Effective voltage flicker calculation algorithm using indirect demodulation method

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Abstract: The voltage flicker is one of the major power quality disturbances in a weak power system. Better measurement and limitation techniques are always desired. An effective and accurate calculation method is presented to obtain the voltage flicker components and the 10 Hz equivalent value. By using the indirect demodulation method, the RMS values of a voltage waveform are calculated cycle by cycle to obtain the envelope. Then the fast Fourier transform (FFT) is used to obtain the flicker components. This method can increase the computing speed and reduce the hardware requirement in a power quality instrument when the FFT is used. The effects of sampling rate, harmonics, and system frequency shifting are investigated. The latter two are common disturbances in addition to the voltage flicker when arc furnace loads are connected in a weak power system. A calibration procedure is used to improve the frequency leakage effect and increase the calculation accuracy. The calculation results from given voltage flicker waveforms and field measured waveforms reveal the effectiveness of the proposed method. It can be used in both 50 and 60 Hz systems.

List of symbols

f_n	flicker modulation frequency
f_s	sampling frequency
f_{sys}	power frequency
G_A	attenuation factor
G_C	calibration factor
H	number of RMS values (number of windows)
h	jump-sampling number
M	number of total sampled data
N	sampled data number of a cycle
T	total sampling duration
$V[k]$	frequency spectrum magnitude by FFT
$V_{average}$	average of RMS values
$v(t)$	instantaneous voltage
$v_{rms}(t)$, $v_{rms}[i]$	RMS value of a window
$v_s(t)$, $v_s[i]$	profile of RMS values
ΔV	voltage deviation
$\Delta V10$	voltage flicker 10 Hz equivalent value
$\Delta V_{\_n}$	magnitude modulation component of frequency f_n

1 Introduction

Fluctuating loads, such as electric arc furnaces and arc welders, may cause the disturbances of voltage flicker (voltage fluctuation) in a weak power system and affect the illumination in nearby distribution areas. For an arc furnace in the melting stage, load currents change continuously and extremely. If the system short-circuit capacity is not large enough, the voltage drop in the feeder line will change obviously and irregularly [1]. Many reports indicate that a small voltage flicker from 0.3% to 0.5% in the frequency range of 6–10 Hz will cause visible incandescent lamp flickering [2, 3] and make people feel uncomfortable. The power system in Taiwan is an island system. Voltage flicker problems have appeared in several distribution areas of the Taiwan Power Company for a long time [4, 5]. Voltage flicker is considered to be one of the major power quality disturbances [6].

In evaluation and limitation, there are some definitions and standards to quantify the voltage magnitude variation levels, such as IEEE 519-1992 and IEC 61000 [7–9]. Many measurement techniques and equipments have been studied and applied [10, 11]. In order to evaluate the level of voltage fluctuation correctly, the definition of voltage-flicker severity was proposed and a standard meter was also developed by the Disturbance Committee of the International Union for Electroheat (UIE), in cooperation with the International Electrotechnical Commission (IEC) [12]. The voltage-flicker severity is expressed as short-term severity, P_{st}, and long-term severity, P_{lt}. The values recommended by IEC 61000-3-3 [8] and IEC 61000-3-5 [9], are $P_{st} = 1.0$ pu and $P_{lt} = 0.65$ pu, with a nominal voltage fluctuation less than 3% and a maximum voltage fluctuation less than 4%, for a 220–250 V (to neutral point voltage) low-voltage system.

The voltage flicker 10 Hz equivalent value, $\Delta V10$, is used by some Asian utilities [13, 14] to represent the severity of voltage flicker and to evaluate customers with fluctuating loads. This method converts all amplitude modulation components (flicker components) of the waveform into the 10 Hz equivalent value to represent the equivalent effect. Each flicker component has a different weighting value. In order to obtain the flicker components, methods based on

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the discrete Fourier transform (DFT) or the fast Fourier transform (FFT) can be used. If the DFT or FFT is carried out directly for the sampled data of a voltage waveform in a specified duration, it is called the direct demodulation method (DDM) [15]. The flicker components can be obtained from the frequency spectrum. Although this method is simple, the difficulty is that the sampled data size should be extremely large considering the resolution. This increases hardware requirement in a power quality instrument. The indirect demodulation method (IDDM) is an alternative. First, the RMS values of the sampled voltage waveform are calculated cycle by cycle to obtain the waveform envelope. Then the FFT is carried out with data from the envelope to obtain the flicker components. The data size can be small. The benefits are higher computing speed and less instrument hardware requirement.

