

# Experimental Study on Harmonic Mitigation in A Grid Connected Solar Power Plant

V. A. Deshmukh

M.Tech Scholar

Department of electrical engineering  
Christian College of Engineering and Technology  
Bhilai, India

B. Sridhar

Assistant Professor

Department of electrical engineering  
Christian College of Engineering and Technology  
Bhilai, India

**Abstract**—Solar energy is converted into electrical energy through the use of solar power plants. Solar power plants have a photovoltaic array, a maximum power point monitoring unit, a DC to DC converter and, typically, a multi-level inverter. In these types of devices, power filters are used to counteract harmonics. The trouble with active power is that it adds expense to an otherwise costly solar power plant.

**Keywords**—Solar Power Plant, Harmonic mitigation, Power Quality, Power Filter

## I. INTRODUCTION

Harmonics are introduced in the system due to extensive use of power electronic converters as well as due to non-linear loading on the grid side, harmonics can also be introduced into the system due to lightning discharges and switching, here we are focused on the mitigation of harmonics generated due to converters and nonlinear loads. The harmonics introduced into the system will eventually lead to the following harmful effects:

1. Overheating of windings present in generators, Transformers and measuring pieces of equipment.
2. Early degradation of power cables.
3. Interference with power line carrier communication and other electronic devices.

Therefore mitigation of harmonics is an essential part of an optimum functioning power system, mitigation of harmonics also leads to lower downtime and therefore increased consumer satisfaction which eventually leads to higher profit margins. There are at least six types of filters which are used for harmonic mitigation. We are mainly concerned about harmonic mitigation in the grid-connected solar power plant.

Extensive literature review of the past 10 years helps us to ensure that there is almost no article that compares and summarises harmonic mitigation techniques especially for a solar power plant.

The motivation behind this paper can be summarised as follows

1. To act as a helpful guide for design engineers consultants and customers concerning solar power plant.
2. To provide comprehensive details regarding harmonic mitigation techniques so as to increase the profitability and efficiency of a solar power plant.

## II. HARMONIC MITIGATION THROUGH THE USE OF PASSIVE POWER FILTERS

Passive Filters use passive components, such as inductors, capacitors, and resistors. These cannot increase the signal energy; the frequency range for harmonic filters is limited to approximately 3000 Hz. It is common to characterize the frequency-selective filters with respect to their passbands.

### A. Double tuned filter

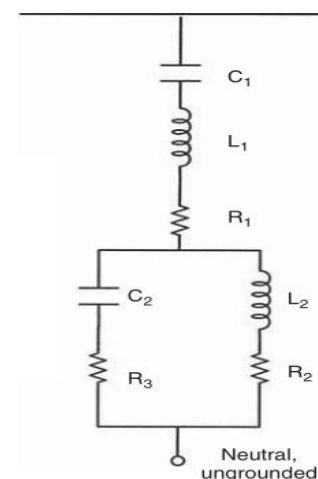


Figure 1. A double tuned filter

A double-tuned filter is derived from two Single Tuned filters and is shown in Fig. 1. The advantage with respect to two Single Tuned filters is that the power loss at fundamental frequency is less and one inductor instead of two is subjected to full impulse voltage. This is an advantage in HV applications. Two Single Tuned filters of different frequencies into a single double-tuned filter

Double-toned filter and two parallel single-toned filters have the same feature that each of them will filter two distinct frequency harmonics.

Basically it filters out only two different frequency harmonics so it acts as if two single tuned filter are connected together. Mathematical explanation about the working of a double tuned filter is given below:

$$C_1 = C_a + C_b$$

$$L_2 = \frac{[L_a C_a - L_b C_b]^2}{[C_a + C_b][L_a + L_b]}$$

$$R_2 = R_a \left[ \frac{a^2(1-x^2)}{(1+a^2)(1+x^2)} \right] - R_b \left[ \frac{1-x^2}{(1+a^2)(1+x^2)} \right]$$

$$+ R_1 \left[ \frac{a(1-a)(1-x^2)}{(1+a^2)^2(1+x)^2} \right]$$

$$C_2 = \frac{C_a C_b (C_a + C_b) (L_a + L_b)^2}{(L_a C_a - L_b C_b)^2}$$

$$R_3 = -R_a \left[ \frac{a^2 x^4 (1-x^2)}{(1+ax^2)^2(1+x^2)} \right] + R_b \left[ \frac{(1-x^2)}{(1+ax^2)^2(1+x^2)} \right]$$

$$+ R_1 \left[ \frac{(1-x^2)(1-ax^2)}{(1-x^2)(1-ax^2)} \right]$$

$$L_1 = \frac{L_a L_b}{L_a + L_b}$$

where,

$$a = \frac{C_a}{C_b}$$

$$x = \sqrt{\frac{L_b C_b}{L_a C_a}}$$

Generally, R1 is omitted and R2 and R3 are modified so that the impedance near resonance is practically the same. Note that inductor L1 will have some resistance, which is considered in the above equations.

### B.High pass filter

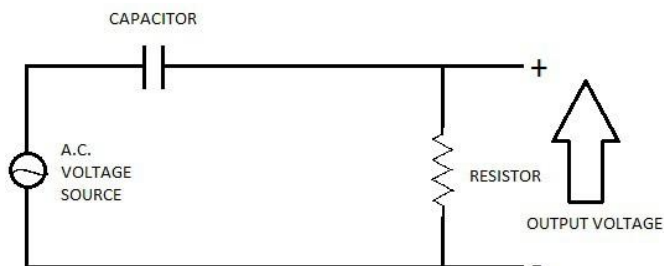


Figure 2. A high pass filter

The above figure depicts a typical high pass filter, It works according to the frequency-impedance characteristic of the capacitor.

A high-pass filter (HPF) is an electronic filter that transmits signals with a frequency greater than a certain cut-off frequency and attenuates signals with a frequency lower than the cut-off frequency. The sum of attenuation for each frequency depends on the configuration of the filter. Typically a high-pass filter is modelled as a linear time-invariant system. In the field of audio engineering, it is often called a low-cut filter or a bass-cut filter. High-pass filters have many applications, such as DC blocking from circuits vulnerable to non-zero average voltages or radio frequency systems. They can also be used in combination with a low-pass filter for the production of a bandpass filter.

Mathematical explanation of a high pass filter is given below:

$$Z = \frac{1}{2\pi fC}$$

where  $Z$  is the impedance offered by the capacitor  
 $\pi$  is a mathematical constant  
 $f$  is the frequency of voltage across capacitor  
 $C$  is the capacitance of the capacitor

Lets put  $f = 0$

Then  $Z = \infty$  ie. Capacitor is open circuit

Lets put  $f = \infty$

Then  $Z = 0$  ie. Capacitor is short circuit

Thus, the capacitor offers very high impedance to low frequency voltage and very low impedance to high frequency voltage thereby acting as a high pass filter.

