TELKOMNIKA, Vol.12, No.4, December 2014, pp. 753~762
ISSN: 1693-6930, accredited A by DIKTI, Decree No: 58/DIKTI/Kep/2013
DOI: 10.12928/TELKOMNIKA.v12i4.300

Spectrum Comparative Study of Commutation Failure and Short-Circuit Fault in UHVDC Transmission System

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Abstract

When commutation failure occurs in UHVDC transmission system, the transient process of DC voltage and current are similar to grounding short-circuit fault. In order to differentiate them effectively, the paper introduces mathematical morphology methods to analysis the spectrum of transient current. Base on Yunnan-Guangzhou ± 800 *kV UHVDC transmission system, the paper simulates the commutation failure and DC line short-circuit fault under different fault conditions in PSCAD/EMTDC. By modified morphology filter, the transient signal of DC (* I_d *) is decomposed into six scales, and morphological characteristics of aerial mode component of* I_d *is analyzed under different scales. The simulation results show that when DC line short-circuit faults occurs, wherever in the rectifier side, in the DC transmission line midpoint or in the inverter side, the aerial mode component of* I_d *have more high frequency weight in* $d_1 \sim d_5$ *and decays gradually; When commutation failures, which are caused by the inverter side AC system single-phase grounding fault, phase to phase fault, three phase grounding fault or the inverter side transformer ratio increased, the aerial mode component of* I_d *have less frequency weight in* d_6*.*

Keywords*: UHVDC, commutation failure, DC line short circuit fault, PSCAD/EMTDC, morphology*

1. Introduction

Commutation failure is one of the highest probable failures in UHVDC transmission system [1].When commutation failure occurs, it will cause DC voltage sharply declining and DC current suddenly increasing which will seriously affect the power quality of DC transmission system [2] and may cause the incorrect operation of relay protection equipments in AC system [3],[4]. Grounding short-circuit fault in DC transmission system has similar DC voltage and DC current transient characteristics compare with commutation failure. Therefore, it is great significance to the safe and stable operation of UHVDC transmission system [5] to distinguish commutation failure and DC line short-circuit fault is of great importance.

At present, the traditional discriminating methods of commutation failure include the minimum voltage drop method, the minimum arc angle criterion method, etc [6]-[8]. Nonetheless, these methods take many factors into account and can't distinguish commutation failure from DC line short circuit [9]. By using MATLAB/Simulink, reference [10] emulates 500kV HVDC transmission system and decomposes the DC current into six scales by wavelet multi-scale analysis. The experiment results point that the DC current has more high frequency divisions in DC line short circuit fault and more low frequency divisions in commutation failure.

In recent years, mathematical morphology has been widely applied in power quality detection, singular point detection, harmonic analysis of transient signal, fault diagnostic, relay protection and fault location, etc [11]. When processing multi-scale of signals, mathematical morphology decomposes signals in time domain, which can make up for deficiencies that Fourier transform can't fully describe time variant non stationary signal [12],[13] and avoid the phase shift and amplitude attenuation problem [14]-[16]. This paper simulates commutation failure and DC line short circuit fault under different fault conditions based on Yunnan-Guangdong $\pm 800\text{kV}$ UHVDC transmission system in PSCAD/EMTDC the electromagnetic simulation software. The aerial mode component of the DC current transient signal I_d is decomposed into six scales of divisions with the modified morphological filter. The morphological characteristics under different frequencies of the aerial mode component of I_d in

Received August 27, 2014; Revised October 12, 2014; Accepted October 25, 2014

the two kinds of faults are studied, which will give the theory to distinguish between commutation failure and DC line short circuit fault.

2. Mathematical Morphology Basic Theory

2.1. The Basic Operations of Mathematical Morphology

Erosion and dilation are the two basic morphological operations in mathematical morphology Corrosion and expansion. The operations are equivalent to filter minimum and maximum value within structuring element of one dimensional discrete signal. In one-dimensional signals, erosion is used to suppress the positive pulse signal and keep the negative pulse signal. In contrast, dilation is used to suppress the negative pulse signal and keep the positive pulse signal. Let $f(n)$ as one-dimensional sampling signal, $g(n)$ as one dimensional structuring element, D_f is the definition domain of $f(n)$ and D_g is the definition domain of $g(n)$. The signal of the erosion and the dilation computing formula with structural elements are respectively shown in formula (1) and formula (2).

$$(f \ominus g)(n) = min[f(n+m) - g(m)] \quad (1)$$

$$(f \oplus g)(n) = max[f(n+m) + g(m)] \quad (2)$$

Where, $n+m \in D_f$, and $m \in D_g$.

