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Online Neutral Line Fault Locator (nLFL) for HVdc Applications

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SUMMARY

This paper discusses the implementation and the online testing of the Online Neutral Line Fault Locator (nLFL) in the Eastern Alberta Transmission Link (EATL).

HVdc transmission systems with a Dedicated Metallic Return (DMR), are often used in areas where critical metallic infrastructure is buried. Removing the return path from the earth and placing it in the DMR will prevent circulating currents from corroding buried metallic systems such as piping. Fault location on a DMR cannot use the commonly used approach found on the HVdc pole conductors, known as traveling wave fault location, since the voltages on the DMR are much lower than the Pole conductors and the DMR is grounded on one end. These issues prevent the appropriate waveform capture needed for traveling wave fault location.

The Online Neutral Line Fault Locator (nLFL) resolves this issue by using the impedance-based calculations from the existing HVdc measurement data to calculate the fault location. The nLFL uses the measured data and nonlinear regression to curve fit the measured data to determine the impedance of the faulted transmission line in the faulted state. Specifically, the nLFL system determines the impedance of the faulted transmission line, without any HVdc protection systems operating. This is needed since the fault location can only be accurately calculated when the system has reached its new faulted steady-state condition without any protective action.

The nLFL system has been deployed and tested on the ideally situated Eastern Alberta Transmission Link (EATL) HVdc system. The EATL is a 485 km, ±500kV, 1000MW monopolar LCC HVdc link interconnecting the central and the southern Alberta regions. The EATL transmission line is designed as a bipolar scheme for future expansion, and owing to the large proliferation of pipelines in Alberta, the link is designed to use a DMR instead of a ground return.

The nLFL system has been successfully installed and tested in the EATL HVdc system. and is presented in this paper. The testing of the nLFL system was completed, with an Electro Magnetic Transient (EMT) simulator and in the real world on the EATL HVdc system.

KEYWORDS

Protection and Automation, High Voltage Direct Current (HVdc), Dedicated Metallic Return (DMR)

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1 Introduction

The use of the Dedicated Metallic Return (DMR) conductor has grown, owing to the modern use of the High Voltage Direct Current (HVdc) system, to avoid the issues associated with circulating ground currents and buried metallic structures. As a result, there is a demand for accurate line fault location technologies to detect line fault locations on the DMR conductor reliably. Thus, the paper proposes a novel Neutral Line Fault Locator (nLFL) system capable of accurately locating the fault on both DMR and return conductors.

1.1 Issues with Circulating Ground Currents

The operation of an HVdc system that utilizes an earth return rather than a DMR conductor can result in circulating ground currents that could lead to a variety of issues for buried metallic structures such as:

- Pipeline damage to pipe coating which could lead to the corrosion of underground pipes [1] and such corrosion which could result in an environmental incident if the pipe is transporting toxic or non-environmentally friendly substances (e.g., Oil, gas).
- A rise in the voltage potential of the pipe could lead to a dangerous or hazardous shock potential on the pipe [1].
- Saturation of AC wye grounded transformers owing to the circulating DC currents, which result in the creation of harmonics in the ac system and can cause the vibration and the overheating of equipment or lead to the maloperation of protection systems [2].

1.2 Existing HVdc Fault Location Methods

1.2.1 HVdc Fault Location Based on Traveling Wave Detection

Currently, the most used HVdc fault location method, is the online passive double ended traveling wave line fault location. The detection of the initial wave front's arrival time at each station is the key to determining the line fault location. After the arrival time is determined, the line fault location can be calculated by using Equation (1.1) [3]. Although this method is susceptible to wavefront distortions, the method is robust since the readings are taken at both sides and only have the need to determine and distinguish the first wave front's arrival at the station. This method is very effective in determining the fault location. Thus, this method has been implemented in commercially available products.

$$D = \frac{L}{2} + \frac{(t_A - t_B)v}{2} \tag{1.1}$$

Where:

L = Length of the transmission line
D = Distance from the station to the fault location
v = Propagation velocity of the transmission line
t_A = The time of arrival of the first wave fronts at a station A
t_B = The time of arrival of the first wave fronts at a station B

The online passive double-ended traveling wave line fault location system is typically used on the pole conductors which are normally energised. However, the online passive double ended traveling wave line fault location system is not typically used on DMR conductors or on pole conductors which are acting as return conductors or electrode conductors since these conductors are typically at a very low voltage due to one end being grounded. Furthermore, the fact that one end of the return conductor is grounded prevents the successful detection of the traveling wave.

