A Protection Method for DC Distribution Network with Single Pole Grounding Based on Integrative Two-terminal MMC

Hua Jiang¹, Xinglai Shen¹ and Bing Ma²,*

¹State Grid Xuzhou Power Supply Company, Xuzhou, China
²School of Electrical and Power Engineering, China University of Mining and Technology, Jiangsu, China

*Corresponding author e-mail: mabing@cumt.edu.cn

Abstract. Based on the analysis model of unipolar grounding fault occurred in two-terminal MMC DC distribution network, the characteristics of unipolar grounding fault are studied. The similarity characteristics of transient currents between the fault line and the non-fault line are analyzed when the fault is located in the feeder, tie line and bus respectively. According to the characteristics of single-pole grounding fault and the similarity principle, a new single-pole grounding protection method for DC distribution network based on two-terminal MMC is proposed. The simulation results show that the proposed single-pole grounding protection method can accurately determine the single-pole grounding fault at any position of the DC distribution network. The research results can effectively solve the problem of single-pole grounding protection in DC distribution network, and effectively improve the security and reliability of DC distribution network.

Keywords: Single-pole Grounding Protection, Similarity Coefficient Method, Integrated Protection, Two-terminal DC Distribution Network, MMC

1. Introduction
Modular multilevel converter, because of its advantages such as good output characteristics, easy to expand and modular structure, the DC distribution network based on MMC has gradually become a research hotspot [1]. The fault of DC side includes bipolar short circuit fault and single pole ground fault, the single pole ground fault can eliminate the effects of the fault on the system by choosing a reasonable transformer neutral grounding mode. Therefore, the existing research on MMC-based protection schemes for DC distribution network is mostly focused on bipolar short circuit fault, while the research on unipolar ground fault protection scheme is less [2]. At present, there are short-time energy and wavelet time entropy methods based on the differential current at the ends of the line and directional pilot protection method based on transient wavelet transform, but these methods have the shortcomings of high sampling frequency or depending on communication, and have certain delay.

In this paper, the MMC-based two-terminal DC distribution network is taken as the main research content, the system configuration and fault characteristics are carried out detailed analysis, and according to the transient current characteristics of each line when occurring the single-pole grounding
fault, a method to identify whether the single-pole grounding fault is formed. The correlation coefficient is used to describe the correlation degree of the transient current of each line to realize the identification of the fault line and location; the reliability of the protection method is verified by simulation analysis.

2. Fault Characteristic Analysis

A double-ended MMC DC distribution network is in Figure 1. Among them, the AC measurement adopts the transformer with wiring \( \Delta / Y \), and the DC side is grounded by the clamp resistance.

![Figure 1. Schematic diagram of two-terminal MMC DC distribution network](image)

A single-pole grounding fault occurs in a DC distribution network, the line voltage will have a damping oscillation process before reaching a stable state due to the distributed parameter characteristics of the DC line changing with frequency [3]. The constant change of line voltage in the process of oscillation leads to the constant change and attenuation of oscillation current generated by the distributed capacitance of the line to the ground. For the purpose of analysis and fault identification, the DC side of the DC distribution network is divided into bus, tie line and feeder, such as M1-M4, L1-L3 and K1-K6 in Figure 1.

![Figure 2. The transient current distribution when a single-pole ground fault occurs on the feeder K3](image)

As shown in the figure, when a single-pole grounding fault occurs on a feeder (such as K3), the transient current direction of the feeder is negative, and all other feeders are positive; Transient currents at both ends of all tie lines are in opposite directions, positive at one end and negative at the other. Similarly, when a single-pole ground fault occurs on a bus (e.g M3), all lines connected to the but (L1, L2, K3, K4) The direction of the transient current of the fault pole is the bus to the line. The current direction of L1 on the bus M1 is negative, and the others are positive; The current direction of L3 on the bus M2 is negative, and others are positive; The current direction of L2 on bus M4 is negative, and the other is positive [4]. When a single pole grounding fault occurs on a tie line (such as L2), the transient current of the fault pole at both ends of the tie line is all negative in the same direction; Transient currents at two ends of other tie lines are in different directions, one end is positive and the other end is negative; The direction of the transient current in the first section of all feeders is positive. Therefore, the monopole base fault line can be distinguished according to the
3. Single-pole Grounding Protection Method Based on Similarity Coefficient Method

