Characteristic of Conducted EMI in Compact Fluorescent Lamps Application Assessment based on CISPR-11

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Abstract— **This paper presents the assessment of aggregated conducted emission resulted from dynamic interaction of multiple frequency sources in grid in the frequency range of 9 kHz to 150 kHz. The study involves multiple Compact Fluorescent Lamps (CFL) connected in a typical indoor lighting configuration. Based on the current standardized Intermediate Frequency Bandwidth (IFBW) laid out in CISPR-11 (Band A), the aggregation by dynamic interaction of highly volatile interference signals generated by these lamps is inadequate to represent the peak total emission. This paper discusses this specific issue accompanying measurements of conducted Electromagnetic Interference (EMI) in this particular multi-converter system. Our measurement results confirm the phenomenon with simple mathematical theorem and simulation illustrations.**

Keywords—CFL, CISPR-11, conducted emission, electromagnetic disturbance, DM, EMI, grid, IFBW

I. Introduction

Understanding the electromagnetic disturbance properties and behavior of non-linear loads is essential to predict the collective interference occurred in a network. The disturbance is affected by the presence of adjacent equipment in the network. The adjoining equipment, depending on their power consumption and internal impedance properties, may increase or decrease the disturbance occurred in the network. In this subject matter, previous researches have emphasized the necessity for Electro-Magnetic Compatibility (EMC) assurance of reliable operation of complex energy systems such as in [1] [2]. Hence, EMC evaluation assesses the EM emissions of a product in both the frequencies and levels of EM energy generated, the assessment is usually based on designated technical standards available. These standards determine the permissible limit values for EMI, product classification, equipment and the method of measurements [3].

The increasing usage of power converter devices over the last few decades whether in residential or industry has indeed contributed significantly to the increase in the emission of EMI especially in the field of lighting application. For example in Brazil, comparative study published by the Brazilian Lighting Industry Association (ABILUX) reported that, Fluorescent lamps (FL) are still widely used in homes and offices [4]. Several reports have also indicated the up trending for lighting business in the market for foreseeable future [5] [6]. Hence, with large number of lamps connected in electrical grid, the interaction among such devices becomes the interest of many researchers. Although there have been some papers had already acknowledged about the issue of the total emission increases with respect to the number of devices [7] [8] [2] meanwhile some manuscripts reported vice versa [9] [10] in FL lighting research. From the technical viewpoint, the increase of total emission is subject to either absolute frequency or small frequency difference of sinusoidal components contributed from each device in a multi-converter system. This situation is further complicated if the differences among switching frequencies are large with each sinusoidal component in a highly volatile (random) motion, this signal behavior is observed even though the devices are of the same model and power rating. Therefore, without proper acknowledging this underlying issue, this phenomenon may lead to misinterpretations in EMC assessment concerning this application.

In this paper, analysis concerning total aggregated Differential Mode (DM) signals generated by a series of CFL lamps is compared with the current abiding IFBW in the CISPR-11 standard. The number of lamps was varied from 1 to 4 to observe the trend of the aggregated EMI level in a typical household electrical lighting connection. This approach allows us to comprehend the behavior of signals aggregation phenomena beyond the traditional knowledge related with the volatility of individual sinusoidal components and the IFBW selection based on current CISPR standard. The analyses presented in this paper consider simulations and experimental results based on a standardized testing setup. This paper is structured as follows: Section II describes the standardized measurement for low-volatility sinusoidal components, followed by Section III: Aggregation of high-volatility sinusoidal components, Experiment results discussed in Section IV, and conclusion in Section V.