1.2.2 HVdc Fault Location Based on Impedance Measurements

The proposed HVdc fault location method, is the online passive double-ended impedance measurement line fault location system. Here, the measurements from both stations are used to calculate the impedance of the line from both before and after the fault. The fault location can be calculated using Equation (1.2) [4]. The calculation is based on the measured voltages and currents present on the line. The fault location is determined by the change in the line impedance which is proportional to the change in the length of the line. One benefit of this method is that the impedance of the fault is not needed since it can be mathematically eliminated from the calculation. This method has one main challenge. The settling time for very long transmission lines becomes an issue as the system may not have stabilised sufficiently for the impedances to be accurately calculated from the measured values. This can result in a reduction of the fault location accuracy.

$$D = \frac{R_D}{R_L} L \qquad (1.2)$$

Where:

L = Length of the transmission line
D = Distance from the station to the fault location
R_D = Resistance of the transmission line from the station to the fault
R_L = Resistance of the total transmission line

The online passive double-ended line fault location system based on impedance measurements can be used for pole conductors, DMR conductors or pole conductors which are acting as return conductors or electrode conductors. This is possible provided that the controls and/or the protection systems give sufficient time for the system to settle, to the new faulted steady-state mode of operation, before clearing of the fault occurs. Furthermore, the shorter the transmission line is, the better this system would work since it would take less time for the HVdc system to settle.

1.3 Implementation Challenges for an Online Line Fault Locator (nLFL)

Fault location systems that use impedance calculations rely on the existing HVdc measurements and timestamps to calculate the fault location in the faulted steady-state condition of the HVdc system. The timestamping of the event is only used for ensuring that the measurements used are from the same time instant. However, obtaining measurements from the faulted steady-state condition can become increasingly difficult as the length of the transmission lines or the cables is increased. Increases in line length result in a longer transient settling time for the system, which further delays the faultedsteady-state measurements needed for the calculation. In addition, the fact that the HVdc protection system can react to clear the fault from the system prior to the system reaching the new faulted steady-state condition is also problematic. If the HVdc system does not reach its faulted steady-state condition, prior to the activation of the HVdc protection system, the accuracy of the fault location system will be reduced.

1.4 Proposed Line Fault Location Technology

A innovative fault location system based on impedance measurements is presented to interpolate the faulted steady state condition of the HVdc system without any protective control action. It enhances the capability and accuracy of this fault location scheme and overcome the issues associated with existing and proposed line fault location technologies.

The new system is called Neutral Line Fault Locator (nLFL) system, and it is a point-to-point online passive double-ended line fault location system that utilizes the existing voltage and current measurements of the HVdc system to calculate the line fault location on a DMR or a return conductor. The nLFL uses the measurements it collects from the HVdc system before (pre-transient period) and after (transient period) the fault, prior to the protective actions of the HVdc system taking effect to clear the fault. The nLFL uses nonlinear regression of the transient period data to calculate the faulted steady-state condition of the HVdc system without the HVdc protection systems activating. The nLFL system can calculate the line fault location with the HVdc system projected to time infinity without any protective control actions,

2 HVdc Topologies with Dedicated Metallic Return (DMR)

Each of the several HVdc topologies that can utilize a DMR conductor would require an nLFL system. Two HVdc topologies that can utilize a DMR conductor are: the Monopolar HVdc Scheme and the Bipolar HVdc Scheme.

2.1 Monopolar HVdc Scheme with Dedicated Metallic Return (DMR)

In a Monopolar HVdc scheme with a DMR, power is transferred either by a positive or negative pole and the return path is via a DMR conductor. [5] [6]. The nLFL system can be used for online line fault location on a Monopolar HVdc scheme with a DMR. This configuration does not require any alterations in the operating modes of the Monopolar HVdc scheme. Since the DMR is energised during monopolar operation of a Monopolar HVdc system, the fault location can be determined during the normal operation of a Monopolar HVdc system.