The IDDM is used in this paper to calculate voltage flicker components and the 10 Hz equivalent value. The effects of sampling methods and data length are considered. In order to improve the frequency leakage effect (side-lobes effect) in the FFT, a calibration procedure is given. The calculation results from given voltage flicker waveforms and field measured waveforms show that the method is effective and accurate. This method also can sustain the influences of harmonics and system frequency shifting.

2 Voltage flicker

At steady state without any disturbance, the voltage waveform in a power system is sinusoidal with constant amplitude. However, the operation of fluctuating loads, such as electric arc furnaces, would cause disturbances of voltage flicker in the neighbouring power system. For a short duration, a voltage flicker waveform [15] can be described as

$$\begin{aligned} v(t) &= s(t)\sin(2\pi f_{sys}t) \\ &= \sqrt{2}V_{rms}\left[1+\frac{1}{2}\sum_{n}\Delta V_{\_n}\sin(2\pi f_n t+\varphi_n)\right] \\ &\quad \times \sin(2\pi f_{sys}t) \end{aligned} \quad (1)$$

where f_{sys} is the power frequency (50 or 60 Hz), V_{rms} is the average RMS value of the voltage, and $\Delta V_{\_n}$ is the amplitude modulation value of the modulation frequency f_n. Expression (1) is an amplitude modulation (AM) function with the signal $s(t)$ and the carrier frequency f_{sys}. For voltage flicker limitation, we usually consider f_n in the range 0.1 Hz$\sim$30 Hz only. Fig. 1 shows a simplified voltage flicker waveform, which contains one

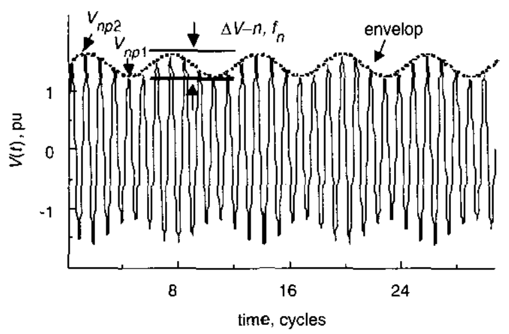

Fig. 1 *Voltage flicker waveform with $\Delta V_{\_n} = 0.3\,pu$ and $f_n = 10\,Hz$*

modulation component with $\Delta V_{\_n} = 0.3\,\pi$ and $f_n = 10$ Hz. Under simple circumstances with only one modulation component, the voltage variation in Fig 1 can be expressed as [16]

$$\Delta V_{\_n} = V_{np2} - V_{np1} \quad (2)$$

However, a voltage flicker waveform usually contains many modulation components, and therefore the practical voltage variation ΔV can be expressed as [4]

$$\Delta V = \sqrt{\sum_n (\Delta V_{\_n})^2} \quad (3)$$

The voltage flicker 10 Hz equivalent value $\Delta V10$ is

$$\Delta V10 = \sqrt{\sum_n (a_n \Delta V_{\_n})^2} \quad (4)$$

The flicker sensitivity coefficient a_n, as a function of flicker frequency f_n, is shown in Fig. 2 which describes the sensitivity of man's eye-brain mechanism to illumination flicker. The method using $\Delta V10$ is used by the Taiwan Power Company for voltage flicker limitation [14].

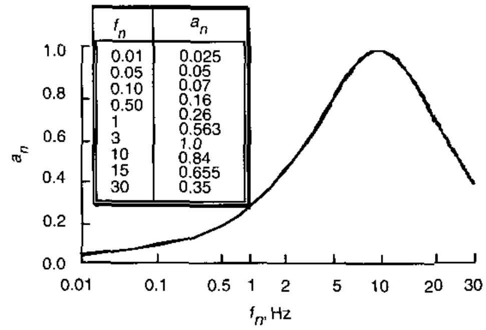

Fig. 2 *Flicker sensitivity coefficient curve*

3 Voltage flicker calculation method

The requirement is to obtain the frequency components of the signal $s(t)$ in (1). This is a general demodulation procedure. The indirect demodulation method (IDDM) is used in this Section. The flowchart is shown in Fig 3. Fig. 4 shows the concept of data handling. A simple illustration is given in Fig. 5.

