Equivalent Evaluation Method of Three-Phase Voltage Flicker Evaluation

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Abstract: - Owing to violent and stochastic load fluctuation, different voltage flicker components may exist in different phases. Traditionally, the averages of three single-phase values are given. However, in this paper, it wants to investigate a fast computation algorithm to calculate directly the equivalent three-phase values. After the voltage waveforms of three phases are recorded, the voltage flicker components are obtained from the voltage envelopes constructed by the RMS values and instantaneous voltage vectors, respectively. Some given simulation waveforms and field-measured waveforms are adopted to reveal the advantages of those methods. The calculation results demonstrate the proper approach to obtain the equivalent three-phase voltage flicker components.

Key-Words: - **Voltage flicker, Power quality, Instantaneous voltage vector, Voltage waveform, Fast Fourier transforms.**

1 Introduction

Loads with continuous and rapid variations in the current magnitudes may cause voltage flicker disturbances [1], [2]. Several definitions had been proposed and developed [3]. The short-term severity P_{st} is 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 equivalent voltage flicker value ΔV_{10}. The Taiwan Power Company (TPC) also uses ΔV_{10}, which is considered in this study.

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 areas of the Taiwan Power Company (TPC) [8].

This study proposes and compares four methods to calculate the equivalent voltage flicker values of three-phase circuits. 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. 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 equivalent voltage flicker components are calculated. Method 4 uses the instantaneous voltage vectors to build the three-phase equivalent voltage envelopes for flicker computation [9]. Based on the calculation results of given waveforms and field measured waveforms of arc furnace loads, those methods may give different computation results. The comparison and analysis are also revealed.

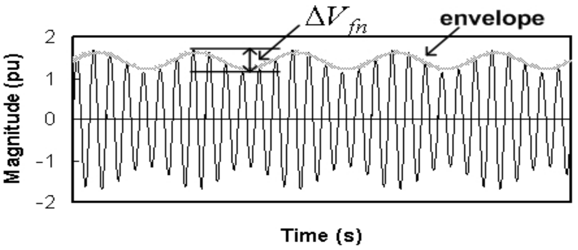


Figure 1. A voltage flicker waveform with $\Delta V_{fn} = 0.4pu$ and $fn = 10Hz$

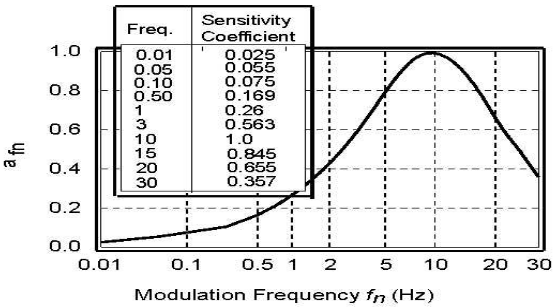


Figure 2. Flicker sensitivity coefficient curve

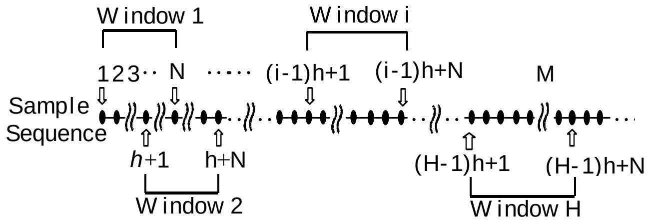


Figure 3. Moving window method to obtain RMS values of $v(t)$

2 Voltage Flicker Evaluation

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

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

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

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

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

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

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

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

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.

3 Voltage Envelope

A. Moving window for RMS values

The voltage 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 each phase with N samples in each 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

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

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

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

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

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

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

To obtain the three-phase equivalent voltage flicker values, the equivalent three-phase deviation

RMS values must be given. The arithmetic and geometric mean deviation RMS values to represent the three-phase voltages are, respectively, defined as,

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

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

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 equivalent three-phase voltage envelopes. For a three-phase circuit, the magnitude of the instantaneous voltage vector is defined as

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

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

In order to explain the method to obtain equivalent three-phase voltage flicker components from the instantaneous voltage vectors, let phase-R have a single voltage flicker component and let the other two phases be purely sinusoidal.

