Experimental study on harmonic mitigation in a grid connected solar power plant.

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Abstract

With the decrease in fossil fuel and the increasing threat of climate change, renewable sources of energy like solar energy are a very logical and sustainable choice for ever-increasing energy demand. Solar energy is converted into electrical energy through the use of solar power plants. These plants contain a photovoltaic array, maximum power point tracking device, a DC to DC converter and generally a multilevel inverter. Due to such extensive use of power electronic devices which generally have unknown linear voltage-current characteristics, harmonics in these kinds of systems are a very real problem. To mitigate this problem power filters are utilized. There are basically two kinds of filters namely active and passive power filters, passive power filters usually provide less impedance Path to the ground for harmonic frequency currents however active power filters mitigate harmonics by injecting active power with the same frequency but with reverse phase. The problem with active power filters is that they add cost to an already expensive solar Power plant that is why there is a need for a comparative study between active power filters and passive power filters to keep the cost low and performance as optimum. This study is an effort towards achieving the above-mentioned goal. Here Simulink model office solar Power plant with two non-linear loads on the grid side have been studied with active as well as passive filters and it is therefore concluded that for a given harmonic frequency the count of which should be less than two and dc component or zero frequency component are absent in the given waveform passive har- monic filters are a cheap and robust option, similarly for a given waveform of current or voltage if the harmonic frequencies present in them have a count more than two and/or contains dc component or zero frequency component of harmonic active power filter are better in terms of performance.

Keywords: Solar Power Plant, Harmonic mitigation, Power Quality, Power Filter

1 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 inthe 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 summarizes harmonic mitigation techniques especially for a solar power plant.

The motivation behind this paper can be summarized 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.**

Introduction

1.1 Harmonic mitigation through the use of passive power filters

Passive ilters 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.

1.1.1 Double-tuned filter

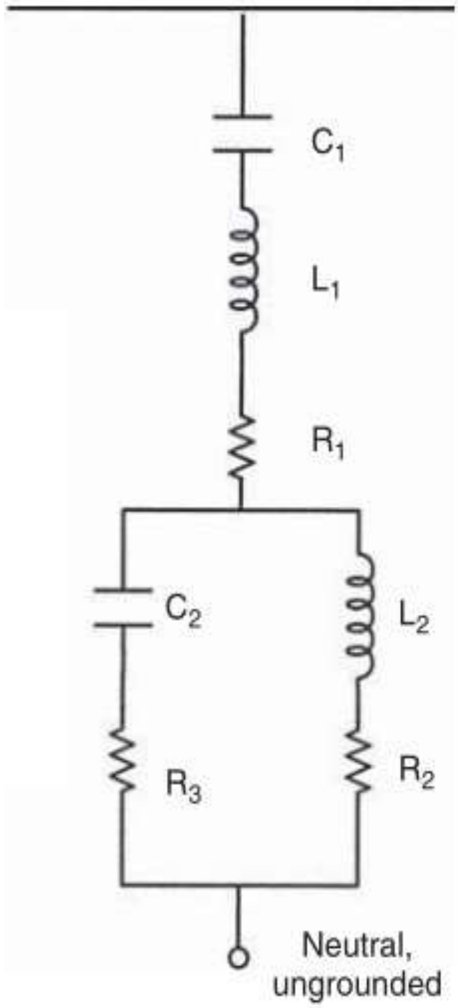

FIGURE 1.1.1. A DOUBLE TUNED PASSIVE FILTER.

A double-tuned filter is derived from two Single Tuned ilters and is shown in Fig. 1.1.1

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:

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$$
\begin{aligned}
C_1 &= C_a + C_b \\
L_2 &= \frac{\left[L_a C_a - L_b C_b\right]^2}{\left[C_a + C_b\right]\left[L_a + L_b\right]} \\
R_2 &= R_a\left[\frac{a^2(1-x^2)}{(1+a^2)(1+x^2)}\right] - R_b\left[\frac{1-x^2}{(1+a^2)(1+x^2)}\right] \\
&\quad + R_1\left[\frac{a(1-a)(1-x^2)}{(1+a)^2(1+x)^2}\right] \\
C_2 &= \frac{C_a C_b (C_a + C_b)(L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \\
R_3 &= -R_a\left[\frac{a^2 x^4 (1-x^2)}{(1+\mathrm{ax}^2)^2(1+x^2)}\right] + R_b\left[\frac{(1-x^2)}{(1+\mathrm{ax}^2)^2(1+x^2)}\right] \\
&\quad + R_1\left[\frac{(1-x^2)(1-\mathrm{ax}^2)}{(1-x^2)(1-\mathrm{ax}^2)}\right] \\
L_1 &= \frac{L_a L_b}{L_a + L_b}
\end{aligned}
$$

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.

where,

$$
\begin{aligned}
a &= \frac{C_a}{C_b} \\
x &= \sqrt{\frac{L_b C_b}{L_a C_a}}
\end{aligned}
$$

Introduction

1.1.2High-pass filter

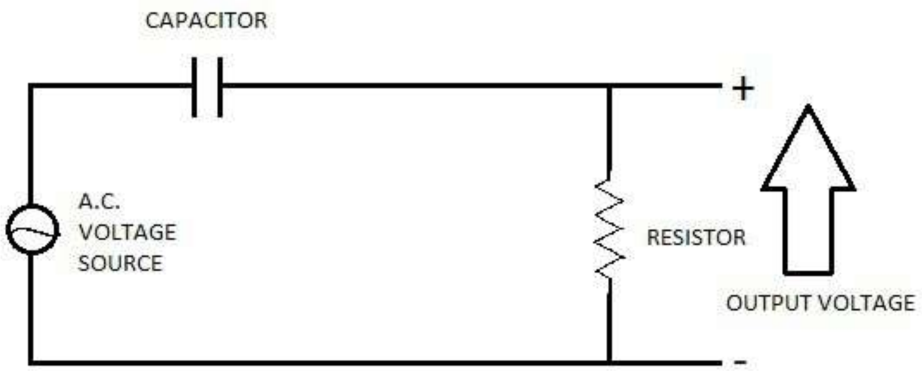

FIGURE 1.1.2. A HIGH PASS FILTER.

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

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

where Z is the impedance offered by the capacitor
π 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.

Section 1

1.1.3Single tuned filter

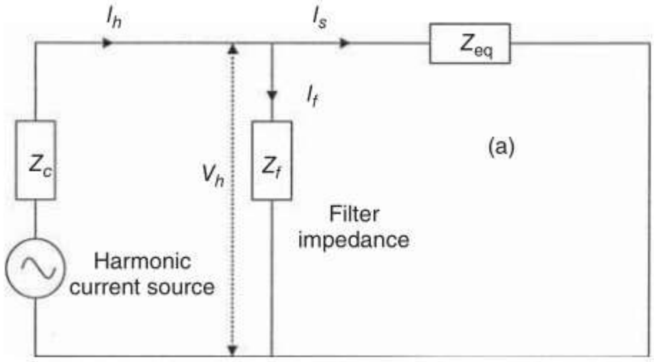

Figure 1.1.3. A SINGLE TUNED FILTER.

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 over voltages 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 Fig. 1.1.3.

Harmonic current injected from the source through impedance Zc divides into Filter and system equivalent impedance Zeq. This system impedance can be found by circuit reduction - this is in fact the short-circuit equivalent impedance.

The current Is divides into two parallel paths with magnitude as Ih and If.

$$I_h = I_f + I_s$$

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

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

$$I_f = \sigma_f I_h$$

$$I_s = \sigma_s I_s$$

Where, σ_f and σ_s are complex quantities that determine distribution of current in filter and system impedance

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Introduction

1.2 Harmonic mitigation through the use of active power filters

1.2.1 Series active power filter

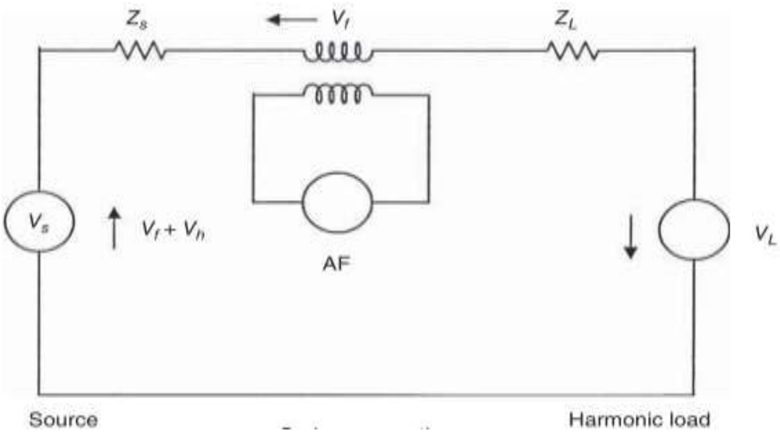

FIGURE 1.2.1. A SERIES ACTIVE POWER FILTER.

