

Classification of Composite Power Quality Disturbance Signals Based on HHT and S-Transform

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Abstract—The correct classification of single and composite power quality disturbances is the premise and basis of governance and control of power quality problems. This article extracts the high-frequency and low-frequency characteristics by S-transform of the disturbance signals, combining HHT to extract the instantaneous amplitude of the signal before and after the disturbance. Some characteristic functions is defined as the classification criterions by analyzing the characteristics of the disturbance signals, as to achieve the classification of power quality disturbances. Experimental results show that the fusion of the two methods can accurately detect the categories and characteristics of power quality disturbance signals, the starting and ending time of transient disturbance signals.

Keywords- Power quality disturbances; HHT; S-transform; Signal classification

I. INTRODUCTION

Along with the wide application of power electronic equipments, the power quality of distribution grid is polluted by various types of non-linear and impact load. At the same time, supplying higher power quality is also required by significantly increased detection, analysis and control of electrical equipments, which is based on computer and microprocessor. Power quality detection is the most important prerequisite for improving power quality^[1]. In order to classify the disturbance signals correctly, signal feature extraction is needed. The usual approach is primarily based on the transformation and reconstruction of the original waveform, extracting classification features, impelling a large number of signal processing methods applied to the detection of power quality problems. The most commonly used feature extraction method is Wavelet Transform^[2-7], Fourier Transform^[4], dq Transform^[8], S-transform^[9-12], Walsh Transform^[11] and HHT^[13] were also used for disturbance features extraction.

Currently, most studies of the power quality problems is for single disturbance, however, studies involve the analysis of composite disturbances is rare. The literature [14] [15] [16] discussed the harmonics and sag, harmonics and swell. In addition, the literature [17] is also referred to a composite

disturbance during the data analysis process, but did not indicate the specific type. In literature [18], based on mathematical morphology and grille fractal, a novel approach on power quality disturbance detection and location is presented. S-transformation is a time-frequency analysis method developed from CWT combining with STFT. It brings in the Gaussian window in which the width and frequency changes reversely and has the relevant resolution with frequency. HHT absorbed the advantages of Wavelet Transform's multi-resolution and overcame difficulties in selecting wavelet basis^[14], this method accessed the concept of the base function from the signal itself, which has a good self-adaptability^[15] directly.

In this paper, Matlab is used to simulate six kinds of single power quality disturbance signal and eight kinds of composite disturbance signal, including voltage sags, voltage swells, voltage interruption, transient shocks, voltage flicker, voltage harmonics, and composite disturbances, witch are created by mixing long-term disturbances(harmonics, flicker) and short-term disturbances (voltage swells, voltage sags, voltage interruption, transient shocks), in order to acquire the corresponding disturbance signals. We can get the instantaneous amplitude of these signals before and after the disturbance moment by means of HHT. On the other hand, we can use the result of S-transform of the disturbance signals to get the high-frequency and low-frequency characteristics to accurately detect power quality disturbance signals' categories and disturbance characteristics, as well as disturbance signals' starting and ending time.

II. HHT

HHT is a non-linear analysis method, which can be used for transient signals. The method is composed of EMD and Hilbert transform, the core part is EMD.

A. EMD decomposition and IMF function

EMD method assumes that every signal is formed by different intrinsic mode functions (IMFs) and each IMF is a set sequence of smooth linear or nonlinear data. Signal is decomposed into a set of intrinsic mode functions by EMD:

$$x(t) = \sum_{i=1}^n \text{imf}_i(t) + r_n(t) \quad (1)$$

B. Hilbert transform

The most important feature of HHT method is that each IMF component can be Hilbert transformed directly, in order to achieve the extraction of the signal's instantaneous parameters. Hilbert transform is defined as follows:

$X(t)$ is a continuous time series:

$$Y(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{X(\tau)}{t-\tau} d\tau = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{X(t-\tau)}{\tau} d\tau = x(t) * \frac{1}{\pi t} \quad (2)$$

$Y(t)$ can be regarded as the output of the filter of $x(t)$, and the inverse transform is:

$$X(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{Y(\tau)}{\tau-t} d\tau \quad (3)$$

Analytical form:

$$Z(t) = X(t) + jY(t) = a(t)e^{j\theta(t)} \quad (4)$$

$a(t)$ is the instantaneous amplitude, $\theta(t)$ is the instantaneous phase. The instantaneous frequency is:

$$f(t) = 1/2\pi(d\theta(t))/dt \quad (5)$$

III. THE BASIC PRINCIPLES OF S-TRANSFORM

S-transform was put forward by U.S. geophysicist Stockwell in 1996[12], concordance the advantages of short-time Fourier transform and Wavelet transform and avoided their shortcomings. It is a linear, multi-resolution and non-destructive reversible time-frequency analysis method.