It can create a variety of operations to combine corrosion and dilation. The opening operation is that first to compute erosion and then to dilation, as shown in formula (3). As well as, the closing operation is that first to compute dilation and then to erosion, as shown in formula (4).

$$(f \circ g)(n) = ((f \ominus g) \oplus g)(n) \quad (3)$$

$$(f \bullet g)(n) = ((f \oplus g) \ominus g)(n) \quad (4)$$

2.2. The Selection of Structural Element

The shape and length of structuring element have great affect on the results of signal processing [17]. Nevertheless, Similar to wavelet analysis selecting basis function, there is no special principle that can be obeyed to when selection proper shape for structuring element which is. That is what kind of structure elements is suitable for processing the signal, it needs to test and prove again and again [18]. Linear, flat structuring elements, square, round, semicircle, etc are often used to process the power system electrical signals. And the more complex the shape is, the greater the amount of computation will be. The length of the structuring element is important in determining the filtering characteristics. In general, the short structuring element is used to capture high frequency and the morphological filter is used to filter out high frequency noise and smooth signal. Long structuring element has good low-pass performance, but it takes longer time. Therefore, in determining the shape and length of structuring element, signal feature, target and computational complexity should all be taken into account.

2.3. Multi-Scale Morphological Operations

Multi-scale morphological operation is a rough to fine signal hierarchical process to do several erosion or dilation operations on signal using structure elements of different size. For signal $f(n)$ and the structural element $g(n)$, if *F* is the morphological transform, the multi-scale morphological operation $\{F_i \mid i > 0\}$ based on F can be defined as in formula (5).

$$F_i(f) = iF(f / i) \quad (5)$$

By the same token, the multi-scale opening and closing operations are as shown in formula (6) and formula (7).

$$(f \circ ig)(n) = ((f \ominus ig) \oplus ig)(n) \tag{6}$$

$$(f \bullet ig)(n) = ((f \oplus ig) \ominus ig)(n) \tag{7}$$

2.4. The Construction of A Morphological Filter

Signal decomposition is actually a process of multi filtering on original signal. The opening and the closing operation of morphology have low-pass characteristic and can be cascaded to compose open-closing filter and close-opening filter. Because the output amplitude of open-closing filter is larger and the output amplitude of close-opening filter is smaller, average combination of two kinds of filter is usually adopted as shown in [19] and formula (8).

$$h_i = [(f \circ g \bullet g)(n) + (f \bullet g \circ g)(n)] / 2 \tag{8}$$

In the filtering process, structuring elements are like filter windows. Only when the shape of structural elements is match with the shape of signal, will the original signal be retained or extracted. And when the type of structural element is the same and the size differs, the filtering effect is not the same.

In this paper, the wave shape of electric signal is too complex to be analyzed using filter shown in formula (8). So, considering the electrical signal characteristic, the paper uses the improved filter shown in formula (9) instead.

$$\begin{cases} y_1 = f \ominus g_i \oplus g_{i+1} \oplus g_{i+2} \ominus g_{i+3} \\ y_2 = f \oplus g_{i+4} \ominus g_{i+5} \ominus g_{i+6} \oplus g_{i+7} \\ h_i = (y_1 + y_2)/2 \\ i = 1,2,\cdots,N \\ G_i = \{g_i, g_{i+1}, \cdots, g_{i+7}\} \end{cases} \tag{9}$$

Where, y_1 is the result of open-closing operation; y_2 is the result of close-opening operation; G_i is assemble of structural element of i-th scale.

