Detection method of voltage sag disturbance based on improved HHT

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Abstract. In order to improve the detection accuracy of Hilbert Huang transform (HHT) for voltage sag signal, an improved HHT method is proposed: the boundary local feature scale method is combined with CEEMDAN, the former is used to suppress the end effect in the EMD process, and the latter is used to improve the mode aliasing between IMF components. The simulation results show that the improved method can extract the instantaneous characteristics of the disturbance signal more accurately and quickly, and realize the accurate positioning of the start and end moments of the sag. Finally, the measured data is used to compare the traditional HHT and the improved HHT method. The results show that the improved HHT method improves the detection accuracy of the sag signal, and has certain reference value for the study of voltage sag feature extraction.

1. Introduction

1.1 Research status of HHT and voltage sag
In 1998, Norden E. Huang et al.[1] proposed Empirical Mode Decomposition (EMD) and combined with Hilbert Transform (HT) theory to form HHT. Because of its good adaptability to nonlinear and non-stationary signals, since the advent of the method, it has been widely used in disturbance signal detection[2], and also used in power grid fault diagnosis[3], load and power prediction[4], etc.

Voltage sag is a kind of common fault in power system, which accounts for a high proportion in common faults. It is a kind of power quality problem threatening the safe and stable operation of power system.

1.2 Purpose and Meaning
The detection method of voltage sag has always been the research focus of voltage sag events. The HHT method is also used to detect the voltage sag and extract the corresponding features due to its sensitivity to the abrupt signal. However, due to the problem of HHT algorithm itself, the EMD decomposition results will have certain endpoint effect, and there is a certain degree of modal aliasing between IMF components, which will affect the accuracy of feature detection.

In order to improve the endpoint effect in the detection process, suppress the error caused by mode aliasing, and improve the detection accuracy of HHT method for voltage sag, this paper will improve the traditional HHT, and use the improved method to extract the characteristics of complex sag and measured data.
2. Materials and Methods

2.1 HHT theory and voltage sag detection

2.1.1 HHT theory

HHT is a method suitable for nonlinear and non-stationary signal analysis. It mainly includes two parts: HT and EMD. The method itself also has the problems of end effect and mode aliasing.

(1) HT

HT can effectively extract the instantaneous characteristics of the amplitude and phase of each IMF component in HHT, and form the HT spectrum of time-frequency distribution and the marginal spectrum of amplitude frequency composition. By analyzing the HHT spectrum, the time of frequency change can be located.

(2) EMD

EMD is the core of HHT theory. By assuming that the signal is composed of simple modes, the original signal is decomposed according to certain steps, and finally a series of IMF congruences with single component characteristics are formed. The specific implementation process is as follows:

(1) Firstly, all extremum points of the original signal are obtained, and the mean value is obtained according to the upper and lower envelope of the signal

\[ m_1(t) = \frac{x_{\text{up}}(t) + x_{\text{down}}(t)}{2}. \]

(2) The first suspected IMF component \( h_1(t) \) is constructed by subtracting \( m_1(t) \) from the original signal \( x(t) \). According to the criterion, we can judge whether it is IMF component or not.

\[ h_1(t) = x(t) - m_1(t). \quad (1) \]

(3) If \( h_1(t) \) component is IMF component, it is regarded as the first IMF component. If \( h_1(t) \) is not satisfied, \( h_1(t) \) is regarded as a new basis function. According to the above steps, the first IMF component \( h_n(t) \) is obtained.

\[ h_n(t) = x_{n,1}(t) - m_n(t). \quad (2) \]

(4) The residual component \( c_1(t) \) is obtained to judge whether the decomposition is terminated or not and to obtain other IMF components. If satisfied, the iteration is terminated,

\[ r_1(t) = x(t) - c_1(t). \quad (3) \]

If not, repeat the above steps \( m \) times until the termination conditions are met and the iteration is stopped.

\[ r_m(t) = x_{m,1}(t) - c_m(t). \quad (4) \]

(5) The signal is expressed as the sum of several IMF components and residual components.

\[ x(t) = \sum_{i=1}^{m} c_i(t) + r_m(t). \quad (5) \]

After layer by layer screening, the mode components in the signal to be processed are extracted according to IMF definition. As in equation(5), the original signal can be reconstructed in the form of superposition after screening, so the original information of the signal can be saved, and the EMD process has good completeness.

