Comparison of Computation Algorithm for Three-Phase Voltage Flicker Equivalent Value

Shu-Chen Wang, Yu-Jen Chen, and Chi-Jui Wu

***Abstract*—**Four simple but effective computation algorithms have been compared to calculate the three-phase voltage flicker equivalent values. Owing to violent and stochastic fluctuation in different phases of three-phase circuits, different voltage flicker components may exist in different phases. Traditionally, the flicker components in each phase should be calculated separately. And the averages of three single-phase values are given to be the three-phase equivalent values. However, in this paper, it wants to investigate fast computation algorithms to calculate directly the three-phase equivalent values. After the three-phase voltage waveforms are recorded, the voltage flicker equivalent components are obtained from the voltage envelopes constructed by the RMS values or instantaneous voltage vectors. The effects of jump sampling, harmonic, and power frequency shifting are examined. Some given waveforms and field-measured waveforms are adopted to reveal the advantages of those methods. From the study results, the method by using the instantaneous voltage vectors are more simple and effective to obtain the three-phase voltage flicker equivalent values.

***Keywords*—**Voltage flicker, power quality, instantaneous voltage vector, voltage waveform, fast Fourier transforms.

I. INTRODUCTION

Voltage flicker is one of major power quality disturbances in a weak power system feeding fluctuating loads, such as electric arc furnaces and arc welders [1], [2]. During arc furnace operation, electric poles may be in short circuit situations stochastically, and extremely fluctuation currents are produced, which causes stochastic fluctuation in voltage magnitudes at the feeding bus. Several definitions had been proposed and developed [3]. The short-term and long-term severity was the IEC standard, and was established by the Union for Electroheat (UIE) [4]. The Central Research Institute of the Electric Power Industry (CRIEPI) in Japan proposed using the 10-Hz voltage flicker value, ΔV_{10} . The Taiwan Power Company (TPC) also uses ΔV_{10} . So this definition is considered in this study.

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Shu-Chen Wang is with the Department of Computer and Communication Engineering, Taipei College of Maritime Technology, 212, Sec. 9, Yan-Pin N. Rd., Taipei 111, Taiwan (corresponding author to provide phone: 886-2-27376676; fax: 886-2-27376699; e-mail: scwang@ mail.tcmt.edu.tw).

Yu-Jen Chen is with the Chung-Shan Institute of Science and Technology, Armaments Bureau, MND, Tao-Yuan, 32599, Taiwan. (e-mail: youren.chen@msa.hinet.net).

Chi-Jui Wu is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, 43, Keelung Rd., Sec. 4, Taipei 106, Taiwan. (e-mail: cjwu@mail.ntust.edu.tw).

The flicker components between 0.1 Hz to 30 Hz are extremely important owing to being visually irritating [5], [6], [7]. Numerous reports have established that a small voltage flicker, ranging from 0.3% to 0.5% in the frequency range of 6-10 Hz, could cause visible incandescent flickering and human discomfort. Persistent voltage flicker problems have existed in several distribution networks of the TPC [8].

Owing to violent and stochastic fluctuation in three-phase load currents, it may yield different voltage flicker values in different phases. Traditionally, the voltage flicker measurement is taken only by using single-phase voltage waveforms. So, it obtains the single-phase voltage flicker values. If it wants to reveal the three-phase conditions, each phase should be measured separately. And the three-phase values are the averages of three single-phase measurement values.

It is desired to obtain an effective and direct method to calculate the three-phase voltage flicker values. Consequently, this paper proposes and compares four approaches to calculate the three-phase voltage flicker equivalent values. Method 1 uses moving windows to get the RMS values of each phase and to build the voltage envelopes. The voltage flicker components of each phase are calculated individually and separately. Then the three-phase equivalent values are obtained from the roots of squared sums of three single-phase values. Meanwhile, Method 2 and Method 3 use the arithmetic and geometric means, respectively, of three single-phase RMS values to construct the three-phase equivalent voltage envelopes. And than the three-phase voltage flicker equivalent components are calculated. Method 4 uses the instantaneous voltage vectors to build the three-phase equivalent voltage envelopes. Three three-phase voltage flicker equivalent components can also be calculated directly [9]. Furthermore, the jump-sampling skills are used to reduce the data size for flicker calculation using the fast Fourier transform (FFT). Based on the calculation results of given waveforms and field measured waveforms of arc furnace loads, Method 4 is a more compact but effective methods to obtain the three-phase voltage flicker values. The effects of harmonics and frequency shifting are also examined.