The moving window method is used to calculate the RMS values of the instantaneous voltage $v(t)$ with N samples in each cycle as a window as shown in Fig. 5*a*. Then it is shifted h samples (jump-sampling) to reach the next window. At window i, the RMS value is

$$v_{rms}(t) \equiv v_{rms}[i] = \sqrt{\frac{\sum_{m=(i-1)h+1}^{(i-1)h+N} v^2[m]}{N}}, \quad (5)$$
$$i = 1, 2, \ldots, H$$

With a total of H RMS values in H windows, the envelope of the original waveform is obtained as shown in Fig. 5*b*. The average value of the RMS values within the measurement period is

$$V_{average} = \left(\sum_{i=1}^{H} v_{rms}[i]\right)/H \quad (6)$$

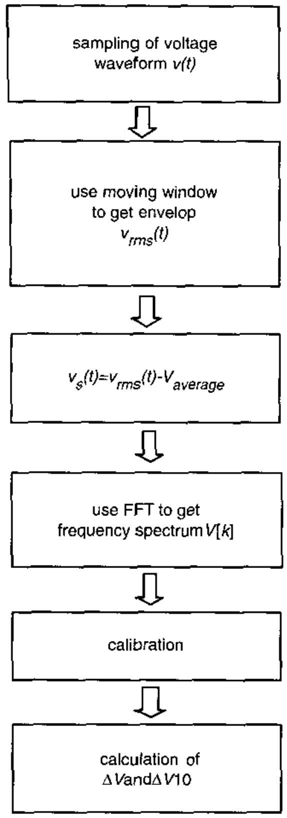

Fig. 3 *Flowchart of the IDDM*

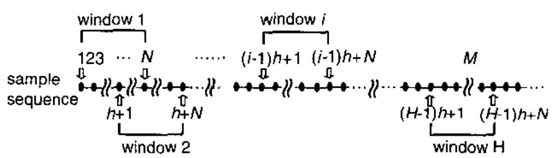

Fig. 4 *Moving window method to obtain RMS value of v(t)*

Then the average value is subtracted from the RMS value in each window. Hence

$$v_s(t) \equiv v_s[i] = v_{rms}[i] - V_{average}, \quad i = 1, 2, \ldots, H \qquad (7)$$

The final envelope is obtained as shown in Fig. 5*c*. The reason for subtracting the average value is that it will appear as a DC component in the frequency spectrum, which causes a spike and affects the accurate values of the nearby components.

The frequency components of $v_s[i]$ are the flicker components of $v(t)$. An FFT is used to calculate the frequency spectrum [17]. Thereby

$$V[k] = \frac{1}{H}\sum_{i=1}^{H} v_s[i]\exp\left(-j\frac{2\pi i}{H}\right)k, \quad k = 1, 2, \ldots, H/2 \qquad (8)$$

Therefore the f_n Hz amplitude modulation value in (1) can be obtained from the data sequence of $V[k]$ [18], i.e.

$$\Delta V_{\_n} = \frac{2\sqrt{2}}{V_{average}} V\left[\frac{f_n}{(f_s/M)}\right] \times 100\% \qquad (9)$$

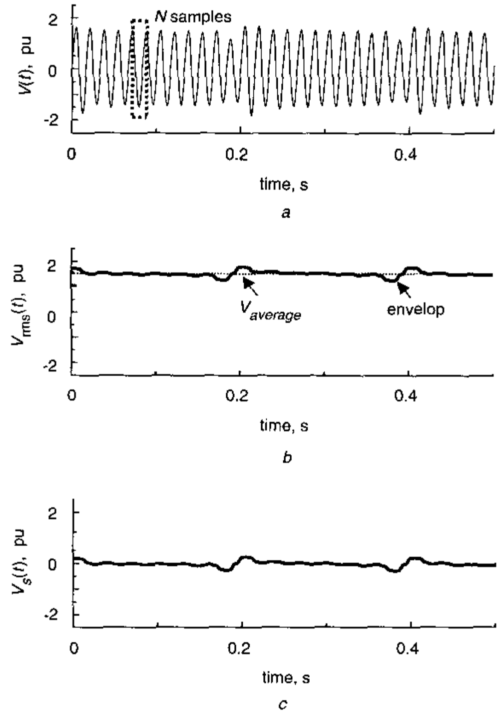

Fig. 5 *Method used to obtain the envelope*
a *N* samples in a window
b Envelope curve of original waveform
c Envelope curve of b by subtracting the average value

where $f_s = \frac{M}{T}$ is the sampling frequency, and M is the total sampling number within the total sampling duration T. The values of ΔV and $\Delta V10$ can then be calculated.

