INTRODUCTION

Power quality problems affect people’s life safety, so it is particularly important to study it\(^{[1]}\). Whether it is household electricity or factory electricity, there are various disturbances causing great economic losses\(^{[2]}\). Power quality can be classified into two types: transient and steady-state power quality disturbance\(^{[3]}\). The steady-state power quality includes voltage fluctuation and flicker, harmonics and voltage unbalance, which mainly detect the wave amplitude, unbalance factor, frequency and other characteristics\(^{[4]}\). Transient power quality includes pulse oscillation, voltage swell, voltage interruption, and voltage sag, and the main detection is the peak, spectrum, starting and stopping time\(^{[5]}\). In real life, there’s often not one single form of power quality, but a mixture of two or more power quality\(^{[6]}\). The mixture of voltage sag and harmonic is the most typical mixed disturbance. The solution to this type disturbance is also more difficult\(^{[7]}\).

There are many methods to detect power disturbances\(^{[8]}\), such as Fourier transform, short-time Fourier transform (STFT), and wavelet transform\(^{[9]}\). However, these methods are more suitable for only one kind of disturbance, and the result is not ideal for the detection of multi-disturbance types\(^{[9]}\).

S transform and Hilbert-Huang transform (HHT) are two new time-frequency algorithms, which are more accurate when dealing with non-stationary and nonlinear signals\(^{[10-12]}\). S transform is the development of the STFT, and the window width and the area can be adjusted completely\(^{[13]}\). Literature\(^{[14]}\) by comparing the S transform and STFT of the voltage sag detection results, elaborated the advantage of S transform to deal with the transient disturbance signal. The practicability of S transform is stronger, and the detection accuracy is higher. S transform has obvious advantages in non-linear processing; HHT is the development of the wavelet transform, which has the characteristics of self adaptation\(^{[15]}\). Literature\(^{[16]}\) by comparing the HHT and Wavelet transform of the harmonic detection results, expounded the advantages of HHT processing steady disturbance signal. HHT has stronger adaptability than wavelet transform, and it does not involve the selection of wavelet basis. HHT is more concise and accurate, which has obvious advantages in the non-steady signal processing. Based on these analyses, the combination of HHT and S transform can accurately identify any form of disturbance signal in electric energy.

In order to improve the detection accuracy, first of all, improve the S Transform and HHT, and then carry on the combination of both. Finally the combination algorithm is applied to the mixture of voltage sag and harmonic disturbance detection.

ABSTRACT: The type of disturbance in power quality is complex, and the form is changeable. Single algorithm is difficult to get accurate detection results. Thus the idea of the combination of Hilbert-Huang transform (HHT) and generalized S transform is produced. Harmonic and voltage sags are two typical voltage disturbances, and their mixed disturbances are selected as the target signal. Making the ensemble empirical mode decomposition (EEMD) of the multi-disturbance to get intrinsic mode function (IMF) and detect the basic components of the signal. Then, make rapidly generalized S transform detect the precise information of the relevant IMF. The simulation results show that this method is effective for the detection of multi-disturbance.

Keywords: harmonic; voltage sag; multi-disturbance; HHT; generalized S transform
2 TWO ALGORITHMS AND THEIR IMPROVEMENT

2.1 S Transform and its improvement

2.1.1 S Transform

The S Transform of the signal \( h(t) \) is defined as follows\(^{[17]}\):

\[
S(\tau, f) = \int_{-\infty}^{+\infty} h(t) g(\tau-t)e^{(-2\pi j ft)} dt
\]

(1)

\( g(t-t) \) represents Gauss window function. It is the most important part of the S transform, which determines its resolution.

The Gauss window is defined as formula (2):

\[
g(\tau-t) = \frac{|f|}{\sqrt{2\pi}} e^{\left[-\frac{(\tau-t)^2}{2f^2}\right]}
\]

(2)

\( f \) is the frequency; \( \tau \) is a parameter which controls Gaussian window in the timeline position; \( h(t) \) is the original signal. From formula (1) and (2) we can know that Gaussian window width is inversely proportional to the frequency, that is to say, S transform in the low frequency band has higher frequency resolution and lower time resolution. This provides a theoretical basis for the following improvement.

2.1.2 Generalized S transform: adding frequency adjustment coefficient and its fast algorithm

The improvement of S transform is called generalized S transform.

For certain types of disturbance signals, such as voltage sag in the low frequency, have high temporal resolution requirements. And standard S transform compared to the previous frequency detection accuracy improved, but there are still some errors. To improve this defect, it is should to make adjustments to the Gauss window coefficient. So adding the frequency adjustment coefficient \( \sqrt{f} = \alpha f + \beta \), by adjusting the values of \( \alpha \) and \( \beta \) can make the improved S transform in time-frequency plane with different resolution. That is, by changing the frequency of the Gauss window function to adjust the frequency resolution

\[
g(\tau-t) = \frac{|f|}{\sqrt{f^2 + 2\pi \beta}} e^{\left[-\frac{f^2(\tau-t)^2}{2f^2}\right]}
\]

(3)

Through a large number of simulations, this voltage disturbance detection takes \( \sqrt{f} = 0.05f + 0.5 \). Due to the large amount of calculation of S transform, it is hard to meet the requirements, so using fast generalized S transform to the simulation. Literature \(^{[18]}\) introduces the application of fast S transform in disturbance signal detection.