II. DEFINITION OF VOLTAGE FLICKER

Voltage flicker means the fluctuation in the amplitude of voltage waveforms, typically at a frequency lower than the power frequency. Let ΔV_{fn} denote the degree of amplitude deviation at the modulation frequency f_n for a waveform with the RMS value V_{rms} . Consequently, the flicker component is

$$v_f(t) = \frac{1}{2}\Delta V_{fn}\cos(2\pi f_n t)\sqrt{2}V_{rms}\cos(2\pi f_{sys}t) \quad (1)$$

Where f_{sys} is the 50/60-Hz power frequency. The total voltage waveform with several flicker components can be expressed as

$$v(t) = \sqrt{2}V_{rms}\left[1+\frac{1}{2}\sum_{n}\Delta V_{fn}\cos(2\pi f_n t)\right]\cos(2\pi f_{sys}t) \quad (2)$$

Figure 1 shows a simplified voltage flicker waveform, which contains one modulation component with $\Delta V_{fn} = 0.4\,pu$ and $fn = 10Hz$.

Generally, the components in the range 0.25-30 Hz must be considered for specifying the limitations. The voltage fluctuation is defined as

$$\Delta V = \sqrt{\sum(\Delta V_{fn})^2} \quad (3)$$

Moreover, the 10-Hz equivalent voltage flicker value is defined as,

$$\Delta V_{10} = \sqrt{\sum(a_{fn}\Delta V_{fn})^2} \quad (4)$$

Where a_{fn} denotes the flicker sensitivity coefficient corresponding to the modulation frequency f_n component. Figure 2 plots the distribution curve of the sensitivity coefficients, which shows the sensitivity of the human eye-brain system to illumination flicker. The frequency to which it is most sensitive is 10 Hz, at which the visual sensitivity coefficient is one. When the frequency is below 0.25 Hz or over 30 Hz, the sensitivity coefficients are so small and negligible.

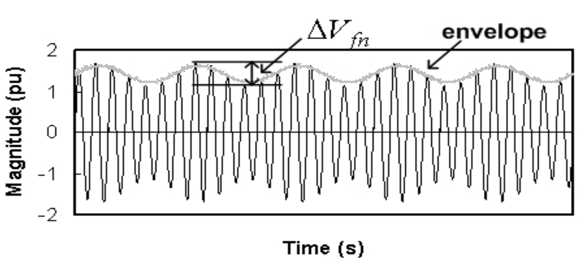


Fig. 1 A voltage flicker waveform with $\Delta V_{fn} = 0.4\,pu$ and $fn = 10Hz$

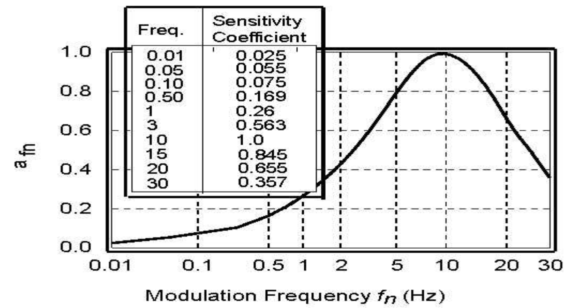


Fig. 2 Flicker sensitivity coefficient curve

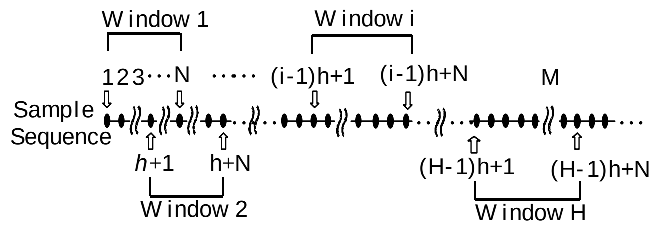


Fig. 3 Moving window to obtain RMS values

III. Voltage Envelope

A. Moving window for RMS values

The voltage magnitude envelopes contain the information of flicker components. The moving window method as shown in Figure 3 is used to calculate the RMS values of the instantaneous voltage $v(t)$ of a single-phase voltage waveform with N samples per cycle as a window [10]. To reduce the computation loading, h samples are shifted (jump-sampling) to reach the next window. The RMS values of all windows are calculated from

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

In the frequency spectrum calculation, the DC component in $v_{rms}[i]$ may cause spike and affect the accuracy of the flicker calculation. Consequently, the RMS deviation values can be obtained from

$$v_s[i] = v_{rms}[i] - v_{average}\ ,\ i = 1, 2, ..., H. \quad (6)$$

Where $v_{average}$ denotes the average value of the RMS values during the measurement period and is given by

$$v_{average} = \left(\sum_{i=1}^{H} v_{rms}[i]\right) / H \quad (7)$$

The frequency components of $v_s[i]$ are the flicker components of $v(t)$.

