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Harmonic mitigation for power rectifier using passive filter combination

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Abstract. Power rectifiers are widely used in different industrial applications that deliver DC voltage supply for many types of loads like electrolysis cells, metal electroplating and other DC loads. These rectifiers act as nonlinear loads injecting harmonic currents to the AC mains with lots of troubles and negative impact on the utility grid and the load itself, like increasing losses, measurement error, protection device false tripping and distortion of the voltage at the PCC affecting other loads at the same point. For this reason, many researches focus on this problem and how to mitigate it. In this research, power analysis measurements are taken for 750 KW power rectifier feeding electrolysis cells and define the power quality indices compared to IEC 519 Standard. Passive filter is selected to mitigate the recorded harmonics. Two types of filters are designed. The first is three single tuned passive filter to mitigate the 5th, 7th and the 11th harmonics. The second type is 2nd order high pass filter to mitigate harmonics equal and greater than 13th harmonics. MATLAB simulation is performed to validate the proposed solution. The current total harmonic distortion can be reduced from 29.6 % to 1.5 % and supply voltage total harmonic distortion is also improved from 3.25 % to 0.62% which meet the international standard and improve the power quality of the voltage at point of common coupling.

Keywords: Power Quality Indices, Total harmonic distortion, single tuned passive filter, high pass filter, Point of Common Coupling

1. Introduction

Power electronic equipment has many applications in various industrial fields. Meanwhile, they are normally the main sources of power system harmonic distortion, which negatively affect the system in the following: 1) Increase losses in electric equipment and overheating (like transformers); 2) telephone interference; 3) False tripping of protection relays; and 4) error in the power meters [1]-[6]. Many researches have been published to mitigate the harmonic distortion resulted from nonlinear loads. A passive filter is generally a series-connected, parallel connected or hybrid-connected circuit. The filter LC parameters are properly tuned to make the circuit resonance at a certain frequency to mitigate the harmonic distortion. The passive filter has the advantage of a simple structure, low cost and high reliability.

Many studies have been done on designing a passive filter topology in order to meet the harmonic mitigation requirement set by IEEE 519 standard [7]. The application of a passive filter is wide. First, at the harmonic source in a distribution system, the passive filter is installed to trap the harmonic current from injecting into the transmission system [8]. Second, renewable energy sources, such as wind generator converters and photovoltaic (PV) inverters, are installed with a passive filter, which mitigates the switch-



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frequency harmonic [9]-[12]. Third, the passive filter is also installed at the high-speed trains to mitigate its harmonic emission. Many valuable works have been done in this area [13]-[14]. The remaining sections of this paper are organized as follows. Section 2 presents the measured power quality indices; ac mains current and voltage waveform THD and individual current harmonic. Section 3 discusses the different types of passive filters and the recommended type employed in this paper. Section 4 presents the simulation results and Section 5 concludes the whole paper and introduces future research works.

2. Harmonics Measurements

To properly define the suitable mitigation method, the level and nature of harmonic should be determined. Actual measurement for the system have been recorded using HIOKI 3196 Power analyzer. This measurement is recorded for different load levels from 100% loading to 33% loading. Table 1 presents the measured THD for current and voltage at different loading levels. The measured values in this Table show clear deviation against IEEE 519 Standard for voltage, as the maximum permissible total harmonic distortion for low voltage defined by this standard is 3% [7] while the actual reading is around 4.5%. On the other hand the current total harmonic distortion varies between 14.5% to 24.7% which also doesn't meet the international standard. The measured power factor was very poor with value of 0.6.

Table 1. Measured current and voltage total harmonic distortion using HIOKI power analyzer

Current (KA)	12	10	8	6	4
Loading Level	100%	83%	67%	50%	33%
Voltage total Harmonic Distortion %	4.7	4.5	4.6	4.4	4.7
Current total Harmonic Distortion %	14.5	18.1	21	23.5	24.7
PF	0.6	0.6	0.6	0.6	0.6

Figure 1 and figure 2 show the measured current and voltage waveforms recorded by the power analyzer. Individual harmonic of both current and voltage are indicated in Figure 3. with respect to harmonic order. The distortion of the voltage at the point of common coupling is due to the current distortion and the source inductance; L_s as per the below equation:

$$V_{pcc} = V_s - (L_s \cdot dI_s/dt) \quad (1)$$

where V_{pcc} is the voltage at the point of common coupling, V_s is the supply voltage, L_s is the source inductance and I_s is the source current.

