Aspects of Power Quality Improvement in a Driving System Using an Active Filter

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***Abstract*— The paper deals with a series of issues relative to power quality in drive systems and the behavior of a load composed from a uncontrolled rectifier, chopper and a DC motor. A MATLAB-Simulink scheme was designed in order to study the possibility to eliminate the unwanted power-related effects from the system. An equipment having the role of active filter is modeled and studied. The active filter is initialized through the charging of a capacitor. The initial voltage across the capacitor was increased by 30% by using an exponential filter. FFT analysis was also done in order to compare the values of currents flowing through the secondary winding of the uncontrolled rectifier's transformer before and after filtering.**

Keywords— active filtering; power quality computing; modeling and simulation.

I. INTRODUCTION

Non-sinusoidal permanent regimes (symmetric or non-symmetric) have been representing a permanent concern – mainly because of continuously utilization of power electronics and electric machines. They generate the need for measuring and filtering signals used both in industrial and domestic applications. Studies and actual research are heading into finding solutions to improve the quality of electric power [1].

Therefore, new methods have been found to compensate distorted powers from electrical grids.

Power systems belong to a domain which has known a great development related to general activity, transport and power distribution to consumers, where the power voltage levels have to be maintained.

Filters are the most common devices used to improve power quality in the applications mentioned above and represent an effective method for harmonic compensation. The specialty literature is mainly focused on the basic filtering circuits and principles to operate active filters designed to protect supplying sources [1]-[2].

Thus, active filters efficiency needs to be evaluated taking into consideration the harmonic distortions both for voltages and currents, when the load is coupled to the power system. Also the reactive power compensation to the fundamental harmonic has to be considered [3].

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Active filters can provide various functions, such as: harmonics filtering, reactive power control, power factor correction, voltage regulation etc. [3]-[4].

II. THEORETICAL CONSIDERATION

The Fourier decomposition in steady state regime for an electric periodical quantity is given by [5]:

$$y(t) = Y_0 + \sum_{k=1}^{n} \sqrt{2} Y_k \sin(k\omega t + y_k) \quad (1)$$

The total harmonic distortion is determined with:

$$THD = Y_d / Y_l = \left(\sqrt{Y_0^2 + \sum_{k=2}^{n} Y^2 k} \right) / Y_1 \quad (2)$$

where Y_d is the distorting residue and Y_1 is the RMS value of the fundamental harmonic

Based on the decomposition from (1) one could determine quality factors for the recorded waveforms [5]:

- Peak factor:

$$k_v = Y_{\max} / Y = Y_{\max} / \sqrt{\sum_{k=0}^{n} Y_k{}^2} \;; \quad (3)$$

-Shape factor:

$$k_f = y / \frac{2}{T} \int_{t_0}^{t_0 + \frac{T}{2}} y(t) dt \;; \quad (4)$$

- Distorting factor:

$$k_d = Y_d / Y = \sqrt{\sum_{k=2}^{n} Y_k{}^2} / Y_1 = THD \;. \quad (5)$$

The powers were determined with the following relations [6]:

- single phase fundamental active power:

$$P_{11} = U_1 I_1 \cos\varphi_1 \;; \quad (6)$$

- single phase active power:

$$P_1 = U_0 I_0 + \sum_{k=1}^{n} U_k I_k \cos\varphi_k \; ; \qquad (7)$$

- single phase fundamental reactive power:

$$P_{11} = U_1 I_1 \cos\varphi_1 \, . \qquad (8)$$

III. SYSTEM SIMULATION

The analyzed three phase load is composed from an uncontrolled diode rectifier from which a DC motor is fed through a step down chopper (Fig.1) [3].

This load is fed from an AC power supply through the step down transformer of 20 kV/0.4 kV (Medium voltage/Low voltage - MV/LV).

Voltage and currents waveforms from the rectifier transformer's secondary winding have been recorded with a data acquisition system (Fig.2).

