

An Analysis of Harmonic and Interharmonic Contribution of Electric Arc Furnace by Using Periodogram

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ABSTRACT

Fast and accurate detection of the harmonic and interharmonic contribution of electric arc furnace (EAF) is crucial in identifying and to mitigate the undesired effects to the system. In this paper, periodogram, a fast and accurate technique is introduced for the analysis of the contribution. Based on a rule-based classifier and the threshold settings that referred to the IEEE Standard 1159 2009, the analysis of the harmonic and interharmonic contribution of EAF are carried out successfully. Moreover, the impact of contribution is measured using total harmonic distortion (THD) and total non-harmonic distortion (TnHD). In addition, periodogram also gives 100 percent correct detection and able to analyze the contribution impact. It is proven that the proposed method is accurate, fast and cost efficient for analyzing the impact of harmonic and interharmonic of EAF.

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1. INTRODUCTION

The power quality refers to variation of electromagnetic phenomena that distinguishes the voltages and currents at a stipulated time and location and the availability of pure sinusoidal voltage and current waveforms at 50 Hz (frequency power-line in Malaysia) without any disturbances at the incoming point of the supply system [1]. The power quality disturbances can cause failure or disoperation of equipment and economic problem [2]. Widely use of nonlinear equipments in power system is seriously polluting the power quality. Before improving the power quality, it needs a power quality diagnosis system to identify source of the power quality disturbance. Many techniques were presented by various researchers for detect, analyzing or classifying power quality problems in real time. The difficulty of power quality disturbances diagnosis requires an engineering expertise and proficient knowledge in many areas of electrical power. Many techniques were presented by various researchers for analyzing or classifying power quality problems [3]. To improve the power quality, an effective monitoring system must be developed for detection and classification of power quality disturbances [4]. Harmonic source is one of the most concerned disturbances in the power quality. The limitation of harmonics pollution present at the point of common coupling (PCC) had been control by IEEE Std. 519 to improve the power quality, which widely accepted in industry [5]. The detection of the harmonic source is necessary for power quality strategy development [6].

Electric arc furnaces (EAF) is the one of harmonic producing load that contributes large number of harmonic and interharmonic components due to the operation principles [7-8]. Detection of the harmonics and interharmonics at the point of common coupling (PCC) is necessary for analysing the impact to the

system and to identify the best mitigation method as clearly mentioned the IEC Standard 61000-4-7 [9]. Apparently, the EAF is characteristically time-variant load, non-linear and it can cause power quality problems such as current–voltage harmonics, voltage flicker and voltage unbalance [10]. The circulated harmonic current in the distribution system can affect other users within the distribution network. Due to non-linear of the EAF, the parameters of furnace such as voltage, current, resistance, reactive and real power and reactance unveil the significant variations, mainly during fusion. These variations root of flicker and harmonic problems at the PCC [11]. The generated harmonics also contributed to the conductor overheating, capacitor bank failures and breakdown of electronic system [12]. Therefore, a modelling and analysis of harmonic components that caused by EAF is crucial due to study the characteristics and to solve the problems concerning to EAF [13]. Most of previous studies bring about the EAF with the single-phase with the time domain analysis [13-15]. The analysis of the 3-phase EAF is costly pertaining computational time and a single phase EAF analysis does give an exact results of harmonic contribution [14]. Therefore, an analysis of 3-phase EAF by using time domain analysis is needed due to analyse the harmonic and interharmonic contribution of EAF and time domain analysis offer fast analysis, accurate and low.

In this paper, a time domain analysis which is periodogram is introduced in detecting and analyzing the harmonic and interharmonic contribution of 3-phase EAF. The detection of harmonic and interharmonic components is based on a ruled-based classifier which is established accordingly IEEE Standard 1159-2009. Moreover, the harmonic and interharmonic indices instantaneous total harmonic distortion, $THD(t)$ and instantaneous total non-harmonic distortion, $TnHD(t)$ voltage and current are used for measuring the harmonic and interharmonic contribution impact to the system. Modeling and analysis of 3-phase EAF are carried out using Matlab..

2. RESEARCH METHODOLOGY

Periodogram is a fast and accurate technique in analyzing the power signal. Meanwhile, the distinguishing of harmonic and interharmonic components can be accomplished by using harmonic indices which are $THD(t)$ and $TnHD(t)$. Figure 1 shows the implementation of proposed method.

