Fault Location Using the Natural Frequency of Oscillation of Current Discharge in MTdc Networks

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Abstract—This paper discusses a novel fault location approach using single ended measurements. The natural dissipation of the circuit parameters are considered for fault location. A relationship between the damped natural frequency of oscillation of the transmission line current and fault location is established. The hybrid dc circuit breaker (dcCB) interrupts the fault current, whereby the transmission line current attenuates under the absence of any driving voltage source. The line capacitance discharges into the fault at a specific frequency of oscillation and rate of attenuation. Utilizing this information, the fault location in a multi-terminal direct current (MTdc) network can be predicted. A three terminal radial model of a MTdc is used for performance evaluation of the proposed method using Power System Computer Aided Design (PSCAD)/Electromagnetic Transients including dc (EMTdc).

Index Terms—Attenuation, capacitor, fault location, frequency, HVdc, multiterminal.

I. INTRODUCTION

THE electric grid is undergoing a technological transformation as a result of increasing environmental awareness to reduce carbon emissions. As a result of the push for more renewable energy integration with resources like solar, wind, tidal energy etc. where the generation source is located at a distance far away from load centers, the High Voltage direct current (HVdc) transmission technology has taken prominence over High Voltage alternating current (HVac) transmission [1]. Larger power transfer capability, lower power losses and flexible control have made HVdc a popular choice [2].

Such advantages can be achieved through the implementation of Voltage Source Converter (VSC) HVdc networks [3]. HVdc networks have also been found to be beneficial in interlinking multiple ac asynchronous generation systems with the help of underground cables and overhead transmission lines. The modular multi-level converter (MMC) has emerged as a popular choice for VSC-HVdc systems, due to certain salient features including (1) the absence of large dc link capacitors; (2) better scalability; (3) higher operational efficiency, etc. [4]. Conventional MMC design, as shown in Fig. 1, uses half-bridge submodules (HBSM) rather than full-bridge modules (FBSM). FBSMs are fault tolerant, but have lower operational efficiency than HBSMs due to higher number semiconductor switches.

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Given the remote locations of HVdc lines it is a challenge to detect faults early enough to prevent instability. Rapid isolation of faults is essential as it might cause indelible damaged to the converter stations and the network infrastructure [5]. Extensive research has been carried out for ac transmission systems for fault location, but such techniques are generally not applicable for HVdc systems [6].

Traditional ac systems utilize phasor and voltage angle information from Phasor Measurement Units (PMU) [7], for fault location. Lack of phasor information and frequency data makes it difficult to use those methods. Multiple techniques have been used for identification of fault locations of dc lines. They can be broadly classified into two categories (1) single ended measurements and (2) double ended measurements [8]. Current approaches mostly discuss the use of time-domain based fault-location algorithms [9], [10]. The high frequency fault transients contain information about the fault and its characteristics [11]. These traveling wave based methods have gained prominence due to the presence of time synchronized Global Positioning System (GPS) devices. These devices are expensive and their accuracy is dependent on the ability to
capture the arrival of wave peaks [12]. Accurate detection of the traveling waves are also dependent of the length of the line. Traveling waves are not affected by fault resistance, system parameters etc. [13]. Single ended measurements are cheaper but they tend to provide inaccurate results as the devices must have the capability to detect the reflected peak [14]. The reflected surge waves are usually making it difficult to detect. The wave speed has an influence on the fault location accuracy. The surge propagation of the waves are dependent on the line parameters, controlling the accuracy of the results [15]. Modern methods also involve the use of digital signal processing methods requiring high sampling frequency to achieve the desired accuracy [11]. Simultaneous time-frequency based methods like wavelet transform has been widely used for fault location. Discrete wavelet transform (DWT) and continuous wavelet transform (CWT) methods have been implemented. CWT tends to provide better resolution as compared to DWT. CWT involves a smooth shift of the mother wavelet over the time-domain, whereas in DWT, the mother wavelet is shifted using a dyadic pattern over time [11], [16]. Active fault location detection techniques using external injection of voltages using a power probe unit (PPU) has been suggested in [17] or as a pre-charged capacitor connected to a circuit breaker [18]. The external oscillation circuit injects a signal whose under-damped oscillation and attenuation is used to locate the fault. The requirement of an external probe unit or a pre-charged capacitor has been suggested for low voltage dc (LVdc) networks [19]. They are difficult to achieve for large HVdc networks, as discharging a pre-charged external capacitance into the network can cause over voltage problems and can damage the infrastructure.

