Spectral analysis of electric current in compact fluorescent lamps

D. H. Peluffo-Ordóñez, E. J. Revelo-Fuelagan, G. A. Alarcón-Lancheros, O. M. Diaz-Betancourt

***Abstract*— This work presents an analysis of electric current signal in compact fluorescent lamps (CFLs). Electrical signals are measured in two circuits, one that corresponds to the CFL shunt connected with the AC source and another one that incorporates a control system into the CFL. Such control system works as a power factor correction (PFC) and is designed by employing a boost converter and a current controller. Signals are analyzed in terms of frequency-based representations oriented to estimate the power spectral density (PSD). In this study, three approaches are employed: Fourier transform, periodogram and a window-based PSD. The goal of this work is to show that more complex PSD estimation methods can provide useful information for studying the quality energy in electric power systems. Proposed spectral analysis represents an alternative to traditional approaches.**

***Keywords*: Compact fluorescent lamps, Fourier transform, frequency representation, spectral analysis.**

I. Introduction

Becuase of the technological advance, several electronic devices has been incorporated into power systems and electric installations, and most of them harm the waveform of electrical signals. Then quality energy has become an important and urgent issue. Nowadays, the use of devices in incandescent sockets and fluorescent lamps to improve or reduce energy is very common [7]. These devices have low power factor and/or high total harmonic distortion [1]. Nevertheless, they have significant services and therefore are widely recommended. Then, it must be found an equilibrium point or a good tradeoff between their benefit and affectation. Several approaches have proposed to correct the power factor in electric power systems [8]-[11].

In this study, compact fluorescent lamps (CFLs) are analyzed. Electrical signals (current and voltage) are measured and analyzed mainly in the frequency domain. Because of the effects of CFLs, this work has a particular interest in the current signal. To that end electrical signals are measured in two circuits, one that corresponds to the CFL shunt connected with the AC source and another one that incorporates a control system into the CFL. Such control system works as a power factor correction (PFC) and is designed by employing a boost converter and a current controller, similar as is explained in [8]. Signals are analyzed in terms of frequency-based representations oriented to estimate the power spectral density (PSD). In this study, three approaches are employed: Fourier transform, periodogram and a window-based PSD. Time domain is also considered.

The goal of this work is to show that more complex PSD estimation methods can provide useful information for studying the quality energy in electric power systems. Proposed spectral analysis represents an alternative to traditional approaches.

II. Implemented circuits

To assess the harmful effect that can cause the use of CFL in electric installations, circuit shown in Fig. 1 is implemented. An Essential PLE15W127 CFL is used that has as nominal power 15 W and as power factor 0.55. Such effect is measured through the changes of the electrical signals, mainly the current signal. The signal analysis is carried out in both time domain and frequency domain.

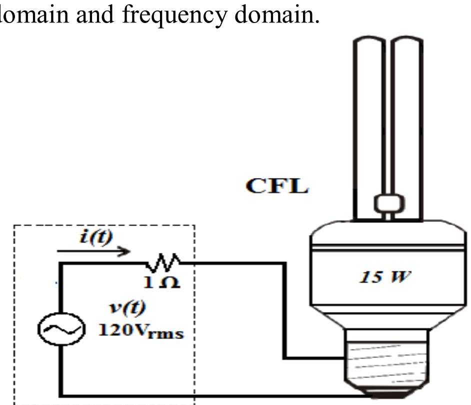

Fig. 1. Implemented circuit for assessing the quality of current signal

In this work, a power factor correction (PFC) is applied as control. This control is implemented internally in the lamp and connected after the rectifier circuit containing the same lamp. The control consists of boost converter (BC) and current controller (CC) that are in charge of raising the tension and adjust the power factor, respectively. A block diagram of the implemented control system is shown in Fig. 2.

The scheme used for the control design employed in this work is similar to that presented in [8]. Detailed design of the control will be presented in another paper written by one of the authors and for this reason it is not explained in this study. This work is only focused on the signal analysis.

