A Method of Single-terminal MMC Single-pole Grounding Protection for DC Distribution Network Based on Multi-class Similarity Analysis

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Abstract. Based on the analysis model of single-pole to ground fault occurred in single-ended MMC DC distribution network, the characteristics of single-pole to ground fault are studied. The similarity of positive and negative current between the fault feeder and the non-fault feeder, the similarity of fault current between the fault feeder and the non-fault feeder, and the similarity of positive and negative current sum between the two feeders are analyzed. Based on the differences among the three types of similarity, a new method of single-pole grounding protection for DC distribution network with MMC based on multi-type similarity analysis is proposed. The simulation results show that this method can accurately determine the fault feeder, and has the characteristics of strong anti-interference ability, simple calculation and easy implementation. It can effectively solve the problem of single-pole grounding protection of DC distribution network and effectively improve the safety and reliability of power supply of DC distribution network.

Keywords: DC Distribution Network, Single Pole Grounding, Multiclass Similarity, Variable Weight, 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]. Bipolar short-circuit fault and monopole grounding fault are DC side faults. The influence of monopole grounding fault on the system can be reduced by selecting a reasonable neutral grounding mode of transformer. 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 grounding fault protection scheme is less [2]. At present, there are mainly directional pilot protection methods based on transient wavelet transform for single-pole grounding fault, but these methods have the shortcomings of high sampling frequency or depending on communication, with a certain delay [3].

The similarities of positive and negative currents between fault line and non fault line, fault
currents between fault line and non fault line, and sum of positive and negative currents are analyzed. According to the difference between fault line and non fault line, this paper proposes a method of variable weight protection for single ended MMC DC distribution network based on multi class similarity analysis [4]. The method realizes the identification of faulty lines by multi class correlation coefficient, and is verified by simulation [5].

2. Fault Characteristic Analysis
Figure 1 is the schematic diagram of single ended MMC DC distribution network. Among them, the AC measurement adopts the transformer with wiring $Y_N / \Delta$

![Figure 1. Structure diagram of single-ended MMC DC distribution network](image)

Because the DC transmission line has the distributed parameter characteristic which changes along with the frequency, the line voltage will have a damping oscillation process before entering the stable state when the DC transmission line is single-pole grounded [6]. The constant change of line voltage in the process of oscillation leads to the changing attenuation of oscillation current flowing in and out of the distributed capacitance of the line to the ground.

When the feeder L1 is single-pole grounded, the capacitive current distribution of each line to ground is shown in Figure 2.

![Figure 2. Transient capacitive current distribution of single-pole grounding feeder](image)

(A) Feeder L1 positive and negative measuring current

(B) Feeder L2 positive and negative measuring current

The transient capacitive current at the head end of the fault feeder L1 is as shown in formula (1), and its current direction is from branch to bus.

$$i_{k1} = -(i_{k2} + i_{k3} + i_{k4})$$  \hspace{1cm} (1)

The magnitude of the transient capacitance at the head end of other non fault line is equal to the current of the line itself to the ground, and the direction is from the bus to the line.

Through the analysis, it can be seen that the transient capacitive current of the fault line is equal to the sum of the transient capacitive current of all other lines, while the other feeders are equal to their own transient capacitive currents [7]. The direction of the measured current on the side of the tie line
close to the fault feeder is positive, and the direction of the measured current on the other end of the tie line is negative. Similarly, when a fault occurs on a tie line, the currents at both ends of the fault tie line are negative; All feeders are positive and equal to their own capacitive currents; And one end of other tie line close to that fault tie line is positive, and the other end is negative. According to the above characteristics, the fault location and the fault feeder can be judged [8].

3. A New Single-pole Grounding Protection Method Based on Multi-class Similarity Analysis.
When the expression (1) is satisfied, it is determined that a single-pole ground fault has occurred.

\[
\begin{cases}
U_p \leq 0.4 \cdot 0.5 \cdot U_{PV_g} \\
U_N \leq 0.4 \cdot 0.5 \cdot U_{PV_g} \\
U_{PN} \geq 0.8 \cdot U_{PV_g}
\end{cases}
\]  

(2)

Where in: \( U_p \), \( U_N \), \( U_{PN} \), and \( U_{PV_g} \) are respectively the rated values of the positive pole-to-ground voltage, the negative pole-to-ground voltage, the inter-electrode voltage and the inter-electrode voltage.

