COMPARATIVE ANALYSIS AMONG LC AND LCL FILTERS IN A SOLAR BASED MICROGRID

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Abstract: Microgrid is a small-scale power supply network that can effectively integrate various sources of distributed generation such as renewable energy and other sources. Microgrid operates in grid connected and islanded mode. In this paper, microgrid configuration considered has a solar PV system along with normal AC source and utility grid. The generated power from renewable energy source like solar is always varying as it depends on the environmental factors such as temperature and sunlight (irradiance). Here, boost converter serves the purpose of stepping-up the voltage level and maintaining constant output D.C voltage. Solar PV is intermittent in nature so there is a need to interface DC-DC converter along with MPPT algorithm to extract maximum power point. The output of boost converter is given as input to the inverter. Here, three phase VSI model connected to the output of DC-DC converter and gate pulses to the VSI are provided from the output of PLL such that the microgrid should always be in synchronism with the utility grid. When microgrid operates without using filter at inverter output terminals, it contains harmonics and THD in isolated system is very high. So, filters are compulsory to reduce the harmonics and to required sine wave. This paper mainly presents a methodology of passive filters (LC, LCL) that are designed to mitigate the harmonics in the VSI output. The pulses for inverter in grid connected mode are generated by using parameters such as voltage, current and frequency as reference. Total harmonic distortion is one of the power quality issues which is considered and measured at various locations. Results for improvement in power quality are verified by using MATLAB/Simulink.

Index Terms: **Microgrid (MG), Photovoltaic (PV) panels, MPPT, Perturb & Observe(P&O), Boost converter, VSI inverter, Power quality, LC filter, LCL filter grid connected system.**

1. INTRODUCTION

Microgrid

Electricity has become one of the most essential need in present day human's life. Without Electrical energy can't imagine ourselves as each and every moment in our day to day life. For example, all the electronic gadgets, domestic appliances, industrial machinery, Modes of transport etc., each and every utility works with the help of electrical energy. The power which use to make our day has to be generated either by means of renewable energy sources or non-renewable energy sources. Renewable or non-conventional energy sources are those whose energy is freely available and can be reused such as Solar energy, Wind energy, Biogas energy, Tidal energy, Hydel energy etc., whereas Non-renewable or Conventional energy sources are those which is mortal in nature. On excess of usage they may be exhausted one day. Coal, Petroleum, Fossil fuels, etc., come under these energy sources. By means of either Renewable or non-renewable energy sources or may be the combination of both energies are also used to produce electric energy [1].

The conventional grid cannot fulfil the increase in power demand. The grid facing multimode challenges such as infrastructural problem, service interruptions, various outage and inflexibilities. Microgrid technology growing very fast with using renewable energy and other sources of network in distributed power generation system combined with power electronic system which will be produce the further network technologies.

The recent advancement in power electronics technology there has been a step-growth in the increase of renewable source of energy can fed both stand-alone and grid-connected mode. [2]. In stand-alone there are several issues related with the microgrid structures which need to considered for its better improvement. Some of these power quality issues include voltage imbalance, seg, swell, reduction in harmonic distortion etc., [3]-[4]. This paper discusses about solar PV with grid-connected system of power quality improvement and designing of filters (LC, LCL).

2. Solar energy

The sun is the most abundant and sustainable source of energy, and provide over 150,000Tw of power to the earth. Half of this power reaches the earth's surface, and the rest of the absorbed or reflected back into outer space. Earth receives solar radiation from nuclear fusion reactions accruing at the core of sun. The rate at which energy reaches a unit area of the earth is known as solar irradiance which is measured in J/m^2[5].

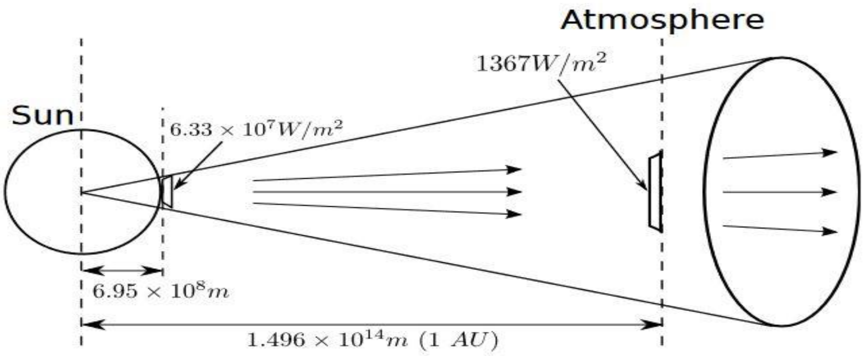

Figure1: Energy Divergence of sun to the earth

3. Photovoltaic cell

The photovoltaic (PV) generation systems are expected to increase significantly worldwide. PV's are an attractive source of solar energy for distributed urban power generation due to their relatively small size and noiseless operation. There are many advantages that more units can be added to meet load increase demand.

Major advantages of the solar PV cell as:

- Very short duration of time to install and startup new plant.
- Highly modular, hence the plant economy is not a strong function of size.
- Power output matches very well with peak load demands.
- It is static structure and noiseless.
- High power capability per units of weight.
- There are no moving parts and maintenance will be little and often a longer life.

Solar radiation can be converted directly into electricity using photovoltaic (PV) cells, PV cells are constructed from a variety of semiconductors, but mostly from silicon (Si), cadmium sulphide (CdS), copper sulphide (Cu_2S) and gallium arsenide (GaAs) [6]. With the help of photovoltaic PV cell which is convert heat energy in to electrical energy.

