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A Quick Classification Method of the Power Quality Disturbances

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Abstract

This paper introduces a quick classification method of the power quality disturbances. Based on analyzing the characteristics of different electrical disturbance signals in time domain, four distinctive features are extracted from electrical signals for classifying different power quality disturbances and then an automatic classifier is proposed. Using the proposed classification method, a PQ monitor of the classifying power quality disturbances is developed based on the TMS320F2812 DSP micro-processor. Semi-physical simulation, lab experiment and field measurement results have verified that this proposed method can classify single or complex disturbance signals effectively.

Keywords

Power Quality, Disturbance Classification, Noise

1. Introduction

To detect and improve power quality, we first need to monitor and analyze the power quality disturbances. There have been many methods presented, such as Fourier transform [1], wavelet transform [2]-[4], S transform and so on. The Fourier transform is suitable to analyze stationary signals, and has a good effect on stationary disturbance like harmonics; the wavelet transform has advantage of analyzing singularity and nonstationary signals [5] [6]; S transform is the inheritance and development of short-time Fourier transform and wavelet transform. So it has the advantages of the both [7]-[11]. And it analyzes signal features more comprehensively and it has been a hot research tool of power quality disturbance classification. They are all the time frequency transform methods. This paper presents a method based on the time domain analysis of the power quality disturbance signals and it has some advantages compared to the time frequency transform methods. It will be discussed in details in Section 4.

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2. The Analysis of Power Quality Disturbances in Time Domain

The general single-phase voltage signal can be expressed as the superposition of the fundamental wave voltage and the disturbance signals:

$$u(t)=\sqrt{2}U_1\sin(\omega t+\varphi_1)+\sqrt{2}\sum_{h=2}^{n}U_h\sin(h\omega t+\varphi_h)+\sum_{s=1}^{m}\sqrt{2}U_s\sin(\omega_s t+\varphi_s)\mathrm{e}^{-\gamma_s(t-t_s)}1(t-t_s) \quad (1)$$

where U_1 is the RMS (root mean square) voltage with the system fundamental frequency; ω is the system fundamental angular frequency; φ_1 is the initial phase angle; U_h is the h_{th} harmonic RMS voltage; φ_h is the h_{th} harmonic initial phase angle; ω_s is the angular frequency between harmonic waveforms and not an integer multiple of the system fundamental frequency, for example, the frequencies of interharmonics and oscillatory transients; U_s is the ω_s RMS voltage with ω_s angular frequency; φ_s is the initial phase angle of the ω_s angular frequency voltage; γ_s is the oscillatory transient attenuation constant. When $\gamma_s=0$, U_s is the interharmonic RMS voltage and when $\gamma_s\neq 0$, U_s is the oscillatory transients RMS voltage; t_s is the starting time; l(t) is the unit step function. **Table 1** shows that characteristics of the disturbances which IEEE classified [12]. All the simulation parameters in this paper are chosen from **Table 1** randomly.

In Equation (1), when U_1 is stationary, equal to the rating value and

$$\sqrt{2}\sum_{h=2}^{n}U_h\sin(h\omega t+\varphi_h)+\sum_{s=1}^{m}\sqrt{2}U_s\sin(I_s\omega t+\varphi_s)\mathrm{e}^{-\gamma_s(t-t_s)}1(t-t_s)=0,$$

Equation (1) represents the ideal voltage. So the voltage disturbance can be divided into two categories. One is the disturbances with the change of the U_1 amplitude, including voltage sag, swell, interruption, under voltage, over voltage, fluctuation, flicker and so on. The other is the additive disturbances, including harmonics, oscillatory transients, impulse voltage, interharmonics and so on. From the aspect of disturbance duration, we can also divide the disturbances into two categories. One is stationary disturbance, including voltage fluctuation and flicker, under voltage, over voltage, continuous interruption, harmonics, interharmonics and so on. The other is transient disturbances, including voltage sag, swell, instantaneous interruption, oscillatory transients, impulse voltage and so on. So the power quality disturbances can be divided into four categories by time domain features, shown in **Table 2**.

For voltage sag, swell and interruption has the similar characteristics, the author only takes voltage sag as the analyzing object. The other two can also be identified by the method presented in this paper.

If $u(t)$ in Equation (1) is multiplied by $\sqrt{2}\sin(\omega t+\varphi_1)$, we can get:

$$u(t)*\sqrt{2}\sin(\omega t+\varphi_1)=u_{1d}+u_{1i}(t)+u_{1un}(t) \quad (2)$$

Table 1. Typical characteristics of power system disturbances.