2.2 *Bipolar HVdc Scheme with Dedicated Metallic Return (DMR)*

In the Bipolar HVdc scheme with Dedicated Metallic Return (DMR), the system utilizes both a positive polarity and a negative polarity pole. Normally, the pole currents are made equal to minimize the current through the return path. However, this is not perfect, and a small, mismatch current still flows into the station or electrode ground. Therefore, the modern trend is to have a DMR conductor to prevent the issues described in section 1.1. A Bipolar HVdc system with a DMR. [5] [6]

The nLFL system can be used for online fault location in a Bipolar HVdc system with a DMR, but it requires an operating mode that energises the DMR with sufficient magnitude to monitor and measure the voltage and the current on the DMR conductors. Since, there is little to no current flowing through the DMR in the bipolar operating mode of a Bipolar HVdc system. Therefore, fault detection using the proposed nLFL algorithm does not work in this scenario.

Fault location on a DMR in a bipolar system can be achieved if the two poles have different current orders (i.e., unbalanced operation) and there is a spillover current in the DMR conductor, which causes a voltage drop on the DMR conductor. This can be used for fault location.

Secondly, fault on the DMR of a Bipolar HVdc can be determined when the Bipolar HVdc system is running in a metallic return mode of operation. This operating mode essentially converts the operation of a Bipolar HVdc scheme to a Monopolar HVdc scheme, in which one pole is energized as normal and the DMR and/or the opposite pole acts as the return path.

2.3 *East Alberta Transmission Link (EATL) HVdc Scheme*

For the purpose of practical analysis and testing, the nLFL system has been implemented on the East Alberta Transmission Link (EATL) HVdc System. The EATL HVdc scheme is a 458 km overhead link that runs from Brooks, Alberta, Canada (Newell Converter Station) to Gibbons, Alberta, Canada (Heathfield Converter Station). The EATL HVdc system is owned and operated by ATCO Electric.

The EATL HVdc scheme is currently configured as a 500 kV Monopolar HVdc system capable of transmitting 1000MW. The conductor for a second HVdc pole has been installed for future expansion. This conductor is currently used as a return path in parallel with the DMR.

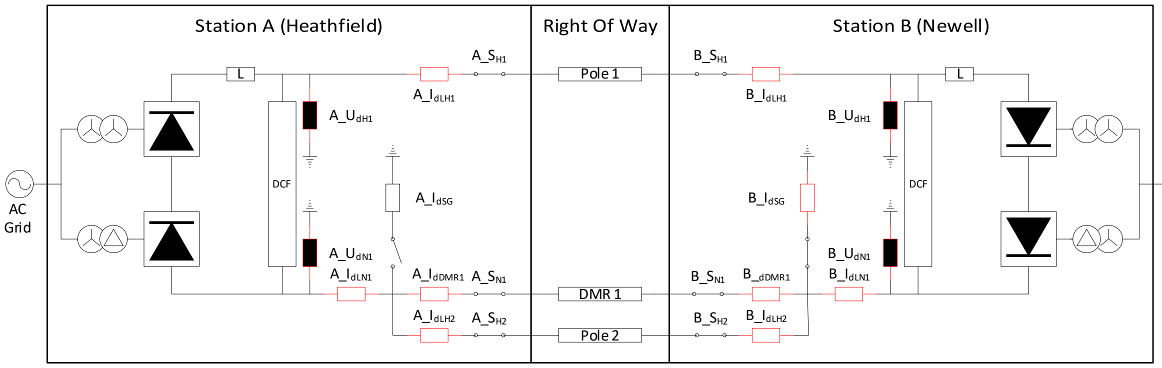

Figure 2-1: EATL HVdc system configuration.

3 The Online Neutral Line Fault Locator (nLFL)

The nLFL system can be directly integrated into new or existing HVdc systems, by connecting the HVdc system to the measurement system of the nLFL system. The nLFL system consists of two main components. The first component is the hardware used to capture the real time current measurements and voltage measurements for analysis. The second component of the nLFL system is the software that processes and analyses the measured data, to determine the fault location.