In practical conditions, any phase of three-phase circuits may have different voltage flicker components. If it wants to obtain directly the three-phase voltage flicker equivalent values, the three-phase equivalent RMS deviation values must be obtained firstly. The arithmetic and geometric mean values to represent the three-phase equivalent RMS deviation values are, respectively, defined as,

$$v_A[i] = \frac{v_{s-R}[i] + v_{s-S}[i] + v_{s-T}[i]}{3} \quad (8)$$

$$v_G[i] = \sqrt{\frac{(v_{s-R}[i])^2 + (v_{s-S}[i])^2 + (v_{s-T}[i])^2}{3}} \quad (9)$$

Where $v_{s-R}[i]$, $v_{s-S}[i]$ and $v_{s-T}[i]$ are the deviation RMS values of corresponding phases.

B. Instantaneous voltage vectors

The instantaneous voltage vectors also can be used to obtain the three-phase equivalent voltage magnitude envelopes. For a three-phase circuit, the magnitude of the instantaneous voltage vector can be obtained from

$$|v_i(t)| = \left| \frac{\sqrt{2}}{3} [v_R(t) + v_S(t) e^{j\frac{2\pi}{3}} + v_T(t) e^{j\frac{4\pi}{3}}] \right| \quad (10)$$

Where v_R , v_S , and v_T are instantaneous voltages of the corresponding phases.

In order to explain this method, let phase-R have a single voltage flicker component and let the other two phases be purely sinusoidal. Then

$$v_R(t) = \sqrt{2} V_{rms} \left[1 + \frac{1}{2} \Delta V_{fn} \cos(2\pi f_n t) \right] \cos(2\pi f_{sys} t) \quad (11)$$

$$v_S(t) = \sqrt{2} V_{rms} \cos(2\pi f_{sys} t - \frac{2\pi}{3}) \quad (12)$$

$$v_T(t) = \sqrt{2} V_{rms} \cos(2\pi f_{sys} t + \frac{2\pi}{3})$$

(13)

Then the magnitude of instantaneous voltage vector is given by

$$|v_i(t)| = \frac{2V_{rms}}{3} \left| \begin{array}{l} \left[1 + \frac{1}{2} \Delta V_{fn} \cos(2\pi f_n t) \right] \left(\frac{e^{j2\pi f_{sys} t} + e^{-j2\pi f_{sys} t}}{2} \right) \\ + \left[\frac{e^{j(2\pi f_{sys} t - \frac{2}{3}\pi)} + e^{-j(2\pi f_{sys} t - \frac{2}{3}\pi)}}{2} \right] e^{j\frac{2\pi}{3}} \\ + \left[\frac{e^{j(2\pi f_{sys} t + \frac{2}{3}\pi)} + e^{-j(2\pi f_{sys} t + \frac{2}{3}\pi)}}{2} \right] e^{j\frac{4\pi}{3}} \end{array} \right|$$

(14)

It can be obtained from (14) that

$$|v_i(t)| = V_{rms} \{ 1 + \frac{1}{2} [\frac{\Delta V_{fn}}{3} \cos(2\pi f_n t) + \frac{\Delta V_{fn}}{3} \cos(2\pi f_n t) \cos(2\pi f_{sys} t) + \frac{\Delta V_{fn}^2}{9} \cos^2(4\pi f_{sys} t) + \cdots] \}$$

Thus

$$|v_i(t)| \cong V_{rms} [1 + \frac{\Delta V_{fn}}{6} \cos(2\pi f_n t) + \frac{\Delta V_{fn}}{6} \cos(2\pi f_n t) \cos(2\pi f_{sys} t)]$$

(15)

The frequency spectrum of (15) has four components. The second contains the useful information to obtain the corresponding flicker component. Then the sampled data sequence of $|v_i(t)|$, that is $v_i[i]$, can be used in FFT to obtain the three-phase voltage flicker equivalent values.