Disturbances	Typical spectral content	Typical duration	Typical voltage magnitude
Voltage sag		0.5 cycles - 1 min	0.1 - 0.9 pu
Fluctuation and flicker	<25 Hz	Intermittent	0.1% - 7%
Harmonics	0 - 100th Hz	Steady state	0% - 20%
Oscillatory transients	<5 kHz	0.3 - 50 ms	0 - 4 pu
Interharmonics	0 - 6 kHz	Steady state	0% - 2%

Table 2. The categories of the voltage disturbance.

Voltage amplitude disturbances	Stationary	Fluctuation and flicker, under voltage ,over voltage
	Transient	Voltage sag, swell, transient interruption
Additive disturbances	Stationary	Harmonics, interharmonics
	Transient	Oscillatory transients, impulse voltage

where, $u_{1d} = U_1 - U_1\cos(2\omega t + 2\varphi_1)$, and $U_{1d} = \int_0^T u_{1d}\mathrm{d}t = U_1$

$$u_{1i} = U_1\cos(2\omega t + 2\varphi_1) + \sum_{h=2}^{N} U_h\left\{\cos\left[(h-1)\omega t + \varphi_h - \varphi_1\right] - \cos\left[(h+1)\omega t + \varphi_h + \varphi_1\right]\right\}, \text{ and } U_{1i} = \int_0^T u_{1i}\mathrm{d}t = 0$$

$$u_{1un} = \sum_{s=1}^{m} U_s\left\{\cos\left[(I_s\omega - \omega)t + \varphi_s - \varphi_1\right] - \cos\left[(I_s\omega + \omega)t + \varphi_s + \varphi_1\right]\right\}\mathrm{e}^{-\gamma_s(t-t_s)}1(t-t_s), \text{ and } U_{1un} = \int_0^T u_{1un}\mathrm{d}t \neq 0$$

Equation (2) consists of three parts. First is DC component u_{1d}. Second is an AC component u_{1i} with an integer multiple system frequency. Third is an AC component u_{1un} with a non-integer multiple system frequency. After a full cycle (0 - T) integral of the (2) we can see that $U_{1i} = 0$, and some AC components still exist in U_{1un}. **Figure 1** is the curve of the full cycle integral of (2). In **Figure 1(a)** and **Figure 1(b)** only contain U_{1d}. **Figure 1(c)** contains U_{1d} and U_{1i} $(U_{1i} = 0)$. **Figure 1(d)** and **Figure 1(e)** contain U_{1d} and U_{1un}. For u_{1un} is the sine wave AC value of non-integer multiple system frequency, after a full cycle integral $U_{1un} \neq 0$. It shows the existence of the sine wave AC disturbance of non-integer multiple system frequency. The simulation parameters of the following pictures are chosen in the range of **Table 1**.

The square of Equation (1) is:

$$u(t) * u(t) = u_d + u_i + u_{un} \tag{3}$$

The expanded formula of (3) is long, but also is consists of three parts: DC component u_d, an AC component u_{1i} with an integer multiple system frequency, an AC component u_{1un} with a non-integer multiple system frequency. In it:

$$U_d = \int_0^T u_d\mathrm{d}t = U_1^2(t) + \sum_{h=2}^{N} U_h^2 + \sum_{s=1}^{m} U_s^2\mathrm{e}^{-2\gamma_s(t-t_s)}1(t-t_s) \tag{4}$$

The curve of a full cycle integral of (3) is shown in **Figure 2**.

By comparing **Figure 1** and **Figure 2**, we can find that **Figure 1(a)** and **Figure 1(b)** are the same with **Figure 2(a)** and **Figure 2(b)** because there is no additive disturbance in the voltage sag and fluctuation and flicker. The harmonics is additive disturbance, so the U_d/U_N in **Figure 2(c)** is larger than U_1/U_N in **Figure 1(c)**. And the difference between them is the amplitude of the additive disturbance $\sqrt{\sum_{h=2}^{N} U_h^2}$. The oscillatory transients and interharmonics are the additive disturbances. So the U_d/U_N in **Figure 2(d)** and **Figure 2(e)** is larger than the U_1/U_N in **Figure 1(d)** and **Figure 1(e)**. And the difference is also the amplitude of additive disturbance $\sqrt{\sum_{s=1}^{m} U_s^2\mathrm{e}^{-2\gamma_s(t-t_s)}1(t-t_s)}$.

