Simulation modelling and feature extraction to voltage compound disturbances by modified generalised S-transform

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Abstract: Voltage sag disturbances are the most important type of disturbance in power quality analysis and the extraction to voltage compound disturbances is more difficult. Here, four composite voltage sag disturbance models are constructed and the feature extraction method by modified generalised S-transform (GST) is given. By optimising the introduced r-parameters, it can obtain better time resolution and frequency resolution by the modified GST. Results of simulation experiments and the application in a steel plant main line show that both time domain disturbance and frequency domain disturbance information can be extracted with higher resolution.

1 Introduction

With the popularity of electric network, microelectronic devices are used more and more, and they are very sensitive to the voltage change. Even a little bit of voltage fluctuation will cause a significant impact on their accuracy, longevity, and normal work. Power quality issues are more important than ever. Simulation models of voltage sag disturbances are important for the analysis of the characteristic information of the voltage sag signals. Furthermore, effective method of detecting and identifying disturbance signals is of great significance for analysing and improving power quality [1–5]. Common detection methods include wavelet transform [6–8], Hilbert–Huang transform (HHT) [9–11], S-transform [12–15] etc. The mother wavelet selection of wavelet analysis method lacks of theoretical basis. Component determination in HHT method lacks self-adaptiveness. The S-transform time-frequency matrix can simultaneously characterise the start-stop time, amplitude, and harmonic components of the disturbance, but its window function is fixed and its time-frequency resolution is low. Generalised S-transform (GST) improves the time-frequency resolution to a certain extent by introducing control parameters to the window function, but the optimisation of its parameters is still a difficult problem.

Here, four kinds of composite voltage sags are presented for the further analysis and recognition of the voltage sag signals. A new parameter optimisation method is proposed for the window function of the S-transformation. The parameter values at the fundamental frequency point are set separately to highlight the time-domain disturbance information. When the parameter values of other frequency points are modified, they can focus on the disturbance information in the frequency domain, reducing the concerns more of time domain disturbances, so that the time domain disturbance and frequency domain disturbance information can be achieved higher accuracy. Simulation experiments were performed on four kinds of composite power quality disturbance signals, indicating the priority of this method. It applied to a steel plant and achieved good results.

2 Simulation modelling for compound voltage sag disturbances

The simulation models of the normal signal and four signals are shown in Table 1, including the type of disturbance, the mathematical model, and the corresponding parameter settings.

| Signal types | Normal signals | Harmonics plus temporary rise | Oscillation plus sags | Oscillation Harmonic Sags | Oscillation Harmonic Swells |
|--------------|----------------|-----------------------------|-----------------------|--------------------------|---------------------------|
| h(t) = A sin(ωt) | h(t) = A(1 + α(u(t − t1)−u(t − t2)))(αsin(ωt) + α3sin(3ωt) + α5sin(5ωt) + α7sin(7ωt)) + exp(x(−(t−t1)−u(t)) + sin(ω(t−t1))(α4+α6)) | 0.1 ≤ α ≤ 0.8; T ≤ t2 − t1 ≤ 9 T ≤ 0.05 ≤ α ≤ 0.15; 0.05 ≤ α ≤ 0.15; 0.05 ≤ t2 ≤ 1300 Hz | 0.1 ≤ α ≤ 0.8; T ≤ t2 − t1 ≤ 9 T ≤ 0.05 ≤ α ≤ 0.15; 0.05 ≤ α ≤ 0.15; 0.05 ≤ t2 ≤ 1300 Hz | 0.1 ≤ α ≤ 0.8; T ≤ t2 − t1 ≤ 9 T ≤ 0.05 ≤ α ≤ 0.15; 0.05 ≤ α ≤ 0.15; 0.05 ≤ t2 ≤ 1300 Hz | 0.1 ≤ α ≤ 0.8; T ≤ t2 − t1 ≤ 9 T ≤ 0.05 ≤ α ≤ 0.15; 0.05 ≤ α ≤ 0.15; 0.05 ≤ t2 ≤ 1300 Hz |

Table 1 Voltage compound disturbances model

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Among them, the window function is as (2)

\[ w(\tau, f, r) = \frac{1}{\sqrt{2\pi r}} e^{-\frac{\tau^2}{2r}} \]

and the standard deviation of the window function \( \sigma \) is:

\[ \sigma = \frac{r}{\sqrt{1}} \]

\( r \) is the introduced adjustment parameter.