### B.Single tuned filter

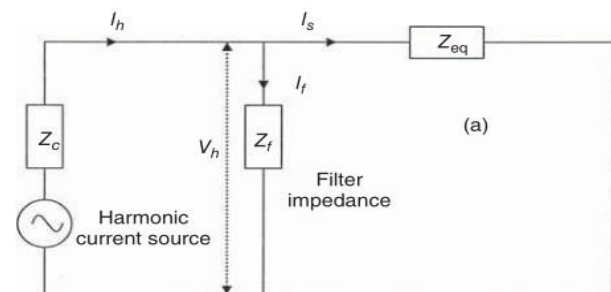


Figure 3. A single tuned filter

The single-tuned (ST) Filters are efficient filters and will bypass a certain harmonic to which these are tuned. These are most widely used Filters in all applications of harmonic mitigation. However, care is required in their design, so that the components are not overloaded, and overvoltages due to their applications are controlled. Many times a group of ST Filters are applied, each tuned to a specific frequency.

The operation of an ST shunt filter is explained with reference to Figure 3.

Harmonic current injected from the source through impedance  $Z_c$  divides into Filter and system equivalent impedance  $Z_{eq}$ . This system impedance can be found by circuit reduction this is in fact the short-circuit equivalent impedance.

Care is taken in their design so that the components are not overwhelmed and the over voltage due to their application is regulated.

This device impedance can be found by circuit reduction, which is actually a short-circuit impedance counterpart. The current  $I_s$  divides into two parallel paths with magnitude as  $I_h$  and  $I_f$ .

$$I_h = I_f + I_s$$

$I_h$  is the harmonic current injected into the system

$I_f$  is the current through the filter and ;

$I_s$  is the current through the system impedance

Also,

$$I_f Z_f = I_s Z_s$$

ie. Harmonic voltage across filter impedance equals to Harmonic voltage across system impedance

$$I_f = \left[ \frac{Z_s}{Z_f + Z_s} \right] I_h$$

$$I_f = \sigma_f I_h$$

$$I_s = \sigma_s I_h$$

Where,  $\sigma_f$  and  $\sigma_s$  are complex quantities that determine distribution of current in filter and system impedance

### III. HARMONIC MITIGATION THROUGH THE USE OF ACTIVE POWER FILTERS

Basically there are two types of active power filters, namely

1. Series active power filter and;
2. Shunt active power filter

Active power filters (APF) are filters, which can perform the job of harmonic elimination. Active power filters can be used to filter out harmonics in the power system which are significantly below the switching frequency of the filter. The active power filters are used to filter out both higher and lower order harmonics in the power system.

The main difference between active power filters and passive power filters is that APFs mitigate harmonics by injecting active power with the same frequency but with reverse phase to cancel that harmonic, where passive power filters use combinations of resistors (R), inductors (L) and capacitors (C) and does not require an external power source or active components such as transistors. This difference, make it possible for APFs to mitigate a wide range of harmonics

Let us examine in detail the two filters.

#### A. Series active power filter

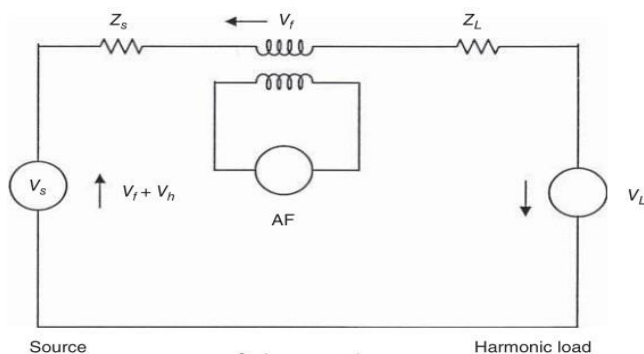


Figure 4. A series active power filter

A voltage  $V_f$  is injected in series with the line and it compensates the voltage distortion produced by a nonlinear load. A series active Filter is more suitable for harmonic compensation of diode rectifiers where the DC voltage for the inverter is derived from a capacitor, which opposes the change of the voltage.

Figure 4.1 and 4.2 show the equivalent circuit of series active filter for harmonic current and voltage source.

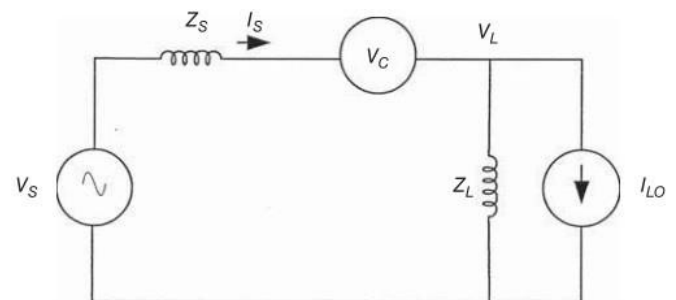


Figure 4.1 Series active power filter for harmonic current load.

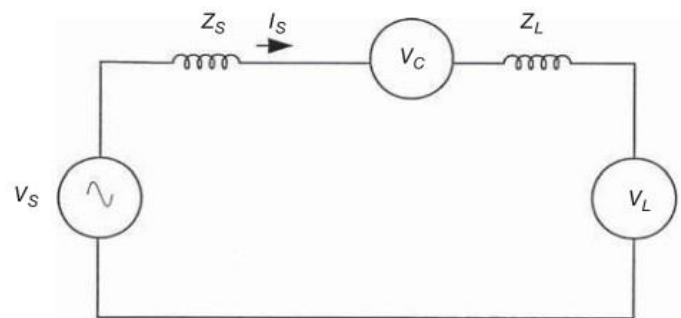


Figure 4.2 Series active power filter with harmonic voltage load.

#### B. Shunt active power filter with D space.

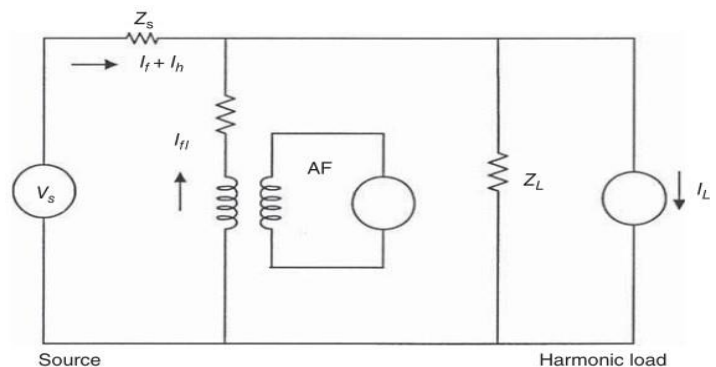


Figure 5. A shunt active power filter with D space.

The voltage distortion in a weak system is very much dependent on harmonic current, while a stiff system of zero impedance will have no voltage distortion. Thus, provided that the system is not too stiff, a non sinusoidal voltage can be corrected by injecting proper harmonic current. A harmonic current source is represented as a Norton

equivalent circuit, and it may be implemented with a pulse width modulation (PWM) inverter to inject a harmonic current of the same magnitude as that of the nonlinear load into the system, but of harmonics of opposite polarity. A shunt connection is shown in Figure 5. The load current will be sinusoidal, so long as the load impedance is higher than the source impedance.

