A novel fault-location method for VSC-MTDC transmission lines based on EMTR

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Abstract. This paper presents a novel method for locating faults on VSC-MTDC transmission lines using electromagnetic time reversal (EMTR) theory. A method named "First fault-segment, Second fault-location" is proposed. The observed currents are time-reversed and back-injected into the simulation system, which equals to the actual system. In this procedure, a fault is not necessary to be assumed in the simulation system. After fault segment has been screened, the fault location can be verified with minor calculation burden. Moreover, the performances of the EMTR-based technique are discussed under different time-asynchronous cases. The simulation test cases are: a five-terminal VSC-HVDC modified from the China Nan- au demonstration project. Considering the effects of protection and control system, the proposed method presents its straightforward application with low sampling rates and ultra-short time-windows, and robustness against fault type and fault impedance.

1. Introduction

Given the exhaustion of fossil fuel, wind energy becomes one of the effective ways to replace it. The wind turbine is a useful way to transform wind energy to electric power. The sea islands are where the wind is concentrated. [1-4] Therefore, there are many engineering for wind grid-connection. The voltage source converter based multi-terminal high voltage direct current systems (VSC-MTDC) are under great development. The submarine cables face big challenges of insulation, so the fault location is important when the cables breakdown. [5]

There are two traditional methods for fault location in HVDC (High Voltage Direct Current) systems. One is traveling-wave-based line fault-location principle, and the other is transients-based line fault location method. The wave speed and the detection of the surge arrival time determine the accuracy of the results for traveling-wave-based method. The transients-based method uses the Bergeron transmission-line model to calculate the actual fault point. Because the cables are short and the observed transients have abundant harmonics, these two methods lack generalization for fault location of VSC-MTDC. [6-9]

For the step signal transmitted in HVDC system, the observed signals of high frequency-domain are much smaller than these of full frequency-domain. So the existing method, using the transients of high frequency-domain is easily affected by measurements. This paper presents a novel fault-location algorithm as well as the travelling-wave method, which theoretically enhances the capability of dealing with fault impedance and fault types. Based on the electromagnetic time-reversal (EMTR) theory, the transients from each converter are time-reversed and transmitted back into the simulation system which is simply equivalent to the actual system, except for the precise frequency-dependent
line model. The effective value of the assumed fault current along the fault segment is calculated by the simulation system. It reaches its peak at the real fault location. The EMTR-based fault-location algorithm is strictly demonstrated, using Maxwell’s equation in the lossless transmission line. Considering the effects of protection and control system, performance of the proposed algorithm is evaluated through a five-terminal VSC-MTDC simulation system carried out by utilizing the electromagnetic transient simulation software PSCAD/EMTDC [10-12].

2. EMTR-based method for fault-location in VSC-HVDC

2.1. Application of EMTR by using two observation points at each line terminal

In literature [10], the basic theory of EMTR method for fault location has been justified. Figure 1 shows the typical diagram of a two-terminal flexible HVDC system. It mainly consists of ac systems, transformers, converter stations and dc transmission lines. The flexible HVDC system can be divided into VSC-HVDC and MMC-HVDC (modular multilevel converter-HVDC) judging by the type of the converter valves.

As shown in figure 1, the dotted lines in the figure indicate two points. One is that dc capacitors are unnecessary in the MMC-HVDC. And the other one is that the flexible HVDC system allows monopole operation without neutral grounding.

Figure 2 is the fault additional network for VSC-HVDC in figure 1. \( Z_{11} / Z_{12} / Z_{21} / Z_{22} \) represent the impedances equivalent to the systems at the both ends of the line. Besides the fact that the frequency-dependent line model is used to simulate the real line precisely. The system in reality is neutral grounded, so does the simulated system. Consider a line-to-ground, a line-to-line or a line-to-line-to-ground fault at \( F \), observers at each end of line record the fault currents. Due to the mutual inductance between the two lines, to guarantee a more accurate fault-location, currents at the two poles of each end, \( i_{mp} / i_{np} / i_{mn} / i_{nn} \), should be tracked.

As shown in figure 3, these observation ends are replaced with four sources imposing the time-reversed transient fault current, namely, \( i_{MP}^{TR} / i_{NP}^{TR} / i_{MN}^{TR} / i_{NN}^{TR} \) which are expressed as follows:

\[
\begin{align*}
    i_{MP}^{TR}(t) &= i_{MP}(T-t), \\
    i_{MN}^{TR}(t) &= i_{MN}(T-t), \\
    i_{NP}^{TR}(t) &= i_{NP}(T-t), \\
    i_{NN}^{TR}(t) &= i_{NN}(T-t)
\end{align*}
\]  

Since the location of the faults is the unknown in the problem, it can be supposed to happen at an arbitrary location \( x \). In what follows, we will make use of PSCAD/EMTDC to calculate the fault
current at the assumed location along the line. The fault current reaches its maximum, \( \max \left\{ |i_{TR}|, |i_{FB}| \right\} \), at \( x=F \).

