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Energy Procedia 14 (2012) 1709 – 1716

Energy Procedia

Conference Title

Research on Flicker Measurement Algorithm Based on FFT

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Abstract

Voltage fluctuation and flicker is an important indicator of power quality, so accurate measurement of it is important. This paper researches on voltage fluctuation and flicker measurement algorithm based on fast Fourier transform (FFT) in depth. Voltage fluctuation and flicker measurement based on LabWindows/CVI virtual instrument is realized by use of this algorithm and C language programming. Flow chart of measurement soft and detailed instructions is given. Finally, the measurement result is verified, and error analysis is carried. The calculation result of the algorithm can be consistent with IEC standards after amending the instantaneous flicker values.

Key Words: voltage fluctuation; flicker; fast Fourier transform (FFT); virtual instrument

1. Introduction

As an important indicator of power quality, voltage fluctuation and flicker has gained more and more attention. In order to measure voltage fluctuation and flicker, International Electrotechnical Commission (IEC) standard IEC61000-4-15[1] and national standard GB/T 12326-2008 *Power Quality, Voltage Fluctuation and Flicker*[2] have both proposed functional block diagram of flicker measurement system. According to this block diagram, the flicker tester[3-5], which meets the IEC standard, can be designed. However, this method requires several designs on filter, and many filtering calculations have to be done. These lead to complicated realization process. Document [6] put forward the flicker measurement method based on fast Fourier transform (FFT). This method has left out the complicated filter design work in IEC, thus, simplifying calculation process. This paper conducts in-depth research on flicker measurement algorithm based on FFT. Voltage fluctuation and flicker measurement based on LabWindows/CVI virtual instrument is realized by the use of this algorithm. Furthermore, the measurement result is verified, and reasons for error are analyzed.

2. Flicker measurement algorithm based on FFT

The procedure of calculation on flicker measurement algorithm based on FFT is as follows[6]:

Sampling signal $u(n)$ is gained by m point sampling in every half cycle in instantaneous voltage signal

doi:10.1016/j.egypro.2011.12.887

u*(t)*. And then, use formula (1) to get voltage root mean square on $u(n)$ in every half cycle. So, voltage RMS sequence $U(N)$ in a period is gained, forming discrete voltage RMS curve, which is:

$$U(N) = \sqrt{\frac{1}{m}\sum_{n=1}^{m} u(n)^2} \quad (1)$$

Voltage fluctuation is[2]:

$$d = \frac{U_{\max} - U_{\min}}{U_N} \times 100\% \quad (2)$$

In the formula, $U_{\max}$ and $U_{\min}$ respectively represent two adjacent extremes of voltage RMS, and U_N is rated voltage.

Conduct fast Fourier transform (FFT) to sequence $U(N)$ to get its discrete frequency spectrum. The voltage fluctuation $d(i)$ under the frequency can be obtained from dividing twice of the corresponding spectrum amplitude of every frequency (the peak values of sinusoidal voltage RMS curve under this frequency) by resolved DC component amplitude. After that, substitute $d(i)$ into formula (3) to gain instantaneous flicker values under this frequency.

$$S_i = [d(i)/d_i]^2 \quad (3)$$

In this formula, d_i is required voltage fluctuation to produce 1 unit instantaneous flicker value (S=1) in this frequency. This value can be found in IEC61000-4-15 standard [1] or be gained by fitting of it.

As the square of RMS value of a period wave equals to squares sum of frequency component RMS of this wave, the corresponding instantaneous flicker value S of voltage RMS sequence $U(N)$ is the sum of corresponding instantaneous flicker values S_i of every frequency in frequency spectrum, which is:

$$S = \sum_{i=1}^{K} S_i = \sum_{i=1}^{K} [d(i)/d_i]^2 \quad (4)$$

The above three steps constitute discrete calculation process of instantaneous flicker value $S(t)$. Afterwards, interval sampling can be done to instantaneous flicker value $S(t)$. After grading timing, cumulative probability function (CPF) can be calculated. Finally, short-term flicker value P_{st} and long-term flicker value P_{lt} can be gained. In them, the calculating formula of P_{st} is[2]:

$$P_{st} = (0.0314P_{0.1} + 0.0525P_1 + 0.0657P_3 + 0.28P_{10} + 0.08P_{50})^{1/2} \quad (5)$$

In the formula, $P_{0.1}$, P_1, P_3, P_{10} and P_{50} are respectively $S(t)$ value in 0.1%、1%、3%、10% and 50% time in CPF curve in 10min.