The data were afterward transferred to a laptop and processed by original programs implemented in Matlab.

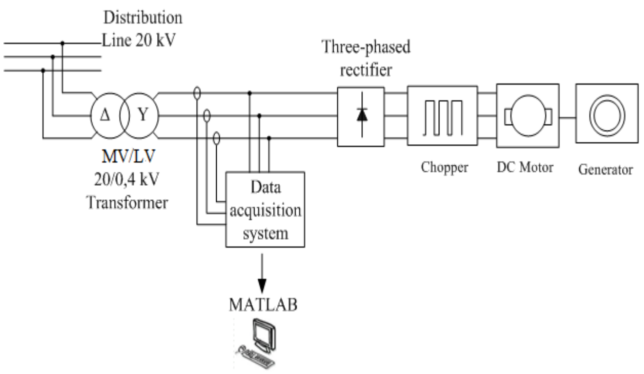

Fig.1. Bloc schema of the MCC and chopper driving system.

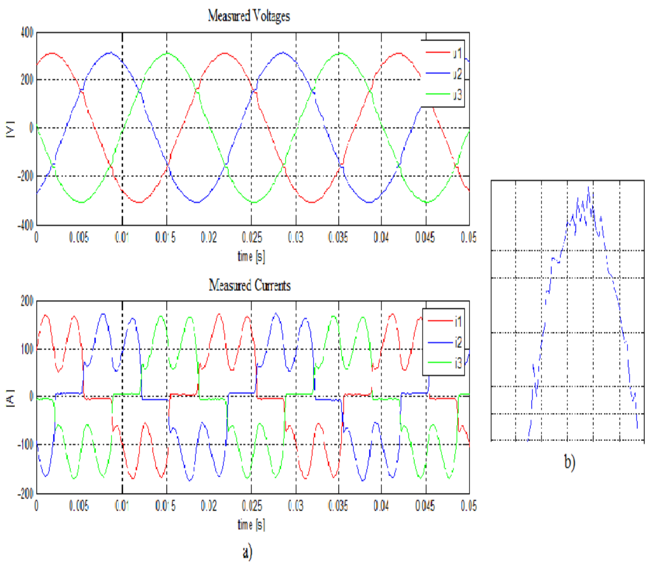

Fig.2. a) Measured voltages and currents acquired from the driving system b) current zoom.

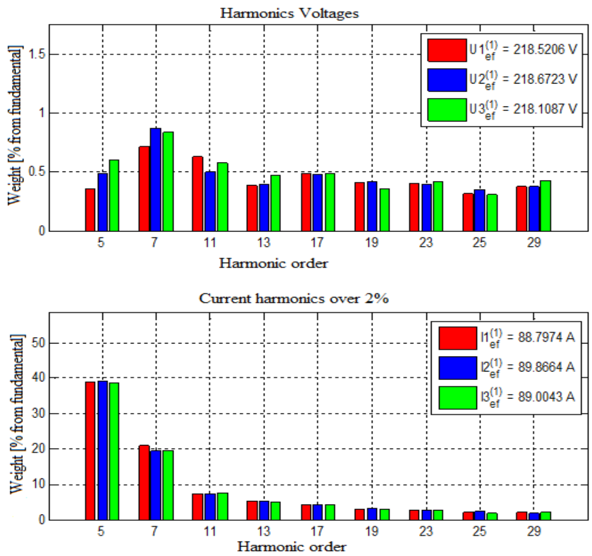

Fig.3. Harmonic spectra of voltages and currents.

