

# Design of a New LCL-LCL Harmonic Filter for High Attenuation in PV Array System

\*<sup>1</sup>Kumar Indrajeet; <sup>2</sup>Lakra Pradeepti

<sup>1</sup>Research Scholars, Electrical engineering department, JEC Collage, Ranjhi, Jabalpur (India)

<sup>2</sup>Assistant Professor, Electrical engineering department, JEC Collage, Ranjhi, Jabalpur (India)

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### Corresponding Author

Email: indrajeetkumar325[at]gmail.com

## ABSTRACT

The use of Distributed or Disperse Generation is rapidly increasing in the modern distribution networks because of their potential advantages. They need DC/AC converter in order to interface to the grid. These type of active rectifiers/inverters are used more frequently in regenerative systems and distributed power systems. The switching frequency of these converters is generally between 5 kHz to 20 kHz and causes high order harmonics that can disturb other EMI sensitive loads/equipment on the grid side. Choosing a high value for the line-side inductance can solve this problem, the main goal is to ensure a reduction of the switching frequency ripple at a reasonable cost and, at the same time, to obtain a high performance active rectifier. As a drawback these LCL filters have very high gain at the filter cut-off frequency. As a result system becomes highly sensitive to outside disturbances. One way of reducing the resonance oscillation in current & voltage of the system is by adding a passive damping circuit to the filter. In which LCL-LCL filter which has high frequency and high attenuation than previous and better response at high frequency.

## 1. Introduction

Non-conventional energy sources of are such as solar, wind and geothermal have gained popularity now a days, which requires grid interfacing converters. These are basically power electronic converters which acts as an interface between electrical load and distributed generation to the grid. This inverter match the characteristics of renewable energy source and the requirements of the grid connections, provides the DPGS with power system control capabilities, improves power quality and their effect on power system stability [9]. However, due to non-linear switching characteristics of inverter switches, the grid current waveform contains higher order harmonics A filter connected in series with the inverter makes sure that the harmonic content is below the specified limit.

There are different kinds of filters like L, LC and LCL are extensively studied in the available literature. Among all of them, LCL filter is proved to have better harmonic attenuation for the same value of inductance [10]. The resonance problem in the filter is overcome by using different damping methods. The LCL filter is connected in series with the inverter on the output side. The schematic diagram of single-phase grid connected inverter is shown in Fig.1.1 with incorporation of LCL filter on grid side.

In this work optimal design of LCL filter for grid connected inverter system is also studied. Here, initially normal design is studied. Then the conduction and switching losses that are caused by the filter are calculated and are optimized considering the level of reduction of harmonics. The main aim is to attenuate harmonics along with the reduction in switching losses. Also different switching schemes for single phase unipolar full bridge inverter are studied and compared to get the switching scheme which gives lesser switching losses. The LCL filter [17] is designed accordingly and optimal inductance and

capacitance values are obtained. All the related models are simulated using the MATLAB software and graphs are studied.

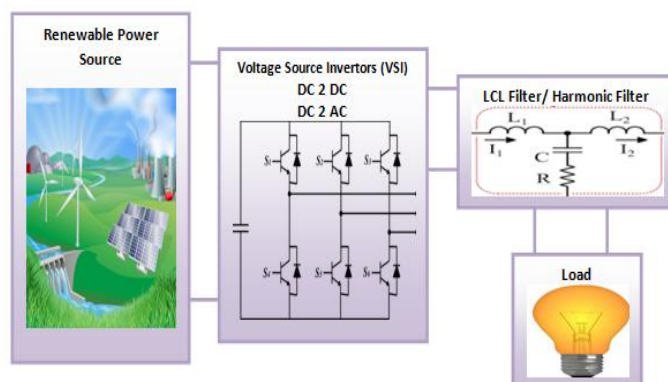


Fig.1 Single phase grid connected inverter with LCL filter [3]

## 2. Passive Damping Topology

The whole Idea basically depends on the type of filter and we need damping factor for greater attenuation and that we have chosen for the passive damping topologies. Damping is essential in LCL filter [17] based grid connected system or in the case, when it is connected to light load (standalone mode of operation). This resonance effect can cause instability in the output, especially if some harmonic voltage/current is near the resonant frequency. Damping by control algorithm (Active damping) is most attractive however; the control bandwidth is quite limited in high power converters due to their low switching frequency. Therefore passive damping (by addition of passive circuit elements) is considered in most of the cases. The criteria for the following comparison are effective resonance suppression without deteriorating the attenuation at switching frequency. As been discussed by different authors that L and LC filter [19] are not suitable for as this filters provides very less attenuation and high impedance.

