Inverter Losses, Filter design, THD and FFT analysis for Three Phase Full Bridge IGBT based inverter using MATLAB Simulink

Dieudonné Musongya Bisimwa [1]

Lecturer Assistant, Department of Electrical and Computer Engineering,

Université Libre des Pays des Grands Lacs, Goma, DRC[1]

Abstract: Nowadays, the insulated gate bipolar transistor have been more useful in many applications as in HVDC systems, in FACTS systems and in many devices of power electronics. Comparing to this device to power MOSFET and bipolar transistors, it has the advantages to operate at much higher current density and higher blocking capability. This paper presented inverter losses calculation, a LC filter design for Three Phase Full Bridge IGBT based inverter. The filter is used while simulating in Matlab simulink a Three Phase Full Bridge IGBT based inverter to evaluate the Total Harmonic Distortion using the Fast Fourier Transform analysis and inverter loss calculation. Before filtering the THD is 48.62% and after filtering the THD is equal to 0.70%. The inverter LC filter parameters designed are the cutoff frequency of 400 Hz, the inductor of 3.105 *mH* and the capacitor of 3.22 10^{-5} *F*. The efficiency of the filter is very high as it reduces the total harmonic distortion of the inverter to less than 5%.

Keywords: IGBT inverter, THD, FFT analysis, LC Filter, IGBT losses.

I. INTRODUCTION

The insulated gate bipolar transistor (IGBT) is a new switching device developed as a monolithic integration of a MOSFET and a wide base bipolar transistor. The devices have the advantages of operating at much higher current density and higher blocking capability than power MOSFET and bipolar transistors, and are now widely used in the power electronic industry [1, 2]. For reducing design costs and increasing electronic power circuit' reliability, the modeling of power semiconductor devices becomes indispensable. Over the past 10-15 years, the power electronics community has shown significant interest in THD analysis. Most projects end up with numerical THD evaluation by built-in simulation tools based on FFT [3, 4]. In this work we are focused on Frequency domain analytical approach that involves double Fourier series and inverter loss calculation.

II. MODEL AND STRUCTURE

The system considered is this paper is consisting of a Three Phase Full Bridge IGBT based inverter as shown in Fig. 1. Before the load, we insert a LC filter which helps to reduce harmonic distortions produced by the inverter.
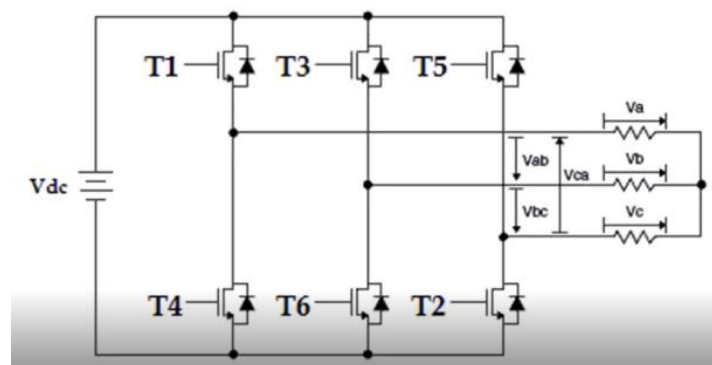

Fig.1. Three Phase Full Bridge IGBT Based Inverter

The Fig. 2 below presents the system designed in matlab simulink. It is formed by a *DC* voltage source of a amplitude of $230\sqrt{2}$; an universal bridge of three phase IGBT inverter, Series *RC* snubber circuits are connected in parallel with each switch device with a Snubber resistance R_s *(Ohms)* of 100000 and a Snubber capacitance *Cs (F)* of infinity.

