

Identification method based on correlation analysis for SPTG fault in MMC-MVDC system

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Abstract: Due to the labyrinthine topology of the MMC-MVDC system, identification of the faulty feeder especially for a single-pole-to-ground (SPTG) fault is a challenging task. Based on the characteristics analysis of capacitance charge–discharge, this article obtains the typical characteristics of the faulty feeder. To improve the sensitivity, the characteristic frequency band of capacitance current is extracted by S-transform which has excellent time–frequency resolution. According to the analysis, S-transform characteristic frequency band (STCFB) of positive and negative differential current of faulty feeder is negatively correlated while the healthy feeders are positively correlated. To distinguish the faulty feeder, an identification method based on Pearson correlation coefficient (PCC) is constructed. In terms of the energy difference between the positive and negative differential current, the faulty pole can be verified. Finally, a typical radial flexible DC distribution grid model is constructed in PSCAD, and the simulation results confirm the reliability and sensitivity of the identification method.

1 Introduction

Nowadays, modern power electronic technologies have developed more and more rapidly, which has further improved the development of flexible medium-voltage DC (MVDC) distribution grid [1, 2]. Due to the lack of converter links, DC distribution grid can further decrease the system loss and meet the large demand of renewable energies, so it will have a bright prospect [3, 4]. Compared to the two-level converter which has high switching frequency and large energy loss, modular multilevel converter (MMC) has high quality of output waveform and of fault handling, which is favoured in flexible DC projects [5, 6]. As DC storage capacitors have been assigned into the sub-modules (SMs), it is better for MMC to utilise small current grounding mode. When a SPTG fault occurs on the feeder, the voltage of healthy pole is twice the size of the original, threatening the safety of DC distribution network. On the other hand, the current is so small that the SPTG fault is difficult to identify. Thus, it is very necessary to propose a reliable and sensitive faulty feeder identification method.

Existing identification methods for SPTG fault on DC distribution network are basically aimed at two-level voltage source converters. An algorithm utilises the change rate of initial capacitance current of the line to identify the fault [7]. However, since the capacitors of MMC are embedded in the sub-module, they do not have a discharging circuit when SPTG fault occurs.

The speed of the algorithm based on the traveling wave and wavelet transform is high [8], but they are vulnerable to transient resistance. In addition, based on the boundaries of current-limiting reactor, the faults are identified by the change rate of voltage at two ends of the line [9]; however, the protection threshold needs to be re-set in case of power inversion.

Based on the excellent time–frequency resolution of S-transform, this paper proposes a faulty feeder identification method for SPTG fault. The rest of the paper is structured as follows: first of all, combined with several typical grounding modes of MMC, the fault characteristics of different feeders for SPTG fault are analysed in detail, and the characteristic frequency band of distributed capacitor discharge is obtained in Section 2. In order to extract characteristic band, Section 3 introduces S-transform and its related theory, and then the identification methods of faulty feeder are given in Section 4. In Section 5, a simulation model of radial flexible DC distribution grid is constructed, and the proposed

method is verified and discussed. Finally, Section 6 summarises the full text and draws the conclusion.

2 Fault analysis of DC distribution grid

2.1 Topology

In order to develop the future power system into an advanced system hybrid of AC and DC, the main grid of MVDC distribution will be ± 10 kV, and the low-voltage part of the user side will include the ± 750 V grid of industrial load and 400 V grid of civilian load. Compared with two-terminal topology and ring topology, the radial topology is more suitable for the data centre DC grid and residential DC distribution grid with relatively lower reliability requirements. In this system, the converter station connected with AC system is the DC source. Fig. 1 shows a typical radial DC distribution grid topology.

As shown in Fig. 1, the system is composed by single MMC converter station which works in DC voltage control. 0.25 MW photovoltaic power and 0.25 MW energy storage battery boost access ± 10 kV DC bus through the DC/DC converters, respectively, which reflects the diversification concept of ‘source-grid-load-storage’. The frequency-dependent DC cable model is used to simulate DC feeders F₁–F₄, and the parameters are shown in Table 1.

