

A Protection Algorithm Based on Transient Current Spectrum Characteristic for MMC-HVDC Line

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Abstract—When a fault occurs on a transmission line, fault generated high frequency transient components are a series of natural frequencies in frequency domain. This paper proposes a protection algorithm for MMC-HVDC transmission line based on spectrum characteristic of natural frequency. Spectrum correlation coefficient is used to determine whether a fault is internal or external fault. The scheme performance was proven using PSCAD/EMTDC simulations in $\pm 500\text{kV}$ MMC-HVDC power system. The simulation results show that it can identify fault quickly and accurately.

Keywords—MMC-HVDC transmission line; natural frequency; protection; transient current; spectrum characteristic

I. INTRODUCTION

Power system protection has traditionally relied on the measurement of power frequency components for identifying internal and external faults, fault-generated high-frequency transient signals are considered as interference and filtered out [1]. However, these high-frequency components contain extensive fault information. In fact, these high-frequency transient signals contain more information about the fault than power frequency signals.

For the stability of the electric network, it is important to clear faults from transmission lines quickly with the aid of a high speed protection. The protection scheme based on fault transient signals will achieve fast detection time. The fault-generated travelling wave information has been used to identify internal and external faults in transmission lines [2]–[8].

However, the scheme based on travelling wave may fail to detect faults under certain conditions [9]. Firstly, for traveling wave protection, the transducer used to measure voltage and current signals must have a large bandwidth since fault generated waveforms may contain high frequencies. Secondly, when phase-to-ground fault occurs near zero voltage level, the amplitude of wave fronts will be small and the relay might not be able to detect the fault. Thirdly, the traveling wave distance protection is to measure the time interval between the arrival of an incident wave towards the fault points and that of the corresponding wave reflected from it, but in some cases the second wave front is not from fault point and the protection might fail. Fourth, for a close-up fault, the time difference between the arrival of an incident wave and the arrival of its reflection from the busbar will be so short that the traveling wave fronts are unlikely to be detected separately.

In this paper, a protection algorithm based on spectrum characteristic of natural frequency component for MMC-

HVDC line was proposed. In Section II, the characteristics of natural frequency component are analyzed in frequency domain. It is a series of natural frequencies in frequency domain. In Section III, a protection algorithm using spectrum correlation coefficient is proposed to determine whether a fault is internal or external to the protected zone. In Section IV, the protection scheme performance is tested extensively using PSCAD/EMTDC-generated data, the simulation verified that the proposed scheme can identify internal and external fault accurately. The results also show that the scheme is insensitive to fault position, fault inception angle, fault resistance.

II. SPECTRUM CHARACTERISTIC OF NATURAL FREQUENCY COMPONENT

A. Fundamental Spectrum Characteristic of Natural Frequency Component

The equivalent circuit of fault network in the Laplace domain using distributed parameter model is shown in Figure I, where Z_c is surge impedance, Z_1 and Z_2 is source impedance and fault resistance, E_1 and E_2 is source and imposing source in fault position, W_1 and W_2 is equivalent source of traveling wave [10].

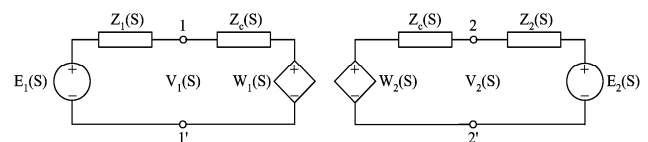


FIGURE I. EQUIVALENT CIRCUIT OF FAULT NETWORK USING DISTRIBUTED PARAMETER MODEL

The voltages in 1-1' and 2-2' can be expressed that

$$V_1(s) = \frac{Z_1(s)}{Z_1(s) + Z_c(s)} W_1(s) + \frac{Z_c(s)}{Z_1(s) + Z_c(s)} E_1(s) \quad (1)$$

$$V_2(s) = \frac{Z_2(s)}{Z_2(s) + Z_c(s)} W_2(s) + \frac{Z_c(s)}{Z_2(s) + Z_c(s)} E_2(s) \quad (2)$$

where

$$W_1(s) = \frac{P(s)}{1 - \Gamma_1(s)\Gamma_2(s)P^2(s)} \cdot [\Gamma_2(s)P(s) \frac{2Z_c(s)}{Z_1(s) + Z_c(s)} E_1(s) + \frac{2Z_c(s)}{Z_2(s) + Z_c(s)} E_2(s)] \quad (3)$$

$$W_2(s) = \frac{P(s)}{1 - \Gamma_1(s)\Gamma_2(s)P^2(s)} \cdot \left[\frac{2Z_c(s)}{Z_1(s) + Z_c(s)} E_1(s) + \Gamma_1(s)P(s) \frac{2Z_c(s)}{Z_2(s) + Z_c(s)} E_2(s) \right] \quad (4)$$