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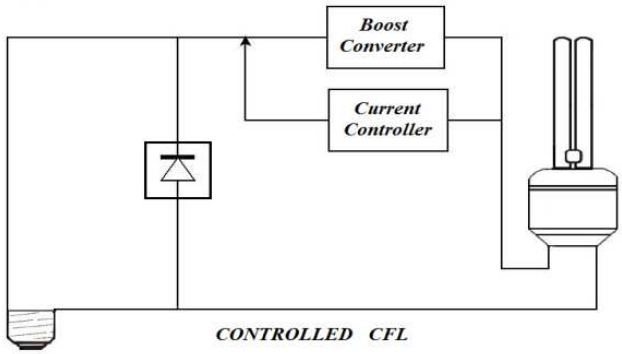

Fig. 2. Power factor correction for CFL

Henceforth, circuit from Fig. 1 will be called circuit without PFC or control and denoted as "*NC*", and circuit adding that shown in Fig. 2 will be named controlled circuit and denoted as "*CC*". Signals were captured by means of a scopometer fluke 192 and recorded with sampling frequency $F_S = 1/T_S = 20$ Khz.

Figures 3 and 4 shows the real signals acquired with the scopometer. Input voltage $v_{NC}(t)$ and current signal $i_{NC}(t)$ associated with the circuit without control are shown in Fig. 3, and the signals measured on controlled circuit, $v_{CC}(t)$ and $i_{CC}(t)$, are shown in Fig. 4.

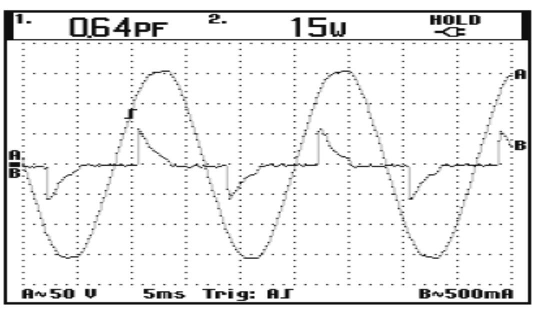

Fig. 3. Real signals without using PFC. Channel A: Input voltage; channel B: Current signal.

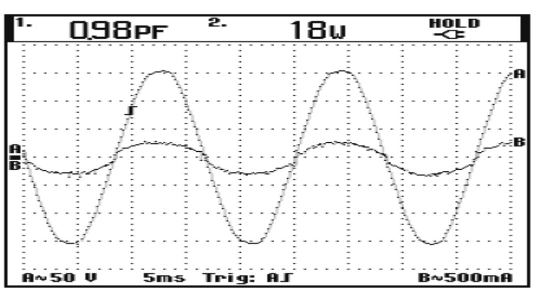

Fig. 4. Real signals using PFC. Channel A: Input voltage; channel B: Current signal.

III. Spectral Analysis

For spectral analysis, besides those previously mentioned signals, the following signals are considered as reference signals:

- $v(t)$ is the ideal input voltage given by $v(t) = \sin(2\pi f_0 t)$, where f_0 is the fundamental frequency set to be 60 Hz.
- $i(t)$ corresponds to the ideal current signal and is: $i(t) = \sin(2\pi f_0 t + \theta)$, where $\theta = \cos^{-1}(P.F.)$ and *P.F.* denotes power factor.

Ideal signals $v(t)$ and $i(t)$ are sampled by using a time vector ranged into the interval (t_A, t_B) so: $t = t_A : T_S : t_B$, where T_S is the sampling time.

A. Fourier transform

Fourier transform (FT) is the most frequently used method to estimate the PSD or extract some spectral information in power system analysis [1]. This can be attributed to its simplicity and non-parametric nature. Typical FT is defined as:

$$S(\omega) = \Im\{S(t)\} = \int_{-\infty}^{\infty} S(t)e^{-j\omega t}dt \qquad (1)$$

where ω denotes the frequency.

Because the acquired signals are discrete, we use the discrete version of FT, given by:

$$S[k] = \Im\{s\} = \sum_{n=0}^{N-1} s[n]e^{-j\frac{2\pi nk}{N}} \qquad (2)$$

where k = 0, ..., N-1, n =0, ..., N-1 and N is the length of signal *s*.

Given that the *S* is a complex variable, it can be expressed in the form:

$$S(\omega) = \alpha(\omega) + j\beta(\omega) \qquad (3)$$

Then, its magnitude can be written as:

$$\mathrm{mod}(S(\omega)) = (\alpha^2(\omega) + \beta^2(\omega))^{1/2} \qquad (4)$$

From this frequency-based representation, a PSD estimation approach can be achieved where the power is given by:

$$P(\omega) = S(\omega)S^*(\omega) \qquad (5)$$

where *S** denotes the conjugate of *S*.