Figure 1 and 2 are the voltage sag signal detection simulation diagrams. Figure 1 is a standard S transform to detect curves; Figure 2 is a detection profile of generalized S transform. Extract information from the graphs, as shown in Table 1. The table shows that the generalized S transform detection accuracy is higher, which overcomes some defects of the standard S transform. Because of the fast algorithm, the computation time is obviously reduced and the efficiency is higher in the simulation process. Figure 1, Figure 2 and Table 1 show the feasibility of the fast generalized S transform.

2.2 HHT and its improvement

2.2.1 HHT

HHT is the improvement and development of wavelet transform, which has self-adaptability. It is suitable for

<table>
<thead>
<tr>
<th>Jump time (s)</th>
<th>S transform detection time (s)</th>
<th>Generalized S transform detection time (s)</th>
<th>The error of S transform (e1)</th>
<th>The error of the generalized S transform (e2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3143</td>
<td>0.30144</td>
<td>+4.7%</td>
<td>-0.48%</td>
</tr>
<tr>
<td>0.7</td>
<td>0.71982</td>
<td>0.6993</td>
<td>+2.8%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>
nonlinear and non-stationary signal analysis. The composition principle can be divided into two parts: empirical mode decomposition (EMD) and Hilbert transform. The academic thoughts of EMD are as follows:[19]:

Find out signal \( x(t) \) maximum (minimum) value point as the upper envelope curves \( v_1(t) \) and the lower envelope curves \( v_2(t) \), and get the average value of the signal:

\[
m_t(t) = \frac{1}{2} [v_1(t) + v_2(t)]
\]

The signal \( x(t) \) minus the average \( m(t) \) is obtained as follows:

\[
h_t(t) = x(t) - m_t(t)
\]

The \( h(t) \) is used as the original signal repeat (1) (2), in order to obtain the intrinsic mode function (IMF) components until the termination condition is satisfied. Decomposition expressions are as follows:

\[
x(t) = \sum_{i=1}^{n} c_i(t) + r(t)
\]

2.2.2 The improvement of HHT
The analysis quality of HHT method depends largely on the quality of EMD decomposition. So we want to improve the HHT, the most important is to optimize the EMD process. And when there are multiple frequency components, the EMD decomposition may cause the mode mixing phenomenon. So we need to replace it with a more advanced method. The literature [20] proposed ensemble empirical mode decomposition (EEMD) method. General academic ideas are as follows: adding white noise to the decomposition process, due to the presence of noise, making the new decomposition result is more complex than the decomposition of EMD. Then it will use enough means to test, and the noise will be eliminated. The resulting average of several tests will be considered the final result signal decomposition.

EEMD is optimized for EMD, which solves the problem of mode mixing in EMD, and the decomposition results are more accurate. On this point, many articles are involved, so we will not repeat the discussion.

2.3 The application of these two improved algorithms
For the mixture disturbance of harmonic and voltage sag, due to the different characteristics, only using an algorithm will inevitably cause purely trade-off phenomenon. Therefore, the two improved algorithms are combined together to make use of their respective advantages to further improve the detection accuracy.

Specific academic ideas are as follows: Use improved HHT to extract the frequency components of the mixed signal (IMF). Then each layer of the IMF makes fast generalized S transform, extracting the feature information. The flow chart is shown in Figure 3.

3 SIMULATION AND ANALYSIS OF RESULT
Disturbance signal is shown in Figure 4, which contains three parts. The first part is the power frequency signal (Amplitude: 311v); the second part is the harmonic signal (Amplitude: 113V, Duration: 0.1s-0.7s, Frequency: 250Hz); the third part is the voltage sag signal (Amplitude: 200V. Duration: 0.6s-0.7s). These three parts constitute the target signal to be detected. Target signal simulation waveform as shown in Figure 4.

EEMD decomposition of target signal is shown in Figure 5, the left part is the time-frequency curve of each layer of IMF and the right part is the IMF amplitude-frequency distribution. The IMF time frequency diagram shows that IMF1 contains two kinds of frequency components of the signal (250Hz and 50Hz).
and the emergence time of the harmonic signal of 250Hz is from 0.1s to 0.7s. The amplitude of the spectrum shows that the main signal component of IMF1 is harmonic and voltage sag, but no power frequency signal; IMF2 only has the signal of 50Hz, which presenting time is from 0.1s to 0.7s. Combined with its corresponding amplitude knows the main component is the voltage sag signal, and its existence time is from 0.6s to 0.7s; IMF3 and IMF4 are pseudo signals. Therefore, it only needs to carry on S transform to IMF1 and IMF2, and then extract more accurate information from them.