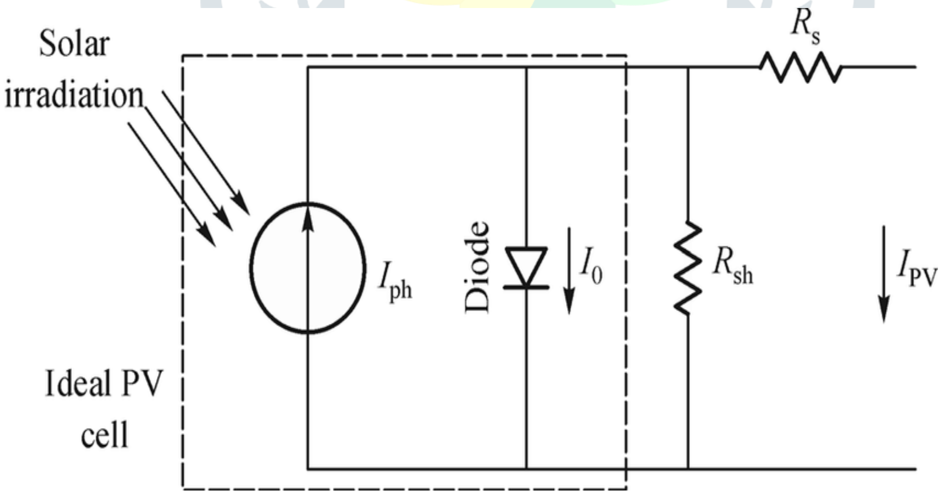

Figure 2: Equivalent circuit of a PV module.

4. DC-DC (Boost converter) with MPPT grid connected system

A photovoltaic cell (PV) is a specialized semiconductor diode that converts visible light into direct current (DC). PV cell can also convert infrared (IR) or ultraviolet (UV) radiation into DC electricity. Solar PV is intermittent in nature so there is a need to interface DC-DC converter along with MPPT algorithm to extract maximum power from it. More number of PV panels are connected in series in order to achieve high level of voltage and also boost converter is used as an interfacing converter between source and load. The maximum power of PV cell changes with the environmental conditions as well as with the change of load extract maximum power from PV cell [7].

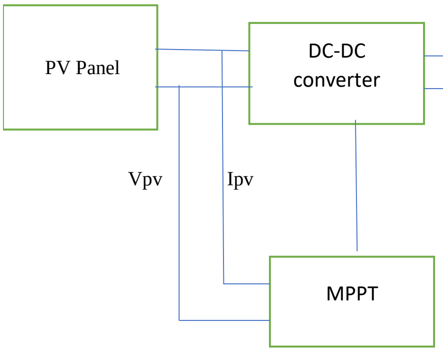

Figure 3: The concept of a system using MPPT

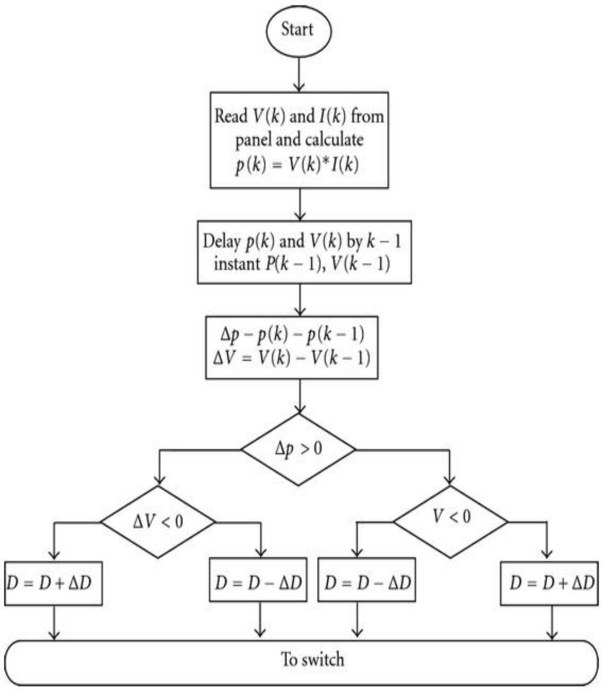

Figure 4: MPPT algorithm

The operating characteristics I-V and P-V of solar are not at their maximum values due to continuous change in environmental conditions. In order to overcome these problems, MPPT methodology is used [7]-[8].

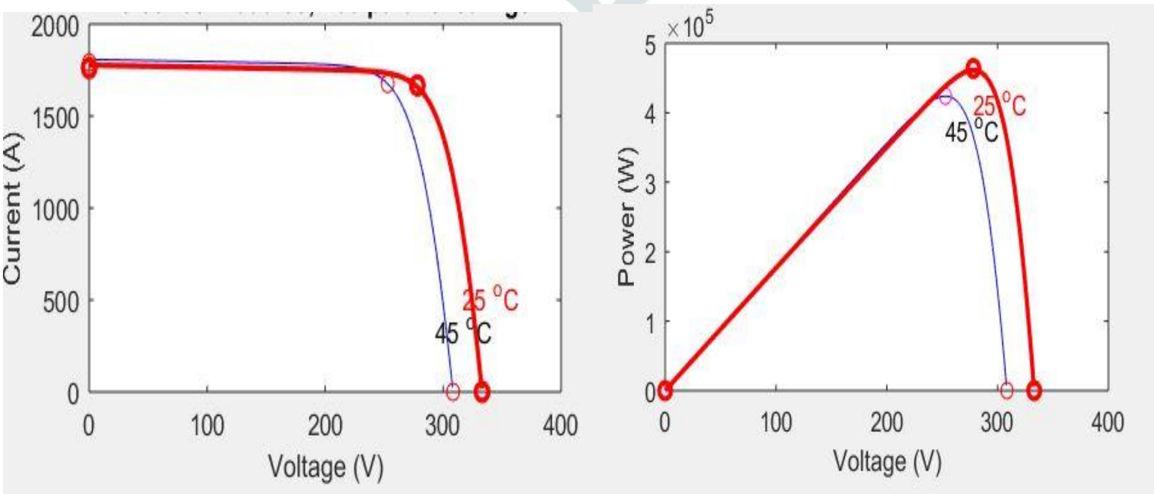

Figure 5: MPPT V-I and V-P characteristics

4.1. DC-DC Converter (Boost Converter)

Voltage from PV Panel is very low for the grid-connected system, so stepping up of voltage level is required. Here, boost converter is used to increase the voltage level. The main components of a boost converter are diode, capacitor, inductor and high frequency switch. [9]

