The Traveling Wave Protection of HVDC Based on HHT Conversion

Yunhai Hou*, Shuhan Zhang and Haoxin Sun
School of Electrical & Electric Engineering, Changchun University of Technology, Changchun 130012, Jilin Province, China

*Corresponding author email: houyunhai@ccut.edu.cn

Abstract. It is significant to the whole system or its connected network and to run safely and steadily by detecting and cutting out faults fast and accurately. In this paper, a new transient signal analysis method is got based on the Hilbert-Huang Transform conversion. It’s original is that by making simulation on interior and external district of direct current through HVDC transmission model, and using MATLAB to analyze transient voltage signal on every fault, and then a protection project of high voltage direct transmission line is proposed based on HHT. The simulation results show that the scheme overcomes the inherent defects of the traditional algorithm, and makes up for the shortage that the protection is easily affected by the transition resistance and can not be accurately judged when the ground fault occurs, which effectively improves the detection accuracy and speed of the line protection.

Keywords: HVDC; HHT conversion; Traveling wave protection; Transient voltage.

1. Introduction
In recent years, HVDC has been greatly developed in the whole country [1]. However, due to the high voltage level, large transmission capacity, long transmission distance, and the complex and changeable regional environment, the probability of DC line failure is greatly increased [2]. According to the operation data of the domestic and foreign DC transmission projects, the line fault accounts for about 50% of the operation fault of the system [3]. After most of the DC lines fail, the DC control system responds and acts, which is easy to cause DC blocking and unnecessary DC outage. This will not only affect the operation of the system, but also threaten the normal operation of the power grid or even the whole power grid [4]. Therefore, how to improve the safety and stability of HVDC system should be the first problem to be solved.

2. Analysis of Fault Characteristics of HVDC Transmission Lines
The inherent filtering characteristics of smoothing reactor and DC filter are mainly used to distinguish faults in and out of the region. In Figure 1, the dotted line frame contains DC filter, L is smoothing reactor, additional voltage for AC side fault, and DC voltage at DC side. The smoothing reactor and DC filter are regarded as a whole, It is called the physical boundary inside and outside the zone, and the transfer function is defined as :

\[ L(j\omega) = \frac{U_1}{U_2} = \frac{Z_1(j\omega)}{Z_1(j\omega) + Z_2(j\omega)} \]  

Formula \( Z_1(j\omega) \) is DC filter impedance; \( Z_2(j\omega) \) is smoothing reactor impedance.
As can be seen from Figure 2, the boundary element composed of smoothing reactor and DC filter can be regarded as a high-frequency wave arrester. When the DC line goes out, the high frequency collected by the recording device in the area is very small; but when the DC line goes out in the area, it has a large high frequency component.

3. A Protection Scheme Based on HHT Transformation

3.1. Instantaneous Frequency

The instantaneous frequency represents the transient frequency characteristics of the signal at local time points. The instantaneous frequency of the whole duration reflects the time-varying law of the signal frequency [5].

For random time series \( X(t) \), After Hilbert transformation, we can get the following results:

\[
Y(t) = \int_{-\infty}^{\infty} X(\tau) h(t - \tau) \, d\tau = \frac{1}{\pi} \int_{-\infty}^{\infty} X(\tau) \, d\tau
\]

By this definition, \( X(t) \) and \( Y(t) \) form a conjugate complex pair, so an analytic signal \( Z(T) \) can be obtained, shown as formula 3..

\[
Z(t) = X(t) + jY(t) = a(t)e^{j\theta}
\]

Among

\[
\begin{align*}
\alpha(t) &= \left[ X^2(t) + Y^2(t) \right]^{1/2} \\
\theta(t) &= \arctan\left( \frac{Y(t)}{X(t)} \right)
\end{align*}
\]

Then instantaneous frequency:

\[
f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt}
\]

3.2. Empirical Mode Decomposition

(1) Natural mode function

The function of EMD is to decompose complex signals into finite intrinsic mode functions (IMF), so that the instantaneous frequency of Hilbert transform has practical physical significance. The IMF
meets the following two conditions [6]:
① In a range of data, the number of extreme points and zero crossing points is equal or one difference;
② At any point, the average value of the envelope formed by all maximum points and all minimum points is zero.

(2) Decomposition process of EMD
① Set the average value of upper envelope \( x_{\text{max}}(t) \) and lower envelope \( x_{\text{min}}(t) \) of signal \( x(t) \) as \( m_1(t) \);
② The first component \( c_1(t) = x(t) - m_1(t) \) is obtained by subtracting the mean value \( m_1(t) \) from the original signal \( x(t) \). If the two conditions of IMF are met by \( c_1(t) \), then \( c_1(t) \) is the first IMF. If not, then \( c_1(t) \) is regarded as the original signal and steps ① and ② are repeated until the conditions are met. The specific process of EMD decomposition is detailed in literature [7].