To reduce the calculation of the protection, the data length \( N \) of the current criterion is determined by Equation (2). For the equation (2), the calculation is started from \( t=1 \), and the calculation is stopped when the equation (2) is satisfied, wherein the value of \( t \) is the length \( N \) of the data window [9].

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

(3)

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

At first, that positive and negative pole current sample values of all the feed lines are utilized to respectively calculate the positive and negative pole similarity coefficients \( p'_i \) of all the feed lines according to a formula (3); Find all the values \( p'_i < 0 \) in \( p'_i \) and sum them according to equation (4) to find the relative criteria \( p'_i \) based on \( k'_i \).

\[
p'_i = \frac{\sum_{k=1}^{N} (i_+(k) \frac{1}{N} \sum_{j=1}^{N} i_+(j)) (i_+(k) \frac{1}{N} \sum_{j=1}^{N} i_+(j))}{\sqrt{\sum_{k=1}^{N} (i_+(k) \frac{1}{N} \sum_{j=1}^{N} i_+(j))^2} \cdot \sqrt{\sum_{k=1}^{N} (i_+(k) \frac{1}{N} \sum_{j=1}^{N} i_+(j))^2}}
\]  

(4)

\[
\begin{cases}
W' = \sum_{i=1}^{M} p'_i \\
k'_i = \frac{p'_i}{W'}
\end{cases}
\]  

(5)

Whereinto: \( i_+(k) \) and \( i_-(k) \) are respectively the \( i \) th sampling value of the positive current and the second sampling value of the negative current of the feeder \( k \).

Secondly, the cross-similarity coefficient and \( p^*_i \) of fault pole current of all feeders are calculated according to Equation (5) by using the sampling value of fault pole current of each feeder. Find out the values of \( p^*_i \) of all \( p^*_i < 0 \), sum \( W'' \) according to Equation (6), and calculate the relative criterion

\[
W'' = \sum_{i=1}^{M} p^*_i
\]  

(6)
where, \( k_i^* \) is based on each feeder.

\[
\begin{align*}
    P_i^* &= \sum_{s=1}^{M} P_{i,s}^* \\
    P_{i,s}^* &= \frac{\sum_{k=1}^{N} (n_i \cdot i_{g,k}(k) - \frac{1}{N} \sum_{j=1}^{N} n_j \cdot i_{g,j}(j))(n_i \cdot i_{g,k}(k) - \frac{1}{N} \sum_{j=1}^{N} n_j \cdot i_{g,j}(j))}{\sqrt{\sum_{k=1}^{N} (n_i \cdot i_{g,k}(k) - \frac{1}{N} \sum_{j=1}^{N} n_j \cdot i_{g,j}(j))^2}} \\
    W^* &= \sum_{s=1}^{M} P_{i,s}^* \\
    k_i^* &= \frac{P_i^*}{W^*}
\end{align*}
\]

Where: \( P_{i,s}^* \) is the mutual correlation coefficient of fault pole current of the feeder \( i \) th and the feeder \( k \) th; \( i_{g,k}(k) \) is the \( k \) sampling value of fault pole current of the fifth feeder; \( n_i \) and \( n_s \) are the ratio of current transformers of the \( i \) th feeder and the \( s \) th feeder respectively. \( M \) is the total number of all feeders of the distribution network.

Calculate that sum of the mutual similarity coefficient \( p_{i,s}^* \) base on the sum of the current sampling values corresponding to the positive and negative pole of all the feeders according to the formula (7) by using the current sampling values of the positive and negative poles of all the feeders; Find out the values of \( p_{i,s}^* \) of all \( p_{i,s}^* < 0 \), sum \( W^* \) according to Equation (8), and calculate the relative criterion \( k_i^* \) based on each feeder.

\[
\begin{align*}
    P_{i,s}^* &= \sum_{k=1}^{N} (n_i \cdot (i_{p,k}(k)+i_{s,k}(k)) - \frac{1}{N} \sum_{j=1}^{N} (n_j \cdot (i_{p,j}(j)+i_{s,j}(j)))(n_i \cdot (i_{p,k}(k)+i_{s,k}(k)) - \frac{1}{N} \sum_{j=1}^{N} (n_j \cdot (i_{p,j}(j)+i_{s,j}(j)))) \\
    P_{i,s}^* &= \sum_{k=1}^{N} (n_i \cdot (i_{p,k}(k)+i_{s,k}(k)) - \frac{1}{N} \sum_{j=1}^{N} (n_j \cdot (i_{p,j}(j)+i_{s,j}(j)))) \\
    W^* &= \sum_{s=1}^{M} P_{i,s}^* \\
    k_i^* &= \frac{P_i^*}{W^*}
\end{align*}
\]