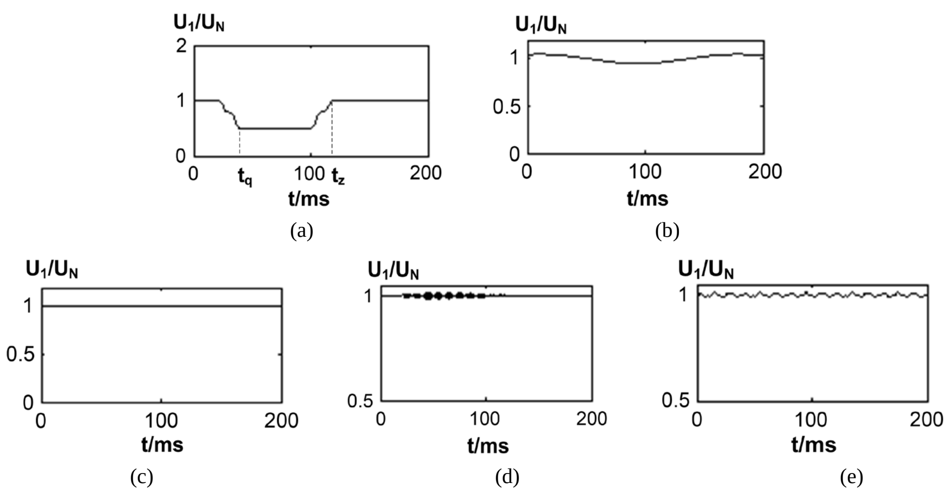


Figure 1. The curve of full cycle integral of (2). (a) Voltage sag; (b) fluctuation and flicker; (c) harmonics; (d) Oscillatory transients; (e) Interharmonics.

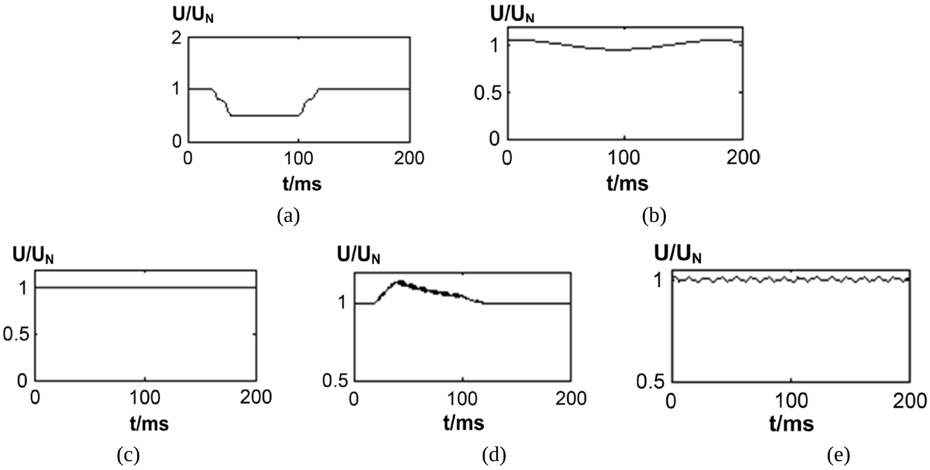


Figure 2. The curve of full cycle integral of (3). (a) Voltage sag; (b) Fluctuation and flicker; (c) Harmonics; (d) Oscillatory transients; (e) Interharmonics.

3. Basic Idea of the Classification of the Power Quality Disturbances

Though above analysis, some individual features of the power quality disturbance singles can be shown in time-domain:

1) Equation (2) has the effect of selecting system fundamental frequency. The DC component, which can be gotten by low pass filter from Equation (2), is the RMS voltage with system fundamental frequency, which is not affected by additive disturbance. And its change is equivalent to the amplitude disturbance of the RMS voltage (like voltage sag, swell, transient interrupt, under voltage, over voltage, continuous interrupt, fluctuation, flicker and so on).

2) The DC component of Equation (3) is the geometric sum of the RMS voltage with system fundamental frequency and all other additive disturbance RMS voltages. So the geometric difference of the Equation (3) and Equation (2)'s DC component is exactly equivalent to the amplitude of the additive disturbance (like harmonics, oscillatory transients, impulse voltage and interharmonics).