TABLE I. COMPUTED POWER QUALITY INDICES (1-ST PART)

	Total RMS values	Distorted residue	Distortion factor THD [%]
U1	218.55 V	3.58 V	1.63
U2	218.7 V	3.77 V	1.72
U3	218.14 V	3.89 V	1.78
I1	97.66 A	40.66 A	41.63
I2	98.65 A	40.69 A	41.25
I3	97.51 A	39.84 A	40.86

TABLE II. COMPUTED POWER QUALITY INDICES (2-ND PARD)

S [kVA]	P [kW]	Q [kVAr]	D [kVad]	PF (inductive)
64.19	58.09	70.79	26.35	0.9

One can notice from the waveforms that the driving system is a nonlinear load generating harmonic currents flowing through the impedance transformer secondary winding. Therefore harmonic voltage drops proportional to the impedance are produced.

The most important power quality indices obtained through numerical processing of the acquired signals with an original MATLAB program are gathered by Tables 1 and 2.

Harmonic spectra of voltages and currents from the transformer secondary winding (weights from the fundamental harmonic) are depicted in Fig.3. For partial compensation a 5% percentage is recommended for the most significant current harmonic orders (5, 7, 11, 13 and 17).

IV. EXPERIMENTAL SETUP

A Simulink model was built based on the driving system parameters in order to test the solutions for distorted regime and reactive power compensation through an active power filter. The bloc scheme has been achieved starting from the solution presented in [10] and is depicted in Fig.4.

The active power filter is composed by a RC low power filter for the switching ripple. The power electronics consist in an IGBT inverter, PWM coils and controller.

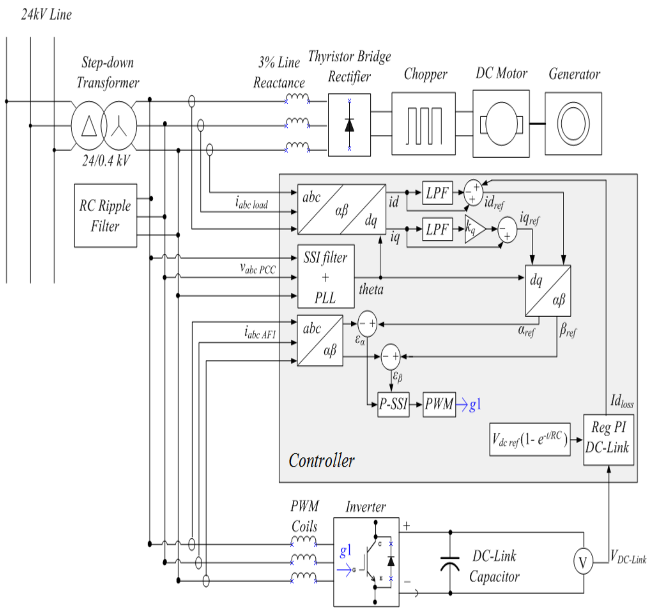

Fig.4. Chopper driving system and active filter bloc scheme.

The APF controller is receiving at input: three phase load currents, APF currents, voltages at the Common Connection Point (CCP), the DC capacitor voltage and the compensation active command signals used for initialization (Fig.4).

V. ACTIVE POWER FILTER DESING

The passive RC switching ripple filter is used to filter high frequency switching currents generated by the APF inverter. When the switching frequency is chosen, cutting frequency RC switching ripple filter must be taken into consideration [8]-[12]:

$$f_{RC\ cut} = 1/(2\pi RC) \tag{9}$$

The cutting frequency must be ten times higher than the fundamental frequency and half from the switching frequency. It also should be lower than the highest harmonic frequency to be compensated [3]. The cutting frequency determines the RC filter since these parameters are interdependent. A switching frequency of 10 kHz and a cutting frequency of 5 kHz were considered.

The active filter is using a synchronized bloc of type Phase Locked Loop (PLL) in order to generate a sinusoidal reference current which is in phase and has the same RMS as the load current [11], [12]. The error current (difference between the source current and the reference current) is generated by the IGBT Bridge through hysteresis based switching.