The harmonic current components multiplied by the source impedance at this frequency represent a voltage drop and cause a voltage distortion for the supply voltage affecting other consumer at the point of common coupling.

Table 2 presents break down for the detailed individual harmonic current in percentage from fundamental to the 50th harmonic order, a snap shoot is taken for the harmonics analyzed by the measuring instruments. (All even and triple multiplier harmonics are equal zero)

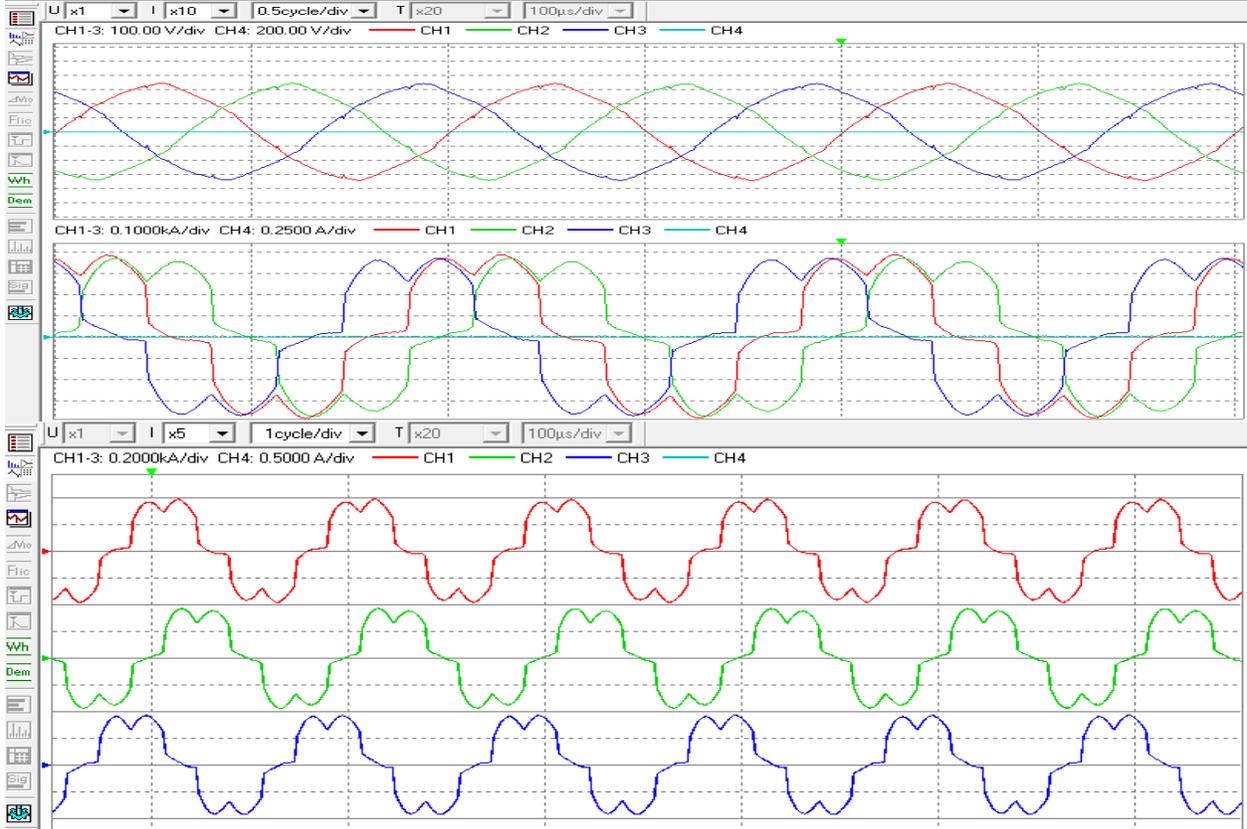


Figure 1. Source current and Voltage measured waveforms

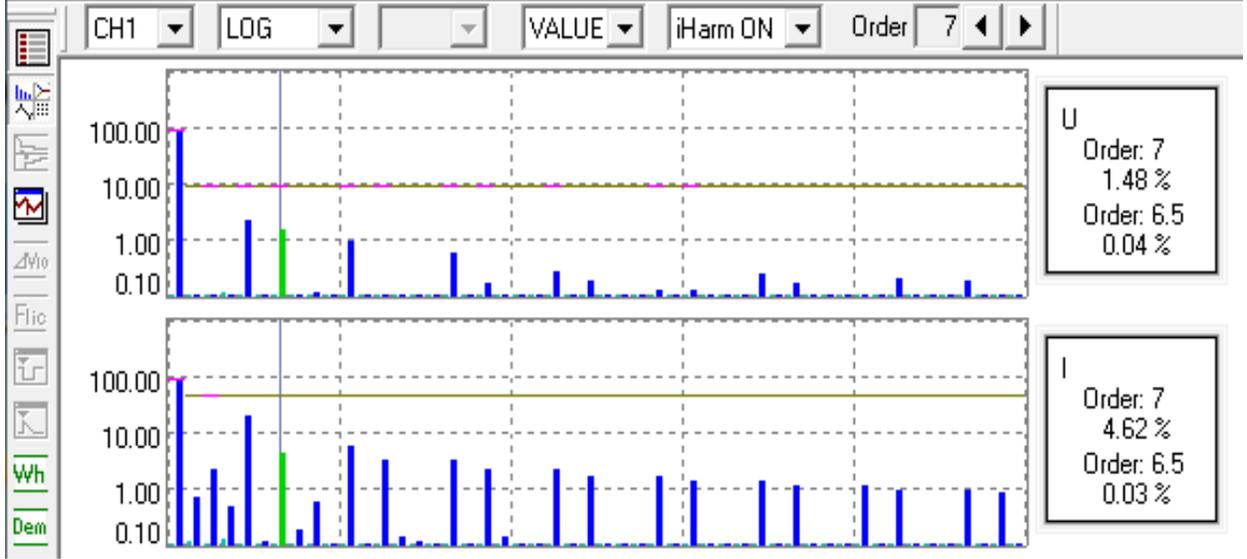


Figure 2. Measured Source voltage and current harmonic spectrum

Table 2. Measured source current Individual Harmonic Distortion

Order	(%)	Order	(%)	Order	(%)
1	100.00	18	0.04	35	1.35
2	0.73	19	2.21	36	0.05
3	2.19	20	0.14	37	1.13
4	0.49	21	0.04	38	0.09
5	21.27	22	0.06	39	0.06
6	0.12	23	2.27	40	0.06
7	4.62	24	0.06	41	1.12
8	0.20	25	1.67	42	0.05
9	0.58	26	0.10	43	0.95
10	0.09	27	0.09	44	0.08
11	6.00	28	0.05	45	0.06
12	0.06	29	1.68	46	0.05
13	3.18	30	0.04	47	0.95
14	0.14	31	1.35	48	0.04
15	0.12	32	0.09	49	0.85
16	0.08	33	0.05	50	0.06
17	3.31	34	0.05	THD	23.69
					0.32 (%)

3. Filter design

Harmonic mitigation by passive filter based on bypassing the harmonic current from the harmonic source by creating a low-impedance path at the specified frequency [15]. Meanwhile, the filter impedance should be high at the fundamental frequency [16].

Therefore, a well-designed harmonic filter should have the following characteristics [15], [16]: 1-Low impedance: at the tuned frequency in order to trap the harmonic current. 2- High power factor at the fundamental frequency. Otherwise it may cause over-voltage or under-voltage problems. 3-Low power loss as filter resistor is usually inserted to damp the undesired parallel resonance. However, a large resistor can lead to a high power loss.