2.5. Multi-Scale Morphological Decomposition Algorithm

If $d_i(n)$ is the decomposition shape of the i-th scale signal, multi-scale morphological algorithms are as shown in formula (10) and formula (11).

$$\begin{cases} d_1(n) = f(n) - h_1 \\ d_{i+1}(n) = h_i - h_{i+1} \\ d_N(n) = h_{N-1} \\ 1 \le i \le N-2 \end{cases} \tag{10}$$

$$f(n) = \sum_{i=1}^{N} d_i(n) \tag{11}$$

3. Spectrum Analysis of The Fault Based on The Multi-Scale Morphology Decomposition

3.1. UHVDC Simulation Model

This paper uses PSCAD/EMTDC to create a simulation model based Yunnan-Guangdong $\pm 800\text{kV}$ UHVDC transmission system as shown in Figure 1. Its nominal voltage is 800 kV. Nominal current is 3.125kA. Total installed capacity is 5000MW and the total length of transmission line is 1418 km.

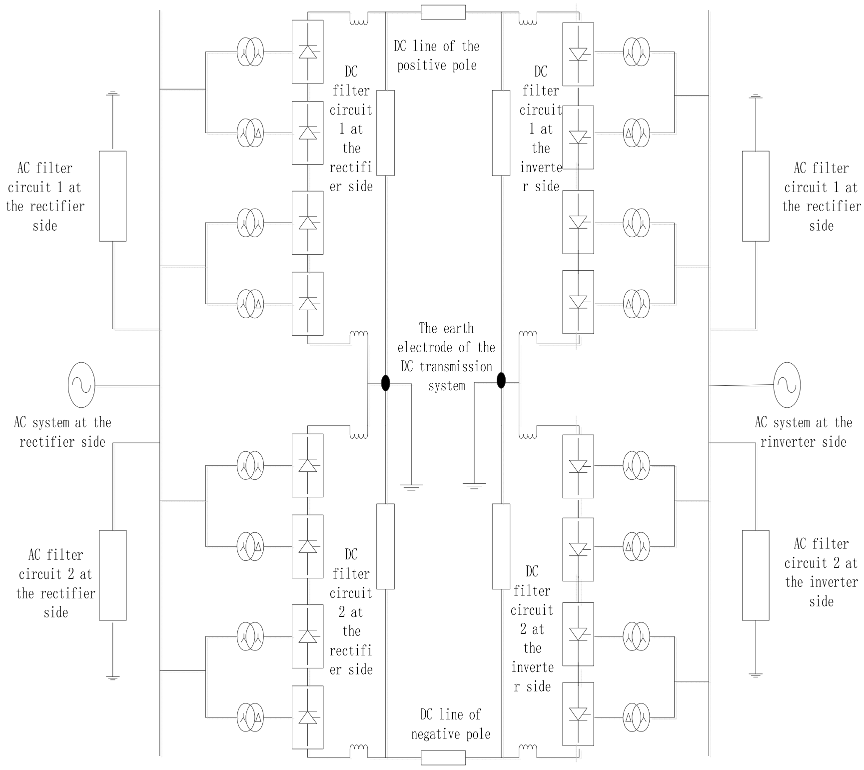


Figure 1. $\pm 800\text{kV}$ simulation model of Yunnan-Guangdong UHVDC system

Simulate DC line short circuit fault and commutation failure based on the system shown in Figure 1. The following failures are mainly considered. Direct grounding short circuit fault happening in the positive transmission lines with fault point located in the rectifier side, midpoint, the inverter side respectively; Commutation failure fault is caused by single-phase grounding fault with fault switching angle of 270° in the inverter side AC system; Commutation failure fault is caused by phase to phase shorting fault with fault switching angle of 270° in the inverter side AC system; Commutation failure fault is caused by three phase grounding fault in the inverter side AC system; Commutation failure is caused by the larger transformation ratio of inverter side converter transformer.

In this article, the selected electric parameter is DC current I_d (p.u.)of the inverter side. I_d is decomposed by mode decomposition. The aerial mode component of I_d is the analyzed data. The sampling frequency is 200KHz.The sampling time length is 100ms (5 periodic waves).