A voltage Vf 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 1.2.1(a) and 1.2.1(b) show the equivalent circuit of series active filter for harmonic current and voltage source.

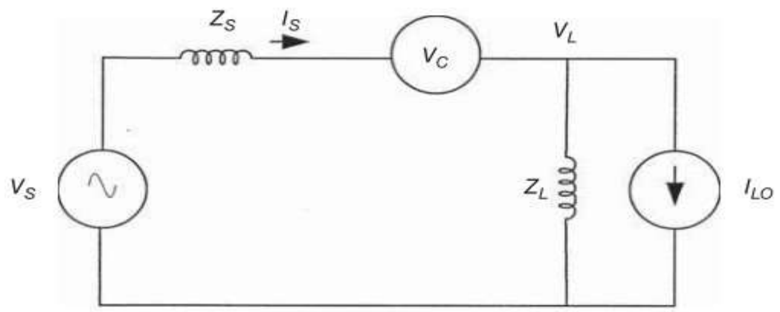

FIGURE 1.2.1(a).SERIES ACTIVE POWER FILTER FOR HARMONIC CURRENT LOAD

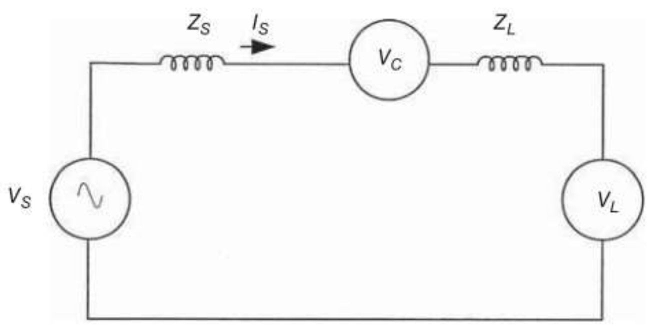

FIGURE 1.2.1(b).SERIES ACTIVE POWER FILTER. FOR HARMONIV VOLTAGE LOAD.

1.2.2 Shunt active power filter

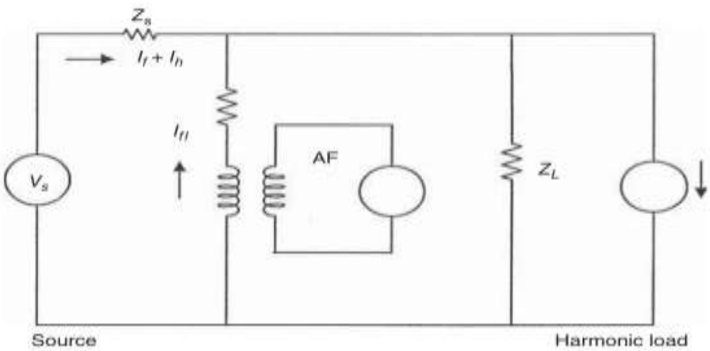

FIGURE 1.2.2. A SHUNT ACTIVE POWER FILTER

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, providedthat the system is not too stiff, a nonsinusoidal 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 PWM inverter to inject a harmonic current of the same magnitude as that of the nonlinear load into the system, but of harmonics of oppo- site polarity. A shunt connection is shown in Fig.1.2.2. Theload current will be sinusoidal, so long as the load impedance is higher than the source impedance.

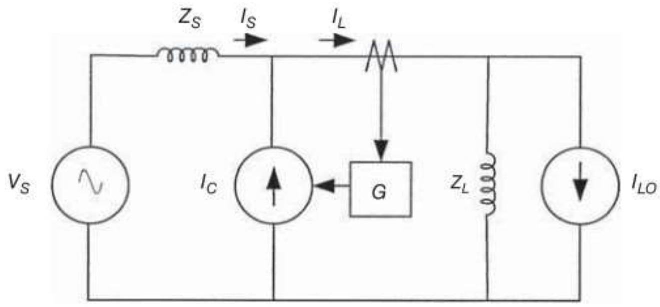

FIGURE 1.2.2(a). SHUNT ACTIVE POWER FILTER FOR HARMONIC CURRENT LOAD.

Figure 1.2.2(a) and 1.2.2(b) show the equivalent circuit of parallel active filter for harmonic current and voltage source.
Fig. 1.2.2(a), equation for Is can be written as

$$I_s = \frac{Z_l I_{l0}}{Z_s + \frac{Z_L}{1-G}}$$

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

$$\text{that is if } |1-G|_h \approx 0$$

$$\text{then} \quad I_{sh} \approx 0$$

The subscript h signifies harmonic component.

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

if the shunt active filter is controlled such that,

$$V_c = \mathbf{kGI_s}$$

then source current is

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

In order that the source current becomes sinusoidal

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

then,

$$V_C = Z_L I_{\mathrm{Lh}} + V_{\mathrm{sh}}$$

However, these conditions cannot be satisied. 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 ZL is almost infinite. The requiredoutput voltage Vc also becomes infinite.
In Fig.1.2.2 (b), forseries filter compensating a harmonic voltage source, the current is

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

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

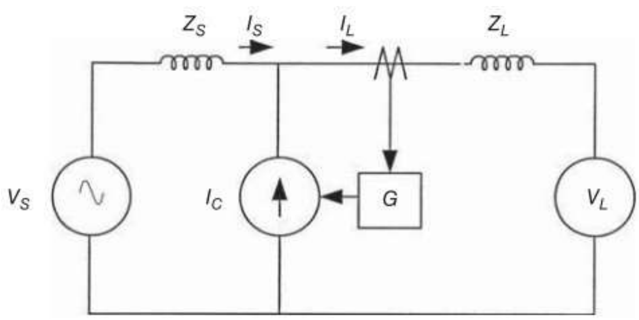

FIGURE 1.2.2(b) SHUNT ACTIVE POWER FILTER. FOR HARMONIC VOLTAGE LOAD.

1.3 Methodology and Experimentation

For detailed model of the experimental setup please visit-

https://in.mathworks.com/matlabcentral/fileexchange/ 87062-grid-connected-solar-power-plant-with-active- passive-p-f?s__tid=mlc__lp__leaf

1.3.1 Experimental Setup

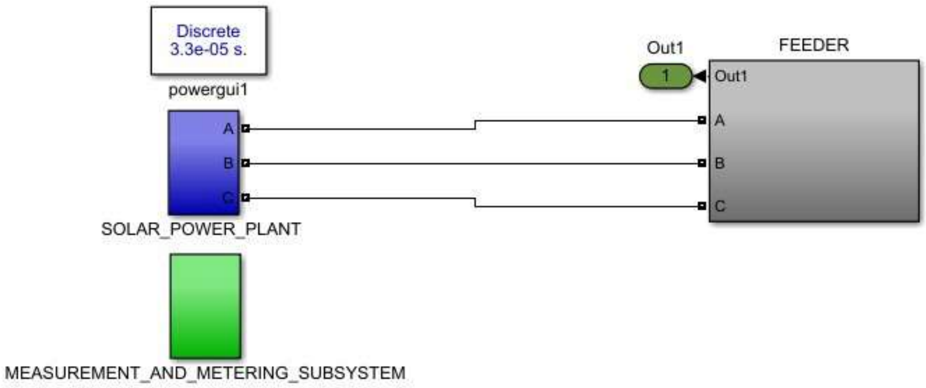

FIGURE 1.3.1 THE POWER SYSTEM .