Based on the Fourier transform and the convolution theorem, GST is expressed in the frequency domain as (4):

\[ S(\tau, f) = \int_{-\infty}^{\infty} h(\alpha) e^{-j2\pi f\tau} e^{j2\pi \alpha \tau} d\tau \]

(4)

let \( \tau \rightarrow nT, f \rightarrow n/N, T \) is the sampling period, \( N \) is the signal sampling point, \( m \) and \( n \) correspond to the time sampling point and the frequency sampling point, respectively, then the discrete expression of ST is:

\[ S[mT, \frac{n}{N}] = \sum_{k=0}^{N-1} H\left(\frac{k+n}{NT}\right) e^{-j2\pi \frac{k+n}{NT} m} e^{j2\pi \frac{k+n}{NT} \cdot \alpha f} \quad n \neq 0 \]

\[ S[mT, 0] = \frac{1}{N} \sum_{m=0}^{N-1} h\left(\frac{m}{N}\right), \quad n = 0 \]

In the formula, \( H(\cdot) \) represents the Fourier transform of the original signal, where \( k, m, n = 1, 2, \ldots, N \). The GST can adjust the effective window width of the window function by adjusting the parameters. The influence of the window width of the Gaussian window function with the change of \( r \) is shown in Fig. 2.

As can be seen from the figure, the window width increases linearly with increasing frequency when \( r \) is constant. When \( r \) decreases, the angle between the straight line and the horizontal axis increases, that is, the slope becomes larger, the window width becomes higher, and the resolution in the frequency domain becomes better. It is not difficult to infer from the knowledge of mathematics that when \( r \) becomes smaller, the trend of change is opposite.

GST can adjust the effective window width of the window function by adjusting the parameter \( r \), but due to the limitation of the Heisenberg uncertainty principle, the time domain resolution and the frequency domain resolution cannot reach the best at the same time. From (3), we can see that the shape of the window changes with \( r \). When \( r \) increases, the effective window width widens, the time domain resolution decreases, and the frequency domain resolution increases; when \( r \) decreases, \( r \) decreases, the effective window width narrows, the frequency domain resolution decreases, and the time domain resolution increases. Therefore, it is difficult to satisfy the requirement of high time-frequency resolution at the same time only by adjusting \( r \).

Comprehensive analysis of power quality disturbance signals needs to start from both the time domain and the frequency domain. At present, the time domain disturbance mainly refers to amplitude detection, and the frequency domain disturbance mainly refers to harmonic detection. Frequency is the focus of time-frequency domain analysis, and the situation of the fundamental frequency point is the most important thing. In order to comprehensively analyse the time domain and frequency domain characteristics, we choose to set the \( r \) value at the fundamental frequency point particularly prominently, so as to improve the time-frequency disturbance resolution. Constrain the parameter \( r \) in (3) to (6)

\[ \sigma = \frac{r}{\sqrt{1}}(r = r_0, f = f_0, r = r_0, f \neq f_0) \]

The corresponding discrete form of the window function is:

\[ w(m, m) = e^{-j2\pi m^2 n^2}, n = n_0 \]

\[ w(m, m) = e^{-j2\pi n^2 m^2}, n \neq n_0 \]

In (6) and (7), \( f_0 \) and \( n_0 \) correspond to the fundamental frequency points of the continuous and discrete forms of the original signal, respectively. The GST at this time is recorded as an \( r \)-parameter modified GST (modified GST). Modified GST considers frequency domain and time domain separately and has certain adaptability. Only when \( r = r_0 \), modified GST degenerates to GST.

The calculation steps for optimising generalised S-transform method are as follows:
(a) Perform the FFT calculation on the original signal to obtain the Fourier spectrum \( H(m) \) and obtain the fundamental frequency point.
(b) Adaptively determine \( r_0 \) and \( r_n \) and obtain the Fourier transform corresponding to the Gaussian window function at each frequency \( n(i = 1, 2, \ldots, N) \);
(c) Shift \( H(m) \) to obtain \( H(m + n) \) and multiply it by \( w(m, n) \), then find its inverse Fourier transform to obtain the time-frequency matrix \( S(i, n) \);
(d) Repeat steps b to c to obtain the components corresponding to all frequency points \( n \), and finally obtain the time-frequency matrix \( S(i, n) \).

