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A New Method of Voltage Flicker Detection for Hilbert Vibration Decomposition

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Abstract

Hilbert Vibration Decomposition (HVD) is introduced to the voltage flicker analysis. When voltage flicker accompanies with high order harmonics, the instantaneous frequency of its analytic signal in principle consists of two different parts, power frequency and a rapidly varying asymmetrical oscillating part. The important property of the instantaneous frequency offers a direct way to estimate the power frequency using a low-pass filter and remove the high order harmonics without pre-treatment procedures. Corresponding voltage flicker envelope is estimated using synchronous detection. The HVD method does not involves basic functions that the wavelet transform method needs. It can also adaptively estimate the frequency and amplitude of every modulation frequency component. Simulation results prove that the proposed method could accurately detect voltage flicker with high order harmonics. It has higher calculation efficiency and detection precision than wavelet transform method. Experimental results show that the new algorithm is feasible and efficient.

***Keywords**: voltage flicker; Hilbert Vibration Decomposition (HVD); wavelet transform; envelope detection*

1. Introduction

With the development of industrial technology, a large number of non-linear impact load input into the grid, it is leading to rapid changes in power demand. The resulting voltage fluctuations will not only interfere with the public grid, but also they seriously affect the operation of the electrical network of various electrical equipment, such as lighting equipment flashing, control equipment malfunction, motor speed fluctuations [1, 2]. When the frequency of voltage fluctuations are in the 0.5 ~ 35 Hz, it is the maximum awareness of incandescent light fluctuations, that is, "flicker". As the general electrical equipment on the voltage fluctuation sensitivity is much lower than the incandescent lamp, so flash is the evaluation of indicators into a measure of the degree of voltage fluctuations [1]. The voltage fluctuations and flicker are studied, and measures are actively taken to ensure that power quality, it has become an important and urgent task for power supply.

Common flicker amplitude modulation wave detection methods are half-wave valid values method, square demodulation method and full-wave rectification method [3]. These three methods are mainly suitable for single-frequency voltage flicker component detection, it is not suitable for multi-frequency, non-stationary flicker signal detection, it is vulnerable to the impact of fundamental voltage and fundamental frequency. Stable flicker signal detection is susceptible to the impact of fundamental voltage and fundamental frequency. Fast Fourier transform can be used to detect flicker signals [3], but non-stationary signal processing can cause spectral leakage, it is affecting the accuracy of the measurement results. A voltage flicker estimation method is proposed based on the minimum absolute value estimation [4]. This method has high detection accuracy for the flicker component, and it is necessary to know the flicker frequency in advance and fast algorithm is lacked. The extended Kalman filter method is proposed in eference [5], it is suitable for non-stationary flicker signal estimation, but the parameters are very accurate and it is difficult to implement. In recent years, it has been proposed to extract the envelope signal by wavelet analysis and to detect the frequency components and their amplitudes in the flicker signal [6, 7]. Wavelet transform method has the characteristics of multi-resolution and time-frequency localization, which is suitable for dealing with non-stationary signal of power system. However, the frequency domain aliasing of wavelet affects its detection

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accuracy, and the selection of basis function is more difficult. In addition, the above methods are based on the power frequency carrier, and it does not contain high harmonics on the basis of the voltage flicker model, and the actual voltage flicker signal often contains a certain amount of high harmonics. The Hilbert transform is used to detect the voltage flicker envelope in the flicker signal after noise removal [8], it is considering the influence of noise such as higher harmonics, but it requires the pretreatment filtering of mathematical morphology.

In 2006, M. Feldman et al. proposed a new method of non-stationary signal analysis, it is Hilbert vibration decomposition (HVD) [9], and it was successfully applied to mechanical vibration signal analysis [9, 10]. Based on the Hilbert transform, the instantaneous frequency, instantaneous amplitude and phase of each non - stationary frequency component are estimated by low - pass filtering and synchronization detection. In this paper, HVD is applied to the detection of voltage fricher envelope and the modulation frequency components for the first time. The power frequency carrier with high harmonics is analyzed. The simulation results show that the HVD method is effective for voltage flicker detection.