3) **Figure 1(d)** and **Figure 1(e)**'s curves contain U_{1d} and U_{1un}.The component U_{1un} exists usually because of the existence of the interharmonics and the oscillatory transients which are non-integer system fundamental frequency sine wave signal. $U_{1un} \neq 0$ indicates the existence of the interharmonics or oscillatory transients.

So, the next 4 features (F_1 - F_4) can be used to classify power quality single disturbances and the mixed disturbances can be considered as the "superposition" of the single disturbances. The calculating flow chart of the 4 features is shown in **Figure 3**.

1) $F_1 = U_1'/U_N$ is taken as a feature after Equation (2) is filtered by a low pass. Because of the (2)'s effect of frequency selection, F_1 is the system fundamental wave voltage amplitude variation value which is not affected by additive disturbance. It reflects the extent of the fundamental wave amplitude change. So the information of system fundamental RMS voltage change can be known from the extent of the F_1 change. Then it can be used to identify whether there are the voltage sag, swell, instantaneous interruption, under voltage, over voltage, continuous interruption, fluctuation and flicker in electrical singles (shown in **Table 3**).

2) $F_2 = \frac{100}{N}\sum_{k=1}^{N}\sqrt{\left[U^2(k) - U_1^2(k)\right]/U_1^2(k)}$. N is the total sample points during the analysis period of time τ (for F_2 is used to detect stationary additive disturbances, the analysis period of time can be enlarged. This paper takes $\tau = 2\text{ s}$, 100 cycles). F_2 is the RMS value of the additive disturbance during the analysis period of time τ. If $F_2 > 0$, the additive disturbance must exist. If F_2 is stationary, the disturbance must be harmonics and F_2 is equivalent to THD. $F_2 > 1.5$ can be the threshold value of the harmonics and interharmonics.

3) If $F_2 > 0$, $F_3 = \frac{100}{N}\sum_{k=1}^{N}\left|U_1(k) - U_1(k-1)\right|$ means the average increment of the U_{1un}. It can be used to classify the additive disturbances harmonics and interharmonics. If interharmonics exist in Equation (2), the curve of U_{1un} will contain AC component of non-integer system fundamental frequency (shown in **Figure 1(c)**

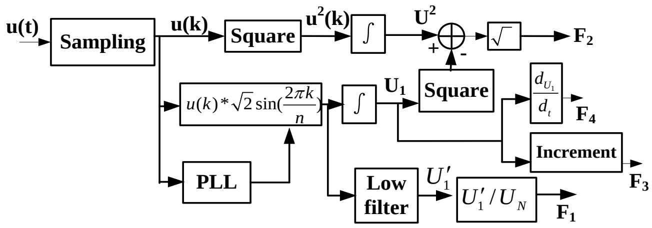


Figure 3. The flow chart of calculating classification features.

Table 3. Amplitude change disturbance classifications with F_1.

c	F_1 = 1.1 - 1.2 pu, duration > 1 min
Under voltage	F_1 = 0.8 - 0.9 pu, duration > 1 min
Voltage interruption	F_1 < 0.1 pu, duration: 10 ms - 3 s instantaneous interruption; 3 - 60 s temporary interruption; >60 s power off
Voltage sag	F_1 = 0.1 - 0.9 pu, duration 10 ms - 1 min
Voltage swell	F_1 = 1.1 - 1.8 pu, duration 10 ms - 1 min
Fluctuation and flicker	F_1 is voltage fluctuation in 0.9 - 1.1 pu randomly

and **Figure 1(e)**). Then value of F_3 is much larger than that when only harmonics exist. The MATLAB simulation shows that when $F_3 \geq 1$, interharmonics exist; when $F_3/F_2 \geq 0.5$, only interharmonics exist; when $F_3/F_2 < 0.5$, both harmonics and interharmonics exist.

4) $F_4 = \text{Max}\left\{\left|U_1(k) - U_1(k-1)\right|\right\} - F_3$. F_4 is the maximum differential value of U_{1un}. The characteristic that the amplitude of instantaneous disturbance changes fast determines F_4 a large number. But to stationary disturbance, F_4 is small or even zero. The value of F_4 can determine the instantaneous disturbances exist or not. The MATLAB simulation shows that the threshold can be 15. If $F_4 > 15$, the instantaneous disturbance exists; if $F_4 < 15$, no instantaneous disturbance exists. For instance, when F_1 shows amplitude disturbance exists, if $F_4 > 15$, the disturbance should be instantaneous amplitude disturbance such as the voltage sag, swell, instantaneous interruption, and if $F_4 < 15$, the disturbance should be stationary amplitude disturbance such as under voltage, over voltage, fluctuation and flicker and when F_1 shows no amplitude disturbance exists, if $F_4 > 15$, the disturbance must be the additive instantaneous disturbance such as oscillatory transient.

