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The Application Study of S-Transform Modulus Time-frequency Matrix in Detecting Power Quality Transient Disturbance

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Abstract: This study proposes a new algorithm, which makes use of S-transform modulus time-frequency matrix to detect the power quality transient disturbance. And respective mathematical models are established according to transient disturbances such as voltage sags, voltage rises, voltage interruption and transient oscillation. It calculates the modulus time-frequency matrix of the four disturbance signals by using S-transform and extracts their features. Simulation and analysis are made in Matlab. The simulation results show that the proposed algorithm can extract the features of different disturbances effectively. It provides a new option for power quality transient disturbance detection.

Key words: Power quality, S-transform, disturbance

INTRODUCTION

The issue of power quality is currently one of the problems urgently to be solved in electric power system. In order to take reasonable measures to improve power quality we must establish power quality monitoring and analyzing system so as to accurately monitor, analyze and evaluate the grid. The most critical issue is how to seek the rapid and effective analysis method to analyze monitored data. At present, there are three power quality disturbance detection methods which include time domain analysis method, frequency domain analysis method and the method based on transform domain. For power quality problems such as voltage fluctuations and harmonic wave, whose change is relatively slow and with long duration, the time domain analysis methods (Lin, 2001; Li *et al*., 2010) are frequently used while Fourier transform is the most commonly used among frequency domain analysis methods. For the power quality problems of voltage transient sags and rises, due to their short duration and great randomness, the traditional time frequency domain analysis method can't meet the detection requirements and cannot make correct identifications. At present the most frequently used method among the transient power quality disturbance detection is the method of wavelet transform (Chen, 2002). The dq 0 transform based on instantaneous reactive power theory are attracting more and more scholars' attention in the transient power quality disturbance detection. In addition to the detection method mentioned above, the transient power quality detection algorithms also include mathematical morphological transform, Hilbert. Huang transform (Li *et al*., 2005), S-transform, artificial intelligence technology, etc. Focus on transient power quality problems, the main task of this paper is to apply S-transform, the time-frequency reversible analysis method, in power quality transient disturbance analysis.

S-TRANSFORM POWER QUALITY TRANSIENT DISTURBANCE DETECTION ALGORITHM

Basic principles of S-transform: Making use of the frequency reciprocal to decide the size of Gaussian window for multi resolution analysis is the basic principle of S-transform. S-transform combines and develops short time Fourier transform and wavelet transform. By comparison, S-transform overcomes the weakness that in the analytical process the window function of short time Fourier transform is invariable. Compared with wavelet transform, S-transform retains the phase factor (Zhao and Yang, 2006). Researchers applied S-transform in power quality analysis in 2002 initially and pointed out the advantages of S-transform in the characteristic quantity extraction, classification and recognition of short power quality disturbance (Zhan *et al*., 2005).

The one dimensional forward S-transformation expression of Signal y(t) is as follows:

$$S\,(\tau,f) = \int_{\infty}^{\infty} y\,(t) \frac{|f|}{\sqrt{2\pi}} e^{\frac{(\tau-t)^2 f^2}{2}} e^{-2\pi i f t} dt \qquad (1)$$

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In the expression:

$$q\,(t,f) = \frac{|f|}{\sqrt{2\pi}} e^{\frac{t^2 f^2}{2}}$$

is the Gaussian window function, t is a shift factor for controlling the position of Gaussian window in the timer shaft and f is the frequency.

The one dimensional inverse S transformation expression of Signal y (t) is as follows:

$$y\,(t) = \int_{\infty}^{\infty} \{\int_{\infty}^{\infty} S\,(\tau,f)\,d\tau\}\, e^{-j2\pi ft} dt \qquad (2)$$

Time-frequency function of S-transform: The result of S-transform is a duplicate time-frequency matrix, its row vector reflects the frequency distribution of a certain time, and its column vector reflects the changes of a certain frequency with time changing. The modulus of an element in S-transform's certain row and column is the amplitude of S-transform in its corresponding frequency and time. We define the modulus time-frequency matrix of S-transform as the matrix obtained after respective mod operating of the elements in the complex time-frequency matrix Sa [l T, n/NT] getting from S-transform. Its expression is as follows:

$$S_a[lT, n/NT] = |\, S[lT, n/NT] \,| \qquad (3)$$

S_a[lT, n/NT] retains the amplitude information of S-transform, making the result of S transform easily to be displayed by frequency chart.