From Fig. 4 and (5)–(8), it can be found that $M = hH = TNf_{sys} = Tf_s$. To use the FFT in (8), it is required that $H = 2^j$ where j is a positive integer, and so there should be special combinations of these parameters. It can be found that the choice of h is limited. It is also noted that although M data may be needed in the DDM, only H data are used in the FFT of the IDDM. The number of data for the FFT can be as small as possible. The benefits are high computing speed and less instrument hardware requirement.

4 Effect of sampling and data length

In the spectrum calculation of $v_s[i]$ using FFT, the frequency resolution is f_s/M. Therefore, different f_s, T or N will give different M, and result in different frequency

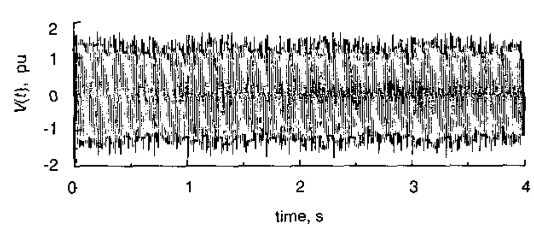

Fig. 6 *The given voltage flicker waveform*

Table 1: Simulation cases for given voltage flicker waveform

	f_{sys}, Hz	N	T (s)	f_s (samples/s)	h	H	M
Case 1	60	128	4	7680	15	2048	30720
Case 2	60	64	8	3840	15	2048	30720
Case 3	60	32	16	1920	15	2048	30720
Case 4	60	64	4	3840	15	1024	15360
Case 5	60	32	8	1920	15	1024	15360
Case 6	60	16	16	960	15	1024	15360
Case 7	50	256	4	12800	25	2048	51200
Case 8	50	128	8	6400	25	2048	51200
Case 9	50	64	16	3200	25	2048	51200
Case 10	50	128	4	6400	25	1024	25600
Case 11	50	64	8	3200	25	1024	25600
Case 12	50	32	16	1600	25	1024	25600

Table 2: Calculation results with 1-cycle period as a window

	$\Delta V_{\_n}$ %										
f_n, Hz	1	6	10	15.25	17	20	23	25.75	30	ΔV %	ΔV 10 %
Given value	10	10	10	10	10	10	10	10	10	30	20.71
Case 1	9.99	9.83	9.53	8.97	8.72	8.26	7.73	7.22	6.36	25.77	18.51
Case 2	9.97	9.83	9.52	8.96	8.7	8.27	7.74	7.22	6.35	25.76	18.50
Case 4	9.95	9.82	9.54	8.95	8.73	8.26	7.73	7.23	6.36	25.76	18.51
Case 5	9.96	9.84	9.52	8.94	8.71	8.27	7.75	7.23	6.36	25.76	18.50
Case 7	9.98	9.74	9.33	8.51	8.18	7.55	6.86	6.15	5.03	24.25	17.66
Case 8	9.97	9.76	9.33	8.52	8.18	7.56	6.84	6.16	5.03	24.26	17.67
Case 10	9.98	9.76	9.35	8.52	8.18	7.55	6.85	6.16	5.03	24.27	17.68
Case11	9.97	9.77	9.33	8.52	8.19	7.54	6.85	6.15	5.03	24.26	17.67

resolution. There are twelve cases in Table 1 for comparison, where both 50 Hz and 60 Hz systems are considered. Fig 6 shows a given voltage flicker waveform, which has 1 pu average RMS value and contains 1 Hz, 6 Hz, 10 Hz, 15.25 Hz, 17 Hz, 20 Hz, 23 Hz, 25.75 Hz and 30 Hz flicker components. Each flicker value is 0.1 pu (10%) for the purpose of showing the calculation ability. The calculation results of the twelve cases have been carefully examined. While the others have serious leakage effects (side-lobes effect) in the FFT calculation, a few feasible cases are given in Table 2. However, it can be found that there are still obvious calculation errors for higher frequency components. It is observed that the higher the modulation frequency, the larger the error that occurs. The reason may be that the signal frequencies (modulation frequencies) are very close to the carrier frequency (power frequency) ,and so the 50 Hz system has larger errors.