Table 4 shows the simulation value of 5 single disturbances and 4 mixed disturbances. **Figure 4** is the flow chart of the automate classification of the disturbances.

Disturbances can be classified into two categories: voltage amplitude disturbance and additive disturbance as shown in **Table 2**. F_1 is used to identify whether voltage amplitude disturbances exist, and F_2 is used to identify whether additive disturbances exist. F_3 is used to identify whether (there is interharmonics in additive disturbances) interharmonics exist when $F_2 > 1.5$. In the disturbances classification, it is very hard to identify the circumstance that both harmonics and interharmonics exist. The interharmonics have effect on F_2 and F_3. When the interharmonic disturbance is heavy, F_3 is large, and F_2 is large, too. So F_3/F_2 is relatively steady. When harmonics and interharmonics both exist, F_3/F_2 is smaller than that when only interharmonics exist. A lot of simulation results indicate that F_3/F_2 can identify the circumstance that both harmonics and interharmonics exist correctly. F_4 is used to identify whether transient disturbances exist.

4. Discussion

Comparing with the other power quality disturbance classification methods using some kinds of transforms, the method presented by this paper has advantages as follows:

1) The single disturbance can be identified by one feature or the combination of some features. That means if one feature or some features satisfied some conditions, a disturbance or mixed disturbances can be sure. Then the disturbance classification will not be probable, but be definitive and the correct rate of the disturbance classification would be very high. And it makes the classification simpler. For example, as shown in **Figure 4**, if

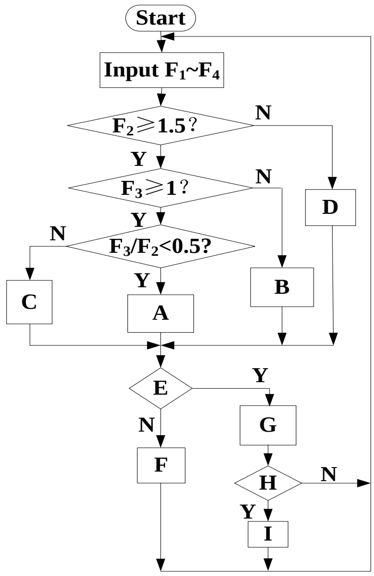


Figure 4. The flow chart of the automate classification. A: Harmonics + Interharmonics; B: Harmonics; C: Interharmonics; D: No stationary additive disturbance; E: $F_1 = \text{Constant} \approx 1$ pu ?; F: Identify the amplitude disturbances by F_1; G: No amplitude disturbance; H: $F_4 > 15$?; I: Osillatory transients.

Table 4. The simulation value of the features.

The disturbances	The disturbance parameters	F_2	F_3	F_4
Fluctuation and flicker	Amplitude: 0.95 - 1.05	0.68	0. 91	1.96
Voltage sag	Sag amplitude: 0.5 pu	0.49	0. 40	38.66
Harmonics	*5th 4%; 7th 3%	5.0	0	0
Oscillatory transients	M_s = 0.8 pu, f_s = 1025 Hz; U_s = 0.1	0.49	0.22	59.95
Interharmonics	f = 125 Hz, amplitude 2%	1.99	1.27	1.78
Voltage sag and harmonics	0.5 pu, 5th 4%; 7th 3%	5.41	0. 40	39.45
Fluctuation and harmonics	Amplitude: 0.95 - 1.05; 5th 4%; 7th 3%	5.05	0. 91	1.31
Harmonics and oscillatory transients	5th 4%; 7th 3%, γ_s = 0.1, U_s = 0.8 pu, f_s = 1025 Hz	5.34	0. 22	59.92
Harmonics and interharmonics	5th 4%; 7th 3%; f_s = 125 Hz, U_s = 2%	5.37	1.27	1.73

$F_2 \geq 1.5$ and $F_3 < 1$, only harmonics exist; if $F_2 \geq 1.5$, $F_3 \geq 1$ and $F_3/F_2 \geq 0.5$, only interharmonics exist; if $F_2 \geq 1.5$, $F_3 \geq 1$ and $F_3/F_2 < 0.5$, both harmonics and interharmonics exist.

