DESIGN OF NEW HARMONIC FILTER FOR RENEWABLE ENERGY SOURCE WITH HIGH ATTENUATION AND LESS DAMPING

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***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 and 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. The greater emphasis is given to active damping in proposed work. Some of the techniques are available in the literature based on current control strategy of the converter, but all above methods solve the problem up certain level but still the problem remains that to deal with switching frequency and so harmonics can be reduced proposed work has come up with a new design in which 2-LCL type filter which has high efficiency and high attenuation than previous and better response at high frequencies.**

***Abbreviations*: THD – Total Harmonic Distortion, PWM – Pulse Width Modulation, VSI – Voltage Source Inverter, GCI - Grid Connected Inverter, PID - Proportional, Integral and Derivative, IGBT - Insulated Gate Bipolar Transistor, SRF - Synchronous Reference Frame**

I-Introduction

Non conventional energy sources of energy such as solar, wind, and geothermal have gained popularity now a days. Which requires grid interfacing converters are basically power electronic converters 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.

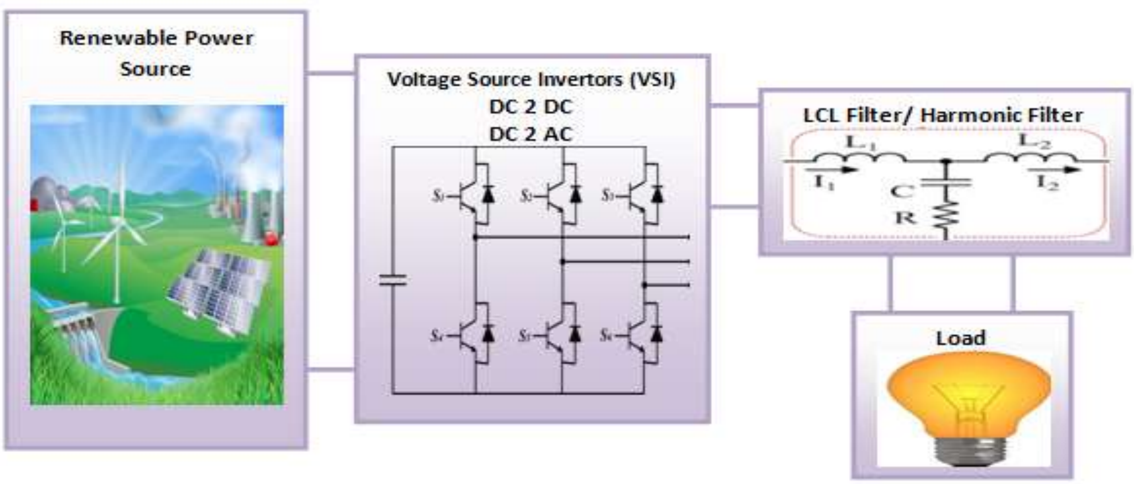

Fig 1 Single phase grid connected inverter with LCL filter [3]

In this thesis 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. Hence our 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.

II-METHODOLOGY

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. Here in this chapter different passive damping topologies are described & compared. The criteria for the following comparison are effective resonance suppression without deteriorating the attenuation at switching frequency. As been discussed in previous chapter that L and LC filter[19] are not suitable for as this filters provides very less attenuation and high impedance.

Normal LCL filter: a standard choice is LCL filter in which we have

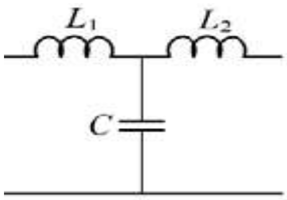

Figure 2 LCL filter without passive damping[17]

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

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

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

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.

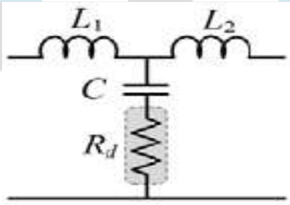

Figure 3 LCL filter with resistive passive damping[17]

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

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

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 exits between losses & damping in this case as a result this method cannot be used for higher power rating like KW or MW level[12].

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

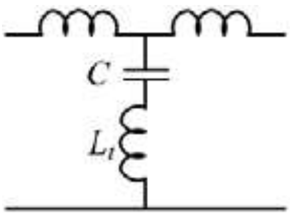

Figure 4 TRAP harmonic Filter[1]

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

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.