To improve the frequency leakage effect, the data length used to calculate the RMS values is investigated. Since voltage flicker is fluctuation of voltage magnitude, another possible way to obtaining the RMS values may be to use sampled data in a half or quarter cycle only. This method is revealed in Fig. 7. The calculation results for a few feasible cases are given in Tables 3 and 4. There is significant improvement. Fig. 8 shows the comparison of demodulation results for case 4. The method with half-cycle sampled data as a window is better because it has lower errors for modulation components under 17 Hz. It has been reported

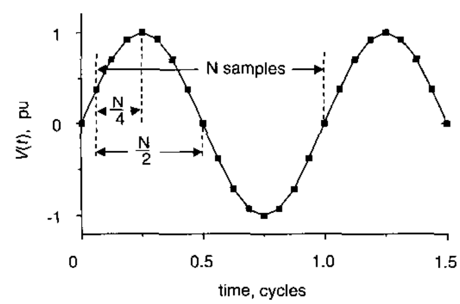

Fig. 7 *Window size (number of data) used to calculate RMS values*

that arc furnace loads usually produce lower frequency voltage flicker [1–3], and the 6–10 Hz components are critical in the calculation of $\Delta V10$. From Table 3, case 4 is chosen for the 60 Hz system and case 10 for the 50 Hz system when both calculation accuracy and data length are considered. They are used for the following study.

To improve the calculation accuracy still further, a calibration method can be adopted in practical instrument designs. In this paper, the rectangular window method is used in the FFT process. It contains the narrowest main-lobe, and the widest side-lobe [19]. Therefore, all FFT calculations are carried out with limited data, which would cause a leakage effect. To reveal the effect, the attenuation

Table 3: Calculation results with 1/2-cycle period as a window

	$\Delta V_{\_n}$ %										
f_n, Hz	1	6	10	15.25	17	20	23	25.75	30	ΔV%	ΔV10 %
Given value	10	10	10	10	10	10	10	10	10	30	20.71
Case1	10.0	9.96	9.88	9.75	9.67	9.55	9.39	9.26	9.00	28.84	20.12
Case 2	9.98	9.96	9.87	9.73	9.66	9.56	9.4	9.25	9.00	28.82	20.11
Case 4	9.97	9.95	9.89	9.73	9.68	9.56	9.39	9.27	9.01	28.83	20.12
Case 5	9.98	9.97	9.87	9.71	9.66	9.56	9.41	9.26	9.01	28.83	20.11
Case 7	9.99	9.93	9.83	9.61	9.52	9.35	9.16	8.93	8.57	28.33	19.86
Case 8	9.99	9.95	9.83	9.62	9.53	9.36	9.14	8.94	8.57	28.34	19.87
Case10	9.99	9.94	9.85	9.62	9.52	9.35	9.15	8.93	8.58	28.34	19.87
Case 11	9.98	9.96	9.83	9.61	9.53	9.33	9.15	8.93	8.58	28.33	19.87

Table 4: Calculation results with 1/4-cycle as a window

	$\Delta V_{\_n}$ %										
f_n, Hz	1	6	10	15.25	17	20	23	25.75	30	ΔV%	ΔV 10%
Given value	10	10	10	10	10	10	10	10	10	30	20.71
Case 1	9.71	9.71	9.68	9.66	9.64	9.60	9.55	9.52	9.46	28.84	19.97
Case2	9.76	9.61	9.56	9.65	9.76	9.61	9.55	9.51	9.45	28.82	19.91
Case 4	9.75	9.61	9.58	9.64	9.78	9.61	9.55	9.53	9.47	28.84	19.93
Case 5	9.77	9.67	9.58	9.63	9.76	9.62	9.59	9.53	9.43	28.86	19.95
Case 7	9.72	9.70	9.67	9.61	9.59	9.55	9.50	9.43	9.32	28.70	19.89
Case 8	9.72	9.76	9.67	9.62	9.60	9.56	9.48	9.44	9.33	28.73	19.92
Case 10	9.71	9.75	9.69	9.62	9.59	9.55	9.49	9.43	9.34	28.73	19.92
Case11	9.69	9.76	9.67	9.61	9.59	9.52	9.48	9.42	9.33	28.69	19.91