3.1 Principle of Correlation Coefficient Method

When one electric quantity increases in the power system, the other electric quantity also increases or decreases, we say that there is a covariant phenomenon between the two electric quantities and there is a correlation between them. There are many methods of correlation coefficient algorithm, for different research objects, correlation coefficient has many definitions, Pearson correlation coefficient is a statistical method for asymptotically unbiased optimal estimation of two variables, which is very suitable for analyzing the correlation degree of two random signals and widely used in the field of relay protection [5]. In this chapter, the protection method for single-pole grounding fault is the Pearson similarity coefficient method, and its mathematical expression is as shown in formula:

\[ P_r = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2} \sqrt{\sum (Y_i - \bar{Y})^2}} \]  

In that formula (1), \( r \) is the correlation coefficient, \( n \) is the number of sampling points in a period of time, \( X \) and \( Y \) is the electrical quantity sample of each sampling point, \( \bar{X} \) and \( \bar{Y} \) is the average value of two electrical signals.

The correlation coefficient can represent the degree of correlation between two discrete electrical signals, the larger the correlation coefficient is, the stronger the correlation between two discrete electrical signals is, and the value of the correlation coefficient is between -1 and +1. If it is greater than zero, the two electrical quantity discrete signals are positively correlated, that is, the larger the value of one electrical quantity is, the larger the value of the other electrical quantity is; If the correlation coefficient is less than zero, it indicates that the two discrete signals of electrical quantity are negatively correlated, that is, the larger the electrical quantity is, the smaller the other electrical quantity is, and the smaller one electrical quantity and the larger the other electrical quantity are; When the correlation is zero, the results show that there is no correlation between the two discrete signals [6]. In the relay protection of power system, the correlation coefficient can be used to analyze the correlation of fault electrical quantities to identify the location of the fault line [7].

3.2 Single-pole Grounding Protection Method Based on Similarity Coefficient Method

Through measuring the positive and negative voltages to ground and the relative voltage, we can comprehensively judge whether there is a single-pole ground fault and pole. To reduce the amount of calculation and improve the accuracy, the data length \( N \) of current criterion is determined by the change characteristics of fault voltage [8]. Such as type(2), starting from \( t = 1 \), according to equation (2) When (2) is satisfied, the calculation is stopped, and the value of \( t \) at this time is the length \( N \) of the data window [9].

\[ \frac{\sum_{i=1}^{T} |u_g(t)| - \frac{1}{T} \sum_{j=1}^{T} |u_g(j)|}{\sum_{i=1}^{T} |u_g(t)| - \left| \frac{1}{T} \sum_{j=1}^{T} u_g(j) \right|} \geq 0.8 \]  

Where: \( T \) is the number of 5ms sampling points.
\( u_g(t) \) is the value of the fault pole-to-ground voltage;

When a single-phase ground fault occurs, firstly, the capacitive current charging and discharging current sampling values of the lines connected with each bus are utilized to respectively calculate the
capacitive current similarity coefficient $P_{M,i}$ of each bus according to the formula (3); When the similarity coefficient $P_{M,i}$ of a certain bus is positive, the fault occurs on the bus; The similarity coefficient $P_{M,i}$ calculation method of the $i$th bus is shown in formula (3):

$$P_{M,i} = \frac{\sum_{k=1}^{N} \prod_{j=1}^{H} (n_s \cdot i_{s,g}(k) - \frac{1}{N} \sum_{j=1}^{N} n_s \cdot i_{s,g}(j))}{\sqrt{\sum_{k=1}^{N} \prod_{j=1}^{H} (n_s \cdot i_{s,g}(k) - \frac{1}{N} \sum_{j=1}^{N} n_s \cdot i_{s,g}(j))^2}}$$

Among: $P_{M,i}$ is the similarity coefficient of the $i$th bus; $N$ is that length of the calculate data window; $H$ is the number of lines connected to the $i$th bus; $n_i$ is the transformation ratio of the current transformer of the $s$th line; $i_{s,g}(k)$ is the $k$th sampling value of the fault pole of the $s$th line;

When the fault is not on the bus, the similarity coefficient $P_{L,i}$ of each tie line is respectively calculated according to the formula (4) by using the sampling value of the charge and discharge current of the capacitive current at the head end and the tail end of the tie line; When the similarity coefficient $P_{L,i}$ of the capacitive current at the beginning and the end of only one tie line is positive, and the similarity coefficients of the capacitive current at the two ends of other tie lines are all negative, the tie line is a fault line.