3.2. Morphological Decomposition Steps

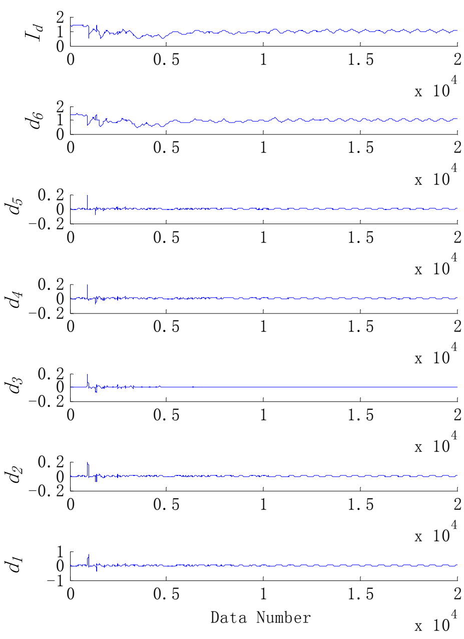
The aerial mode component of DC current under all kinds of fault conditions is decomposed by morphological decomposition. Power system of electric signal has a lot of noise which has a great deal of uncertainty. The amplitude of flat structuring element is 0. Its structure is simple and will not modify the amplitude of original signal. It is more accurately to extract the morphological characteristics of signal compared with the structure of non-zero element [20]. So, choosing flat structuring elements on signal process is a good method to get ideal filtering effect. Choose flat structuring element $g_1 = [0\ 0\ 0]$ as the unit of structuring element. Calculate structuring element assembles of various scales according to formula $R = (r-1) \times k + 1$[21]. The steps of 6 scales morphological decomposition of the aerial mode component of DC current signal I_d under different fault conditions are as follows.

(1) Decompose inverter side DC current I_d (p.u.) based on morphological decomposition. And extract the aerial mode component of I_d .

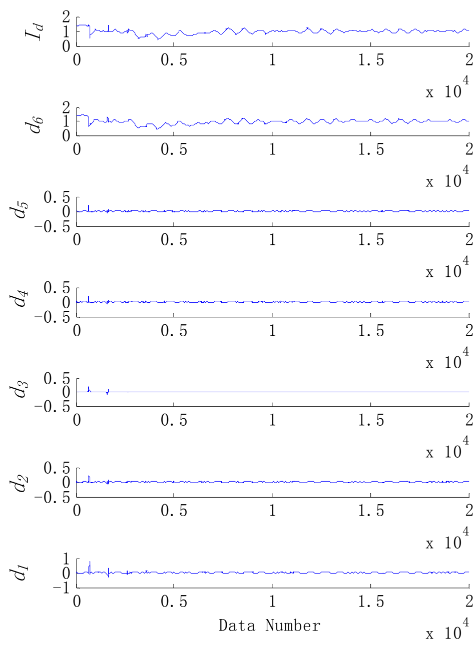
(2) Calculate structure element assemble under different scales.
(3) According to formula (10), calculate filtering output h_i of the aerial mode component of DC current signal I_d under different scales.
(4) According to step (2), calculate filtering output under scale *i*=1,2,3, ...,5. The detail component under different scale $d_1 \sim d_5$ and the approximation d_6 of the sixth scale can be calculated according to formula (10).