$$P(s) = e^{-st} \quad (5)$$

t is the travel time of traveling wave in transmission line, $\Gamma_1(s)$ and $\Gamma_2(s)$ are the voltage reflection coefficients in 11' and 22':

$$\Gamma_1(s) = \frac{Z_1(s) - Z_c(s)}{Z_1(s) + Z_c(s)} \quad (6)$$

$$\Gamma_2(s) = \frac{Z_2(s) - Z_c(s)}{Z_2(s) + Z_c(s)} \quad (7)$$

The natural frequency ω is the roots of the equation:

$$1 - \Gamma_1(s)\Gamma_2(s)P^2(s) = 0 \quad (8)$$

Equation (8) has an infinite number of roots, and they are the solution of the equation

$$1 - A_1 A_2 e^{i\theta_1} e^{i\theta_2} e^{-2\omega t} = 0 \quad (9)$$

$$A_1 A_2 e^{i\theta_1} e^{i\theta_2} e^{2k\pi i} = e^{2\omega t} \quad k = 0, \pm 1, \pm 2, \dots, \quad (10)$$

where

$$A_1 = |\Gamma_1|$$

$$A_2 = |\Gamma_2|$$

$$\theta_1 = \angle(\Gamma_1)$$

$$\theta_2 = \angle(\Gamma_2)$$

From which we obtain

$$\omega = \frac{1}{t} \ln(\sqrt{A_1 A_2}) + i \left(\frac{\theta_1 + \theta_2 + 2k\pi}{2t} \right) \quad k = 0, \pm 1, \pm 2, \dots, \quad (11)$$

$$f = \frac{\text{imag}(\omega)}{2\pi} = \frac{\theta_1 + \theta_2 + 2k\pi}{2t \times 2\pi} \quad k = 0, \pm 1, \pm 2, \dots \quad (12)$$

These frequencies are called natural frequency of transmission line. If Z_1 and Z_2 are zero, natural frequencies satisfy the condition:

$$\omega = n\omega_0 \quad n = 1, 2, 3, \dots, \quad (13)$$

$$f_k = k f_0 \quad k = 1, 2, 3, \dots \quad (14)$$

where

$$\omega_0 = \frac{\pi}{t}$$

Figure II shows the spectrum of natural frequency component after fault. It is clear that natural frequencies are discrete, and they are multiple of main natural frequency.

When the system is in normal condition, there is no natural frequency component, so its spectrum is zero.

B. Spectrum Characteristics of Natural Frequency Component When External Fault

Figure III shows a four-side-MMC-HVDC system, F1 and F2 are fault points on lines. Relays are installed at two sides of line.

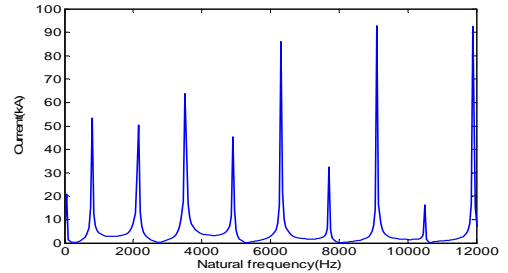


FIGURE II. NATURAL FREQUENCY COMPONENT SPECTRUM

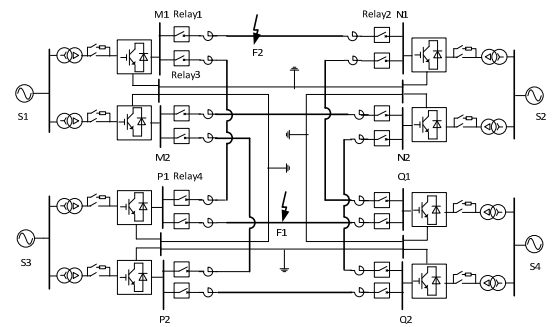


FIGURE III. MMC-HVDC SYSTEM

When a fault occurs at F1, it is an external fault for line MN. The natural frequencies of currents flowing through relay 1 and 2 are the same, so the natural frequency component spectrums of relay 1 and 2 are similar. Fig. IV shows the spectrums of

natural frequency component in relay 1 and 2 when the fault is in F1. It can be seen from it that the spectrums in two sides of line MN are similar and the natural frequency component amplitudes of relay 1 are smaller than that of relay 2, this is the result of natural frequency component decayed.