Use of Artificial Intelligence (AI) to locate faults and also improve its accuracy has been previously suggested in the literature [20]. Measured voltage and current are utilized as inputs to the neural network. The corresponding features are utilized for fault location on transmission systems. Other methods using statistical data classifications like Support Vector Machine (SVM) have been studied in [21] for fault location in transmission lines. The data driven methods for fault location requires a training dataset and the neural network has to be retrained for every new dataset, that requires significant time and effort, and is computationally burdensome.

In this paper, a passive method for fault location using the natural attenuation of the transmission line current following the isolation of the fault, is suggested. After fault isolation, the transmission line capacitance discharges into the fault through the line inductance and resistance. Under the absence of any active voltage source, the damped response of the transmission line current provides us with the rate of attenuation of the fault current. This information along with the damped natural frequency of the transmission line current calculated using Fast Fourier Transform (FFT) analysis is suggested in the paper for fault location. The attenuation constant of the damped transmission line current is calculated using the linear regression (LR) method [22]. The paper also investigates fault isolation using a hybrid dcCB and then the damped natural frequency of the transmission line current helps to provide the fault location. A double ended local measurement is utilized for better accuracy in fault location. The passive method of fault location is achieved without any signal injection or external circuits, thereby reducing costs and complexities associated with it.

The accuracy of the proposed method is verified under varying fault locations and fault resistances. Sensitivity to measurement noise and other parameters is performed in a three terminal MTdc network. The rest of the paper is organized as follows: Section II discusses the modeling of the MTdc network; Section III discusses the proposed fault location methodology; Section IV discusses the performance of the fault location methodology through simulation studies performed in PSCAD/EMTdc; Section V discusses the contributions and finally Section VI concludes the paper with major findings.

II. MODELING

A. The MMC

The modeling of the three terminal MMC in this paper is based on the design suggested in [23]. The MMC model consists of 400 half bridge sub-modules (HBSM) per arm. Hybrid discretization and relaxation algorithms described in [23] are used to define the numerical stiffness in the differential algebraic equations. The control of the MMCs is based on the strategies explained in [24], [25]. More details about the system parameters are provided in Table I.

B. MTdc Network

The model of a radial three-terminal MTdc symmetric monopole is shown in Fig. 2. The system is equipped with hybrid dcCB at the MMC terminals. The dc transmission lines are designed as frequency dependent models having 6 conductors with a vertical spacing of 5m and horizontal spacing of 10m between the conductors.

C. Hybrid dcCB

The hybrid dc breaker model represents the breaker designed by ABB in [26]. The breaker design, as shown in Fig.
comprises of three major sections, (1) load commutation branch, (2) main breaker branch and (3) the energy absorption branch. Under normal operating conditions, the load commutation branch remains operational. As the fault detection command is generated, the load commutation switches turn-off, the current recedes through the ultra-fast disconnector into the main breaker branch. On current zero detection, the ultra-fast disconnect switch is opened. The fast mechanical switch protects the commutation switch from the entire dc line voltage during final interruption. The final interruption happens in the main breaker branch. The excess energy is absorbed by the Metal Oxide Varistor (MOV’s). The maximum time required to dissipate the energy depends on the capacity of the MOV banks. The MOV’s were designed and rated at 800 kV. The introduction of two parallel branches reduces the on-state losses to 0.01% of the transmitted power [5], [27]. Faults occurring on the dc transmission line need to be interrupted very quickly. Current limiting inductors connected in series with the dc breakers act as protective devices for the switches, and limit the rate of change of fault current across them.