2.2 DC feeder transient characteristics analysis

The fault characteristics of a SPTG fault of MMC-MVDC are closely related to the grounding mode. In order to maintain the symmetry of the positive voltage and negative voltage of DC bus, the grounding modes of MMC converter stations are usually divided into two types: grounding mode on AC side and grounding mode on DC side. As shown in Fig. 2a, grounding mode on DC side is neutral point of split resistors grounding mode. The modes of grounding on AC side include two types: the first mode is that converter uses Δ/Y_0 or Y/Y_0 connection form, the neutral point of valve side is grounded via a large resistor, as shown in Fig. 2b; the other mode uses Y_0/Δ , the star reactance of valve side constructing neutral point via large resistance, as shown in Fig. 2c. When the SPTG fault occurs on these three modes, there is no ground loop for the fault current. The current value is small, so all of these modes can be considered as a small current grounding mode. At

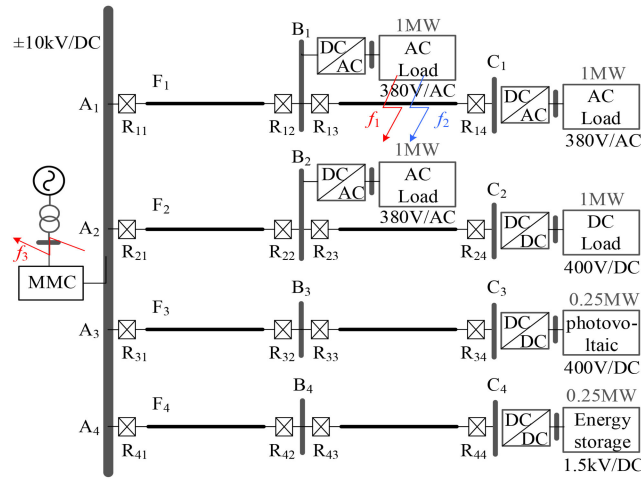


Fig. 1 Radial DC distribution grid topology

Table 1 Line parameters of system

Parameters	Value
resistance	0.125 Ω/km
inductance	0.72 mH/km
capacitance	0.0048 $\mu\text{F}/\text{km}$
$A_k B_k, B_k C_k (k = 1, 2, 3, 4)$	10 km

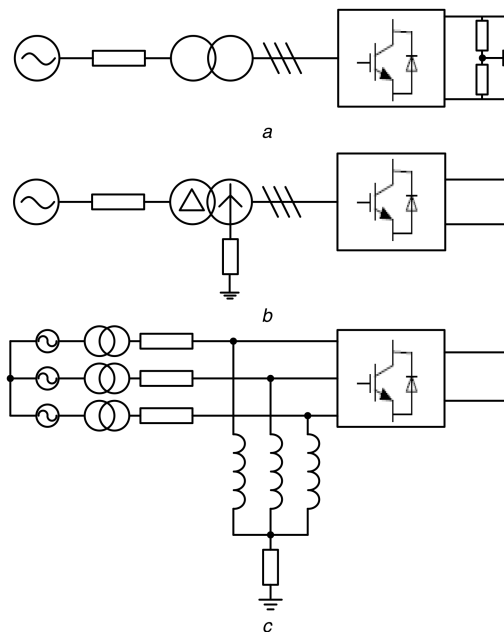


Fig. 2 Grounding modes of MMC

(a) Neutral point of split resistors grounding mode, (b) Valve side of transformers grounded via a large resistor, (c) The star reactance of valve side constructing neutral point grounding via large resistance

the same time, the capacitor of MMC does not discharge, the pole-to-pole voltage maintains constant, so the SPTG fault only changed the zero potential of MMC-MVDC system.

When a SPTG fault occurs on MMC-MVDC, the steady-state voltage and current of faulty feeder are the same as normal feeder. Only using steady-state voltage and current cannot identify the fault line. So it is necessary to analyse the fault component of transient capacitance current in each feeder.