1.1 Normal LCL filter

A standard choice is LCL filter in which we have

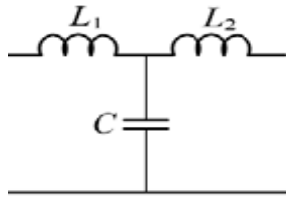


Fig. 2 LCL filter without passive damping [17]

$$\frac{i_{L_2}}{U_{inv}} = \frac{1/(L_1+L_2)}{s(1+s^2(L_1||L_2.C))} \tag{1}$$

$U_{inv}$  is applied voltage From the transfer function it is clear that, at the frequency of

$$f_0 = \frac{1}{2\pi\sqrt{(L_1||L_2.C)}} \tag{2}$$

1.2 LCL with Damping Resistance

It has high gain (infinite 'Q') the simplest solution may be the addition of series resistance with the capacitor to reduce the 'Q' as the capacitor current[16] is most responsible for resonance in LCL filter.

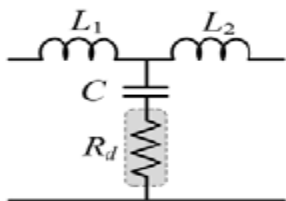


Fig. 3 LCL filter with resistive passive damping [17]

$$\frac{i_c}{U_{inv}} = \frac{L_2}{L_1+L_2} \cdot \frac{sC}{(1+CR_d s+s^2(L_1||L_2.C))} \tag{3}$$

$$\frac{i_{L_2}}{U_{inv}} = \frac{1+sCR_d}{(s^3 L_1 L_2 C+s^2(L_1+L_2)CR_d+s(L_1+L_2))} \tag{4}$$

So, here damping factor is proportional to  $R_d$ . But on the other hand, larger resistance tends to reduce the attenuation above the resonant frequency. It is undesirable from the harmonic filtering point of view. Moreover higher  $R_d$  can also increase the losses at low frequency. So, there is a trade-off exists between losses & damping in this case as a result this method cannot be used for higher power rating like KW or MW level [12].

1.3 TRAP Filter

In Previous Method larger resistance tends to reduce the attenuation above the resonant frequency. It is undesirable from the harmonic filtering point of view, so an inductor is connected in series with the capacitor as a part of damping scheme called as TRAP filter [1]. In TRAP filter [2][5] the attenuation at switching frequency is improved but at the same time damping is bit affected. But the major advantage of this type damping loss at fundamental frequency is considerably improved.

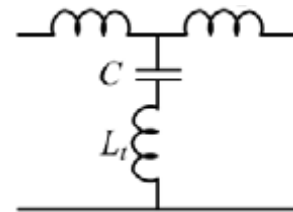


Fig. 4 TRAP harmonic Filter [1]

$$G_{trap}(s) = \frac{L_r C s^2}{(L_1 L_2 C+(L_1+L_2)L_r C)s^3+(L_1+L_2)s} \tag{5}$$

From the earlier discussion, we can know that the trap filter can be equivalent to an L filter in the frequency band higher than the LC resonant frequency. So, in the high-frequency band, its harmonics attenuation rate is only -20 dB/decade. It means that grid-side current harmonic amplitudes at twice and more times of switching frequency may still be relatively high and cannot meet the requirements of grid codes.

1.4 LCL with Damping resistance and bypass Inductance

Another solution is a slight modification over the previous one. In the series damping method the disadvantage was losses at fundamental & that restricts us to use that type of damping method for higher power ratings [2]. Here one more inductance is inserted in parallel to damping resistance. As a result current at fundamental will be bypassed through  $L_f$  & loss will be considerably saved.

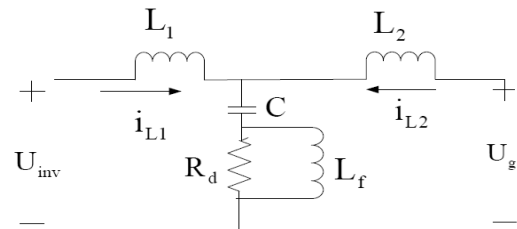


Fig 5 Frequency response with bypassing inductance [2]

In this type of damping process, if we see the transfer characteristic the attenuation at switching frequency is improved but at the same time damping is affected. But the major advantage of this type damping loss at fundamental frequency is considerably improved. It can be found that the resistor can effectively damp the resonant peak. However, it also weakens the ability of bypassing current harmonics and causes a great increase of harmonic amplitude at switching frequency.