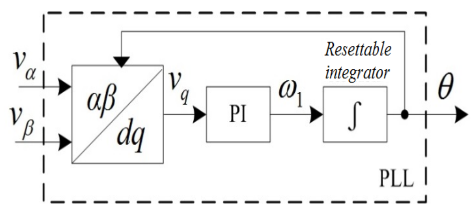

Fig. 5. Synchronous Reference Frame Phase Locked Loop.

The active power filter is intended to inject the error current in CCP in order to adjust the source current such as to get maximum similarity to the generated reference current.

Fig.5. depicts the Synchronous Reference Frame PLL (PLL-SRF). The main feature of PLL-SRF is related to the estimation of the fundamental positive sequence voltage V^{+}_{abc1} phase angle. Therefore the estimated phase angle corresponds to the phase angle v^{+}_{a1}. If the wave V^{+}_{abc} is considered as sinusoidal, the implementation will be done by Park transformation.

Afterwards, αβ are translated to the synchronously reference (d,q). Only the q axis is used, which represents an input for the PI controller (it behaves as an error signal). At the time the phase is detected, the q axis takes the fundamental pulse value ω_1. It is integrated by an integrator reset to the value of 2π in order to obtain the θ angle.

The current controller is implemented by using a fixed PWM switching technique (Fig.6). This is a constant switching technique and therefore the switching ripple currents are defined around the switching frequency integer multiples. As compared with variable switching techniques, switching losses are lower and the switching ripple filtering operation is more efficient. The band width is increased by the use of a current controller proportional sinusoidal signal integrator (P-SSI) with a multiple sinusoidal signal integrator (SSI) in the synchronous reference frame [11], [12].

For the harmonic currents compensation, the current error $\varepsilon_{F,\alpha\beta}$ is converted in synchronous reference frame (d,q) aligned with the voltage vector CCP. Then, the resulting error is applied to the SSI controllers tuned to the resonance frequencies $6\cdot\omega_1, 12\cdot\omega_1, 18\cdot\omega_1$ etc. The outputs of these regulators are summed and afterward converted into the reference frame (αβ) by the counterclockwise rotation transformation in order to obtain the reference voltage $v^{*}_{F,\alpha\beta}$ for inverter. This voltage is then added to the P-ISS controller output and used at the fundamental frequency to obtain the final voltage command $v^{*}_{F,\alpha\beta}$ in the reference frame $\alpha\beta$. [12].

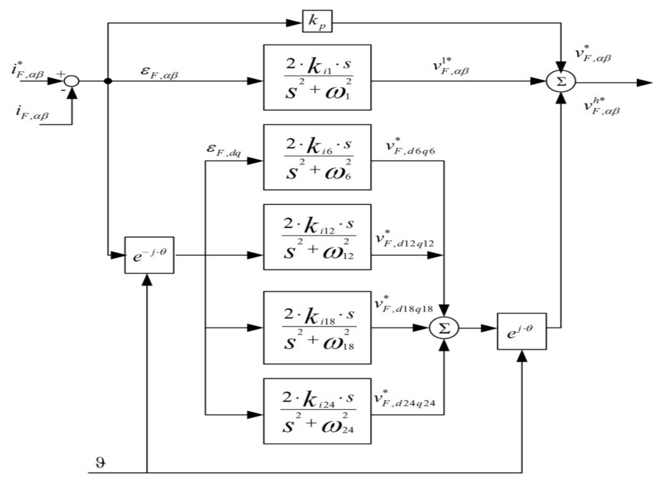

Fig. 6. Active Power Filter Controller.

Since the APF requires injecting a current higher than 400A, the coupling inductance is chosen as a compromise between the ripple voltage and current peaks.

VI. DETECTING THE REFERENCE CURRENT

The harmonic detection methods are implemented in the time domain and frequency domain.

Time-domain methods offer greater speed and fewer calculations compared to methods using frequency domain because no storage space is needed. Instead, only low-pass filters or digital band pass filters are employed.

The problem caused by voltage's distortion and imbalance can be solved by using a fundamental positive sequence detector.