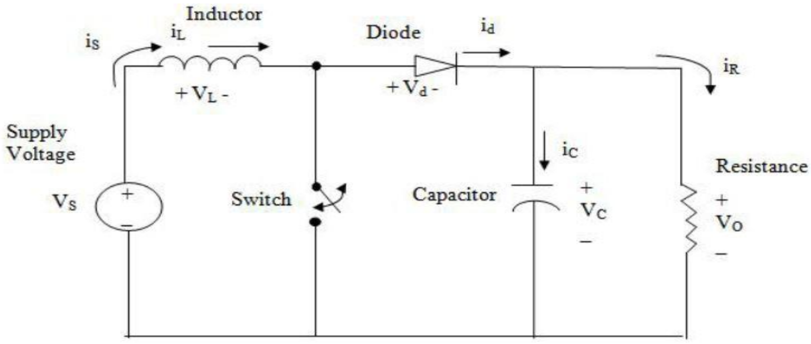

Figure 6: Boost converter

$D = Vs(Vo - Vs) / Vo$
$Lmin = Vin\ (Vout - Vin) / \Delta IL * Vout * Fs$
$Cmin = Iout * D / Fs * \Delta Vout$

Where
- Lmin= Minimum inductance;
- Cmin= Minimum capacitance;
- D = Duty ratio;
- Vs = Input voltage;
- Vo = Output voltage;
- R = Boost output resistance;
- Fs = Switching frequency;
- Vr = Output ripple Voltage = $(\Delta Vout/Vout)$;

4.2. Modeling of Boost Converter

The DC link voltage should be maintained constant to minimize the ripple content from PV source as well as for power balancing. To satisfy above criteria a DC link capacitor ($C_{DC\ Link}$) is used [10].

$C_{DC\ Link} = 2*Pmax /f*V_{dc}{}^{\wedge 2}*(1-k)^{\wedge 2}$

Where
P_{max}= Maximum power
F = Grid frequency
V_{dc} = DC link voltage
K = Constant= $Vdcmin/Vdc$

5. Voltage Source Inverter

The voltage source inverter is the electronic circuit which is used to convert the DC input voltage to AC output. These voltage source inverters are of available for both single phase and three phase configurations. The single-phase voltage source inverters are used for low power ratings whereas the three phase voltage source inverters are used for medium as well as high power rating operations. Three phase VSI model connected to the output of DC-DC converter. The gate pulse to the switches in the VSI is provided from the output of PLL such that the microgrid should always be in synchronism with the utility grid [11].

6. Phase Locked Loop

As the renewable source are varying in nature, it is very difficult to integrate this varying natured microgrid with the utility grid. PLL is the control technique employed in microgrid in order to establish a secure synchronism with grid. Failure of this control results in collapse of entire microgrid. PLL consists of a phase detector, loop filter, voltage-controlled oscillator. It is provided with the utility grid voltage as reference voltage such that, it can send the signal to the inverter so as to get the desired voltage, frequency and phase from the inverter output. Here the PLL employs abc-dq transformation in which it generates the output pulses depending on the reference.

