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Cubic Spline Interpolation Method for the Envelope Tracking of Middle and Low frequency Voltage Flicker

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Abstract. Flicker envelope tracking is the key of analyzing voltage flicker signal. A novel method, i.e., cubic spline interpolation method is applied in the detection of the voltage flicker envelope. The typical flicker signals, such as one or multi-frequencies and frequency time-varying flicker signal are selected and analyzed by this method. Simulation results indicate that this method is effective in the detection of the envelope of voltage flicker signal. Results of one or multi-frequencies flicker signal simulation show that, when flicker frequency is less than 15Hz , the error of this method is quite tiny. The detection precision of this method is higher, especially in the scope of low frequencies of flicker and this method makes up for the disadvantage of square demodulation. Furthermore, results of frequency time-varying flicker signal simulation show that, the occurrence and recover time of voltage flicker signal can be accurately detected by cubic spline interpolation method.

Introduction

In various power quality problems, voltage fluctuation and flicker is considered as one of the major power quality disturbances [1-2]. With the development of the national economy, larger quantities of high-power impulsive, fluctuating and nonlinear loads, such as arc furnaces, arc welders, spot welders, resistance welders and repetitive operation machinery are used in power networks. The active power and reactive power change rapidly and violent during these equipments operate, which results in voltage fluctuation at the point of common coupling (PCC) [3]. In order to minimize voltage fluctuation, numerous reactive power compensation devices are applied in the power system. However, these devices are required to provide accurate tuning flicker parameters to make the right suppression decisions. The amplitude and frequency information of the voltage fluctuation is contained in the envelope of voltage flicker signal. Therefore, the key to analyze voltage flicker signal is the detection of flicker envelope. After separation of the flicker envelope, flicker-related parameters can be easily calculated according to selected criteria [4-5].

At present, square demodulation, rectifier detection and RMS detection are three main methods to be selected to detect voltage flicker by flicker meter at home and abroad [6]. However, these three methods are not suitable for detecting multi-frequency flicker signal and time-varying flicker signal. Especially, square demodulation is the method which based on the IEC recommended [7]. References [8-9] proposed that the error of square demodulation method to extract the envelope of flicker increases with the flicker frequency decreasing. In the vicinity of the most sensitive flicker frequency 8.8Hz, the detection error reduces to a minimum, and then increases again. In a word, the detection precision of square demodulation method is high, only in the scope of low frequencies.

The interpolation method is one of the important numerical approximation methods [10], which is based on the given variable value and function value to get the approximate value of unknown function. The task of interpolation is known by the observation points to set up a simple, continuous analytical model, in order to be able to deduce the physical quantities in the non observation points according to the characteristics of the model. However, in practice, there are many interpolation function curve with high smoothness. In the whole curve, curve can not be a turning point, but also can not have the mutation of curvature. Therefore, the interpolation functions must be continuous and constant micro No. two times; this requires cubic spline interpolation which has the best smoothness.

For this feature of cubic interpolation method, and considering the flicker signal characteristic, this method is used in this paper for the first time to track voltage flicker envelope.

The cubic spline interpolation method

The definition of cubic spline interpolation. For an interval $[a,b]$, $a = x_0 < x_1 < \cdots < x_n = b$, the corresponding function values are $y_0 < y_1 < \cdots < y_n$. If function $S(x)$ meets the following three conditions, $S(x)$ is called cubic spline interpolation on interval $a \le x_i \le b, i = 0,1,\cdots n$.

(1) $S(x_i) = y_i$, $i = 0,1,\cdots n$;(2)$S(x)$ is not more than three times polynomial on interval $[x_{i-1}, x_i](i=1,2,\ldots n)$;(3) $S(x)$ is continuous second-order derivative on interval $[a,b]$.

In constructing the cubic spline interpolation function, requiring $S(x)$ only determined a cubic polynomial on the each sub-interval $[x_{i-1}, x_i]$, set:

$$S_i(x) = a_i x^3 + b_i x^2 + c_i x + d_i, i = 0,1,\cdots,n \tag{1}$$

In which a_i, b_i, c_i, d_i are undetermined coefficients, and $S(x_i) = y_i$; $S(x_i - 0) = S(x_i + 0), i = 1,2,\cdots,n-1$; $S'(x_i - 0) = S'(x_i + 0), S''(x_i - 0) = S''(x_i + 0), i = 1,2,\cdots,n-1$ .There is $4n$-2 conditions, so $4n$ coefficients need to be determined. To uniquely identify a cubic spline interpolation, additional two boundary conditions are also needed and they are usually given by the endpoints status of cubic spline interpolation in practical.