S-transform (ST) of the signal $h(t)$ is defined as:

$$S(\tau, f) = \int_{-\infty}^{+\infty} h(t) \frac{|f|}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}(\tau-t)^2 f^2\right] \exp(-i2\pi ft) dt \quad (6)$$

$\frac{|f|}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}(\tau-t)^2 f^2\right]$ is Gaussian window; τ controls the location of Gaussian window on the time axis t ; f is for the frequency; i is the imaginary unit. We can see that S-transform is different from the short-time Fourier transform, as the height and width of the Gaussian window varies with frequency. It overcomes the defect that the height and width of STFT window is fixed.

Formula (6) can be discreted:

$$S(m, n) = \sum_{k=0}^{N-1} H(n+k) \exp\left(-\frac{2\pi^2 k^2}{n^2}\right) \exp(i2\pi km/N), n \neq 0 \quad (7)$$

$$S(m, n) = \frac{1}{N} \sum_{k=0}^{N-1} h[k], n = 0 \quad (8)$$

$$H(n) = \frac{1}{N} \sum_{k=0}^{N-1} h[k] \exp(-i2\pi kn/N) \quad (9)$$

For the discrete signal of N points $h[i]$ ($i = 0, 1, 2, \dots, N-1$), we can get the S-transform result as a matrix of $n+1$ rows and m columns using the formula(7) and (8), referred to as the S matrix. The columns of S matrix correspond to the sampling time points, the lines correspond to the sampling

frequencies. The first row ($n=0$) corresponds to the DC component of the signal and the frequency difference between adjacent rows is:

$$\Delta f = \frac{f_s}{N}, f_n = \frac{f_s}{N} n \quad (10)$$

N is the number of samples, f_s is the sampling frequency.

S modular matrix is obtained by module operation for each element of the S matrix. Its column vector represents the signal's amplitude-frequency characteristic at a particular moment. the row vector represents the time domain distribution of signal in a certain frequency component.

IV. FEATURE EXTRACTION OF POWER QUALITY DISTURBANCES

In this paper, the fourteen kinds of power quality disturbance characteristics are conformed to the IEEE standard^[16] and evenly distributed, including voltage sags, voltage swells, voltage interruption, transient shocks, voltage flicker, voltage harmonics, and composite disturbances, which are created by mixing long-term disturbances (harmonics, flicker) and short-term disturbances (voltage swells, voltage sags, voltage interruption, transient shocks). Various power quality disturbance signals are randomly generated, which is similar to the literature [22].

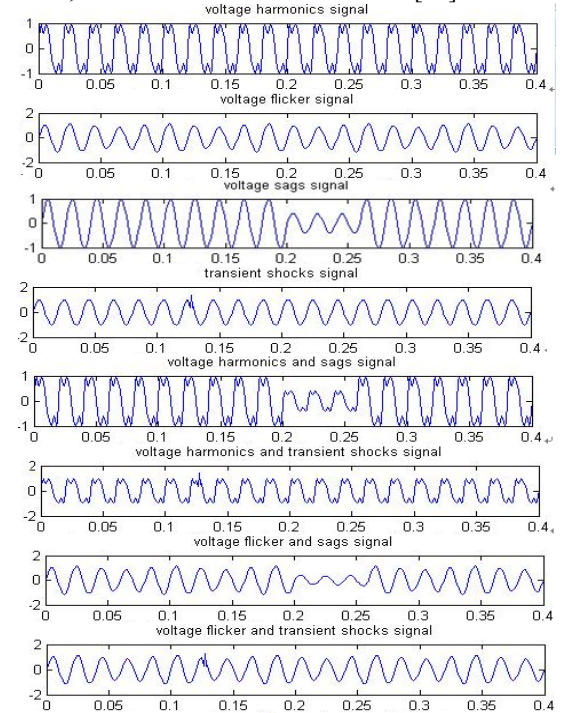


Figure 1. Figure1. Power quality disturbance signals

They are generated by Matlab, the sampling frequency is 1 kHz, the voltage fundamental frequency is 50Hz and the simulation length is 0.4 s. Among them, the voltage amplitude of voltage sags is randomly generated from 0.1(p.u.) to 0.9(p.u.), the voltage amplitude of voltage swells is randomly generated from 1.1(p.u.) to 1.8(p.u.). The