III. PROPOSED FAULT LOCATION METHODOLOGY

Fault detection is a challenge in MTdc systems and various research work have been reported in [11], [28], [29]. Once a fault is detected, the hybrid dcCBs’ operate to isolate the faulted section of the network. The other non-faulted sections remain operational. The entire MTdc network has been divided into multiple protection zones as shown in Fig. 2. For a hybrid dcCB, faults occurring internally are within their zones of protection. Zone B and zone D are the internal zones of protection for dcCB 1 and 2, and dcCB 3 and 4 respectively. The formulation of the problem is carried out on a single phase long line shown in Fig. 4 (a). $R_k$, $L_k$ and $C_k$ are the series resistance, inductance and shunt capacitance, measured in $\Omega$, $mH$ and $\mu F$ per unit length respectively. It is assumed they are constant and are uniformly distributed along the line length. Line conductance is neglected. Once the fault current is interrupted, the stored energy in the transmission line capacitance discharges into the fault. The stored energy of the transmission line capacitance at a certain distance from the terminals is finite. In the absence of any external voltage source, the transmission line current $i_{line}$ discharges into the fault over time. Since the faulted section is isolated, MMC controls do not affect the current discharge. The rest of the isolated network up to the fault point can be considered a $RLC$ oscillating circuit, with the current resonating similarly as an $LC$ circuit and the presence of the resistance decays the oscillations over a period of time. By analyzing the discharging transmission line current $i_{line}(t)$, the fault location in the transmission line can be estimated.

A. Faulted section formulation

Once the faulted section of the transmission line is isolated, the remaining portion of the transmission line beyond the hybrid dcCB up to the fault point can be represented by an equivalent $RLC$ circuit as shown in Fig. 4. Differential equations governing the state of the circuit can be calculated from Kirchhoff’s Voltage Law (KVL), and the constitutive equations for the transmission line inductance, resistance and stored capacitance is given as [1],

$$V_R + V_L + V_C = V(t)$$  \[1\]

where $V_R$, $V_L$ and $V_C$ are the voltages across the transmission line resistance, inductance and capacitance respectively. $V(t)$ is a time-varying voltage source. After the fault isolation in the absence of any time-varying voltage source $V(t) \rightarrow 0$. Substituting, $V_R = R_{tot}i_{line}(t)$, $V_L = L_{tot} \frac{di_{line}(t)}{dt}$ and $V_C = \frac{1}{C_{eq}} \int_0^t i_{line}(t)dt$ in (1), we get (2).

$$R_{tot}i_{line}(t) + L_{tot} \frac{di_{line}(t)}{dt} + \frac{1}{C_{eq}} \int_0^t i_{line}(t)dt = 0$$  \[2\]

Differentiating (2) with time, we get a second order differential equation (3).

$$\frac{d^2i_{line}(t)}{dt^2} + \frac{R_{tot}}{L_{tot}} \frac{di_{line}(t)}{dt} + \frac{1}{L_{tot}C_{eq}} i_{line}(t) = 0$$  \[3\]

Now $R_{tot}$ is the equivalent resistance up to the fault path including the transmission line resistance $R_{line}$ and the fault resistance $R_{fault}$. $L_{tot}$ is the net transmission line inductance and $C_{eq}$ is the equivalent capacitance from the point of consideration.

A more general solution to (3) can be given as (4).

$$\frac{d^2i_{line}(t)}{dt^2} + 2\alpha \frac{di_{line}(t)}{dt} + \omega_0^2 i_{line}(t) = 0$$  \[4\]

where $\omega_0$ is the undamped resonance frequency of oscillation, the rate at which the oscillation decays determined by the attenuation $\alpha$ and they are represented as (5).

$$\alpha = \frac{R_{tot}}{2L_{tot}}; \quad \omega_0 = \frac{1}{\sqrt{L_{tot}C_{eq}}}$$  \[5\]

As stated previously, in the absence of a driving voltage source other than the discharging transmission line capacitance, the solution for the transmission line current $i_{line}$ can be given as an under-damped response for a $RLC$ circuit. The general solution for the under-damped response is given as (6).

$$i_{line}(t) = D_1 e^{-\alpha t} \cos(\omega_d t) + D_2 e^{-\alpha t} \sin(\omega_d t)$$  \[6\]

where $\omega_d$ is the damped natural frequency of the capacitor and $\alpha$ is the rate of attenuation of the stored energy of the capacitor. An example of the discharge profile of capacitor current in the transmission line after the dcCB has operated is shown in Fig. 5.
B. Attenuation Constant