It can be obtained:
\[
x(t) = \sum_{k=1}^{n} c_k(t) + r_k(t)
\]  
\hspace{1cm} (6)

3.3. Hilbert Spectrum and Marginal Spectrum
Hilbert transform is applied to each IMF component, then [8]:
\[
h_k = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{X(\delta)}{t - \delta} d\delta
\]  
\hspace{1cm} (7)
The analytical signal can be obtained:
\[
z_k = c_k(t) + jh_k(t) = a_k(t)e^{j\phi_k t}
\]  
\hspace{1cm} (8)
Then another expression can be obtained:
\[
x(t) = \text{Re} \sum_{k=1}^{n} c_k(t)e^{j\phi_k dt}
\]  
\hspace{1cm} (9)
In the above formula, the distribution of signal amplitude with time-frequency is called Hilbert spectrum \( H(\omega, t) \)
\[
H(\omega, t) = \text{Re} \sum_{k=1}^{n} c_k(t)e^{j\phi_k dt}
\]  
\hspace{1cm} (10)
Hilbert instantaneous energy [9]
\[
IE(t) = \int H^2(\omega, t) d\omega
\]  
\hspace{1cm} (11)
Then Hilbert energy spectrum:
\[
HE = \int_{t_1}^{t_2} IE(t) dt
\]  
\hspace{1cm} (12)

3.4. Traveling Wave Protection Criterion Based on HHT Energy Spectrum
From the perspective of signal Hilbert energy, the Hilbert energy value of transient signal in the area of fault will be significantly greater than that in the area of fault, so this paper proposes the following criteria for HVDC transmission line protection: if the Hilbert energy value of the collected transient signal of transmission line fault is greater than the set value, namely [10]:
\[
HE > K_{set}
\]  
\hspace{1cm} (13)
Determine the fault in the area where the DC transmission line occurs; when the Hilbert energy value of the collected fault signal is less than the set value, namely:

\[ HE < K_{set} \]  \hspace{1cm} (14)

It is considered that DC transmission line has out of area fault. See Figure.3 for specific protection scheme.

4. Simulation Analysis

4.1. Simulation Model

Using the electromagnetic transient simulation software PSCAD / EMTDC, the single pole 12 pulse HVDC system model is established, as shown in Figure 3.

![Simulation model of HVDC system.](image)

The main parameters of the system model are as follows: DC rated voltage class is 500kV, transmission capacity is 1000MW, transformation ratio of converter transformer is 213.46kv/345kV, capacity is 603.73MVA, total length of DC transmission line is 1200km, adapting frequency-Dependent Line Model.

4.2. Simulation Analysis

Simulation time is 1s, simulation step length, and various simulation fault types are as follows:

1. Ground fault at 20% distance between F1 transmission line and rectifier side;
2. Ground fault 50% in the middle of F2 transmission line;
3. Ground fault at 80% of rectifier side of F3 transmission line;
4. Ground fault at DC outlet of F4 inverter;
5. F5 rectifier side AC bus single-phase ground short circuit;
6. Short circuit of AC AB two phase bus at F6 inverter side.

During simulation, the time of fault occurrence is set at 0.43s, and the simulation waveforms of various fault types are as follows:

![Instantaneous energy spectrum of fault voltage signal of F1 fault voltage signal.](image)
Figure 5. Instantaneous energy spectrum of F2 fault voltage signal.

Figure 6. Instantaneous energy spectrum of F3 fault voltage signal.

Figure 7. Instantaneous energy spectrum of F4 fault voltage signal.

Figure 8. Instantaneous energy spectrum of F5 fault voltage signal.
Figure 9. Instantaneous energy spectrum of F6 fault voltage signal.

Fig.4, 5 and 6 are the instantaneous energy spectrum of the fault voltage signal in the area, fig.7, 8 and 9 are the instantaneous energy spectrum of the fault voltage signal out of the area. For the instantaneous energy spectrum of the voltage signal in different fault positions, use formula 12 to calculate the corresponding Hilbert energy $E$ (refer to energy spectrum), and the total Hilbert energy of the fault signal can be obtained, as shown in Table 1:

| Fault location | Regional fault | Out of zone fault |
|----------------|----------------|------------------|
| Energy $E$     | F1             | F2               |
|                | 23.3278        | 28.6837          |
|                | F3             | 52.3695          |
|                | F4             | 10.6251          |
|                | F5             | 7.8452           |
|                | F6             | 6.1368           |