Generate pulses for PWM-controlled 2-Level converter, using carrier-based two-level PWM method with a switching frequency of *27*50*3*. There are also three phase resistive load of Nominal phase-to-phase voltage *Vn (Vrms)* of $230\sqrt{2}$, Nominal frequency f_n *(Hz)* of 50 and Active power *P(W)* of 1000. Powergui is the block parameters that helped us to choice the simulation type of the solver and the FFT analysis is performed by it.
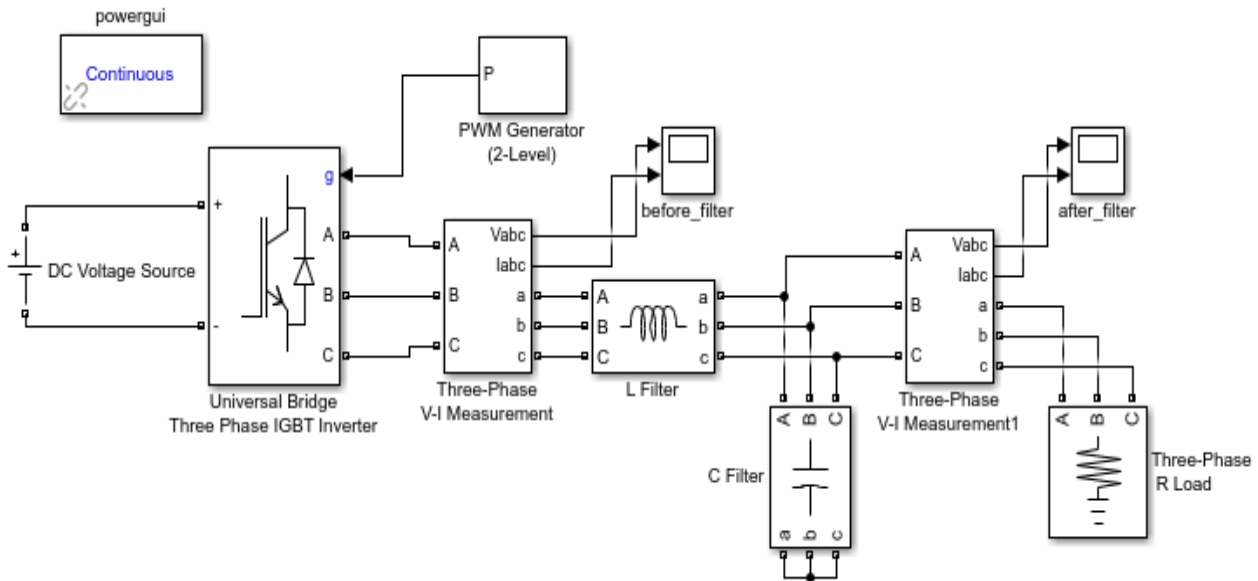

Fig. 2. System Considered Designed in Matlab Simulink

III. INVERTER IGBT TOTAL LOSS AND THD CALCULATIONS

A. Inverter IGBT Total loss

The inverter is composed mainly by the IGBT, and its antiparallel diode. Both work in the on-off state and periodically experienced a variety of dynamic and static process. Each process will produce the portion of the loss, summing these losses, that is, the total loss of the switching device. The total loss is composed mainly by conduction losses and switching losses, so this paper focused on the conduction losses and switching losses [5].

When conducting voltage $V_{CE} < 1.1$ *V*, the IGBT output characteristic curves can be described by quadratic function at different junction temperatures in Fig. 3. When conducting voltage $V_F < 1.2$ *V*, the diode output characteristic curves can be described by quadratic function in Fig. 4. In references [5], nonlinear equilibrium equations are linearized. The relationship between threshold voltage and resistance voltage are approximated by a linear model, shown in Equation (1).

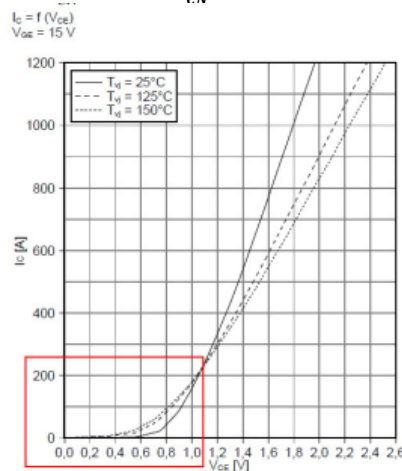$$V_{CE} = \frac{V_{CEN} - V_{CEO}}{I_{CN}} i_C + V_{CEO} \tag{1}$$

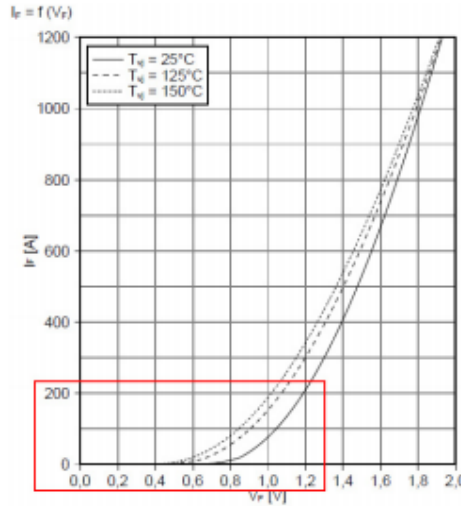Fig. 3. IGBT Output Characteristic Curves [6].