The synchronous reference frame method (*d, q*) [9] is aligned with the voltage vector CCP, and the harmonic content is extracted from the oscillating components i_d and i_q with Eq. (2). Butterworth filters are used with the cutoff frequency equal to 100 Hz.

The cutoff frequency of 100 Hz for the Butterworth filters is selected such as to prevent the interference with the components of the oscillating currents i_d and i_q generated by the load current variations [7].

The lowest order harmonics to be considered for compensation must be mentioned (3-rd harmonic for unbalanced cases and 5-th harmonic respectively).

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_\beta \\ i_\alpha \end{bmatrix} \tag{10}$$

This method receives as the input load currents measured in the stationary αβ reference, the capacitor DC's output voltage and the voltage vector's position at the CCP, computed by means of a filter voltage scheme which includes a SSI algorithm and a phase locked loop (Fig. 7) [12].

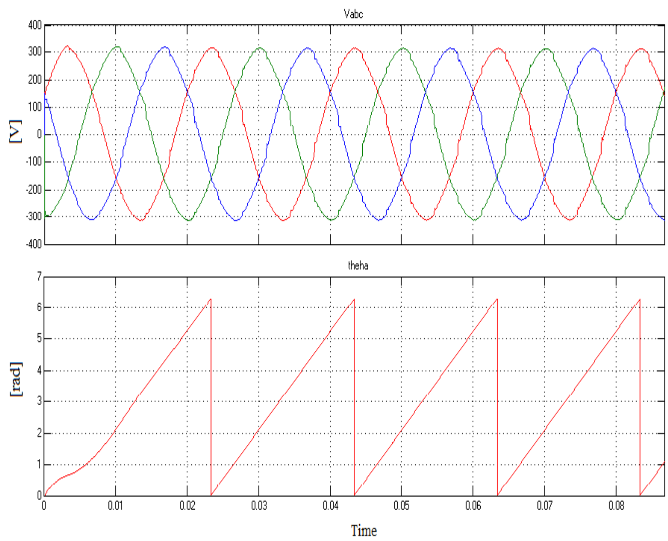

Fig.7. PLL diagram: operation with CCP distorted voltages, V_{abc} and θ controller.

This provides a more accurate position of the voltage vector at the CCP for the APF control scheme considering the distorted and non-symmetrical voltages of CCP. PLL is locked in less than 10 ms.

Because the power factor correction is intended, the reference for the fundamental reactive component i_a is also considered for compensation. When the full reactive compensation is intended, k_q=0.

At this level, selective harmonic compensation can be carried out by rotating the frame d-q with the selected harmonic frequency pulsation.

If the d-q frame harmonic is a DC signal, the rest of frequencies, including the fundamental, are components of DC.

In digital implementations the SSI can be implemented by using discrete models with state variables.

VII. SIMULATION RESULTS

In Fig.8 the total distortion factor of the reference current extracted from the active filter controller is rather small both before and after the effect of active filtering respectively (it falls from 0.30% to 0.12%). The voltage distortion in CCP also plays a role in this scenario.

Fig.9 depicts the current waveform in the transformer's secondary winding before and after the effect of active filtering. Before filtering, the current through the secondary is distorted, whilst after the compensation the signal is sinusoidal. THD is falling to 1.87% as compared to the configuration without filter, when values over 40% were recorded. The filter efficiency is therefore proved.

Fig.10 depicts the harmonic spectrum and THD index of the voltages in CCP, obtained using a FFT based algorithm at a maximum frequency of 12.5 kHz.

VIII. CONCLUSION

To demonstrate APF skills was chosen an control based approach. A simple and robust circuit interface, without load current sensors was used, along with original code segments.

The experimental setup can be used in various operational scenarios: active filtering, power factor correction and balancing of linear or nonlinear loads which cause disturbances and degradation of distribution systems' electric power performances.