The inherent frequency-varying parameter characteristics of transmission lines make the transient voltage of the circuit of MMC-MVDC produce attenuation oscillation when a SPTG fault occurs, resulting in the capacitance current flowing into and out of the grounding point. In Fig. 3, the grounding point is on DC side. Taking the SPTG fault of both positive and negative poles of F_1 as an example, the transient characteristics of capacitance charge-

discharge of faulty feeder and normal feeders are shown in Fig. 3, $\{u_p, u_n\}$ represent positive and negative bus voltages, respectively, $\{i_{p1}, i_{n1}\}, \{i_{pk}, i_{nk}\}$ represent positive and negative currents of the head of faulty feeder and healthy feeders ($k = 2, 3, 4$), and i_{L1}, i_{Lk} represent the positive and negative currents of the end of faulty feeder and healthy feeders, respectively. When the positive-pole-to-ground fault at f_1 occurs, both positive and negative poles generate a negative voltage drop $\Delta u < 0$. At this time, the capacitors of positive and negative feeders need discharging. As the red arrow shows, the capacitance current flows from the line to the grounding point. Similarly, when the negative-pole-to-ground fault occurs, as the blue arrow shows, the capacitors of positive and negative feeders need charging and the capacitance current flows from the grounding point to the line. The analysis above shows that capacitance current of positive and negative lines flows in and out

of the grounding point in the same direction and does not counteract.

Due to no current loop of SPTG fault, the fault current of grounding point is only determined by the current of capacitance charge–discharge. Assume the positive direction of the current is from the bus to the grounding point, for the fault point f_1 , we can get the fault current according to Kirchhoff's law:

$$i_f = \sum_{k=2}^4 \sum_{i=1}^8 i_{Cki} + \sum_{i=1}^8 i_{C1i} \quad (1)$$

where i_f is the fault current flowing from the bus to the grounding point, i_{C1i} is capacitance current of the positive and negative poles of faulty feeder while i_{Cki} is of healthy feeders. Defining the differential currents of positive and negative poles of normal feeders are $i_{\text{dif-Lkp}}$, $i_{\text{dif-Lkn}}$, respectively, so:

$$i_{\text{dif-Lkp}} = i_{Lk} - i_{pk} = - \sum_{i=1}^4 i_{Cki} \quad (2)$$

$$i_{\text{dif-Lkn}} = -i_{Lk} - i_{nk} = - \sum_{i=5}^8 i_{Cki} \quad (3)$$

Taking the positive-pole-to-ground fault as an example, define the differential currents of both positive and negative poles of faulty feeder are $i_{\text{dif-L1p}}$, $i_{\text{dif-L1n}}$, so:

$$i_{\text{dif-L1p}} = i_{L1} - i_{p1} = i_f - \sum_{i=1}^4 i_{C1i} = \sum_{k=2}^4 \sum_{i=1}^8 i_{Cki} + \sum_{i=5}^8 i_{C1i} \quad (4)$$

$$i_{\text{dif-L1n}} = -i_{L1} - i_{n1} = - \sum_{i=5}^8 i_{C1i} \quad (5)$$

The negative-pole-to-ground fault is similar, so it will not be discussed here. It can be seen that when SPTG fault occurs on the feeder, the direction of the differential current is opposite between positive and negative poles of the faulty feeder; Meanwhile, the value of the differential current at the faulty pole is much larger than that of the normal pole; on the other hand, as the normal feeder, the direction of the differential current of the positive pole is the same as negative pole. The waveform is positively correlated. So we can identify the faulty feeder and faulty pole by these characteristics.

2.3 Analysis of capacitance current characteristic frequency band

The capacitance current signal of DC feeder has a continuous spectrum from low frequency to high frequency. However, low-frequency part is easily affected because the distributed power supply is inhomogeneous. The high-frequency part is easily attenuated due to the amplitude–frequency characteristics of feeders reaching the resonance peak value. Therefore, it is necessary to analyse the characteristic frequency band of capacitance current. As shown in Fig. 4, F_1 in Fig. 1 is modelled by a π -type equivalent circuit, and the frequency characteristics of the DC distribution grid are analysed as follows.