4 Optimisation index of the parameter \( r \) of GST
Different types of power quality disturbances contain different time domain information and frequency domain information. Some disturbance types mainly rely on time-domain information to distinguish, such as voltage swells, voltage interruptions, and voltage sag etc., which are identified by time-domain characteristics. Some types of disturbance rely mainly on frequency domain information. For example, harmonics, transient oscillations etc. are all identified by frequency domain features. The S-transform time-frequency matrix contains rich time and frequency domain information. Time-maximum amplitude plots (TMA-plots) can be used to characterise time-domain disturbances features such as disturbance amplitude and start-stop time. Frequency-maximum amplitude plots (FMA-plots) can characterise frequency-domain disturbance features such as harmonic components. Therefore, based on the characteristics of the TMA-plots and FMA-plots, the following optimisation indicators are proposed to optimise the parameter \( r \), as shown in Fig. 3.

(a) The time domain indicator \( t_r \) is used to calculate the parameter \( r_0 \). Let the maximum value of the TMA graph be \( A_m \), the standard value be \( A_r \), and their difference be \( \Delta A \). On the TMA plots, the time taken from \( A_r + 0.1\Delta A \) to \( A_r - 0.1\Delta A \) is \( t_r \), the smaller the time domain, the higher the resolution.
(b) The frequency domain indicator \( f_r \) is used to calculate the parameter \( r_n \). On the FMA plots, \( f_r \) represents the amplitude energy of the fundamental frequency point, and \( f_d \) represents the frequency difference from the amplitude \( A_r \) at the fundamental frequency to 0.7 \( A_r \). So, \( f_r \) can be expressed as \( f_r = f_d / f_d \). The larger \( f_r \) is and the smaller \( f_d \) is, the larger \( f_r \) is, and the corresponding frequency domain performance is better.

5 Feature extraction based on modified GST
5.1 TMA plots and FMA plots of the disturbance signal
The feature extraction in this section is based on the time-frequency matrix of the modified GST. The time domain disturbance feature is obtained from the TMA plots of the time-frequency matrix, and the frequency domain disturbance feature is obtained from the FMA plots of the time-frequency matrix. The modified GST processing was performed on the above four disturbance signals. The TMA plots and the FMA plots are shown in Figs. 4 and 5, respectively.

The TMA plots mainly represent time-domain characteristic information such as amplitude fluctuation of the disturbance signal. The TMA curve of the normal signal has no apparent amplitude fluctuation as shown in Fig. 4a. The TMA curve of oscillation sags and oscillatory harmonic sags has a distinct amplitude dip interval as shown in Fig. 4b. The TMA curve with harmonic swells and oscillation harmonics swells has a significant amplitude range as shown in Fig. 4c. Therefore, the TMA curve can effectively characterise the disturbance signal's amplitude disturbance characteristics.

The FMA plots mainly characterise the frequency domain features such as the frequency spectrum components of the disturbance signal. Fig. 5a describes that the frequency component contains only the fundamental frequency component (50 Hz), there is no other obvious frequency component, and the main type of disturbance involved is a little single disturbance which is ignored here. Fig. 5b shows that in addition to the fundamental frequency components, the FMA curve also has harmonic components, mainly concentrated at 100–600 Hz, and the main disturbance type involved is Harmonics plus temporary rise. Fig. 5c shows that there is a frequency component in the range of 1000–1600 Hz. This frequency band mainly corresponds to the oscillation frequency of the transient oscillation disturbance. The main disturbance type involved is oscillation plus sags. The FMA curve depicted in Fig. 5d shows that harmonic components exist in the low-frequency region of <500 Hz, and there is an oscillation frequency in the frequency region of 1000–1600 Hz. The types of disturbances involved are mainly oscillatory harmonic sags and oscillation harmonic swells. Therefore, the FMA curve can effectively characterise the frequency components of the compound disturbance signal. In summary, TMA curves and FMA curves can provide abundant time-frequency information. Based on
From the above discussion we can see, TMA plots and FMA plots, effective disturbance features can be extracted for classification.

5.2 Feature extraction

From the above discussion we can see, TMA plots and FMA plots can provide abundant time-frequency information. Based on TMA plots and FMA plots, effective disturbance features can be extracted for classification. The following four feature vectors are proposed.

The amplitude disturbance based on TMA plots defining the feature quantity is as follows.

\[ \Delta A = \bar{A}_{mc} - A_i \]  

(8)

In the equation, \( \bar{A}_{mc} \) refers to the average of all amplitudes >0.9 \( A_m \) in the TMA plots, \( A_m \) refers to the maximum value, and \( A_i \) refers to the standard value.