From Table 1, it can be seen that the Hilbert energy of faults in the area is much larger than that of faults outside the area. After comparing the fault simulation and the value calculation at the end of DC line with that at the outlet of DC side of converter, and considering certain margin, this paper determines that the threshold $K_{set}$ in formula 13 and formula 14 is 12. A large number of simulation tests show that the threshold $K_{set}$ of 12 in the protection criterion can meet the correct identification of all internal and external faults, so as to ensure the correct operation of DC line protection. In the simulation, F4 is the fault at the DC outlet of the inverter, which can still be identified accurately by the protection criterion proposed in this paper, so the protection scheme should be very effective for the fault identification in and out of the HVDC line area.

4.3. Influence of Grounding Impedance on Protection

The transition resistance increases by $100\Omega$ from 0 to $300\Omega$, and a lot of simulation experiments are carried out for different faults set above. The measured data is shown in Table 2.

| Transition resistance | F1     | F2     | F3     | F4     | F5     | F6     |
|-----------------------|--------|--------|--------|--------|--------|--------|
| 0.1$\Omega$           | 23.3278| 28.6837| 52.3695| 10.6251| 7.8452 | 6.1368 |
| 100$\Omega$           | 20.6788| 26.8244| 47.3219| 9.2416 | 6.5868 | 5.1256 |
| 200$\Omega$           | 18.6245| 23.6931| 42.3927| 7.0796 | 5.3273 | 4.5231 |
| 300$\Omega$           | 17.6452| 21.7683| 38.2216| 5.7542 | 4.2639 | 3.7283 |

From the data in Table 4.2, it can be concluded that the he value of the same fault decreases with the increase of the transition resistance, the he value of direct grounding is the largest, and the he value of 300 resistance grounding is the smallest. A large number of simulation results can show that the size of the transition resistance has little influence on the protection criterion proposed in this paper. The HVDC line protection scheme based on Hilbert energy value can correctly identify the internal and external faults and send out the correct protection action instructions.
5. Conclusion
Due to the physical boundary of DC filter and flat wave reactor on DC line, it is equivalent to the function of wave arrester and has great attenuation effect on high frequency components. There is a major difference in the high frequency signal energy between the internal and external faults of the DC line, so the criterion of DC line transient protection was established based on Hilbert energy is proposed. Set a Hilbert energy threshold value, and compare the Hilbert energy value of transient signal on the line with the threshold value to determine the fault in or out of the DC transmission line. The results of modeling and simulation show that when HVDC system fails, the protection scheme can accurately judge whether the DC line is in or out of the area fault, and it is not easily influenced by the value of grounding resistance, fault location and type.

References
[1] Zhao Wanjun. HVDC transmission and transformation engineering technology [M]. Beijing: China Electric Power Press, 2010
[2] Yang Mingyu, Tan Shuping, Zhang Ju. Transient traveling wave directional protection scheme based on mathematical morphology. North China Electric Power UniversityNewspaper, 2006, 33 (6): 1-5
[3] Dong Xingli, Dong Xinzhou, Zhang cangyan, et al. Study on the principle of traveling wave polarity comparative directional protection based on Wavelet Transfor[J] , power system automation, 2000, 25 (7): 11-21
[4] Zhang Ju, Zhang Xiaodong, Lin Tao. Traveling wave current polarity comparative directional protection based on wavelet transform [J], grid technology,2004, 28 (4) :51-54
[5] Wang Gang, Li zhikeng, Li Haifeng. Transient protection of ± 800kV UHV DC line [J]. Power system automation, 2007, 31 (27): 40-43
[6] Norden E. Huang, Z. Shen, S. R. Long, et al. The empirical mode decomposition andHilbert spectrum for nonlinear and non-stationary time series analysis[J]. Proc. Roy. Soc.London A, 1998, Vol. 454, pp. 903-995.
[7] Li Tianyun, Zhao Yan, Li Nan. Application of Hilbert transform based on EMD to transient signal analysis. Power system automation, 2005,29 (4): 49-52
[8] Sun Shujie. HVDC system simulation and transmission line traveling wave protection scheme [D]. Shanghai: Master Thesis of Shanghai Jiaotong University, 2008
[9] Li Aimin, Cai Zexiang, Li Xiaohua, et al. Analysis and improvement of influence factors of traveling wave protection for HVDC transmission lines [J]. Power system automation, 2010, 34 (10): 76-80
[10] Li Aimin, Cai Zexiang, Li Xiaohua. Analysis of traveling wave propagation characteristics of DC lines [J]. Chinese Journal of electrical engineering, 2010, 30 (25): 94-99