The shunt filter is usually installed at the load bus to trap the typical harmonic current produced by the aggregated load. Common shunt filters are classified into the single-tuned filter and the high-pass filter. The single-tuned filter is aimed at filtering a single order of harmonic while high-pass filters are intended to reduce harmonics above certain frequencies. The high-pass filters have several configuration, such as the first order high pass, second order high pass, and third order high pass, shown in Figure 3 [16]. Sometimes the industry utilize the combination of several different topologies of filters to achieve desired harmonic mitigation.

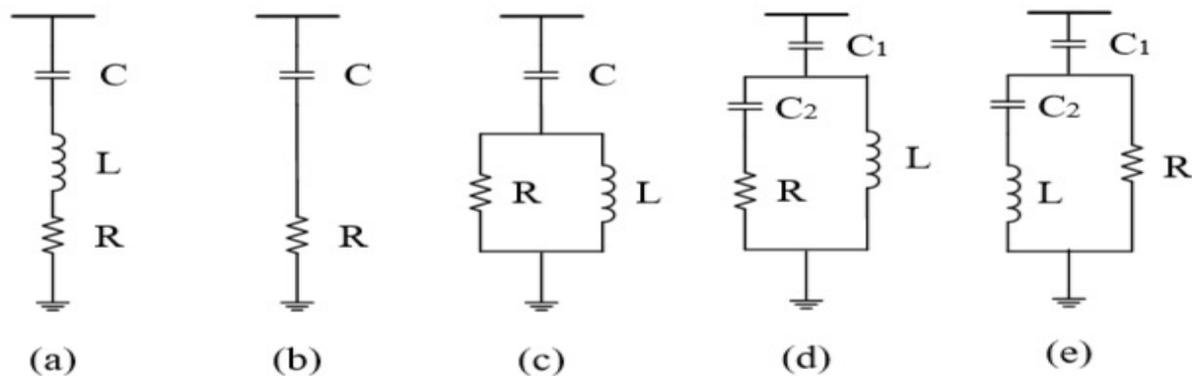


Figure 3. Passive shunt filters configuration: (a) single tuned, (b) first order, (c) second order, (d) third order, (e) C-type

The measured current contains multiple orders of harmonics, such as the 5th, 7th and 11th. Therefore, we have two choices of filter installation: one is to use a single high pass filter such as second-order, C-type. The other is to use several parallel-connected single-tuned filters, namely a combined filter. Based on a detailed analysis, Ref. [16] concluded that it is most effective to use a set of combined single-tuned filters which is tuned to the 5th, 7th and 11th harmonic orders, respectively, in order to mitigate these three orders of harmonics. On the other hand, the second order high pass filter for harmonics from 13th ~49th is employed.

3.1. Single tuned filter design:

Using the below equations (2)-(6);

$$C = \frac{Q_c}{2\pi fV^2} \quad (2)$$

$$X = \frac{1}{2\pi fhC} = \sqrt{\frac{L}{C}} \quad (3)$$

$$L = \frac{X}{2hf} \quad (4)$$

$$Q = \frac{2\pi fL}{R} \quad (5)$$

$$R = \frac{1}{2\pi fC} \quad (6)$$

The Measured reactive power; $Q_c = 23,262$ KVar, for quality factor = 50, the filter elements can be calculated for 5th order filter as follow:

$C_5 = 9.3 \mu\text{F}$, $L_5 = 0.44$ mH and $R_5 = 0.14 \Omega$.

Similarly, for 7th and 11th order filters will be:

$C_7 = 50.6 \mu\text{F}$, $L_7 = 4.1$ mH and $R_7 = 9.1 \Omega$.

$C_{11} = 11.6 \mu\text{F}$, $L_{11} = 7.2$ mH and $R_{11} = 0.5 \Omega$

3.2. Second order high pass filter:

The below equations will be applied,

$$Z(W) = \left(\frac{1}{R} + \frac{1}{jWL}\right)^{-1} + \frac{1}{jWC_1} \quad (7)$$

$$Q = \frac{R}{\sqrt{\frac{L}{C}}} = \frac{R}{X_{LN}} = \frac{R}{X_{CN}} \quad (8)$$

Calculated 13th order filter parameter will be as follow:

$C_{13} = 5.2 \mu\text{F}$, $L_{13} = 11.4$ mH and $R_{13} = 46.6 \Omega$.