starting and ending times of short-term disturbances are randomly generated within a predetermined range, as shown in Figure 1. The analysis principles and performance of image for voltage sags have a similar nature with voltage swells and voltage interruption, so in Figure 1, Figure 2, Figure 3 and Figure 4, we just take voltage sags as a representative.

The S modular matrix can express the changes from low frequency to high frequency of signals' characteristic clearly and intuitively, so it is available to use the S-transform for the feature extraction of power quality disturbance signals. After the transformation of the signal by HHT, it can clearly reflect the instantaneous amplitude of the voltage signals before and after the disturbance moment. The disturbance's starting and ending time of short-term signals can be worked out by the instantaneous frequency of imf1, which is obtained by the result of EMD. We can also get them by the high-frequency amplitude characters of S modular matrix. For the convenience of features' extraction, the following characteristic functions and values are defined:

- The function of amplitude of the time-varying fundamental frequency $V_{fb}(t)$

$V_{fb}(t)$ is defined in S modular matrix, corresponding to the amplitude of the fundamental frequency (50Hz in this article) changing over time.

$$V_{fb}(t) = S_a(t, f_b) \quad (11)$$

Where t represents the sampling time, fb is the fundamental frequency (50Hz in this article).

- The average value of amplitude for the fundamental frequency F_{bav}

$$F_{bav} = \frac{1}{L} \sum_{l=1}^L S_a(t, f_b) \quad (12)$$

L is the number of samples.

- Maximum/minimum of fundamental frequency's amplitude F_{bmax} / F_{bmin}

$$F_{bmax} = \max[V_{fb}(t)] \quad F_{bmin} = \min[V_{fb}(t)] \quad (13)$$

- Characteristic time-varying function of high-frequency's amplitude $V_{fh}(t)$

$V_{fh}(t)$ is defined in S modular matrix, corresponding to the mean square of the amplitude of the high frequencies changing over time. The minimum frequency value is more than two times the fundamental frequency's, and its expression is as follows:

$$V_{fh}(t) = \frac{1}{n-m} \sum_{f_h=m}^n [S_a(t, f_h)^2] \quad (14)$$

For S_a , n is the total number of rows, that is, the number of frequencies which can be analyzed; m is the row's number of the frequency whose value is 2 times of the fundamental frequency's. The mold square for frequency values in the matrix is to reduce the impact of noise in the signal processing.

- Mean of high-frequencies' amplitude in S modular matrix

It is defined as the mean of $V_{fh}(t)$, namely, it is the mean square of the high-frequency component's amplitude in the entire time period, as the following expression shows:

$$F_{hav} = \frac{1}{L} \sum_{l=1}^L V_{fh}(t) = \frac{1}{L} \sum_{l=1}^L \frac{1}{n-m} \sum_{f_h=m}^n [S_a(t, f_h)^2] \quad (15)$$

- Maximum of Characteristic time-varying function of high-frequency's amplitude F_{hmax}

$$F_{hmax} = \max[V_{fh}(t)] \quad (16)$$

- The short-term disturbance's starting time T_s , ending time T_e

The short-term disturbance's starting time is T_s and the termination time is T_e

- The instantaneous amplitude's flatness during non-transient disturbance moment F_{ba} :

$$F_{ba} = |(AF_{max} - 1) - (AF_{min} - 1)| \quad (17)$$

Where AF_{min} / AF_{max} is the maximum/ minimum of the instantaneous amplitude during non-transient disturbance moment.