In the model time-frequency matrix getting from S-transforming of power quality disturbance signals, its elements corresponding to the amplitude of disturbance signal in time and frequency respectively. With the characteristics of power quality transient signal, we can define the model time-frequency matrix fundamental frequency amplitude time-varying functions $V_{fb}(l)$ (Wei *et al.*, 2004). This function is defined as in S-transform modulus time-frequency matrix, the corresponding base wave's amplitude variation with time. The expression is as follows:

$$V_{fb}(l) = S_a(l, f_b) \qquad (4)$$

In this expression, l stands for the sampling time and f_b stands for base wave frequency.

RESULTS AND ANALYSIS OF THE SIMULATION

Simulation of power quality disturbing signals: In Matlab we take advantage of the proposed new algorithm to simulate four kinds of transient electric energy quality events: Voltage sags, voltage rises, voltage interruption and transient oscillation. Various power quality disturbance signals are randomly generated with similar method as in literature (Youssef *et al.*, 2004). The base wave frequency of all power quality disturbance signals is 50 Hz. The time sequence takes 20 cycles of the signals. Suppose the base wave expression is:

$$y\,(t) = A\sin(\omega t) \qquad (5)$$

Simulation model of voltage sags: Generally speaking, voltage sags and rises are caused by load transient, motor start or remote fault which can lead to the equipment's halting, abnormal operation of the sensitive load. The mathematical model of voltage sag is as follows:

$$y\,(t) = A\,[1-k\,(u\,(t-t_2)-u\,(t-t_1))]\sin(\omega t) \qquad (6)$$

In the expression, k is the amplitude of the voltage sag. $0.1<k<0.9$:

$$u\,(t) = \begin{cases} 1, t \geq 0 \\ 0, t < 0 \end{cases}$$

which also works in the following expressions. t_2-t_1 is the duration of voltage sag. $T<t_2-t_1<8T$ ($T = 2\pi/\omega$ = 20 ms is the signal period. t_1 is the starting time of voltage sag, t2 is the ending time. Assuming that A = 1, k = 0.3,t = t-0.2, $t_1 = t_2 = 0.05$ we can get the waveform diagram of voltage sag as shown in Fig. 1.

Simulation model of voltage rises: The mathematical model of voltage rises is:

$$y\,(t) = A\,[1+k\,(u\,(t-t_2)-u\,(t-t_1))]\sin(\omega t) \qquad (7)$$

In this expression, k is the amplitude of voltage rise. $0.1<k<0.9$; t_2-t_1 is the duration of voltage rise. $T<t_2-t_1<8T$; t_1 is the starting time of voltage rise and t_2 is the ending time. Assuming that A = 1, k = 0.7, t = t-0.2, $t_1 = t_2 = 0.05$ we get the waveform diagram of voltage rise as shown in Fig. 2.

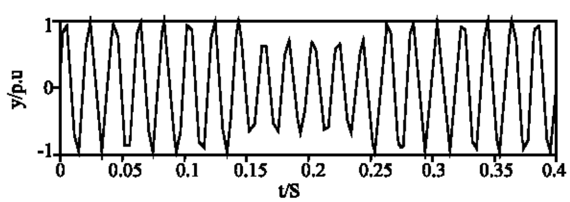

Fig. 1: Waveform diagram of voltage sag

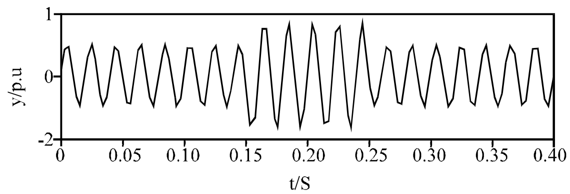

Fig. 2: Waveform diagram of voltage rise

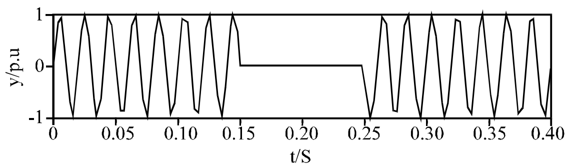

Fig. 3: Waveform diagram of voltage interruption

Simulation model of voltage interruption: Voltage interruption is generally caused by the faults in power supply system such as line destruction by man or by lightning, which would lead to the voltage of a phase or multiphase voltage lower than 0.1 (p.u.) in a certain time for a user. Its mathematical model is as follows:

$$y(t) = A[1-k(u(t-t_2)-u(t-t_1))]\sin(\omega t) \tag{8}$$

k is the amplitude of voltage interruption. $0.9<k<1$; t_2-t_1 is the duration of voltage interruption. $T<t_2-t_1<8T$, t_1 is the starting time of voltage interruption and t_2 is the ending time. Assuming that A = 1, k = 0.995, t = t-0.2, $t_1 = t_2 = 0.05$, we can get the waveform diagram of voltage interruption as shown in Fig. 3.