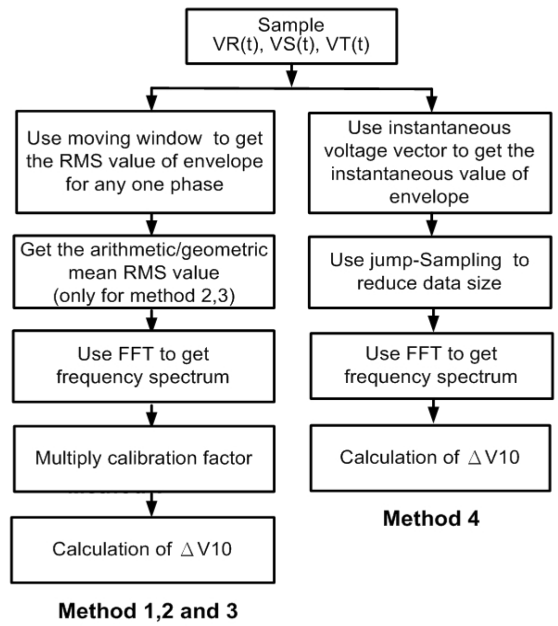


Fig. 4 Computation flowchart of four methods

IV. Voltage Flicker Calculation Method

A. Method 1: average of three single-phase voltage flicker values

Figure 4 shows the flowchart of Method 1. This method calculates the voltage flicker components of each phase individually and separately. An FFT is used to calculate the frequency components of $v_s[i]$ in (6). Thereby

$$V[k] = \frac{1}{H} \sum_{i=1}^{H} v_s[i] e^{-j\frac{2\pi ki}{H}}, k = 1, 2, \ldots \frac{H}{2} \quad (16)$$

Then the flicker value corresponding to f_n is

$$\Delta V_{fn} = \frac{2\sqrt{2}}{v_{average}} V \left[\frac{f_n}{(N_s/M)} \right] \times 100\% \quad (17)$$

Where N_s denotes the sampling rate of signal, and M represents the total number of samples within the total sampling interval T. The three-phase voltage flicker equivalent value of frequency f_n is given by

$$\Delta\hat{V}_{fn-3\phi} = \sqrt{\frac{\left(\Delta V_{fn-R}\right)^2 + \left(\Delta V_{fn-S}\right)^2 + \left(\Delta V_{fn-T}\right)^2}{3}}$$
(18)

However, this method has the difficulty of higher frequency leakage effect. To improve the calculation accuracy, a calibration approach can be adopted. Then the final three-phase voltage flicker equivalent value is obtained

$$\Delta V_{fn-3\phi} = K_{fn}\Delta\hat{V}_{fn-3\phi} \quad (19)$$

Where K_{fn}, depending on flicker frequency, is the calibration factor given in [10].

B. Method 2: using arithmetic mean RMS values

Figure 4 also shows the flowchart of Method 2. In FFT, this method can directly calculate the three-phase voltage flicker equivalent components by using the arithmetic mean RMS values $v_A[i]$ in (8), that is,

$$V[k] = \frac{1}{H}\sum_{i=1}^{H} v_A[i]e^{-j\frac{2\pi ki}{H}}, k = 1,2,...\frac{H}{2} \quad (20)$$

The three-phase voltage flicker equivalent components can be obtained directly from $V[k]$. The calibration approach is also needed.

C. Method 3: using geometric mean RMS values

Figure 4 shows the flowchart of method 3. Similarly, this method also directly calculates the three-phase voltage flicker equivalent components by using the geometric mean RMS values $v_G[i]$ in (9), that is,

$$V[k] = \frac{1}{H}\sum_{i=1}^{H} v_G[i]e^{-j\frac{2\pi ki}{H}}, k = 1,2,...\frac{H}{2} \quad (21)$$

The three-phase voltage flicker equivalent components can be also obtained directly from of $V[k]$. The calibration approach is also needed.

D. Method 4: using instantaneous voltage vectors

Figure 4 shows the flowchart of this method. This method can calculate directly the three-phase voltage flicker equivalent values. The sampled values of instantaneous voltage vector magnitude $v_i[i]$ in (15) are used in FFT to obtain the three-phase voltage flicker equivalent components. The jump-sampling approach is also used to reduce the data size. However, the calibration approach is not required in this method.

V. VOLTAGE FLICKER CALCULATION RESULT

Considering the use of FFT, the sampling rate of voltage waveforms in this study is 32 samples per power cycle. If the desired frequency resolution in the flicker calculation is 0.25 Hz, the signal measurement period should be 4 seconds. The calculations are performed on a personal computer (Pentium , 2.8 GHz), and all algorithms are implemented using MATLAB in Windows XP.