For stable periodical voltage fluctuation, $S(t)$ is constant, so formula (5) can be rewritten as:

$$P_{st} = \sqrt{0.5096S(t)} = 0.714\sqrt{S(t)} \quad (6)$$

Long-term flicker value P_{lt} is calculated by short-term flicker value P_{st} in measurement time period (2h), which is:

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{k=1}^{12} P_{stk}^3} \quad (7)$$

It is worthy of mentioning that 5 specified values used to determine formula (5) through CPF calculation are very cumbersome, which is not beneficial to software programming. These 5 specified values can be gained by sequencing statistics. They are respectively 99.9%, 99%, 97%, 90% and 50% probability maximum value in S sequence during this period[6].

3. Realization of flicker measurement algorithm based on FFT

3.1. Software design

In line with the above flicker measurement algorithm based on FFT, the voltage fluctuation and flicker measurement system software is designed by the use of LabWindows/CVI virtual instrument development platform of National Instruments (NI) Company and C language programming. Its flow chart is shown in figure 1. This software mainly accomplishes parameters set, signal collection, voltage RMS calculation and its frequency spectrum analysis, voltage fluctuation and flicker value measurement, result display, data store and other functions.

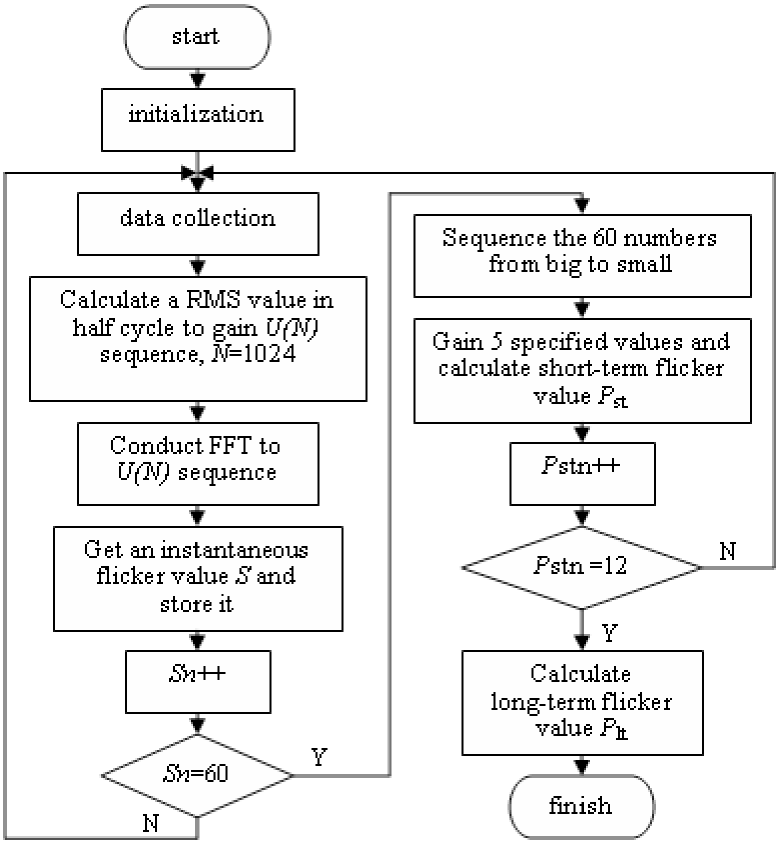

Fig.1 Software flow chart of measurement system

In the first hand, the program conducts system initialization. Then, the cycling of data collection (setting the sampling point in every cycle as 128) and data analysis calculation will start. FFT requires that N value has to be integral power of 2. After comparison and verification, it is believed that N equals 1024 is appropriate after consideration on calculated amount. So time for sampling to get an instantaneous flicker value S is 10.24s(1024 × 0.01s=10.24s), and spectral resolution of $U(N)$ is 0.097656Hz(1/10.24s=0.097656Hz). Spectral distribution of $U(N)$ is in the range of 0~50Hz(1024 × 0.097656/2Hz=50Hz), covering the largest perceivable frequency range of flicker 0.05~35Hz[8]. In this way, 60 (10.24s × 60 ≈ 10min) instantaneous flicker values S can be calculated and 5 specified values used in formula (5) can be gained by sequence statistics. After that, by substituting them, short-term flicker value P_{st} can be acquired. After calculation of 12 (10min × 12=2h) P_{st} , a long-term flicker value P_{lt} can be computed by the use of formula (7).