3.1 *Online Neutral Line Fault Locator (nLFL) Hardware Architecture*

The nLFL hardware consists of two main components. These are the real-time system known as the Data Measurement Unit (DMU) and non-real-time system that is run on an industrial computer. The DMU performs real-time capture of the voltage and the current measurements. Here each measurement is simultaneously collected and GPS time-stamped for coordination of station measurements. The DMU is also responsible for detecting the fault event. The DMU utilizes a rate of change fault detection algorithm to determine the occurrence of a fault. Once the DMU detects a fault event, the DMU captures the pre-transient event and the transient event voltage and current measurements. The DMU then transfers the captured measurements to the non-real-time system for analysis. The DMU has the following main specifications: Data Acquisition (8 - ±10 V, 16-bit channels with 1.0 million samples / second / channel), Global Positioning System (GPS) Clock (Accurate to within ±100 ns, greater than 99.0% of the time) and 4 Dry Alarm contacts (Major Alarm, Minor Alarm, LFL Operated and LFL Self-Test Operated)

The non-real-time system is an industrial computer. The computer hosts a SQL database to store the measurements from the DMU and the nLFL results while also hosting a webpage to display the results of the nLFL system. More importantly, the computer also hosts the nLFL service that processes the DMU data and calculates the nLFL algorithm.

3.2 *Online Neutral Line Fault Locator (nLFL) Algorithm*

The nLFL system implements an online double-ended passive fault location algorithm. This utilizes the impedance of the transmission line derived from the measured values of the HVdc system to calculate the fault location on the neutral conductors. The nLFL's fault location algorithm uses an equivalent model of the HVdc system to simplify the HVdc transmission line to a resistive electric circuit. The resistances of the line can be calculated before and after the fault occurred. The nLFL uses the derived equations from the impedance of the line and the measured values from the DMU to calculate the fault location. The HVdc system must reach steady-state after the fault to obtain an accurate fault location. However, such steady-state is not directly possible if protection action is triggered and the steady-state is never reached. The nLFL algorithm uses regression to forecast the future values of the HVdc system in the faulted steady-state to overcome this problem.

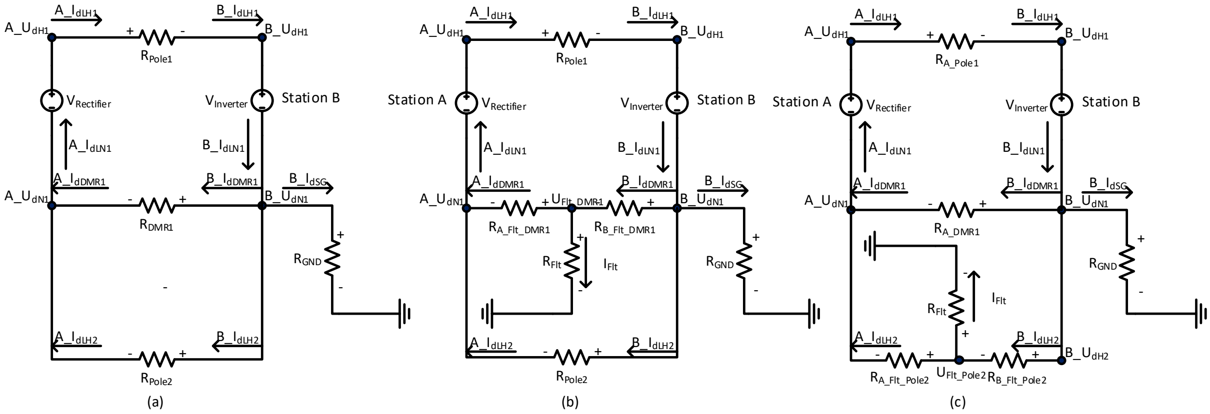

Figure 3-1: Equivalent circuit of the EATL HVdc system with available measurement points (a) unfaulted; (b) DMR1 faulted; (c) Pole2 faulted.