Fig. 4. Diode Output Characteristic Curves [6]

Therefore, IGBT conduction loss can be expressed as [6]:

$$P_{con\_IGBT} = \frac{1}{T_{on}} \int_0^{Ton} I_C(t) V_{CE}(t) D_Q(t)\, dt \qquad (2)$$

Wherein, P_{con_IGBT} represented IGBT conduction loss; $D_Q(t)$ represented duty cycle of IGBT; $I_c(t)$ represented drain current; $V_{CE}(t)$ represented conducting voltage; T_{on} represented modulation wave cycle.

Therefore, Diode conduction loss can be expressed as [6]:

$$P_{con\_D} = \frac{1}{T_{on}} \int_0^{Ton} I_F(t) V_F(t) D_D(t)\, dt \qquad (3)$$

Wherein, P_{con_D} represented diode conduction loss; $D_D(t)$ represented duty cycle of diode $I_F(t)$ represented drain current; $V_F(t)$ represented conducting voltage; T_{on} represented modulation wave cycle.

Therefore, switching losses can be expressed as [6]:

$$P_{sw\_IGBT} = P_{on\_IGBT} + P_{off\_IGBT} \qquad (4)$$
$$P_{on\_IGBT} = E_{on\_IGBT}/t_{on} \qquad (5)$$
$$P_{off\_IGBT} = E_{off\_IGBT}/t_{off} \qquad (6)$$

Wherein, E_{on_IGBT} represented IGBT turn-on energy consumption; E_{off_IGBT} represented IGBT turn-off energy consumption.

Therefore, the inverter total losses were derived in Equation (7) by simultaneous equations which were Equation (2), Equation (3) and Equation (4).

$$P_T = 6 \times (P_{con} + P_{sw}) = 6 \times \left(P_{con_{IGBT}} + P_{con\_D} + P_{sw\_IGBT} \right) \qquad (7)$$

After using different values on the datasheet of *FGA25N120ANTD 1200 V, 25 A NPT Trench IGBT;* following results were found in Table 1

TABLE I LOSS CALCULATION RESULTS

Temperatures values (°C)	Parameter names	Values (W)
25	P_{con_IGBT}	40.072
25	P_{con_Diode}	4.565
25	P_{sw_IGBT}	129.901
25	**P_T**	**174.538**

It can be seen that the junction temperature of IGBT and the loss had the mutual influence, so during the loss calculation we obtain the associated losses according to the ambient temperature.

B. THD Calculations

The total harmonic distortion is a measurement of the harmonic distortion present in a signal and defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

Therefore, Total Harmonics Distortion can be expressed as

$$THD = 100 \times \sqrt{\frac{V^2 - V_1^2}{V_1^2}} \tag{8}$$

Wherein, V is the rms value of the out waveform, in our case it is $230\sqrt{2}$ *Volts* and V_1 is the rms value of the fundamental. V_1 can be found use the Equation (9).

$$V_n = \sum_{n=1,3,5}^{\infty} \frac{4V_{in}}{n\pi} \sin(n\omega t) \tag{9}$$

As only it is the amplitude which is need,

$$V_1 = \frac{4V_{in}}{\pi} \tag{10}$$

Wherein, the rms value of V_{in} is 230 *Volts*.

After calculations, *THD = 48.34%*. This show that the inverter needs a filter to come up with those harmonics because the IEEE 519 recommends that equipment have no more that 5% total harmonic voltage distortion with the largest single harmonic being no more that 3% of the fundamental voltage[7,8].

IV. INVERTER LC FILTER DESIGN

The Filter designed in this work is a LC filter and its parameters are calculated like this:
The cutoff frequency (*fc*) is calculated using the Equation (11).

$$fc < \left(\frac{1}{10}\right) \times fsw \tag{11}$$

The switching frequency here considers is
$$fsw = 27 \times 50 \times 3$$

Then, $fc < \left(\frac{1}{10}\right) \times 27 \times 50 \times 3$
Hence, $fc < 405 \, Hz$

The Inductor value is calculated with the expression of Equation (12).

$$L < \frac{(0.03 \times U_{inv})}{2\pi f I_{Lmax}} \tag{12}$$

In which: - $U_{inv} = 230\sqrt{2}$
         - $f = 50 \, Hz$
         - $I_{Lmax} = 10A$

Hence, $L \leq 3.105 \, mH$

Capacitor value is found considering Equation (13).

$$C = \frac{1}{(2\pi f_c)^2 \times L} \tag{13}$$

In which: - $U_{inv} = 230\sqrt{2}$ *Volts*
         - $f_c = 400 \, Hz$
         - $L = 3.105 \, mH$

Hence, $C = 3.22 \times 10^{-5} \, F$

V. SIMULATION AND RESULTS

In order to validate the presented considerations, computations in Sections 2 and 3 are implemented in the circuit shown in Fig.2. And here we are presenting different results of simulation done in matlab simulink.