2. Analysis of HVD Voltage Flicker

2.1. Mathematical Model of Voltage Flicker

Voltage flicker is the low frequency modulation of the power frequency voltage carrier. Because the power frequency carrier contains high harmonic noise, the voltage flicker signal can be expressed as formula (1):

$$\begin{gathered} v(t)=u(t)\upsilon(t)=[U_0+\sum_{l=1}^{L}U_l\cos(2\pi\lambda_l t+\varphi_l)]\cdot \\ [\cos(2\pi f_0 t+\theta_0)+\sum_{k=1}^{K}m_k\cos(2\pi f_k t+\theta_k)] \end{gathered} \tag{1}$$

Where: u(t) is the envelope signal (amplitude modulation wave); υ(t) is the high frequency harmonic carrier frequency; U0 is the amplitude of the power frequency carrier voltage; U_l is the amplitude of the amplitude modulation wave voltage; λ_l is the frequency of the amplitude modulation wave voltage; φ_l is the initial phase of the amplitude modulation wave voltage; L is the total amplitude of the amplitude modulation wave frequency. f_0 is the frequency of the power frequency carrier voltage; θ_0 is the initial phase of the power frequency carrier; m_k is the percentage of the harmonic frequency of the power frequency carrier voltage to the frequency; f_k is the higher harmonic frequency of the power frequency carrier voltage; θ_k is the initial phase of the harmonic of the power frequency carrier; K is the total number of harmonics.

2.2. Flicker Envelope HVD Method Analysis

It can be seen from equation (1) that the envelope u(t) of the voltage flicker signal carries the amplitude and frequency information of the flicker. When the power frequency carrier voltage does not contain harmonic components and other noise, the voltage flicker signal can be directly requested by Hilbert transform, the instantaneous amplitude of the analytical signal is used to determine the flicker envelope, and then the flicker parameters are obtained. The frequency carrier voltage contains high harmonics, the envelope is detected by the Hilbert transform, the envelope will also contain the corresponding higher harmonic components. If it is directly used, the estimated flicker parameter will bring a large error. Mathematical morphology method is used for pretreatment, the high harmonics is filtered out the voltage flicker [8]. In this paper, HVD is used to extract the fission envelope with higher harmonics, and no other pretreatment is needed.

In order to simplify the analysis without losing the generality, we first consider the flicker signal with a single high-frequency harmonic component (K = 1 in equation (1)), which can be expressed as follows:

$$\begin{gathered} v(t)=u(t)\cdot[\cos(2\pi f_0 t+\theta_0)+m_1\cos(2\pi f_1 t+\theta_1)]= \\ u_0(t)\cos(2\pi f_0 t+\theta_0)+u_1(t)\cos(2\pi f_1 t+\theta_1) \end{gathered} \tag{2}$$

Where u(t) is the envelope signal; f_0 is the frequency of the carrier frequency; θ_0 is the initial phase of the power frequency carrier; m_1 is the percentage of the harmonic frequency of the carrier voltage in the carrier frequency; f_1 is the harmonic Frequency; θ_1 is the initial harmonic phase; $u_0(t)=u(t)$; $u_1(t)=m_1u(t)$.

After the Hilbert transform, the analytic signal of v(t) can be expressed as follow.

$$X(t)=u_0(t)\mathrm{e}^{i(2\pi f_0 t+\theta_0)}+u_1(t)\mathrm{e}^{i(2\pi f_1 t+\theta_1)} \tag{3}$$

The instantaneous amplitude A(t) and the instantaneous frequency F(t) can be expressed as:

$$A(t)=[u_0^2(t)+u_1^2(t)+2u_0(t)u_1(t)\cos(2\pi(f_1-f_0)t+\theta_1-\theta_0)]^{1/2} \tag{4}$$

$$F(t)=f_0+(f_1-f_0)[u_1^2(t)+u_0(t)u_1(t)\cos(2\pi(f_1-f_0)t+\theta_1-\theta_0)]/A^2(t) \tag{5}$$

In equation (5): F(t) consists of two parts, the first part is the power frequency f_0, and the second part is the rapidly changing asymmetric oscillation part. The latter is set to zero in the interval [0, T = 1 / (f_1-f_0)], which can be proved to be zero [9]. Then the frequency f0 can be obtained by estimating the integral mean of F(t). Low-pass filter method F(t) can also used in the rapid conversion of the frequency components, frequency f_0 is estimated.