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

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

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

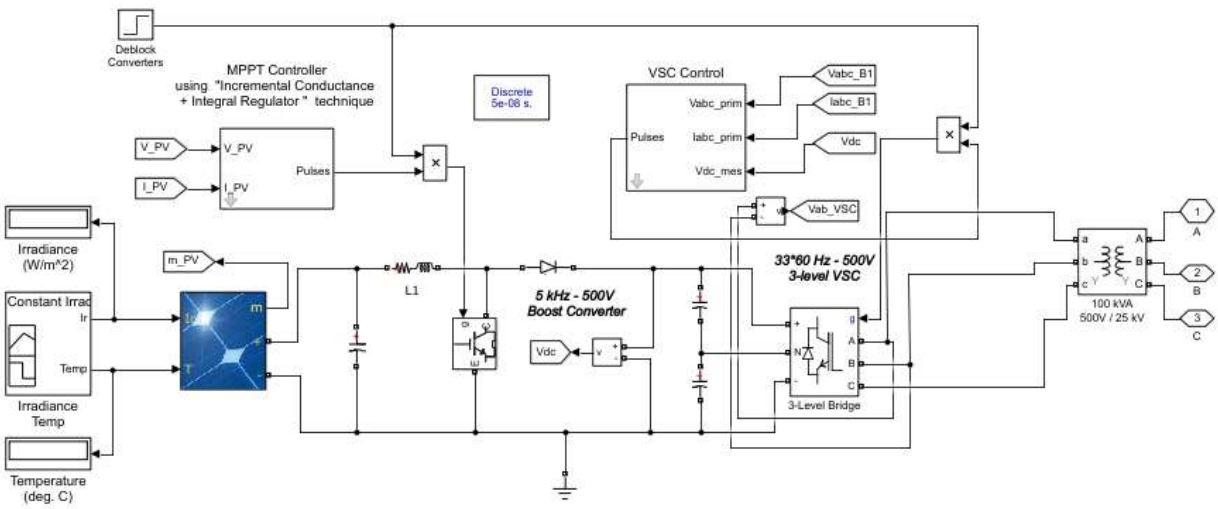

FIGURE 1.3.2 THE SOLAR POWER PLANT.

Introduction

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 Simulinkr 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:

- **PV array delivering a maximum of 100 kW at 1000 W/m^2 sun irradiance.**

- **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 Conduc- tance + Integral Regulator' technique. This MPPT system automatically varies the duty cycle in order to generate the required voltage to extract maximum power.**
- **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:**

1. an external control loop which regulates DC link voltage to +/- 250 V and;

2. An internal control loop which regulates Id and Iq grid currents (active and reactive current components). Id current reference is the output of the DC voltage external controller.

3. Iq current reference is set to zero in order to maintain unity power factor. Vd and Vq voltage outputs of the current controller are converted to three modulating signals Uabc_ref used by the PWM Generator. The control system uses a sample time of 100 microseconds for voltage and cur- rent controllers as well as for the PLL synchronization unit. Pulse generators of Boost and VSC converters use a fast sample time of 1 microsecond in order to get an appropriate resolution of PWM waveforms.

- **10-kvar capacitor bank filtering harmonics produced by VSC.**
- **100-kVA 260V/25kV three-phase coupling transformer.**
- **Utility grid (25-kV distribution feeder + 120 kV equiv- alent transmission system).**

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).

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/).

The manufacturer specifications for one module are:

- **Number of series-connected cells : 96**
- **Open-circuit voltage: Voc= 64.2 V**
- **Short-circuit current: Isc = 5.96 A**
- **Voltage and current at maximum power : Vmp =54.7 V, Imp= 5.58 A**

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The PV array block menu allows you to plot the I-V and P- V characteristics for one module and for the whole array.
The PV array block has two inputs that allow you varying sun irradiance (input 1 in W/m^2) and temperature (input2 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 written below-

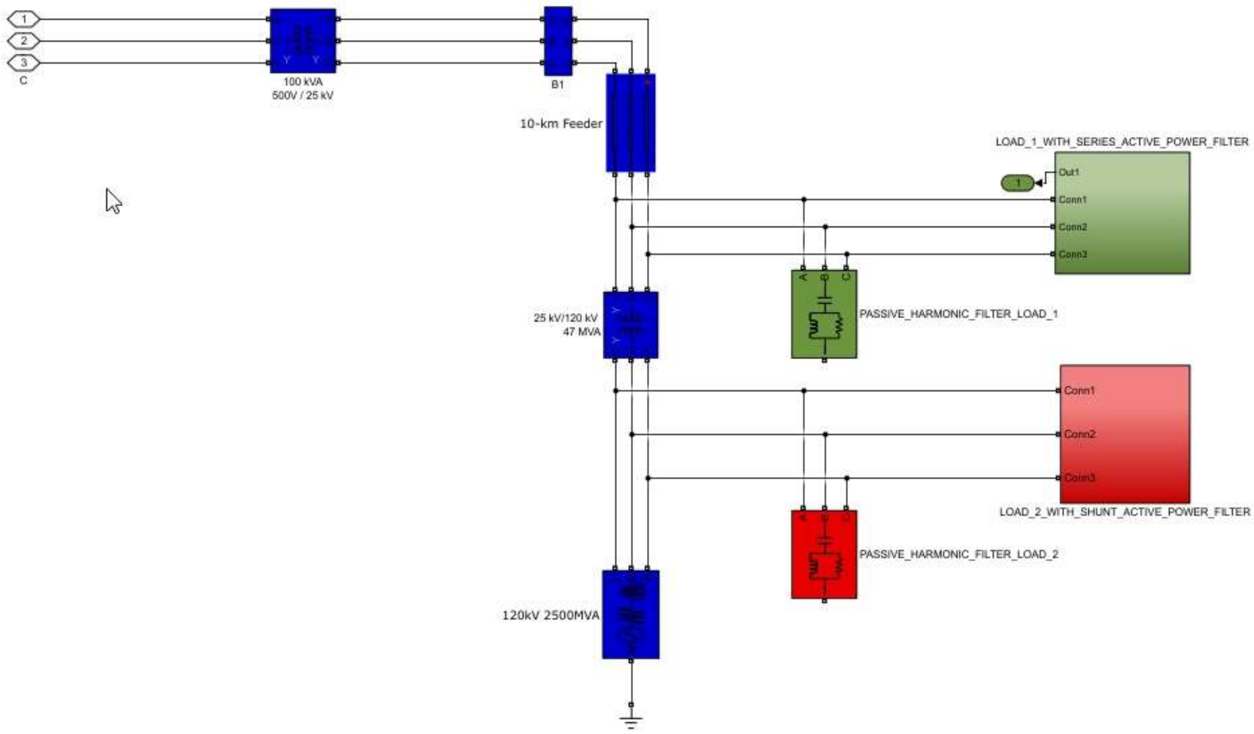


FIGURE 1.3.3 THE FEEDER.

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.

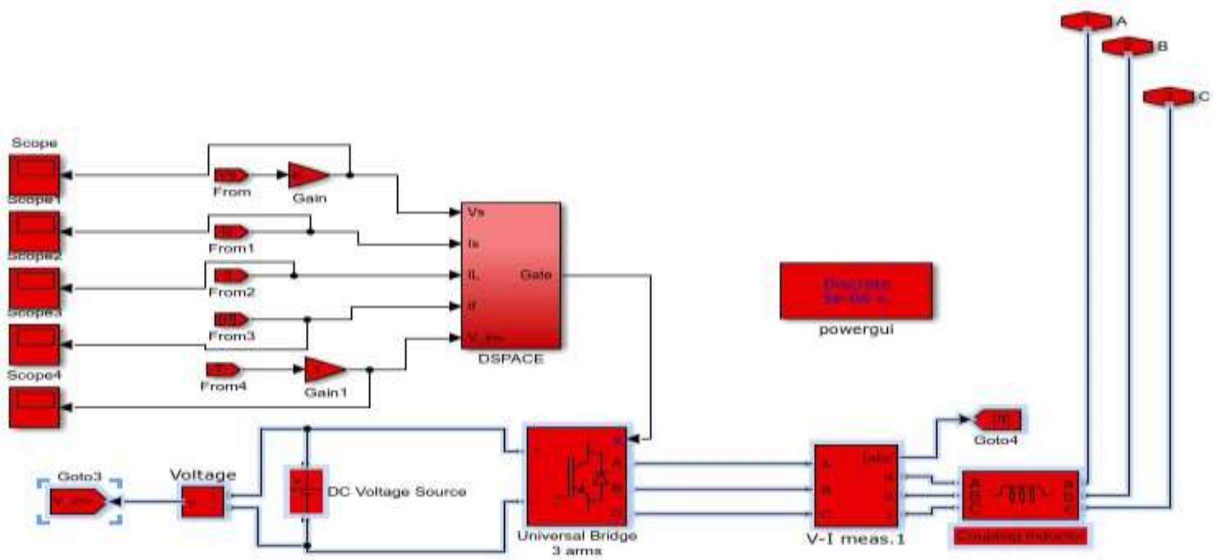


FIGURE 1.3.4 THE SHUNT ACTIVE POWER FILTER.

Introduction

The above block diagram 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 Dspace block for additional simplicity.