Still taking F_1 of Fig. 1 as an example for analysis, according to the two-port grid equation, the current–voltage expressions can be obtained as follows:

$$\begin{cases} \dot{I}_{p1} = (Y_1 + Y_2)\dot{U}_{p1} - Y_1\dot{U}_{L1} \\ \dot{I}_{L1} = Y_1\dot{U}_{p1} - (Y_1 + Y_2)\dot{U}_{L1} \end{cases} \quad (6)$$

where $\dot{I}_{p1}$, $\dot{U}_{p1}$ represent the current phasor and voltage phasor of the head of F_1 . $\dot{I}_{L1}$, $\dot{U}_{L1}$ represent the current phasor and voltage

phasor of the end of F_1 . Y_1 , Y_2 represent the Y parameters of two-port network.

Define the transfer function of the head and the end of the DC feeders as follows:

$$G(s) = \frac{I_{L1}(s)}{I_{p1}(s)} \Big|_{U_{L1}(s)=0} \quad (7)$$

Substituting parameters into (7):

$$G(s) = \frac{Y_1}{Y_2 + Y_1} = \frac{2}{CL^2s^2 + CRl^2s + 2} \quad (8)$$

where R , L , and C represent the unit resistance, inductance, and capacitance of the feeder, respectively; l represents the length of the line.

Transfer function of oscillation part can be expressed as follows:

$$G^*(s) = \frac{1}{(s/\omega_n)^2 + 2\zeta(s/\omega_n) + 1} \quad (9)$$

The resonant angle frequency is as follows:

$$\omega_r^* = \omega_n \sqrt{1 - 2\zeta^2} \quad (10)$$

Simplifying (8) into the standard form of (9), $G(s)$ will be:

$$G(s) = \frac{1}{(s/\sqrt{2/CLl^2})^2 + 2(Rl\sqrt{C/8L})(s/\sqrt{2/CLl^2}) + 1} \quad (11)$$

$$\omega_n = \sqrt{\frac{2}{CLl^2}}, \quad \zeta = \frac{Rl}{2} \sqrt{\frac{C}{2L}} \quad (12)$$

Therefore, the resonant frequency f_r can be calculated as follows:

$$f_r = \sqrt{\frac{2}{CLl^2} - \frac{R^2}{2L^2}} / 2\pi \quad (13)$$

According to the line parameters shown in Table 1, the amplitude–frequency characteristic curves of the transmission function $G(s)$ of DC feeders can be obtained by substituting the different feeder lengths $l = 20, 15$, and 10 km into formula (8), respectively. The curve is shown in Fig. 5.

From the formula (11), we can get the resonance frequency $f_{r1} = 6054$ Hz, $f_{r2} = 8072$ Hz, $f_{r3} = 12107$ Hz corresponding to different feeder lengths. It can be seen from Fig. 5 that for the same line length, the amplitude–frequency characteristic $A(\omega)$ of the transfer function $G(s)$ gradually increases from 1 in the low-frequency band range $0 < f < f_r$; when $f = f_r$, the amplitude–frequency characteristic reaches the resonance peak. In this case, the circuit has the least attenuation effect on the capacitance current. For high frequency band $f > f_r$, the amplitude–frequency characteristic $|A(\omega)|$ decays rapidly from the resonant peak. That is, as the frequency increases, the attenuation effects on the capacitance current become stronger. When the length of the feeder reaches maximum length of 20 km, f_r reaches a minimum of 6054 Hz. Therefore, in order to reduce the attenuation effect of the feeder on capacitance current, the frequency should not be greater than 6054 Hz. At the same time, most of AC distributed generation works in 50 Hz, and most of DC distributed power works in low-frequency band. So the low-frequency band of the capacitance current is easily affected by the load current and distributed power. Therefore, this paper selects characteristic frequency band between 500 and 4000 Hz for analysis.