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 parallel to damping resistance. As a result current at fundamental will be bypassed through L_f & loss will be considerably saved.

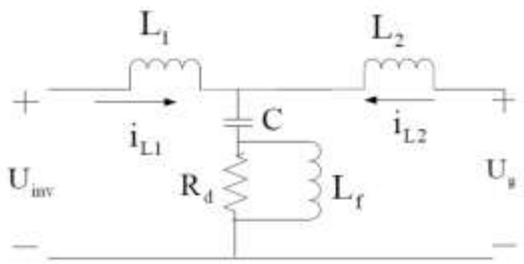

Fig 5 Frequency response with bypassing inductance[2]

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 bit 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.

LCL-LC [1] 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:

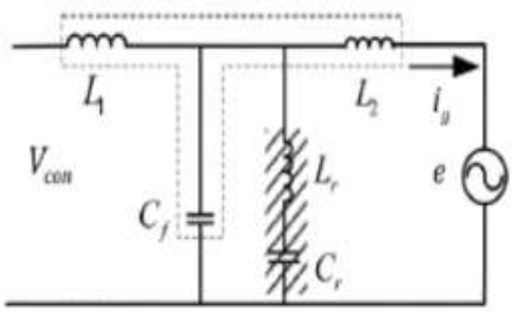

Figure 6 LCL-LC filter by Fei li et al[1]

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

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

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

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-LC 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.

Filter Type	Attenuation	Damping at resonant freq	Maximum Freq
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

Table 1 Harmonic Filter Analysis

Proposed 2-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) ratio .It is shown by following frequency plots: -

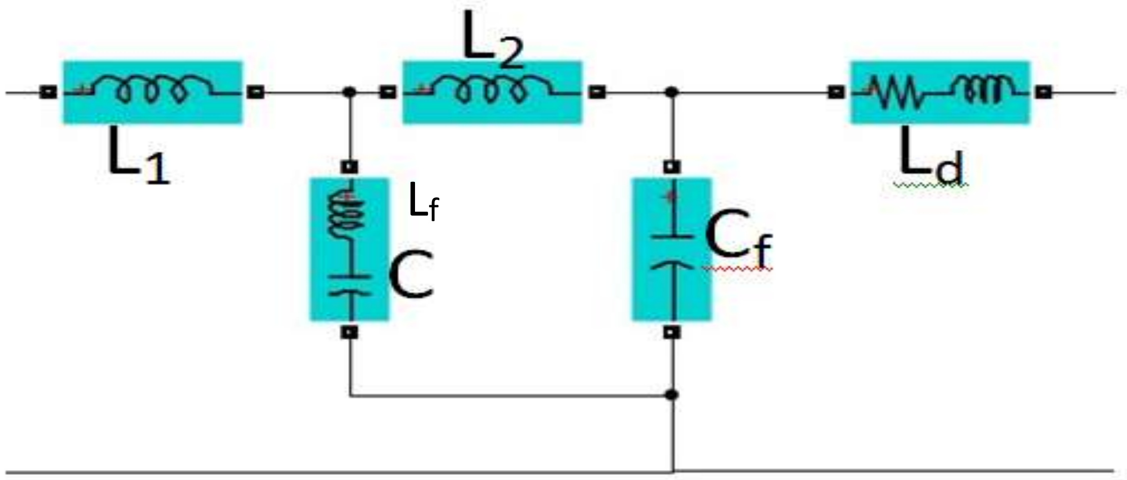

Figure 7: Proposed 2-LCL Filter

Now if we see the transfer function

$$\frac{I_{R_f}}{V_{in}} = \frac{1 + sC_fL_fR_f}{s^4CC_fL_dL_1L_2 + s^3L_1L_1(C + C_f) + s^2C_fR_f(L_1 + L_2)R_f + s(L_1 + L_2)}$$

Harmonic tuned order is

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

And Quality factor is
$Q = nX_L/R = X_C/nR = 0.5$

Figure 8 shows the Comparative Results and bode plot of all methods which are been discussed above and plot is been developed for the phase and frequency both for the figure it can be clearly observed that the attenuation and damping in proposed work is best in proposed work.