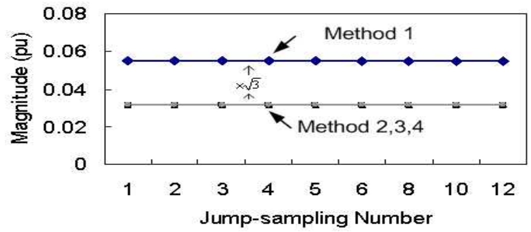


Fig. 5 ΔV_{10} Calculation results of Case 12 with different methods and jump-sampling numbers

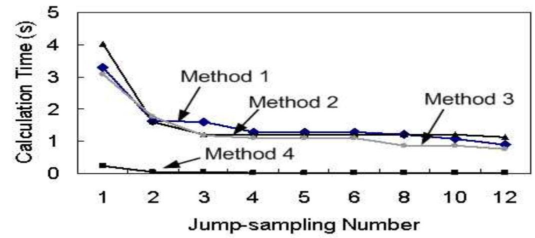


Fig. 6 Comparison of calculation time with different methods and jump-sampling numbers of Case 12

Table 1 lists 12 given cases for comparison of calculation methods, where the flicker components in each phase are given. Figure 5 illustrates the calculation results of Case 12 with different methods and jump-sampling numbers, and Figure 6 compares the computer calculation time. With the same sample size, Method 4 requires less calculation time. When the jump-sampling number exceeds 8, the calculation time remains approximately 1 second, therefore this number is chosen for use in this study.

Table 2 presents the calculation results of Cases 4, 7, 9 and 12. The values obtained by using method 2, 3, and 4 are very close. In these three methods, it can be observed that if only one phase has a flicker component, the three-phase voltage flicker equivalent value will be 1/3 of the given value. And if two phases have the same flicker component, the equivalent value will be 2/3 of the given value. Only when all three phases have the same flicker component, the equivalent value will be the same value. Table 3 lists the calculation results of ΔV and ΔV_{10} of the 12 given cases. It can be observed that the values of $\Delta V_{fn-3\phi}$ and ΔV_{10} from different methods have the following characteristics

$$\Delta V_{fn-3\phi}|_{method-1} = \sqrt{\frac{3}{m}}\Delta V_{fn-3\phi}|_{method-2,3,4} \quad (22)$$

$$\Delta V_{10}|_{method-1} = \sqrt{\frac{3}{m}}\Delta V_{10}|_{method-2,3,4}$$
(23)

Where m is the number of flicker components. However, for practical situation, a C factor can be defined as

$$C = \frac{\Delta V_{10}\,|_{method-1}}{\Delta V_{10}\,|_{method-2,3,4}} \tag{24}$$

From Table 3, it can be observed that

$$1 \le C \le \sqrt{3} \tag{25}$$

TABLE I
COMPONENTS IN TWELVE GIVEN CASES FOR FLICKER CALCULATION

	CASE 1	CASE 2	CASE 3	CASE 4
v_R (pu)	0.1,5Hz	0.1,5Hz 0.1,10Hz	0.1,5Hz 0.05,10Hz	0.1,5Hz
v_S (pu)	×	×	×	0.1,5Hz
v_T (pu)	×	×	×	×
	CASE 5	CASE 6	CASE 7	CASE 8
v_R (pu)	0.1,5Hz	0.1,5Hz	0.1,5Hz	0.1,5Hz
v_S (pu)	0.1,10Hz	0.05,5Hz	0.05,10Hz	×
v_T (pu)	×	×	×	0.1,10Hz
	CASE 9	CASE 10	CASE 11	CASE 12
v_R (pu)	0.1,5Hz	0.1,5Hz	0.1,5Hz	0.1,5Hz
v_S (pu)	0.1,5Hz	0.1,10Hz	0.05,5Hz	0.05,10Hz
v_T (pu)	0.1,5Hz	0.1,15Hz	0.02,5Hz	0.02,15Hz

TABLE II
CALCULATION RESULTS OF FOUR GIVEN CASES

		Calculation Method			
		Method 1	Method 2	Method 3	Method 4
CASE 4	$\Delta V_{fn-3\phi}$ (pu)	0.0817,5Hz	0.0667,5Hz	0.0667,5Hz	0.0667,5Hz
	ΔV (pu)	0.0817	0.0667	0.0667	0.0667
	ΔV_{10} (pu)	0.0645	0.0527	0.0527	0.0527
CASE 7	$\Delta V_{fn-3\phi}$ (pu)	0.0578,5Hz 0.0291,10Hz	0.0334,5Hz 0.0168,10Hz	0.0333,5Hz 0.0168,10Hz	0.0333,5Hz 0.0167,10Hz
	ΔV (pu)	0.0647	0.0374	0.0373	0.0373
	ΔV_{10} (pu)	0.0541	0.0313	0.0312	0.0312
CASE 9	$\Delta V_{fn-3\phi}$ (pu)	0.1001,5Hz	0.1001,5Hz	0.1001,5Hz	0.1001,5Hz
	ΔV (pu)	0.1001	0.1001	0.1001	0.1
	ΔV_{10} (pu)	0.079	0.079	0.079	0.079