Figure 5.1 and 5.2 show the equivalent circuit of parallel active filter for harmonic current and voltage source.

Figure.5.1, equation for  $I_s$  can be written as

$$I_s = \frac{Z_L I_{L0}}{Z_s + \frac{Z_L}{1-G}}$$

$$\text{If } \left| \frac{Z_L}{1-G} \right|_h \gg |Z_s|_h \text{ is satisfied}$$

that is if  $|1-G|_h \approx 0$   
then  $I_{sh} \approx 0$

The subscript “h” signifies harmonic component.

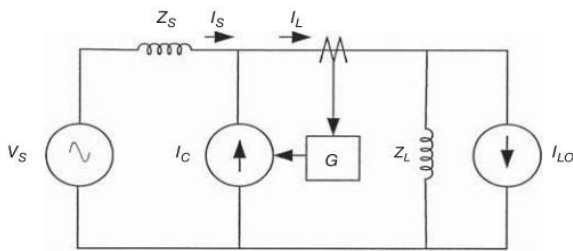


Figure 5.1 Shunt power filter for harmonic current load

If the following equation is satisfied, then in figure 5.2

$$\left| Z_s + \frac{Z_L}{1-G} \right|_h \gg 1 \text{ pu}$$

if the shunt active filter is controlled such that,

$$V_c = kGI_s$$

then source current is

$$I_s = \frac{Z_L I_L + V_s}{Z_s + Z_L + KG}$$

In order that the source current becomes sinusoidal

$$K \gg |Z_L|_h$$

$$K \gg |Z_s + Z_L|_h$$

then,

$$V_c = Z_L I_{Lh} + V_{sh}$$

However, these conditions cannot be satisfied. K should be large, and impedance on the load side should be small for

harmonics in order to suppress the source harmonic current. This cannot be satisfied for a conventional phase-controlled thyristor rectifier, and  $Z_L$  is almost infinite. The required output voltage  $V_c$  also becomes infinite. In Figure 5.2, for series filter compensating a harmonic voltage source, the current is

$$I_s = \frac{V_s - V_L}{Z_s + Z_L + KG}$$

When K is much greater than 1 pu,  $I_s$  is zero. To realize a large gain, a hysteresis or ramp-comparison control method can be used.

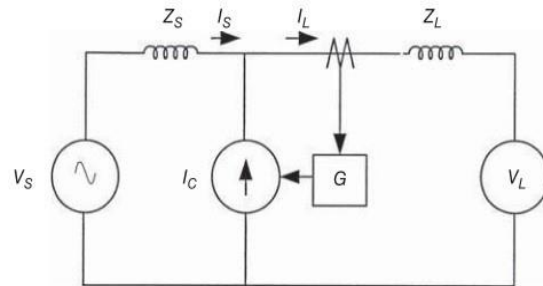


Figure 5.2 Shunt power filter for harmonic voltage load

### III METHODOLOGY AND EXPERIMENTATION

For detailed model of the experimental setup please visit-  
[Model for harmonic mitigation](#)

#### A.Experimental Setup

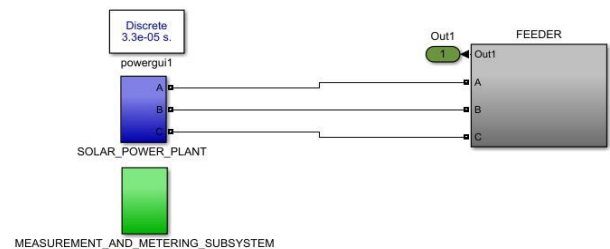


Figure 6. The experimental setup

The power system consists of a solar PV array connected to a 3 phase 500V grid with a fundamental frequency of 60Hz.

1.The powergui block is a discrete block with sample time 33 micro-seconds.

2.Measurement and metering subsystem contains block that measure Active Power(kW), Reactive Power(kVAr), Power Factor, Total Harmonic Distortion and Maximum Power Point Tracking Measurements.

The grid-connected system is connected to a wider independent grid (usually a public utility grid) which feeds

energy directly into the grid. This energy can be exchanged by a residential or industrial building before or after the revenue assessment stage, depending on whether the attributed energy output is measured independently of the energy usage of the consumer (feed-in tariff) or only on the difference in energy consumption (net metering).

The detailed diagram of the solar pv array has been described below -

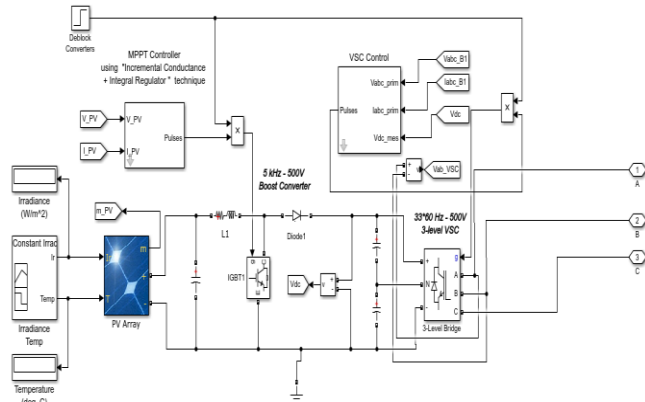


Figure 7. Solar pv array (detailed diagram)

A 100-kW PV array is connected to a 25-kV grid via a DC-DC boost converter and a three-phase three-level Voltage Source Converter (VSC). Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink® model using the 'Incremental Conductance + Integral Regulator' technique.

Another example (see power\_PVarray\_grid\_avg model) uses average models for the DC\_DC and VSC converters. In this average model the MPPT controller is based on the 'Perturb and Observe' technique.

The detailed model contains the following components:

1. PV array delivering a maximum of 100 kW at 1000 W/m<sup>2</sup> sun irradiance.
- 2.5-kHz DC-DC boost converter increasing voltage from PV natural voltage (273 V DC at maximum power) to 500 V DC. Switching duty cycle is optimized by a MPPT controller that uses the 'Incremental Conductance + Integral Regulator' technique. This MPPT system automatically varies the duty cycle in order to generate the required voltage to extract maximum power.
- 3.1980-Hz 3-level 3-phase VSC. The VSC converts the 500 V DC link voltage to 260 V AC and keeps unity power factor. The VSC control system uses two control loops:
4. An external control loop which regulates DC link voltage to +/- 250 V and;
5. An internal control loop which regulates  $I_d$  and  $I_q$  grid currents (active and reactive current components).  $I_d$  current reference is the output of the DC voltage external controller.  $I_q$  current reference is set to zero in order to maintain unity power factor.  $V_d$  and  $V_q$  voltage outputs of the current controller are converted to three modulating signals  $U_{abc\_ref}$  used by the PWM Generator. The control system uses a

sample time of 100 microseconds for voltage and current controllers as well as for the phase locked loop (PLL) synchronization unit. Pulse generators of Boost and voltage source converters(VSC) use a fast sample time of 1 microsecond in order to get an appropriate resolution of PWM wave forms.

6.10-kvar capacitor bank filtering harmonics produced by VSC.

