Critical Voltage Flicker Detection based on Pair of Inter-harmonics Analysis Method

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Abstract—This paper presents a critical voltage flicker detection based on a pair of inter-harmonics analysis method. The proposed algorithm can be applied in any crowded human place for human awareness purpose. Moreover, the correlation between pair of inter-harmonics and voltage flicker is described in details and the related formulas have been derived as well. According to simulation and experimental results, the amplitude of pair of inter-harmonics is able to detect the severity of critical voltage flicker. Furthermore, the experimental results are compared with the results which obtained by using the Fluke power analyzer (P_{inst}).

Keywords—voltage flicker; inter-harmonics; FFT

I. INTRODUCTION

Nowadays, utilization of nonlinear loads with asymmetrical i-v characteristics such as motor drive and arc furnace creates voltage fluctuation to the power system [1]. Specifically, voltage fluctuation with certain frequency value is considered as voltage flicker [2]. Moreover, unsteadiness of light luminance may occur due to the aforementioned voltage flicker [3]. Practically, IEC flickermeter is introduced by IEC standard for voltage flicker severity measurement [4]. Instantaneous flicker sensation (P_{inst}), Short Term Perceptibility (P_s) and Long Term Perceptibility (P_l) are the voltage flicker severity measurement’s indicators which are covered by IEC flickermeter. P_s and P_l are referred to voltage flicker severity indicators under observation of 10 minutes and 2 hours respectively.

Some of research works have been conducted to improve the accuracy of the IEC flickermeter [5]. Other than that, voltage flicker mitigation has been done by many researchers [6-8]. Analysis on reducing the observation time of P_s [9] has also been done by researchers. Voltage flicker detection [10] has been proposed by many researchers such as atomic method [11], wavelet Fourier transform [12], Chirp-z transform [13], and new modified S-transform algorithm [14]. Interrelationship between inter-harmonics and voltage flicker has been investigated by many researchers too [2, 15-18].

The critical voltage flicker’s frequency which is the most sensitive to human eyes is located at 8.8 Hz, according to IEC standard [4]. Additionally, headaches, eye strains, and in the worst case, seizures may happen due to the aforementioned critical voltage flicker [19]. Nevertheless, till now, there is no such work yet on implementing and developing an algorithm for detecting the critical voltage flicker. Subsequently, this paper proposes Critical Voltage Flicker Detection (CVFD) based on pair of inter-harmonics analysis method. Basically, there are some changes on the amplitudes of pair of inter-harmonics due to intrinsic characteristic of a critical voltage flicker waveform [20]. Therefore, CVFD can be done by detecting a pair of inter-harmonics’ amplitudes.

A number of signal processing algorithms based on different techniques for inter-harmonics detection such as Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT), Short-Time Fourier transform (STFT) [21], and spectrogram [22] have been reported over the past years [23]. The FFT is considered direct improvement of the DFT which is able to perform faster conversion from time to frequency domain, but number of samples must fulfill 2n where n is an integer number. Otherwise, operation of the FFT may lead to inaccurate result due to phenomena of aliasing [24], leakage effects [25], and picket fence effects [25]. Meanwhile, STFT is considered improvement of the FFT as it is generated based on sliding FFT process. The sliding FFT is done by dividing the measurement signal into many small divisions and FFT is applied to these tiny divisions. Next, spectrogram is considered as squared magnitude of the STFT and the output of spectrogram are plotted in spectrograph. Subsequently, the STFT and spectrogram are considered mathematical burden due to many times of applying FFT. Therefore, directly using FFT is merited, to be utilized in the proposed algorithm due to its speed capability to convert time domain to frequency domain.

The explanation regarding the correlation between voltage flicker and inter-harmonics are presented in Section II. The description of critical voltage flicker is discussed in Section III. Sections IV discusses the background of the FFT. Section V presents the proposed algorithm. The experimental works is presented in Sections VI. Lastly, the conclusion is in Section VII.

II. CORRELATION BETWEEN INTER-HARMONICS AND VOLTAGE FLICKER

Basically, modulated waveform can happen due to the
appearance of inter-harmonics in a power system. The fluctuation frequency of the instantaneous voltage is considered as voltage flicker frequency. The voltage flicker frequency \[ f_{\text{flicker}} = \left| f_{\text{IH}} - f_{l} \right| \]

where, \( f_{\text{IH}} \) and \( f_{l} \) are considered as inter-harmonic frequency and fundamental frequency respectively of the power system.