B. Periodogram

This method corresponds to another approach to calculate the PSD of the discrete signal *S* using a periodogram [12]. PSD is calculated in units of power per radians per sample and the corresponding vector of frequencies is computed in radians per sample. Periodogram estimation is as follows:

$$s(e^{j\omega}) = \frac{1}{N}\mathrm{mod}\left(\sum_{l=1}^{N} s[l]e^{-j\omega l}\right)^2 \qquad (6)$$

where $\mathrm{mod}(\cdot)$ represents the magnitude of the complex quantity

C. Window-based estimation

For window-based estimation (WBE), the modified periodogram is considered, which makes use of a window vector so:

$$s(e^{j\omega}) = \frac{\frac{1}{n}\,\mathrm{mod}\left(\sum_{l=1}^{n} w_l s[l]\, e^{-j\omega l}\right)^2}{\frac{1}{n}\sum_{l=1}^{n} |w_l|^2} \tag{7}$$

where vector $w=[w_1,\ldots,w_n]$ contains the coefficients of the window.

III. Experimental Setup

The experiments are focused on to show the effect that causes the CFLs on the electrical signals, particularly, the current signal. For this we consider the voltage and current signals in both time domain and in frequency. Before applying transformations on measures and to be studied, they are normalized using:

$$\tilde{s}(t) = \frac{s(t)-\mu(s(t))}{\max|s(t)|} \tag{8}$$

where $|\cdot|$ denotes the absolute value of its argument and $\mu(\cdot)$ represents a mean operator. By using this normalization, the dc and amplitude effects are avoided. Normalized signal $\tilde{s}(t)$ is centered (i.e. with mean equals to 0) and ranged into [-1, 1], therefore frequency transformations depend only on the morphological nature of signals.

For reference signals, as time interval was set [-0.01, 0.0405] s and as power factor is considered the nominal value mentioned above.
Window vector for WBE employed in this work is a Welch one [12].

In the time domain, signals are morphologically compared through the mean square error given by:

$$MSE(x,y) = \frac{1}{N}\int_{-\infty}^{\omega} (x(t)-y(t))^2 = \frac{1}{N}\sum_{n=0}^{N-1} (x[n]-y[n])^2 \tag{9}$$

In this case we use the discrete form of the equation of MSE.

By other hand, in the frequency domain, we consider the area difference (Fig. 5) and relative spectrum energy (Fig. 6). The area difference is estimated only taking into account the spectral elements corresponding to the 90 % of energy.

Mathematically, difference area is defined as:

$$A_{diff}(x,y) = \sum_{k\in 90\,\%} |x[k]-y[k]| \tag{10}$$

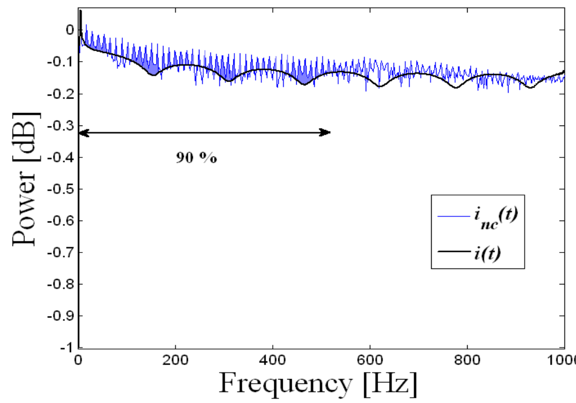

Fig. 5. Area difference between reference signal and real signal spectra using window-based estimation

Energy estimation is done by calculating the value frequency (F_m), which corresponds to the 90 % de accumulated energy, in other words, the spectral elements that more contribute to the power spectrum. An example of such estimation is shown in figure 6, using the magnitude of Fourier transform (eq. (4)) applied over the signal $i_{NC}(t)$ that is the signal of interest.