2) The features extracted from one disturbance won't change a lot for the existence of the other disturbance. This is shown clearly in **Table 4**. For example, when the voltage sag and harmonics both exist, F_1 which is used to identify voltage sag won't change for the existence of harmonics. And F_2 (only harmonics exist, $F_2 = 5.0$), which is used to identify harmonics changes a little by the existence of voltage sag (harmonics + voltage sag, $F_2 = 5.41$). When the oscillatory transients exist in harmonics, F_2 increases a little (from 5.0 to 5.23). The harmonics and interharmonics are both additive disturbances, so F_2 is the approximate geometric summation of their amplitude ($\sqrt{4^2+3^2+2^2} = 5.39$, the simulation result in **Table 4** is 5.37). For another example, F_4 which is used to identify transient voltage sag $(F_4 = 38.66)$ and oscillatory transients $(F_4 = 59.95)$ will not change a lot for the existence of harmonics (voltage sag + harmonics, $F_4 = 39.45$; oscillotary + har-

monics, $F_4 = 59.92$). This characteristic of the features is the key of the classifying the mixed disturbances. For the idea of this paper considers the mixed disturbances as the "superposition" of the single disturbances. For the characteristics above, all single or mixed disturbances can be classified correctly by simple classifying program, and the classifying results won't conflict and are definitive.

3) The classifying features have clear physical meanings. So it profits the evaluation of the power quality disturbance. The physical meaning of F_1 is the per unit value of the system fundamental RMS voltage, so the amplitude of all the voltage amplitude disturbances can be gained from F_1. And the starting time t_q and the ending time t_z of the transient amplitude disturbance can also be gained from F_1 (shown in **Figure 1**). The physical meaning of F_2 is the content of the additive disturbances. So F_2 gives the content of the harmonics and interharmonics accurately. The oscillatory amplitude and the attenuation constant of the oscillatory transients can be gained by fitted method from **Figure 2(d)**.

4) The calculating time is much less, and profits to be used in real-time power quality disturbance classification.

5) The features extracted are low-pass filtered or the full cycle integral values, so it has good ability of noise proof.

5. Verifications

Using the proposed power quality disturbance classification method, a PQ monitor is developed based on the TMS320F2812 DSP micro-processor. Semi-physical simulation, lab experiment and field measurement results have verified the proposed method.

5.1. Semi-Physical Simulation Results

The authors use D space semi-physical experiment platform as the disturbance signal generator. The PQ monitor samples the signals generated by D space, identifies disturbances and evaluates their parameters. **Table 5** shows that it identifies the disturbance types correctly and evaluates their parameters accurately.

Table 5. The experiments results.

The disturbance type	The experiments times	The correct ratio of identifying the disturbance type	The average error of the parameters evaluation
The voltage sag	100	100%	2.12%
The fluctuation and flicker	100	99%	3.01%
The harmonics	100	98%	2.00%
The oscillatory transients	100	98%	2.45%
The interharmonics	100	97%	6.33%
The harmonics + The voltage sag	100	100%	3.58%
The harmonics + The fluctuation and flicker	100	96%	2.99%
The harmonics + The oscillatory transients	100	100%	3.07%
The fluctuation and flicker + The voltage sag	100	100%	4.28%
The fluctuation and flicker + The oscillatory transients	100	100%	4.14%
The interharmonics + The voltage sag	100	100%	2.78%
The interharmonics + The oscillatory transients	100	99%	2.99%
The interharmonics + The fluctuation and flicker	100	96%	3.46%
The interharmonics + The harmonics	100	97%	2.53%
The interharmonics + The harmonics + The voltage sag	100	99%	4.01%
The interharmonics + The harmonics + The voltage sag + The fluctuation and flicker	100	98%	3.98%

The authors give three types of disturbances: the voltage sag, the voltage sag plus harmonics, the fluctuation plus harmonics plus interharmonics plus voltage sag to present 5 single disturbances and 11 mixed disturbances.

1) The voltage sag

In the following tables the same symbols have the same meanings.

Table 6 doesn't give the true or false results because the PQ monitor gives the correct results every time. **Table 6** shows that the PQ monitor can evaluate the voltage sag parameter very well. The relative error is a little big when the voltage sag amplitude is close to the voltage sag threshold value, but the absolute error is not big.