7.100-kVA 260V/25kV three-phase coupling transformer.

8.Utility grid (25-kV distribution feeder + 120 kV equivalent transmission system).

9.The 100-kW PV array uses 330 SunPower modules (SPR-305E-WHT-D). The array consists of 66 strings of 5 series-connected modules connected in parallel (66\*5\*305.2 W= 100.7 kW).

10.The 'Module' parameter of the PV Array block allows you to choose among various array types of the NREL System Advisor Model (<https://sam.nrel.gov/>).

11.The manufacturer specifications for one module are:

12. Number of series-connected cells : 96

13. Open-circuit voltage:  $V_{oc} = 64.2$  V

14.Short-circuit current:  $I_{sc} = 5.96$  A

15.Voltage and current at maximum power :  $V_{mp} = 54.7$  V,  $I_{mp} = 5.58$  A

16.The PV array block menu allows you to plot the I-V and P-V characteristics for one module and for the whole array.

17.The PV array block has two inputs that allow you varying sun irradiance (input 1 in W/m<sup>2</sup>) and temperature (input 2 in deg. C). The irradiance and temperature profiles are defined by a Signal Builder block which is connected to the PV array inputs.

The solar pv array has been connected to a grid with two unbalanced and one balanced load, the details of which has been given below-

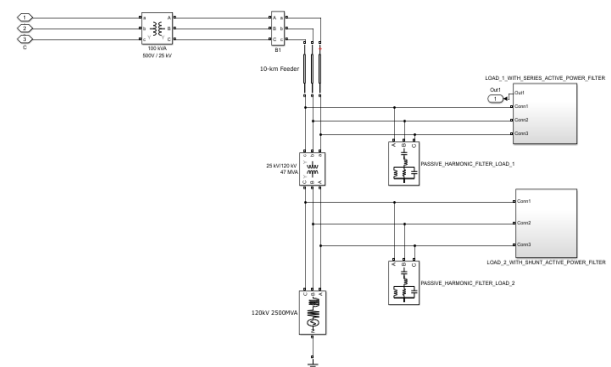


Figure 8. The grid with its loads

The first load is an unbalanced load connected with a Series Active Power Filter for harmonic mitigation. It consists of a universal bridge with snubber resistance of 100 ohms, and snubber capacitance of 0.212 millifarad. The second load consists of a three phase bridge configuration diode rectifier with ON state resistance of 0.1 ohms. The passive power filters are Simulink® model



named passive harmonic filter they are configurable as single tuned, double tuned and as a high pass filter.

When the currents on the three live wires of a three-phase system are not equal or are not at an exact  $120^\circ$  phase angle, the power loss is greater than for a perfectly balanced system. The method of symmetrical components is used to analyze unbalanced systems.

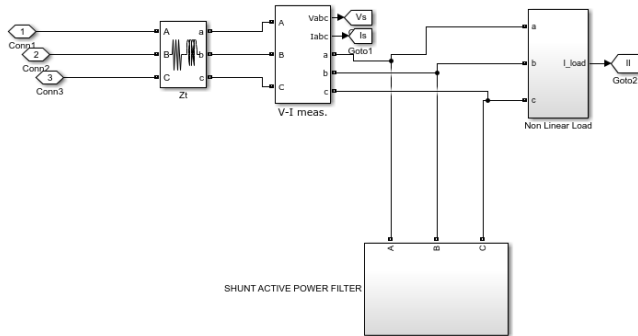


Figure 9. The shunt active power filter

The above block diagram(Figure 9) is named as **LOAD\_2\_WITH\_SHUNT\_ACTIVE\_POWER\_FILTER** and can be subdivided into shunt active power filter and non linear load. An additional powergui block(discrete) is present here with sample time of 5 micro-seconds. The shunt active power filter is based on p-q theory and contains a D space block for additional simplicity.

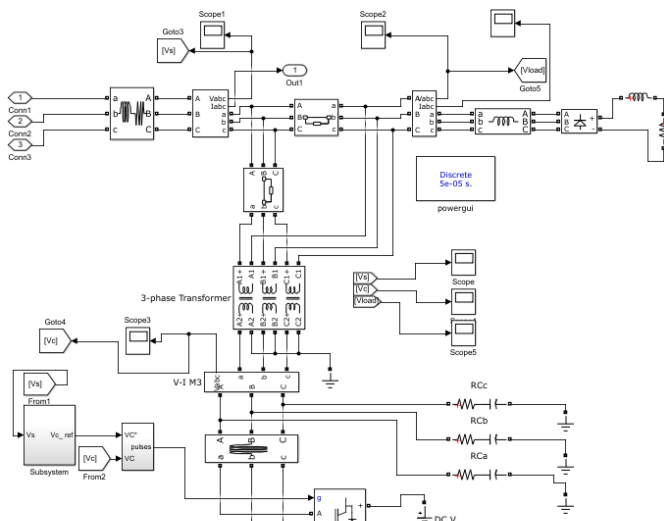


Figure 10. The series active power filter

The above block diagram(Figure10) describes block named as **LOAD\_1\_WITH\_SERIES\_ACTIVE\_POWER\_FILTER**. This block consists of a non linear load and a series active power filter.

#### IV. METHODOLOGY

The simulation is performed in Simulink® with time of simulation being from 1 second to 2 second. The solver used to simulate is ode4(Runge-Kutta) with step size as fixed. The format for input and output data is set to array and maximum number of data points is set to have value of 1000. All the other solver parameters contain default values.

A fast Fourier transform (FFT) is an algorithm that computes the discrete Fourier transform (DFT) of a sequence, or its inverse (IDFT). Fourier analysis converts a signal from its original domain (often time or space) to a representation in the frequency domain and vice versa. The currents and voltages of which fast fourier transform (fft) analysis has been done are listed in the following table.

TAG NAME	LOCATION
AVabc=V1	pqi_pvarray/FEEDER/LOAD_1_WITH_SERIES_ACTIVE_POWER_FILTER/Scope2
Iabc=I1	pqi_pvarray/FEEDER/LOAD_1_WITH_SERIES_ACTIVE_POWER_FILTER/Scope6
IL=I2	pqi_pvarray/FEEDER/LOAD_2_WITH_SHUNT_ACTIVE_POWER_FILTER/SHUNT_ACTIVE_POWER_FILTER/Scope3
Vs=V2	pqi_pvarray/FEEDER/LOAD_2_WITH_SHUNT_ACTIVE_POWER_FILTER/SHUNT_ACTIVE_POWER_FILTER/Scope1

Table11. Tag names and address of Fourier transformed voltage and current

The simulations are performed such that only one filter is active at a time or none of the filters are active in the given time interval. The sequence of which would be as follows -

- 1.No filters are connected
- 2.Only Shunt Active Power Filter is connected
- 3.Only Series Active Power Filter is connected
- 4.Single tuned Passive filter is connected across load 1
- 5.Double tuned Passive Filter is connected across load 1
- 6.High Pass Filter is connected across load 1
- 7.Single Tuned Passive Filter is connected across load 2
- 8.Double Tuned Passive Filter is connected across load 2
- 9.High Pass Filter is connected across load 2

The single tuned filter connected across load 1 is tuned for 5th harmonic frequency while double tuned filter has been tuned for 5th and 7th harmonic. The high pass filter connected across load 1 has a cut off frequency of 180 Hz or third harmonic. The single tuned filter connected across load 2 is tuned for 2nd harmonic while the double tuned filter is tuned for 2nd and 5th harmonic. The high pass filter connected across load 2 has a cut off frequency of 120 Hz of 2nd harmonic.