Let's consider a 50 Hz power system consists of 3 Hz of voltage flicker frequency, then the related inter-harmonics are 47 Hz and 53 Hz. Essentially, the voltage flicker may occur due to a pair of inter-harmonics (47 and 53 Hz together) or single inter-harmonic (47 or 53 Hz). In practical situation, voltage flicker waveform occurs mainly due to a pair of inter-harmonics. Therefore, the derivation of formula for aforementioned situation is shown as follow \[ \text{V.26} \]:

\[
v_{2}(t) = \alpha_{1}e^{j\omega_{1}t} + \alpha_{2}e^{j(\omega_{2} - \omega_{1})t} + \alpha_{3}e^{j(\omega_{3} - \omega_{1})t}
\]

\( \omega_{2} \) is represented as factorized exponential form of fundamental frequency. The amplitude are represented as \( \alpha_{1} + \alpha_{2}e^{j(\omega_{2} - \omega_{1})t} + \alpha_{3}e^{j(\omega_{3} - \omega_{1})t} \). Therefore, the amplitude can be calculated as following:

\[
\text{Amp}_{2H} = \left| \alpha_{1} + \alpha_{2}e^{j(\omega_{2} - \omega_{1})t} + \alpha_{3}e^{j(\omega_{3} - \omega_{1})t} \right|
\]

After the expansion,

\[
\text{Amp}_{2H} = \left| \alpha_{1} + \alpha_{2} \cos(\omega_{2} - \omega_{1})t + j\alpha_{2} \sin(\omega_{2} - \omega_{1})t \right| + \left| \alpha_{3} \cos(\omega_{3} - \omega_{1})t + j\alpha_{3} \sin(\omega_{3} - \omega_{1})t \right|
\]

The calculation for the amplitude is as follow:

\[
\text{Amp}_{2H} = \left[ \alpha_{1} + \alpha_{2} \cos(\omega_{2} - \omega_{1})t \right]^2 + \left[ \alpha_{3} \cos(\omega_{3} - \omega_{1})t \right]^2 + \left[ \alpha_{2} \sin(\omega_{2} - \omega_{1})t + \alpha_{3} \sin(\omega_{3} - \omega_{1})t \right]^2
\]

Further elaboration is:
The substitution of the \( \cos(\omega_2-\omega_1)t \) to 1 and -1 is for calculating the maximum and minimum values of the instantaneous voltage respectively. The voltage flicker waveform (Fig. 1) shows a 50 Hz voltage supply with presence of pair of inter-harmonics, in which are 47 Hz (\( \omega_3 \)) and 53 Hz (\( \omega_2 \)) with amplitude of 0.1 p.u. (\( \alpha_3 \)) and 0.2 p.u. (\( \alpha_2 \)). The maximum and minimum values of the instantaneous voltage in Fig. 1 are 1.3 and 0.7 p.u respectively. Let assume the amplitudes of \( \alpha_3, \alpha_1 \) and \( \alpha_2 \) are already determined, which are 0.1, 1 and 0.2 p.u. respectively. Eq. (12) and eq. (13) can be used to calculate the maximum and minimum values of the instantaneous voltage which are 1.3 and 0.7 p.u. respectively. Therefore, the formulas generated in this paper (eq. (12) and eq. (13)) are proven correct via comparing the calculation’s values and Fig. 1. Thus, as to evaluate the severity of the voltage flicker, relative fluctuation voltage (\( \Delta v/v \)) is needed to be calculated by using formula below:

\[
\Delta v/v = \frac{Amp_{2H\text{max}} - Amp_{2H\text{min}}}{\alpha_1} \times 100
\]

For Fig. 1, \( \Delta v/v \) is 60%. Again, the amplitudes of fundamental (\( \alpha_1 \)) and two inter-harmonics (\( \alpha_2 \) and \( \alpha_3 \)) are the key values to identify \( \Delta v/v \).

To summary, any generated voltage flicker may produce significant effect to the amplitudes of pair of inter-harmonics [20]. Therefore, the relationship between pair of inter-harmonics and voltage flicker frequency is discussed clearly above. Additionally, the formula for maximum and minimum values of instantaneous voltage, and relative fluctuation voltage are being discussed too. Finally, the amplitudes of fundamental (\( \alpha_1 \)) and pair of inter-harmonics (\( \alpha_2 \) and \( \alpha_3 \)) are found to be crucial in order to identify \( \Delta v/v \). The usage of \( \Delta v/v \) will be discussed for further details in the next section.