4. Simulation results

Simulation is performed using MATLAB 7.7 software. The below figures indicate the simulation results. Figure 4 represents the model used for simulation choosing three phase bridge rectifier to simulate the nonlinear load under study. Figure 5 shows the filter impedance characteristics and the effect of the tuning

frequencies to minimize the filter impedance at 5th, 7th, 11th orders (corner frequencies) using single tuned filters and 13th order using second order high pass filter.

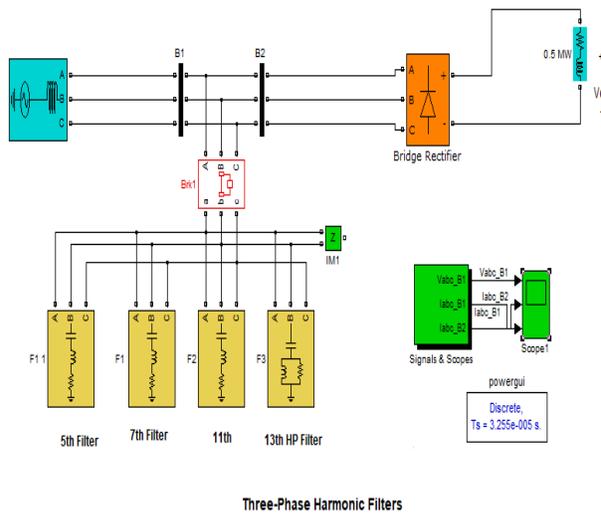


Figure 4. MATLAB Model

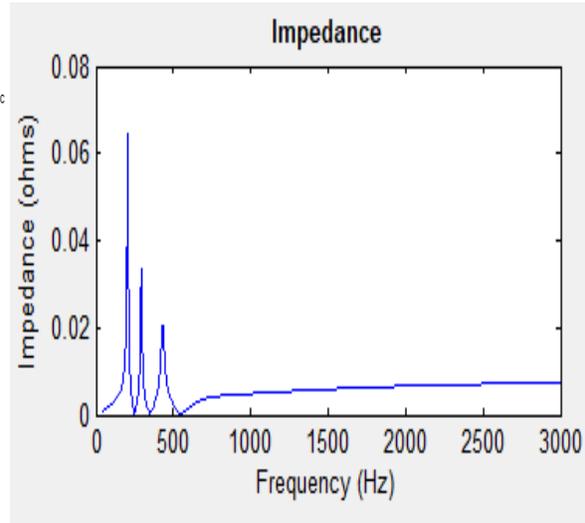


Figure 5. Impedance characteristics of passive filter

Figure 6 presents the simulated source current and voltage, where the current at B2 Bus is the drawn current from the nonlinear load without the filter, while the current waveform at Bus B1 is the current drawn from the supply considering the filter deliver the harmonics to the nonlinear loads. This figure shows the nearly sine wave source current waveform reflecting the improvement of the filter done by the filter.