3 Application of S-transform

S-transform has excellent time–frequency resolution characteristics. The height and width of Gaussian window changes

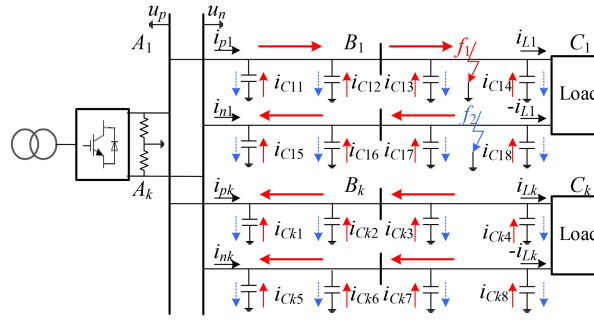


Fig. 3 Capacitance currents distribution during SPTG fault

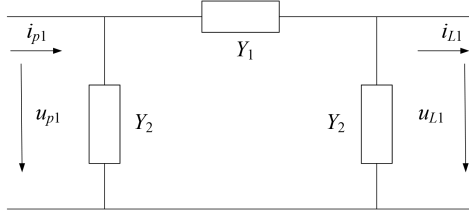


Fig. 4 π -type equivalent circuit

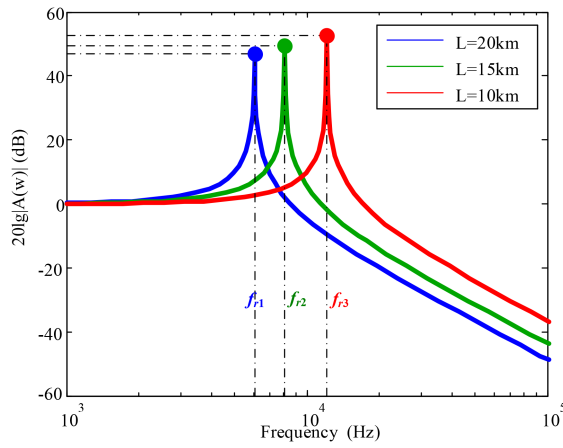


Fig. 5 Amplitude-frequency characteristics of DC feeder

with the variation of frequency, so the S-transform has good frequency resolution in the low-frequency part and has good time resolution in the high-frequency part. According to the above analysis, it is very easy to extract the characteristic frequency band of current fault component using S-transform.

3.1 S-transform theory

S-transform is the development of wavelet transform and short-time Fourier transform, and the S-transform of a signal $x(t)$ can be expressed as follows:

$$S(\tau, f) = \int_{-\infty}^{+\infty} x(t) \omega(\tau - t, f) e^{-j2\pi f \tau} dt \quad (14)$$

where f and τ are frequency-shift factor and time-shift factor; $\omega(\tau - t, f)$ is Gaussian window function which can be defined as follows:

$$\omega(\tau - t, f) = \frac{|f|}{\sqrt{2\pi}} e^{-((\tau - t)^2 f^2 / 2)} \quad (15)$$

The S-transform of a discrete signal $x[jT]$ can be realised by the fast Fourier transform:

$$\begin{cases} S[kT, \frac{n}{NT}] = \sum_{m=0}^{N-1} X[\frac{m+n}{NT}] e^{-(2\pi^2 m^2 / n^2)} e^{(i2\pi m k / N)}, n \neq 0 \\ S[kT, 0] = \frac{1}{N} \sum_{m=0}^{N-1} X[\frac{m}{NT}], n = 0 \end{cases} \quad (16)$$

where $k, m, n \in (0, N-1)$. T is the sampling interval, and N is the total number of sampling points. $X[n/NT]$ is the discrete Fourier transform of $x[jT]$, and $e^{-2\pi^2 m^2 / n^2}$ is the Fourier spectrum of Gaussian window function.

3.2 S-transform characteristic frequency band (STCFB)

The S matrix obtained by S-transform is defined as $Sa[p, q]$, where q is a column vector representing the amplitude-frequency characteristics of the signal at one sampling point, and p is a row vector representing the time-domain characteristics of the signal at a certain frequency. Then the STCFB of a signal at a certain time q can be defined as follows:

$$S[q] = \sum_{p=500}^{p=4000} S[p, q] \quad (17)$$

where $q = 1, 2, \dots, N$. The STCFB waveform can be drawn by calculating $S[q]$ at each time.