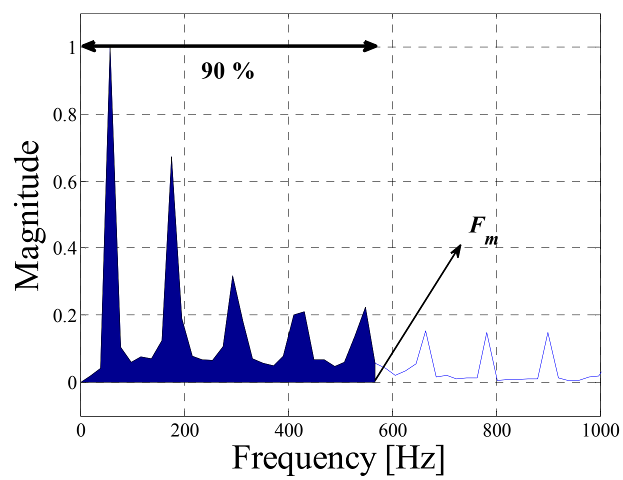

Fig. 6. Spectrum at 90 % of energy using the FT magnitude spectrum

Energy is computed using the standard equation, so:

$$E_x = \sum_{k\in 90\,\%} x[k]^2 \tag{11}$$

For better interpretability, a relative energy is employed that is defined as:

$$E_r = \frac{|E_x - E_{ref}|}{E_{ref}} \tag{11}$$

where E_{ref} is the energy of the reference signal.

PSD estimations given in equations (5), (6) and (7) were normalized by employing $P_{dB}(\omega)=10\log(P(\omega))$ so that their values will be represented in dBs, this transformation is called log-normalization. In addition, all power estimations were normalized in amplitude in that way their magnitude will be ranged into [-1, 1] (similar to eq. (8)).

As another measure, total harmonic distortion (THD) was also considered, calculated as:

$$\partial = \frac{\sum_{i=1}^{\infty} P_i}{P_1} \approx \frac{\sum_{i=1}^{M} P_i}{P_1} \tag{12}$$

where P_i represents the i-th spectral element, P_1 is the element associated with the fundamental frequency and value M was set to be 30 because it corresponds to 90 % of energy regarding the FT spectrum of signal $i_{NC}(t)$.

Taking advantages of the spectral information given by PSD estimations, a relative error is introduced that can be written as:

$$Err=\frac{\left\|P-P_{ref}\right\|}{\left\|P_{ref}\right\|} \tag{13}$$

where $\left\|\cdot\right\|$ denotes Euclidean norm, P is the power estimation to be compared and P_{ref} is the PSD estimation applied over the reference signal.

IV. Results and Discussion

Measurements over the signals in the time domain are shown in table I. MSE is calculated comparing one of the electrical signal with its corresponding reference signal ($v(t)$ or $i(t)$). THD is computed taking into account that experimental fundamental frequency was determined at 58.71 Hz (see Fig. 7) and then P_1 is its associated spectral magnitude according to equation (4).

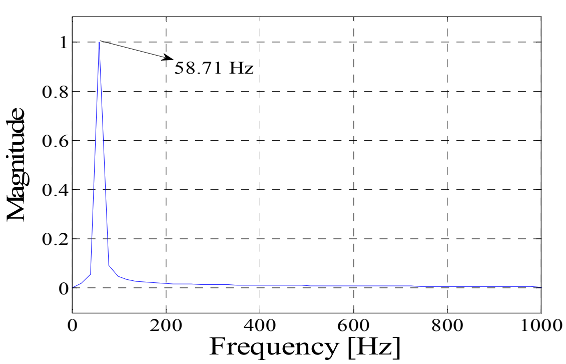

Fig. 7. Spectrum magnitude of reference voltage signal using FT

MSE and THD values probe that the evident morphological difference between $i_{NC}(t)$ and $i(t)$ as well as the evident benefit on waveform given by designed PFC. Table also shows that there exist a depreciable difference between $v_{NC}(t)$ and $v_{NC}(t)$, then it is possible to say that the PFC does not affect the voltage signal.

TABLE I
MSE and THD for Considered Signals in the time domain

Signal	MSE regarding reference signal	∂ (THD)
$i_{NC}(t)$	0.2823	3.2281
$i_{CC}(t)$	0.1026	0.6855
$v_{NC}(t)$	0.1636	0.4470
$v_{NC}(t)$	0.1583	0.4601

The following result tables show the measurements over the signals in the frequency domain. Applied measurements are relative error (table II), difference area (table III) and relative energy (table IV). For Fourier transform three spectrum estimations were considered: magnitude $|S(\omega)|$ (eq. (4)), power P (eq. 5) and normalized power P_{dB} (dBs). In the last row of table II, the value of F_m for each PSD approach is registered. Per. is an abbreviation of periodogram.