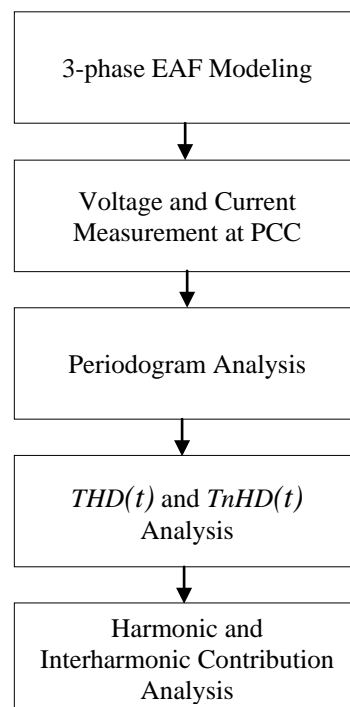


Figure 1. Implementation chart for harmonic and interharmonic signals detection and classification

2.1 Electric Arc Furnace

The arc furnace impedance varies arbitrarily and tremendously asymmetrical, this is due to the carbon electrodes in contact with iron have different impedances between the negative and positive flows of current. Thus, it will cause interference to the power system. The key reasons are [16]:

- The EAF resistance is not constant and varies in the half cycle of alternating current arc. This will lead to the generation of non-sinusoidal distortion.
- The positive and negative half cycle commutation of current, graphite electrode and steel alternately as the cathode and anode. Even order harmonic is caused by the current of negative and positive two and a half asymmetric waveforms.

Figure 2 shows the 3-phase EAF of 400 V, 1MVA, 50 Hz with 3-phase power supply. Meanwhile, the EAF subsystem block was developed in Simulink and shown in Figure 3.

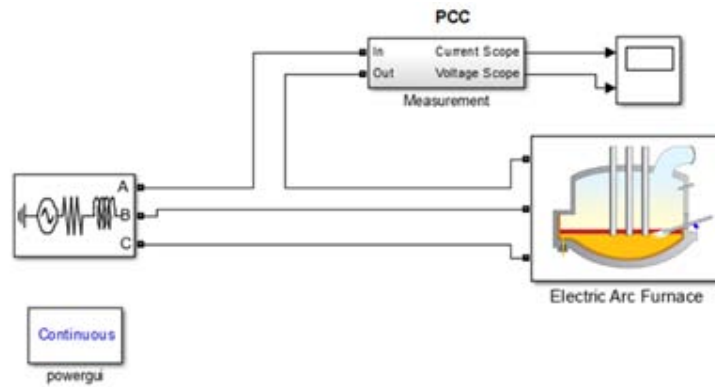


Figure 2. Electric Arc Furnace Model

For a 3-phase system, three sets of resistive and inductive networks and controlled voltage source are used. The EAF model used a hyperbolic model [15] as defined in **Equation 1**, where v and i are arc voltage and arc current per phase and V_{at} is the threshold magnitude. This voltage is reliant on the arc length which is well-defined by constants C and D that representing the arc power and arc current respectively [17].

$$v(i) = \left(V_{at} + \frac{C}{D + |i|} \right) \text{sign}(i) \tag{1}$$

Each electrode at each phase is represented by MATLAB Function block. The C is set at 19 kW, while D is fixed at 5 kA and the threshold voltage is 200 V. In the meantime, the modulation index is set at 0.2 and 0.01 Ω and 1 mH for the coupling network, respectively [18].

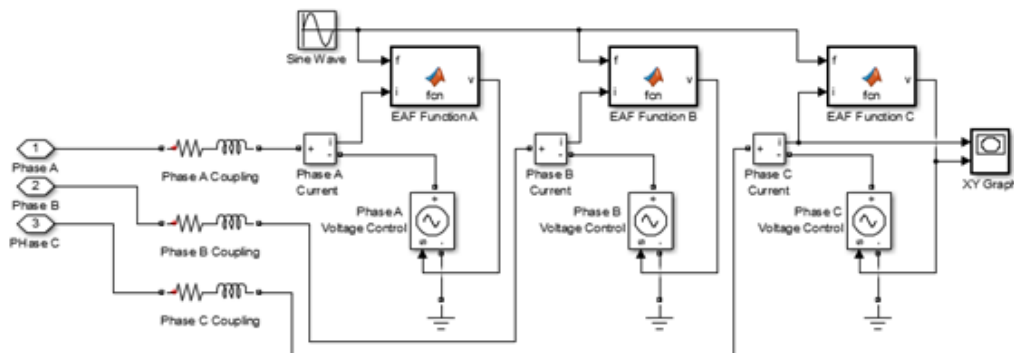


Figure 3. Electric arc furnace block subsystem

2.2 Periodogram

The accuracy of harmonic spectrum is obtained by using periodogram technique [19]. The periodogram power spectrum represents the distribution of power signal over frequency and can be expressed as [20]:

$$S_v(f) = \left| \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} v(t) e^{-j2\pi ft} dt \right|^2 \quad (2)$$

$$V_{DC}(t) = \sqrt{\int_{-\frac{\Delta f}{2}}^{\frac{\Delta f}{2}} S_v(f) df} \quad (3)$$

Where, $S_v(f)$ in frequency domain; $v(t)$ is voltage waveform; V_{DC} is direct current voltage and $\frac{\Delta f}{2}$ is system frequency.

2.3 Harmonics and Interharmonics

According to the IEEE Std. 1159-2009, harmonic is a component of order greater than one of the Fourier series of a periodic quantity and interharmonics are frequency components that are not integer multiples of the fundamental frequency. Furthermore, interharmonics can lead to excitation of low frequency mechanical oscillations, and failure in ripple control [7].

2.3.1 Instantaneous Total Harmonic Distortion ($THD(t)$)

Total harmonic distortion, THD, is used to measure of how much harmonic content in a waveform [21]. The instantaneous total harmonic distortion, $THD(t)$ of a waveform is defined as

$$THD(t) = \frac{\sqrt{\sum_{h=2}^H V_{h,rms}(t)^2}}{V_{1,rms}(t)} \quad (4)$$

where $V_{h,rms}(t)$ is RMS harmonic voltage. With refer to the IEEE Std. 1159-2009, the measured harmonic number until 50th are required for harmonic analysis.

2.3.2 Instantaneous Total Nonharmonic Distortion ($TnHD(t)$)

Moreover, the signal also comprises interharmonic components that are not multiple integer of the fundamental frequency. The instantaneous interharmonic component can be identified by using $TnHD(t)$ [21] and written as

$$TnHD(t) = \frac{\sqrt{V_{rms}(t)^2 - \sum_{h=0}^H V_{h,rms}(t)^2}}{V_{1,rms}(t)} \quad (5)$$

where $V_{h,rms}(t)$ is RMS harmonic voltage with consideration of harmonic number up to 50th.

2.4 Signal Classification

The rule-based classifier will be utilized for signal classification and this classifier is a deterministic grouping technique that has been utilized as a part of genuine application [20]. The performance of classification is much dependent on the principles and threshold values. The utilization of rule-based classifier agreeing Equation 4 and 5 [10],[21].

$$THD_{ave} > TnHD_{thres} \text{ and } TnHD_{ave} < TnHD_{thres} \quad (6)$$

$$TnHD_{ave} \geq TnHD_{thres} \text{ and } THD_{ave} < TnHD_{thres} \quad (7)$$

Classification of THD and $TnHD$ is necessary due to analyze the harmonic contribution in the signal. The harmonic component is classified when the signal has only THD whereas interharmonic index is $TnHD$.

3. RESULTS AND ANALYSIS

In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Figure 4(a) demonstrates the sample of instantaneous waveform of measured voltage and current at PCC. According to the IEEE Std 519-2014, the measurement window width should be minimum of 10 cycles and must considering harmonic components up to 50th order. With refer to the IEC 61000-4-7, a method based for the grouping concept of Harmonic Groups and Interharmonic Groups, minimum of 5 Hz frequency resolution is used in this study. Furthermore, the frequency spectrum of voltage and current are illustrating in Figure 4(b) and Figure 4(c). The voltage frequency spectrum, shows that the DC voltage exist in the signal and with a value of 43.22 V.