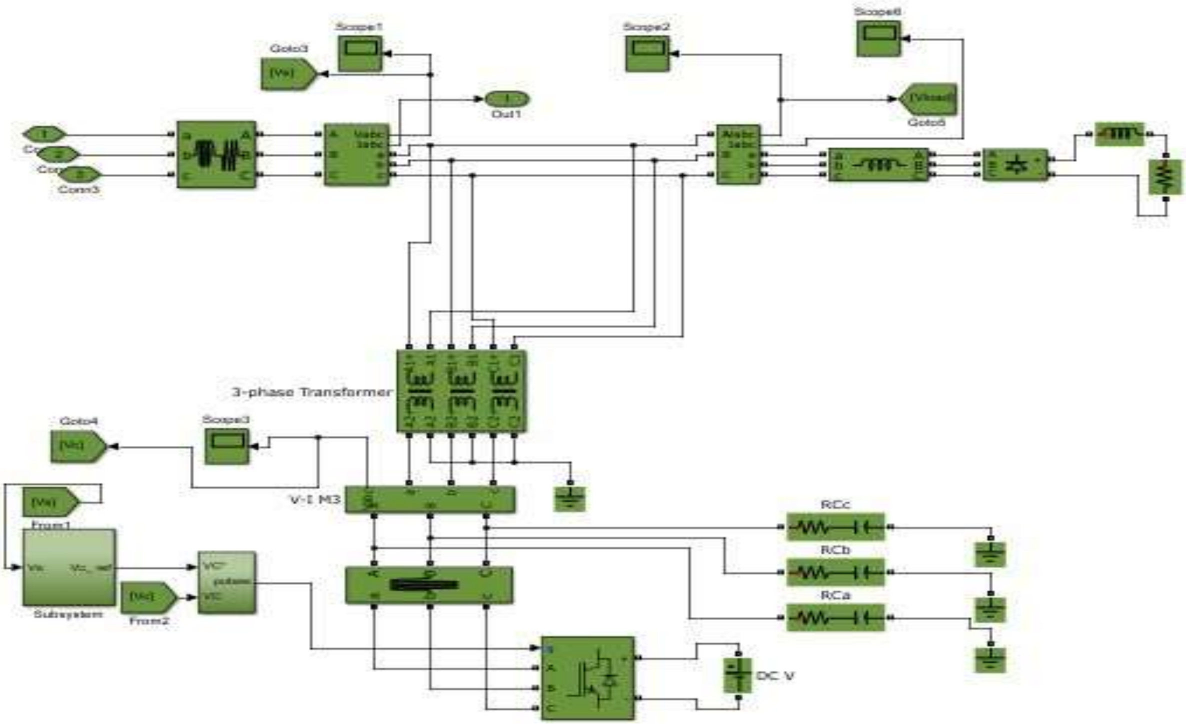


FIGURE 1.3.5 THE SERIES ACTIVE POWER FILTER.

The above block diagram 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.

1.3.2 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. The currents and voltages of which fft analysis has been done are listed in the following table.

TABLE 1.3.2 TAG NAME AND LOCATION OF CONCERNED VOLTAGE AND CURRENT IN THE SIMULINK MODEL

•

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

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 flter 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

Section 2

Result of simulation

Every waveform is arranged in the following order-

1.Load current waveform

2.Load voltage waveform

3.Fast fourier transform of load current waveform

4.Fast fourier transform of load voltage waveform

2.1With no filters connected to Load 1 the following wavefrom of load current and load voltage are obtained -

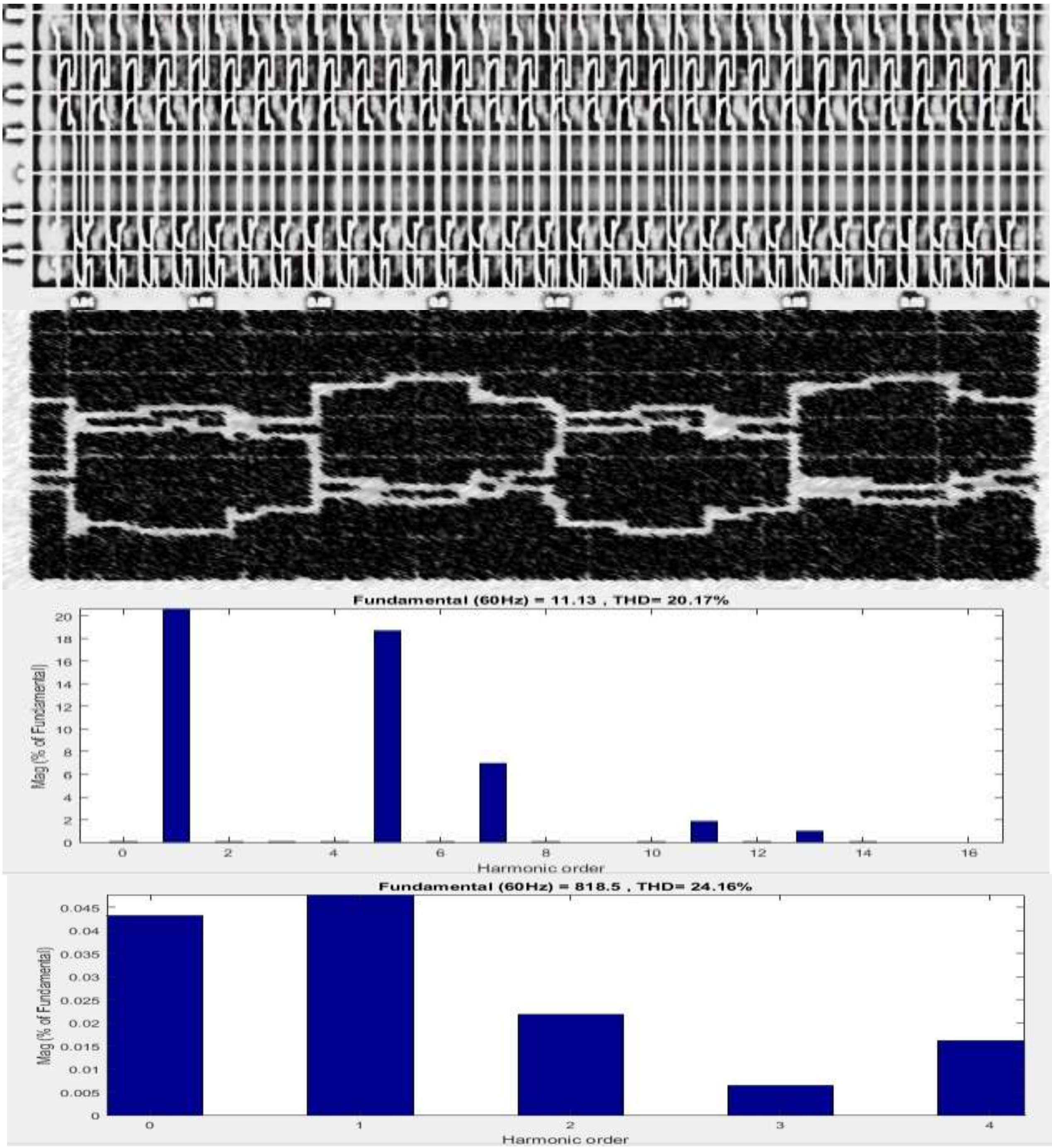


FIGURE 2.1 NO FILTER WAVEFORMS(LOAD 1)

Result of simulation

With no filters connected to load 2 the following load current and load voltage waveform are observed-