3.3. Multi-Scale Morphological Decomposition Spectrum Analysis Form

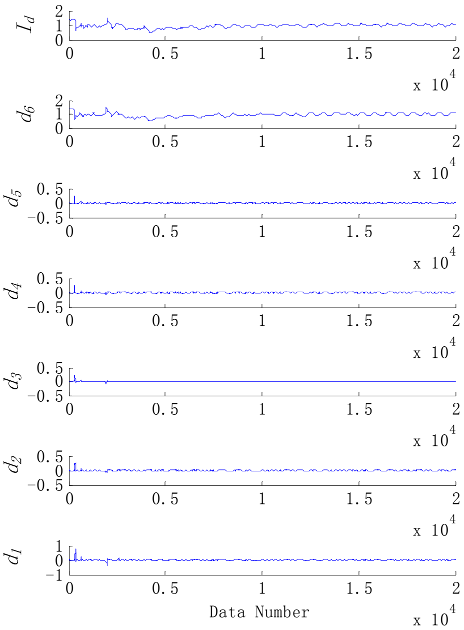
DC line short circuit fault happens on transmission line at 300km, 700 km, 1200 km at 0.3s and lasts for 100ms.The morphological decompositions of the aerial mode component of I_d under different scales are shown in Figure 2(a),(b),(c). Three phase grounding fault in the inverter side AC system happens at 0.3s and lasts for 100ms. The morphological decompositions of the aerial mode component of I_d under different scales are shown in 3(a). The phase to phase shorting fault with fault switching angle of 270 ° happens on the inverter side AC system and lasts for 100ms.The morphological decompositions of the aerial mode component of I_d under different scales are shown in 3(b). The single phase grounding fault with switching angle of 270 ° happens on the inverter side AC system and lasts for 100ms.The morphological decompositions of the aerial mode component of I_d under different scales are shown in 3(c). Increase the transformation ratio of the inverter side transformer to 3.5 that leads to the commutation failure. The morphological decompositions of the aerial mode component of I_d under different scales are shown in Figure 3(d).