2.2. Fault-location algorithm using EMTR method

The flowchart shown in figure 4 illustrates the step-by-step fault-location procedure proposed in this study. As can be seen, the proposed procedure, which is similar to other methods proposed in previous literature, requires knowledge of the network topology as well as its parameters. Such knowledge is used to build a corresponding network model where the lines are represented, for instance, by using the frequency-dependent phase model.

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**Figure 4.** Flow diagram of fault-location method based on EMTR.

The transient current initiated by the fault is assumed to be recorded within a specific time window, namely \( i(x,t), t \in [t_f, t_f + T] \), where \( t_f \) is the fault triggering time detected by wavelet maximum module, and \( T \) is the recording time window.

The unknowns of the problem are the fault type, fault location and fault resistance. To reduce computation, a unique method, named "First fault-segment, Second fault-location", is presented. Firstly, the current energy along all the lines is calculated after back-injection of the time-reversed signals without a fault assumed in the simulation lines. The fault segment with distinguished line poles can be selected for further work. Secondly, with the assumed fault location in the fault segment, the fault current energy along the segment is calculated and the location of maximum energy is chosen as the estimated fault location.

Concerning the fault impedance, for all the speculating fault locations, a priori value of the fault impedance is assumed. Because different values of impedance do not affect the fault-location accuracy. Therefore, the fault impedance is set to 0.01\( \Omega \) in this paper. In addition, the assumed fault is set every 1km along the line, which means the calculated step of each line is 1km.

As shown in figure 4, whatever the current energy along the transmission or the fault current energy along the fault-segment is, the energy can be calculated as follows:

\[
\Gamma (i_{TR}) = \frac{\sum_{j=1}^{N} |i_{TR}(j)|^2}{N} = \frac{T}{\Delta t}
\]

Where \( N \) is the number of samples and \( \Delta t \) is the sampling time.

According to the EMTR method presented in the previous subsection, the energy given by (4) is maximized at the real fault location. Thus, the maximum calculated signal energies will indicate the real fault point \( \Gamma (i_{TR}) = \max \left\{ \Gamma (i_{TR}) \right\} \)
3. Simulated case study

3.1. Simulation model
A five-terminal VSC-HVDC, modified from the China Nan-au demonstration project, was used in simulation studies. A diagram of the test network is shown in figure 5. PSCAD/EMDTC is used for the VSC-MTDC system simulation, and the time-reversal procedure was implemented in MATLAB.

This model consists of five nodes, connecting with two wind farms, three AC grids and four bipolar undersea power cables (±160kV). The DC-link capacitors are midpoint-earthed. So the transmission line between each converter consists of two undersea cables of 70km in length, which is represented by using distributed parameter transmission-line models in PSCAD, and the cable structure is shown in figure 6.

The main cable protection scheme for VSC-HVDC is travelling wave and derivative under-voltage protection. Because the high power DC breaker is under development, the DC line faults are isolated by AC breakers. The fault transients are not only affected by fault and terminal conditions, but also influenced by the control and protection system.

Simulations were performed in PSCAD/EMDTC with a solution time step of 20μs. The valve current will reach twice the rated current or more within hundreds of microseconds after a fault occurred on a line at 2.5s. Thus, the converter valve will block in 2ms by its protection circuit. The fastest disconnection of the AC breakers is in the 20ms, which is instructed by the main cable protection.

![Figure 5](image)

**Figure 5.** Scheme of the five terminal VSC-MTDC.

Assuming an appropriate case that, the main cable protection trips at 20ms after fault occurrence, the transient data within 20ms can be effectively utilized. Considering a fault at DC bus outlet of VSC1, the control system is in standby mode at fault-occurred time, three types of faults are simulated. And both positive and negative currents were monitored as solid lines shown in figure 7. The dotted lines represent the transients if the AC breakers disconnect at 2.5s, thus the transients suffer from the effect of AC side.

As shown in figure 7(a), the transients are almost the same in the first 2ms after a double-pole-line fault occurs. As shown in figure 7(b), after a single-pole-line fault occurs, the fault transients at fault line are almost the same in two cases, while there are some differences between the transients of non-fault line within 2ms. However, the differences do not affect the fault location accuracy. In practice, the time window is usually 2-5ms, because the fault can be cleared within a few milliseconds.

Therefore, in this paper, the transients within 2ms after the fault occurs will be applied to avoid the effects of control system and currents from AC side.

