Single-pole grounding fault location method for flexible HVDC transmission lines

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Abstract. One of the key problems of flexible HVDC transmission line is HVDC transmission fault location. A fault location method based on an improved traveling wave natural frequency flexible HVDC transmission line single-pole ground fault is proposed. The integrated empirical mode is used to decompose the fault signal to obtain the required traveling wave component, and then the improved MUSIC algorithm is used, according to the frequency spectrum analysis obtains the natural main frequency, and uses the relationship between the natural frequency and the fault distance to gain the fault location. Finally, use PSCAD to build simulation for simulation test and combine MATLAB fault location algorithm program to get the fault distance. The simulation results show that the proposed ranging algorithm is not affected by transition resistance and fault distance, and can accurately obtain the fault point distance, which shows the feasibility and effectiveness of the proposed fault ranging method.

1. Introduction

Flexible HVDC transmission is a new type of HVDC transmission technology with large transmission capacity and flexible control at the core of a voltage source converter. It has broad prospects in offshore wind power running on islands, interconnection of multiple new energy sources, and urban power grid transformation. Among them, the flexible HVDC transmission line is very important for the bridge of HVDC transmission. From the data of fault operation, it is found that the frequency of unipolar grounding outage of the DC transmission line is relatively high. Therefore, in order to solve the single-pole ground fault of the line, it is necessary to find out the fault point in time and accurately, which is particularly important for solving the single-pole ground fault of the line.

At present, in order to better solve the problem of accurate fault location of flexible HVDC transmission lines, experts at home and abroad respectively detect the relationship between electrical quantity and fault distance from three different angles of time, frequency and space, and propose the traveling wave method, natural frequency method and fault analysis method. These are also the three mainstream methods used in flexible HVDC transmission lines. Reference[5] is based on the instantaneous frequency of fault location methods for HVDC transmission lines. Reference[6] applies the traveling wave natural frequency to the overhead line-cable hybrid of AC power systems. In the line, the location of the fault point can be well detected. Reference [7] uses single-ended fault current after VSC-HVDC system unipolar grounding, uses Prony algorithm to perform spectrum analysis to obtain the natural main frequency, and then uses the fault location formula to find the distance. Reference [8] uses particle swarm algorithm to search the place where the voltage difference of the entire line is the smallest to obtain the actual fault distance. Reference[9] conducts fault location on HVDC transmission lines using a single-ended fault location combined algorithm. Reference [10]
LCC-VSC-HVDC hybrid high-voltage DC line uses a single-ended fault location combined algorithm, using the natural frequency for initial fault detection, and then using the traveling wave method for fault location. At present, the fault location of DC transmission lines mainly depends on how to calibrate the initial traveling wave head problem, and it is affected by high resistance to accurately calibrate the wave head. The sampling rate is higher and the corresponding traveling wave velocity needs to be accurate. The fault analysis method needs to be very accurate for the line model to obtain good results. The natural frequency method does not need to identify the wave head. It only needs the transient voltage or current information after the fault and then performs frequency spectrum analysis on the transient information to obtain the natural dominant frequency and use the ranging formula to perform the fault location.

In this paper, the single-phase ground fault occur in the HVDC line system, using the EEMD method to accurately obtain the fault traveling wave, and then use the improved MUSIC algorithm to extract its natural main frequency, and then combine the system end and the fault reflection coefficient, using the natural frequency and the distance relationship to achieve fault location.

2. Unipolar ground fault analysis

In analyzing the system topology diagram of MMC-HVDC, due to the grounding of the AC side of the system, the unipolar grounding can be divided into three stages: DC side capacitor discharge, grid current feedback, and voltage recovery in three stages, and for different grounding situations the transient characteristics of the system are understood, and the voltage oscillation characteristics during each fault are analyzed [11]. The following figure shows the topological diagram 1 of single-phase grounding of flexible DC transmission.

![Figure 1. MMC HVDC transmission system single-phase grounding model topology.](image)

Under a single-pole ground fault, the voltage of the fault pole suddenly drops to 0, and the voltage of the non-fault pole will rise to twice the rated value under the action of the system's constant voltage control strategy, which will cause greater insulation for the non-fault pole Hazards. Therefore, single-phase grounding not only affects the DC side but also has an offset overvoltage hazard to the AC side. Therefore, it is necessary to find and deal with single-phase ground faults in time to be able to quickly remove the faults.