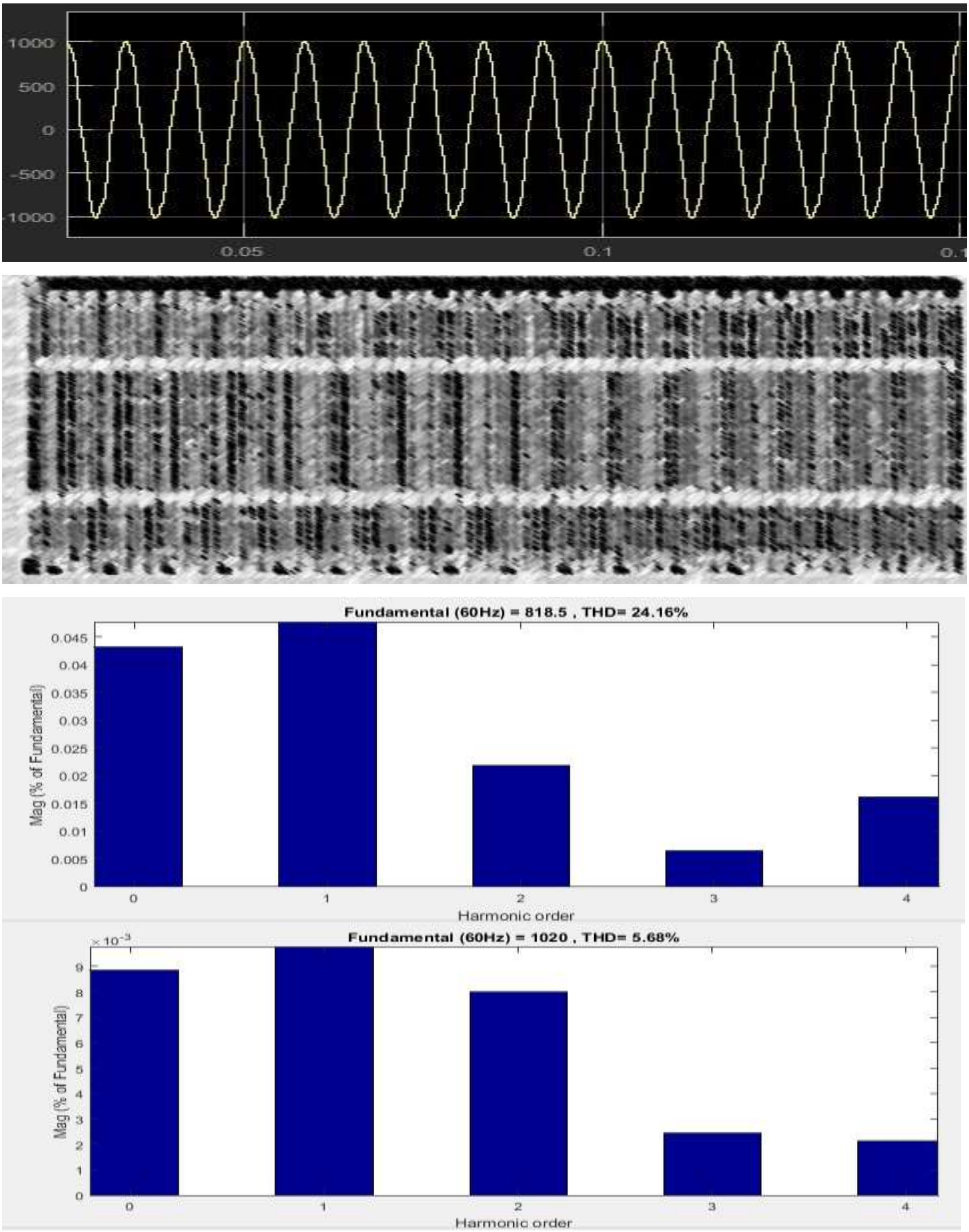


FIGURE 2.1 NO FILTER WAVEFORMS(LOAD 2)

Section 2

2.2 With only shunt active power filter connected to load 2 the following load current and load voltage waveforms are observed -

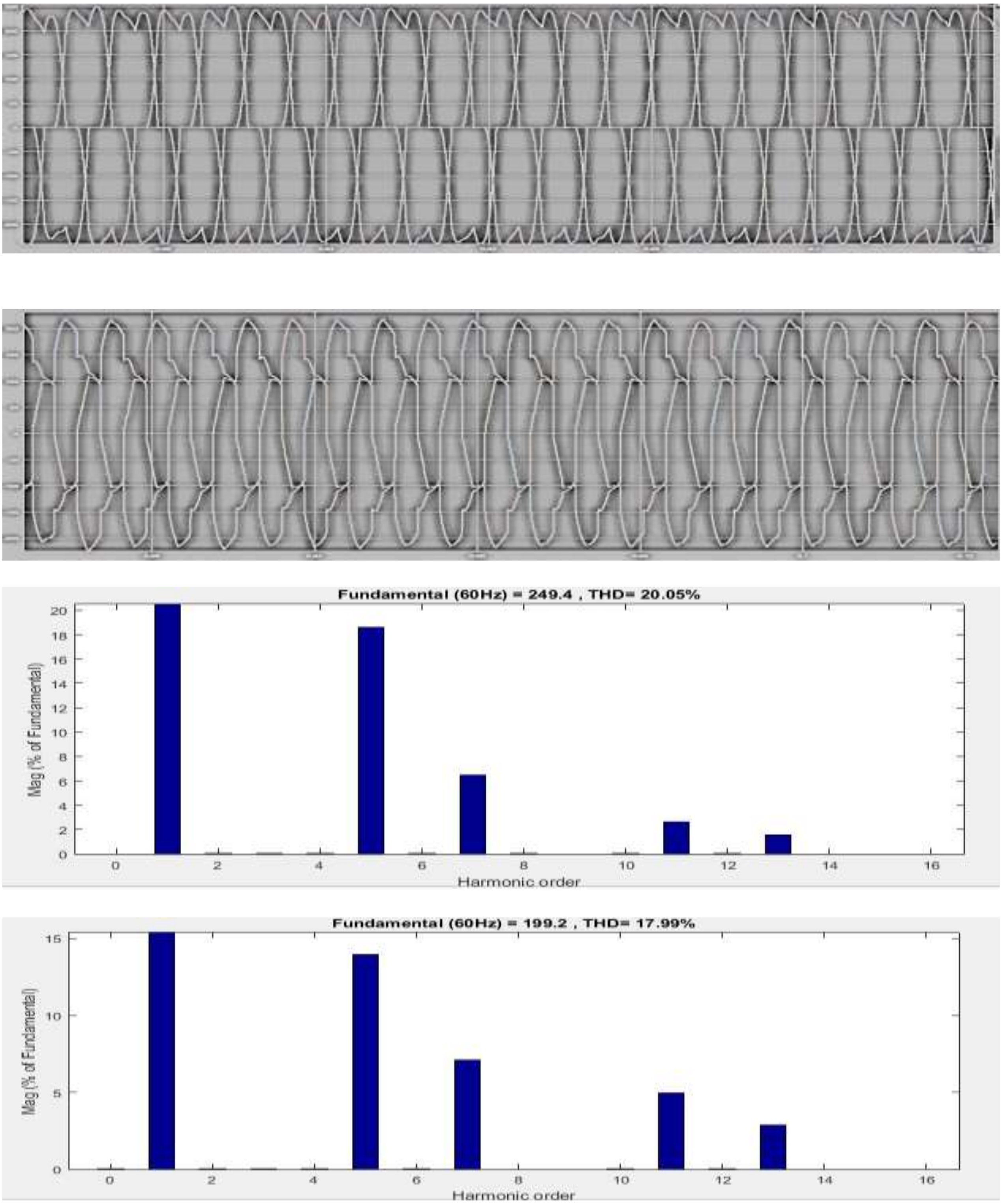


FIGURE 2.3 SHUNT ACTIVE POWER FILTER WAVEFORM(LOAD 2)