1.5 LCL-LC filter

The topology of the filter is composed of a traditional LCL filter (dotted box) and a series resonant circuit (dashed area). The transfer function  $i_g(s) / V_{con}(s)$  of the presented filter can be derived as follows

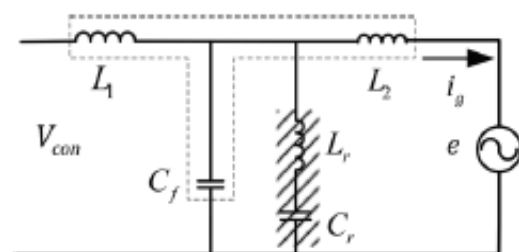


Fig. 6 LCL-LC filter by Fei li et al [1]

$$G_{LCL-LC}(s) = \frac{L_r C_r s^2}{As^5 + Bs^3 + Cs} \tag{6}$$

Where

$$A = L_1 L_2 L_r C_r C_f$$

$$B = L_1 L_2 (C_f + C_r) + L_r C_r (L_1 + L_2)$$

$$C = L_1 + L_2$$

The LC circuit resonates at the switching frequency

$$\omega_{sw} = \frac{1}{\sqrt{L_r C_r}} \tag{7}$$

The current harmonic amplitude at switching frequency in LCL-LC filter is almost equal to zero. It proves that the presented filter has the ability of bypassing switching current harmonics and damping resistor has no effect on this ability.

The amplitudes of the twice and triple switching frequency current harmonics in LCL-LC filter are lower than the ones of trap filter. It proves that presented filter has a higher rate of high-frequency harmonic attenuation than that of trap filter. Their presented filter is the only one which meets the grid-code requirement in the three kinds of filters. It validates the performance of designed parameters. Issue with the LCL-L filter that it was frequency dependent at low frequency the attenuation was very good and -60db but at high frequency attenuation reduces to -40 db and also the damping at high frequencies.

Table-1  
Harmonic Filter Analysis

Filter Type	Attenuation	Damping at resonant frequency	Maximum Frequency
LCL Filter	20 db	0 db	10 KHz
LCL-R filter	37 db	100 db	10 KHz
TRAP filter	25 db	10 db	20 KHz
LCL with Damping resistance and bypass Inductance	40 db	11 db	20 KHz

### 1.6 Active Damping Method For proposed LCL-LCL filter

In proposed work damping is much more preferred compared to simple series damping as here damping is not only depends on resistance but also on the  $(C_f / C_r)$  ratio .It is shown by following frequency plots

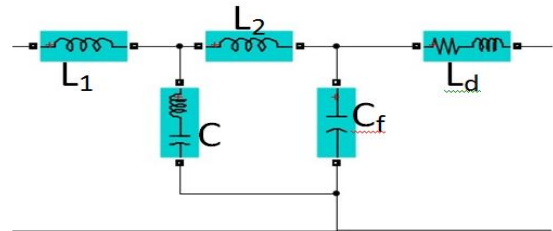


Figure 7: Proposed LCL-LCL Filter

The LCL-LCL filter is composed of a traditional LCL filter and LCL series resonance circuit as shown in figure 7. The transfer function of the inverter output is shown in equation 8.

Transfer function

$$\frac{I_{Rf}}{V_{in}} = \frac{1 + s C_f L_f R_f}{s^4 C C_f L_d L_1 L_2 + s^3 L_1 L_2 (C + C_f) + s^2 C_f R_f (L_1 + L_2) + s (L_1 + L_2)} \tag{8}$$

Harmonic tuned order is

$$n = \sqrt{\frac{X_C}{X_L}} \tag{9}$$

### 3. Simulation Results And Discussion

Figure 11 shown below described that the block has been developed on Simulink. In figure 12 we can see the input DC supply for the DC buck converter and the output developed by DC/AC buck converter here we can easily observed the harmonics at the 3 phase output voltage.