The capacitor discharge upto the faulted point is an under-damped response. The attenuation constant can be calculated from the discharge current by considering the envelope of the oscillating signal. The measured under-damped oscillating current is sampled at regular intervals to obtain peaks of the signal. The envelope of the under-damped oscillating current can be represented as (7):

$$i_{\text{discharge}}(t_n) = i_{\text{peak}}(t_n)e^{-\alpha t_n}$$  \hspace{1cm} (7)

Taking natural logarithm, the above equation can also be represented as (8),

$$\ln(i_{\text{discharge}}(t_n)) = \ln(i_{\text{peak}}(t_n)) - \alpha t_n$$  \hspace{1cm} (8)

Thus, (8) takes the form of a straight line (9),

$$y = mx + c$$  \hspace{1cm} (9)

Since (8) can be represented as (9), a linear regression (LR) approach can be considered to compute the slope of the line i.e., $\alpha$. From the data obtained by sampling $i_{\text{discharge}}$ at regular intervals the unknown model parameter can be estimated. For a given set of observations the model takes the form (10),

$$y_1 = c_0 + m_1 x_1$$

$$y_2 = c_0 + m_2 x_2$$

$$y_3 = c_0 + m_3 x_3$$

$$...$$

$$y_i = c_0 + m_i x_i$$

where, $i = 1, 2, ..., n$  \hspace{1cm} (10)

The equivalent matrix form of (10), can be written as (11),

$$y = Ax^T$$

$$y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ ... \\ y_i \end{bmatrix}; x^T = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ ... & ... \\ 1 & x_i \end{bmatrix}; A = \begin{bmatrix} c \\ m \end{bmatrix}$$  \hspace{1cm} (11)

Here $y$ is is the set of observed variables at different time-steps, $x$ is the set of exogenous or input variables. Solving (11), we calculate the attenuation $\alpha$ from the entries of matrix $A$.

C. Fast Fourier Transform (FFT)

One can transform a given sequence in time into its respective frequency components using Discrete Fourier Transform (DFT) [30]. FFT is useful to perform the DFT of a sequence. FFT performs the computation of the DFT matrix as a product of sparse factors. The DFT for such a sequence can be given as (12),

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-j2\pi kn/N}$$  \hspace{1cm} (12)

where $N$ is the length of the signal. Since, the sampling frequency of the signal is varied between 10 kHz to 100 kHz, the maximum represented frequencies are half of the sampling frequency. We try to capture all the representative frequencies in that range. The peak amplitude of the damped natural frequency is $\omega_d$. To calculate the damped natural frequency of the capacitor discharge $\omega_d$, we perform FFT analysis to determine the dominant frequency of the under-damped oscillating transmission line current. As stated earlier, the transmission line current $i_{\text{discharge}}(t)$ decays at a frequency of $\omega_d$ as shown in (6). The undamped response of the decaying oscillation can be calculated as (13),

$$\omega_d = \sqrt{\omega_0^2 - \alpha^2}$$  \hspace{1cm} (13)
The damping factor $\zeta$ is given as a ratio of $\omega_d$ and $\alpha$ as 

$$\omega_d = \omega_0 \sqrt{1 - \zeta^2}$$ \hspace{3cm} (14)$$

where,

$$\zeta = \frac{\alpha}{\omega_0} = \frac{R_{tot}}{2} \sqrt{\frac{C_{eq}}{L_{tot}}}$$

**D. Fault Location Calculation**

From the PSCAD transmission line modelling parameters, the per unit (p.u) length line inductance ($L_k$), resistance ($R_k$) and the per unit capacitance ($C_k$) from the point of measurement can be calculated. The undamped resonance frequency of oscillation $\omega_0$ of the capacitor discharge current through the transmission line can be calculated as (15):

$$\omega_0^2 = \omega_d^2 + \alpha^2$$ \hspace{3cm} (15)$$

Thus, fault location $d_{cal}$ can be calculated as (16),

$$d_{cal} = \frac{1}{(\omega_d^2 + \alpha^2)L_k C_k}$$ \hspace{3cm} (16)$$

where, $L_{tot} = L_k d_{cal}$. To verify the robustness of the algorithm, faults are created at various length of the transmission line and the fault resistance is also varied between 0.01Ω and 200Ω. The error % between the actual fault location and the measured location is given by $\epsilon$ (11). $d_{act}$ is the actual location of the fault in the transmission line and $d_{cal}$ is the calculated fault location using (16).