When the flicker signal contains a plurality of higher harmonic components (K≥2), the expression of the instantaneous amplitude A(t) and the instantaneous frequency F(t) of the v(t) resolution signal is more complicated, but the low-pass filter method can also be extracted from the frequency f_0 [9].

v(t) multiplies respectively with 2cos(2πf0t), 2sin(πf0t) by synchronous detection, the following expression is obtained:

$$Z(t)=v(t)\cdot 2\cos 2\pi f_0 t=u_0(t)\cos(\theta_0)+u_0(t)\cos(4\pi f_0 t+\theta_0)+2u_1(t)\cos 2\pi f_0 t\cos(2\pi f_1 t+\theta_1) \tag{6}$$

$$\tilde{Z}(t)=v(t)\cdot 2\sin 2\pi f_0 t=-u_0(t)\sin(\theta_0)+u_0(t)\sin(4\pi f_0 t+\theta_0)+2u_1(t)\sin 2\pi f_0 t\cos(2\pi f_1 t+\theta_1) \tag{7}$$

Both (6) and (7) contain three parts. The low-pass filter can filter the following two parts to get the following expression:

$$<Z(t)>=u_0(t)\cos(\theta_0) \tag{8}$$

$$<\tilde{Z}(t)>=-u_0(t)\sin(\theta_0) \tag{9}$$

From the formula (8), (9), we obtain voltage flicker envelope $u_0(t)$ and the initial phase θ_0.

$$u_0(t)=\sqrt{<Z(t)>^2+<\tilde{Z}(t)>^2} \tag{10}$$

$$\theta_0=-\arctan\frac{<\tilde{Z}(t)>}{<Z(t)>} \tag{11}$$

The above Hilbert transform, corresponding to the low-pass filter and the simultaneous analysis of the integrated analysis is called the HVD method. Firstly, the instantaneous frequency of the fricative analytic signal is obtained by Hilbert transform, and then the carrier frequency with the largest envelope amplitude is separated by the low-pass filter, that is the instantaneous frequency of the power frequency, and finally the power frequency carrier voltage flicker envelope is estimated by synchronous detection.

2.3. Analysis of Flicker Frequency and Amplitude by HVD Method

The HVD method not only can effectively extract the flicker envelope signal, but also it can detect the frequency and amplitude of each modulation component.

The DC component is removed, the flicker envelope signal can be expressed as:

$$u(t) = \sum_{l=1}^{L} U_l \cos(2\pi\lambda_l t + \varphi_l) \tag{12}$$

Where: L is the total number of amplitude modulation wave; U_l, λ_l and φ_l, respectively, said the amplitude, frequency and initial phase of the l-th modulation frequency components.

When L = 2, the initial phase is ignored, the instantaneous amplitude A(t) and instantaneous frequency F(t) of the u(t) analytical signal can be expressed as formula(13),(14) after Hilbert transform:

$$A(t) = [U_1^2 + U_2^2 + 2U_1U_2\cos(2\pi(\lambda_2 - \lambda_1)t]^{1/2} \tag{13}$$

$$F(t) = \lambda_1 + \frac{(\lambda_2 - \lambda_1)[U_2^2 + U_1U_2\cos(2\pi(\lambda_2 - \lambda_1)t]}{A^2(t)} \tag{14}$$

In equation (13): F(t) consists of two parts, the first part is the flicker modulation frequency λ_1, and the second part is the asymmetric oscillation part of the fast transformation. In practical applications, when the L ≥ 2 and the modulation component amplitudes are not equal, the flicker modulation frequency λ_1 can be detected with the low-pass filter method[9]. On the basis of this, the amplitude U1 and the initial phase angle φ_1 are obtained by using the synchronization detection method.

$$\mu_1(t) = U_1\cos(2\pi\lambda_1 t + \varphi_1) \tag{15}$$

□μ_1(t) subtracts from the initial signal u(t), and it repeats the above operations to obtain other modulation components and their amplitude and frequency parameters in turn. When the corresponding standard deviation of the formula (15) is less than a certain limit, the iteration is stopped.