The real system simulation was realized in laboratory conditions based on Simulink software. By using data calculated with MATLAB for the electric energy quality indices are identified in this case (when the active filter acts). In this way it was able to observe the efficiency of the active power filter.

The filter reduces harmonic distortion of current through the secondary winding from 30.67% to 1.87%. The voltage at the CCP also falls from 3.73% to 1.58%. Thus one could conclude that the filter was sized correctly.

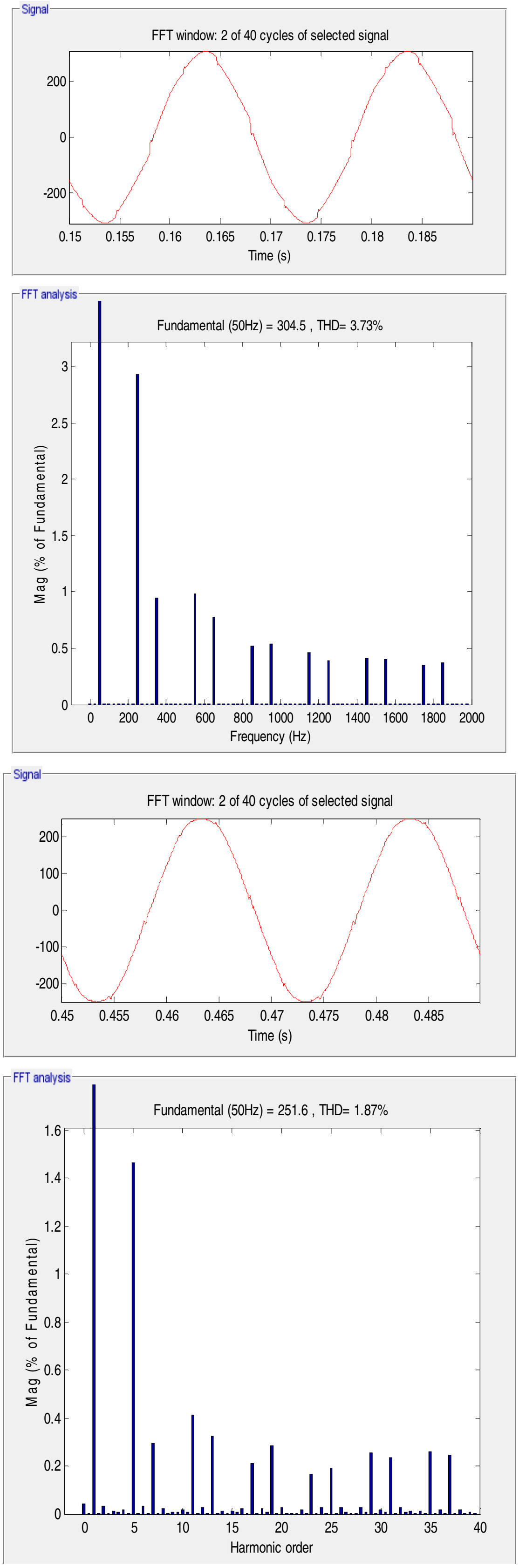

Fig.8. Harmonic spectrum and THD index of the refference current before and after filtering obtained with FFT.