Simulation model of transient oscillation: Transient oscillation is generally caused by cuts in lines, loads and capacitor sets which can lead to the power electronic equipment damage and destruction of equipments' insulation. Its mathematical model is as follows:

$$\begin{aligned} y(t) &= A[\sin(\omega t) + k e^{\frac{t-t_1}{\tau}} \sin(n\omega(t-t_1)) \\ &= (u(t-t_2) - u(t-t_1))] \end{aligned} \tag{9}$$

k is the amplitude of transient oscillation and $0.1<k<0.8$ is the transient oscillation attenuation coefficient. $0.001<f<0.002$; n is the relative coefficient of oscillation frequency and $9<n<13$; t_2-t_1 is the duration of transient oscillation. $T<t_2-t_1<2T$, t_1 is the starting time of transient oscillation and t_2 is the ending time. Assuming that A = 1, k = 0.7, t = t-0.2, $t_1 = t_2 = 0.015$, $\omega = 100\pi$, n = 10 we can get the waveform diagram of transient oscillation as shown in Fig. 4.

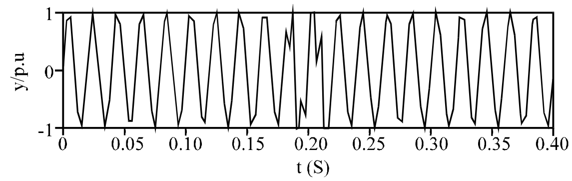

Fig. 4: Waveform diagram of transient oscillation

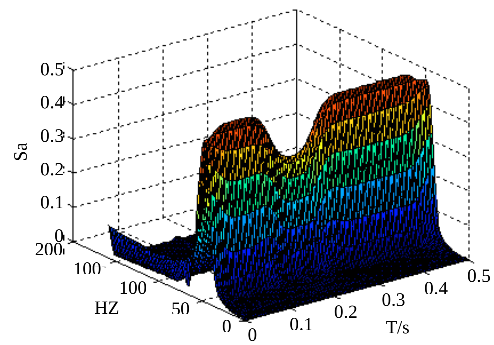

Fig. 5: S transform time-frequency diagram of voltage sag

In the mathematical models of the above four kinds of power quality disturbance events, the values of each controlled parameters (k_3, k_5, k_7, k_9, k_{11}, k, n, t_1, t_2, τ) in each sample are all generated by program in random so as to make analysis results more universal.

Simulation and analysis of all kinds of transient disturbance signal frequency matrix

Time-frequency matrix of voltage sag signal: Figure 5 is the S transform time-frequency matrix diagram of the transient disturbance signals of voltage sag stimulated by programming in the Matlab.

The time-frequency diagram of voltage sag reflects the real-time changes of sag signals on low and high frequency. From the simulation diagram we get that signals mainly concentrated around the base frequency of 50 HZ. With the increase or decrease of the frequency, signal amplitude becomes smaller and smaller, finally it comes to 0. When no sag disturbance happened near the base frequency, the time-frequency view of the signal would be a horizontal line. When there happened sag disturbance at the place of 0.15-0.25 S, the time-frequency view would be a drop waveform. The voltage is decreased by 0.3 p.u. Obviously, such kind of disturbance is sag disturbance. The simulation results show that the time-frequency diagram based on S-transform is a very successful realization of sag disturbance signal detection.

Time-frequency diagram of voltage rise signals: Figure 6 is the S-transform time-frequency matrix diagram

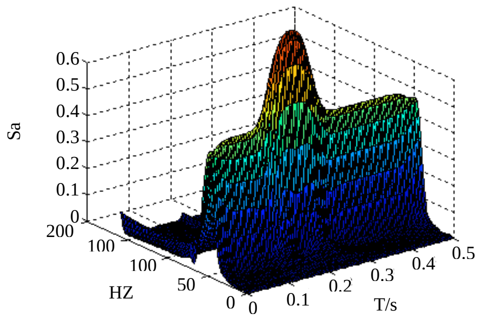

Fig. 6: S transform time-frequency diagram of voltage rise

of the transient disturbance signal of voltage rise stimulated by programming in the Matlab.

The time-frequency diagram of voltage rise reflects the real-time changes of rise signals on low and high frequency. From the simulation diagram we get that signals mainly concentrated around the base frequency of 50 HZ. With the increase or decrease of the frequency, signal amplitude becomes smaller and smaller, finally, it comes to 0. When no rise disturbance happened near the base frequency, the time-frequency view of the signal would be a horizontal line. When there happened a rise disturbance at the place of 0.15-0.25 S, the time-frequency view would be a rise waveform. The voltage is increased by 0.7 p.u. Obviously, this disturbance is rise disturbance. The simulation results show that the time-frequency diagram based on S transformation can be a very successful realization of rise disturbance signal detection.