A. Before Filtering

We placed a scope just after the Three Phase inverter to evaluate the THD generated by the inverter before the filter. The Fig.5 shows the three phase waves of voltages (up) and currents (down).
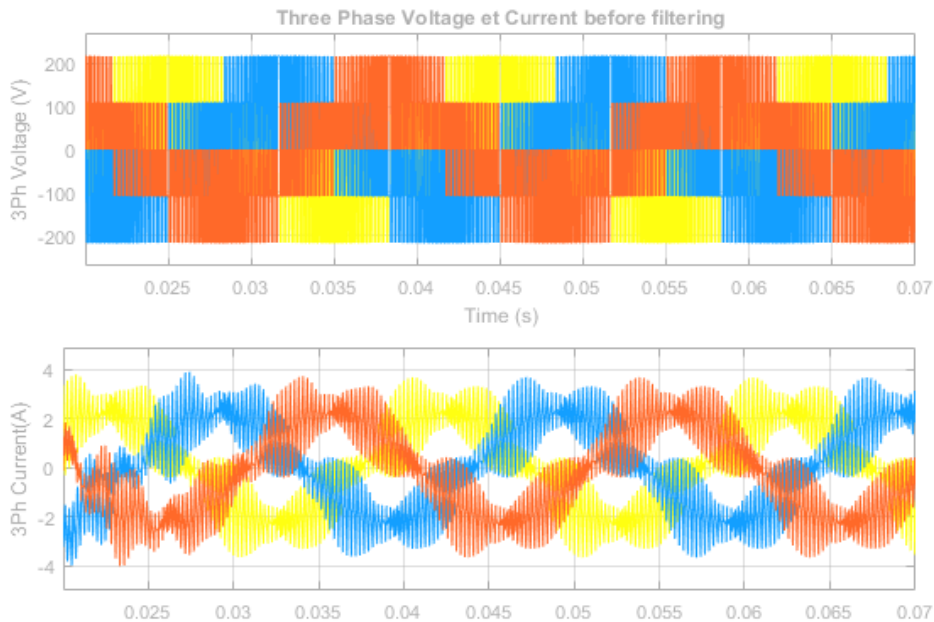

Fig. 5. Three Phase Waves of Voltages and Currents Before Filtering

As you can see Fig. 3, the inverter produces waveform with many harmonics and many devices don't work well with a source full of harmonics.

To analyze the Total Harmonic Distortion we used simulation tools based on Fast Fourier Transformation. We consider just one signal among the three phrase of the voltage and we take only 5 of 50 cycles of selected signal as shown on Fig. 6.
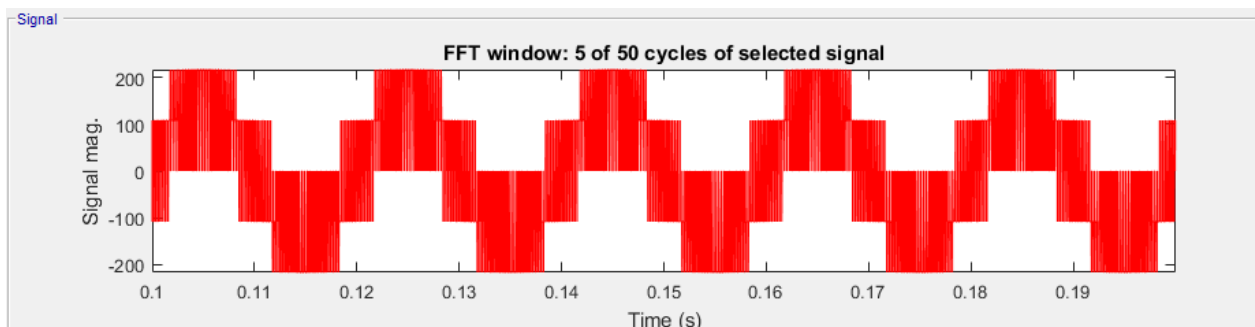