Section 2

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

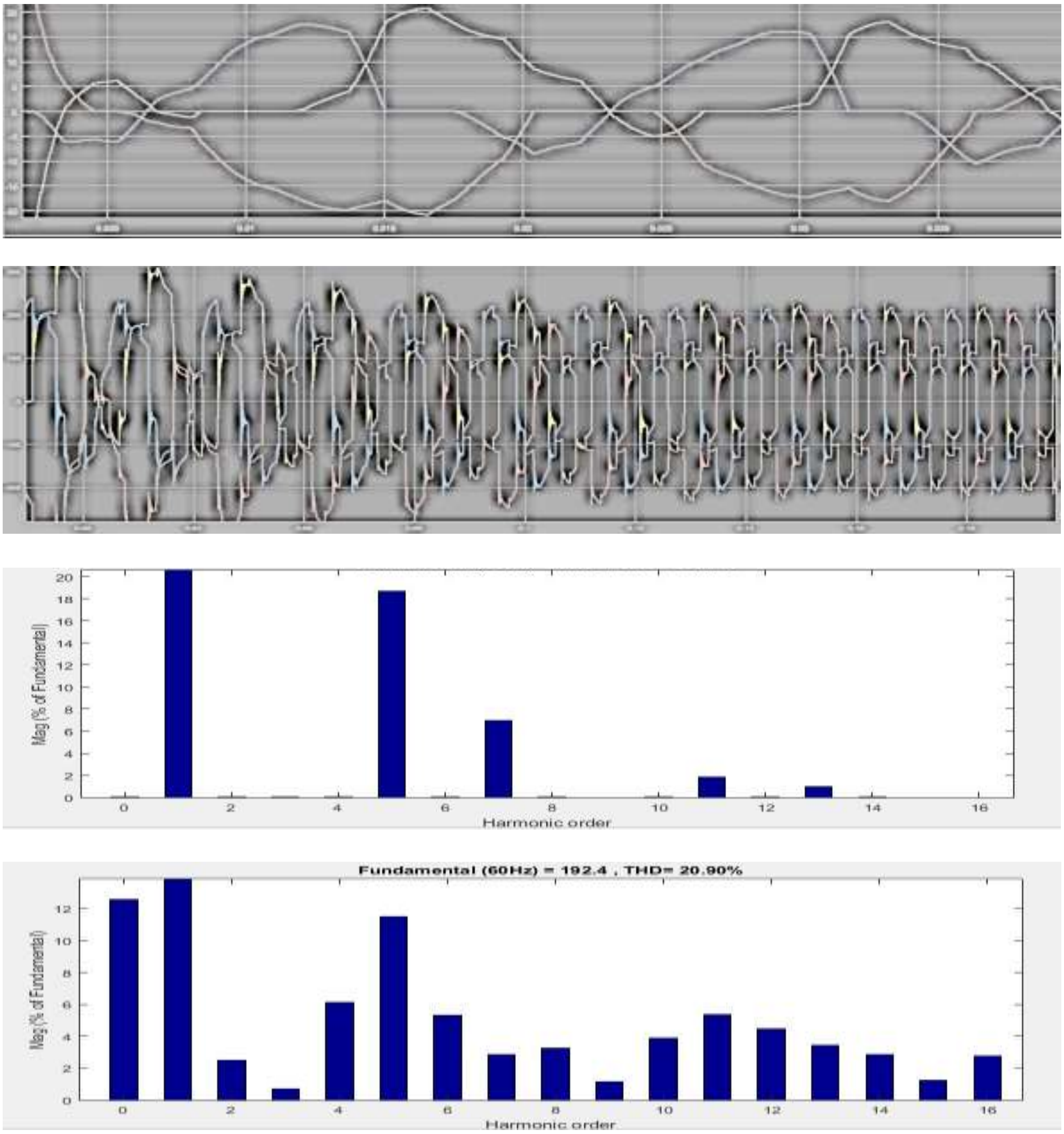


FIGURE 2.3 SERIES ACTIVE POWER FILTER WAVEFORM (LOAD 1)

Result of simulation

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

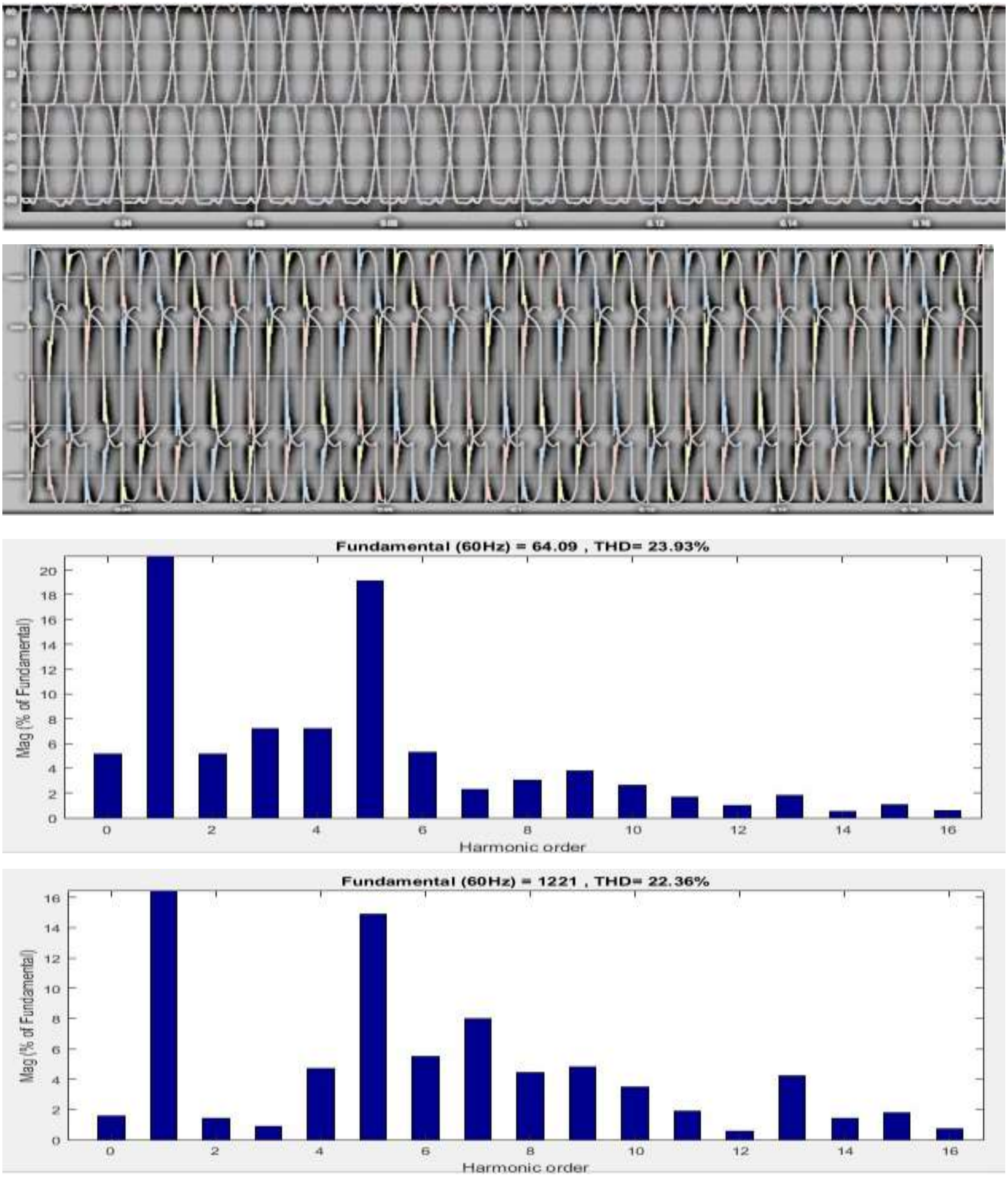
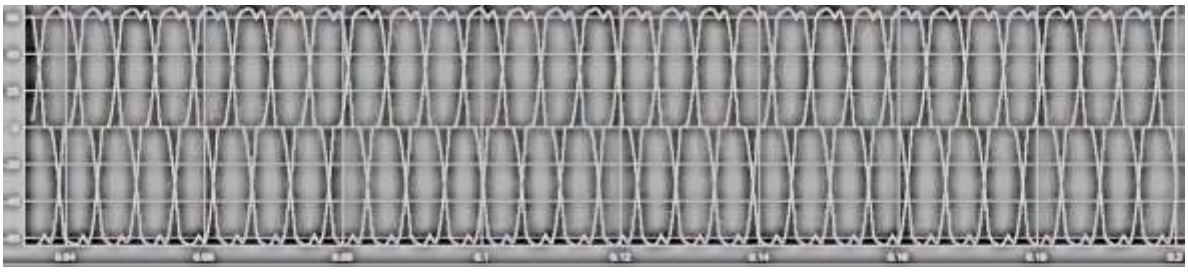
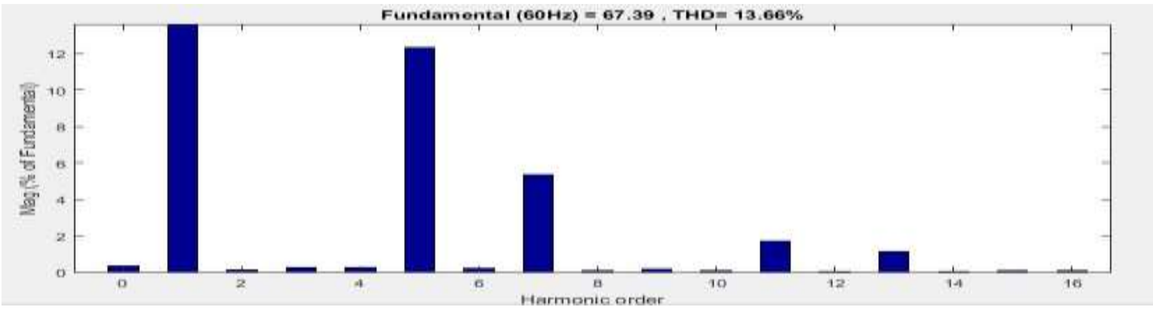


FIGURE 2.4 SINGLE TUNED FILTER WAVEFORM(LOAD 1)

Result of simulation

2.5 With only double tuned filter tuned for 5th and 7th harmonic connected across load 1 the following load current and load voltage waveform are obtained -