The construction of cubic spline interpolation function. Cubic spline interpolation function $S(x)$ approaches to the real function $y=f(x)$ through piecewise cubic polynomial, and satisfies three conditions mentioned above.

To make $M_i = S''(x_i)$, the interpolation condition $S(x_i) = y_i, i = 1,2,\cdots,n$ and formula (2)

$$S''(x) = \frac{x - x_{i-1}}{h_{i-1}} M_i - \frac{x - x_i}{h_{i-1}} M_{i-1}, i = 1,2,\cdots,n \tag{2}$$

By two continuous integration, you can get the cubic spline interpolation function $S(x)$ expressed as formula (3):

$$\begin{aligned} S(x) &= \frac{M_i}{6h_{i-1}}(x - x_{i-1})^3 - \frac{M_{i-1}}{6h_{i-1}}(x - x_i)^3 \\ &+ \left(\frac{y_{i-1}}{h_{i-1}} - \frac{M_{i-1}}{6} h_{i-1}\right)(x_i - x) + \left(\frac{y_i}{h_{i-1}} - \frac{M_i}{6} h_{i-1}\right)(x - x_{i-1}) \end{aligned} \tag{3}$$

Where $x_{i-1} \le x \le x_i, i = 1,2,\cdots,n$, $h_{i-1} = x_i - x_{i-1}, i = 1,2,\cdots,n$.

The function $S(x)$ has a continuous second derivative at the sample point x_i , and according to cubic spline interpolation method principle, besides, increasing the natural boundary conditions:

$$\begin{aligned} S''(x_0) &= y_0'' = 0 \\ S''(x_n) &= y_n'' = 0 \end{aligned} \tag{4}$$

Obtain the following equations represented by the matrix:

$$\begin{bmatrix} 2 & j_0 & & & \\ \lambda_1 & 2 & j_1 & & \\ & \ddots & \ddots & \ddots & \\ & & \lambda_{n-1} & 2 & j_{n-1} \\ & & & \lambda_n & 2 \end{bmatrix} \cdot \begin{bmatrix} M_0 \\ M_1 \\ \cdots \\ M_{n-1} \\ M_n \end{bmatrix} = \begin{bmatrix} J_0 \\ J_1 \\ \cdots \\ J_{n-1} \\ J_n \end{bmatrix} \tag{5}$$

Where $\begin{cases} j_i = \dfrac{h_{i+1}}{h_i + h_{i+1}} \\ \lambda_i = 1 - j \\ J_i = \dfrac{6}{h_i + h_{i+1}}\left(\dfrac{y_{i+1} - y_i}{h_{i+1}} - \dfrac{y_i - y_{i-1}}{h_i}\right) \end{cases}$, and i=1， 2， …， n-1， j_0=0， J_0=0， λ_n=0.

To solve the equations above, obtained by M_i(i= 0, 1, 2,…,n) into formula (3), then get the cubic spline interpolation function on each sub-interval $[x_{i-1},x_i]$(i= 1, 2,…,n).

The envelope tracking of voltage flicker based on this method

Voltage flicker is caused by voltage fluctuation. The analytical expression of periodic voltage flicker signal can be expressed by formula (6).

$$u(t) = A(1+\sum_k m_k \cos\Omega_k t)\cos(\omega t+\theta) \tag{6}$$

Where, A—the amplitude of power frequency carrier voltage;

ω—the angular frequency of power frequency carrier voltage;

m—the coefficient of amplitude modulation(AM) wave, i.e. AM wave voltage amplitude and power frequency carrier wave voltage amplitude ratio.

Ω_k—the angular frequency of amplitude modulation wave.

As power frequency voltage is the carrier of flicker signal, its peak value or root mean square voltage fluctuation component is modulated in amplitude as the waves, flicker frequency is generally between 0.5~25Hz. The amplitude and frequency information of the voltage fluctuation is contained in the envelope of voltage flicker signal. Therefore, the key to analyze voltage flicker signal is the detection of flicker envelope [11].