Possibly the greatest challenge pertaining interharmonics is on the low-frequency and is necessary to examine the model and analysis technique due to determine the applicability to harmonics at frequency below the fundamental frequency. Nevertheless, using periodogram the harmonic and interharmonic components for voltage signal were distinguished from 25 Hz up to 1575Hz. The harmonic and interharmonic component for current signal exist between 25 Hz to 725 Hz. In the meantime, the DC component with a magnitude of 21.27 A was detected in the signal. To measure the distortion impact onto the system, the harmonic and interharmonic indices which are $THD(t)$ and $TnHD(t)$ are introduced. These indices are useful in identifying and to distinguish the harmonic and interharmonic contribution.

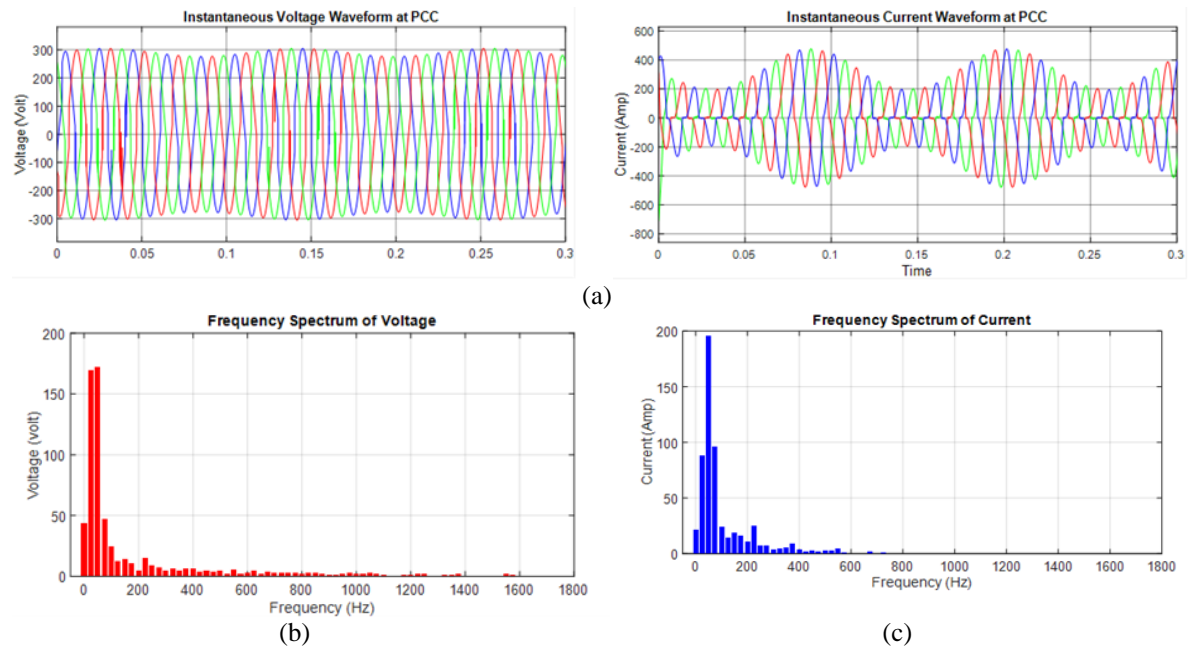


Figure 4. (a) Instantaneous voltage and current waveform at PCC, (b) Frequency spectrum of voltage signal, (c) Frequency spectrum of current signal