Wherein, \( P_{i,s}^* \) is the sum of the positive and negative pole currents of the \( i \) th and \( s \) th feeder lines; \( i_{p,k}(k) \) is the \( i \) th sampling value of the positive electrode current of the \( k \) th feeder , and \( i_{s,k}(k) \) is the \( i \) th sampling value of the negative electrode current of the \( k \) th feeder.

Finally, the comprehensive relative criterion \( k_j \) of each feeder is calculated according to the formula (9), and the feeder corresponding \( k_j \) to the maximum value \( k_{j_{\text{max}}} \) is the fault feeder.

\[
k_j = k_j^* + k_j^* + k_i^*
\]
4. Simulation and Verification

As shown in the structure diagram of the single-ended MMC DC distribution network in Figure 1, the rated voltage of the DC side is +10kV; The sampling frequency is 24 kHz; There are four tie lines L1 ~ L4 in this power network, the length of which are 5km, 8km and 3km respectively [10]. When the voltage drop of positive pole (or negative pole) to ground exceeds 20% of the rated voltage to ground, it is considered that a single pole grounding fault has occurred [11]. The calculation results of the sum of the mutual similarity coefficients based on the similarity of the feeder positive and negative pole currents, the sum of the mutual similarity coefficients based on the feeder fault pole currents, and the sums of the positive and negative pole corresponding current sampling values are respectively shown in Tables 1 to 4:

| Table 1. Calculation conclusion based on similarity of positive and negative current of feeder |
|-----------------------------------------------|
| Name   | $p_1'$ | $p_2'$ | $p_3'$ | $p_4'$ | $W'$ | $k_1'$ | $k_2'$ | $k_3'$ | $k_4'$ |
|--------|---------|---------|---------|---------|------|--------|--------|--------|--------|
| Criterion | -0.90  | 0.84    | 0.88    | 0.81    | -0.90| 1.00   | -0.93  | -0.98  | -0.90  |

| Table 2. Calculation conclusion based on sum of mutual similarity coefficient of feeder fault pole current |
|-----------------------------------------------|
| Name   | $p_1''$ | $p_2''$ | $p_3''$ | $p_4''$ | $W''$ | $k_1''$ | $k_2''$ | $k_3''$ | $k_4''$ |
|--------|---------|---------|---------|---------|------|--------|--------|--------|--------|
| Criterion | -2.65  | 0.86    | 0.85    | 0.79    | -2.65| 1.00   | -0.32  | -0.32  | -0.30  |

| Table 3. Calculation conclusion based on the sum of mutual similarity coefficients of the sampled current values corresponding to the positive and negative poles of the feeder |
|-----------------------------------------------|
| Name   | $p_1'''$ | $p_2'''$ | $p_3'''$ | $p_4'''$ | $W'''$ | $k_1'''$ | $k_2'''$ | $k_3'''$ | $k_4'''$ |
|--------|---------|---------|---------|---------|------|--------|--------|--------|--------|
| Criterion | -2.77  | 0.91    | 0.89    | 0.83    | -2.77| 1.00   | -0.33  | -0.32  | -0.30  |

| Table 4. Calculation conclusion of comprehensive relative criterion for each feeder |
|-----------------------------------------------|
| Name   | $k_1$  | $k_2$  | $k_3$  | $k_4$  |
|--------|--------|--------|--------|--------|
| Criterion | 3.00   | -1.58  | -1.62  | -1.5   |

5. Conclusion

In this paper, an integrated single-pole grounding protection method based on the similarity coefficient method is proposed for MMC two-terminal DC distribution network. The method is feasible to be apply to various MMC-based direct-current distribution networks; The method can judge the fault line and is not influenced by the connection mode of the line; As long as the data acquisition accuracy meets the requirements, the fault point transition resistance basically has no effect on the method. However, this method can only be used to identify single-pole grounding fault, and the inter-pole short circuit fault needs further study.

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