2.1 Natural frequency generation of traveling wave of MMC-HVDC transmission line

The following figure is the equivalent diagram of the distributed parameter transmission line system, where R, L, G and C are the resistance, inductance, conductance and capacitance of the unit length of the line. \( Z_s, Z_f \) and \( Z_c \) are the power supply impedance, fault point impedance and line wave impedance, respectively. \( H_f \) is the distance from the fault point to the line fault measurement point, \( v_f \) is the wave speed of the traveling wave, \( u_f \) is the voltage at the fault, and \( R_1 \) and \( R_2 \) are the reflection coefficients on the power supply side and the fault point respectively.
From the above analysis, the natural frequency is essentially derived from the distribution parameters of the transmission line and the reflection process of the travelling wave. The natural frequency satisfies the frequency domain characteristic equation:

\[ 1 - \gamma_2^2 e^{2\pi j / \omega} = 0 \]  

(1)

Use the Euler formula to find the characteristic solution. Since the imaginary part of S corresponds to the angular frequency of the natural frequency.

\[ f = \begin{cases} \frac{v}{4\pi H_f} (\theta_1 + \theta_2 + 2k\pi), & 0 < \theta_1 + \theta_2 < \pi \\ \frac{v}{4\pi H_f} (\theta_1 + \theta_2 + 2k\pi), & \pi < \theta_1 + \theta_2 < 2\pi \end{cases} \]  

(2)

At the fault point, the fault voltage travelling wave and the current travelling wave propagate along the line to both ends. When the initial fault travelling wave reaches the side of the MMC side converter station, reflex and reverse emission will occur.

2.2 Natural Frequency Analysis of Fault Travelling Wave

A single-pole ground fault occurs at point \( F_f \), and the travelling voltage wave and current travelling wave of the fault propagate to both ends, thereby forming a reverse and radiating travelling wave. When the reflected travelling wave comes to the fault point \( F \) again, reflection and refraction will also occur. The reflection of the fault signal on the system side and the fault point is the root cause of the natural frequency. Therefore, MMC-HVDC will have a more stable natural frequency signal. Even in the case of high-impedance ground faults, the refractive index will be a very small value, so that the magnitude of the value refracted to the side of the line system is very small, and will not affect the detection of the natural frequency. Then the natural frequency is. The boundary condition on the MMC side can be equivalent to the capacitance \( C_n \), and analysis shows that a full emission will occur when the initial voltage travelling wave after the fault reaches the N side of the MMC side bus[12].

\[ f = \frac{kV_f}{2l} \]  

(3)

The corresponding fault distance at natural frequency is following

\[ l_f = \frac{kV_f}{2f} \]  

(4)

After analysis, the fault distance is only related to the speed and natural frequency corresponding to the travelling wave.

3. MMC-HVDC transmission line fault location

3.1 Acquisition of Natural Frequency

Effective extraction of natural frequencies is the key to fault location in this paper. Multi-signal classification algorithm (MUSIC) is a method of spectrum estimation and analysis. Utilize the orthogonality of signal subspace and noise subspace to construct a spatial spectrum function, and
estimate the signal frequency by spectral peak search algorithm based on the combination of MUSIC algorithm and two-way spatial smoothing algorithm to improve the MUSIC algorithm. Pre-process the array acceptance matrix, and then use the improved MUSIC algorithm (I-MUSIC) to analyze and evaluate the pre-processed data. Finally, the natural dominant frequency of the traveling wave with the lowest amplitude and the highest frequency in the coherent signal can be effectively distinguished.

The following formula 5 is the model representation of harmonics.

\[ X(t) = \sum_{i=1}^{K} a_i e^{i2\pi f_i t} + \delta(t) \]  

In the above formula 5, S and R are the amplitude and frequency of the signal, K is the number of signals, and Y is the standard noise signal. It is obtained by processing the sampled data from the

\[ X(k) = DL(k) + N(k), k = 1, 2, \cdots, K \]

X (t) is the M x 1 dimension data vector, D is the M x N dimension data vector, L (t) is N x 1 the dimension vector, and N (t) is the M x 1 dimension white noise vector.