CASE 12	$\Delta V_{fn-3\phi}$ (pu)	0.0578,5Hz 0.0291,10Hz 0.0116,15Hz	0.0334,5Hz 0.0168,10Hz 0.0067,15Hz	0.0333,5Hz 0.0168,10Hz 0.0067,15Hz	0.0333,5Hz 0.0167,10Hz 0.0067,15Hz
	ΔV (pu)	0.0657	0.0379	0.0379	0.0379
	ΔV_{10} (pu)	0.055	0.0318	0.0318	0.0317
Samples in FFT		1280 × 3	1280	1280	1280
Computation Time(s)		1.3	1.2	1.1	0.02

TABLE III
CALCULATION RESULTS OF TWELVE GIVEN CASES

		CASE 1	CASE 2	CASE 3	CASE 4
ΔV_{10} (pu)	Method 1	0.0456	0.074	0.0541	0.0645
	Method 2,3,4	0.0263	0.0427	0.0312	0.0527
	C	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3/2}$
		CASE 5	CASE 6	CASE 7	CASE 8
ΔV_{10} (pu)	Method 1	0.074	0.0510	0.0541	0.0740
	Method 2,3,4	0.0427	0.0405	0.0313	0.0427
	C	$\sqrt{3}$	$\sqrt{3/2}$	$\sqrt{3}$	$\sqrt{3}$
		CASE 9	CASE 10	CASE 11	CASE 12
ΔV_{10} (pu)	Method 1	0.079	0.0894	0.0528	0.055
	Method 2,3,4	0.079	0.0516	0.0448	0.0318
	C	1	$\sqrt{3}$	$\sqrt{3/2}$	$\sqrt{3}$

TABLE IV
CALCULATION RESULTS OF GIVEN CASES CONSIDERING HARMONICS AND POWER FREQUENCY SHIFTING

		Calculation Method			
		Method 1	Method 2	Method 3	Method 4
CASE A	$\Delta V_{fn-3\phi}$ (pu)	0.0573,5Hz 0.0289,10Hz 0.0115,15Hz	0.0331,5Hz 0.0167,10Hz 0.0066,15Hz	0.0331,5Hz 0.0167,10Hz 0.0066,15Hz	0.0333,5Hz 0.0167,10Hz 0.0067,15Hz
	ΔV (pu)	0.0657	0.0376	0.0376	0.0379
	ΔV_{10} (pu)	0.0546	0.0315	0.0315	0.0317
CASE B (59.9Hz)	$\Delta V_{fn-3\phi}$ (pu)	0.0578,5Hz 0.0291,10Hz 0.0116,15Hz	0.0334,5Hz 0.0168,10Hz 0.0067,15Hz	0.0333,5Hz 0.0168,10Hz 0.0067,15Hz	0.0333,5Hz 0.0167,10Hz 0.0067,15Hz
	ΔV (pu)	0.0657	0.0379	0.0379	0.0379
	ΔV_{10} (pu)	0.055	0.0318	0.0318	0.0317
CASE B (60.1Hz)	$\Delta V_{fn-3\phi}$ (pu)	0.0578,5Hz 0.0291,10Hz 0.0116,15Hz	0.0334,5Hz 0.0168,10Hz 0.0066,15Hz	0.0333,5Hz 0.0168,10Hz 0.0066,15Hz	0.0333,5Hz 0.0167,10Hz 0.0067,15Hz
	ΔV (pu)	0.0657	0.0379	0.0379	0.0379
	ΔV_{10} (pu)	0.0555	0.0318	0.0318	0.0317

CASE C (59.9Hz)	$\Delta V_{fn-3\phi}$ (pu)	0.0573,5Hz 0.0289,10Hz 0.0115,15Hz	0.0331,5Hz 0.0167,10Hz 0.0066,15Hz	0.0331,5Hz 0.0167,10Hz 0.0067,15Hz	0.0333,5Hz 0.0167,10Hz 0.0067,15Hz
	ΔV (pu)	0.0651	0.0376	0.0376	0.0379
	ΔV_{10} (pu)	0.0546	0.0315	0.0315	0.0317
CASE C (60.1Hz)	$\Delta V_{fn-3\phi}$ (pu)	0.0573,5Hz 0.0289,10Hz 0.0115,15Hz	0.0331,5Hz 0.0167,10Hz 0.0066,15Hz	0.0331,5Hz 0.0167,10Hz 0.0066,15Hz	0.0333,5Hz 0.0167,10Hz 0.0067,15Hz
	ΔV (pu)	0.0651	0.0376	0.0376	0.0379
	ΔV_{10} (pu)	0.0546	0.0315	0.0315	0.0317