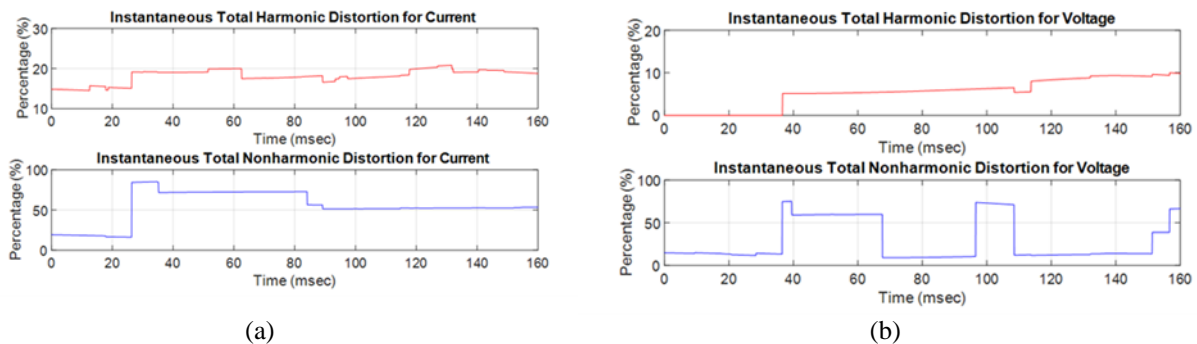


Figure 5. (a) $THD_V(t)$, $TnHD_V(t)$ and (b) $THD_I(t)$, $TnHD_I(t)$

Figure 5(a) depicts the $THD(t)$ and $TnHD(t)$ of voltage signal that been obtained from the periodogram analysis. As can be understood from the figure, the $THD_V(t)$ is in the range of zero percent to 10 percent, meanwhile the $TnHD_V(t)$ value varies from 10 percent to 70 percent, respectively. In the meantime, Figure 5(b) shows that the instantaneous $THD_I(t)$ and $TnHD_I(t)$ for current signal which are vary between 15 percent to 20 percent and 20 percent to 80 percent, correspondingly. According to the IEEE Standard 519-2014, any buses or PCC with a nominal voltage less than 1000 V, the limits may allow 8% THD_V and 5% individual voltage harmonic amplitude. It is shows that the THD_V has exceeded the standard limit values and the harmonic compensator is required due to improve the power quality. The 3-phase EAF has generated more harmonic distortion as the EAF does not has ground return and also using star connection for the three arc and during unbalanced condition which is in meltdown process, it will cause the harmonic and interharmonic components multiplicity generated.

For a better understanding of harmonic and interharmonic contribution of electric arc furnace in distribution system, a tabulation plot of harmonic and interharmonic components is necessary and depicts in Figure 6. By considering all integer harmonics up to 50th and interharmonic components with a minimum resolution of 5 Hz, it is clearly show that the voltage signal comprises large number of harmonic and interharmonic components compare to current signal.

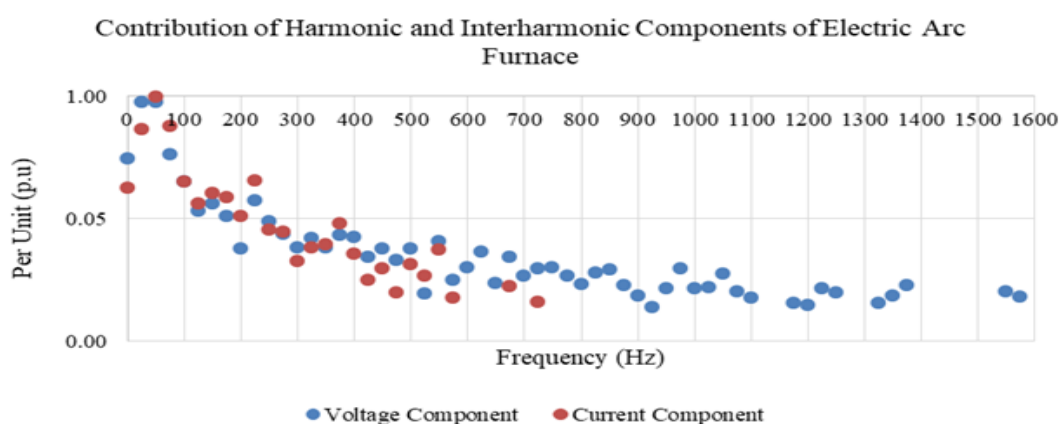


Figure 6. Contribution of Harmonic and Interharmonic Components of 3-phase EAF

Figure 6 shows that the tabulation of harmonic voltage over harmonic current components plainly explain that the 3-phase EAF might be then considered a voltage harmonic source as well as discussed in [11][22]. Establishing 3-phase EAF model accurately is an important prerequisite for determining the impact of its harmonic contribution to the system. Using this model and the proposed method, it is observed that the analysis of harmonic and interharmonic contribution can be defined significantly.

4. CONCLUSION

The analysis of harmonic and interharmonic contribution of the 3-phase EAF in power distribution system by using periodogram successfully implemented in this study. The periodogram analysis able to distinguish the harmonic and interharmonic components. Furthermore, the impact of the signal distortion also been measured using $THD(t)$ and $TnHD(t)$ indices. The results show that the periodogram is a fast and accurate in identifying the harmonic and interharmonic contribution. Hence, the periodogram is an appropriate technique to be implemented for analyzing the harmonic and interharmonic contribution of the 3-phase EAF.

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