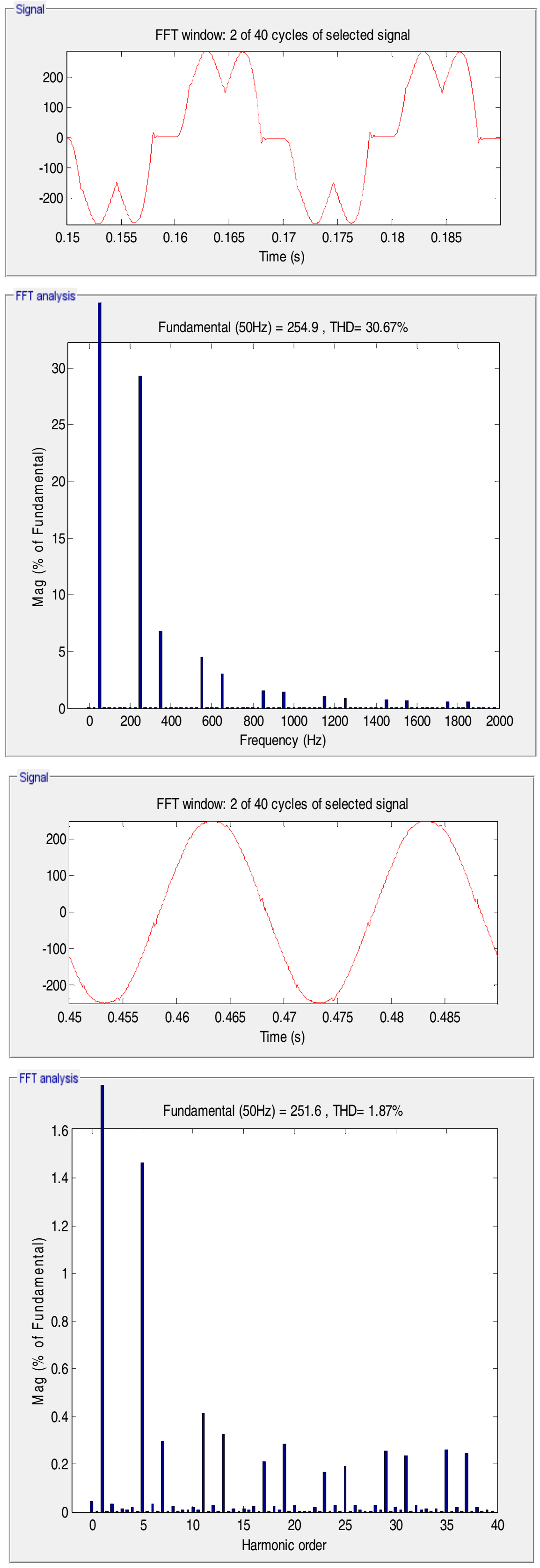

Fig.9. Harmonic spectrum and THD index of the current on the secondary side before and after filtering obtained with FFT.

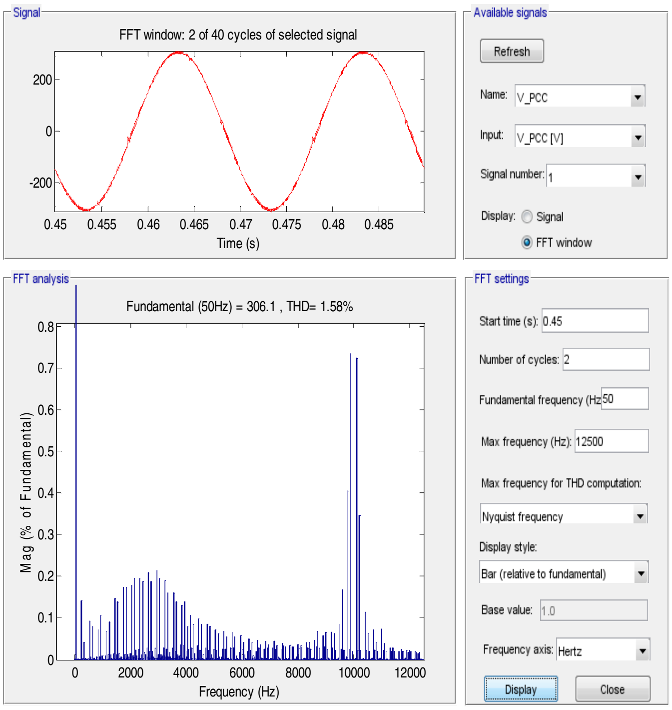

Fig. 10. Harmonic spectrum and THD index of the voltages in PCC, obtained using FFT at a maximum frequency of 12.5 kHz.

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