Electric Power Systems Research 119 (2015) 11–18

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

New power quantities definition for low and high order harmonic distortion

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ARTICLE INFO

Article history:
Received 1 June 2014
Received in revised form 11 August 2014
Accepted 3 September 2014
Available online 17 September 2014

Keywords:
Distortion power
Harmonic analysis
Low/high order harmonic
Power components
Power measurement
Power quality
Time-frequency analysis

ABSTRACT

This paper presents a set of new power quantities that aims to assess the harmonic distortion considering low and high order harmonics. The power quantities in the IEEE Standard 1459-2010 are revisited and new formulations are developed after separating the low order (harmonics below 40th order) and high order (harmonics above 40th order) from the fundamental (i.e. 60-Hz) component of the voltage and current. Two distinct groups of new power quantities are introduced in this study namely: (1) low/high order harmonic distortion powers and (2) low/high order harmonic interference powers. The results of the experimental measurement performed on different light bulb types from different manufacturers are presented in this paper to exemplify the usefulness of the developed power quantities. The results of the measurement reveal that the new power quantities can be useful in assessing the harmonic distortion/interference resulting from low/high order harmonics and also can be useful in many detection applications which require extracting prominent features in high frequency range above 2.4 kHz (or 40th harmonic order).

1. Introduction

1.1. Background

The definitions of power quantities when measured under non-sinusoidal conditions have been controversial during the past decades until the release of the IEEE Standard 1459-2010 [1]. This standard defines five major quantities namely: (1) fundamental (or 60-Hz) power, (2) non-fundamental (or non 60-Hz) power, (3) current distortion power, (4) voltage distortion power and (5) harmonic apparent power. These power quantities are the outcome of separating the power system frequency components of the non-sinusoidal instantaneous voltage or current from the remaining harmonic components which lump both low and high order harmonics. The IEC 61000-3-2 [2,3] set limits for harmonic current emissions up to only 40th harmonic order while the IEC61000-4-7 [4] only shed light on the harmonic range above 40th order and up to 180th harmonic order without setting any emission limits.

1.2. Motivation

The power definitions presented in the IEEE Standard 1459-2010 and hence the harmonic emission limits cover only situations in which power disturbances are due to low order harmonics. Currently there is no standard to define power quantities in any harmonic range above 40th order, and therefore the interaction between different power quantities at high order with low order harmonics and with the fundamental power system frequency (60-Hz) is not well understood [5]. It is worth noting that extending the power quantities that are previously defined in the IEEE Standard document to separate the high order harmonics from the low order harmonic power using the frequency domain decomposition as introduced in the IEEE Standard document using only two main components (i.e., one fundamental and another non-fundamental power components) is not a trivial or straightforward process due to the emergence of new power quantities resulting from the interaction between high order harmonic component and both low order harmonic components and the fundamental frequency components. Since this work has not been taken into consideration in the literature therefore appropriate definitions of these power quantities for high order harmonics need to be developed to help understanding the interaction of these quantities with those at lower harmonic order. This is essential to facilitate the measurement of the associated energies at the high frequency

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http://dx.doi.org/10.1016/j.epsr.2014.09.004
0378-7796/

range for revenue purposes, and also to set limits for emissions to prevent interference with power line communications. The presented mathematical formulations of the new power quantities and their definitions present a comprehensive approach that paves the road to further investigation and assessment of high order harmonic emissions resulting from modern non-linear loads in electric distribution system.

1.3. Previous work

In the last thirty years, all the developed definitions of power quantities in the literature [6–14] are based on separating the fundamental power system frequency (60-Hz) component from the other harmonic (non 60-Hz) components. This was in response to the changes that occurred in the past fifty years resulting from the widespread use of traditional power electronic converters (i.e., controlled/uncontrolled bridge rectifiers/inverters) that inject harmonic currents in the low order harmonic range (i.e., up to 40th order). Today, because most modern power electronic converters used in solar photovoltaic/wind-based distributed generation and in most plug-in electric vehicle battery chargers use pulse width modulation (PWM) with operating frequency usually chosen in the high frequency range (i.e. up to 100 kHz) [15], harmonic frequencies above 40th harmonic order might exit.

Also studies [16–18] have reported high order harmonic emission from fluorescent lamps with high frequency ballast, and some energy efficient light bulbs such as compact fluorescent light bulbs (CFLs) and light emitting diodes (LED) light bulbs by measuring the current in the frequency range 2–150 kHz. In order to address this subject, this paper extends the power definitions introduced in the IEEE Standard 1459-2010 [1] to include the high order harmonics while introducing new power quantities after separating the high order harmonics of the voltage and current from the low order harmonics.