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II. STANDARDIZED MEASUREMENT FOR LOW VOLATILITY SINUSOIDAL COMPONENTS

In earlier paper [2], it has been shown multiple sinusoidal components having very low frequency difference as low as 5 to 100 ppm (part per million) measured with a Super-heterodyne EMI receiver with a normalized IFBW = 200 Hz using the Quasi-peak (QP) and Average (AV) detectors. In our results, the aggregated conducted EMI is enclosed in low frequency envelope, arising from superposition of waves could cause distortion of measurement results in compliant to the standardized EMI measuring techniques standard CISPR-11 (EN 55011). Detailed descriptions of CISPR and detectors with mathematical descriptions can be found in [11]. In addition, the frequency difference between sinusoidal components affects the rate of change of the envelope. The smaller the difference, the rate of change would take longer period. For simplification, multiple sinusoidal signals with very close switching frequency interconnected in a network would produce constructive interference and destructive interference output signal, the instantaneous peak value can be related to the summation of sinusoidal signals similar to the frequency beat concept, the result will be a low frequency envelope as seen in Fig. 1 which is analogous to the Amplitude Modulation of waves. Mathematically, the sum of multiple wave components with the slightly different frequencies ($f_1, f_2, \ldots, f_n$) with amplitudes equal to unity can be expressed as;

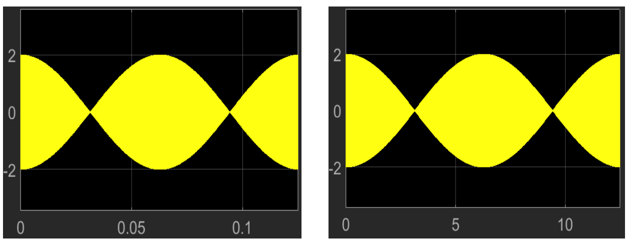
$$Y_n(t;\{f_1,\ldots,f_n\}) = \sum_{i=1}^{n} \sin(2\pi f_i t)$$

$$= \frac{2}{n-1} \sum_{\substack{2\ll i\ll n \\ 1\ll j<i}} \cos\left(2\pi\left(\frac{f_i - f_j}{2}\right)t\right) \times \sin\left(2\pi\left(\frac{f_i + f_j}{2}\right)t\right) \qquad (1)$$

Example for two sinusoidal components with f_1 and f_2, $\frac{f_1+f_2}{2}t$ gives the sinusoidal wave the average of two frequencies, $\frac{f_1-f_2}{2}t$ appears to be the beat envelope. The frequency beat effect appears when $|f_1 - f_2| \ll |f_1 + f_2|$. In such conditions, the absolute value is;

$$Env_n(t;\{f_1,\ldots,f_n\}) = \frac{2}{n-1} \sum_{\substack{2\ll i\ll n \\ 1\ll j<i}} \cos\left(2\pi\left(\frac{f_i - f_j}{2}\right)t\right) \qquad (2)$$

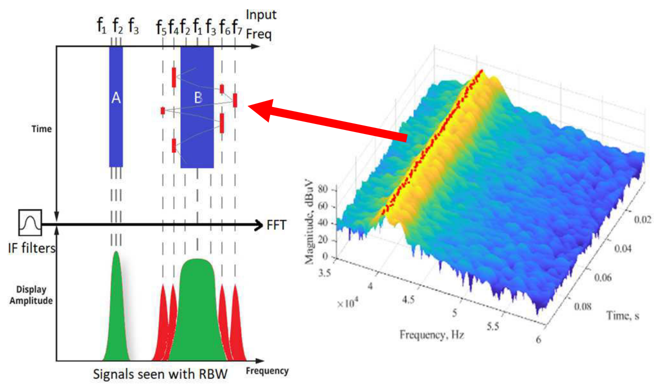
Hence, $Env_n(t;\{f_1,\ldots,f_n\})$ is the low frequency envelope of aggregated signals. It is also possible to observe that the period of the envelope relies on the difference between the frequency of input signals [2]. The period of envelope is inversely proportional to the largest common divisor of all pairs $f_i - f_j$ for $2\ll i \ll n$, $1\ll j \ll i$.



(a) (b)

Fig. 1. Envelope of oscillatory signals resulting from aggregation of two sinusoidal components of frequencies (a) f_1 = 40000 Hz and f_2 = 40100 Hz. (b) f_1 = 40000 Hz and f_2 = 40001 Hz.