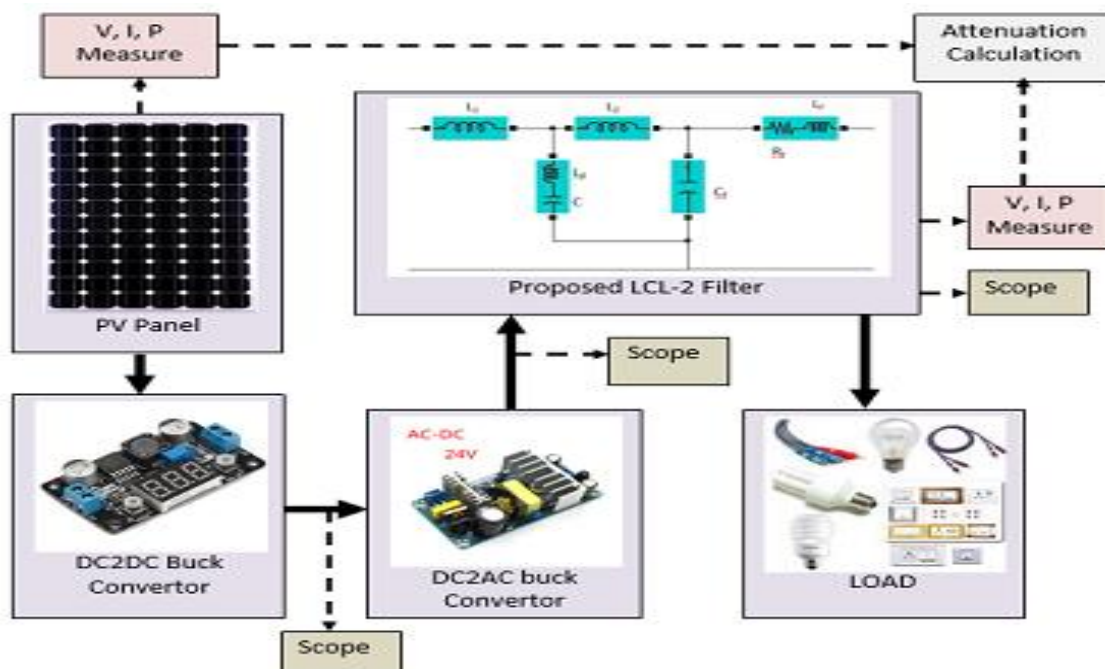


Figure 11: Simulink block design of proposed work

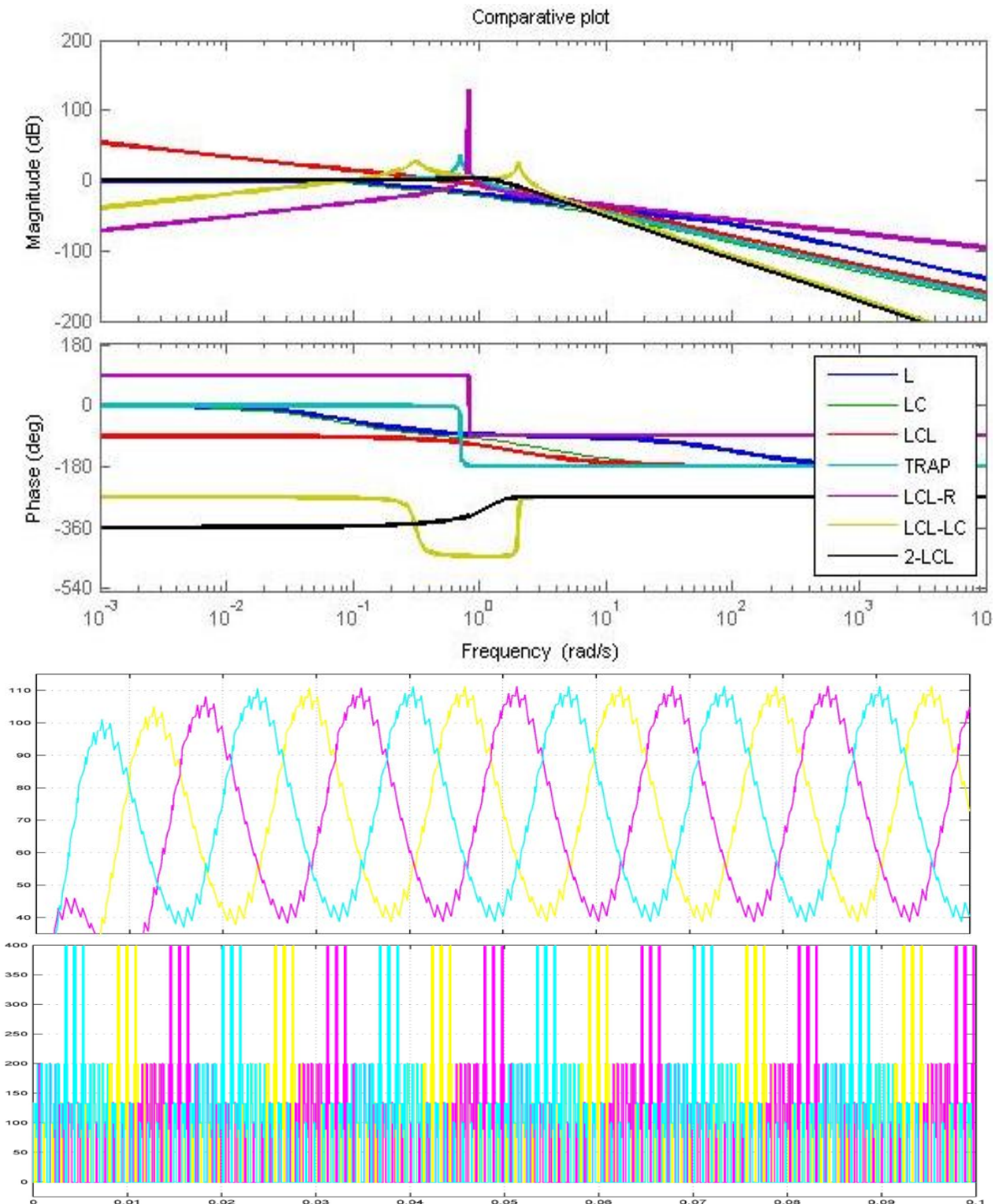
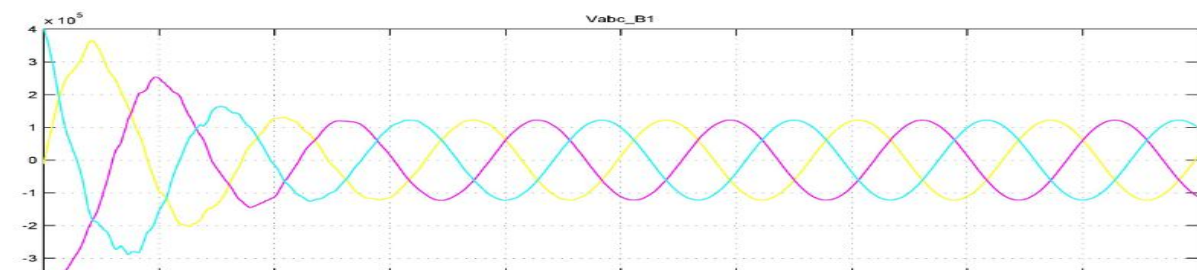


Fig. 11: DC to AC Convertor

From the given figure 11 we can observe that the in three phase output filter input DC supply for the DC buck converter

and the output developed by DC to AC buck converter can easily observed the harmonic at the 3 phase output voltage.