2.4. Low-pass Filter and Parameter Selection

In this paper, we use the Savitzky-Golay (S-G) filter [11] to achieve the key link in the HVD method - low-pass filtering. The main idea of S-G filtering is to fit an M-order polynomial by the least squares method according to the total of 2m + 1 data on each side of the given point x_i. The value of the polynomial at the point of x_i is its filter value. Compared with the average filter, S-G filter can keep the waveform in the case of the maximum elimination of high-frequency noise. Taking into account the computational efficiency and accuracy, the polynomial fitting order M usually is in the range of 2 to 4, the smaller the value of M, the better the smoothing effect, but the greater the error is introduced; otherwise, the larger the value of M, the worse the smoothing effect, many high frequency noise can not be eliminated. Aiming at the HVD detection method of flicker signal in this paper, a satisfactory result can be obtained by calculating M = 3.

The selection of the length of the S-G filter data window 2m + 1 is based on the sampling frequency fc and the desired filter cutoff frequency Fc. It can be seen that the cutoff frequency of the low-pass filter determines the frequency resolution of the HVD method. When the difference between the adjacent sub-harmonic frequencies is greater than the cut-off frequency of the low-pass filter, the two can be separated, the smaller the cut-off frequency of the low-pass filter, it can detect more accurately the harmonic components with similar frequencies. Considering the waveform distortion and the stability of the filter, the cut-off frequency of the low-pass filter can be selected as small as possible. In this paper, the function of S-G filter is to eliminate the fast changing asymmetric oscillation high frequency value when the effective frequency component is retained. When the flicker envelope is detected, the characteristic of the actual voltage flicker signal is taken, the sampling frequency of 6 400 Hz is taken as an example, Fc = 0.02 Fs, M = 3, m = 35,it can effectively extract the frequency carrier voltage flicker envelope of higher harmonics. When the frequency and the amplitude of the power flicker are detected, the flicker frequency is mainly between 0.5 ~ 35 Hz, the detected fricher envelope downs to 100 Hz, the same SG parameters still be used, it can meet requirements.

3. Simulation Research

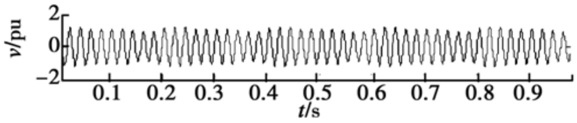
After voltage flicker is researched in the case of multiple modulation frequency voltage flicker, the sampling frequency is 6 400 Hz and the voltage reference is 50 Hz. Analysis formula (1), take L = 2, K = 3, the flicker analysis is as follows:

$$\begin{aligned} v(t) = {} & [U_0 + \sum_{l=1}^{2} U_l \cos(2\pi\lambda_l t + \varphi_l)]\square[\cos(2\pi f_0 t + \theta_0) + \\ & \sum_{k=1}^{3} m_k \cos(2\pi f_k t + \theta_k)] \end{aligned} \tag{16}$$

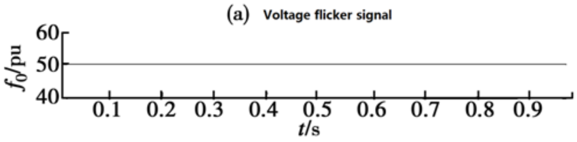
Where: frequency carrier and modulation amplitude, frequency parameters in Table 1. The higher harmonics in the frequency carrier are: the 5th harmonic of amplitude 0.080 pu, the seventh harmonic of amplitude 0.050 pu, the 9th harmonic of amplitude 0.020 pu. Where the initial phase values are zero.