TABLE II
Relative Error for PSD estimations

PSD / Signal	Fourier Transform			Per.	WBE
	mod($S(\omega)$)	P	P_{dB}		
$i_{NC}(t)$	0.9462	0.4741	0.1437	0.2225	0.1590
$i_{CC}(t)$	0.1351	0.0105	0.1679	0.2662	0.0516
$v_{NC}(t)$	0.0511	0.0012	0.1974	0.5470	0.0542
$v_{CC}(t)$	0.0494	0.0010	0.1981	0.5503	0.0528
	F_m = 528.37 Hz	F_m = 156.5Hz	F_m = 9.1KHz	F_m = 934Hz	F_m = 9.29KHz

TABLE III
Difference area for PSD estimations

PSD / Signal	Fourier Transform			Per.	WBE
	mod($S(\omega)$)	P	P_{dB}		
$i_{NC}(t)$	6.7454	1.0315	12.026	12.8667	16.5815
$i_{CC}(t)$	1.8440	0.0348	15.129	16.6299	4.4320
$v_{NC}(t)$	0.6766	0.0073	17.303	29.9892	5.8075
$v_{CC}(t)$	0.6675	0.0067	17.587	30.2215	5.6682

TABLE IV
RELATIVE ENERGY FOR PSD ESTIMATIONS

PSD \ Signal	Fourier Transform mod($S(\omega)$)	Fourier Transform P	Fourier Transform P_{dB}	Per.	WBE
$i_{NC}(t)$	0.4412	$3.56*10^{-4}$	0.1342	0.1926	0.3008
$i_{CC}(t)$	0.0104	$3.78*10^{-5}$	0.2629	0.4655	0.0032
$v_{NC}(t)$	0.0045	$1.66*10^{-5}$	0.2497	0.3340	0.0911
$v_{CC}(t)$	0.0039	$1.12*10^{-5}$	0.2514	0.3352	0.0885

As can be seen in tables II, III and IV, voltage is signal is not harmed for the effects of PCF. All measures present an insignificant difference between $v_{NC}(t)$ and $v_{NC}(t)$.

Because of the formulation of each measurement applied on considered PSD estimations, their values must be higher for signal $i_{NC}(t)$. As it can be appreciated, this is true for $\mathrm{mod}(S(\omega))$ and WBE for all measures. Then, we conclude that they are some of the most proper PSD estimation to characterize and quantify the waveform quality of current signal. WBE presented morphological changes in its respective spectrum (see figures 20 and 21 in Appendix A) and the considered measurements represented then a proper characterization of signal.
Estimation P works well for area difference and relative but not for relative energy. That can be attributed to the quadratic nature of P (eq. 5), which reduces the magnitude in comparison with $\mathrm{mod}(S(\omega))$ as can be seen in figures 14 and 15. Then important morphological details are not taken into account.
In addition, P_{dB} and periodogram do not work well for any PSD estimation. So we tested that the log-normalization of power is not always advantageous.

V. CONCLUSIONS

Given the urgent need to address and compensate for the effects of electronic devices used in power systems and electrical installations, signal processing has taken place in this context. In this case, the harmful effect of CFLs on the electrical current signal.

Typical approaches and measurements are based on standard Fourier transform, for instance THD. With this work, we proved that other estimations and measurements in the frequency domain can give more detailed spectral information to precisely quantify the waveform quality. Among them we have WBE and power-based FT characterized morphologically through the energy and difference area, which showed good results in this work.

As a future work, we propose to continue exploiting the knowledge on signal processing in order to give support to design and control power systems through it. For further experiments we will take into account the voltage distortion caused by impedances connected in series or cables to generalize this study.
PSD estimations with more specific measurement are going to be studied for improving the characterization of current signal when using CFLs.

VI. APPENDIX

Appendix A: Additional graphics

Next, some additional graphics obtained from this study are presented. We first present acquired and reference signals normalized employing eq. (8).