The steps of envelope tracking using cubic spline interpolation method are as follow:

1) For voltage flicker signal $u(t)$, high frequency sampling and the frequency of 3200Hz;

2) Determined all the coordinates of maximum points $p_i(x_i, y_i)$ and minimum points $q_j(x_j, y_j)$;

3) Regarded p_i and q_j as the interpolation nodes which have been known.

4) In order to avoid the end effect, adding the boundary condition and regarding the endpoints of flicker signal $u(t)$ as the maximum points.

5) Fitting the upper and lower envelope, respectively, using cubic spline interpolation.

6) The sum of the upper and lower envelope averaging to obtain the final envelope, i.e. to extract flicker envelope.

This method is simple and fast, just to get extreme points of flicker signal, you can quickly extract flicker envelope with a cubic spline interpolation method.

To reflect the cubic spline interpolation method to extract flicker envelope is valid, using the formula (7) to calculate the detection error of this method, which the relative error extracts flicker envelope is defined is:

$$e = \left|\frac{a(t)-a'(t)}{a(t)}\right| \times 100\% \tag{7}$$

In the formula (7), $a(t)$ is the real instantaneous amplitude, $a'(t)$ is the instantaneous amplitude extracted by cubic spline interpolation method.

Here the use of MATLAB software cubic spline interpolation method for programming method to extract flicker envelope, to verify the validity of this method. In the following case study, the voltage amplitude was represented by per-unit value. The extracted envelope is instantaneous amplitude of the results which the DC component has been filtered out.

Case study

Flicker signal with one frequency. In order to show test results more intuitively, set the example of the signal parameters calculated as follows: The frequency of AM wave: 8.8Hz, the coefficient m is 5%, carrier frequency:50Hz, Initial phase:0, sampling frequency: 3200Hz, sampling duration: 0.5s.

The example signal was shown as formula (8):

$$u(t) = (1+0.05\cos 17.6\pi t)\cos(100\pi t) \tag{8}$$

8.8Hz flicker signal waveform was shown in Figure 1, with cubic spline interpolation method to extract flicker envelope was shown in Figure 2. Figure 2 shows that the two envelopes are almost coincident. The method analyzing the detection error in this paper is that remove the anomalous data which in zero-crossing and endpoints and use the least squares to fit the data points. Take the average of fitting date as detection error of cubic spline interpolation method. Due to space limitations, only the results of a single frequency flicker detection error is shown in figure 3. Fitted by least-squares, it is a straight line parallel to the abscissa of the coordinate. The mean of detection error was 0.2772%.

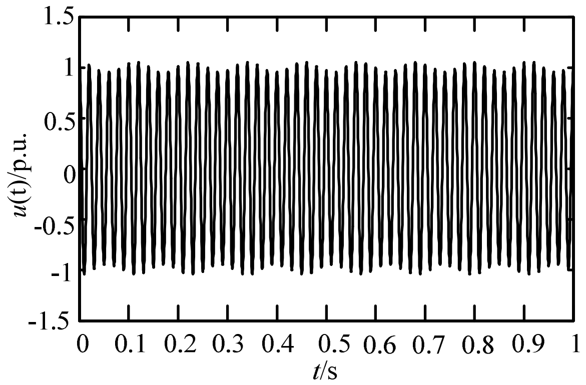

Fig.1 The one-frequency flicker signal

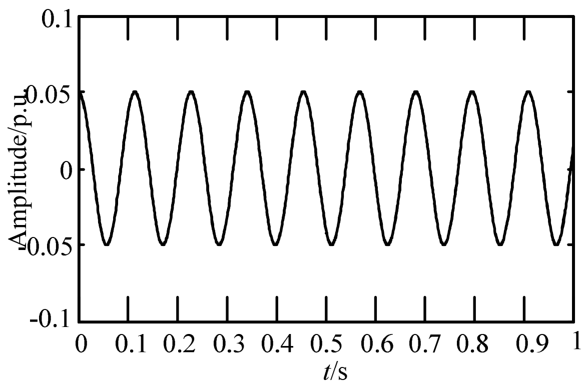

Fig.2 The detection result (dotted line) compare with real value (solid line) of multi-frequency