3.2. Acquisition of sinusoidal voltage fluctuation in any frequency according to S=1

For normal voltage fluctuation, as its fluctuation wave and frequency are random, frequency spectrum of $U(N)$ may be not in the frequencies given by IEC61000-4-15 standard[1]. In order to make flicker measurement method based on FFT suitable for all voltage fluctuation frequency, sinusoidal voltage fluctuation data (see table 1) of corresponding unit instantaneous flicker value (S=1) given by this standard has to be fitted. According to the feature of these data, divide them into two frequency bands: 0.5～8.8Hz and 8.8～25Hz. Least square fitting will be conducted to these two bands. Fitness polynomial is shown in formula (8).

$$d(f)=\sum_{i=0}^{9}a_i(f-f_p)^i \tag{8}$$

In formula, f_p is average of frequency that is in fitness calculation. The average in 0.5～8.8Hz frequency band is 4.518Hz, and that in 8.8～25Hz is 16.015Hz. a_i is the coefficient of fitness polynomial, shown as table 2.

Tab.1 The sinusoidal voltage fluctuation according to S=1

f/Hz	d/%	f/Hz	d/%	f/Hz	d/%	f/Hz	d/%	f/Hz	d/%	f/Hz	d/%
0.5	2.340	3.5	0.568	6.5	0.300	10.0	0.260	14.0	0.388	20.0	0.700
1.0	1.432	4.0	0.500	7.0	0.280	10.5	0.270	15.0	0.432	21.0	0.760
1.5	1.080	4.5	0.446	7.5	0.266	11.0	0.282	16.0	0.480	22.0	0.824
2.0	0.882	5.0	0.398	8.0	0.256	11.5	0.296	17.0	0.530	23.0	0.890
2.5	0.754	5.5	0.360	8.8	0.250	12.0	0.312	18.0	0.584	24.0	0.962
3.0	0.654	6.0	0.328	9.5	0.254	13.0	0.348	19.0	0.640	25.0	1.042

Tab.2 The coefficients of the fitness polynomial

Coefficients of fitness polynomial	0.5-8.8Hz frequency band	8.8-25Hz frequency band	Coefficients of fitness polynomial	0.5-8.8Hz frequency band	8.8-25Hz frequency band
a_0	0.445	0.480	a_5	-5.272×10^{-4}	-1.526×10^{-6}
a_1	-0.102	4.905×10^{-2}	a_6	-3.426×10^{-4}	1.957×10^{-7}
a_2	1.439×10^{-2}	1.635×10^{-3}	a_7	6.970×10^{-5}	8.970×10^{-9}
a_3	-1.264×10^{-3}	-1.339×10^{-5}	a_8	2.072×10^{-5}	-8.259×10^{-10}
a_4	2.523×10^{-3}	-3.257×10^{-6}	a_9	-4.299×10^{-6}	-2.456×10^{-12}

Corresponding fitness curves are displayed by figure 2 and 3. The points of the figures are the discrete primitive values. The two figures show that fitness function of formula (8) has good fitness result. Through this formula, sinusoidal voltage fluctuation d in any frequency according to S=1 can be gained. Therefore, by taking advantage of flicker measurement method based on FFT, any flicker value caused by synthetic voltage fluctuation of fluctuant components in any frequency (<25Hz) can be solved.