- Degree of change of the fundamental frequency's amplitude F_{mm}

If the signal is a stable sine wave, its amplitude of the fundamental frequency would always be 1 by S-transform. The characteristic function is defined as the maximum amplitude of the fundamental frequency minus the minimum one:

$$F_{mm} = |\max[V_{fb}(t)] - 1| - |\min[V_{fb}(t)] - 1| \quad (18)$$

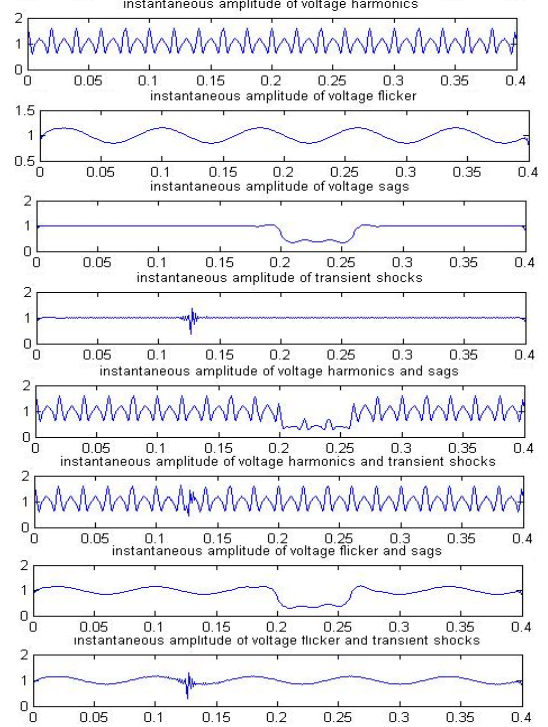


Figure 2. Instantaneous amplitude of disturbance signals after HHT

Figure 2 shows the instantaneous amplitude of power quality disturbance signals after HHT. From the diagram, we can see the corresponding changing process of signal's amplitude. After S-transform, Figure 3 and 4, respectively

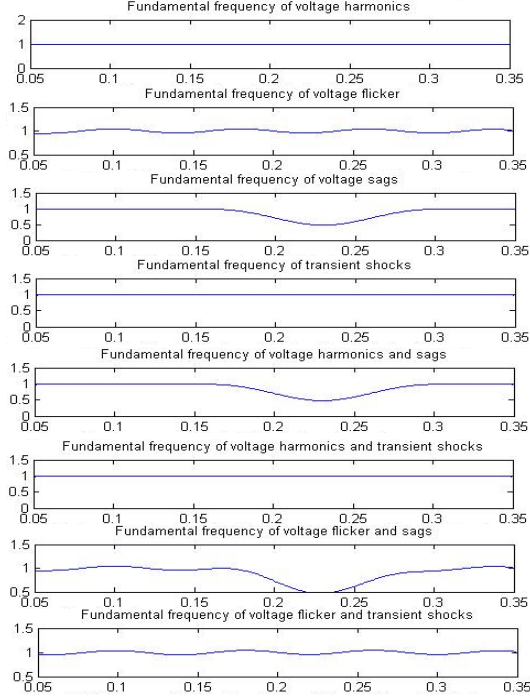


Figure 3. Fundamental frequency of disturbance signals after S-transform

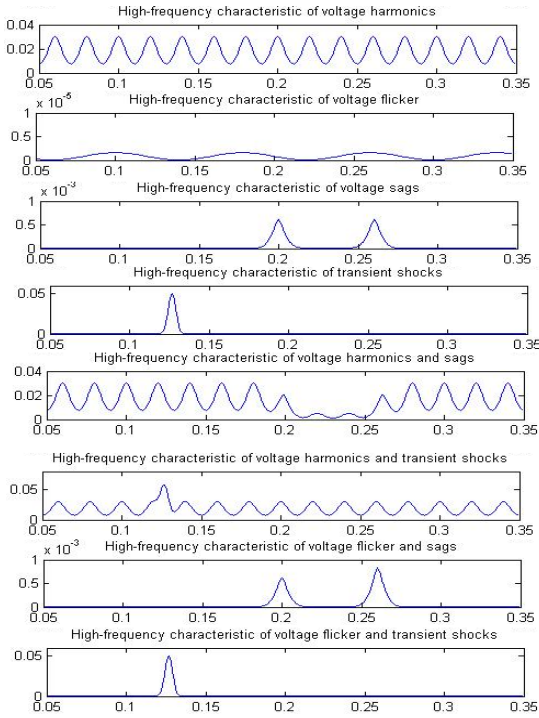


Figure 4. High-frequency characteristic of disturbance signals after S-transform

show the fundamental frequency amplitude curve and the high-frequency time-varying function $V_{fh}(t)$ curve of the disturbance signals. From the two plots, we can see the fundamental frequency's characteristic, the size of the high-frequency component and the corresponding time, which are contained in disturbance signals. In Figures 2, 3 and 4, we have omitted the end data portions of the image, in order to avoid the impact of end effect, so did the algorithm in this article.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