## V. RESULT OF SIMULATION

A. With no filters connected to Load 1 the following waveform of load current and load voltage are obtained -

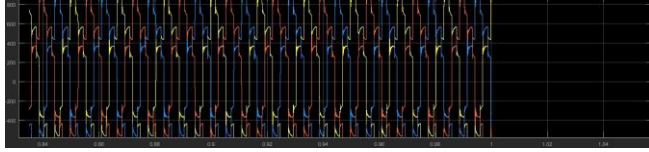


Figure 11. Load current with no filters connected to Load 1



Figure 12 Load voltage with no filters connected to Load 1

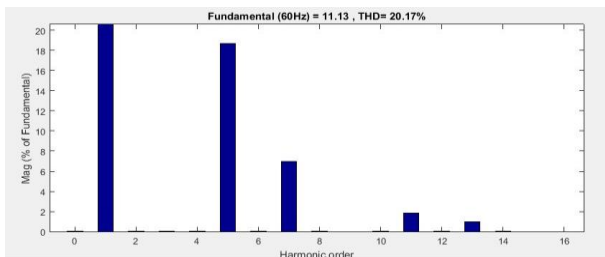


Figure 11.1 Fast Fourier transform of load current waveform

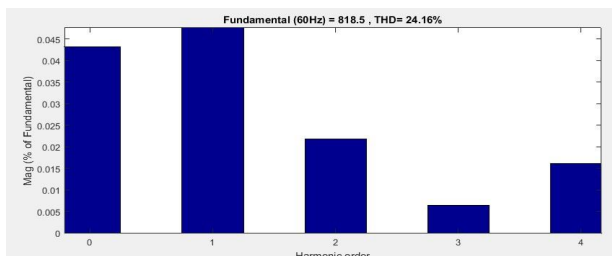


Figure 11.2 Fast Fourier transform of load voltage waveform

B. With no filters connected to load 2 the following load current and load voltage wave forms are observed -



Figure 13. Load current waveform with no filters connected to load 2

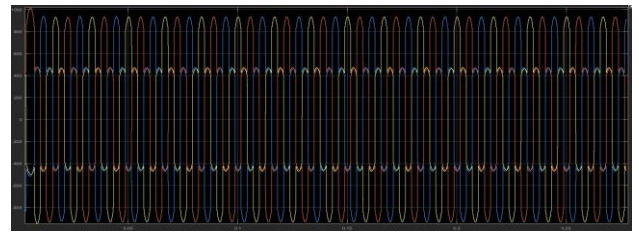


Figure 14. Load voltage waveform with no filters connected to load 2

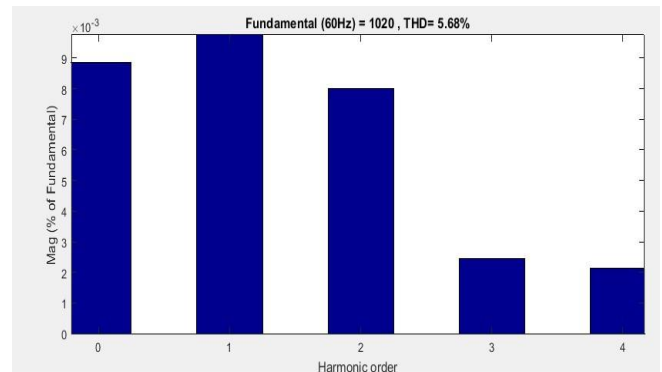


Figure 13.1 Fast Fourier transform of load current waveform

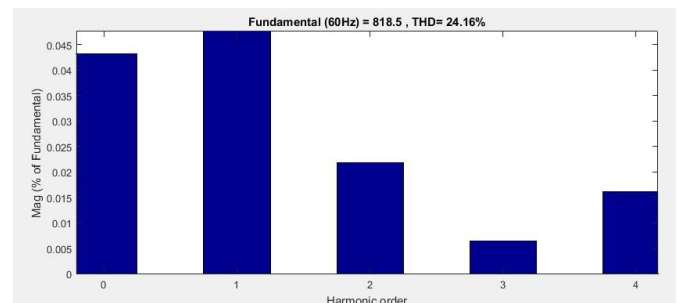


Figure 14.1 Fast Fourier transform of load voltage waveform

C. With only shunt active power filter connected to load 2 the following load current and load voltage wave forms are observed -

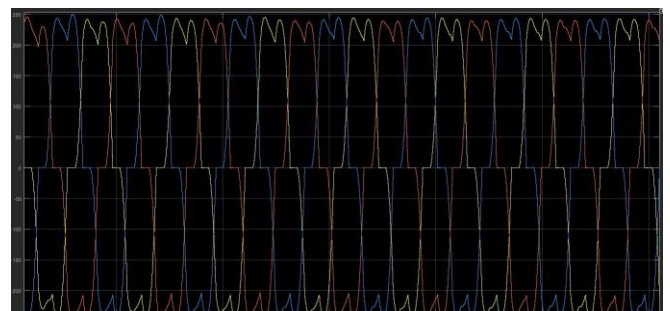


Figure 15. load voltage waveform with only shunt active power filter connected to load 2

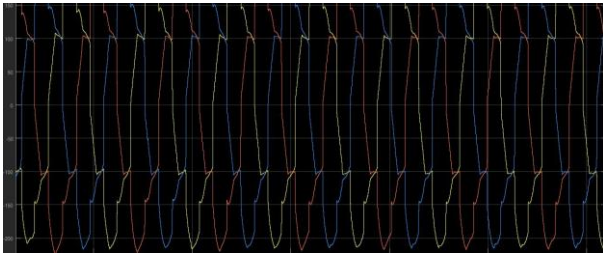


Figure 16. Load current waveform with only shunt active power filter connected to load 2

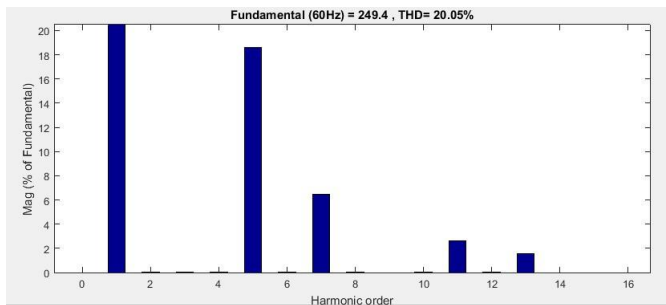


Figure 15.1. FFT analysis of load voltage waveform with only shunt active power filter connected to load 2