2) The voltage sag plus harmonics

The authors do not show the identifying results in **Table 7**, for all harmonics plus voltage sag are identified by the PQ monitor correctly. **Table 7** shows that the superposed disturbance doesn't make the features change a lot, which means the features F_2 and F_3 are relatively independent. The identifying results and the parameters evaluation are not affected by the superposition of the disturbances.

3) The fluctuation plus harmonics plus interharmonics plus voltage sag

Table 8 shows that the addition of the fluctuation and flicker affects the feature F_2 a little, but doesn't affect the feature F_3. The big amount of harmonics may blanket the existence of interharmonics, because the identifying term of the harmonics plus interharmonics is $F_3/F_2 > 0.5$.

5.2. Lab Experiment Results

A lab experiment circuit is shown as **Figure 5**. When the switch S is turned on, there is voltage sag on R_1. The voltage signal u_1 is sampled by the PQ monitor and the oscilloscope.

$U = 380$ V, $R_1 = 1$ kΩ, $R_2 = 2$ kΩ, $R_3 = 3.9$ Ω. S is an AC contact. FU is a fuse. When S is turned on and the current of the FU branch is large enough, the FU will blowing out and the branch will be cut off. Then there will be a voltage sag in u_1 as shown in **Figure 5(b)**.

The experiment results shown in **Table 9** indicate that the PQ monitor can identify disturbances correctly and evaluate the voltage sag lasting time and amplitude accurately.

Table 6. The experiments results of voltage sag.

t_m (ms)	t_s (ms)	e_t	a_m (pu)	a_s (pu)	e_a
35	40	5	0.112	0.1	0.012
53	60	7	0.211	0.2	0.011
77	80	3	0.305	0.3	0.005
98	100	2	0.360	0.35	0.01
116	120	4	0.389	0.40	0.011
138	140	2	0.447	0.45	0.003

t_m: The voltage sag lasting time measured by the PQ monitor; t_s: The setting time of the voltage sag lasting time; e_t: The error between time 1 and time 2; a_m: The voltage sag amplitude measured by the PQ monitor; a_s: The setting amplitude of voltage sag amplitude; e_a: The error between amplitude 1 and amplitude 2.

Table 7. The experiments results of harmonics plus voltage sag.

THD	e_{THD}	t_m (ms)	e_t	a_m (pu)	e_a	F_2	F_3
2.08%	0.0018	38	3.52	0.102	0.011	2.08	0.04
3.12%	0.0029	54	4.76	0.212	0.011	3.12	0.01
4.09%	0.0014	78	2.60	0.307	0.005	4.09	0.02
5.06%	0.0010	98	1.93	0.361	0.010	5.06	0.13
5.97%	0.0019	115	4.77	0.387	0.010	5.97	0.05

e_{THD}: The error between the measured THD by PQ monitor and the setting THD.

Table 8. The experiments results of voltage fluctuation plus harmonics plus interharmonics plus voltage sag.

The disturbance parameters	F_2	F_3	Results	Remarks
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.4 pu	4.72	3.75	Voltage Fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.03, frequency 8 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.4 pu	4.80	3.80	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.4 pu	4.91	3.82	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.05, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.4 pu	4.98	3.80	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 1%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.4 pu	3.12	1.07	Voltage fluctuation plus harmonics plus voltage sag	When the interharmonics content is lower than 1%, and the harmonics content is large, the error is a little large
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 1245 Hz; harmonics THD 2%; voltage sag amplitude 0.4 pu	4.21	3.68	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 3%; voltage sag amplitude 0.4 pu	5.25	3.71	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 5%; voltage sag amplitude 0.5 pu	7.27	3.75	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.7 pu	4.05	3.69	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	
Fluctuation modulating wave amplitude 0.02, frequency 6 Hz; interharmonics content 2%,frequency 125 Hz; harmonics THD 2%; voltage sag amplitude 0.8 pu	4.11	3.70	Voltage fluctuation plus harmonics plus interharmonics plus voltage sag	

Table 9. The voltage sag experiments results comparison table.