V. RECOGNITION AND CLASSIFICATION OF POWER QUALITY DISTURBANCE SIGNALS

The disturbance signals' amplitude, containing voltage sags and voltage interruption, shows a cave shape, the instantaneous amplitude of signals, containing voltage swells, shows a convex shape. According to the standard for the description of the various power quality disturbances[23], which is recommended by IEEE 22 Standard Commission, classification as follows (refer to Figure 5): The value of disturbance signal's F_{bav} , including voltage sags or interruption, will be significantly lower than the corresponding values of the other, in this article, we take 0.99 as the demarcation point to complete the classification 1-1; According to the power system electromagnetic phenomena characteristic parameters and classification, developed by the IEEE, the frequency components of voltage harmonic present in the entire time period, while the high-frequency components of the transient shocks exist only within a short time (less than 50ms). Therefore, the mean of high-frequencies' amplitude F_{hav} of voltage harmonics is much larger than the other corresponding values, 0.005 is taken as the cut-off point to complete classification 2-2, 3-1 and 3-2; The decline values of disturb signals containing voltage interruption have varying degrees with sags, which can be distinguished by F_{bmin} , we take the absolute value 0.1 as the cut-off value to complete classification 3-3 and 3-4; The F_{ba} of disturber signals containing voltage flicker, the instantaneous amplitude's flatness during non-transient disturbance moment, is significantly higher than other signals', 0.05 is the cut-off value in this article, completing classification 4-2,4-3,5-2; The F_{bmax} of signals containing voltage flicker or swells, maximum of fundamental frequency's amplitude, will be higher than the other signals', this paper take 1.01 as categorical values to complete the classification 2-1; In the classification 4-1, F_{mm} of signals containing voltage swells will be significantly higher than the others', the value of 0.1 could be the point to achieve this classification; Voltage signals containing transient oscillation will have a large number of high-frequency components in a short time, however, voltage containing flicker does not. We take 0.001 of F_{hmax} as the demarcation point for classification 5-1.

According to the above classification process, the logic for classification and identification of the fourteen power quality disturbance signals is given, as shown in Figure 5:

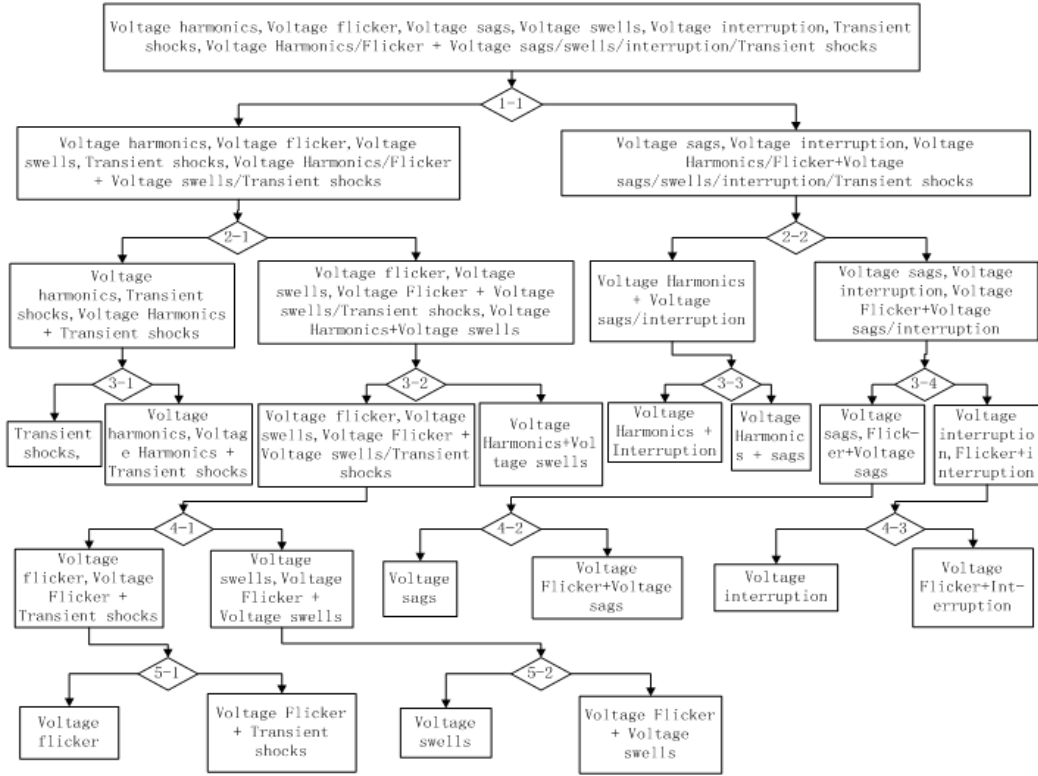


Figure 5. Classification logic diagram of power quality disturbances

In order to verify the effectiveness of the method of this classification, the article conducts several experiments in which the signals are randomly generated within a

predetermined range. Table 1 illustrates one set of experimental data.

TABLE I. EXPERIMENTAL DATA

Eigenvalues	Fbav	Fbmax	Fhav	Fbmin	Fmm	Fba	Fhmax	Ts	Te
Voltage harmonics	0.9986	0.9999	0.0178	0.9756	0.0243	0.9711	0.0304	1e-4	0.400
Voltage flickers	0.9985	1.0433	8.319e-7	0.9461	0.0972	0.3011	1.6145e-6	1e-4	0.400
Voltage sags	0.8795	0.9999	4.0828e-5	0.4789	0.5210	0.0073	6.1644e-4	0.194	0.270
Voltage swells	1.1183	1.5209	4.1104e-5	0.9756	0.5453	0.0107	6.1714e-4	0.155	0.229
Voltage interruption	0.7396	0.9997	9.1632e-4	0.0703	0.9294	0.0102	0.0181	0.157	0.254
Transient shock	0.9966	0.9999	7.7766e-4	0.9755	0.0243	0.0322	0.0504	0.112	0.145
Harmonics and sags	0.8796	0.9999	0.0149	0.4791	0.5207	0.9690	0.0304	0.190	0.268
Harmonics and swells	1.1183	1.5206	0.0234	0.9756	0.5450	0.9746	0.0779	0.151	0.226
Harmonics and interruption	0.7405	0.9997	0.0137	0.0704	0.9294	0.9694	0.0366	0.163	0.261
Harmonics and transient shock	0.9966	0.9999	0.0188	0.9756	0.0243	0.9967	0.0580	0.110	0.147
Flicker and sags	0.8832	1.0433	4.8272e-5	0.4731	0.5702	0.3008	8.2559e-4	0.196	0.268
Flicker and swells	1.1216	1.5856	3.5885e-5	0.9461	0.6394	0.3034	6.3390e-4	0.157	0.223
Flicker and interruption	0.7403	1.0423	9.905e-4	0.0710	0.9713	0.2981	0.0196	0.158	0.251
Flicker and transient shock	0.9965	1.0433	9.765e-4	0.9461	0.0972	0.3145	0.0504	0.115	0.139

It can be concluded that the above experimental data of power quality disturbances can accurately classify the types of disturbance signals according to the above logic method. We can also observe the amplitude before and after the disturbance moment, starting and ending time based on the detection data in the table.

VI. SUBMISSION

This paper extracts the instantaneous amplitude as well as the low-frequency and high-frequency characteristics of the disturbance signals, basing on the HHT and S-transform of thirteen kinds of power quality disturbance signals including

six kinds of single power quality disturbance signals and eight kinds of composite disturbance signals. We also have accurately detected the categories and characteristics of the disturbance signals, as well as their starting and ending time. Multigroup experimental results have showed that the classification logic in this paper is appropriate for the thirteen kinds of power quality disturbance signals' classification, meanwhile, we need to further study that how to distinguish voltage harmonics and voltage harmonics with transient shocks.

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