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

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

$$v_T(t) = \sqrt{2}V_{rms}\cos(2\pi f_{sys} t + \frac{2\pi}{3}) \tag{13}$$

Then the magnitude of instantaneous voltage vector is given by

$$|v_i(t)| = \frac{2V_{rms}}{3}\left| \begin{array}{l} \left[1 + \frac{1}{2}\Delta V_{fn}\cos(2\pi f_n t)\right](\frac{e^{j2\pi f_{sys}t} + e^{-j2\pi f_{sys}t}}{2}) \\ +[\frac{e^{j(2\pi f_{sys}t - \frac{2}{3}\pi)} + e^{-j(2\pi f_{sys}t - \frac{2}{3}\pi)}}{2}]e^{j\frac{2\pi}{3}} \\ +[\frac{e^{j(2\pi f_{sys}t + \frac{2}{3}\pi)} + e^{-j(2\pi f_{sys}t + \frac{2}{3}\pi)}}{2}]e^{j\frac{4\pi}{3}} \end{array} \right| \tag{14}$$

Since the flicker components are usually much smaller than the RMS value, then (14) can be simplified as

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

Thus

$$|v_i(t)| \cong V_{rms}[1 + \frac{\Delta V_{fn}}{6}\cos(2\pi f_n t) + \frac{\Delta V_{fn}}{6}\cos(2\pi f_n t)\cos(2\pi f_{sys} t)] \tag{15}$$

Then the sampled data sequence of $|v_i(t)|$, that is $v_i[i]$, can be used in FFT to obtain the equivalent three-phase flicker component value.

4 Voltage Flicker Calculation Method

(1) Method 1: using RMS values of each phase

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

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

Then the flicker value corresponding to f_n is

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

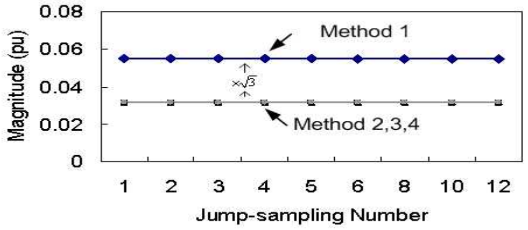


Figure 4. Comparison of ΔV_{10} with different jump-sampling numbers

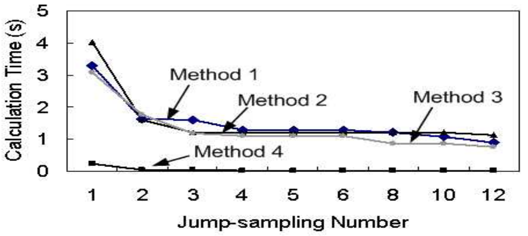


Figure 5. Comparison of calculation time with different jump-sampling numbers

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

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

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 equivalent three-phase flicker value is obtained from

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

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

(2) Method 2: using arithmetic mean RMS values

In FFT, this method directly calculates the equivalent three-phase voltage flicker components by using the arithmetic mean RMS values $v_A[i]$ in (8), that is,

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

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

(3) Method 3: using geometric mean RMS values

Similarly, this method directly calculates the equivalent three-phase voltage flicker components by using the geometric mean RMS values $v_G[i]$ in (9), that is,

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

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

(4) Method 4: using instantaneous voltage vectors

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

5 Voltage Flicker Calculation Result

Considering 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 (PentiumⅣ, 2.8 GHz), and all algorithms are implemented using MATLAB in Windows XP.

Table 1 lists 12 given cases for comparison of flicker calculation, where flicker components in each phase are specified. Figure 4 illustrates the calculation results of Case 12 with different jump-sampling numbers. Figure 5 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, 8 is selected as the jumping-sampling number for use in this study.

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

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

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

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

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

From Table 3, it can be observed that

$$1 \le C \le \sqrt{3} \qquad (25)$$

Table 1 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 2 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 3 Calculation results of twelve given cases

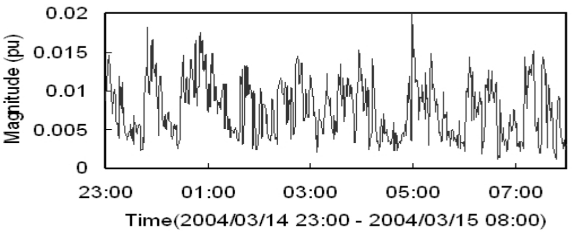
		CASE 1	CASE 2	CASE 3	CASE 4
ΔV_{10} (pu)	Method 1	0.0456	0.074	0.0541	0.0645
	Method 2,3,4	0.0263	0.0427	0.0312	0.0527
C		$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$	$\sqrt{3/2}$
		CASE 5	CASE 6	CASE 7	CASE 8
ΔV_{10} (pu)	Method 1	0.074	0.0510	0.0541	0.0740
	Method 2,3,4	0.0427	0.0405	0.0313	0.0427
C		$\sqrt{3}$	$\sqrt{3/2}$	$\sqrt{3}$	$\sqrt{3}$
		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 4 Voltage flicker field measurement results of the AC arc furnace