1.4. Work organization

The work presented in this paper is organized as follows: Section 2 presents the mathematical formulations of low and high order harmonic power quantities and the newly introduced power quantities. Section 3 describes the experimental set-up used in this work and the utilized measurement methods of these power quantities. Section 4 presents the time-frequency analysis and the results obtained from the measurement of the developed power quantities and finally Section 5 includes the conclusions.

2. Low order and high order harmonic power quantities

2.1. Definitions

In non-sinusoidal situations, according to the IEEE Standard 1459-2010 [1], the instantaneous voltage and current can be separated into two components: (1) fundamental (or 60 Hz), and (2) non-fundamental (or non-60 Hz). The latter can further be separated into two components; (1) low order harmonic ranging from 2nd to 39th harmonic order and (2) high order harmonic which include all harmonic order starting from 40th order and above. According to this separation, the root mean squares (rms) of the voltage and current can be mathematically formulated as:

$$V=\sqrt{V_1^2+V_{HL}^2+V_{HH}^2},\quad I=\sqrt{I_1^2+I_{HL}^2+I_{HH}^2} \tag{1}$$

with

$$V_{HL}=\sqrt{\sum_{m=2}^{39}V_m^2},\quad V_{HH}=\sqrt{\sum_{m=40}^{\infty}V_m^2} \tag{2}$$

$$I_{HL}=\sqrt{\sum_{n=2}^{39}I_n^2},\quad I_{HH}=\sqrt{\sum_{n=40}^{\infty}I_n^2} \tag{3}$$

where the subscripts '*HL*' and '*HH*' denote low and high order harmonics, V_1 and I_1 are the rms of the voltage and current at the fundamental (60 Hz) power system frequency while V_m, I_n are the rms of the voltage and current at the non-fundamental (non-60 Hz) components.

The total active power P can be decomposed into three components: fundamental active power P_1, low order harmonic active power P_{HL}, and high order harmonic active power P_{HH}.

$$P=P_1+P_{HL}+P_{HH} \tag{4}$$

$$P_1=V_1I_1\ \cos\theta_1,\quad P_{HL}=\sum_{h=2}^{39}V_hI_h\ \cos\theta_h,\quad P_{HH}=\sum_{h=40}^{\infty}V_hI_h\ \cos\theta_h \tag{5}$$

Using the rms voltage and currents defined in (1) the total apparent power can be computed by taking the product of the voltage and current at the fundamental, low order, and high order components. Table 1 summarizes the power quantities for low and high order harmonics.

$$\begin{aligned}S^2 &= V^2I^2=V_1^2I_1^2+V_1^2I_{HL}^2+V_1^2I_{HH}^2+V_{HL}^2I_1^2+V_{HL}^2I_{HL}^2+V_{HL}^2I_{HH}^2\\ &\quad +V_{HH}^2I_1^2+V_{HH}^2I_{HL}^2+V_{HH}^2I_{HH}^2\end{aligned} \tag{6}$$

2.2. New power quantities

The first term in (6) can be recognized as the fundamental apparent power S_1 as defined in [1].

2.2.1. Low order and high order harmonic current distortion power

The second and third terms in (6) represent the segment of the non-fundamental non-active power due to low and high order harmonic current distortion which can be defined as low order and high order harmonic current distortion power, D_{IL} and D_{IH} respectively.

$$D_{IL}=V_1I_{HL},\quad D_{IH}=V_1I_{HH}\quad\text{and}\quad D_I^2=D_{IL}^2+D_{IH}^2 \tag{7}$$

2.2.2. Low order and high order harmonic voltage distortion power

The fourth and seventh terms in (6) are the low order and high order non-fundamental non-active power components due to harmonic voltage distortion D_{VL} and D_{VH} respectively.

$$D_{VL}=V_{HL}I_1,\quad D_{VH}=V_{HH}I_1\quad\text{and}\quad D_V^2=D_{VL}^2+D_{VH}^2 \tag{8}$$

2.2.3. Low order and high order harmonic apparent power

The fifth and ninth terms in (6) are the apparent power due to low order and high order harmonics in voltage and current alone. Specifically, the product of the voltage and current at the low order harmonics produces the low order harmonic apparent power S_{HL} while their product at the high order harmonic produces the high order harmonic apparent power S_{HH}.

$$S_{HL}=V_{HL}I_{HL},\quad S_{HH}=V_{HH}I_{HH} \tag{9}$$