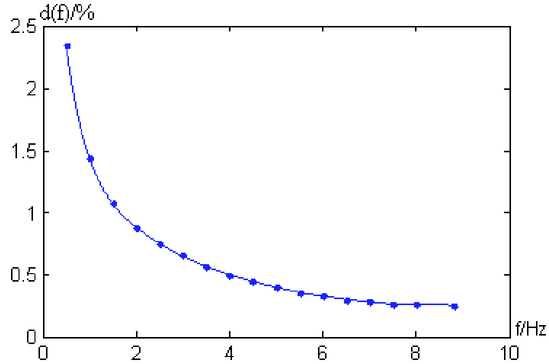

Fig.2 Fitness curve of 0.5~8.8Hz frequency band

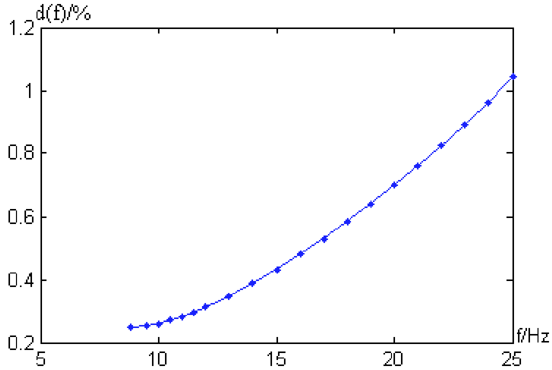

Fig.3 Fitness curve of 8.8~25Hz frequency band

4. Algorithm verification and error analysis

4.1. Algorithm verification

On basis of national standard GB/T 12326-2008 *Power Quality, Voltage Fluctuation and Flicker*[2] and IEC standard IEC868[9] and IEC61000-4-15[1], there are two ways to verify flicker measurement algorithm: (1) use voltage fluctuation produced by sinusoidal/square wave modulation industrial frequency carrier to verify unit instantaneous flicker value(S=1); (2) use voltage fluctuation produced by square wave modulation industrial frequency carrier to verify unit short-term flicker value(P_{st}=1). In this paper, the first method is adopted.

Firstly, construct a fluctuation voltage function as formula (9):

$$u(t) = A(1 + m\cos\Omega t)\cos\omega t \tag{9}$$

In it, A is industrial frequency carrier voltage amplitude; ω is angular frequency of industrial frequency voltage, $\omega = 2\pi f_s$, f_s is frequency of industrial frequency carrier voltage, 50 Hz; m is modulation ration of amplitude-modulated wave voltage; Ω is angular frequency of amplitude-modulated wave voltage, $\Omega = 2\pi f$, f is frequency of amplitude-modulated wave voltage, which is fluctuation frequency, Hz.

A is 5; m is 1/2 of corresponding voltage fluctuation d. And substitute different voltage fluctuation frequency f and corresponding fluctuation value d. According to the sinusoidal voltage fluctuation table of S=1 given by IEC61000-4-15 standard (see table 1), calculate corresponding S value of every fluctuation frequency in line with the above flicker measurement method based on FFT. The result is shown in table 3.

Tab.3 S-values calculated according to the sinusoidal voltage fluctuation table of S=1

f/Hz	d/%	S	f/Hz	d/%	S	f/Hz	d/%	S
0.5	2.340	0.975	6.5	0.300	0.950	14.0	0.388	0.887
1.0	1.432	0.985	7.0	0.280	0.954	15.0	0.432	0.871
1.5	1.080	1.024	7.5	0.266	0.975	16.0	0.480	0.864
2.0	0.882	1.014	8.0	0.256	0.954	17.0	0.530	0.853
2.5	0.754	1.013	8.8	0.250	0.945	18.0	0.584	0.833
3.0	0.654	1.012	9.5	0.254	0.937	19.0	0.640	0.811
3.5	0.568	0.994	10.0	0.260	0.923	20.0	0.700	0.799
4.0	0.500	0.984	10.5	0.270	0.920	21.0	0.760	0.784
4.5	0.446	0.982	11.0	0.282	0.917	22.0	0.824	0.764
5.0	0.398	0.969	11.5	0.296	0.914	23.0	0.890	0.740
5.5	0.360	0.972	12.0	0.312	0.913	24.0	0.962	0.721
6.0	0.328	0.969	13.0	0.348	0.910	25.0	1.042	0.706

From table 3, it can be drawn that when voltage fluctuation frequency is lower than 8Hz, calculation error of instantaneous flicker value S is less than 5%, which is acceptable. When voltage fluctuation frequency is higher than 8Hz, calculation error rate of S will increase with the rise of voltage fluctuation.

4.2. Error analysis

The reason for above result is that the sinusoidal voltage fluctuation table of S=1 (see table 1) is gained by recommended measurement method by IEC. This method adopts square method to test amplitude-modulated wave; however, measurement method based on FFT utilizes half wave RMS to test amplitude-modulated wave. As a result of this, the test results of these two methods have essential difference, which will be analyzed in next part.

Square test method is to square formula (9), which is:

$$u^2(t) = \frac{A^2}{2}(1+\frac{m^2}{2}) + mA^2\cos\Omega t + \frac{m^2A^2}{4}\cos 2\Omega t + \frac{A^2}{2}(1+\frac{m^2}{2})\cos 2\omega t + \frac{m^2A^2}{8}\cos 2(\omega+\Omega)t$$
$$+\frac{m^2A^2}{8}\cos 2(\omega-\Omega)t + \frac{mA^2}{2}\cos(2\omega+\Omega)t + \frac{mA^2}{2}\cos(2\omega-\Omega)t + \cdots \tag{10}$$

Then, filter out DC component, industrial frequency, and above frequency component by 0.05～35Hz band-pass filter. Meanwhile, by considering m is far less than 1, amplitude-modulated wave, which is voltage fluctuation component, can be examined. Its output is:

$$K(t) = mA^2\cos\Omega t \tag{11}$$

Therefore, coefficient is constant.