Table 1. Parameters of voltage flicker with multiple modulation frequencies

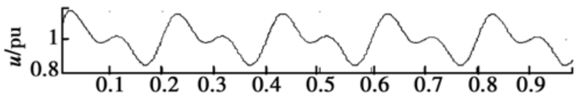
Parameter	U_0/pu	f_0/Hz	U_1/pu	λ_1/Hz	U_2/pu	λ_2/Hz
Setpoint	1.000	50.000	0.100	5.000	0.080	10.000
HVD	0.995	50.010	0.103	4.989	0.076	9.881



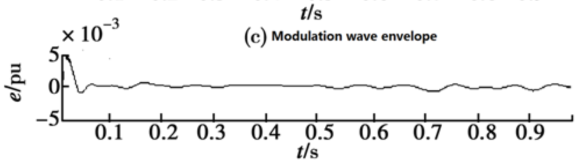
(a) Voltage flicker signal



(b) Power Frequency Instantaneous Frequency



(c) Modulation wave envelope



(d) Envelope error

Figure 1. HVD analysis of voltage flicker envelope with invariable power frequency

Figure 1(a) is for the original signal waveform of the multi-modulation frequency voltage flicker. the power frequency instantaneous frequency waveform is measured by HVD method, as is shown in Figure 1(b), the error is 0.02% between the detection value (50.010 Hz) and the expected value. Figure 1(c) and Figure 1(d) are the hysteresis envelopes and envelope errors for HVD detection. The frequency and amplitude of the flicker envelope were further extracted by HVD for each modulation component. The results are shown in Table 1. It can be seen that the HVD method can be used to detect accurately the amplitude and frequency of the power frequency carrier, the flicker envelope and the frequency modulation components of the multi-modulation frequency flicker signal with certain harmonic noise.