The similarity coefficient $P_{L,i}$ calculation method of the $i$th line is as shown in formula (4):

$$P_{L,i} = \frac{\sum_{k=1}^{N} (i_{L,i-1,g}(k) - \frac{1}{N} \sum_{j=1}^{N} i_{L,i-1,g}(j))(i_{L,i-2,g}(k) - \frac{1}{N} \sum_{j=1}^{N} i_{L,i-2,g}(j))}{\sqrt{\sum_{k=1}^{N} (i_{L,i-1,g}(k) - \frac{1}{N} \sum_{j=1}^{N} i_{L,i-1,g}(j))^2} \cdot \sqrt{\sum_{k=1}^{N} (i_{L,i-2,g}(k) - \frac{1}{N} \sum_{j=1}^{N} i_{L,i-2,g}(j))^2}}$$

Among: $i_{L,i-1,g}(k)$ is the $k$th sampling value of one end of the $i$th connecting line; $i_{L,i-2,g}(k)$ is the $k$th sampling value of the other end of the $i$th connecting line;

When the fault is not on the tie line, the sampling values of the charging and discharging currents of the capacitive currents at the head ends of all the feeders are utilized to calculate the similarity coefficient $P_{k,i}$ of each feeder according to a formula (5); Then the feeder corresponding to the minimum value $P_{k-min}$ of the similarity coefficient $P_{k,i}$ is the fault feeder.

The calculation method of the similarity coefficient $P_{k,i}$ of the $i$th feeder is shown in the formula (5):

$$P_{k,i} = \frac{\sum_{j=1}^{N} (n_k \cdot i_{k,g}(k) - \frac{1}{N} \sum_{j=1}^{N} n_k \cdot i_{k,g}(j)) (n_k \cdot i_{k,g}(k) - \frac{1}{N} \sum_{j=1}^{N} n_k \cdot i_{k,g}(j))}{\sqrt{\sum_{j=1}^{N} (n_k \cdot i_{k,g}(k) - \frac{1}{N} \sum_{j=1}^{N} n_k \cdot i_{k,g}(j))^2} \cdot \sqrt{\sum_{j=1}^{N} (n_k \cdot i_{k,g}(k) - \frac{1}{N} \sum_{j=1}^{N} n_k \cdot i_{k,g}(j))^2}}$$

Among: $P_{k,i}$ is the similarity coefficient of the fault pole current between the $i$th feeder and the
$s$ th feeder; M is that total numb of feeders of the DC distribution network; $P_{k_i}$ is the similarity coefficient of the $i$ th feeder; $n_{k_i}$, $n_{k_s}$ is the transformation ratio of the current transformer of the $i$ th feeder line and the $s$ th feeder line respectively; $i_{k_i e g}(k)$, $i_{k_s e g}(k)$ is the $k$ th sampling value of the fault pole of the $i$ th feeder and the $s$ th feeder respectively.

The implementation process is shown in Figure 3:

**Figure 3.** Implementation Flowchart

### 4. Simulation and Verification

According to the two-terminal MMC DC distribution network in Figure 1, the simulation model is built, and the method is proved when the unipolar ground fault occurs on M3, L2 and K3 respectively. The judgment bases are shown in Tables 1 to 3.
Table 1. Similarity coefficient value of M3 in case of single-pole ground fault

| Name  | N | PM1 | PM2 | PM3 | PM4 | PL1 | PL2 | PL3 | PK1 | PK2 | PK3 | PK4 | PK5 |
|-------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Figure | 46 | 0.90 | 0.88 | 0.81 | 0.92 | -   | -   | -   | -   | -   | -   | -   | -   |