2.1.2 Voltage sag detection process based on traditional HHT

The process of feature extraction of voltage sag using HHT is as follows: the amplitude feature is obtained according to the matrix corresponding to the amplitude curve. According to the absolute value difference of the adjacent extremum points in the time-frequency curve of Hilbert spectrum and the interval between the adjacent maxima and minima, the position of the abrupt point of the sag signal can be determined, and the start and end time of the sag can be obtained.
2.2 Methods to suppress end effects

2.2.1 End effect
In the process of EMD signal decomposition, because it is not sure whether the endpoint is the extreme point, there will be errors in the process of taking the extreme point at the end point for interpolation fitting, and with the continuous iteration of the decomposition process, the error will continue to increase, eventually resulting in the IMF component being distorted and losing its physical significance.

2.2.2 Extension method
There are many researches[6] on how to suppress the end effect, such as mirror extension[7], extremum extension, horizontal extension, polynomial fitting extension, adaptive waveform matching extension, boundary local feature scale extension[8], etc.

2.2.3 Comparison and screening of methods
The endpoint effect and mode aliasing of HHT make it have certain limitations in the detection of voltage sag disturbance signal. In order to make a better comparison and screen out a better method to decompose the abnormal component and apply to the detection of voltage sag disturbance signal, this paper will screen the above extension methods for the end effect through simulation. In the simulation process, the common abnormal components of power quality disturbance signals are analyzed, and a method is selected to suppress the end effect problem in voltage sag signal detection. At the same time, the influence of modal aliasing on the detection of disturbance signal is also considered.

3. Results & Discussion

3.1 Screening of methods to suppress end effects
Let a complex disturbance signal \( x(t) \)

\[
x(t) = x_1(t) + x_2(t)
\]

\[
x_1(t) = 1.3 \times \sin(2\pi \times 100t) \\
x_2(t) = [1 - 0.8 \times [u(t_1) - u(t_2)]] \times 0.7 \times \sin(2\pi \times 50t)
\]

The signal contains a harmonic interference signal component \( x_1(t) \) and a sag component \( x_2(t) \). The sag duration \( t_1 \) and \( t_2 \) are set to 0.2 ~ 0.4s, and the sag depth is set to 0.8.

The comparison diagram of IMF component and real component is obtained. From the graph, when the extreme value of signal endpoint is not processed, there is a large deviation at the end point. After extension processing, the obtained sag signal component and the actual component have higher coincidence degree and smaller error, and the effect of different extension methods is different.
Furthermore, the differences of different continuation methods in extracting sag signal components are compared and analyzed from the obtained IMF component number, similarity coefficient between components, root mean square error and program running time[9].

| IMFs          | Sc (ρ)         | RMSE(R)     | Time (s) |
|--------------|---------------|-------------|----------|
| No extension | 3             | 0.945 0.775 | 0.309 0.341 | 0.009    |
| Parallel extension | 6             | 0.992 0.830 | 0.116 0.253 | 0.051    |
| Mirror extension | 5             | 0.994 0.978 | 0.097 0.096 | 0.176    |
| Polynomial fitting extension | 6             | 0.986 0.929 | 0.155 0.159 | 0.177    |
| Adaptive waveform matching extension | 3             | 0.995 0.965 | 0.089 0.114 | 0.016    |
| ISBM extension | 7             | 0.994 0.982 | 0.097 0.092 | 0.029    |
| Extension method based on boundary local characteristic scale | 5             | 0.996 0.985 | 0.083 0.085 | 0.008    |
| Extremum extension | 14            | 0.992 0.963 | 0.114 0.111 | 3.807    |

It can be seen from the table 1 that the ISBM method and the adaptive waveform matching method have higher similarity coefficient and smaller root mean square error. The running time of the adaptive waveform matching method and the boundary local feature scale method is less than 0.03, and the operation speed is faster. To sum up, the boundary local feature scale method has better performance in suppressing the end effect, and the IMF component is less and the spectrum leakage is the least.

3.2 Improve HHT process
Considering the aliasing phenomenon in the traditional EMD decomposition process, based on the boundary local feature scale, the CEEMDAN[10] with better suppression effect is used to replace the EMD process. Therefore, an improved HHT method based on the combination of boundary feature scale method and CEEMDAN is proposed to extract the characteristics of voltage sag. The process is as follows:

1. The boundary local characteristic scale method is used to extend the voltage sag signal;
2. The processed signals are screened by CEEMDAN process;
3. The amplitude and frequency characteristics of IMF components are analyzed.
3.3 Case analysis

According to the mathematical model of voltage sag, the voltage sag simulation waveform is generated based on MATLAB simulation platform. According to the above process, the traditional HHT and the improved HHT are used to extract the characteristic values. A group of measured data is used to analyze and compare the two methods.