Figure 5. EEMD decomposition information.

Figure 6 is the time-frequency characteristic curve of HHT and Figure 7 is time-amplitude characteristic curve. They give the main information of the objective function, which provides a reference for the detailed analysis below. From Figure 6 and Figure 7, we can know that the detected signal contains two kinds of frequency components and third amplitude informations. But what is the specific signal is not clear. The next task is to do the generalized S transform and analyze the specific confidence

Figure 6. Time-Frequency characteristic curve.

Figure 7. Time-Amplitude characteristic curve.

Figure 8 is the amplitude envelope of the Fast Generalized S Transform. Figure 8(a) is the amplitude envelope of the fast generalized S transform of the multi-disturbance signal. It can reflect the composition of the original signal, because the complex signal (with power frequency component) has interference on the test results, which leads the result is not accurate; Figure 8(b) is the amplitude envelope of the fast generalized S transform of IMF1. Figure 9 shows that the time from 0.1 s to 0.7 s only contains the disturbance signal (voltage sag signal and harmonic signal) without the influence of the power frequency signal, so its detection results are bound to be more accurate; Figure 8(c) is the amplitude envelope of the fast generalized S transform of IMF2 (The frequency is 50Hz). There is no interference of harmonic signal in the graph, where only the voltage sag signal is detected. In order to visually illustrate the problem, the data extracted from the transformation process are shown in Table 3 and Table 2. As can be seen from the tables, the time detection and amplitude detection error of IMF1 and IMF2 are smaller, and the accuracy are higher.
Table 2. Analysis of time test results.

<table>
<thead>
<tr>
<th>T/s</th>
<th>T1/s</th>
<th>T2/s</th>
<th>T3/s</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1091</td>
<td>0.0096</td>
<td>Unwanted</td>
<td>9.10%</td>
<td>0.96%</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>0.6218</td>
<td></td>
<td>Unwanted</td>
<td>0.6067</td>
<td>3.60%</td>
<td>1.10%</td>
</tr>
<tr>
<td>0.7</td>
<td>0.71982</td>
<td>0.6993</td>
<td>Unwanted</td>
<td></td>
<td>2.80%</td>
<td>-0.01%</td>
</tr>
</tbody>
</table>

Notes: T is standard jump time. T1 is time detection result of the fast generalized S transform of the target signal. T2 is referred to time detection result of fast generalized S transform of IMF1, and T3 is time detection result of fast generalized S transform of IMF2, and the errors of them are respectively represented as E1, E2, and E3.

Table 3. Analysis of the results of amplitude detection.

<table>
<thead>
<tr>
<th>U/v</th>
<th>U1/v</th>
<th>U2/v</th>
<th>U3/v</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
</tr>
</thead>
<tbody>
<tr>
<td>312</td>
<td>301.9476</td>
<td>Unwanted</td>
<td>310.0996</td>
<td>3.20%</td>
<td>0.32%</td>
<td></td>
</tr>
<tr>
<td>113</td>
<td>107.0048</td>
<td>110.3671</td>
<td>Unwanted</td>
<td>5.30%</td>
<td>2.30%</td>
<td>0.32%</td>
</tr>
<tr>
<td>200</td>
<td>205.4709</td>
<td>Unwanted</td>
<td>198.0822</td>
<td>2.70%</td>
<td>-0.96%</td>
<td></td>
</tr>
</tbody>
</table>

Notes: U represents the standard amplitudes and U1 is the amplitude detection result of fast generalized S transform of the target signal. U2 is referred to amplitude detection result of fast generalized S transform of IMF1, and U3 is amplitude detection result of fast generalized S transform of IMF2. E4 is referred to the amplitude error of fast generalized S transform of the target signal. E5 and E6 are corresponding to the amplitude errors of IMF1 and IMF2.

Table 2 shows that E2 and E3 are less than E1, while Table 3 shows E5 and E6 are less than E4. That is to say the errors of fast generalized S transform after EEMD decomposition is smaller, so the combination of two algorithms is effective and feasible. Table 2 and Table 3 show that after the combination of the two algorithms, the detection errors are smaller and the detection accuracy is higher. Both in amplitude detection and time detection it has obvious advantages.

4 CONCLUSION

Combined with the disturbance of power quality, select the voltage sag and harmonic as the disturbance signal and use HHT and fast generalized S transform as the research means. From the above analysis, we can get the following conclusions:

(1) Compared with the standard S transform, the detection accuracy of the generalized S transform is higher, which overcomes some defects of the standard S transform.

(2) EEMD solves the problem of mode mixing in EMD, and the decomposition results are more accurate.

(3) Combining improved HHT and generalized S transform to deal with multi-disturbance signal. Firstly, the improved HHT is used to decompose the target signal; after HHT, the generalized S transform is carried on to determine the magnitude of the amplitude and the moment of the mutation. The simulation results show that the combination of two algorithms can effectively extract multi-disturbance informations on all aspects. Compared with the single algorithm, it is more accurate.

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REFERENCES