Fig. 1 illustrates the low frequency envelopes formed by aggregating two sinusoidal components of slightly different frequency with amplitude equals to unity respectively. The duration from peak to trough literally the rate of change of the envelope is different in both cases. For instance, the envelope shown in Fig. 1 (a) having a period of 63 milliseconds while in Fig. 1 (b) is 6.3 seconds, it is 100 times longer duration. In addition, the frequency of each sinusoidal component is usually very stable, thus enabling steady measurement with a standard 200Hz IFBW. In our previous study, we aggregated various number of sinusoidal signals, the assumed central frequency of sinusoidal signals equal to 40 kHz with a random variation of 0.1% among them. The study has allowed us to conclude that, smaller the frequency difference, the slower the rate of change of the envelope was observed. Therefore, it has been recommended to consider longer measurements time to achieve reliable EMC assessment. In the meantime, the research context has covered aggregation of signals considering only small variation of frequency difference among sinusoidal components with low volatility. However, it has not been widely studied about signal aggregation involving high volatility sinusoidal components with large frequency difference. Such scenario will be discussed in the following section.



(a) (b)

Fig. 2. (a) Operational diagram for a standard real-time spectrum analyzer response to low-volatility signals and high-volatility transient signals. (b) 3D spectrogram of aggregated output signal generated by 15 highly volatile sinusoidal components.

We know that modern real-time Super-heterodyne EMI receivers use complex fast Fourier transform (FFT) analysis to convert time-domain signals to frequency-domain signals with compliant IFBW. In fact, the choice of the IFBW has a significant effect on overall measurement results as well as measurement duration. A wide IFBW acquires fewer individual spectrum and faster measurement speeds. In opposite, narrow IFBW setting requires more spectrum acquisitions for a given span and consumes longer measurement time. For comparison shown in Fig. 2 (a), under a narrow IFBW, it is observed the aggregated signal-A in time domain being the superposition of multiple sinusoidal components with only tiny difference of frequencies between each other with low volatility appears as one single continuous spectrum on the spectrogram. Principally, the integral of these discrete components bound within an IF filter bandwidth determines the total peak amplitude of that spectrum. Therefore, aggregating this type of signals inevitably increase the peak total emission proportional to the number of signals.

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III. AGGREGATION OF HIGH VOLATILITY SINUSOIDAL COMPONENTS

In practical EMC compliance measurement, there are various type of devices that work under different architecture. Hence, not only should we consider longer measurements time to achieve reliable results but understanding the characteristic of EMI emission to determine proper IFBW to be used for reliable measurement is also essential, this information is very useful if the frequency variation is very large and spontaneous due to dynamic interaction of multiple sinusoidal components in a network. In this case, a measurement with narrow IFBW can produce different results altogether. For instance in the case of the electronic ballast CFL lamp which is driven by low power-factor (PF) parallel-resonant circuit, the circuit operates with a fluctuating switching frequency in a wide bandwidth resulted from accuracy of its` RLC components [12] [13]. The switching frequency sweeps randomly across wide bandwidth in a skewed distribution pattern. When two or more of these signals are added together, the peak emission in the form of envelop changes rapidly at every instant of time. As a result, the instantaneous peak emission scatters along the time-axis which is indicated by adjoining red dots as shown in Fig. 2 (b). Under this condition, the energy spectrum of signal-B is distributed to its` sideband hence reduces the total peak amplitude of aggregated signal. In this scenario, the main spectrum amplitude will decrease even though higher number of signal is injected to the system. Therefore, this explains why the interaction of these highly volatile dynamic signals can produce lower peak total emission level instead of higher emission for this kind of application. In addition, improper IFBW selection without knowing the characteristic of operating devices could result in unreliable measurement outcome. To simulate this phenomenon, we have used the *spectrogram* function in Matlab® incorporated the *Parseval*`s theorem. The theorem states that the sum (or integral) of the square of a function is equal to the sum (or integral) of the square of its components. In the case of two sinusoidal component having f_1 and f_2, the amplitude of the sum of these emissions can be written as;

$$I_{2\_grid} = \frac{1}{1+i4\pi f_1 RC} I_1 + \frac{1}{1+i4\pi f_2 RC} I_2 \qquad (3)$$