7. Design of LC and LCL Filters with Grid connected system

7.1 LC Filter

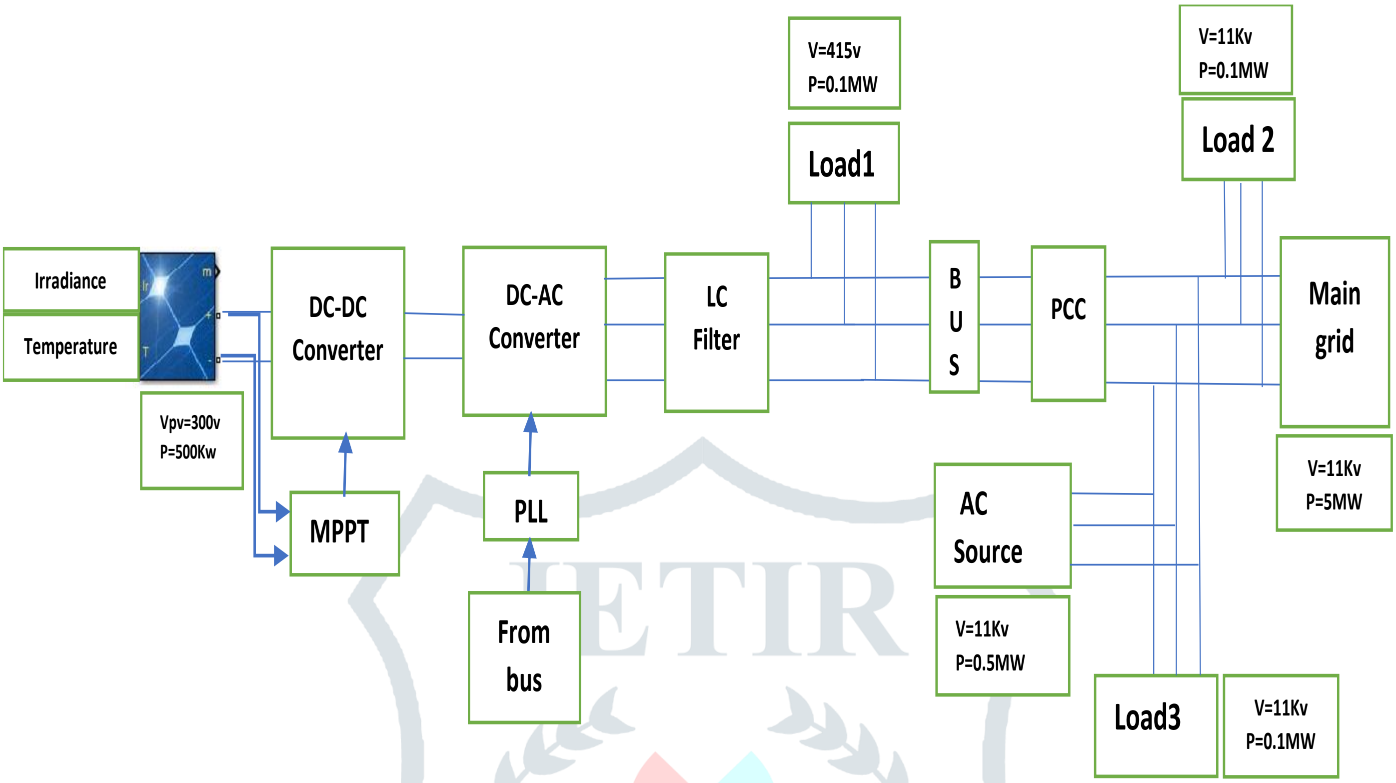

Figure 7: Block diagram of Grid connected solar PV system with LC Filter

Filter will be used to reduce the harmonics, and remove the high-frequency components from inverter output. In this paper low pass LC filter is designed to remove the unwanted harmonics, ripple content in voltage and current and also reduce the switching losses. Here, ripple current can be chosen as 5% to15%. Capacitor is designed based on the reactive power and capacitor ripple voltage of 5%, which is supplied by the fundamental frequency [12].

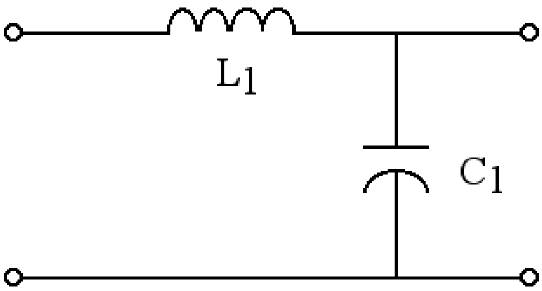

Figure 8: LC Filter

$L_1 = \frac{Vdc}{8*fsw*delta_{Ilmax}}$;

$C_1 = 0.05 * Pn/2 * pi * 50 * (En^{\wedge 2})$;

Pn = Rated active power,

E_n = line voltage,

Vd_C = DC-link voltage,

fsw = Switching frequency,

L_1 = Inverter side of the inductor,

C_1= Capacitor, Fg = Frequency.