(a) DC line direct grounding short circuit fault at 300km

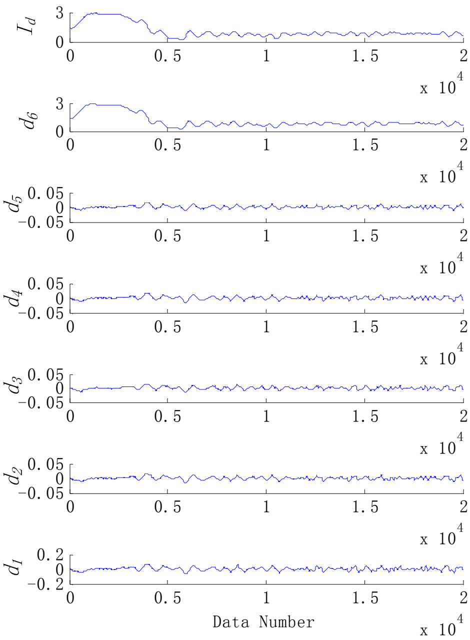


(b) DC line direct grounding short circuit fault at 700km

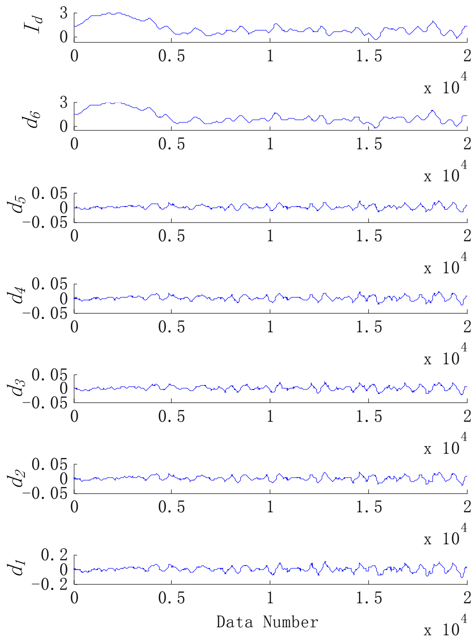


(c) DC line direct grounding short circuit fault at 1200km

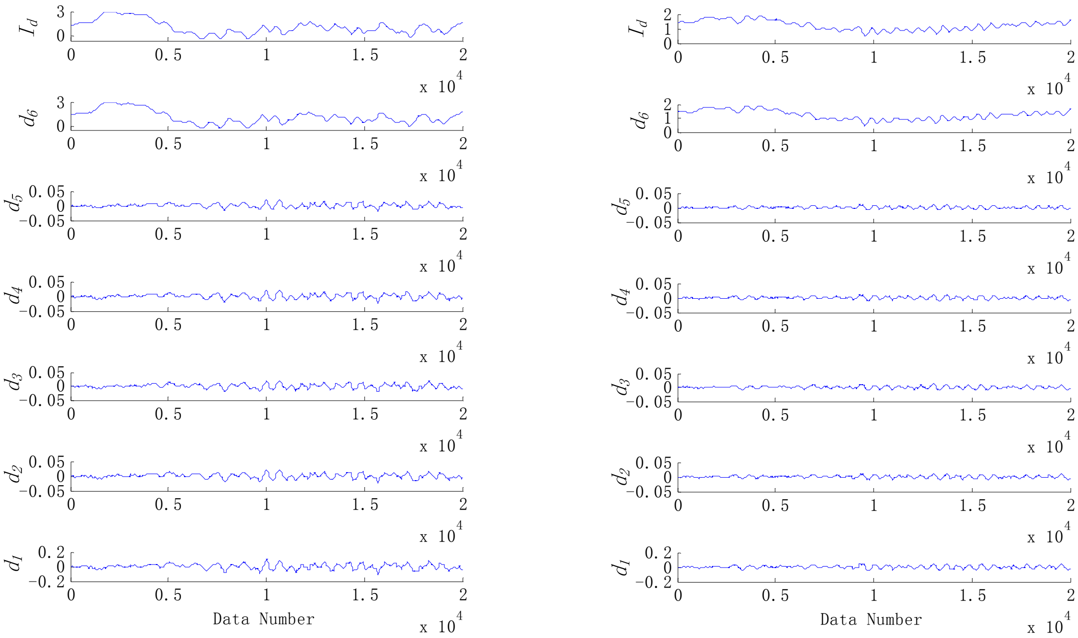
Figure 2. Multi-scale morphology decomposition for the aerial mode component of I_d of DC line short circuit faults



(a) Three phase grounding fault in the inverter side AC system



(b) Phase to phase shorting fault in the inverter side AC system

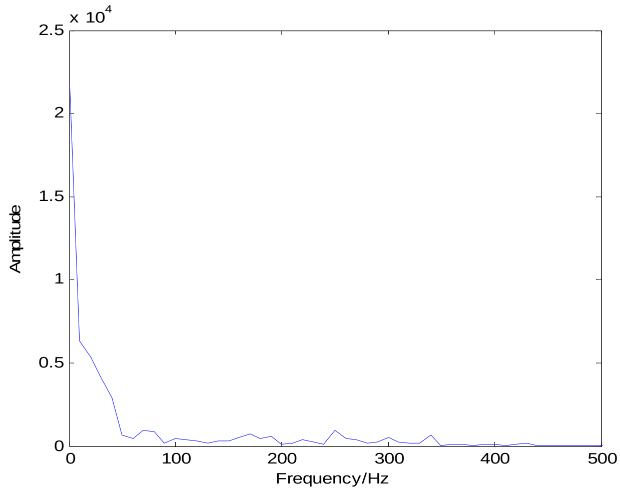


(c) Single-phase grounding fault in the inverter side AC system

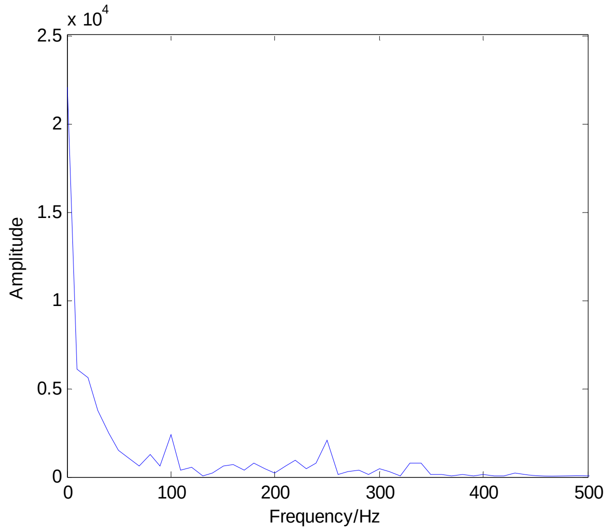
(d) Inverter side converter transformer ratio of 3.5

Figure 3. Multi-scale morphology decomposition for the aerial mode component of I_d of commutation failure