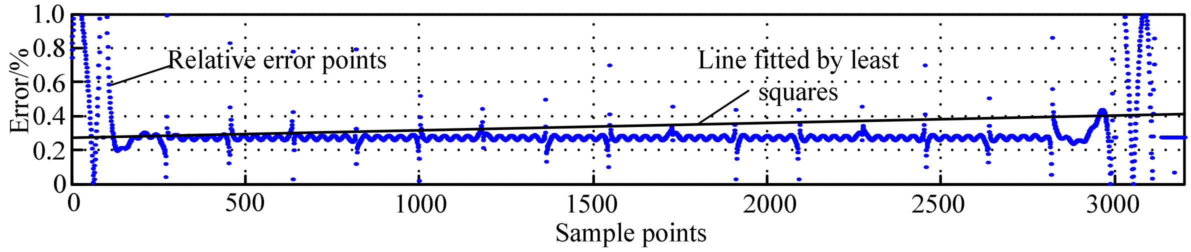

Fig.3 The relative value of detection errors

To get close to actual, take the voltage fluctuation parameters of instantaneous visual sensitivity $S(t)$=1 proposed in literature [6] for analysis. The errors detected by cubic spline interpolation method were shown in table 1.

Tab. 1 The detection errors of cubic spline interpolation method

f/Hz	ΔV/%	error/%	f/Hz	ΔV/%	error/%	f/Hz	ΔV/%	error/%	f/Hz	ΔV/%	error/%
0.5	2.340	2.2×10^{-6}	5.0	0.398	0.0241	**8.8**	**0.250**	**0.2772**	12.0	0.312	1.1900
1.0	1.432	3.5×10^{-5}	6.0	0.328	0.0518	9.5	0.254	0.3943	13.0	0.348	1.7692
2.0	0.882	5.6×10^{-4}	6.5	0.300	0.0730	10.0	0.262	0.4937	14.0	0.388	2.5771
3.0	0654	0.0029	7.0	0.280	0.1002	10.5	0.270	0.6268	15.0	0.462	3.6958
4.0	0.500	0.0095	7.5	0.266	0.1357	11.0	0.282	0.7817	**16.0**	**0.480**	**5.2105**

Analysis of the data in Table 1 shows that the detection error becomes larger and larger with flicker frequency increasing using the proposed method. When the frequency is greater than 15Hz, the error is more than a 5%. Using this method to extract the flicker envelope of which the frequency is below 12Hz, the detection error is small, maintained at 1.5%. And the lower the frequency is, the smaller the error is. In particular, when the flicker frequency is at 3Hz or less, the detection error is less than 0.003%. And this band is exactly in the test frequency range of low frequencies of IEC flicker meter. Literature [8] pointed out: IEC flicker meter for detection error of low-frequency flicker is large, so the cubic spline interpolation method is applicable to the detection of low-frequency flicker caused by wind power connected to grid (1~3Hz). Thus, this method is more suitable for flicker in low-mid frequency envelope detection.

Flicker signal with multi-frequencies. Formula (7) represents multi-frequency flicker signal.

$$u(t) = (1+0.075\cos 10\pi t + 0.05\cos 20\pi t + 0.025\cos 30\pi t)\cos(100\pi t) \tag{7}$$

The frequency of AM wave: 5Hz, 10Hz and 15 Hz; the coefficients are corresponding to 7.5%, 5% and 2.5%, respectively. Sampling frequency: 3200Hz, sampling duration: 0.5s.

Multi-frequency flicker signal waveform was shown in Figure 4, with cubic spline interpolation method to extract flicker envelope was shown in Figure 5. Since the endpoint effect, the two envelopes not coincide except for the envelope at the endpoint, and the rest almost coincide. Detection error is 1.2917% and the detection is ideal.

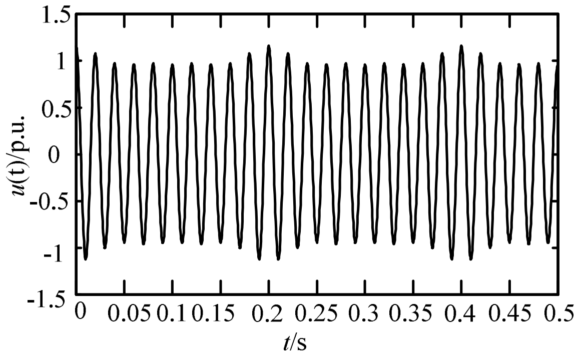

Fig.4 The multi-frequency flicker signal

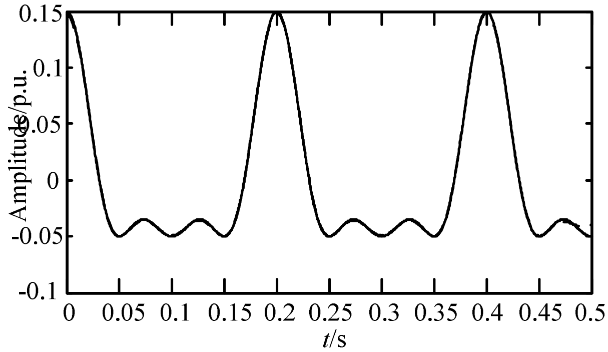

Fig.5 The detection result (dotted line) compare with real value (solid line) of multi-frequency