Thus, to complete the nLFL's algorithmic analysis, the HVdc system seen in Figure 3-1 is represented by the simple equivalent electric circuit model seen in Figure 3-1 (a). The HVdc converter at either end is represented by fixed voltage sources for the purposes of steady state analysis of the system. The three transmission lines of the Right-Of-Way (ROW) can be represented by the standard π–model of a transmission line for each of the three conductors in the ROW. However, since the HVdc system is running at steady-state dc (i.e. 0 Hz), the inductive and the capacitive components elements will be short and open circuits, respectively. Thus, the π–model of each conductor becomes purely resistive as modeled in Figure 3-1 (a). The grounding point of the converter station can be modeled as a fixed resistive element to ground to represent the impedance of the station grounding. The ground resistance is fixed and should fluctuate little over time with the appropriate design of the ground electrode and selection of an appropriate ground electrode location.

Nodal analysis of the equivalent electric circuit seen in Figure 3-1 (a) can be used to derive the unfaulted resistance of any conductor in the HVdc system. The general unfaulted conductor resistance can be calculated from Equation (3.1).

$$R_x = \frac{(A\_U_{dx} - B\_U_{dx})}{A\_I_{dx}}$$

Where:

R_x = Resistance of the x conductor (3.1)
A_U_{dx} = Station A x voltage
B_U_{dx} = Station B x voltage
A_I_{dx} = Station A x current
$_x$ = Is the unfaulted conductor

During a fault, the faulted conductor can be modeled as two resistors with a fault resistor connected at the intersection of the two resistors going to ground. An example of the faulted equivalent circuit can be seen in Figure 3-1 (b) and (c). Since the faulted HVdc system is modeled in its faulted steady state, an equation can be derived for each conductor by representing the fault location along the line as a percentage of the line from either station to the fault location. Using Figure 3-1 (b) and/or (c) the percent fault distance equation for any conductor from either station can be derived as seen in Equations (3.2).

$$X_{A\_Flt\_x} = \frac{A\_U_{dx} - B\_U_{dx} + (B\_I_{dx} \times R_x)}{R_x \times (-A\_I_{dx} + B\_I_{dx})}$$

(a)

$$X_{B\_Flt\_x} = \frac{B\_U_{dx} - A\_U_{dx} - (A\_I_{dx} \times R_x)}{R_x \times (-A\_I_{dx} + B\_I_{dx})}$$

(b)

Where:

$X_{A\_Flt\_x}$ = Percentage of total line length from Station A to the fault location on the x conductor (3.2)
$X_{A\_Flt\_x}$ = Percentage of total line length from Station B to the fault location on the x conductor
Rx = Resistance of the x conductor
A_U_{dx} = Voltage on conductor x at Station A
B_U_{dx} = Voltage on conductor x at Station B
A_I_{dx} = Current on conductor x at Station A
B_I_{dx} = Current on conductor x at Station B
$_x$ = Faulter conductor identifier (i.e., a pole conductor or DMR)

When the percent distance to the fault from the station, is calculated the actual fault location can be calculated using Equation (3.3)

$$D_{y\_Flt\_x} = X_{y\_Flt\_x} \times L_x$$

Where:

$D_{y\_Flt\_x}$ = Distance from Station y to the fault location on the x conductor (3.3)
$X_{y\_Flt\_x}$ = Percentage of total line length from Station y to the fault location on the x conductor
L_x = Total conductor length
$_y$ = Station identifier, i.e., A or B

Note that percent fault distance Equations (3.2) use steady-state values for the faulted condition. However, to prevent damage to the HVdc converter, the HVdc system's control and protection scheme react to clear the fault. The clearing of the fault can be completed in less than one second if a breaker is opened on the return conductor(s). In general, the HVdc system's control and protection scheme will generally operate during the transient period prior to the HVdc system reaching the faulted steady-state conditions.