\( \Delta F \) represents the fluctuation frequency of the TMA plots and can be used to distinguish between disturbances such as flicker.

\[ \Delta F = \text{mean}(\text{FFT}(\text{TMA}_{\text{FT}})) \]  

(9)

In the equation, TMAr refers to the portion remaining after the average of the TMA plots is subtracted, that is, the frequency corresponding to the maximum peak of the TMAr spectrum.

The frequency component based on the FMA plots defining feature quantity is as follows.

\[ \Delta D = \text{mean}(A) \]  

(10)

In the equation, mean( • ) refers to obtaining the mean, and \( A_i \) refers to the amplitude in the range of 800–1500 Hz in the FMA diagram.

The disturbance feature extracted by the modified GST described above is recorded as the following vector: \( F = [\Delta A, \Delta F, \Delta D, \Delta M] \), which is marked as \( F \).

5.3 Disturbance parameter solving method

The power quality disturbance parameters mainly involve start and end time, disturbance amplitude, disturbance frequency and so on. The method for solving the compound disturbance parameter is consistent with that of the single disturbance method. Disturbance parameters are solved as follows:

(i) The disturbance parameter of start and end time \( t_1, t_2 \) of voltage swells (voltage sags).

\[ \begin{align*} 
 t_1 &= \text{min}\left[\text{diff}(A_n)\right] \cdot T \\
 t_2 &= \text{max}\left[\text{diff}(A_n)\right] \cdot T 
\end{align*} \]  

(11)

In the formula, \( t_1 \) and \( t_2 \) respectively, represent the start and end moments of the sag, \( \text{diff}(\cdot) \) represents the difference operation, \( A_n \) represents the amplitude of the TMA, and \( T \) represents the time interval.

Fluctuation amplitude \( A_w \) (Unitary value):

\[ A_w = 1 + \Delta A \]  

(12)

In the formula, ‘1’ represents the unitary value, and \( \Delta A \) represents the feature quantity.

1. ii) Transient oscillation disturbance parameters: The start time \( t_s \) and end time \( t_e \) of oscillation can be calculated by (11). Here, \( A_n \) represents the TMA corresponding to the oscillation frequency.

2. iii) Flicker disturbance parameters: The fluctuation amplitude is found as (12), and the fluctuation frequency is the standard deviation of the TMA plots.

3. iv) Harmonic disturbance parameters: Harmonic amplitude and harmonic frequency are all obtained from the FMA plots.

The disturbance parameters of the above four kinds of voltage compound disturbance signals can be obtained accordingly. Each type of disturbances signal takes 500 sets of data, adds 30 dB of noise, and then performs modified GST analysis, extracts four types of feature quantities, and averages the feature quantities of each signal. The results are shown in Table 2.

From the table, we can see that the disturbances feature \( F = [\Delta A, \Delta F, \Delta D, \Delta M] \) presented here has a good discrimination.

6 Application and data analysis

To verify the practicability of the proposed method, this section analyses two sets of power quality disturbance data for a steel plant main line. The two sets of data were collected by transformers at different time periods, with a sampling frequency of 6.4 kHz and a sampling point of 3200 points. The disturbance parameters \( (t_s, A_w, f_w) \) of the two signals were analysed using modified GST. The results are shown in Fig. 6.

In the figure, measured signal waveforms, TMA plots, and FMA plots are sequentially used. The measured signal is more complex and the features of the disturbance are not obvious. The TMA plots can effectively characterise weak amplitude disturbances. The FMA plots can effectively detect weak harmonic disturbance components.
7 Conclusion
In the light that the disturbance signal contains rich time domain disturbances and frequency domain disturbances, the time domain resolution and frequency domain resolution need to be flexibly adjusted to meet the requirements. This paper constructs four composite voltage sag disturbance simulation models for the further analysis and recognition of the voltage sag signals, and introduces the modified method for generalised S-transform, solving the problem of the fixed time-frequency resolution. The time domain index $t_c$ and the frequency domain index $f_c$ of $r$ are modified, the four kinds of voltage compound disturbance signals are analysed, and the feature quantities are extracted. The method is applied to the measured signals of a steel plant main line, and a good analysis result is obtained, which proves that the validity of the method and the rationality of the selection of optimisation indicators.

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