7.2 LCL Filter

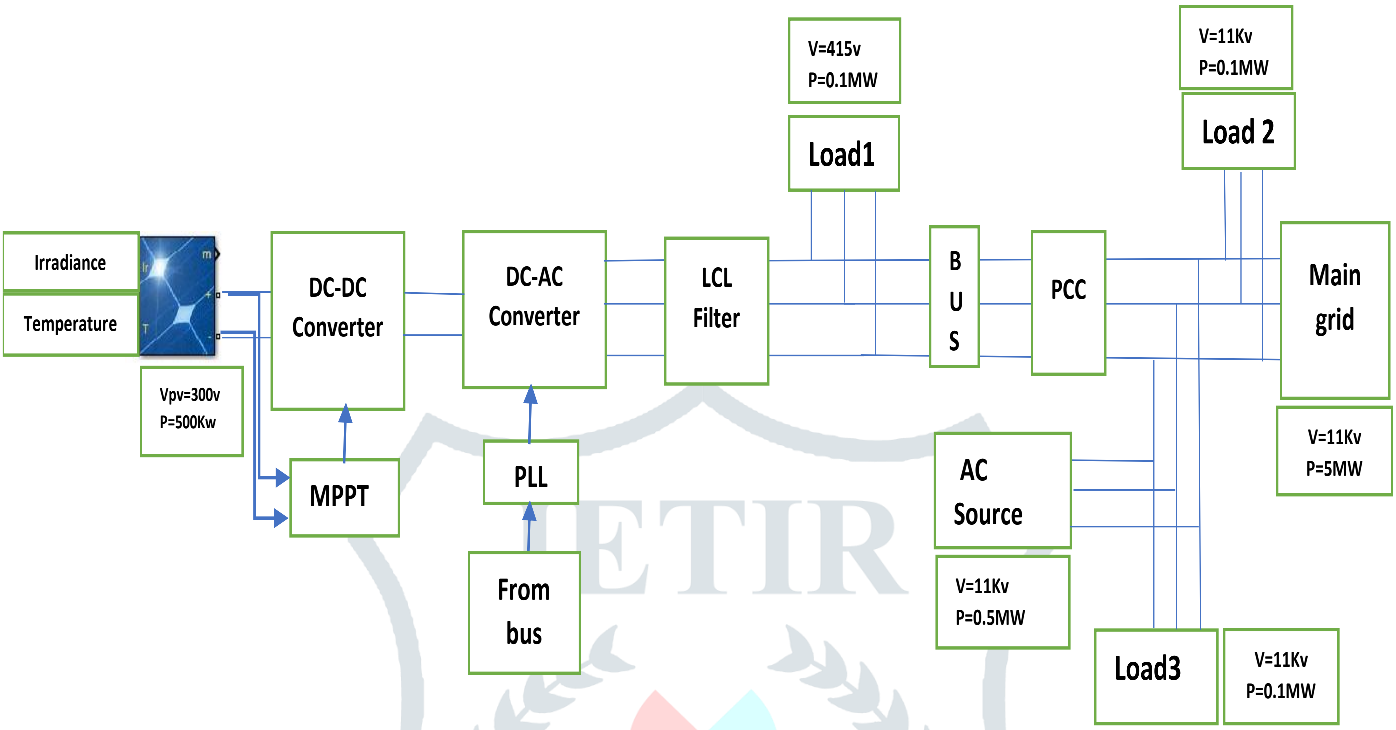

Figure 9: Block diagram of Grid connected solar PV system LCL Filter

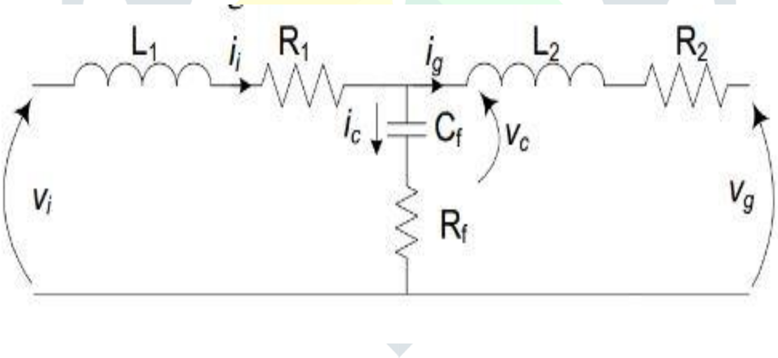

Figure 10: LCL Filter

Here
L_1= Inverter side of the inductor,
L_2 = Grid side of the inductor,
C_f = Capacitor
R_f = Damping resister,
R_1, R_2 are the resistance of the inductors,
V_i = Input of inverter voltage and Vg is the grid voltage.

LCL filters have been used in grid-connected inverters to reduce the harmonics along with cost savings, given the overall weight and size reduction of the components because they minimize the current distortion injected into the utility grid. The higher harmonic attenuation of the LCL filter allows the use of lower switching frequencies to meet harmonic constraints as defined by standards such as, IEEE-519 and IEEE-1547 [13]-[14].

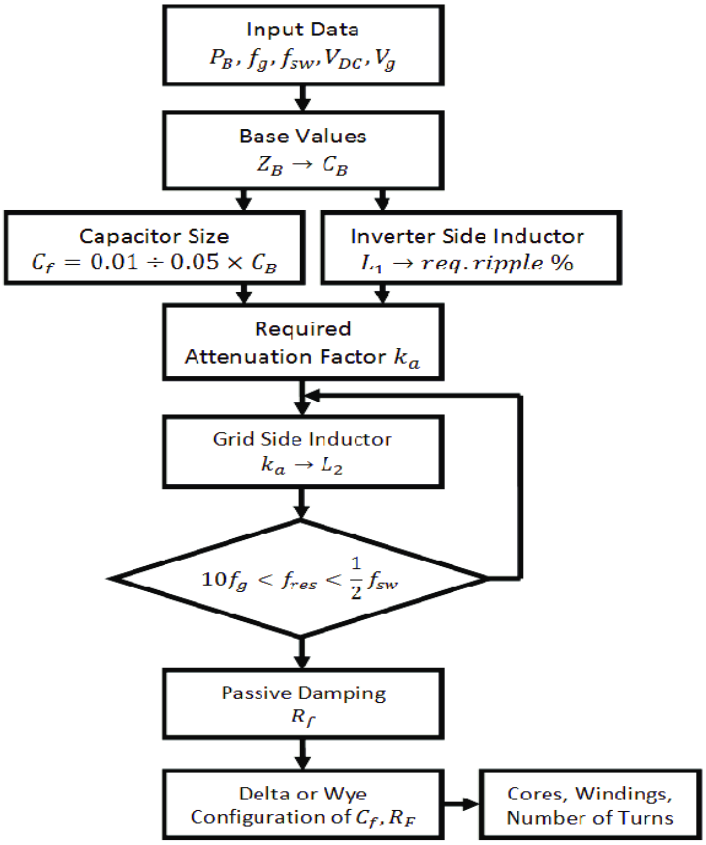

Figure 11: LCL filter design algorithm

Here,
Pg = Rated active power,
Vd_C = DC-link voltage,
Vg = Grid side voltage
Fg = Grid frequency,
Fsw = Switching frequency,
$Fres$ = Resonance frequency,

According to LCL algorithm from the figure.11, Zb is base impedance and Cb is base capacitance. For design of the filter capacitance C_f takes the maximum power factor by the grid of 5% to the base impedance of the system inverter-side inductor. Considering 10% ripple of the rated current for parameters design [15]-[16]. LCL filter will reduce ripple current up to 20% of the harmonic current generated by the inverter [17]-[18].

$$\frac{Ig(h)}{Ii(h)} = 1/[1 + r[1 - L1Cb\omega^2{}_{Sw}\,x]] = Ka$$

Where Ka is the attenuation factor then $Cf = x * Cb$,
Where r is the ratio between inductance of inverter side and utility grid side.
R_f is the resonant frequency, it depends on nominal impedance of utility grid, the value of resister is one-third in impedance of filter capacitor, at resonant frequency [19].

Table.1: Harmonic distortion limits range is considered by IEEE standards of IEE-519 and IEEE-1547.