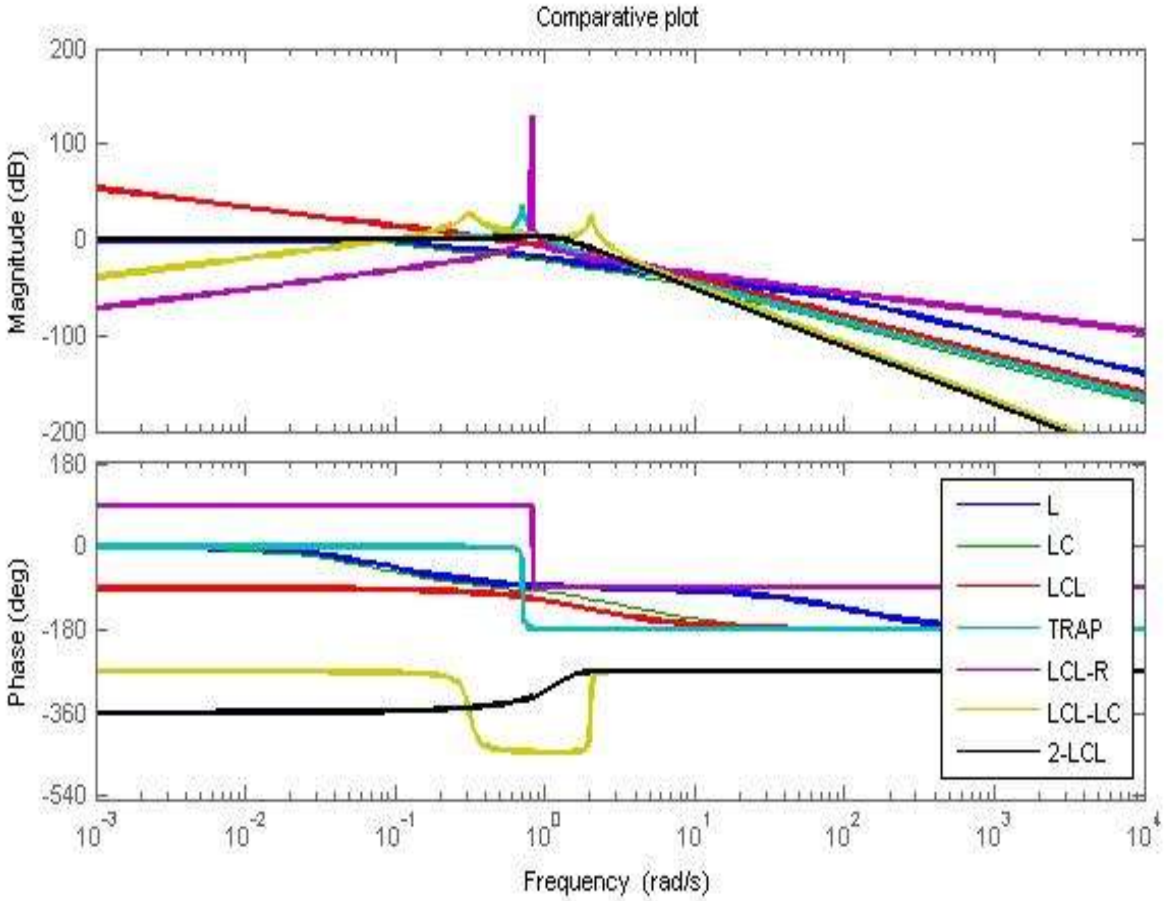

Figure 8 Comparative results

PV panel developed as in new version of MATLAB we have new features in its Simulink which is Simscape and Sim-Electronics this allows us to use photo cell as a physical component and also have some convertor like P to S (Physical to Simulink) and S to P (Simulink to Physical), this develops an DC voltage which varies with some control inputs (temperature, Radiation, maximum voltage etc.) given to it. Next DC 2 DC buck Convertor design is like a regulator which regulate the DC input from the PV panel and output regulated DC output and also down the total voltage to the "$\sqrt{2} *$ maximum voltage requirs for AC" and to have this if significant amout of sunlight is not there it will get the values from DC battery attached with it and if radiation is higher than required it will store the DC power into DC battery. Next Conversion DC input into 3 phase AC supply it is been done with the help of Pulse Width Modulation (PWM) and for achieving this requires a capacitor and a switch. the switch is controlled by PWM and this switch has to be switch at very high speed and this is the main problem of generation of harmonics for this we requires harmonic filter.