Flicker signal with time-varying frequency. EAF is one of the main equipment leading to voltage fluctuations and flicker. The frequency of each frequency component is roughly inversely proportional to the amplitude of the signal caused by it. Formula (7) simulates the flicker signal caused by EAF.

$$u(t)=\begin{cases}\cos(100\pi t)\,; & 0\le t<0.3 \text{ or } 1.7\le t\le 2\text{s}\\ (1+0.1\cos(20\pi t))\cos(100\pi t)\,; & 0.3\le t<1s\\ (1+0.075\cos(20\pi t)+ & \\ 0.05\cos(30\pi t))\cos(100\pi t)\,; & 1\le t<1.7s\end{cases} \tag{7}$$

Time-varying frequency flicker signal waveform was shown in Figure 6, with cubic spline interpolation method to extract flicker envelope was shown in Figure 7.

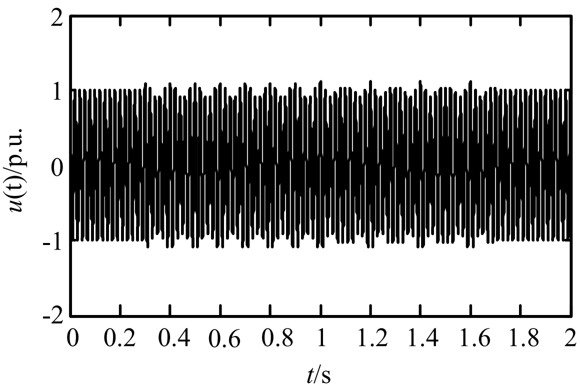

Fig.6 Time-varying frequency flicker signal

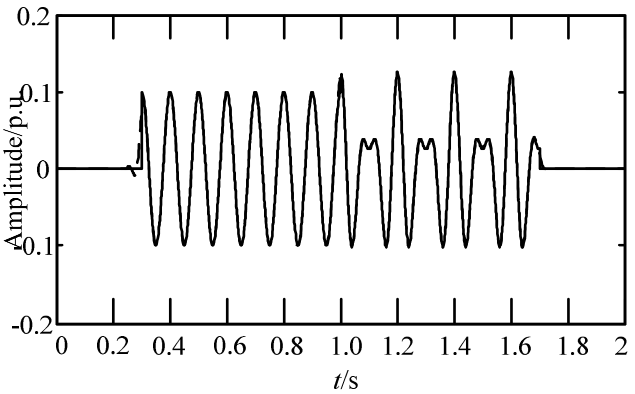

Fig.7 The detection result (dotted line) compare with real value(solid line) of Time-varying frequency

As shown in figure 7, Single frequency flicker occurred at moment 0.28s, changed into a multi-frequency flicker at 1.09s and continued to 1.73s, lastly changed into a power frequency signal. Thus this shows that this method can accurately detect the starting time and end time when flicker frequency component signal changes. Detection error is 1.5094% and the detection is ideal.

Conclusions

The key to analyze voltage flicker signal is to track envelope which contains the amplitude and frequency information of voltage fluctuation. The cubic spline interpolation method was applied in envelope tracking of voltage flicker and a new way was provided to analyze voltage flicker. Simulation examples show that the interpolation method in detecting single-frequency and multi-frequency flicker signal whose flicker frequency is 12Hz or less, the detection error is small. Especially in the low flicker frequency (0.5~3Hz), the error is smaller, making up for the disadvantage that the error is greater in detecting low frequency using square demodulation method.

Therefore, it is suitable for flicker envelope extraction caused by arc furnaces and grid connected wind power. Furthermore, results of frequency time-varying flicker signal simulation show that, the occurrence and recover time of voltage flicker signal can be accurately detected by this method.

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