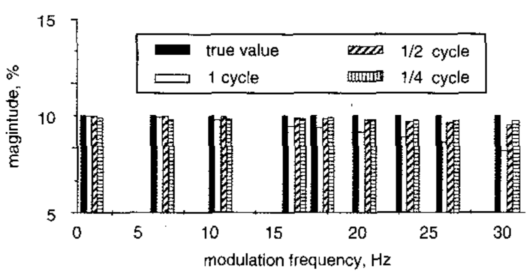

Fig. 8 *Effect of window size on flicker calculation*

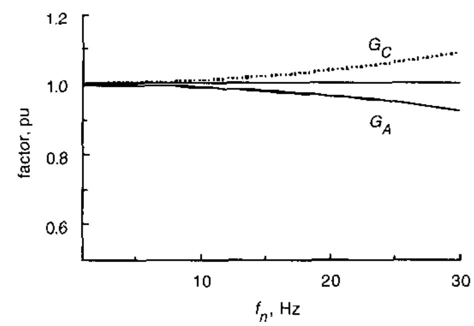

Fig. 9 *The attenuation factor and calibration factor curves for case 4*

factor is defined as

$$G_A(f_n) = \frac{\text{calculated} \quad \Delta V_{\_n}}{\text{given} \quad \Delta V_{\_n}} \tag{10}$$

To obtain attenuation factor values, the IDDM is repeated for 30 voltage waveforms. Each waveform has only one modulation component, i.e. $f_n = 1, 2, \ldots, 29$ or 30 Hz, respectively, for each waveform, and $\Delta V_{\_n} = 10\%$. The attenuation factor curve of the case 4 system is given in Fig. 9. It is found that the curve is smooth. The leakage effect is more serious in higher frequency components.

To recover the leakage, a calibration factor (G_C) should give the result as

$$G_C(f_n)G_A(f_n) = 1 \tag{11}$$

To calibration factors of modulation components, $f_n = 1, 2, \ldots, 29$ and 30 Hz, can be obtained by the reciprocals of the corresponding attenuation factors. However, since the modulation frequencies in a real voltage flicker waveform can be non-integer, a regression function should be used. The regression analysis method uses the least square error criteria [20]. In this paper a sixth-order polynomial is used to approximate the calibration factor curve as given in Fig. 9, which is also smooth.

The calculated f_n Hz amplitude modulation component in (9) is multiplied by its corresponding calibration factor to

Table 5: Comparison of calculation results with and without calibration

	f_n, Hz	Given value	Without calibration		With calibration	
			Case 4	Case 10	Case 4	Case 10
$\Delta V_{\_n}$, %	1	10	9.97	9.98	9.97	9.99
	6.5	10	9.95	9.93	9.99	10
	10	10	9.89	9.83	10	10
	15.25	10	9.73	9.61	9.99	9.99
	17	10	9.68	9.53	10.01	10
	20.25	10	9.55	9.33	10.01	9.99
	23.5	10	9.36	9.11	9.98	10
	25.75	10	9.27	8.93	10.01	9.99
	30	10	9	8.59	10	10.01
ΔV, %		30	28.82	28.312	29.99	29.99
ΔV 10, %		20.78	20.2	19.94	20.78	20.78

Table 6: Effect of harmonics on flicker calculation

	f_n, Hz	Given value	60 Hz system			50 Hz system		
			Case A	Case B	Case C	Case D	Case E	Case F
$\Delta V_{\_n}$, %	1	10	10.05	9.99	10.03	10.03	10	10.03
	6	10	10.03	9.99	10.03	10.02	10	10.04
	10	10	10.02	10.01	10.02	10	9.99	10.04
	15.25	10	10.03	9.99	10.01	10.02	10.02	10.04
	17	10	10.02	10	10.04	10.01	10.03	10.02
	20	10	10.03	10.02	10.02	10.02	10.03	10.07
	23	10	10.04	10.02	10.04	10.03	10.01	10.05
	25.75	10	10.03	10.01	10.01	10.01	10.03	10.03
	30	10	10.03	10.01	10.04	10.04	10.04	10.06
ΔV, %		30	30.09	30.01	30.08	30.06	30.05	30.13
ΔV 10, %		20.71	20.77	20.71	20.76	20.74	20.73	20.79