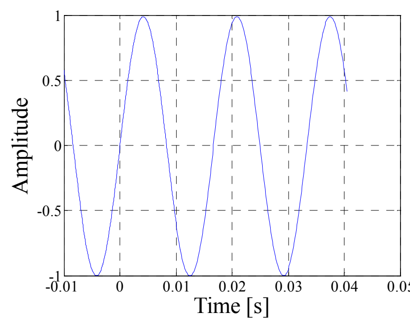

Fig. 8. Ideal (reference) voltage signal

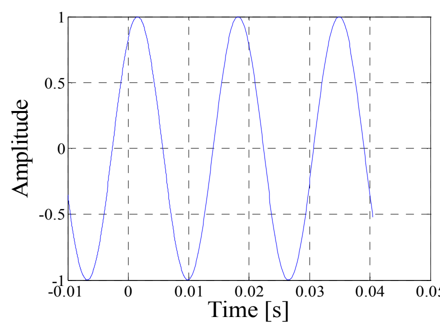

Fig. 9. Ideal (reference) current signal

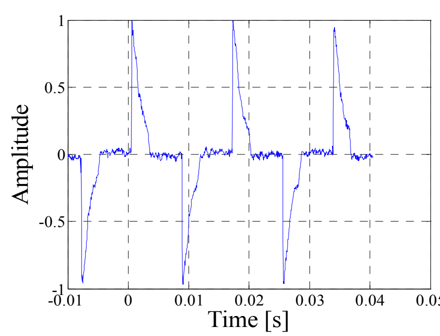

Fig. 10. Current signal without using control

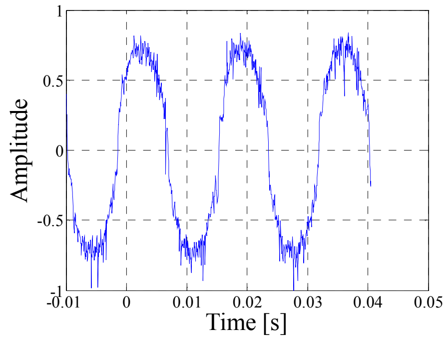

Fig. 11. Current signal with PFC

The following figures correspond to some spectra obtained from the different PSD estimation approaches.