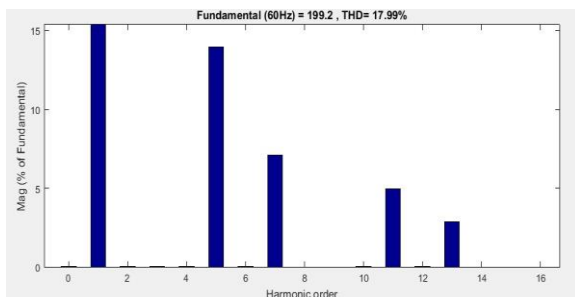


Figure 16.1. FFT analysis of Load current waveform with only shunt active power filter connected to load 2

*D. With only series active power filter connected to load 1 the following load current and load voltage waveform are observed -*

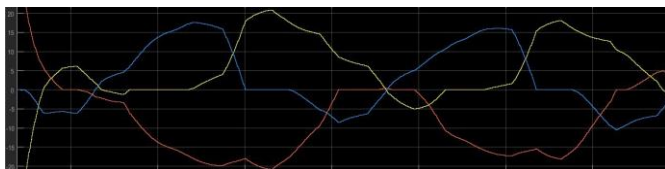


Figure 17. Load current waveform with only series active power filter connected to load 1

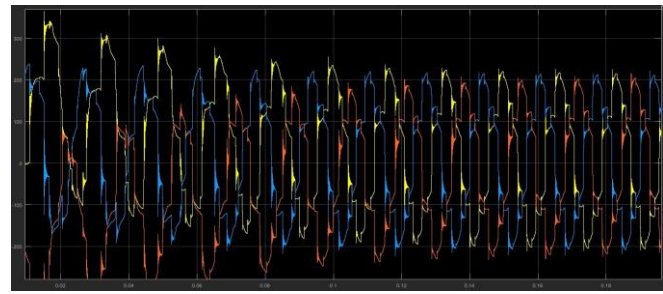


Figure 18. Load voltage waveform with only series active power filter connected to load 1

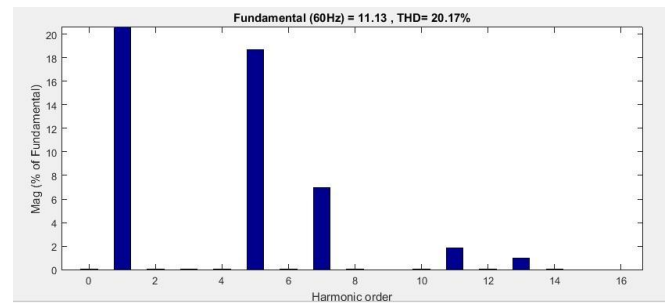


Figure 17.1. FFT analysis of Load current waveform with only series active power filter connected to load 1

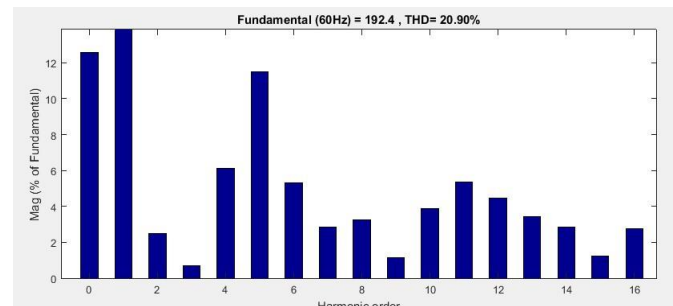


Figure 17.2. FFT analysis of Load voltage waveform with only series active power filter connected to load 1

*E. With only single tuned filter tuned for 5th harmonic connected across load 1 the following load current and load voltage waveform are observed -*

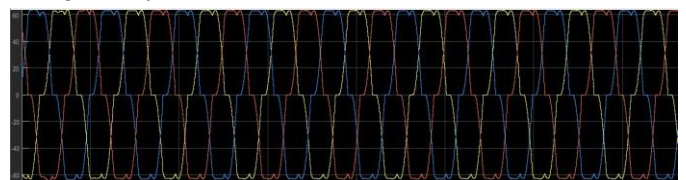


Figure 19. Load voltage waveform with only single tuned filter connected across load 1 tuned for 5<sup>th</sup> harmonic frequency



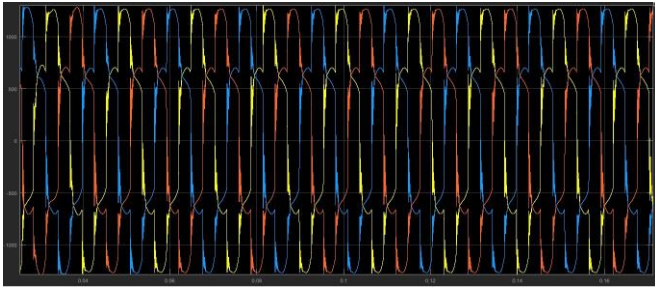


Figure 20. Load current waveform with only single tuned filter connected across load 1 tuned for 5<sup>th</sup> harmonic frequency

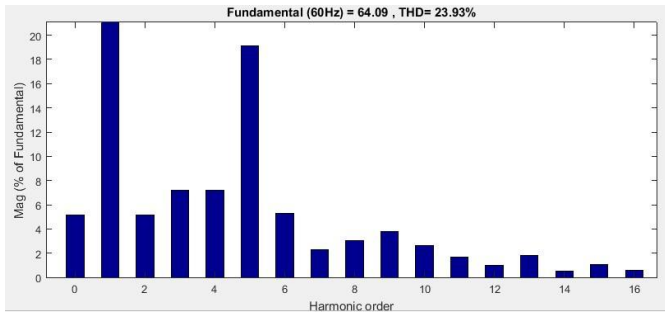


Figure 19.1. FFT analysis of Load voltage waveform with only single tuned filter connected across load 1 tuned for 5<sup>th</sup> harmonic frequency

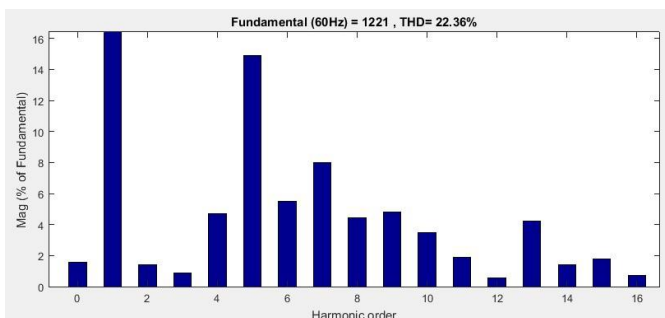


Figure 20.1 FFT analysis of Load current waveform with only single tuned filter connected across load 1 tuned for 5<sup>th</sup> harmonic frequency

*F. With only high pass filter with cut off frequency of 180 Hz connected across load 1 the following load current and load voltage waveform are obtained -*