![Figure 6](image)

**Figure 6.** Geometric parameters of dc cable.
3.2. Definition of fault-location parameters

In this paper, the back-injection and fault-location procedure are also simulated in PSCAD in alliance with MATLAB. As the terminal dc-line currents were monitored as shown in figure 5, they will be time-reversed in MATLAB. The zoomed area was time-reversed as shown in figure 8.

**Figure 7.** Currents affected or not affected by control and protection system at five terminals: (a) a line-to-line fault, (b) a positive-line-to-ground fault.

**Figure 8.** Time-reversal of current signal.

**Figure 9.** Back-injection simulation system.

The fault-occurred time of each transient is demarcated by wavelet modulus maximum, and the smallest one is the result. The time scales between different converters is synchronized by GPS. The spectrum of fault current is especially concentrated in low frequency, so a total reflection of current wave occurs at ends of the dc lines, which links with parallel capacitance. In this case, we will set $Z=1M\Omega$ in figure 9. Figure 9 shows the detailed back-injection simulation model in single line view for figure 5.
3.3. Test for various faults
In order to test the performance of the proposed fault-location method in VSC-MTDC, different case studies were carried out: 1) a positive-line-to-ground fault at line1 with a 0-Ω fault impedance, 20km from OP1; 2) a line-to-line fault at line2 with a 100-Ω fault impedance, 50km from OP2; 3) a line-to-line-to-ground fault at line3 with 200-Ω fault impedance, 55km from OP3; 4) a negative-line-to-ground fault at line1 with a 500-Ω fault impedance, 15km from OP4.

The first step is to locate the fault segment. Without assuming a fault in back-injection simulation system, the currents along each line were calculated, using PSCAD, as shown in figure 10. It can be obviously seen from figure 10(a) that, the current along each positive line is much greater than current of the corresponding negative line, which indicates a positive-line fault. The currents of positive line1 is greater than the currents of others, which shows the fault at line1. Similarly, figure 10(d) is certainly corresponding to case4). Meanwhile, as shown in figure 10(b)-(c), the currents of positive and negative lines are the same, which means, a line-to-line or a line-to-line-to-ground fault occurs. And if the average current of a line is the maximum, the fault occurred in this line.

The proposed method to locate fault segment is easily realized. It only needs to calculate a few points along each line and the results are precise. Consequently, the method can be regarded as a backup cable protection scheme for VSC-MTDC.

After the fault segment was verified, the second step is to assume a uniformly-spaced fault along the segment and calculate the fault current. The fault impedance is set as 0-Ω consistently. Figure 11 shows the fault-location results for four cases. The length versus the maximal effective value of the fault current is the measured fault location. With the fault impedance increases to 500-Ω, the gradient near the extremum diminishes, but the fault location results doesn’t change. In general, the method can achieve a very precise result and is robust to fault type and fault impedance.

![Figure 10](image-url)

**Figure 10.** Current effective values, calculated by PSCAD, along all the lines: (a) a positive-line-to-ground fault, (b) a line-to-line fault, (c) a line-to-line-to-ground fault, (d) a negative-line-to-ground fault.
3.4. Effects of time asynchronization

The measurements at different line terminals can be performed synchronously if the global positioning system (GPS) is available. However, when the signal from the GPS is lost, measurements from line terminals do not share the same time. Without the GPS, the time-tags of sample points in the measurements will deviate from the real time. In this paper, we will discuss the effects of time asynchronization on fault-location precision. And three cases under different unsynchronized measurements are simulated. When a negative-line-to-ground fault, 20km from OP2, occurs at line2, different case studies are carried out: 1) time-tags are synchronous at five observal points; 2) time-tag of OP1 is 100μs slower; 3) time-tag of OP3 and OP4 is 20μs slower; 4) time-tag of OP1 and OP5 is 20μs slower, while time-tag of OP3 and OP4 is 20μs faster.

As shown in figure 12, the gradient near the extremum diminishes under different cases, so the fault-location results are slightly affected by time asynchronization. In most practical operations, the time asynchronization between different measurements is not likely to exceed 20μs even with the absence of GPS, so the EMTR-based fault-location method is hardly influenced by time asynchronization.

4. Conclusions

A new comprehensive method to locate faults in VSC-MTDC based on the EMTR technique is presented in this paper. Compared with the existing EMTR-based methods, the proposed method uses the observed currents of full frequency-domain, which reduces the measurement error and improves reliability.

The analysis, which considered the effects of protection and control system, indicated an ultra-short time-windows data for this method. Besides, the effective anti-time-asynchronous ability of the proposed method has been demonstrated through simulations. The proposed method is robustness
against fault type and fault impedance. In addition, the method can be a back-up protection for the system.

![Graph showing fault-located results for different cases.]

**Figure 12.** Fault-located results for different cases.

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