Fig. 6. 5 of 50 Cycles of Voltage Selected Signal Before Filtering

The FFT settings are as followed: the start time of 0.1 seconds, number of cycles of 5, fundamental frequency of 50 Hz, max frequency of 1000 Hz, max frequency for THD computation is Nyquist frequency. The result is that THD= 48.62% as shown on Fig. 7.
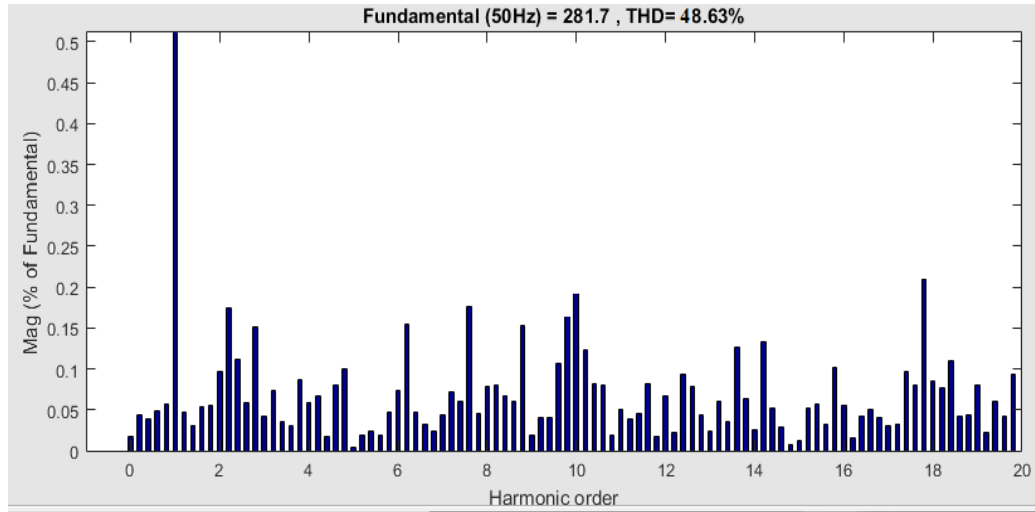
Fig. 7. THD Analysis Before Filtering

This confirms calculations in section III and 48.62% of harmonics are too much, more beyond norms, that is why LC filter must be designed.

B. After Filtering

We put another scope just after the LC filters to evaluate the diminution of THD generated by the inverter after filtering. The Fig. 8 shows the three phase waves of voltages (up) and currents (down).
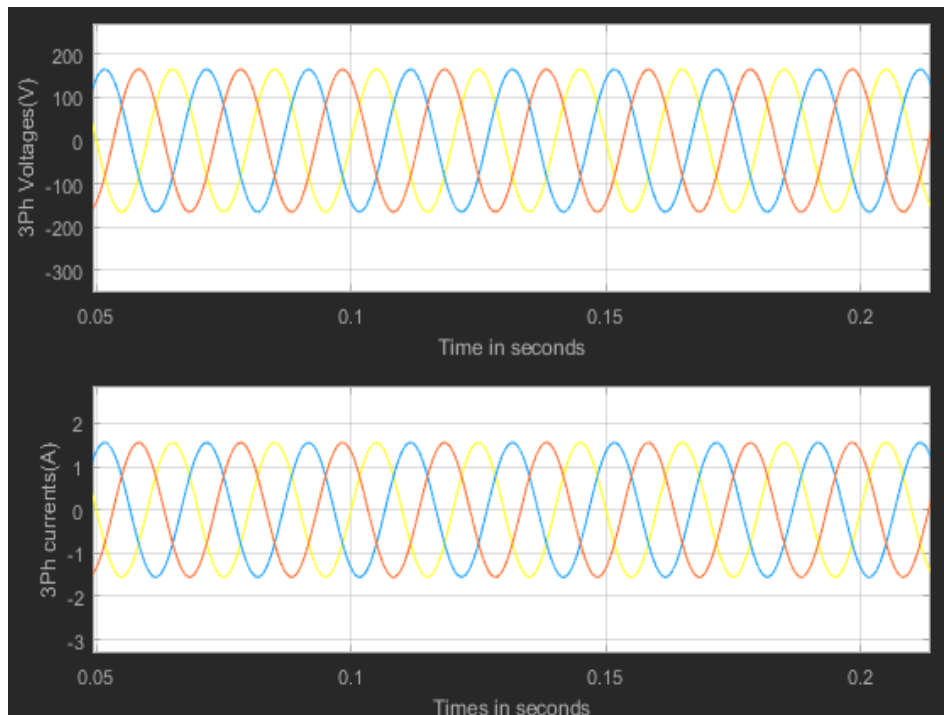