3.3.1 Voltage sag signal detection under complex disturbance

It is pointed out in reference that EMD still has certain accuracy in complex power quality disturbance analysis under harmonic interference[11]. In this paper, considering that the voltage level in the actual power system fluctuates with the load, and the fault types include steady-state and transient faults, so considering the presence of certain transient disturbance in the case of harmonic interference, the characteristic value of voltage sag is extracted.

Setting a complex disturbance signal $x(t)$

$$x(t) = x_1(t) + x_2(t) + x_3(t)$$

$$x_1(t) = \{1 - 0.8 \times [u(t_1) - u(t_2)]\} \times 15 \times \sin(2\pi \times f_1 \times t)$$

$$x_2(t) = 5 \times \sin(2\pi \times f_2 \times t)$$

$$x_3(t) = a_1 \times e^{-c(t-t_s) \times \sin(2\pi f_3 \times t) \times [u(t_{s1}) - u(t_{s2})]}$$

Where $x_1(t)$ signal component is the sag component with amplitude 15 and frequency of 50 Hz. The sag amplitude is set to 0.2, and the start and end time $t_1$ and $t_2$ are set to 0.25 s and 0.75 s respectively. $x_2(t)$ is a high frequency harmonic interference signal with amplitude set to 5 and harmonic frequency of 250Hz. $x_3(t)$ is a transient oscillation interference signal, the amplitude is set to 2, and the oscillation time is between 0.64s and 0.66s. The noise standard deviation of CEEMDAN algorithm is uniformly set to 0.2, the number of adding noise is 100 and the number of iterations is 50. The sampling frequency is 5KHz and the simulation time is set to 1s. The traditional HHT and the improved HHT are used to analyze it.
As can be seen from the figure 5 and figure 6, compared with the traditional HHT, the improved HHT method can better eliminate the influence of transient disturbance components, the frequency and amplitude curves of signal components are relatively gentle, the end effect suppression effect is better, and the Hilbert spectrum can accurately reflect the amplitude accumulation of each signal component on the frequency.

The analysis results of the improved HHT method for the detection of voltage sag component are shown in table 2. The detection results show that the improved HHT method has high detection accuracy for signal component amplitude, frequency, start and end time, and the detection error is small.

| Detection component | Sag component | Other component |
|---------------------|---------------|-----------------|
| A                   | f / Hz        | start time / s  | end time / s | A | f / Hz |
| The theoretical value | 15            | 50              | 0.25         | 0.75 | 5     | 250 |
| The actual value     | 15.01         | 50.14           | 0.2498       | 0.7512 | 4.904 | 250.4 |
| Error /%             | 0.07          | 0.28            | 0.08         | 0.16   | 1.92  | 0.16 |

3.3.2 Analysis of measured data
The measured voltage sag data collected from the power quality monitoring system of central China power grid are used. The sampling time of the sag event is 0.56s, the sampling frequency is 51200hz, and the sag duration is 0.16s. The signal was analyzed by HHT.
Figure 6. Actual measured voltage sag signal.

Figure 7. Instantaneous frequency amplitude of actual measured signal.

It can be seen from the figure 8 that the improved HHT method can avoid the influence of high-frequency system oscillation at the beginning and ending time of sag events on the sag component, and can extract the instantaneous characteristics of sag events more completely. The improvement analysis results are shown in the table below.

|                  | Theoretical value | Actual value | Error   |
|------------------|-------------------|--------------|---------|
| Starting time    | 0.08              | 0.082        | 2.50%   |
| Termination time | 0.24              | 0.244        | 1.67%   |
| The amplitude of voltage rise | 0.16 | 0.162 | 1.25%   |

It can be seen from the table 3 that the deviation between the actual values of line voltage amplitude before detection of sag is 1.25%, and the error is small. Therefore, the improved HHT method is also more accurate for the measured voltage sag events, and it is suitable for the detection and analysis of voltage sag events.

4. Conclusion

In this paper, an improved HHT method based on the combination of boundary local feature scale and CEEMDAN is proposed, which is based on the combination of local feature scale and CEEMDAN. The conclusions are as follows:

1. The boundary local feature scale method can effectively suppress the endpoint effect in the detection process.
2. Ceemdan suppresses the influence of mode aliasing by adding noise, which makes the extracted IMF component closer to the actual component.
3. The experimental data show that the improved HHT method is more accurate in detecting voltage sag events.

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