Harmonic order(h)	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	Total Demand Distortion (TDD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

8. Operation of micro grid (Islanded and Grid connected)

The complete block diagram of microgrid is shown in the above figure:7 using LC filter & figure:9 using LCL filter. Microgrid can be operated in islanded and grid connected modes. In grid connected mode it takes reference from PCC to the inverter. It consists of a solar PV array generates at 300v with output power of 0.5MW. The output of solar power is fed to the DC-DC converter (boost converter) which is used to step up the voltage level to 700v. From the design, parameters of boost converter are calculated as inductance L= 10uH and capacitance C= 2326µF, switching frequency F_{sw}= 25KHz.The output of boost converter is given as input to the inverter. The output of VSI is filtered by using passive filters LC and LCL to reduce the harmonic components in output voltage and current. For LC filter designed values of L and C are 5e-5H and 231.9µF respectively. And for LCL filter, inverter side inductance L1=0.0513mH, capacitance C_f =231.9uF, grid side inductance L2=1.0473mH, resistance Rf=0.022Ω, r=0.02 is the ratio between inverter side and utility side inverter and switching frequency 25KHz with resonance frequency is considered as 10.315kHz. The feedback to inverter is given from PCC through PLL for generating firing pulses using PWM technique. The cutoff frequency for the firing pulse in inverter is maintained at 3KHz. The values considered for solar irradiance is 1000w/m^2 and temperature are 25-45^0 c for both utility grid connected and isolated mode. Ratings for solar panel are given in below table:

Table2: Solar panel ratings

Maximum power (P_{mp})	250Wp -0/+3%
Open circuit voltage (V_{oc})	37.00V
Short circuit current (I_{sc})	8.55A
Voltage at maximum power (V_{mp})	30.91V
Current at maximum Power (I_{mp})	8.09A
Maximum system voltage	DC 1000V
Normal operation	44.6^0 c
Temperature coefficient	-1.036w/^{0} ^{0}C

8.1 Sequence of Micro grid and Grid connected operation

Table3: Micro grid and utility grid connected modes

TIME DURATION	SOLAR	AC SOURCE	UTILITY GRID
0.00-0.1	OFF	ON	ON
0.1-0.2	ON	ON	ON
0.2-0.3	ON	ON	OFF
0.3-0.4	ON	OFF	OFF

As mentioned in the table:3, the microgrid is simulated for time period 0.00 - 0.4 (secs), i.e. it can be operated both in isolated mode and utility grid connected mode. During time period 0.00-0.1 (secs) solar PV is in OFF state and the AC source & utility grid are in ON state. For time period 0.1-0.2 (secs) solar is ON state and AC source & utility grid are also in ON state and it can be said that microgrid is operated as a grid connected mode. For time period 0.2-0.3 (secs) solar PV and AC source are in ON state & utility grid is in OFF state, this means microgrid operates as an islanded mode. During, time period 0.3-0.4 (secs) solar PV is ON state, AC source and utility grid are in OFF state, so it is clearly understood that there is no input to the inverter from PCC. At this condition inverter output voltage and current are zero. The simulation results are carried out with different time periods, they are shown below:

9. Simulations and results:

9.1 Without Filter:

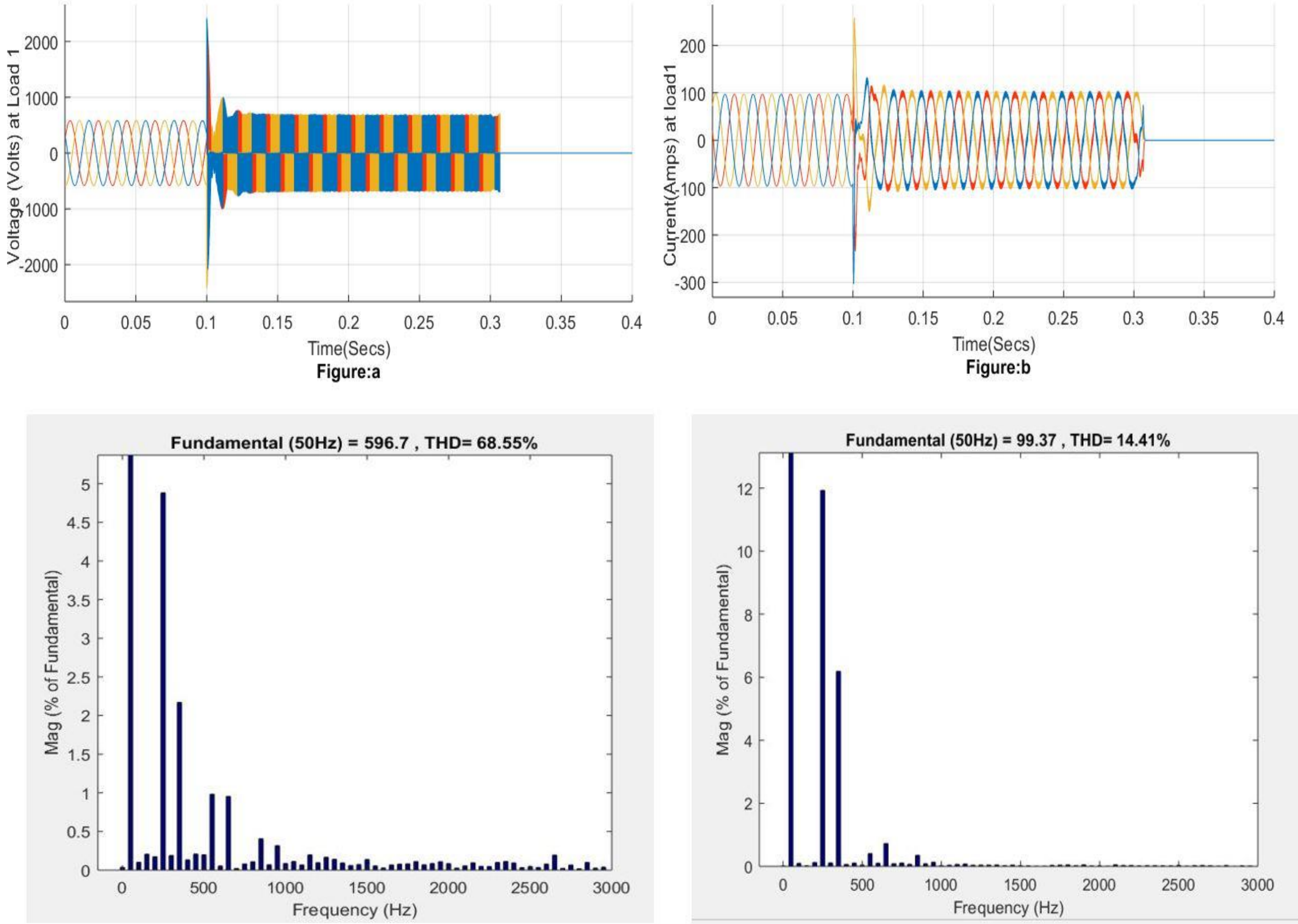

Figure 12: (a) Voltage at load1without filter, (b) Current at load1 without filter