For higher number of oscillatory current sources with different frequency, the amplitude of total emission injected to the grid can be expressed as;

$$I_{N\_grid} = \frac{1}{1+iN\alpha} \sum_{n=1}^{N} I_n \qquad (4)$$

Where $\alpha = 2\pi f * RC$ which α is the reciprocal function of frequency, f, device capacitance, C and grid impedance, R. I_n is the individual device current. As an exemplification, Fig. 4 presents the waterfall plots for magnitude of EMI synthesized with IFBW = 200 Hz and IFBW = 6 kHz which are derived using (4). The central frequency, f is 40 kHz with random frequency variation of ±6.25% (5 kHz) having minimum step of 1 kHz. The instantaneous amplitude of the envelope is the highest peak value at every instant of time that falls within a defined frequency bandwidth shown in Fig. 2 (b). The mean peak value is calculated from these peak values based on various number of signal. Results indicate the mean peak values in Fig. 4 (a) show a downtrend while uptrend is seen in Fig. 4 (b) with respect to the number of signals added.

The presented results have clearly shown discrepancy in outcome despite the parameters of signals are unchanged in both cases.

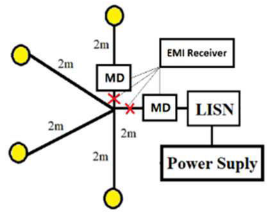
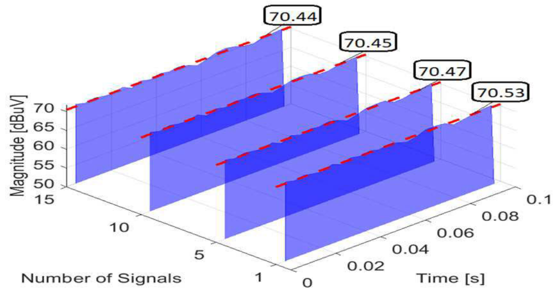
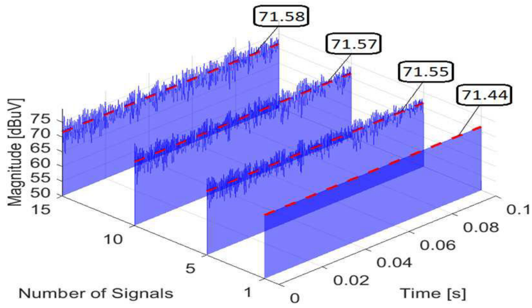


Fig. 3. Single-Line-Diagram of measurement setup with Monitoring Device (MD).



(a)



(b)

Fig. 4. Waterfall plots of aggregated output signal generated by 1-5-10-15 signals with different IFBW resolutions. (a) 200 Hz. (b) 6 kHz.

IV. EXPERIMENTAL MEASUREMENTS

Experiments for standardized EMI measurements have been conducted in laboratory setup fully compliant with EN 55011 and EN55015 [14] as shown in Fig. 3. The measurement involved four standard CFL lamps from the same manufacturer with same power rating. The output for this electronic ballast type CFL lamp operates at unfixed resonant switching frequency, the observed operating switching frequency range is between 37 kHz to 47 kHz for this model. Measurement points are made at the main supply branch and a single load branch of the network using a Monitoring Device (MD) customized by [15]. The function of this MD is to separate the DM and Common Mode (CM) signals from the Equipment-Under-Test (EUT). A Line Impedance Stabilization Network (LISN) is used for isolating the test setup from unwanted grid interference and provide constant impedance during the measurement. The EMI receiver processes signals with the QP and AV detector. Each lamp is separated by 2 meters to mimic the typical indoor ceiling lighting point distance. The experiment was conducted with no overlap to avoid any cross-talk effect. The EMC assessment have been performed using ''the

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presumption of conformity of equipment" based on the fulfillment of harmonized standards requirements [16]. In order to prove our simulation results about the selection of IFBW for this highly volatility multi-converter system, the results are summarized in line graphs derived from the distribution of one-thousand peak values within a reasonable bandwidth measurement for each changes of the number of lamps. Each measurement has been made according to aforementioned standard requirement of the AV detector in a normalized time step of 1 second taken by an EMI receiver.