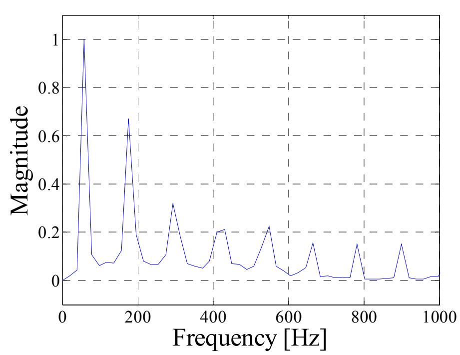

Fig. 12. PSD of non-controlled current using FT spectrum magnitude

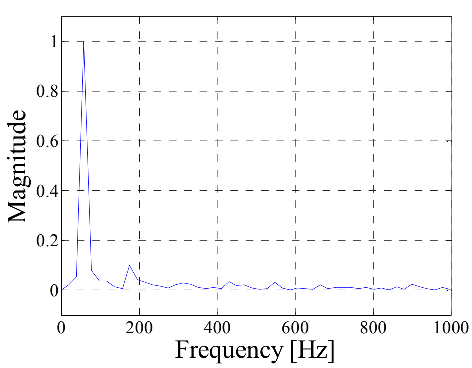

Fig. 13. PSD of controlled current using FT spectrum magnitude

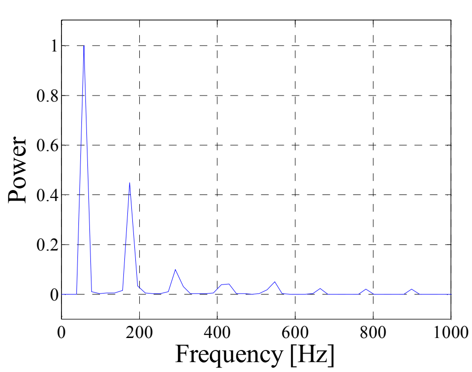

Fig. 14. PSD of non-controlled current using power-based FT

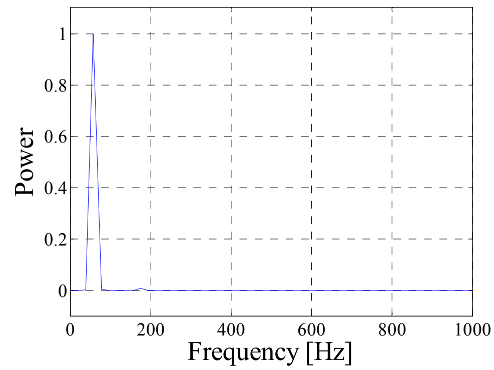

Fig. 15. PSD of controlled current using power-based FT

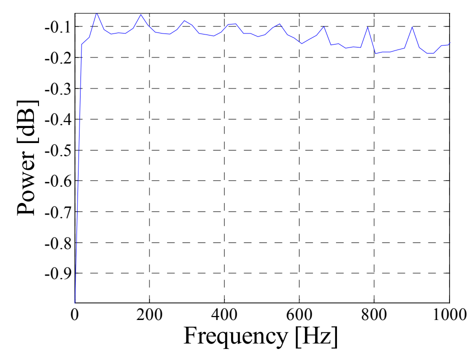

Fig. 16. PSD of non-controlled current using normalized power-based FT

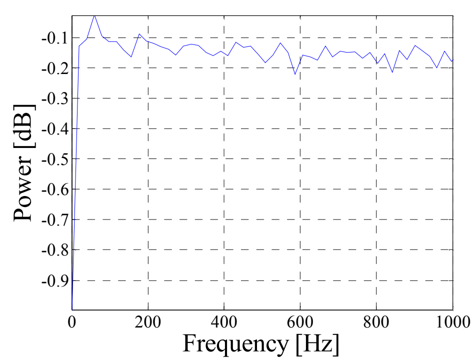

Fig. 17. PSD of controlled current using normalized power-based FT

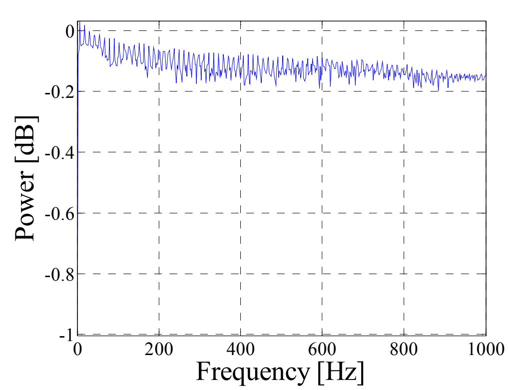

Fig. 18. PSD of non-controlled current using periodogram

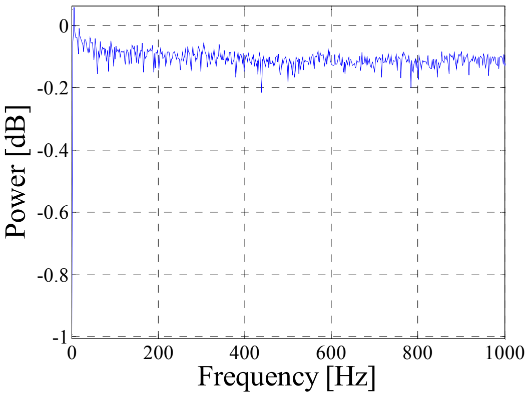

Fig. 19. PSD of controlled current using periodogram

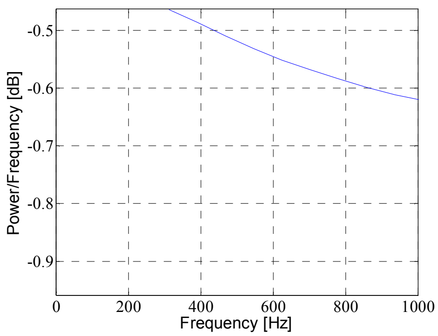

Fig. 20. PSD of uncontrolled current using WBE

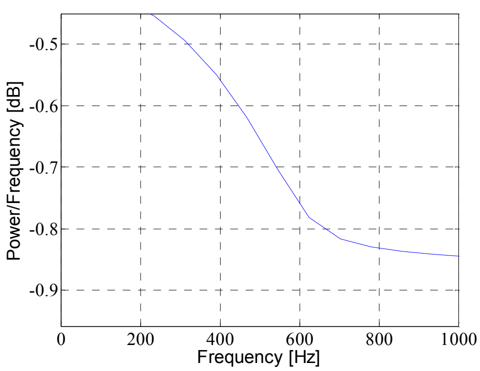

Fig. 21. PSD of controlled current using WBE

VII. Acknowledgment

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