The above plots are corresponding to the microgrid operated in both islanded and utility grid connected modes without using any filter. It is clearly observed that harmonics are present in the inverter output terminals. THD of the voltage and current at load1 for grid connected mode without filter is shown in below table.

Table 4: T.H.D for Grid connected solar PV system without filter

<table>
<tr><td rowspan="3">Without Filter THD (%)</td><td>Time (Secs)</td><td>0.00-0.1</td><td>0.1-0.2</td><td>0.2-0.3</td><td>0.3-0.4</td></tr>
<tr><td>Voltage (V)</td><td>0.00</td><td>68.76</td><td>68.55</td><td>0.00</td></tr>
<tr><td>Current (A)</td><td>0.00</td><td>9.53</td><td>14.41</td><td>0.00</td></tr>
</table>

9.2 LC Filter output:

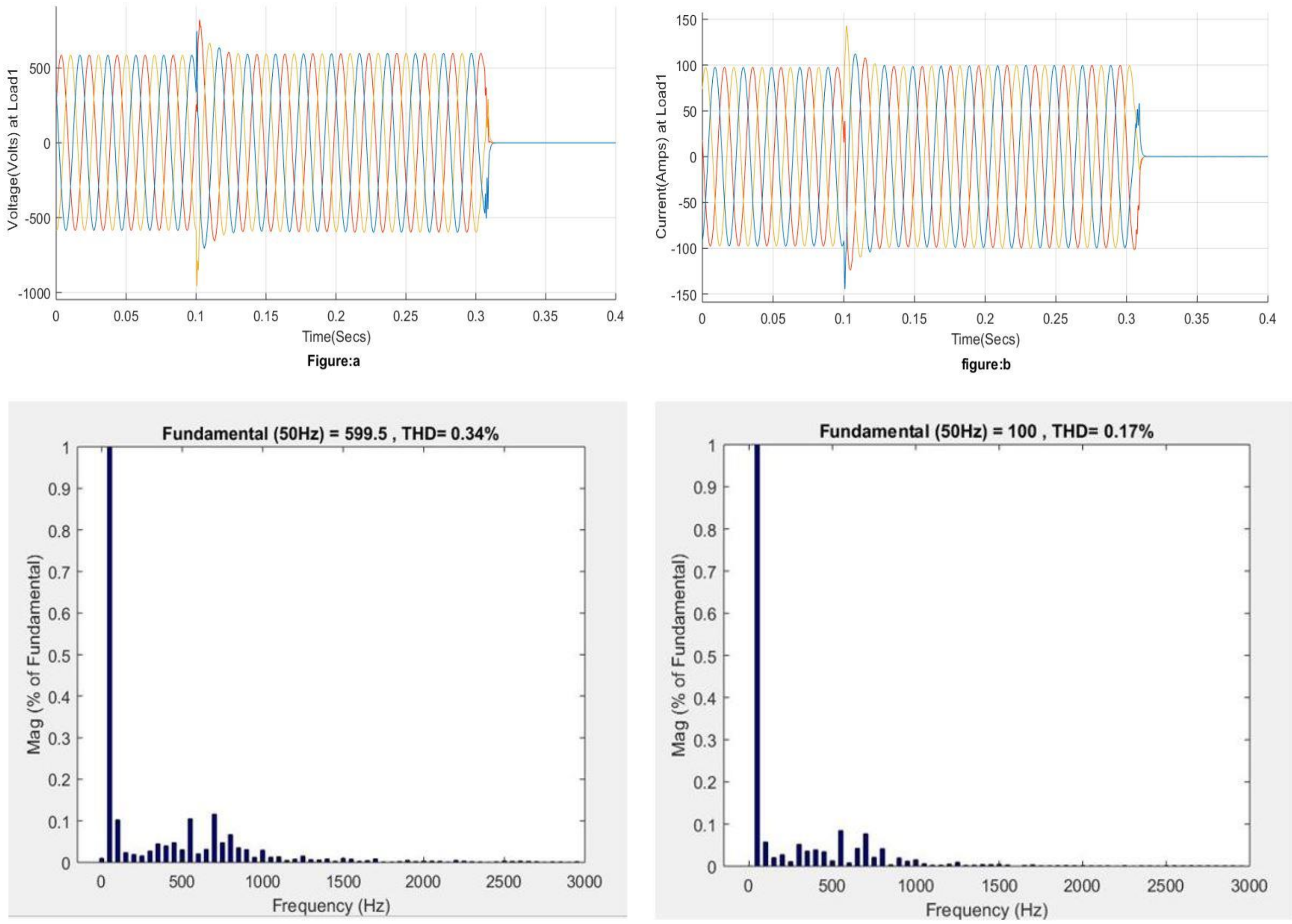

Figure 13: (a) Load voltage 1(Volts) with LC filter, (b) Load current 1(Amps) with LC filter.