**E. Proposed Algorithm**

The following section discusses, in brief, the proposed algorithm to detect the fault location, Algorithm 1 shows the steps in the process.

Local measurements of current and voltage are sampled at each location in real-time. At the onset of the fault, the traveling waves are detected that help to isolate the faulted section of the transmission line. The fault detection algorithm is robust to various changes of operating conditions and measurement noise. After the breakers operate, the current recorder devices start to monitor the transmission line discharge current. The recorded current $i_{discharge}$ is sampled at every 2ms to determine the peaks of the current envelope $I_{peak}$. A FFT analysis is also performed on $i_{discharge}$ to determine the damped natural frequency. Finally, the fault is located using (16).

**IV. Simulation Results**

To verify the accuracy of the proposed algorithm the radial MTdc network shown in Fig. 2 was designed in PSCAD/EMTdc. Varying simulation conditions like fault distances and fault resistances were performed on the 1000km long dc section of the transmission line. As discussed previously, the proposed method does not require any external injection of current or voltage pulses into the network as proposed in [17,18,19]. The fault detection algorithm detects the faults in the zone of internal protection as described in Section III. The fault locations obtained by the proposed method was compared to the actual fault location and an error metric is calculated. A schematic for various fault locations is shown in Fig. 6.

A pole-to-ground fault was simulated in zone B, hybrid dcCBs’ 1 and 2 operated to isolate the fault. The actual location of the fault was 50km from the recorder located at a distance from MMC 2. Fig. 7 shows the sampled discharge current at 2ms; the peak value of $i_{discharge}$ is stored as $i_{peak}$ from (7). Calculate $\alpha$ using LR method from (11). FFT of $i_{discharge}$ to extract $\omega_d$ using (12). Calculate the location of fault using (16).