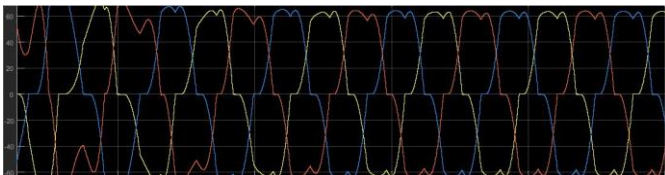


Figure 21. Load current waveform high pass filter with cut off frequency of 180 Hz

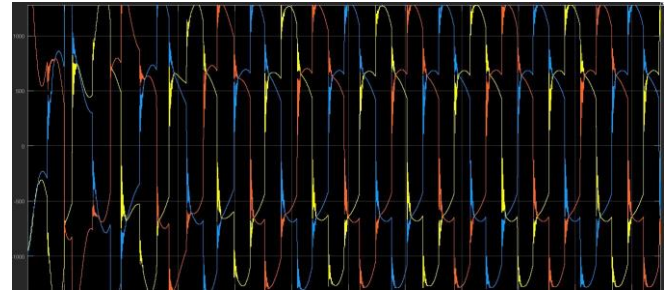


Figure 22. Load voltage waveform high pass filter with cut off frequency of 180 Hz

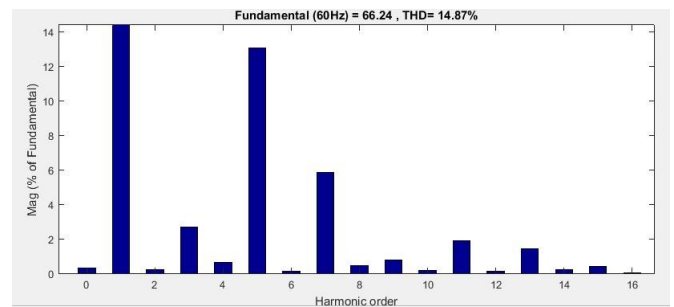


Figure 21.1. FFT analysis of load current waveform high pass filter with cut off frequency of 180 Hz

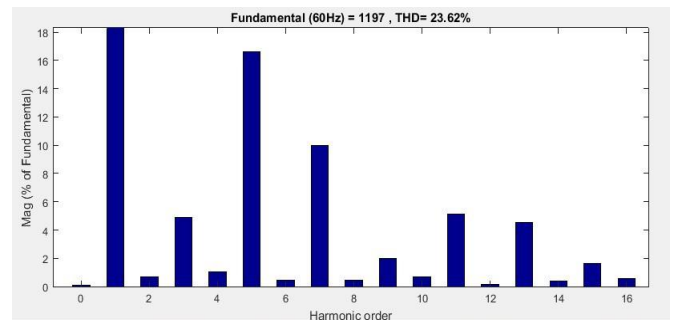


Figure 22.1. FFT analysis of load voltage waveform high pass filter with cut off frequency of 180 Hz

*G. With only single tuned filter tuned for 2nd harmonic connected across load 2 the following load current and load voltage waveform are observed -*

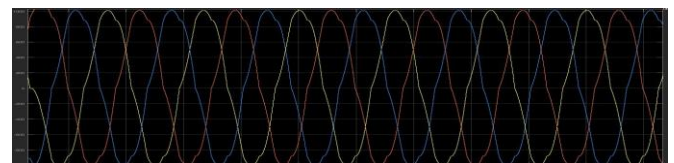


Figure 23. Load current waveform of single tuned filter tuned for 2nd harmonic connected across load 2

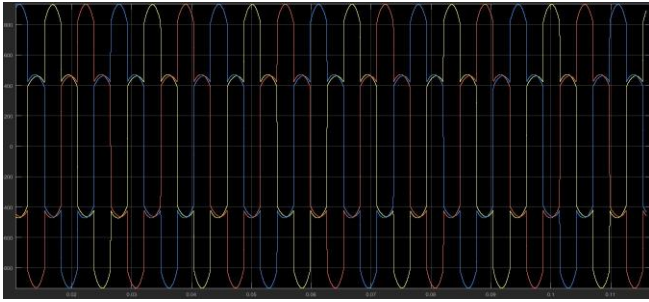


Figure 24. Load voltage waveform of single tuned filter tuned for 2nd harmonic connected across load 2

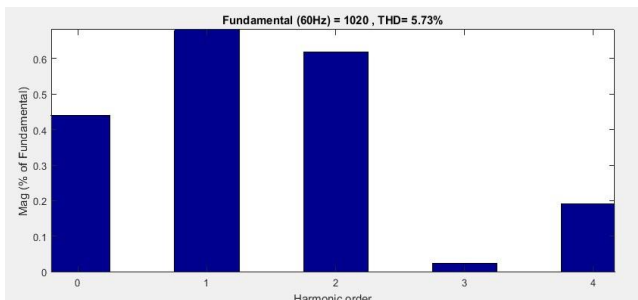


Figure 23.1. FFT analysis of load current waveform of single tuned filter tuned for 2nd harmonic connected across load 2

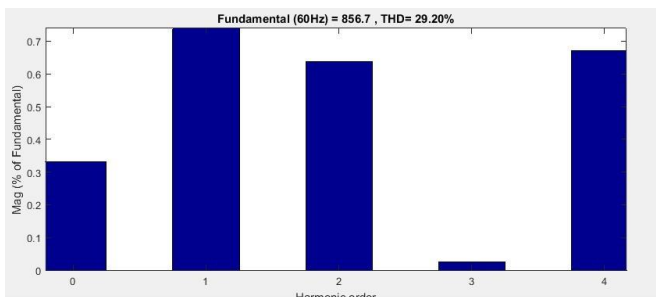


Figure 24.1. FFT analysis of load voltage waveform of single tuned filter tuned for 2nd harmonic connected across load 2

*H. With only double tuned filter tuned for 5th and 7th harmonic connected across load 2 the following load current and load voltage waveform are obtained -*

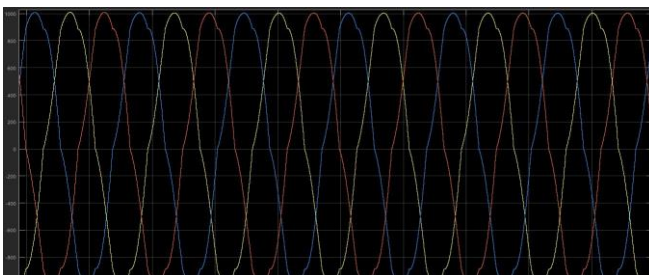


Figure 25. Load current waveform with double tuned filter tuned for 5th and 7th harmonic connected across load 2

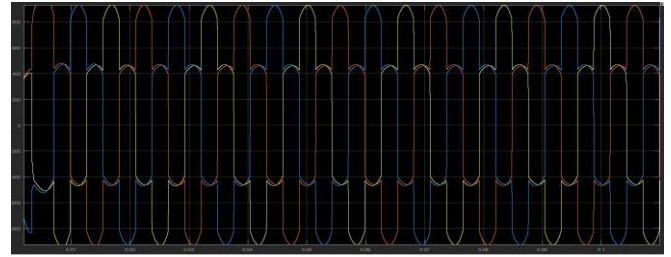


Figure 26. Load voltage waveform with double tuned filter tuned for 5th and 7th harmonic connected across load 2