Table 7: Effect of power frequency shifting on flicker calculation

	f_n, Hz	Given Value	60 Hz system				50 Hz system			
			Case G	Case H	Case I	Case J	Case K	Case L	Case M	Case N
$\Delta V_{\_n}$, %	1	10	10.01	9.99	9.99	10.01	9.99	10.02	10	10
	6	10	9.99	9.99	10.01	10.01	10.01	10	10	10
	10	10	10	9.98	9.99	10	9.99	9.99	10	10.01
	15.25	10	9.97	9.98	10.01	10.02	10	10.01	10	9.97
	17	10	9.99	10	10	9.99	9.99	10	10	9.99
	20	10	9.98	10.01	9.99	10	9.97	10	10.01	9.99
	23	10	9.95	9.99	10	10	9.99	9.98	10..01	10
	25.75	10	10	10	9.99	9.98	9.99	10.01	9.99	9.99
	30	10	9.97	10.01	10.02	10.01	9.97	10	9.99	9.98
ΔV, %		30	29.95	29.98	30	30.01	29.97	30	30	29.98
ΔV10, %		20.71	20.68	20.69	20.71	20.72	20.69	20.71	20.71	20.7

obtain the modified value. Table 5 shows the calculation results and the comparison of ΔV and $\Delta V10$ of the given flicker waveforms without and with calibration. The errors have greatly improved.

5 Effect of harmonics and frequency shifting

Not only DC arc furnaces, but also AC arc furnaces will produce harmonic currents and cause harmonic-distorted voltage waveforms. The voltage flicker values of waveforms with harmonic distortion need to be calculated. The size of AC and DC arc furnaces in a 161 kV customer could be as large as 100 MW. Operation of arc furnaces would also cause frequency shifting in a weak power system. This phenomenon is obvious in an island power system, such as Taiwan. For a digital voltage flicker meter, the effect of power frequency shifting should be considered.

The test voltage flicker waveform in Fig. 6 is also used. Both integral and non-integral harmonics are considered. Several cases are chosen for comparison.

Case A: with 0.05 pu fifth- and seventh-order harmonics, $f_{sys} = 60$ Hz

Case B: with 0.05 pu 187 Hz harmonic, $f_{sys} = 60$ Hz

Case C: with 0.05 pu fifth- and seventh-order and 187 Hz harmonics, $f_{sys} = 60$ Hz

Case D: with 0.05 pu fifth- and seventh-order harmonics, $f_{sys} = 50$ Hz

Case E: with 0.05 pu 187 Hz harmonic, $f_{sys} = 50$ Hz

Case F: with 0.05 pu fifth- and seventh-order and 187 Hz harmonics, $f_{sys} = 50$ Hz

Case G: $f_{sys} = 60.1$ Hz

Case H: $f_{sys} = 60.5$ Hz

Case I: $f_{sys} = 59.9$ Hz

Case J: $f_{sys} = 59.5$ Hz

Case K: $f_{sys} = 50.1$ Hz

Case L: $f_{sys} = 50.5$ Hz

Case M: $f_{sys} = 49.9$ Hz

Case N: $f_{sys} = 49.5$ Hz

While Table 6 shows the effect of harmonics on flicker calculation, the effect of power frequency shifting is revealed in Table 7. These effects are not significant. The calculation results of ΔV and $\Delta V10$ are still very close to their given values.