**Algorithm 1:** Fault location using transmission line current discharge

```plaintext
1. Sampling Frequency ($f_s$) = 10kHz, i.e., $\Delta t$ = 0.1ms;
2. Fault occurs at $T = t_{brk}$;
3. At $T = t_{brk}$ (Hybrid dcCB operates);
4. Hybrid dcCB operate at their respective zones to isolate the fault;
5. if $BreakerStatus = 0$ (Open) then
   6. Enable fault location algorithm;
   7. Measure and store $i_{discharge}$ at $\Delta t$ as $i_{discharge}$;
   8. Sample $i_{discharge}$ at 2ms; the peak value of $i_{discharge}$ is stored as $i_{peak}$ from (7);
   9. Calculate $\alpha$ using LR method from (11);
   10. FFT of $i_{discharge}$ to extract $\omega_d$ using (12);
   11. Calculate the location of fault using (16);
   12. else
      13. Continue Normal operation;
   14. end
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**Table II. Fault distance estimation, without measurement noise**

| $d_{act}$ (km) | $R_{fault}$ (Ω) | $\epsilon$ (%) | $R^2$ |
|----------------|-----------------|----------------|-------|
| 50             | 0.01            | 0.0089 | 0.9722 |
| 150            | 0.01            | 0.0120 | 0.9641 |
| 600            | 0.01            | 0.0141 | 0.8399 |
| 750            | 0.01            | 0.0166 | 0.9649 |
| 50             | 2               | 0.0020 | 0.9796 |
| 150            | 2               | 0.0113 | 0.9795 |
| 600            | 5               | 0.0120 | 0.8345 |
| 750            | 5               | 0.0148 | 0.9773 |
| 50             | 10              | 0.0124 | 0.9821 |
| 150            | 10              | 0.0188 | 0.9864 |
| 600            | 10              | 0.0333 | 0.8145 |
| 750            | 10              | 0.0150 | 0.9768 |
| 150            | 50              | 0.0114 | 0.9745 |
| 200            | 50              | 0.0110 | 0.9858 |
| 150            | 100             | 0.0200 | 0.9783 |
| 200            | 100             | 0.0210 | 0.9446 |
| 150            | 200             | 0.0232 | 0.9758 |
| 600            | 200             | 0.0350 | 0.9438 |

Using the sampled data points from the current envelope we determine $\alpha$ from (11). Coefficient of determination that is used as a statistical measure for the performance of the regression model for the data, is found to be $R^2 = 0.9722$, indicating a high degree of linear relationship for the straight line regression model as explained in (9). Using the equations to calculate the actual fault distance was found with $\%e$ of 0.007. The predicted linear regression model plotted against the measured data is shown in Fig. 9.

Similar events of fault were performed across the transmission line as shown in Fig. 6. Table II shows the various fault distance estimations, error and the coefficient of determination for the calculated regression model for $\alpha$. 
Variations in fault resistance between $R_{\text{fault}} = 0.01\,\Omega$ to 200$\,\Omega$, was performed. The fault locations were also varied and the algorithm was tested for faults in zone B and D.

Variation in error with changes in $R_{\text{fault}}$ and $d_{\text{act}}$ are shown in Fig. 10. From Table III it can be seen that the % error increases ever so slightly with the increment of $R_{\text{fault}}$, as the capacitor discharge attenuates at a faster due to the presence of a larger fault resistance. The rate of attenuation is affected, that causes the % error to vary.

A. Measurement Noise

To verify the influence of the real field measurement noise on the fault location estimation, a Gaussian noise spectrum of SNR 30dB, with a standard deviation of 2%, was added to the measured data as suggested in [32]. Fig. 11 shows a current discharge profile with added measurement noise. The fault location estimation is summarized in Table III. The calculation of the attenuation constant $\alpha$ under the influence of measurement noise is not affected.

B. Sampling Frequency

For the method of locating the fault on the transmission line the data was sampled at $f_s = 10kHz$. To verify the effects of changes in sampling frequency over the observed peaks of discharge current is studied in this section. A similar application was performed with sampling frequencies of $f_s = 50kHz$ and $f_s = 100kHz$, the results of the studies are summarized in IV and Table V respectively.

V. DISCUSSION

The proposed method for identification of fault location has been achieved using a linear regression method to calculate the attenuation constant for the under-damped current
oscillation. After successful fault detection and isolation, the proposed methodology is utilized for fault location on the affected transmission line. Robustness of the proposed method against varying fault resistance and location has been verified. Measurement noise was added to the simulated data to mimic real field measurements. The error, even under the influence of measurement noise was within 1%. The fault location accuracy did not differ from the measurements without the influence of noise.

Methods involving current or voltage discharge into the faulted circuit through a pre-charged capacitor requires external devices to achieve the objective. For large MTdc networks, this is not possible. Besides, the voltage discharge into the network through the capacitor can cause over-current fluctuations that can further damage the overhead transmission lines.

To verify the effects of the sampling frequency on the measured data, a sampling frequency of 50kHz and 100kHz was used. The addition of measurement noise on the data did not result in a significant difference in the estimated fault location.

A comparison with current existing methods exhibited in Table VI shows the overall superiority of the method.

VI. CONCLUSION

To accurately locate faults in a MTdc network, a method using the natural discharge of the transmission line current has been proposed. After a fault is detected in a particular zone the hybrid dcCBs’ in the faulted section operate to isolate the faulted transmission line. Once the faulted transmission line is isolated, the rest of the network forms an under-damped oscillating RLC circuit in the absence of a driving voltage source up to the fault point. A relationship between the damped natural frequency $\omega_d$ and the rate of attenuation $\alpha$ was established. The method of linear regression was utilized for calculation of the attenuation constant. The robustness of the proposed scheme was verified against various fault resistances and different fault locations. Measurement noise did not have much of an influence on the proposed method. The addition of noise causes variations in the peak measurements of the transmission line capacitor current discharge, but since the attenuation constant is calculated through fitting the observed data points through a linear regression model, $\alpha$ calculations are not affected. The fault location method proved quite robust for high resistance faults of upto 200 $\Omega$

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