		Calculation Result			
		Mean	σ	Maximal	Minimal
ΔV (pu)	Method 1	0.0125	0.0060	0.0398	0.0025
	Method 4	0.0106	0.0052	0.0316	0.0022
ΔV_{10} (pu)	Method 1	0.0074	0.0037	0.0221	0.0010
	Method 4	0.0064	0.0031	0.0169	0.0009
C		1.203	0.0614	1.453	1.0

VI. Effect of Harmonics and Power Frequency Shifting

Large arc furnaces also produce harmonic currents and cause power frequency shifting in a weak power system. These disturbances should be considered. Three cases are chosen for comparison.

CASE A：With the same flicker components in Case 12 and with the following harmonic components
5^{th} order, 0.15 pu
7^{th} order, 0.1 pu
11^{th} order, 0.05 pu
$f_{sys} = 60$ Hz

CASE B：With same flicker components in Case 12 and with power frequency shifting.

CASE C：With the same flicker components and harmonics in CASE A, and also with power frequency shifting.

Table 4 presents the calculation results of CASE A, CASE B and CASE C. In those cases, all four methods are not influenced for harmonics and power frequency shifting. The values of $\Delta V_{fn-3\phi}$, ΔV , and ΔV_{10} are very closed to the calculation results of CASE 12 as shown in Table 2. The values of $\Delta V_{fn-3\phi}$ and ΔV_{10} using Method 1 are $\sqrt{3}$ times of those using methods 2, 3 and 4, which is a result consistent with (22) and (23). Since the calculation results of Methods 2, 3 and 4 are very close, Method 4 can be used in later investigations owing to its quickness and simplicity.

VII. Application to Field Measurement Waveforms

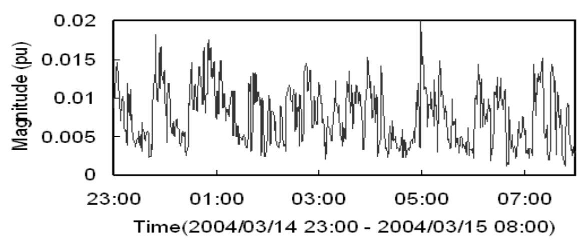
The three-phase measurement data from the medium voltage feeder of a 60-Hz AC arc furnace and another one from a DC arc furnace are used to investigate the application of the above methods to practical cases. The power supply level and the furnace transformer of the AC arc furnace are 69 kV and 35 MVA, respectively. Moreover, those of the DC arc furnace are 161 kV and 82 MVA, respectively. The statistical method is used to reveal the contents of flicker components. Three-phase voltage waveform data are sampled from 23:00 P.M. to 08:00 A. M.

Figures 7-8 show the calculation results of ΔV_{10} and C factor of the AC arc furnace, and Table 5 listed the statistical results. Figures 9-10 and Table 6 also show the results of the DC arc furnace. The average value, standard deviation (σ), maximum, and minimum are examined. The distribution of ΔV_{10} of the AC arc furnace obtained using Method 1 ranges between 0.001-0.0221pu. The calculated results are relatively larger than those using Method 4.

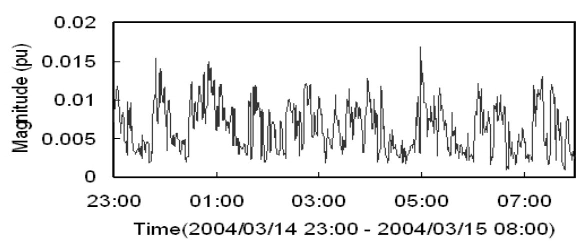
TABLE V
VOLTAGE FLICKER FIELD MEASUREMENT RESULTS OF THE AC ARC FURNACE

TABLE VI
VOLTAGE FLICKER FIELD MEASUREMENT RESULTS OF THE DC ARC FURNACE

		Calculation Result			
		Mean	σ	Maximal	Minimal
ΔV (pu)	Method 1	0.0044	0.0018	0.0149	0.0011
	Method 4	0.0042	0.0018	0.0148	0.0008
ΔV_{10} (pu)	Method 1	0.0024	0.0009	0.0077	0.0007
	Method 4	0.0022	0.0010	0.0077	0.0005
C		1.106	0.086	1.60	1.0