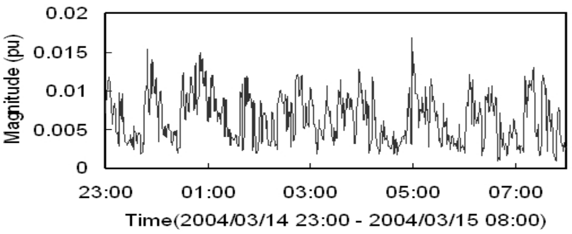
		Calculation Result			
		Mean	σ	Maximal	Minimal
ΔV (pu)	Method 1	0.0125	0.0060	0.0398	0.0025
	Method 4	0.0106	0.0052	0.0316	0.0022
ΔV_{10} (pu)	Method 1	0.0074	0.0037	0.0221	0.0010
	Method 4	0.0064	0.0031	0.0169	0.0009
C		1.203	0.0614	1.453	1.0

Table 5 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

Figure 6. ΔV_{10} Field measurement results of the AC arc furnace

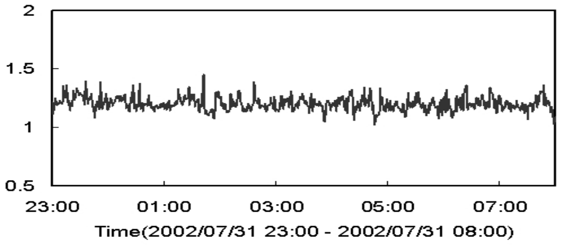
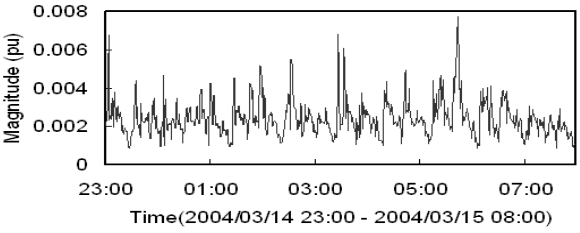
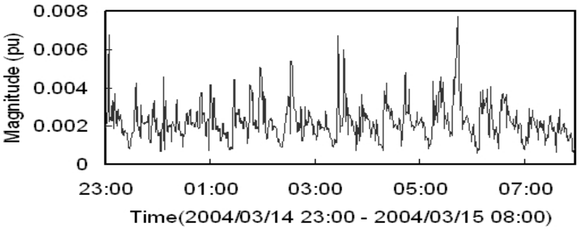


Figure 7. C values of the AC arc furnace field measurement data



(a) method 1



(b) method 4

Figure 8. ΔV_{10} Field measurement results of the DC arc furnace

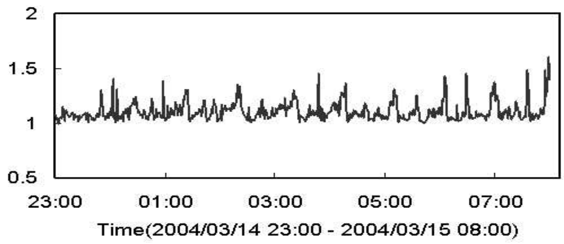


Figure 9. C values of the DC arc furnace field measurement data

6 Application to Field Measurement Waveforms

The three-phase measurement data from the 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 6-7 show the surveying results of ΔV_{10} and C factor of the AC arc furnace, and Table 4 listed the statistical results. Figures 8-9 and Table 5 also show the survey results the DC arc furnace. The average value, standard deviation (σ), maximum, and minimum of two furnaces 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 large compared with those using Method 4. The ΔV_{10} values of the DC arc furnace obtained using Method 1 range between 0.0007-0.0077pu. 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.

7 Conclusion

Four effective equivalent three-phase voltage flicker calculation methods have been investigated and compared. While the three methods that use RMS values to obtain magnitude envelopes need calibration factors to compensate the frequency leakage effect in FFT, however, the method that adapts instantaneous voltage vectors does not need calibration factors. The advantages of those methods are revealed from the calculated results of given voltage flicker waveforms and field-measured waveforms. The technique of moving window and jump sampling can reduce the data size and computation time. Particularly, for the same signal span, the computation time of Method 4 is only one fourth of that of the other methods. How to correctly calculate equivalent three-phase voltage flicker values of a three-phase system is a critical issue.

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