3.3 S transform transient energies based on sampling value theory

Defining the transient energies of the S-transform value $S[p, q]$ of the input signal at a particular frequency p at the particular time point q as $E[p, q]$

$$E(p, q) = \text{abs}(S[p, q]) \quad (18)$$

In order to improve the reliability of the analysis, based on sampling value theory, we can obtain the S transform transient energies W of all sampling points in the characteristic frequency band.

$$W = \sum_{p=f_{\min}}^{p=f_{\max}} \sum_{q=1}^N E(p, q) \quad (19)$$

According to the previous analysis, $f_{\min}$ and $f_{\max}$ are, respectively, taken as 500 and 4000 Hz, and N represents the sampling numbers in the data window.

3.4 S-transform signal analysis based on Pearson correlation coefficient (PCC)

The PCC is a progressive non-biased optimal estimation of the maternal correlation coefficient. It is appropriate to analyse stationary and ergodic random signals, which is widely used in the field of relay protection. For two signals $S_1(q)$ and $S_2(q)$, the expression of PCC to describe the degree of waveform similarity is as follows:

$$\rho_{S_1 S_2} = \frac{\sum_{q=1}^N S_1(q) S_2(q)}{(\sum_{q=1}^N S_1^2(q) \sum_{q=1}^N S_2^2(q))^{1/2}} \quad (20)$$

where $\rho_{S_1 S_2}$ is PCC, which reflects the normalised correlation values of the two signals $S_1(q)$ and $S_2(q)$. The size is between $[-1, +1]$, -1 means that the two signals are completely negatively correlated, $+1$ means that the two signals are completely positively correlated, and 0 means the two signals are completely independent.

4 Fault identification method based on S-transform

4.1 Faulty feeder identification criteria

From the analysis of Section 2.1, the STCFB of differential current between positive and negative poles of normal feeders should be approximately positively correlated when a SPTG fault occurs on DC distribution grid, while the STCFB of faulty feeder is approximately negatively correlated. According to the formula (20), the PCC of the STCFB waveform is defined as ρ_{fi} ($i = 1 \dots 4$), and the faulty feeder identification method can be constructed as follows:

When feeder is a faulty feeder:

$$\rho_{fi} < k_f \quad (21)$$

When feeder is a normal feeder:

$$\rho_{fi} > k_f \quad (22)$$

Based on the previous analysis, when the feeder is normal feeder, ρ_{fi} is close to 1. In consideration of the sensitivity and selectivity, set value k_f as 0.2.

4.2 Faulty pole identification criteria based on sampling value theory

As the DC distribution feeders generally use bipolar mode of operation, there is electromagnetic coupling between two poles. Therefore, after selecting the faulty feeder, the faulty pole should be identified.

According to (20), the transient energies of two poles of all feeders can be defined as W_{pi} and W_{ni} , respectively. Defining the ratio of W_p and W_n measured at the head of the feeder as λ_i :

$$\lambda_i = W_{pi} W_{ni} \quad (23)$$

Based on this ratio, faulty pole identification criteria can be constructed as follows:

$$\lambda_i > 1 + k_{WH} \quad (24)$$

$$\lambda_i > 1 - k_{WH} \quad (25)$$

where k_{WL} , k_{WH} are the reliability coefficients. Considering the sensitivity and reliability, both k_{WL} and k_{WH} are taken as 0.2. If (24) is satisfied, the positive pole is faulty. If (25) is satisfied, the negative pole is faulty.

5 Simulation analysis

Using PSCAD/EMTDC simulation software, a simulation model of ± 10 kV natural bipolar DC distribution system is constructed as shown in Fig. 1. Different types of SPTG faults are set to verify the reliability of the method. System parameters are shown in Table 2, the fault occurs at 3 s, and the sampling frequency is 25 kHz.