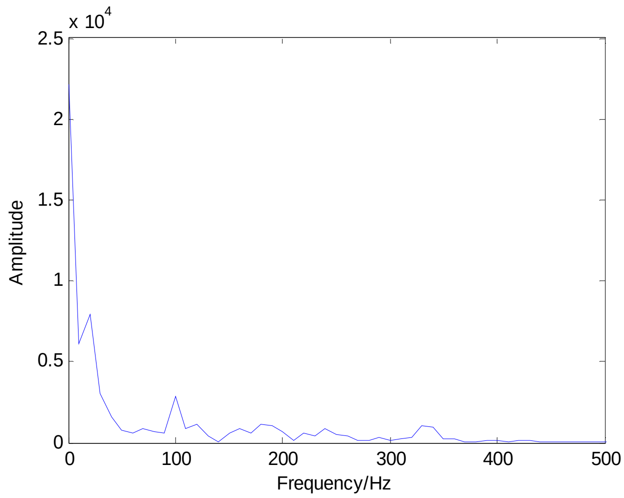
As is shown in Figure 2 and Figure 3, under different fault conditions, the high frequency component on the same scale of the aerial mode component of I_d in the DC line short circuit fault and the commutation failure has different changing trends. When the DC line short circuit fault occurs in different position, the high frequency component of the aerial mode component of I_d during the fault duration is rich, and gradually decreases. Furthermore, the more the DC line short circuit close to the inverter, the greater the change frequency of high frequency component, and the bigger the amplitude increases. In Figure 3, when the commutation failure occurs caused by different fault conditions, the change characteristics of the high frequency component $d_1 \sim d_5$ of the aerial mode component of I_d is very different with of the DC line short circuit fault.. Whereas in Figure 3(a),(b),(c),(d), the low frequency change characteristics in d_6 of the aerial mode component of I_d all are obvious. The morphological spectrum of the sixth scale is analyzed using Fourier transform. As is shown in Figure 4, 0Hz~100Hz in frequency range in d_6 of the aerial mode component of I_d is richer.



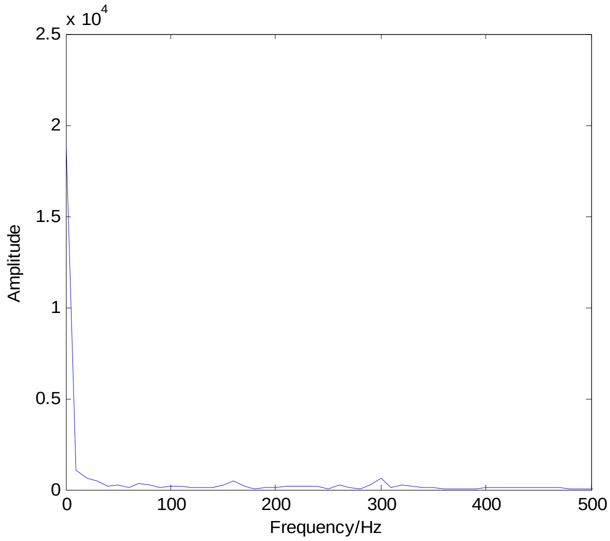
(a) Three phase grounding fault in the inverter side AC system



(b) Phase to phase shorting fault in the inverter side AC system



(c) Single phase grounding fault in the inverter side AC system



(d) Inverter side converter transformer ratio of 3.5

Figure 4. FFT spectrum of sixth scale morphological spectrum of the aerial mode component of I_d

4. Conclusion

This paper simulates commutation failure and short circuit fault in PSCAD/EMTDC based on the model of Yunnan-Guangzhou $\pm 800\text{kV}$ UHVDC transmission system. The fault points of DC line grounding short circuit faults are located at 300km, 700km, 1200km of the positive transmission lines. Simulate commutation failures caused by three phase grounding fault, single-phase grounding fault, phase to phase shorting fault in the inverter side AC system and increasing transformation ratio of inverter side transformer to 3.5. Extract the transient signal of inverter side DC. Then decompose the aerial mode component of I_d into 6 different scales. At last, analyze the high frequency features of $d_1 \sim d_5$ and low frequency features of d_6 in the two kinds of fault cases. The analysis results show that the aerial mode component of I_d has more high frequency component in $d_1 \sim d_5$ in the case of short circuit fault. While in the case of commutation failure the aerial mode component has less frequency divisions in d_6.

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