Time-frequency diagram of voltage interruption signals: Figure 7 is the S-transform time-frequency matrix diagram of the transient disturbance signal of voltage interruption stimulated by programming in the Matlab.

The time-frequency diagram of voltage interruption reflects the real-time changes of rise signals on low and high frequency. From the simulation diagram we get that signals mainly concentrated around the base frequency of 50 Hz. With the increase or decrease of the frequency, signal amplitude becomes smaller and smaller, finally it comes to 0. When no interruption disturbance happened near the base frequency, the time-frequency view of the signal would be a horizontal line. When there happened an interruption disturbance at the place of 0.15-0.25 S, the time-frequency view would be a rapid drop waveform. The voltage is decreased by 0.995 p.u. Obviously, this disturbance is interruption disturbance. The simulation results show that the time-frequency diagram based on S transformation can be a very successful realization of interruption disturbance signal detection.

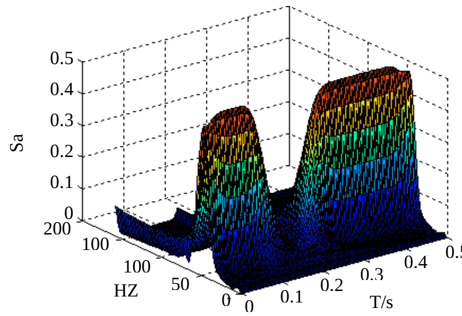

Fig. 7: S transform time-frequency diagram of voltage interruption

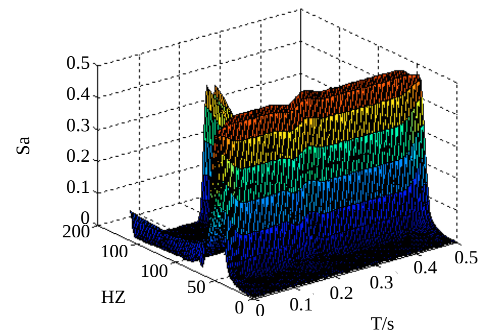

Fig. 8: S transform time-frequency diagram of transient oscillation

Time-frequency diagram of transient oscillation signals: Figure 8 is the S-transformed time-frequency matrix diagram of the transient disturbance signal of transient oscillation stimulated by programming in the Matlab.

The time-frequency diagram of transient oscillation reflects the real-time changes of rise signals on low and high frequency.From the simulation diagram we get that transient oscillation happened at the place of 0.085-0.115S. Its duration is 0.5 period. When the signal is at the base frequency of 50 HZ, the signal amplitude is the maximum and shows as a stable horizontal line. Where there is an oscillation, there is a minor rise of the signals. Different from the other three transient disturbance signals, there is a sudden rise of the signals in the triple base frequency corresponding oscillation place. Therefore, we can assure that such kind of disturbance is transient oscillation disturbance. The simulation results show that the time-frequency diagram based on S-transformation can be a very successful realization of interruption disturbance signal detection.

By comparison of the time-frequency diagrams of the three signals we can get that voltage sag, voltage rise and voltage interruption all do not contain high-frequency components and there is no change in the high-frequency sections of their corresponding S-transform amplitude matrix three dimensional diagrams. The S-transform amplitude matrix three dimensional diagram of transient oscillation reflects the changes of the current signals when oscillation happens in low and high frequency. By using S transform modulus time-frequency matrix, we can clearly and intuitively see the signal frequency components vary with time from the low frequency to high frequency. Experiments verify that different disturbance signals correspond to different S-transform time-frequency diagrams. Utilizing different S-transform time-frequency matrix diagrams, we can push forward the power quality disturbance detection.

CONCLUSION

This article focuses on the difficulty of the current power quality analysis-transient and non-stationary signal detection and analysis. It puts forward the detecting and analyzing method of S-transform whose time-frequency is reversible to extract the characteristics of power quality disturbance. Experiments show that the method can be used to detect and identify the common power quality transient disturbances such as voltage sags, voltage rises, voltage interruptions and transient oscillation. The power quality disturbance events used to test the effectiveness of the method in this paper are simulated calculation examples generated by controlled parameter randomly. The method is convenient and efficient. It conforms to the standards of the definition of disturbance and it is widely adopted method in domestic and foreign literatures at present. But we still need to use enough real samples to test and to verify its fieldwork ability.

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