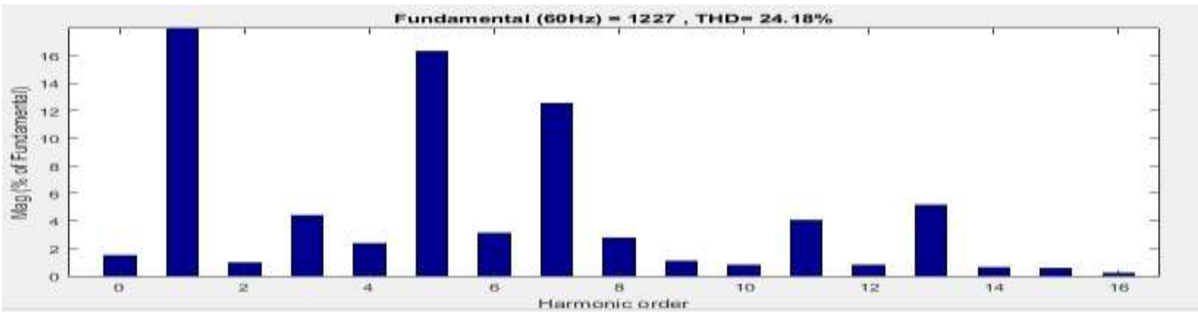


FIGURE 2.5 DOUBLE TUNED FILTER WAVEFORMS(LOAD 1)

Section 2

2.6 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 -

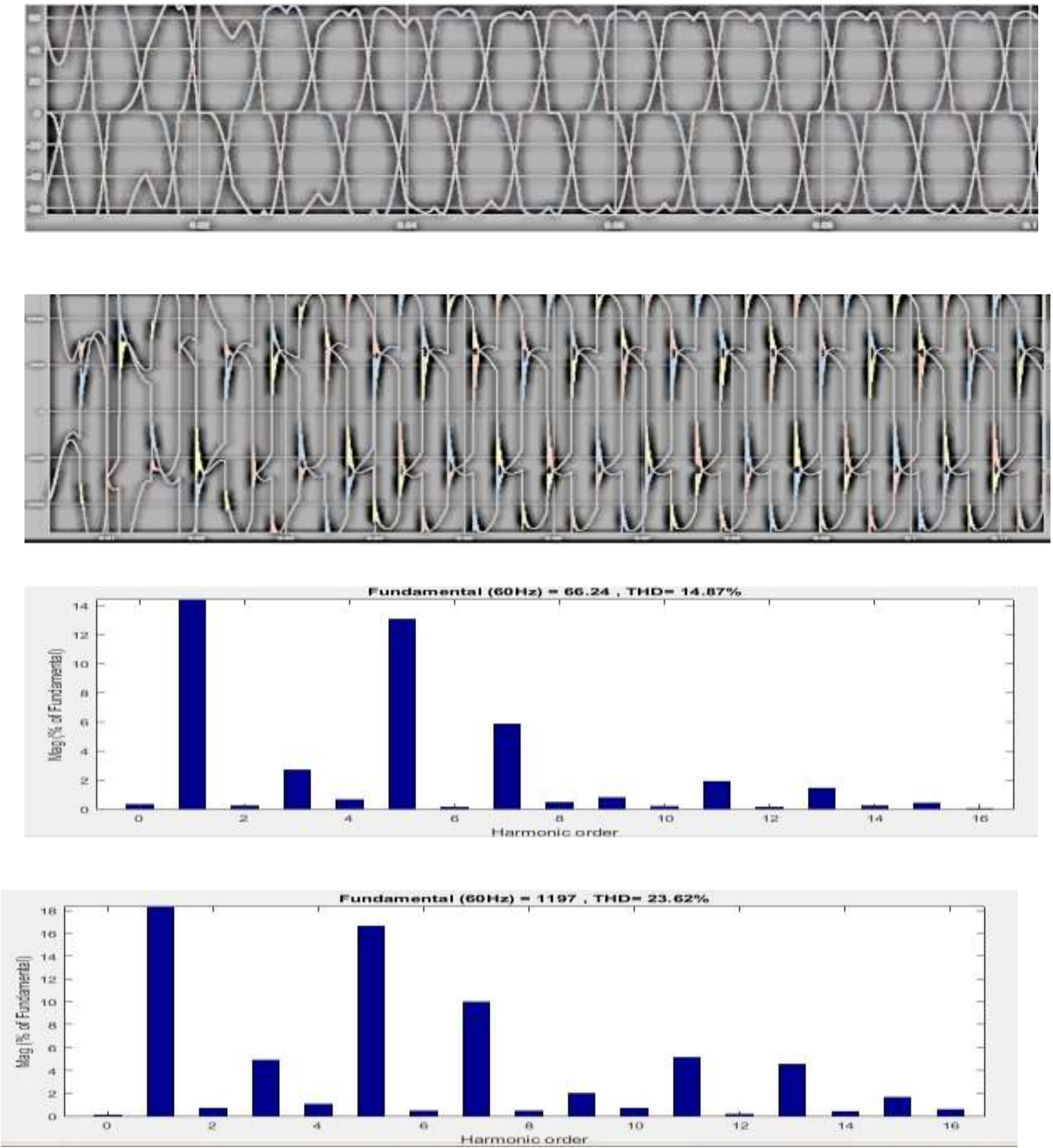


FIGURE 2.6 HIGH PASS FILTER WAVEFORM (LOAD 1)

Result of simulation

2.7 With only single tuned filter tuned for 2nd har- monic connected across load 2 the following load current and load voltage waveform are observed -

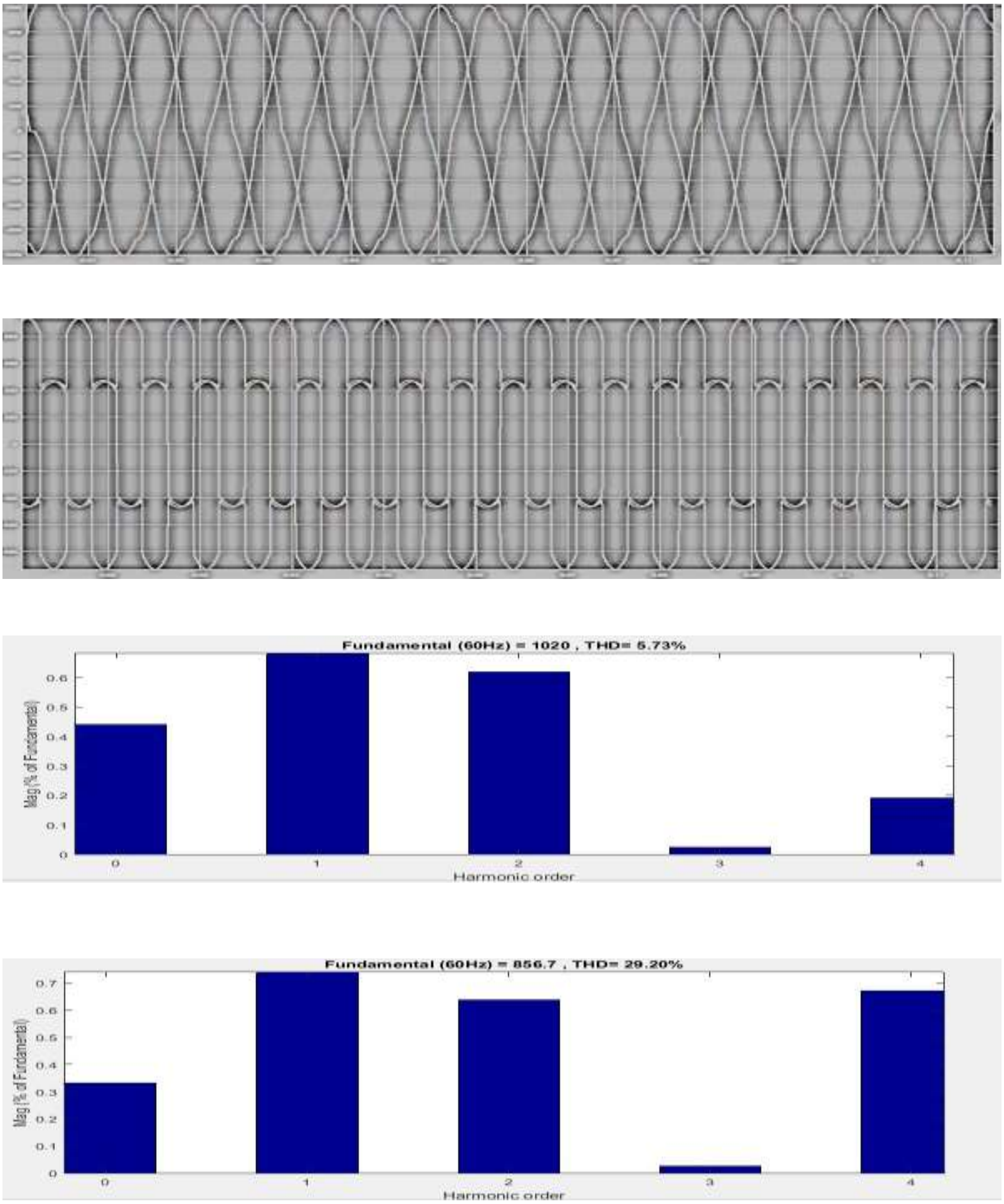


FIGURE 2.7 SINGLE TUNED FILTER WAVEFORMS (LOAD 2)