Identifying results	t_m (ms)	t_{om} (ms)	e_t	a_m (pu)	a_{om} (pu)	e_a
Voltage sag	100	102	2	0.842	0.854	0.012
Voltage sag	102	105	3	0.838	0.833	0.005
Voltage sag	101	103	2	0.857	0.872	0.015
Voltage sag	108	110	2	0.813	0.801	0.012
Voltage sag	113	114	1	0.839	0.825	0.014

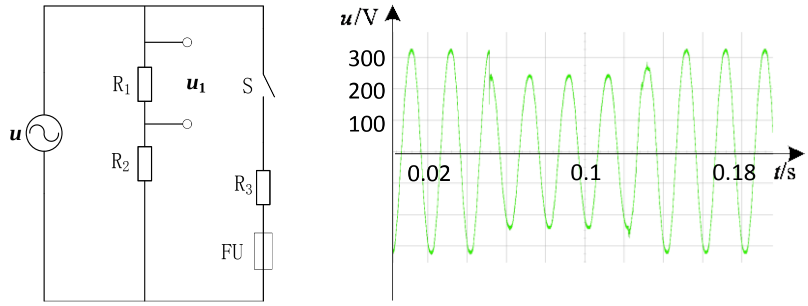
a: Error means the difference between values evaluated by PQ monitor and ones measured by the oscilloscope. For the oscilloscope measured value has error itself, but here, no error is considered. The meaning of error in the other tables is the same.

5.3. Field Measurement Results

A PQ monitor is equipped to a steel pipe factory substation to monitor the harmonics disturbance and the oscillatory transient disturbances. The results are shown in **Table 10** and **Table 11**.

The field monitoring results in **Table 10** show that the PQ monitor identifies harmonics correctly and evaluates the THD accurately.

To catch the oscillatory transients, a PQ monitor is equipped to Shi-Qiao substation. The oscillatory transient signals are generated by switching three phase capacitors. The three phase voltage waveform is shown as **Figure 6**.



(a) (b)

Figure 5. The voltage sag experiment. (a) The voltage sag experiment circuit; (b) The waveform of u_1.

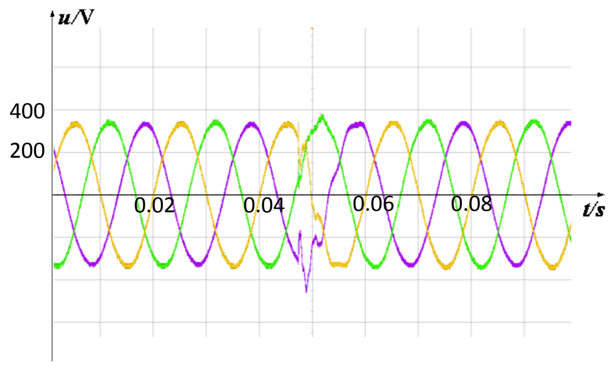


Figure 6. The three phase voltage waveform of capacitors switching in Shi-Qiao substation.

Table 10. The harmonics experiments results comparison table.

Identifying results	THD_m	THD_{om}	Error
Harmonics	4.2%	4.4%	0.0020
Harmonics	5.0%	5.2%	0.0020
Harmonics	4.8%	5.0%	0.0020
Harmonics	4.5%	4.8%	0.0030
Harmonics	5.7%	6%	0.0030

THD_m: THD measured by the PQ monitor; THD_{om}: THD measured by the oscilloscope.

Table 11. The experiments results of oscillatory transient in Shi-Qiao substation.

Identifying results	t_m (ms)	t_{om} (ms)	Error	a_m (pu)	a_{om} (pu)	Error
Oscillatory transients	12.43	12.56	0.13	0.70	0.78	0.08
Oscillatory transients	13.56	13.63	0.070	0.75	0.82	0.07
Oscillatory transients	14.28	14.39	0.11	0.78	0.79	0.01
Oscillatory transients	12.85	12.98	0.13	0.74	0.85	0.11
Oscillatory transients	14.50	14.01	0.49	0.88	0.93	0.05

t_{om}: The oscillatory transients lasting time measured by the oscilloscope; a_{om}: The oscillatory transients amplitude measured by the oscilloscope.

The author takes one phase wave to analyze (the purple one). The field experiment results are shown in **Table 11**.

Table 11 shows that the PQ monitor identifies the oscillatory transients correctly and evaluates their parameters accurately. The difference between the values evaluated by the PQ monitor and ones measured by oscilloscope is small.

6. Conclusion

Comparing with analyzing power quality disturbance signals in frequency domain, the method presented by this paper has some advantages. First, if one feature or some features satisfied some conditions, a disturbance or mixed disturbances can be sure. That is to say, the disturbance classification would not be probable, but be definitive. Second, the features extracted won't change a lot for the existence of the other disturbances. This characteristic is the key of classifying the mixed disturbances. Third, the features have clear physical meanings. So it profits the evaluation of the disturbance parameters.

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