Table 2 System parameters

Parameters	Value
voltage of AC system	110 kV
AC rated voltage	10 kV
rated capacity of MMC	5 MVA
rated active power of photovoltaic	0.25 MW
rated active power of energy storage	0.25 MW
level of converters	11
capacitance of MMC	1000 μ F
inductance of bridge	6.4 mH

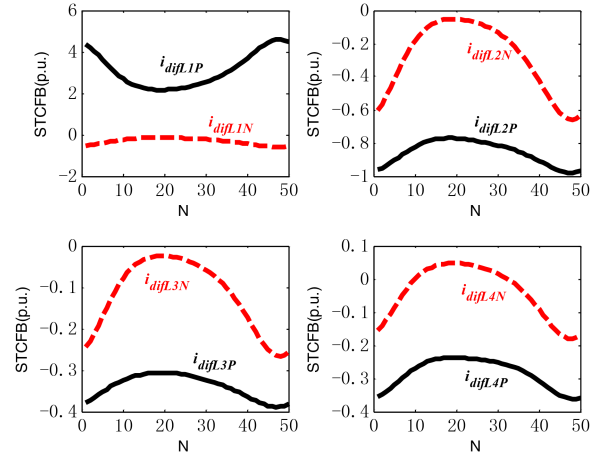


Fig. 6 STCFB of the positive and negative differential currents of different feeders

Table 3 Simulation results of faulty feeders

ρ_f				λ
F ₁	F ₂	F ₃	F ₄	
-0.9997	0.9977	0.9839	0.9934	4.4457

5.1 Simulation of metallic SPTG fault

Set positive-pole-to-ground fault at f_1 in the middle of segment B₁C₁, and the STCFB waveforms of positive and negative poles of all feeders are shown in Fig. 6. The simulation results of faulty feeder are shown in Table 3.

In Fig. 6, $\{i_{difL1p}, i_{difL1n}\}$, $\{i_{difL2p}, i_{difL2n}\}$, $\{i_{difL3p}, i_{difL3n}\}$, $\{i_{difL4p}, i_{difL4n}\}$, respectively, represent the positive and negative differential currents of F₁–F₄. As can be seen from Fig. 6, the STCFB waveforms of differential current of positive and negative poles in F₂–F₄ are approximately positively correlated, while the STCFB waveforms of F₁ are approximately negatively correlated. It can be seen from the ρ_f in Table 3 that F₁ is the faulty feeder.

5.2 Simulation analysis of influencing factors

In order to verify the accuracy of the proposed feeder selection method under different influence factors, the analysis of different influence factors is shown as follows.

5.2.1 Different fault resistance: Faults of different fault resistances are, respectively, set at f_2 on the negative pole of segment B₁C₁, and the identification results of the faulty feeder are shown in Table 4.

According to Table 4, F₁ can be identified as faulty feeder in the condition of different fault resistance.

5.2.2 Fault on AC side: Set different types of fault at f_3 on AC bus, and the simulation results are shown in Table 5.

It can be seen from the data in Table 5 that all feeders of fault on AC side can be judged as normal. The above simulation results

Table 4 Simulation results of faulty feeders with different fault resistance

Resistance/ Ω	ρ_f				λ
	F_1	F_2	F_3	F_4	
0	-0.9997	0.9977	0.9841	0.9933	0.1649
10	-0.9999	0.9997	0.9985	0.9989	0.1534
20	-0.9999	0.9998	0.9991	0.9991	0.1512

Table 5 Simulation of fault on AC side

Fault type	ρ_f				Result
	F_1	F_2	F_3	F_4	
AG	0.9999	0.9999	0.9999	0.9999	normal
ABG	0.9999	0.9998	0.9998	0.9997	normal
BC	0.9999	0.9985	0.9440	0.8559	normal
ABCG	0.9999	0.9997	0.9999	0.9991	normal

show that under various fault conditions, the fault can be correctly identified. So it verifies the correctness of theoretical analysis and simulation results.

6 Conclusion

Based on the analysis of the SPTG fault on a typical DC distribution grid, the identification methods of faulty feeder for SPTG fault are proposed. Theoretical analysis and simulation results show that:

- (i) The identification method does not need the assistance of boundaries of DC line, so it will not affect the stability of the DC distribution grid.
- (ii) The method is hardly affected by the fault resistance and the fault on AC side. Faults in any condition can still be accurately identified.
- (iii) The method analyses the characteristic frequency of the capacitance current and comprehensively utilises the phase information and the amplitude information of all the data, so it will have high reliability.

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