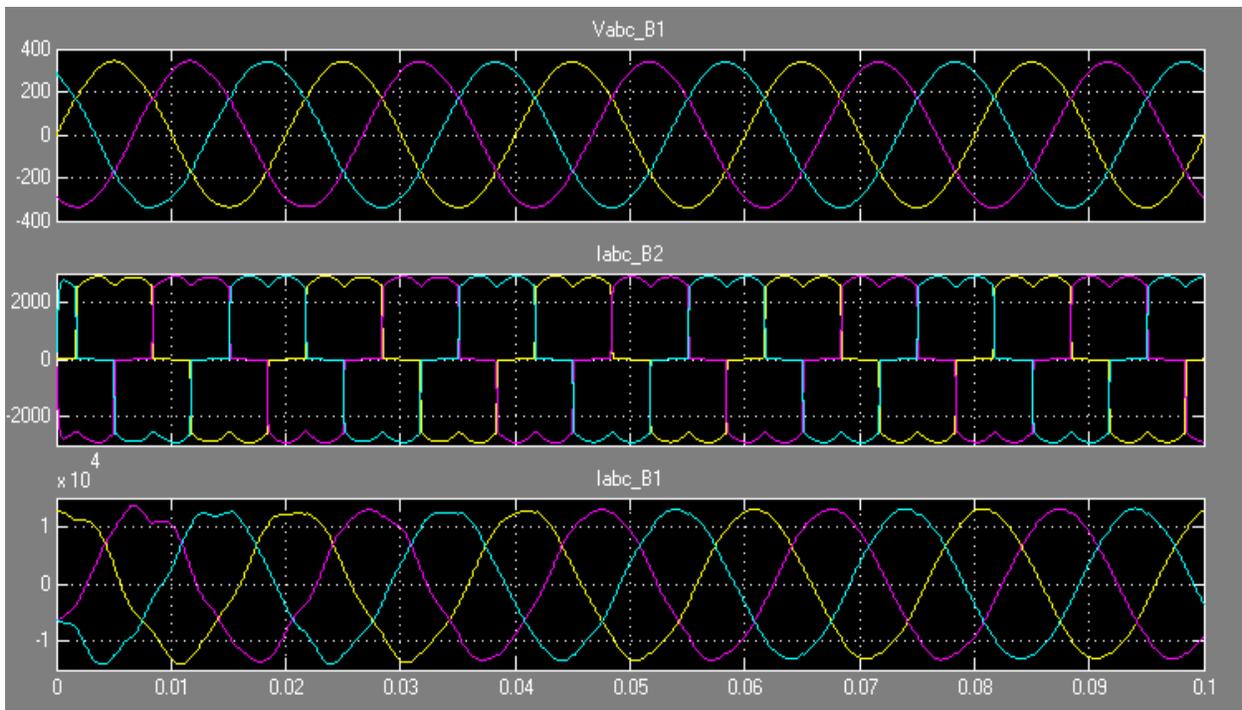


Figure 6. Simulated Supply voltage and current waveforms at B1 and B2 (before and after the filter)

Figure 7 shows the simulated fast Fourier transform; FFT for the source current; I_s and voltage at point of common coupling; V_{pcc} . The simulated Current total harmonic distortion; THD_i is 29.6% and the voltage total harmonic distortion THD_v is 3,25%.

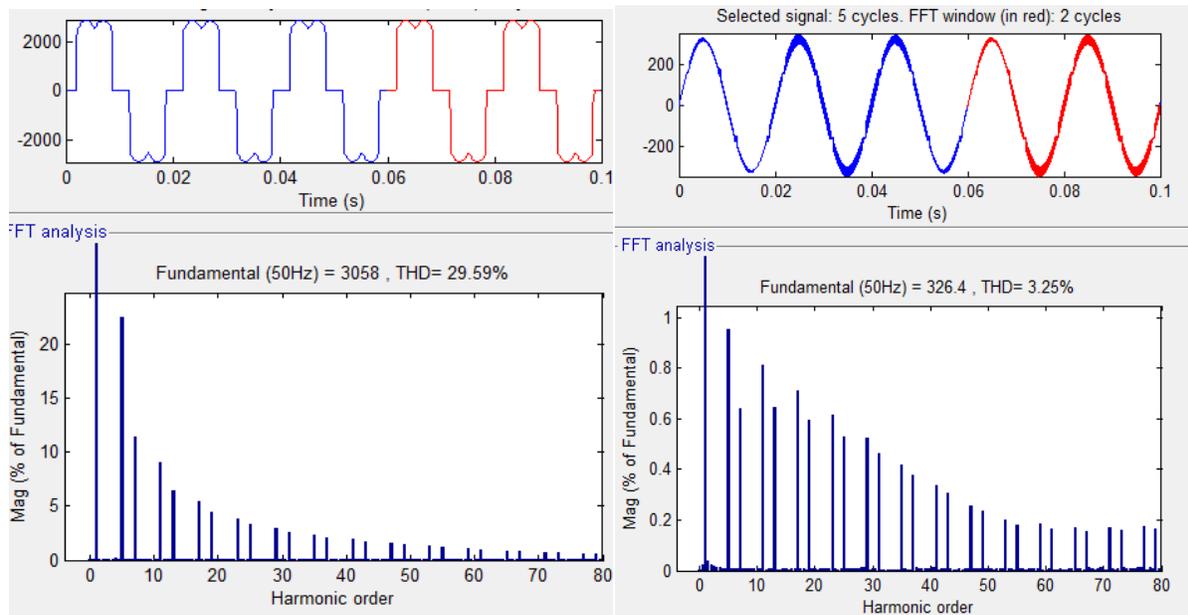


Figure 7. Simulated Supply current and voltage harmonic spectrum before filtering