Section 2

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

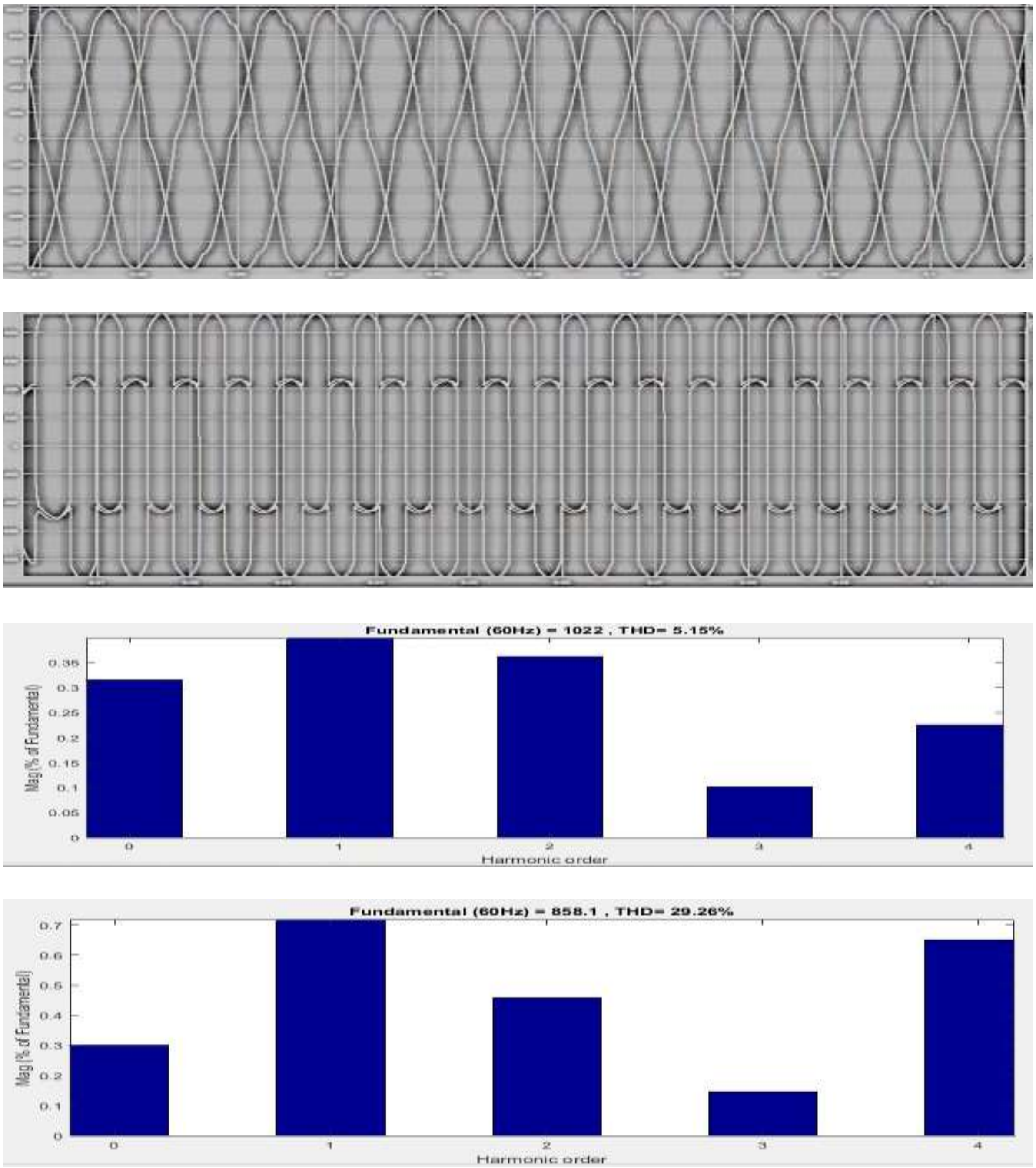


FIGURE 2.8 DOUBLE TUNED FILTER WAVEFORM(LOAD 2)

Result of simulation

2.9 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 -

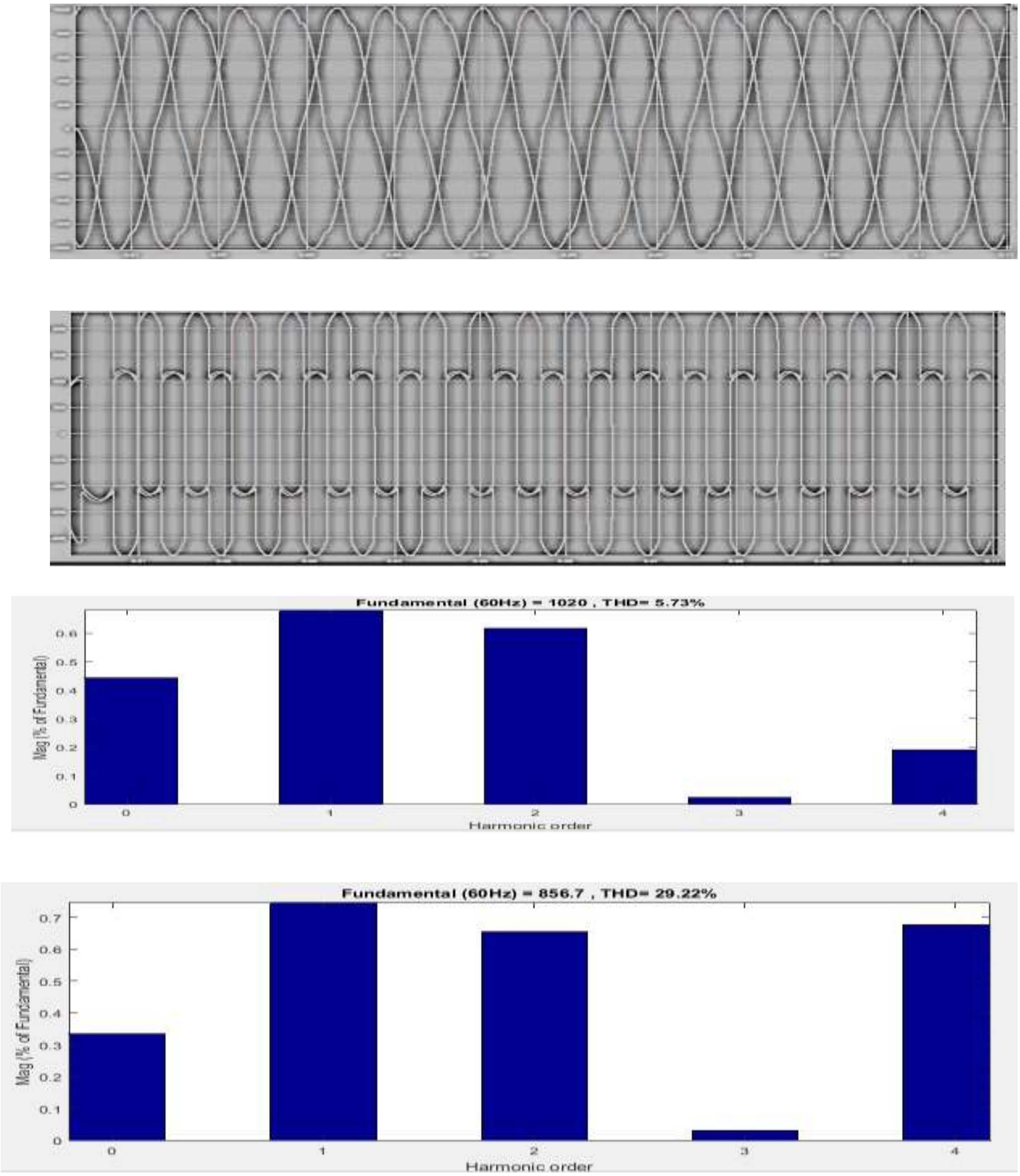


FIGURE 2.9 HIGH PASS FILTER WAVEFORMS (LOAD 2)

3 Conclusions

3.1 TABLE 3.1 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%

3.2 Passive power filters perform best when tuned prop- erly but they are unable to compensate for the dc component of current/voltage waveform

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

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

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