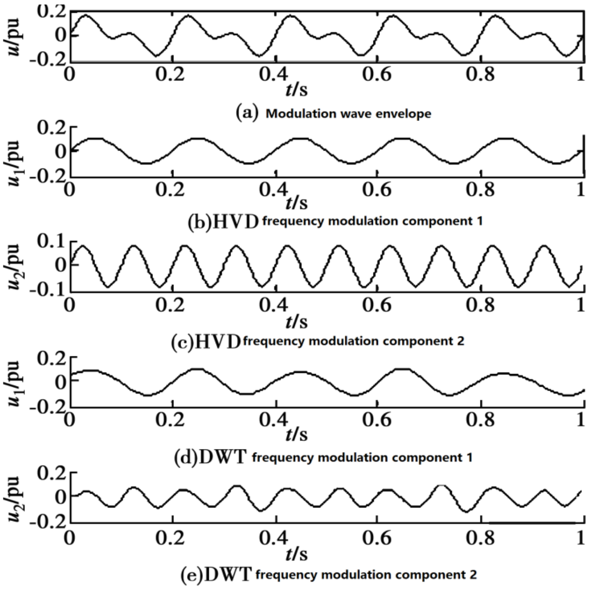


Figure 2. HVD and DWT analysis of voltage flicker modulation component

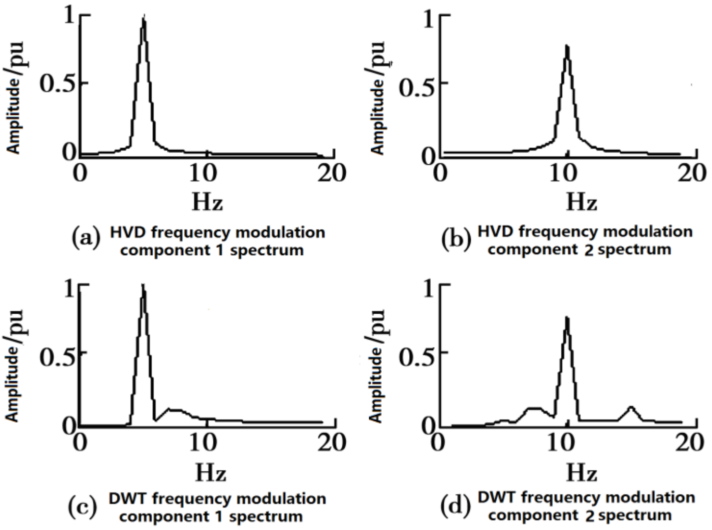


Figure 3. HVD and DWT spectrum analysis of voltage flicker modulation component

In order to verify the accuracy of the HVD method to detect the frequency and amplitude parameters of the modulation component, the voltage flicker envelope is expected to be the original signal (parameter set in Table 1), and the detection results of HVD and Discrete Wavelet Transform (DWT) are compared. The Daubechies 20 wavelet basis function is used. According to the band decomposition characteristic, the two modulation wave frequencies fall in the approximate component band A9 and the detail component band D9 respectively. The measured waveforms of the two methods are shown in Figure 2. Figure 2(a) is a voltage flicker envelope. Figure 2(b) and (c) are two modulated frequency signal waveforms which are extracted by the HVD method. Figure 2(d) and Figure 2(e) are two modulated frequency signal waveforms, which are obtained after the flicker envelope is separated by the DWT method. The modulation component spectrum is measured byHVD and DWT method, the analysis results are shown in Figure 3. From Figure 2 and Figure 3, we can see that HVD and DWT can detect 5Hz and 10Hz modulation frequency components, and the amplitude and the true value are consistent. However, in the DWT modulation component spectrum which are shown in Figure 3(c) and (d), there are other undesired frequency components except for the main frequency component the main frequency components. It is found that the wavelet basis function is difficult to guarantee the frequency division and energy concentration, so the wavelet transform inevitably exists frequency domain aliasing, which affects the precision of the detection. The HVD method does not need the basis function, as long as the low-pass filter cut-off frequency is less than the adjacent sub-modulation frequency difference, you can effectively separate the two.

4. Experimental Verification

dSPACE is a set of hardware and software experimental platform for the development and testing of control system based on MATLAB / Simulink. It can realize the seamless connection with MATLAB / Simulink / RTW. It has the advantages of strong real-time, high reliability and good scalability. The processor in the dSPACE hardware system has high-speed computing power and it is equipped with rich I / O support. The software environment is powerful and easy to use, it includes a complete set of tools for code generation / download and test / commissioning.

In this paper, a dSPACE-based voltage flicker detection experiment platform is constructed to verify the practicability and accuracy of HVD method. The actual grid voltage flicker parameter expectations can not be accurately obtained, it can not be used as a test HVD algorithm accuracy reference standard, the design of the experimental program is as follows (system block diagram shown in Figure 4):

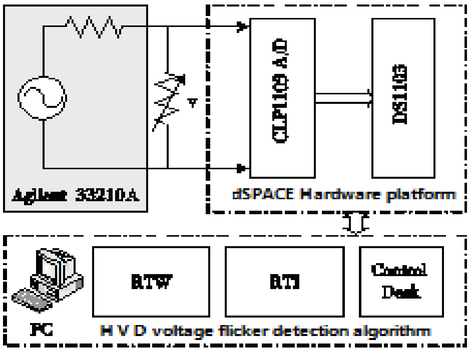


Figure 4. Voltage flicker experiment system block diagram

1) The signal generator generates the specified flicker voltage, which is added to a certain resistor, and the required flicker signal is obtained from both ends of the resistor. Arbitrary Waveform Generator Model is Agilent 33210A. Agilent IntuiLink is applied to create custom waveforms. Resistors is conventional slippery rheostats.

2) The acquisition signal is converted to the digital by dSPACE hardware system DS1003 via the A / D channel, the digital signal is input in the dSPACE I / O interface panel CLP1103.

3) Simulink module is built, self-compiled Simulink / Embedded MATLAB Function function tis used o achieve HVD flicker detection algorithm.

4) Simulink block diagram automatically generated C code by MATLAB / RTW and dSPACE / RTI together, it is downloaded to dSPACE real-time system hardware.

5) After real-time hardware operation, the experimental process and integrated management are monitored through ControlDesk software.

Experimental signal source is for the dual FM flicker voltage signal, power frequency carrier is carrying a certain amount of high harmonics. Sampling frequency is 6 400 Hz. The results are exported to the Agilent IntuiLink display. The results of the experimental acquisition waveform and HVD envelope are shown in Figure 5. The abscissa in the figure represents the number of sampling points for the 2 s data segment and the ordinate represents the amplitude of the normalized signal.