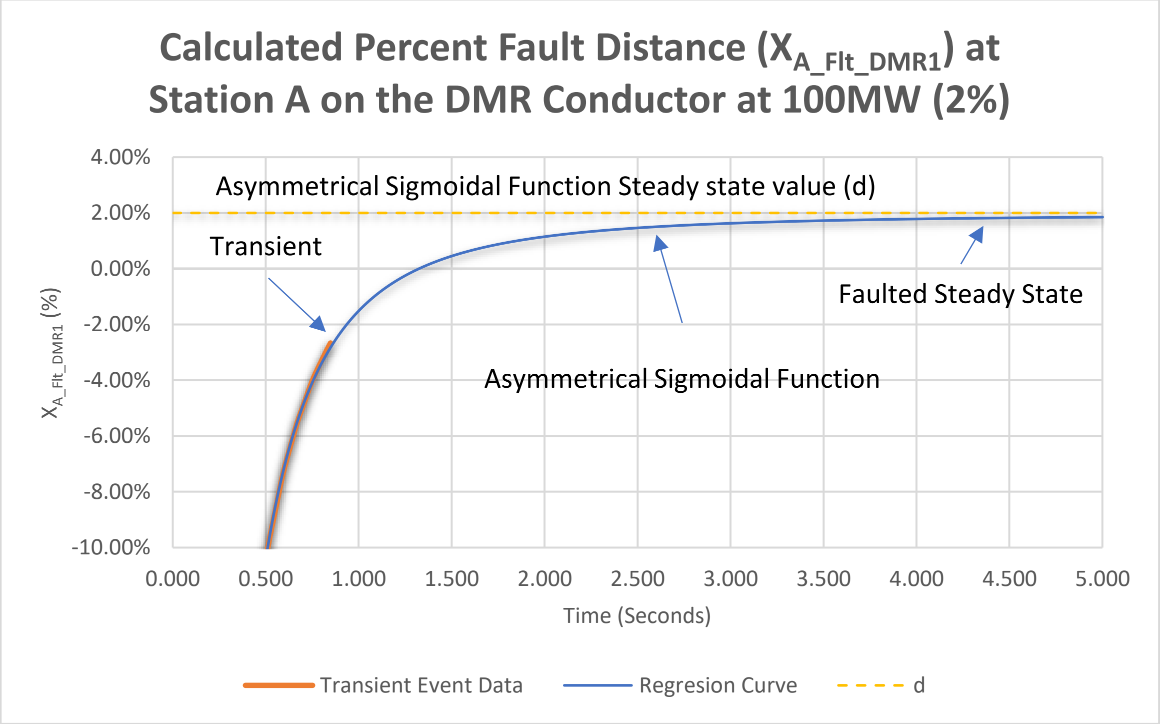

Figure 3-2: Recorded (transient) and Fitted fault position error, for a fault at 2.0% of the transmission line length.

To evaluate the percent fault distance Equations (3.2) ($X_{A\_Flf\_x}$ or $X_{B\_Flf\_x}$), the estimated values of the equation's variables (A_U_{dx}, A_I_{dx}, B_I_{dx}, and B_U_{dx}) are needed. Therefore, it is possible for small errors in each of these estimates to be compounded. To avoid the compounding errors in the calculation, regression analysis can be used to fit the time evolution of the percent fault distance equation itself, where each (time) point of $X_{A\_Flf\_x}$ or $X_{B\_Flf\_x}$ is obtained from either Equation (3.2) with A_U_{dx}, A_I_{dx}, B_I_{dx}, and B_U_{dx} being the instantaneous values during the transient as shown in Figure 3-2. This method can reduce the compounding of errors caused by the derivation of each of the voltages and the currents in the faulted steady state condition, before calculating the percent fault distance equation. The asymmetrical sigmoidal function shown in Equation (3.4) is used to model the time-varying response of the percent fault distance equation. For the asymmetrical sigmoidal function shown in Equation (3.4), the steady state percent fault distance is $y(\infty) = \lim_{t\to\infty} y(t) = d$.

$$y(t) = d + \frac{a - d}{\left[1 + \left(\frac{t}{c}\right)^{b}\right]^{m}} \tag{3.4}$$

Where:

y = Curve fit value
t = Time in seconds
a = Fitting parameter 1
b = Fitting parameter 2
c = Fitting parameter 3
d = Fitting parameter 4
m = Fitting parameter 5

3.2.1 *Online Neutral Line Fault Locator (nLFL) Algorithm sources of error*

There are a few possible sources of error in this nLFL fault detection approach. Incorrect fault locations could be reported because of a short transient period (i.e., insufficient transient event data captured for analysis) or due to noise in measurements and sensitivity of the measured quantities in different locations along the transmission line.