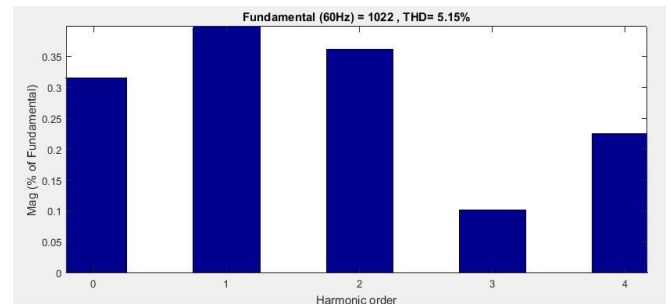


Figure 25.1 FFT analysis of load current waveform with double tuned filter tuned for 5th and 7th harmonic connected across load 2

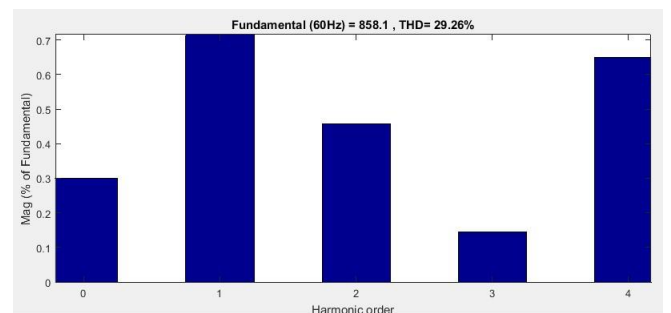


Figure 26.1. FFT analysis of load voltage waveform with double tuned filter tuned for 5th and 7th harmonic connected across load 2

*I. With only high pass filter with cut off frequency of 120 Hz connected across load 2 the following load current and load voltage waveform are obtained -*

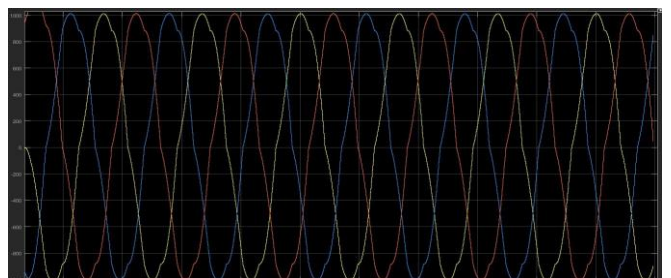


Figure 27. Load current waveform with high pass filter with cut off frequency of 120 Hz connected across load 2

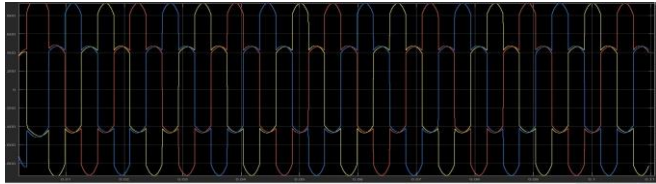


Figure 28. Load voltage waveform with high pass filter with cut off frequency of 120 Hz connected across load 2

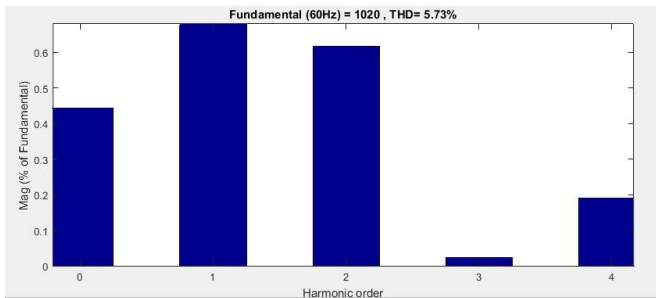


Figure 27.1. FFT analysis of load current waveform with high pass filter with cut off frequency of 120 Hz connected across load 2

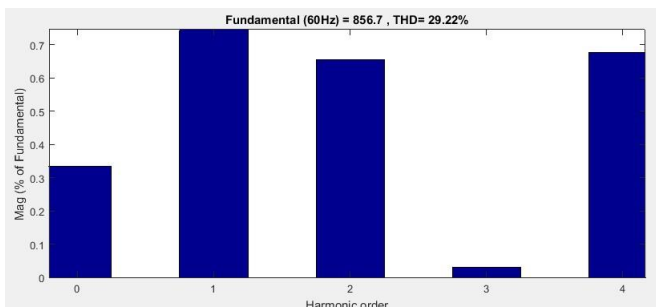


Figure 27.2. FFT analysis of load voltage waveform with high pass filter with cut off frequency of 120 Hz connected across load 2

## VI. CONCLUSION

1. The below table compares total harmonic distortion for various configuration of filters:

T.H.D / #QUANTITY	NO FILTER	ACTIVE FILTER	S.T.	D.T.	H.P.F.
I1	23.83%	20.17%	23.93%	13.66%	14.78%
V1	24.16%	20.90%	22.36%	24.18%	23.62%
I2	5.68%	20.05%	5.73%	5.15%	5.73%
V2	24.16%	17.99%	29.20%	29.26%	29.22%

2. Passive power filters perform best when tuned properly but they are unable to compensate for the dc component of current/voltage waveform

3. Active power filter perform best in almost every scenario but series active power filter is best used for mitigation of voltage sags than harmonic mitigation.

4. If not tuned properly then passive power filters can act as a harmonic source rather than harmonic sinks.

## VII. BIBLIOGRAPHY

- [1] Power system harmonics and passive filter designs by J.C.Das.
- [2] Vaibhav Deshmukh (2021). Grid connected solar power plant with active, passive P.F. (https://www.mathworks.com/matlabcentral/fileexchange/87062-grid-connected-solar-power-plant-with-active-passive-p-f), MATLAB Central File Exchange. Retrieved February 21, 2021.
- [3] Simulation of Dynamic Systems with MATLAB and Simulink by Harold Klee and Randal Allen
- [4] K. Elissa, "Title of paper if known," unpublished.
- [5] P. Gakhar and M. Gupta, "Harmonic Mitigation in a Transformer Less Grid Connected Solar PV System Using Modified LCL Filter," 2018 3rd International Conference and Workshops on Recent Advances and Innovations in Engineering (ICRAIE), Jaipur, India, 2018, pp. 1-4, doi: 10.1109/ICRAIE.2018.8710437.
- [6] Arangarajan Vinayagam, Asma Aziz, Balasubramaniam PM, Jaideep Chandran, Veerapandiyan Veerasamy, Ameen Gargoom, Harmonics assessment and mitigation in a photovoltaic integrated network, Sustainable Energy, Grids and Networks, Volume 20, 2019, 100264, ISSN 2352-4677, https://doi.org/10.1016/j.segan.2019.100264. (https://www.sciencedirect.com/science/article/pii/S2352467719302516).
- [7] Comprehensive Assessment and Mitigation of Harmonic Resonance in Smart Distribution Grid with Solar Photovoltaic Pramod Kumar Bhatt, S. Y. Kumar B.