Figure 8 indicates the same simulated source current and voltage after filtering, improving the current total harmonic distortion from 29.6% to 1.5% and accordingly the voltage at point of common coupling improved from 3.25% to 0.62%

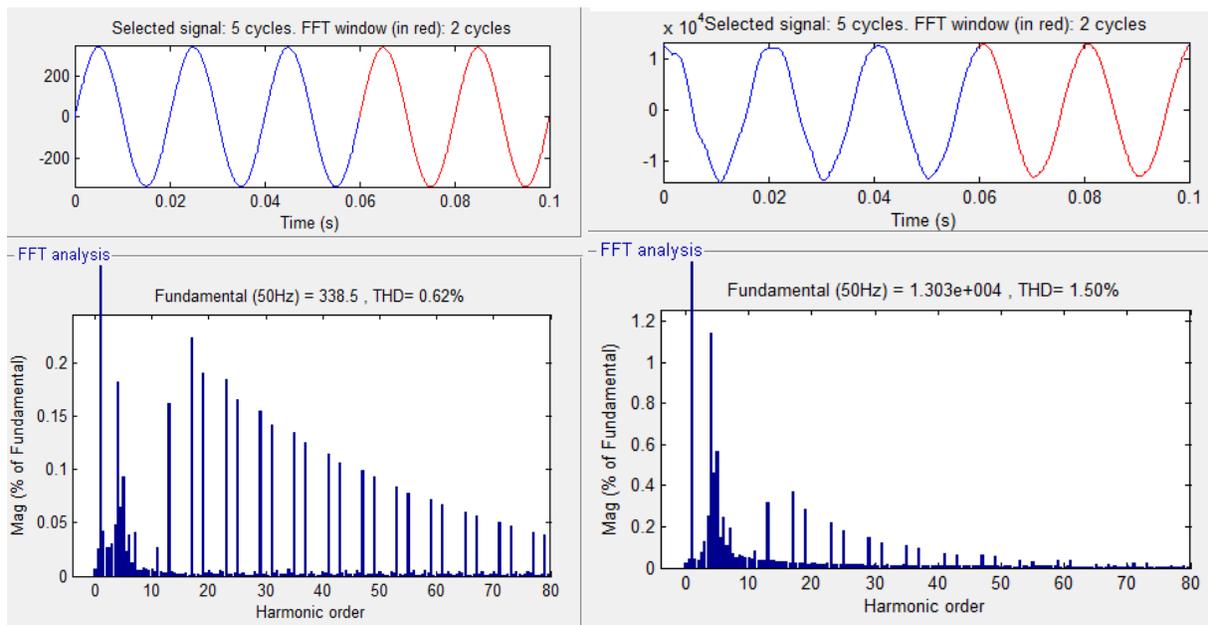


Figure 8. Simulated Supply current and voltage harmonic spectrum after filtering

5. Conclusion

In this paper, Power quality indices are analyzed for an industrial power rectifier as a nonlinear load. Harmonic distortion of source current and voltage are identified for both total and individual harmonic distortion. The measured values exceed the limits of international standard; IEEE 519 for both current and voltage. Passive filter is proposed due to its simplicity, low cost and high reliability. System parameters and measured harmonics are used to design the combination of three single tuned filter and one second order high pass filter to mitigate the 5th, 7th, 11th, and 13th frequencies respectively. The proposed filters are simulated to validate the passive filter design which improve the source current and voltage to become within the accepted level to meet the pre-defined international standard.

Employing active filter for this system instead of passive filter will provide another way of harmonic mitigation giving extra advantages that can be studied in the future work.

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