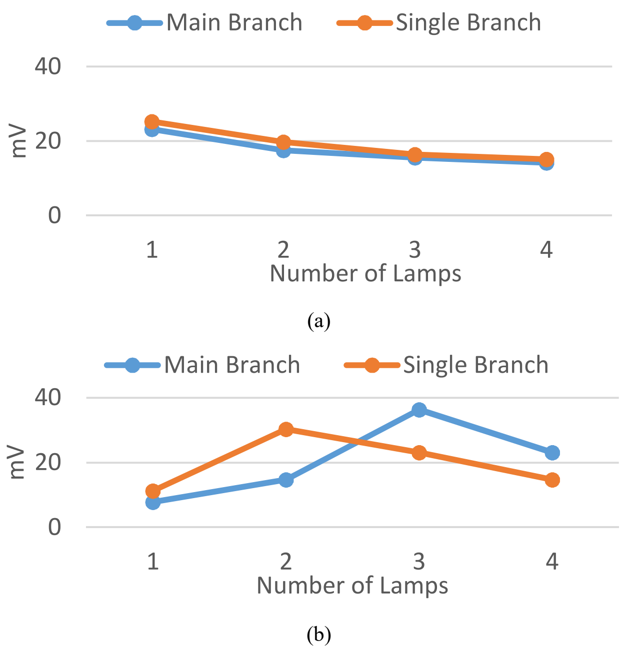

Fig. 5. Mean peak DM signals caused by CFL lamps in terms of mV. (a) IFBW = 200 Hz. (b) IFBW = 5 kHz.

In Fig. 5 (a), it can be seen in these line graphs with the mean V_{DM} values that appear in a logarithmic downtrend with respect to the number of CFL lamps regardless of whether measurement is made at the main supply branch or the single load branch, their V_{DM} values indicate a drop of total emission with respect to higher number of lamp. Meanwhile, the same set of signals are processed using IFBW = 5 kHz, although this IFBW is still relatively smaller than the dynamic frequency bandwidth 10kHz with assumption a 50% overlap of window function in FFT, it is expected the main spectrum amplitude will not be proportional to the number of lamps being turned on. This is mainly due a large portion of the signals energy dispersed outside the main 5kHz IFBW window region (side spectrums in red) as depicted in Fig. 2 (a). Evidently as shown in Fig. 5 (b), the observed mean V_{DM} values for main branch increase from 1 to 3 lamps but drop at 4 lamps. In the case for single branch measurement, the mean V_{DM} values increase for 2 lamps but decrease for 3 and 4 lamps. In these results, it clearly shows that different IFBW has impacted the measurement outcome of conducted EMI in a CFL network. Therefore, we can conclude the proper selection of IFBW plays an important role into obtaining accurate total aggregated EMI emission, especially in a very volatile and complex multi-converter system. In the event to measure high-volatility sinusoidal components with large frequency step variation, it is recommended to use adequate IFBW setting. From the standardization point of view, EMC assessment should consider this recommendation for proper evaluation of conducted EMI in multi-converter system.

V. CONCLUSION

In this paper, the scope of investigation has covered theoretical description of the phenomenon accompanying aggregation of interference signals in both scenarios. It has been shown the effect of suitable IFBW selection into proper EMC assessment in which a measurement should involve highly volatile sinusoidal components interaction such as in the electronic ballast lighting applications. Results obtained have shown that discrepancy of the total aggregated conducted EMI following the current abiding CIPSR-11 standards. Further investigation of statistical analysis of IFBW parameters will be considered in order to determine the optimum mathematical correlation between frequency variation and IFBW selection.

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