6 Application to field measurement waveforms

To apply the above method to practical systems, the measurement data from the arc furnace feeders of customers of a 60 Hz system are used. The sampling rate is 64 samples per cycle (3840 samples/s). Figs. 10*a* and 10*b*, respectively, show the voltage waveforms of DC arc furnace and AC arc furnace feeders inside steel plants. Since the DC arc furnace uses a constant-current control mode, its voltage flicker is not serious, but there is harmonic distortion. However, the voltage flicker problem is much more severe in the AC arc furnace. The system frequency at the DC arc furnace feeder is 59.97 Hz, and that at the AC furnace feeder is 59.894 Hz. The calculation results of ΔV and $\Delta V10$ are given in Table 8, where three cases are compared. Since the 1-cycle window method without calibration is inferior, the calculated values are low due to the leakage effect. The 1/2-cycle window method with calibration should give the most accurate values. The flicker components are also

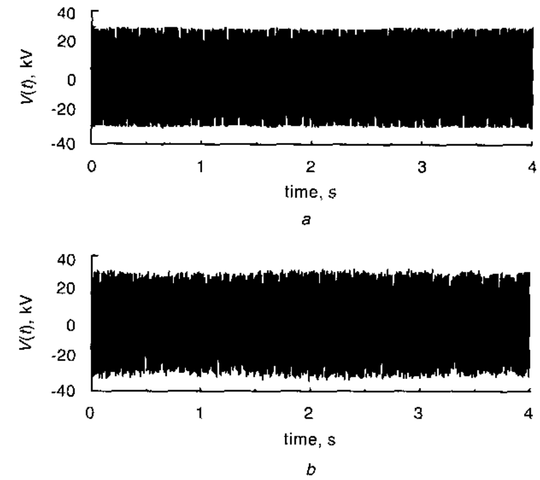

Fig. 10 *Field measurement voltage flicker waveforms*
a DC furnace (light voltage flicker)
b AC furnace (severe voltage flicker)

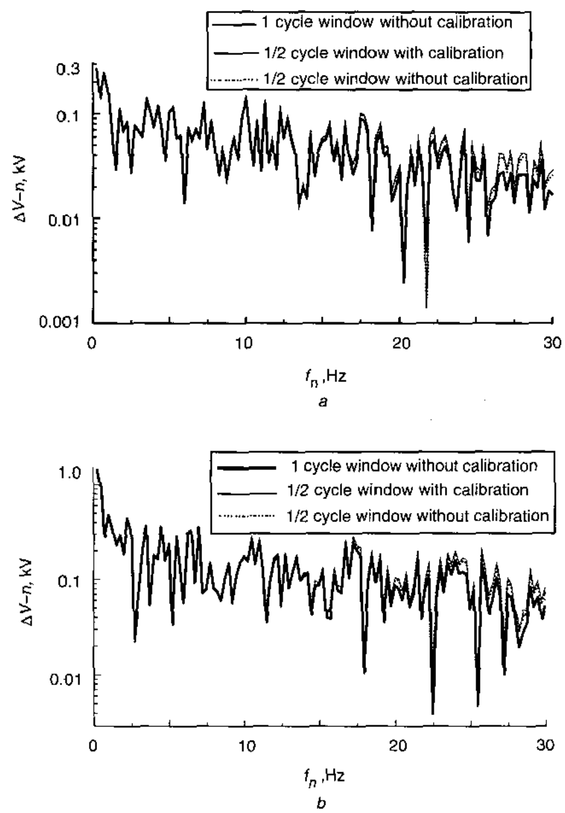

Fig. 11 *Calculation results of flicker components in field measurement waveforms*
a DC arc furnace
b AC arc furnace

Table 8: Calculation results of field measurement voltage flicker waveforms

	1-cycle window without calibration		1/2-cycle window without calibration		1/2-cycle window with calibration	
	DC furnace	AC furnace	DC furnace	AC furnace	DC furnace	AC furnace
ΔV, %	3.7	10.38	3.85	10.65	3.90	10.75
ΔV, 10 %	2.45	5.23	2.57	5.48	2.62	5.57

shown in Fig. 11. The differences are obvious in the higher-frequency components.

7 Conclusions

This paper has presented an effective method of calculating flicker components, which has greatly reduced the leakage effect in FFT and increased the calculation accuracy. Since higher amplitude modulation frequencies are close to the power frequency, they have larger calculation errors if the original indirect demodulation method is used. Both window size and calibration are investigated to reduce the calculation errors. From the calculation results of the given voltage flicker waveform and field measured waveforms, the proposed method has given satisfactory accuracy. This method can be used in both 50 Hz and 60 Hz systems. The effects of harmonics and power frequency shifting are negligible.

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