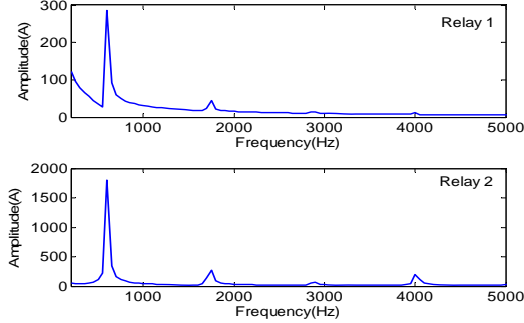


FIGURE IV. CURRENT SPECTRUMS OF NATURAL FREQUENCY COMPONENT DURING EXTERNAL FAULT

C. Spectrum Characteristics of Natural Frequency Component When Internal Fault

When a fault occurs at F2, it is an internal fault for line MN, systems in two sides of fault point are different and the natural frequencies of currents flowing through relay 1 and 2 are different. Figure V shows the natural frequency component spectrums in relay 1 and 2 when the fault is in F2. It can be seen from it that the spectrums in two ends of line MN are different.

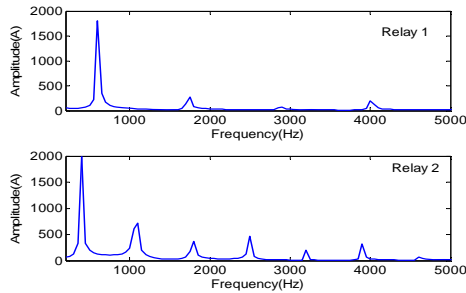


FIGURE V. CURRENT SPECTRUMS OF NATURAL FREQUENCY COMPONENT DURING INTERNAL FAULT

III. PROTECTION ALGORITHM BASED ON SPECTRUM CHARACTERISTIC OF NATURAL FREQUENCY COMPONENT

A. Basic Principle

According to the analysis above, the spectrum characteristic of natural frequency component can be used to identify internal and external faults. If the spectrums of natural frequency component in two ends of transmission line are similar, the fault is an external fault, and if their difference is great, the fault is an internal fault.

In this paper, the relationship between current spectrums of natural frequency component is expressed by spectrum correlation coefficient and the formula is [11]:

$$\rho = \frac{\text{cov}(X, Y)}{\sqrt{\sigma^2(X) \times \sigma^2(Y)}} \quad (15)$$

and $\text{cov}(X, Y)$, $\sigma^2(X)$ and $\sigma^2(Y)$ are defined by

$$\text{cov}(X, Y) = \sum_{n=0}^N x(n)y(n) \quad (16)$$

$$\sigma^2(X) = E(X) = \sum_{n=0}^N x^2(n) \quad (17)$$

$$\sigma^2(Y) = E(Y) = \sum_{n=0}^N y^2(n) \quad (18)$$

where ρ is spectrum correlation coefficient of phase X and phase Y, $E(X)$ and $E(Y)$ are spectrum energy of phase X and phase Y, $x(n)$, $y(n)$ is sampling value of current spectrum of phase X, Y respectively, N is sampling point number in a data window.

If the spectrums of phase X and phase Y are similar, ρ is near to 1, when their spectrums are the same, ρ is equal to 1. If there is larger difference between spectrums of phase X and Y, ρ is near to 0.

For an external fault, spectrum correlation coefficient of natural frequency component between two ends of line satisfies

$$\rho > \delta \quad (19)$$

where δ is a threshold to identify internal or external fault.

For an internal fault, spectrum correlation coefficient of natural frequency component between fault phases of two ends of fault line satisfies

$$\rho < \delta \quad (20)$$

B. Influencing Factor

1) Fault location

When the fault point is close to bus M, natural frequency amplitude may be small and its spectrum is nearby 0, so ρ is near to 0, the fault can be identified as an internal fault.

When the fault is in the middle of line, spectrums of natural frequency component in two sides of fault point are similar and ρ may be bigger than δ , in this condition, the scheme will fail.

2) Noise

Compare to natural frequency component, the amplitude of noise is smaller. It can be filtered through setting a threshold.

3) Fault resistance

The scheme can identify fault phase in high resistance condition. But if the fault resistance is too high, the sensitivity of scheme will reduce.

4) Window length, the sampling time and the maximum frequency of the spectrum

For spectrum by FFT, the maximum frequency of the spectrum is relation to the window length and the sampling time (sampling frequency). The maximum frequency of the spectrum is half of sampling frequency. The window length is bigger than $1/f_{\max}$ and f_{\max} is the maximum frequency of the spectrum.

5) Switching of circuit breakers

For line charging power, the current in one side of line is capacitance current and the current in other side is zero. In this case, ρ is near to 0. Adding criterion $I > I_{\text{set}}$, if $I < I_{\text{set}}$, the protection scheme is locked.