The above figure 13(a) and (b) are corresponding to the microgrid operation using LC filter at inverter output terminals, it is clearly observed that harmonics are reduced in output. THD of the voltage and current at load 1 for grid connected solar PV system are listed in the below table:

Table 5: T.H.D of Grid connected solar PV system LC filter

	Time (Secs)	0.00-0.1	0.1-0.2	0.2-0.3	0.3-0.4
With LC Filter THD (%)	Voltage (V)	0.00	0.37	0.34	0.00
	Current (A)	0.00	0.16	0.17	0.00

9.3 LCL Filter Output:

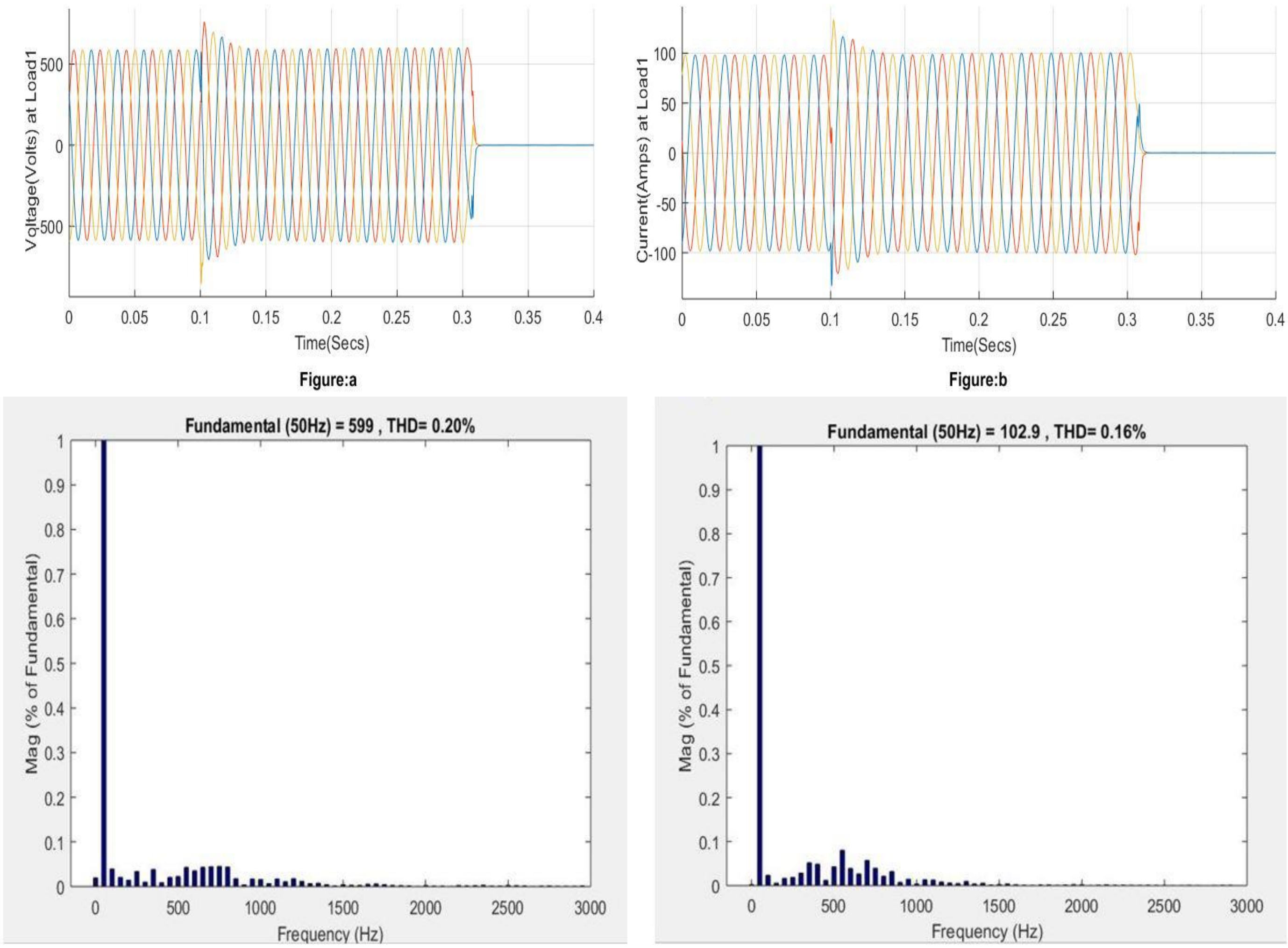

Figure 14 (a): Load voltage 1(Volts) with LCL Filter, (b): Load current 1(Amps) with LCL Filter.

The above figure 14(a) and (b) are corresponding to microgrid operation LCL filter at inverter output terminals, it is clearly observed that harmonics are reduced in output. THD is greatly reduced in voltage and current at load 1for grid connected solar PV system are listed in the below table:

Table 6: T.H.D of Grid connected Solar PV system LCL filter:

	Time(Secs)	0.00-0.1	0.1-0.2	0.2-0.3	0.3-0.4
With LCL Filter T.H.D%	Voltage (V)	0.00	0.25	0.20	0.00
	Current (A)	0.00	0.15	0.16	0.00

CONCLUSION

Microgrid operation is considered for standalone and grid connected modes. While operating in grid connected mode it is connected to main grid through PCC. Passive filters plays an important role in suppressing harmonics. It is observed that when microgrid is operated without filter at load1, THD is high and its values for voltage and current are 68.76% and 9.53% respectively. By designing of LC filter for solar PV grid connected system, THD is reduced at load1 and its values are 0.37% and 0.16% also by using LCL filter for solar grid connected system, THD is greatly reduced at load1 and values for voltage and current are 0.25% and0.15% respectively. Harmonic distortion limits which are obtained within the range of IEE-519 and IEEE-1547(less than 5%). As a part of future work instead of using passive filters, active power filters and filters using AI(artificial intelligence) technique can also be used to mitigate the harmonics.

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