4 Online Neutral Line Fault Locator (nLFL) Testing and Performance Analysis

4.1 *Simulation studies of the Online Neutral Line Fault Locator (nLFL)*

For testing the nLFL system in a practical test environment, the EATL HVdc scheme was modeled in the EMT simulator PSCAD™/EMTDC™. The EMT model of the EATL HVdc scheme consisted of a 12-pulse converter model, with the dc yard modelling the dc line reactors and the dc filters of EATL HVdc system and the voltage transducers and current transducers measurements were made available using standard current and voltage monitoring devices in the EMT simulator. The transmission line right of way was also modeled in the EMT simulator, using the tower design for the EATL HVdc scheme's ROW [1].

Typically, one second is required for opening the Metallic Return Transfer Breaker (MRTB) or Ground Return Transfer Switch (GRTS) to enable the DMR and Pole 2 conductor (respectively), to clear the fault on its' conductors. Thus, a calculation window of 900 ms, would allow for variations of up to 100 ms in the opening of the MRTB or the GRTS to clear the fault. Note that this interval is generally too small for the system to have reached the faulted steady state. However, as will be shown, the proposed algorithm can glean sufficient information from measurements during this interval to estimate the steady state voltages and currents that would have been attained if the protection had not operated.

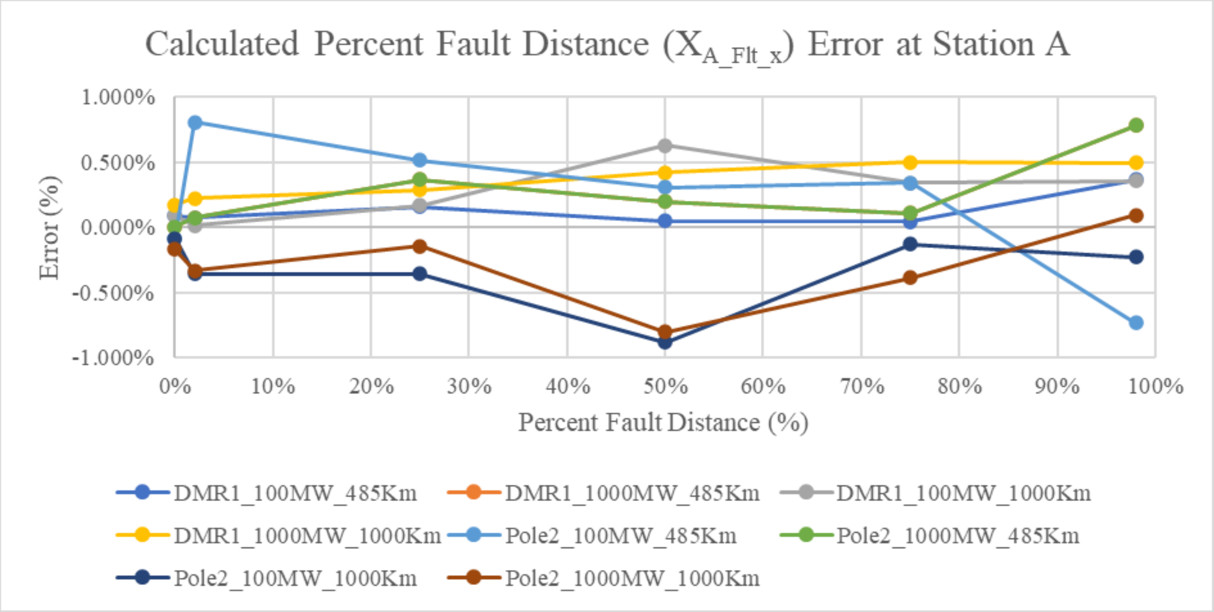

Figure 4-1: Error in calculated percent fault distance ($X_{A\_Flt\_x}$) for a station ground resistance = 0.01 Ω and fault resistance = 0.1 Ω.