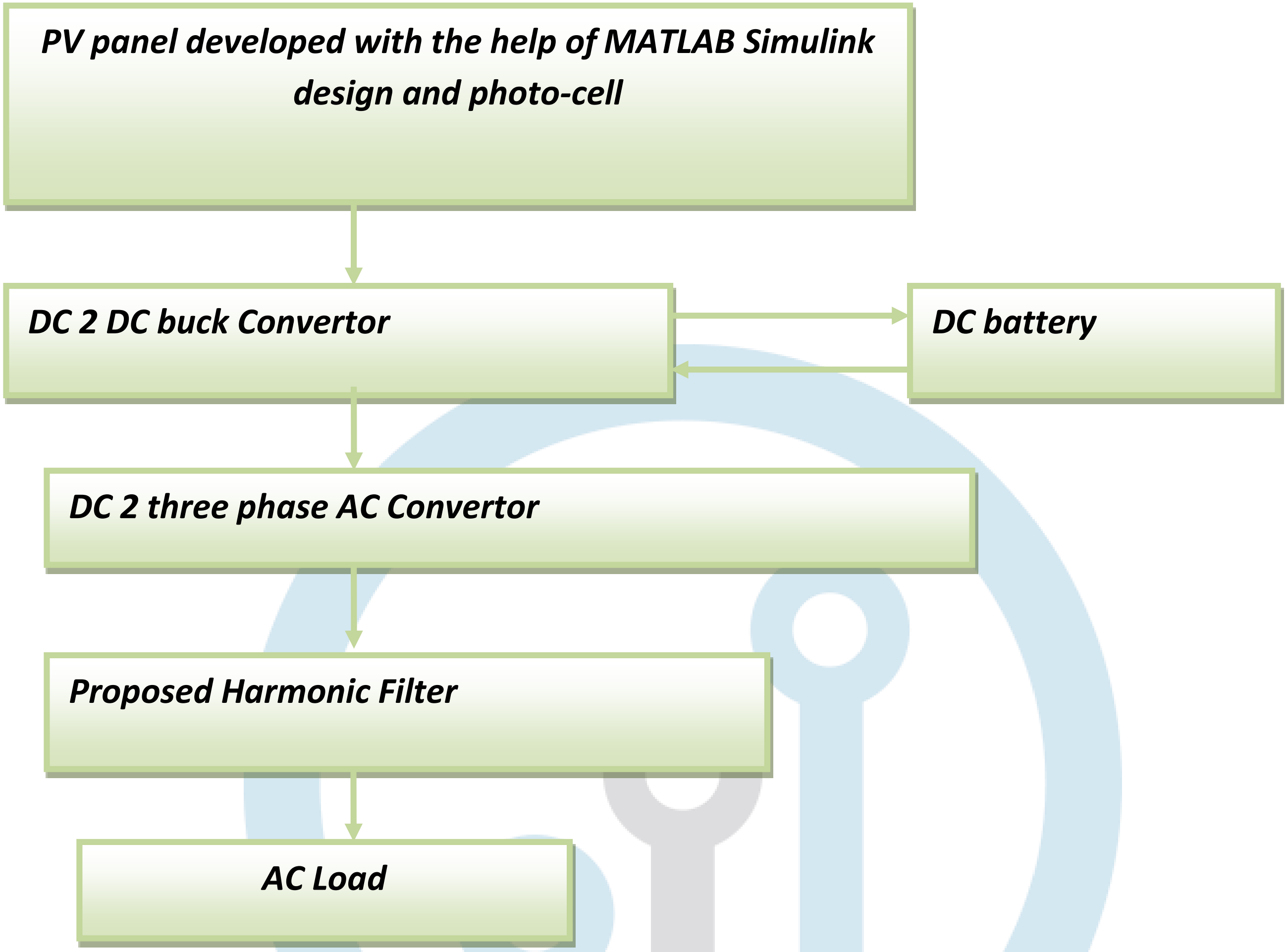

Figure 9 Flow of Proposed Design

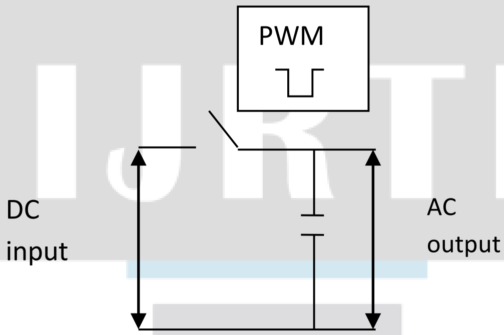

Figure 10: DC 2 AC Conversion Concept

Figure 10 above shows the use of PWM in filtering of harmonics generated during DC 2DC and DC 2 AC conversion, it is been done with proposed filter and harmonics removed with -74 db attenuation and very small damping.