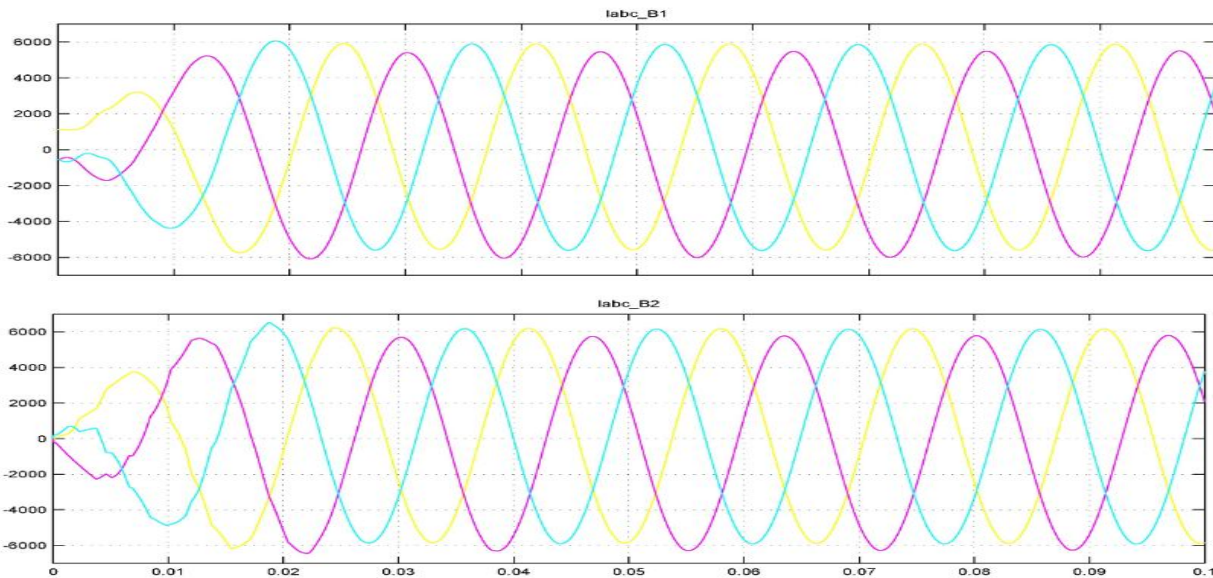


Fig. 12 Filtered 3-Phase output

In figure 12 we can observed that the value of filtered output current, voltage and power and it can be easily observed that there is very less amount of harmonics remains.

From figure 14 it can be seen that L and LCL filters are very good in damping at resonant frequency and base work has damping around 6 db in proposed work it is 1.3 db which is better than base work but not good as L and LCL filter.

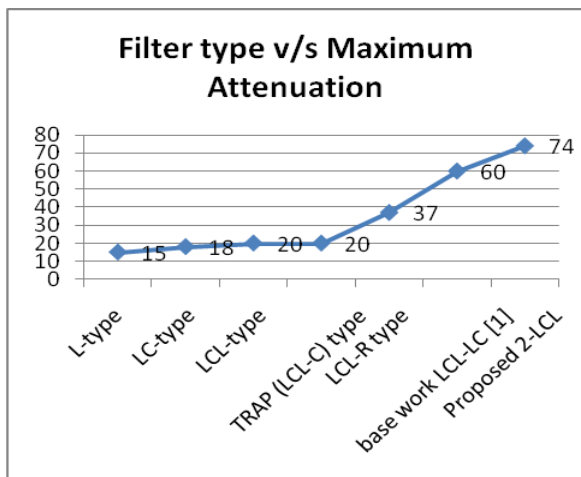


Figure 13 the attenuation observation and comparison

Figure 13 shows the comparative results between the proposed work and other standard filter and base paper also. It can be seen the proposed work has highest attenuation among available methods.

#### 4. Conclusion

The work has been completed with designing of grid array DC/DC convertor and DC/AC convertor and proposed LCL-LCL power filter. A detailed simulation model of the Photo Voltaic Array with a new Active Power Filter is implemented in MATLAB / SIMULINK using SIMPOWER Systems library is proposed and control system for combined operation of new power filter with PV generation system to the grid. This system aids to supply a constant power to the grid. Also, a novel control strategy for active power filter is developed and simulated, the current and DC to DC buck and DC to AC voltage controllers are used to transfer the PV power and synchronize the output converters with the grid. The controller designs for different operation modes of active power filter are studied. The simulation results are carried out by MATLAB and SIMULINK software tools.

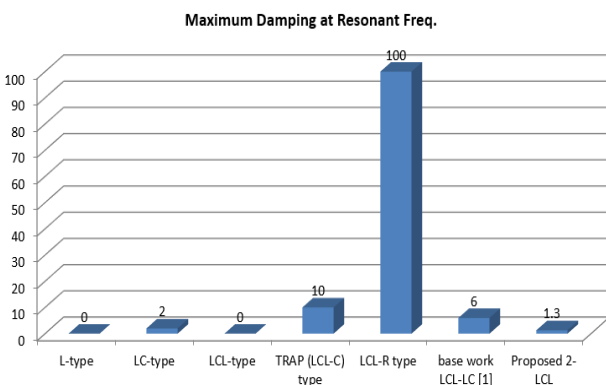


Fig. 14 Damping Comparison with various works

In grid connected PV array system buck convertor are responsible for generation of harmonics and many filters has been developed previously to enhance the attenuation and to reduce the damping so that LCL-LCL filter is showing higher attenuation than all previous work but on cost of small damping at resonance or at fundamental frequency. LCL-LCL filter having very low impedance for the frequency range 0 to 20 khz and attenuation does not change in this frequency range.

In near future following things can be done, Attenuation can be improved maximum attenuation of 74 db. Frequency limit that we have observed is 20 khz maximum after this proposed LCL-LCL filter attenuation starts decreasing and this this problem can be resolve in future, We are getting small damping 1.3 db at resonance frequency this can be completely remove in near future. A better design of DC 2 AC convertor can be developed so generation of harmonics reduces.

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