(a) method 1



(b) method 4

Fig. 7 ΔV_{10} measurement results of the AC arc furnace

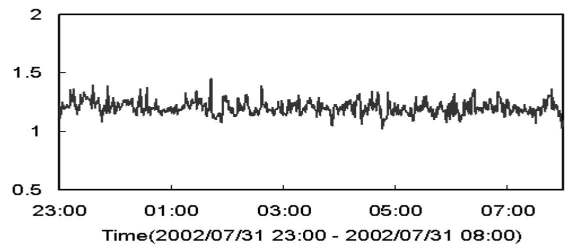
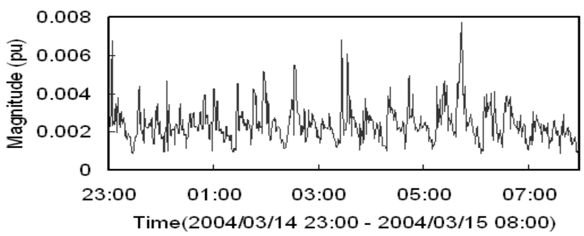
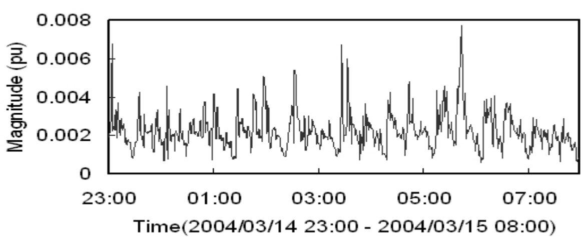


Fig. 8 C values of the AC arc furnace field measurement data

The ΔV_{10} values of the DC arc furnace obtained using Method 1 range between 0.0007-0.0077 pu. Moreover, they are still a little larger than those obtained using Method 4. The C factors of the AC arc furnace range between 1-1.453, a result that consistent with (25), and the average value is 1.203. The C value of the DC arc furnace was between 1-1.6, a result that also consistent with (25), and the average value is 1.106. It is highly probable that the voltage deviation of the AC arc furnace is bigger than that of the DC arc furnace.



(a) method 1



(b) method 4

Fig. 9 ΔV_{10} measurement results of the DC arc furnace

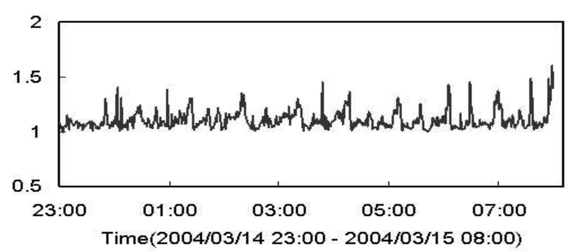


Fig. 10 C values of the DC arc furnace field measurement data

VIII. Conclusion

Four effective methods have been compared to calculate the three-phase voltage flicker equivalent values. While the three methods that use RMS values to obtain magnitude envelopes need calibration factors to compensate the frequency leakage effect in FFT, however, Method 4 that adapts instantaneous voltage vectors does not need calibration factors. The values obtained from methods 2-4 are close but different from that of method 1. So the definition of three-phase voltage flicker calculation should be specified. The technique of moving window and jump sampling can reduce the data size and computation time. Particularly, the computation time of Method 4 is only one fourth of that of the other methods, and this is a more compact method.

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Shu-Chen Wang was born in Taiwan, 1969. She received the B. Sc., M. Sc., and Ph.D. degree from the Department of Electrical Engineering, National Taiwan Ocean University in 1992, 1994, and 2007, respectively. Currently she is an associate professor in the Department of Computer and Communication Engineering, Taipei College of Maritime Technology. Her current research interests include fuzzy theory and power system dynamics.

Yu-Jen Chen was born in Taiwan, 1976. He received the Ph. D. degree in electrical engineering from the National Taiwan University of Science and Technology in 2006. Now he is senior research engineer in the Chung-Shan Institute of Science and Technology, Armaments Bureau, MND. His research interests include system analysis and electric power quality.

Chi-Jui Wu was born in Taiwan, 1961. He received the B. Sc., M. Sc., and Ph.D. degree in electrical engineering all from the National Taiwan University in 1983, 1985, and 1988, respectively. In 1988, he joined the Department of Electrical Engineering, National Taiwan University of Science and Technology. Now he is a full professor in the Department. He is active in

practical power system problems. His current research interests lie in power system stability, power electromagnetic interference, and electric power quality.