C. Protection Scheme

The flowchart of protection scheme base on spectrum characteristic of natural frequency component can be described as following:

- 1) Sample currents of two ends of line, then compute the spectrum respectively.
- 2) Set a threshold value δ_1 which is used to eliminate noise, if the amplitude of frequency in spectrum is smaller than δ_1 , remove it from spectrum. If all frequency amplitudes in one end of line are smaller than δ_1 , let the spectrum be zero. If all amplitudes of frequency in two ends of line are smaller than δ_1 , turn step 4).
- 3) Compute the spectrum correlation coefficient ρ (ρ is between 0 and 1), then set δ_2 which is used to identify internal fault and other conditions, compare ρ and δ_2 , if $\rho < \delta_2$, the fault is an internal fault. If $\rho > \delta_2$, turn step 4).
- 4) Other methods are used to identify internal and external faults.

IV. SIMULATION AND SCHEME RESPONSE EVALUATION

The structure of simulation system is shown in Fig. 3. The parameters of source and transmission line are given in Appendix. Relays are located at two sides of lines. The sampling rate is 50k Hz. FFT is used to compute current spectrums. The values of δ_1 , δ_2 are 100A, 0.7 respectively. The current signals from each ends of transmission lines are determined using PSCAD/EMTDC simulation environment.

MN 500kV line ground fault in three typical fault positions (outlet, middle and end of line MN) were considered respectively to evaluate the influence of fault position for protection scheme. Table I shows ρ of line MP and PN when A-B-short occurs in different points.

Figure VI shows the spectrum of relay 1~4 when fault is at outlet of bus M. It can be seen that the spectrum of relay 1 and 2 are different, the spectrum of relay 1 and 2 is the same.

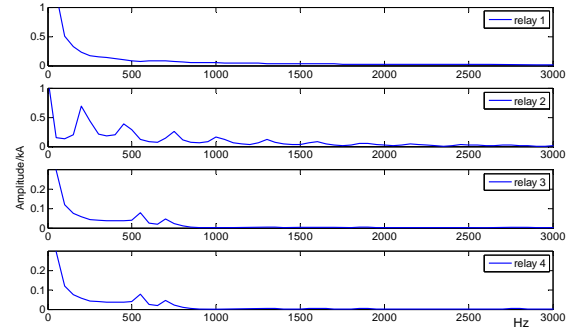


FIGURE VI. CURRENT SPECTRUMS OF NATURAL FREQUENCY COMPONENT OF RELAY 1~4

Table I shows the spectrum correlation coefficients according (20), it can be seen that it is near to 1 for external faults. When faults are near two sides of line MN, spectrum correlation coefficients are much smaller than 1. Obviously the scheme can identify internal fault nearby bus.

TABLE I. SPECTRUM CORRELATION COEFFICIENTS OF FAULT PHASE WHEN GROUND FAULTS IN DIFFERENT FAULT LOCATIONS

Fault Location	$\rho(\text{MN})$	$\rho(\text{MP})$
Outlet of MN	0.08067	0.998
Middle of MN	0.98	1
End of MN	0.06776	0.998

When a fault is in the middle point of transmission line MN, natural frequencies on two sides of fault point are similar, ρ is near to 1. But the current polarities of relay 1 and 2 are the same and the current polarities of relay 3 and 4 are different (shown in Figure VII). So the scheme can identify faults of MMC-HVDC line.

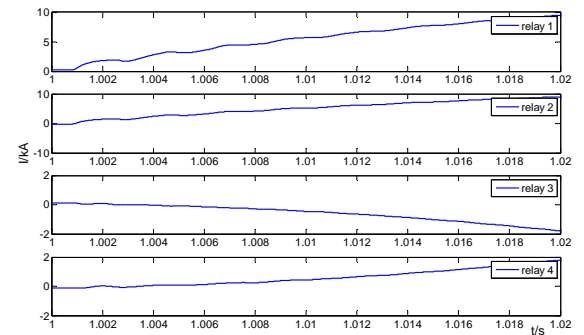


FIGURE VII. CURRENT OF RELAY 1~4 WHEN THE FAULT IS AT MIDDLE OF LINE MN

V. APPENDIX

The system is a $\pm 500\text{kV}$ transmission lines.

	S4	S3	S1	S2
Max Power DC/MW	3000	3000	1500	1500
Module capacitance /mF	15	15	10	10
Module Number	240	240	240	240

Transmission line parameters (Bergeron Model):

MN=500km, NQ=500km, MP=180km, PQ=500km,
 $R_1=0.00758\Omega/\text{km}$, $X_1=0.26365\Omega/\text{km}$, $C_1=0.01397\mu\text{F}/\text{km}$,
 $R_0=0.15421\Omega/\text{km}$, $X_0=0.8306\Omega/\text{km}$, $C_0=0.009296\mu\text{F}/\text{km}$.

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