However, half wave RMS test is based on envelope curve whose amplitude-modulated wave voltage is voltage RMS $U(N)$, which is

$$\Delta u(t) = \sqrt{\frac{2}{T}\int_t^{t+T/2} u^2(t)\mathrm{d}t} - \frac{A}{\sqrt{2}} \tag{12}$$

Minus $u^2(t)$ by reference voltage $A^2/2$, and then integrate. Meanwhile, it is ignorable that m is far less than 1, and frequency in integrate is above or equal to 2ω component.

$$K(t) = \frac{2}{T}\int_t^{t+T/2} mA^2\cos\Omega t\mathrm{d}t = \frac{2mA^2}{\Omega T}\int_t^{t+T/2}\cos\Omega t\mathrm{d}(\Omega t) = \frac{2mA^2}{\Omega T}[\sin\Omega(t+\frac{T}{2}) - \sin\Omega t]$$
$$= \frac{4mA^2}{\Omega T}\sin\frac{\Omega T}{4}\cos\Omega(t+\frac{T}{4}) \tag{13}$$

As $\omega T = 2\pi$, the tested amplitude-modulated wave output is

$$K(t) = \frac{2mA^2\omega}{\pi\Omega}\sin\frac{\pi\Omega}{2\omega}\cos(\Omega t + \frac{\pi\Omega}{2\omega}) \tag{14}$$

It can be seen that coefficient is no longer constant, but relate to fluctuation frequency. Define attenuation coefficient as

$$K_f = \frac{2\omega}{\pi\Omega}\sin\frac{\pi\Omega}{2\omega} \tag{15}$$

Relation curve of this attenuation coefficient and fluctuation frequency f is shown in figure 4.

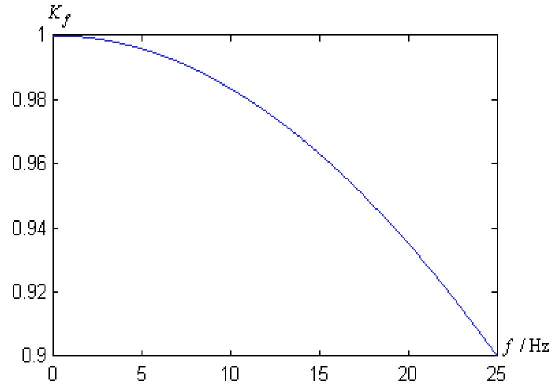

Fig.4 K_f and f relation curve

As flicker is a reflection of voltage fluctuation, the feature of decreasing amplitude-modulated wave with fluctuation frequency tested by half wave RMS will make calculated flicker value decrease with the rise of wave frequency. In order to make sure the flicker measurement result based on FFT is in line with IEC standard, the instantaneous flicker values S calculated according to table 3 have to be modified. In implementation, choose reciprocal of every S in table 3 as the modified factor, and conduct least square curve fitting to the discrete modified factors to get the modified factors of any fluctuation frequency according to S. Therefore, after calculation of instantaneous flicker value S according to fluctuation frequency by flicker measurement algorithm based on FFT, multiply its corresponding modified factors. Then, the error is reduced.

5. Conclusions

Flicker measurement algorithm based on FFT is actually to use discrete method to get instantaneous flicker value $S(t)$. After that, by conducting statistical analysis to $S(t)$ in a period, the short-term flicker value P_{st} and long-term flicker value P_{lt} are calculated. This algorithm skips the complicated filter design in IEC, thus, simplifying the calculation process. This paper takes advantage of this algorithm to design measurement system software in LabWindows/CVI virtual instrument environment, realizing measurement of voltage fluctuation and flicker and laying the foundation for the future research on digital new flicker meter. The result shows that flicker measurement algorithm based on FFT has low error in low frequency band. However, the error may increase with the rise with fluctuation frequency. The reason for this is that the amplitude-modulated wave tested by half wave RMS method adopted by this measurement algorithm has attenuation coefficient. Through the modification on calculated instantaneous flicker value, the result can be in consistent with IEC standard.

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