4.1.1 *Simulation Based Testing of the Online Neutral Line Fault Locator (nLFL)*

To test the EMT model of the nLFL system in the EATL HVdc system, the EATL HVdc system was configured with the Pole 1 conductor being the primary power carrying path and the DMR 1 conductor and the Pole 2 conductor being a parallel return path. Faults were individually applied to each of the return conductors starting from a percent fault distance of 0% at station A- the Heathfield converter station to 100% at Station B - the Newell converter station. These faults were applied for the actual EATL Line length of 485.0 km. To test the robustness of the algorithm, additional testing was done for a hypothetical line of length of 1000 km using the same conductor configuration as the EATL. The minimum and maximum power orders were 100.0 MW and 1000.0 MW. The station ground resistance was 0.01Ω and the fault resistance was 0.1 Ω.

4.1.1.1 *Fault Location Error in the actual nLFL scheme which uses only Transient Event Data.*

Figure 4-1 show the results of calculating a fault location on the DMR 1 conductor and the Pole 2 conductor. The nLFL method presented in this paper determines the fault location using only the transient event data. The errors in this case can be attributed to the reduced sampling window which is limited by the transient period, and by measurement sensitivity and noise.

4.2 *Field testing of the Online Neutral Line Fault Locator*

4.2.1 *Field Testing of the Online Neutral Line Fault Locator on the EATL*

To test the nLFL system on the actual EATL HVdc system, the EATL HVdc system was configured with the Pole 1 conductor being the primary power carrying path and the DMR 1 conductor and the Pole 2 conductor being a parallel return path. Faults were applied by throwing a grounding wire using a drone. Since, no permission was granted to operate the drone outside the station area, all faults were applied at the Station A end (Heathfield) for a percent fault distance 0%. These faults were applied for several power orders of 150.0 MW, 250.0 MW, 500.0 MW and 1000.0 MW.

4.2.1.1 *Fault Location Error in the actual nLFL scheme which uses only Transient Event Data.*

Table 4-1 show the results of calculating a fault location on the DMR 1 conductor in configuration 1 and the Pole 2 conductor in configuration 2. The nLFL method presented in this paper, determines the fault location using only the transient event data. The errors in this case can be attributed to the reduced sampling window which is limited by the transient period, and by measurement sensitivity and noise.

Table 4-1: EATL error in calculated percent fault distance (XA_Flt_x).

Faulted Conductor	Percent Fault Distance (%)	150 MW	250 MW	500 MW	1000 MW
DMR1	0%	0.290%	-0.296%	-0.390%	-0.432%
Pole2	0%	0.182%	-0.286%	-0.296%	-0.411%

4.3 *Online Neutral Line Fault Locator results summary*

The results show that the accuracy of the nLFL method for the DMR 1 conductor and the Pole 2 conductor is less than 1.0% for the entire length of the transmission line. However, faults at the grounded Station B are undetectable because the voltage there is already zero and the fault would not cause a detectable voltage change. These results prove that the nLFL method can accurately calculate a fault location on the DMR 1 and Pole 2 conductor using the measurements collected in the transient event data period.

The proposed nLFL system can detect and calculate the fault location. However, there are practical limitations to the accuracy of the nLFL system. The main sources of error for the nLFL system lies in the measurement devices and the impact of environmental conditions on the characteristics of the transmission line.

Similarly, the measurement devices used to measure the voltage and the current of the HVdc system can also introduce error in the nLFL systems' calculation. This is due to the accuracy and the precision of the measurements taken by the voltage and current transducers.

5 Conclusion

The Neutral Line Fault Locator (nLFL) system is a point to point online passive double ended line fault location system that utilizes the existing voltage and current measurements of the HVdc system to calculate the line fault location on a DMR or a return conductor. The nLFL system uses a novel nonlinear regression approach to line fault location. It is based on impedance measurements to forecast the impedance of the faulted HVdc system in the faulted steady state operating condition of the HVdc system. Simulations and real-world tests of the nLFL system with the EATL HVdc scheme shows that the nLFL has the capacity to calculate a fault location to within 1.0 % of the actual fault location for the entire length of the transmission line excluding the grounded station.

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