### III. CRITICAL VOLTAGE FLICKER FREQUENCY

The critical voltage flicker frequency which is the most sensitive to human eyes is located at 8.8 Hz sinusoidal wave with relative fluctuation voltage (\( \Delta v/v \)) of 0.25%, according to IEC standard [4]. Moreover, when the supplied voltage consists of voltage flicker frequency of 8.8 Hz sinusoidal wave with \( \Delta v/v \) of 0.25%, it will cause the lamp to flick with 8.8 Hz and it may cause human headache. Theoretically, any voltage flicker waveform may increase the amplitudes of pair of inter-harmonics [20]. Based on eq.(1), when the critical voltage flicker (8.8 Hz) happens, it will cause amplitudes of 41.2 Hz (50-8.8) and 58.8 Hz (50+8.8) to increase indirectly for 50 Hz power system. As discussed above, detection of amplitudes for 41.2, 50 and 58.8 Hz are crucial to identify the maximum and minimum values of the instantaneous voltage so that \( \Delta v/v \) can be calculated precisely. Subsequently, if \( \Delta v/v \) is greater than 0.25%, the critical voltage flicker will be detected. Last but not least, eye strains, headaches and in the worst case, seizures [19] may happen due to the aforementioned critical voltage flicker. Therefore, this CVFD is highly potential be applied in any crowded human place (such as shopping complexes, offices, and stadiums) for human awareness purpose.

### IV. BACKGROUND OF FFT

Based on standard IEC 61000-4-7, the general formula for FFT is

\[
X(k) = \sum_{n=1}^{N-1} x(n)e^{-j\omega_k n}
\]

where,

\[
\omega_k = \frac{2\pi k}{N}
\]

N is the number of samples in time domain; k is the samples number in frequency domain (Bin number returned by FFT); x is the data in time domain and X is the data in frequency domain. Since

\[
e^{-j\omega_k n} = \cos\left(\frac{2\pi kn}{N}\right) - jsin\left(\frac{2\pi kn}{N}\right)
\]

Then, the output of the FFT in frequency domain is
It can be written as

\[ X(k) = \sum_{n=1}^{N} [\text{real} - j \cdot \text{imaginary}] \]  

(19)

After that, the amplitude and phase values of the desired signal can be extracted via following equation:

\[ A = \sqrt{\text{real}^2 + \text{imaginary}^2} \]  

(20)

\[ \theta = \tan^{-1} \frac{\text{imaginary}}{\text{real}} \]  

(21)

Based on previous works, optimized sampling frequency for FFT is 12.8k Hz [27, 28] for detecting signal with fundamental frequency of 50 Hz. Specifically, the frequency resolution (eq. (22)) is needed for this proposed algorithm is 0.1. Therefore, the window size is 128k samples (12.8k/0.1). Consequently, 10s is needed for processing a single output data.

\[ \text{Frequency\_resolution} = \frac{\text{Sampling\_frequency}}{\text{Window\_size}} \]  

(22)

V. PROPOSED ALGORITHM

As discussed above, the amplitudes of pair of inter-harmonics and fundamental frequency are the key values to determine the severity of the critical voltage flicker level. Principally, FFT is utilized as the amplitudes detector due to its advantages as mentioned in the introduction above. Next, the particular amplitudes’ values are substituted into eq. (12) and eq. (13) for determining the maximum and minimum values of the fluctuation voltage. Next, the relative fluctuation voltage (Δv/v) is calculated via eq. (14). If the percentage of Δv/v is greater than 0.25 %, critical voltage flicker will be detected. Block diagram of the proposed algorithm is shown in Fig. 2.

VI. EXPERIMENTAL RESULTS

Fig. 3 shows the experimental setup to perform this proposed algorithm. Programmable AC source model 6590 is utilized as the 8.8 Hz voltage flicker waveform generator for this experimental setup. Furthermore, several voltage flicker waveforms are considered in this experimental work for further evaluating robustness of the proposed algorithm. The benchmarking tool used is Fluke power analyzer (P_{\text{run}}). Data acquisition is assessed by using differential probe Gw Instek GDP_025 and Ni USB 6212. 12800 Hz is utilized as sampling frequency for this experimental work. The window width is 128k samples. Therefore, 10 seconds are needed for single output data. Finally, the data is exported to Matlab Simulink to further be analyzed by the proposed algorithm as shown in Fig. 2.

![Fig. 2 Block diagram for the proposed algorithm](image-url)

![Fig. 3 Configuration block for the experimental work](image-url)

Basically, the programmable AC source is supplied by a voltage (rms) of 240 V. Next, the aforementioned voltage waveform is interrupted by an envelope pulse (8.8 Hz) which is generated by the programmable AC source too. The envelope pulse is varied amplitude voltage (rms) from 239 to 240 V with increasing step size of 0.1 V. Subsequently, 11 sets of experimental data are tested. Table I shows the summary of the data analysis for this experimental work. Initially, FFT is utilized to capture and analyze the voltage flicker waveform generated by the programmable AC source.

| Table I |
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