Table 2. Similarity Coefficient Values for Single Pole to Ground Fault in L2

| Name  | N | PM1 | PM2 | PM3 | PM4 | PL1 | PL2 | PL3 | PK1 | PK2 | PK3 | PK4 | PK5 | PK6 |
|-------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Figure | 47 | 0.9  | 0.7  | 0.8  | 0.9  | 0.9  | 0.9  | -   | -   | -   | -   | -   | -   |

Table 3. K3 Similarity coefficient value in case of single-pole ground fault

| Name  | N | PM1 | PM2 | PM3 | PM4 | PL1 | PL2 | PL3 | PL4 | PK1 | PK2 | PK3 | PK4 | PK5 | PK6 |
|-------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Figure | 47 | 0.89 | 0.77 | 0.80 | 0.91 | 0.94 | 0.90 | 0.92 | 2.67 | 2.56 | 4.62 | 2.41 | 2.19 | 2.01 |

The above simulation shows that the method can precisely determine the DC distribution network of the single-pole ground fault line. When the fault pole and the fault position are changed, the method is still accurate and effective [10]. But when the fault point of the transition resistance is larger, because the transient component is very small, easy to produce error judgment, need to continue to study.

5. Conclusion
In this paper, a new method of unipolar earth fault protection for DC distribution network with two-terminal MMC is proposed, which divides the DC side fault of DC distribution network into three kinds of sections: feeder, tie line and bus [11]. The proposed method can be used to identify the single-pole grounding fault at any position of the DC distribution network. The method can effectively solve the single-pole grounding protection of the double-end direct current distribution network and improve the safety of power supply of the direct current distribution network. It is important to the development of DC distribution network and the flexible access of new energy.

Acknowledgments
This work was financially supported by: State Grid Jiangsu Electric Power Company Science and Technology Project.(Contract Number:J2020023)

References
[1] WENIG S, GOERTZ M, HIRSCHING C, et al. On fullbridge bipolar MMC-HVDC control and protection for transient fault and interaction studies. IEEE Transactions on Power Delivery, 2018, 33(6):2864-2873.
[2] Pei Li, Jing Ma, Xiaodong Zhou, Min Zhang, James S. Thorp. A protection scheme for DC-side fault based on a new MMC sub-module topology. International Journal of Electrical Power and Energy Systems, 2020, 114.
[3] Farshad Mohammad. Ultra - high - speed non - unit non - differential protection scheme for busses of MMC - HVDC grids. IET Renewable Power Generation, 2020, 14(9).
[4] Qiang Huang, Guibin Zou, Chunhua Xu, Jie Zhang, Shuo Zhang. Fast single-end line protection method for the meshed multi-terminal HVDC grid. The Journal of Engineering, 2019, 2019(16).
[5] Md Habibur Rahman, Rui Li, Liangzhong Yao, Lie Xu. Protection and post-fault recovery of
large HVDC networks using partitioning and fast-acting DC breakers at strategic locations. The Journal of Engineering, 2019, 2019(16).

[6] Yongjie Luo, Pu Yi, Xiong Xiaofu, Wang Jiang, Song Yonghui. DC fault ride-through method for full-bridge MMC-based MTDC systems. The Journal of Engineering, 2019, 2019(16).

[7] Delta Electronics Inc.; "Fault Protection Method And Wireless Power Transmission Device Using Same" in Patent Application Approval Process (USPTO 20190222064). Telecommunications Weekly, 2019.

[8] Boroyevich D, Cvetkovic I, Dong D, et al. Future electronic power distribution systems: a contemplative view//2020 12th International Conference on Optimization of Electrical and Electronic Equipment. Basov, Russia, 2020: 1369-1380.

[9] Flourentzou N, Agelidis V G, Demetriades G D. VSC-Based HVDC Power Transmission Systems: An Overview. IEEE Transactions on Power Electronics, 2019, 24(3): 592-602.

[10] Zhang J, Zou G B, Xie Z R, et al. A fast non-unit line protection strategy for the MMC-based MTDC grid. 2017 IEEE Conference on Energy Internet and Energy System Integration (E12), Beijing, China, 2017.

[11] WANG Y, YUAN Z, FU J, et al. A feasible coordination protection strategy for MMC-MTDC systems under DC faults. International Journal of Electrical Power & Energy Systems, 2017, 90: 103-111.