Fig. 8. Three Phase Waves of Voltages (up) and Currents (down) After Filtering

As we can realize on Fig.6, the waveforms have been smoothed by the filter. Now, to analyze the Total Harmonic Distortion by using the same simulation tools based on Fast Fourier Transformation. We consider again just one signal among the three phrase of the voltage and we take only 5 of 50 cycles of selected signal as shown on Fig. 9.
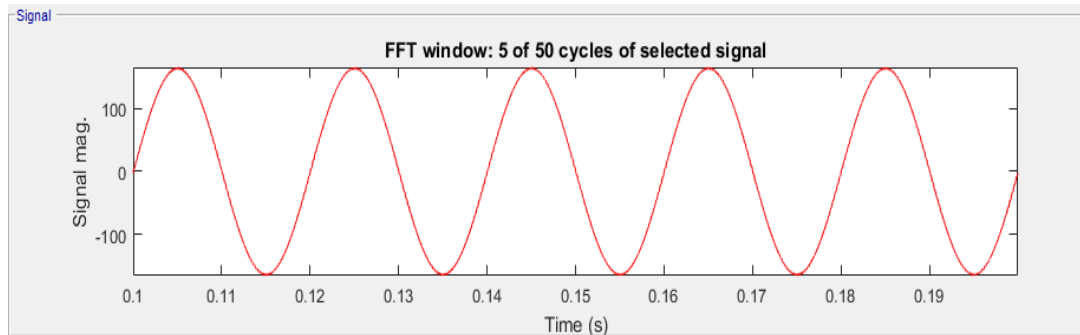
Fig. 9. 5 of 50 Cycles of Voltage Selected Signal After Filtering

The FFT settings are as followed : the start time of 0.1 seconds, number of cycles of 5, fundamental frequency of 50 Hz, max frequency of 1000 Hz, max frequency for THD computation is Nyquist frequency. The result is that THD= 0.70% as shown on Fig.10.
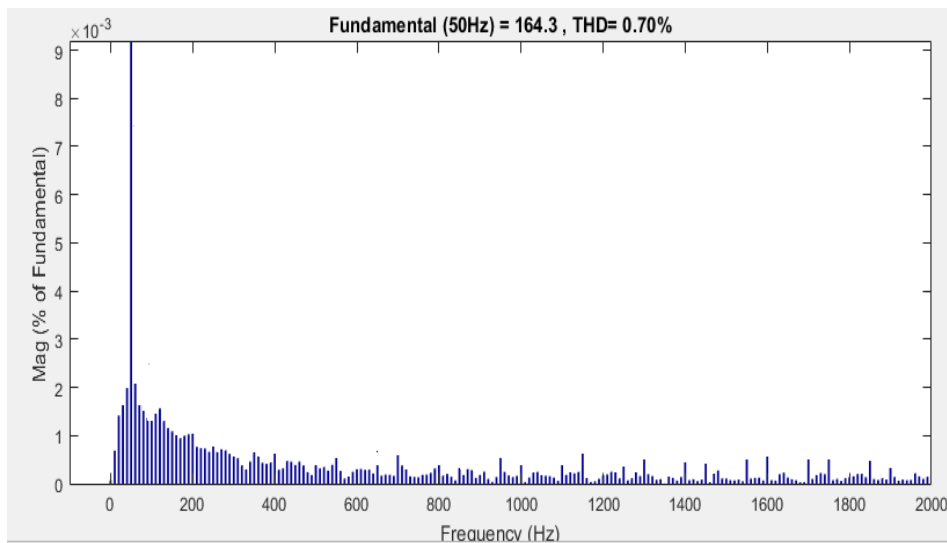
Fig. 10. THD Analysis After Filtering

The fundamental rises till 164.3.
0.70% of THD is an excellent result as it less than the value expected by norms.

VI. CONCLUSION

This work discusses simulation THD determination using calculation and MATLAB-Simulink. This model can simulate different used IGBT switches with different parameters but for loss calculation we take the datasheet of FGA25N120ANTD *IGBT*. The system was composed by three phase full bridge IGBT based inverter connected to LC filter and three phase R load at the end. Here is designed a LC filter to reduce harmonics generated by inverter to make it useable in applications.

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