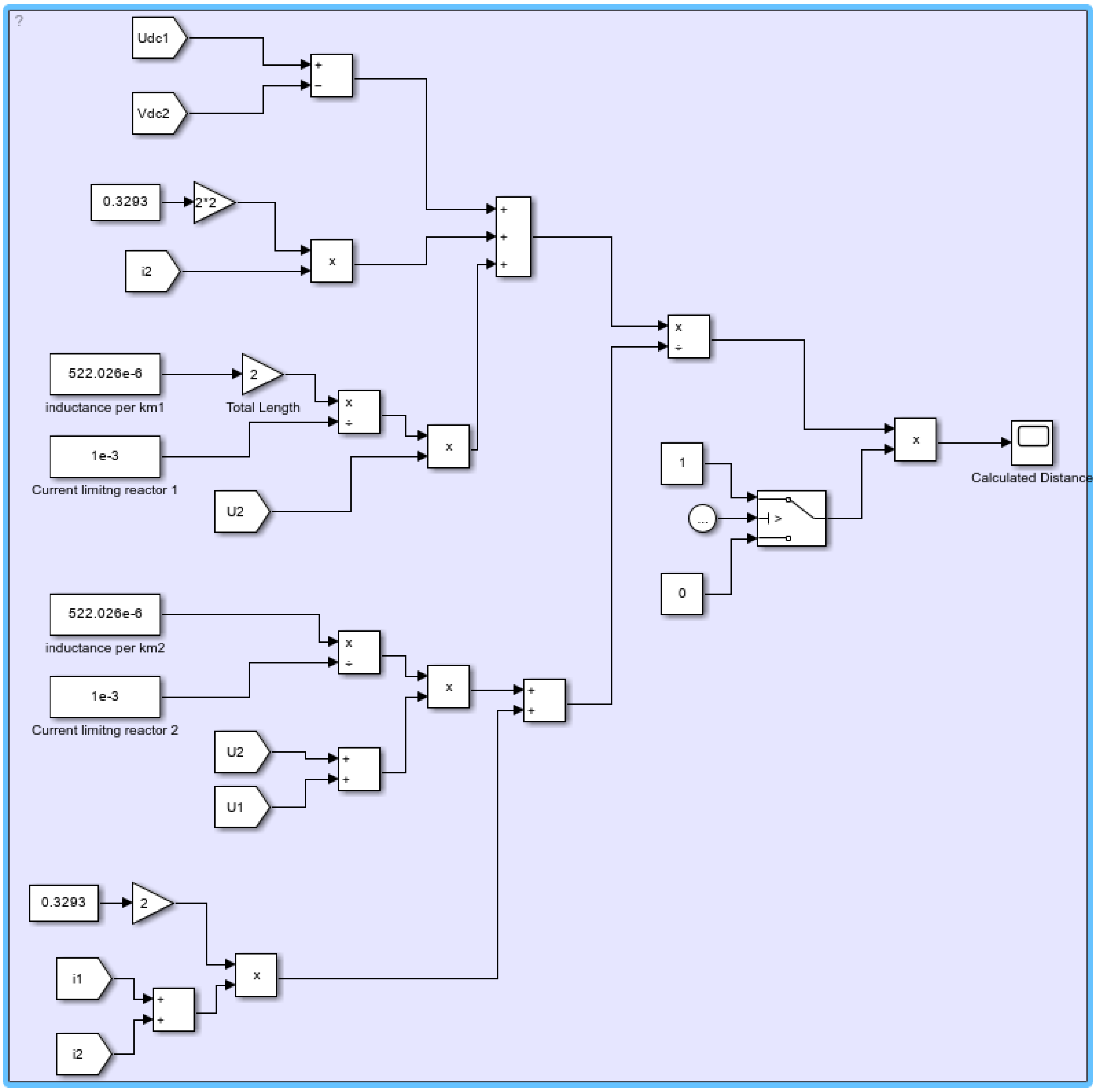

Figure 6: Double-terminal Fault location scheme in MATLAB/Simulink

<u>Assignment:</u>

1. For a fault between terminal 1 and terminal 2, validate the fault identification scheme for the following distances: (a) d=25%, (b) d=50% and (c) d=75%.

2. For a fault between terminal 2 and terminal 3, validate the fault identification scheme for the following distances: (a) d=25%, (b) d=50% and (c) d=75%.

3. For a fault between terminal 1 and terminal 2, observe the fault identification scheme for the following fault resistances: (a) $R_f=1\ \Omega$, (b) $R_f=5\ \Omega$, (c) $R_f=10\ \Omega$, and $R_f=50\ \Omega$. Is the same proposed threshold of 300 applicable for all the cases? Can you conclude something related to the threshold and the upper value of fault resistance until which the method is applicable for the given threshold?

4. For a fault between terminal 1 and terminal 2, report the range of fault distance calculated using the single-terminal and double-terminal methods for the following cases:

D_{true} *(kms)*	$D_{reported}$ *Single-T*	$D_{reported}$ *Double-T*
0.25		
0.5		
0.75		
1		
1.25		
1.5		
1.75		

5. For the following increasing values of fault resistance, observe and compare the performance of single-terminal and double-terminal fault location methods: (a) R_f=1Ω, (b) R_f=5Ω, and (c) R_f=10Ω.