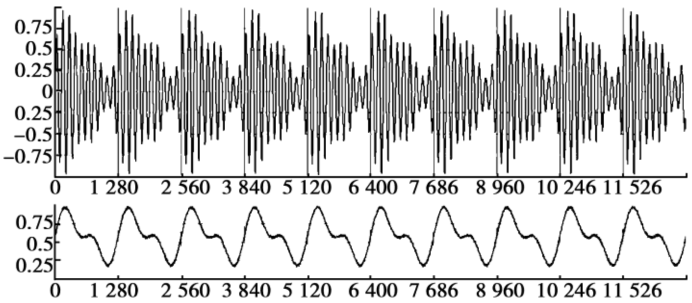


Figure 5. HVD experiment analysis of voltage flicker envelope with multiple modulation frequencies

Since the IEC standard is only applicable to monotonic flicker analysis, the V10 flicker standard is used here [12]. Table 2 shows the v10 flicker detection results for both HVD and DWT methods. It can be seen that the detection error of V10 based on HVD is less than 1.60% under different FM flicker parameters, and the detection error of DWT is up to 9.5%. Therefore, the accuracy of HVD method in this paper is better than that of DWT method, which can meet the high precision requirements of multi-frequency flicker detection.

Table 2. Comparison of HVD and DWT methods for ΔV_{10} value with multiple modulation frequencies

Modulation frequency /Hz	ΔV_{10}/pu		
	Expected value	HVD	DWT
3,8	0.143	0.145	0.133
5,10	0.189	0.188	0.205
6,15	0.188	0.185	0.197
10,20	0.210	0.212	0.230

5. Conclusion

This paper presents a new method of voltage flicker detection based on Hilbert vibration decomposition (HVD). Based on the Hilbert transform, the instantaneous frequency characteristic of the fricative analytical signal is analyzed, and the instantaneous value of the frequency is estimated simply by using the low-pass filter, and the envelope of the voltage flicker is detected quickly and accurately. Modulation components of the amplitude, frequency and other parameters are detected quickly and accurately . When the frequency carrier contains high harmonics, no other preprocessing filtering method is required. Simulation and experiment show that the method can accurately analyze the flicker signal, it is compared with DWT, its accuracy and operation efficiency is higher, it is not need to select the basis function.

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References

[1] Zhou L, Xu WL, Meng J. Review on measurement and analysis of voltage fluctuation. *Electrotechnical Application*. 2007; 26(7): 6-10.
[2] Geng YL, Wang Q, He YG. Wavelet detect ion and location of power quality and its classification based on multi- scale energy curve. *Chinese Journal of Scientific Instrument*. 2006; 27(2): 180-182.
[3] Srinivasan K. Digital measurement of the voltage flicker. *IEEE Transactions on Power Delivery.* 1991; 6(4): 1593-1998.
[4] Soliman SA, El-Hawary ME. Measurement of power systems voltage and flicker levels for power quality analysis: a static lav state estimation based algorithm. *Int. J. Elect Power Energy Syst*. 2000; 22: 447-450.
[5] Girgis A, Makram EB. *Measurement of voltage flicker magnitude and frequency using a kalman filtering based approach*. Proc. Canad. Conf. Electrical and Computer Engineering. 1996; 2: 659-662.
[6] Xie JJ, Wu WL. Wavelet-based method for voltage flicker analysis. *Chinese Journal of Scientific Instrument*. 2003; 24(4): 39-42.
[7] Chen XX. *A shift-invariant wavelet-based method for tracking voltage flicker level*. Proceedings of the CSEE. 2004; 24(10): 1-7.
[8] Shu H, WANG Y. *Voltage flicker detection method based on mathematical morphology filter and hilbert transform*. Proceedings of the CSEE. 2008; 28(1): 111-114.
[9] Feldman M. Time-varying vibration decomposition and analysis based on the Hilbert transform. Journal of Sound and Vibration. 2006; 295(3-5): 518-530.
[10] Feldman M. Theoretical analysis and comparison of the Hilbert transform decomposition methods. *Mechanical Systems and Signal Processing.* 2008; 22(3): 509-519.
[11] Ma YH, Zhao G, Chen WZH. Study of noise reduction for high voltage testing system. *High Voltage Engineering*, 2001; 27(3): 78-80.
[12] Wu CJ, Chen YJ. A novel algorithm for precise voltage flicker calculation by using instantaneous voltage vector. *IEEE Transactions on Power Delivery*. 2006; 21(3): 1541-1548.