Using the forward and backward spatial smoothing algorithms for decoherent signals, the improved MUSIC algorithm can also be used to divide the sub-matrix based on this to get p sub-matrix, and their number of elements is m. Similarly, the received data is rearranged according to this idea, and the front and rear data vectors are \( X^Q(k) \) and \( X^B(k) \) and the corresponding covariance matrix is \( H^Q(k), H^B(k) \), and there are Relationship.

\[ H = \frac{H^Q + H^B}{2} \]

In the formula 5, \( H, H^Q \) and \( H^B \) are respectively the front and back terms of dimension P x P, and the backward and forward spatial smoothing covariance matrix. Let E be the P x P-dimensional inverse identity matrix, so the \( H_0 \) matrix exists as

\[ H_0 = H + EH^*E \]

Where is the complex conjugate matrix of \( H \). At this time, the eigenvalue decomposition of \( H_0 \) can obtain different eigenvalues and their corresponding eigenvectors, which we define as a subspace. After using the improved MUSIC algorithm to process the correlation matrix of the subspace vector, it is substituted into the frequency estimation formula to obtain the size of each frequency peak in the frequency estimation, and the natural frequency value corresponding to the peak at this time is obtained.

4. Simulation establishment and analysis

This article takes the Xiamen flexible DC transmission project as a reference background and uses PSCAD for simulation modeling. This flexible engineering model transmission system has a DC voltage of ±320kV and a transmission power of 1000MVA. The DC transmission line uses LGJ-400 overhead lines with a length of 320km. The M side of the converter station uses constant DC voltage control and constant AC voltage control. At the N side of the converter station, constant AC voltage control and constant active power control are used. The following table shows the transmission system model parameters, and the figure shows the transmission system model[13].

![Figure 3. Flexible HVDC transmission system model](image-url)
4.1 Simulation analysis

Figure 4. Natural frequency at the converter station

Figure 5. The natural frequency at the converter station affected by the transition resistance

Figure 4 is the natural frequency detected at the converter station, and Figure 5 is the natural frequency of the converter station after being affected by grounding resistance. This shows the feasibility of the improved MUSIC algorithm to extract the natural frequency. When the grounding resistance increases, the natural frequency value will not change, but the amplitude will be affected to some extent. Therefore, the analysis shows that when a unipolar fault occurs, as long as the natural dominant frequency is accurately extracted, the fault can be accurately located.

4.2 Ranging results and analysis

Table 1. Unipolar fault location results.

| Fault location /km | Grounding resistance /Ω | Ranging results /km | Relative error /% | Absolute error /km |
|--------------------|-------------------------|--------------------|-------------------|-------------------|
| 0.1                | 59.79                   | -0.35              | -0.21             |
| 60                 | 100                     | 60.22              | 0.36              | 0.22              |
| 300                | 60.32                   | 0.53               | 0.32              |
| 0.1                | 99.51                   | -0.49              | -0.49             |
| 100                | 100                     | 99.40              | -0.60             | -0.60             |
| 300                | 100.57                  | 0.57               | 0.57              |
| 0.1                | 149.39                  | 0.41               | -0.61             |
| 150                | 100                     | 150.88             | 0.59              | 0.88              |
| 300                | 150.74                  | 0.50               | 0.74              |

From the analysis of Table 1, it can be concluded that the fault location method in this paper can achieve accurate positioning within the whole line, and the error range is less than 1%, which shows
the feasibility of the proposed method. According to the analysis, more accurate signal processing and frequency analysis tools are needed to achieve more accurate positioning.

5. Conclusion
Aiming at the problem of online detection of early turn-to-turn short-circuit faults of permanent magnet synchronous motors, this paper proposes an efficient method for abnormal sequence detection based on deep transfer learning. The use of Laplace regular terms to generate more sensitive early fault features not only helps to perform sequence anomaly detection based on permutation entropy, but also strengthens the robustness of the detection model and reduces the false alarm rate. This method has a simple model and reliable results, and is more suitable for online detection of early faults.

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