III-Results

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

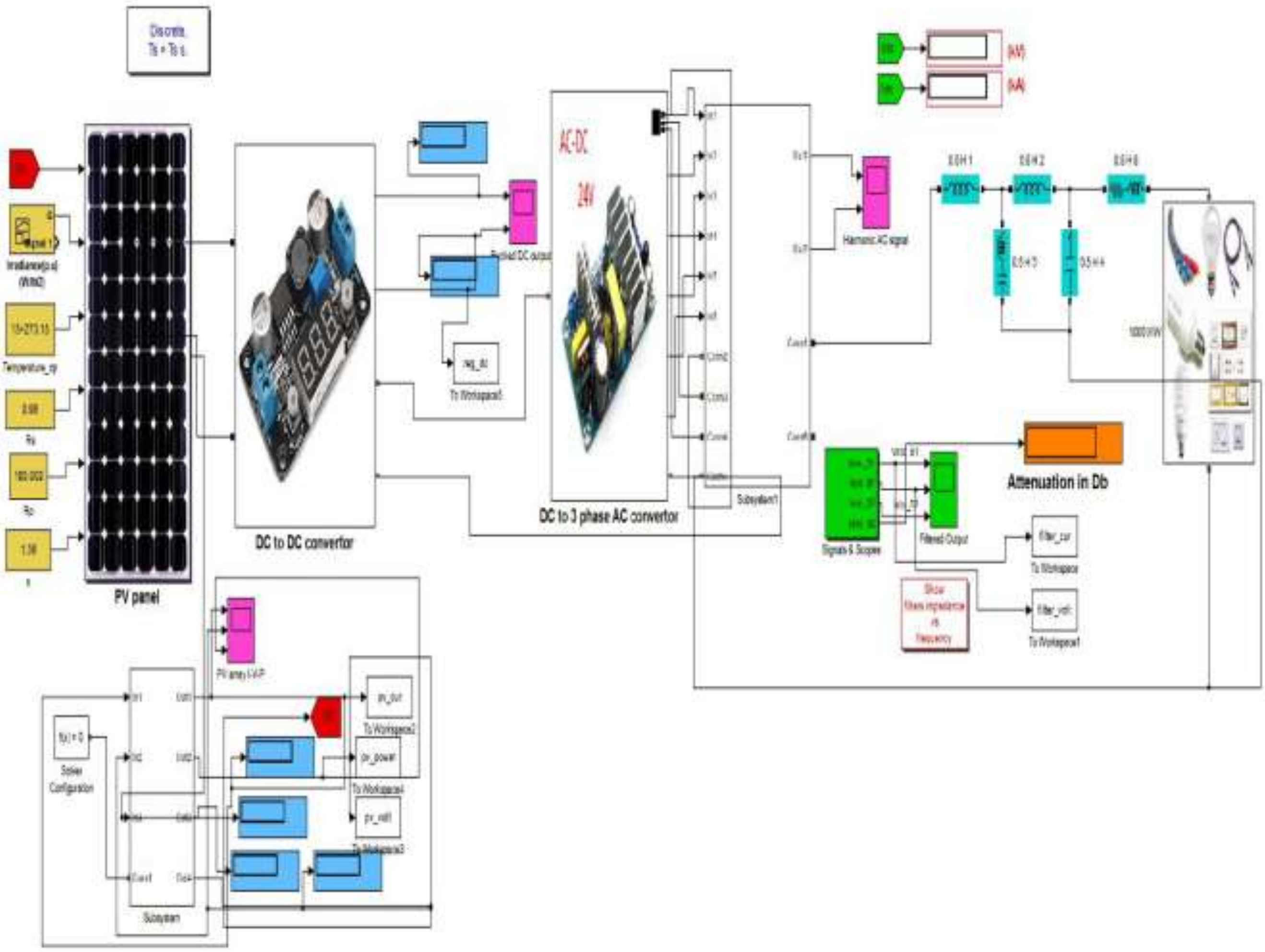

Figure 11: Simulink block design of proposed work

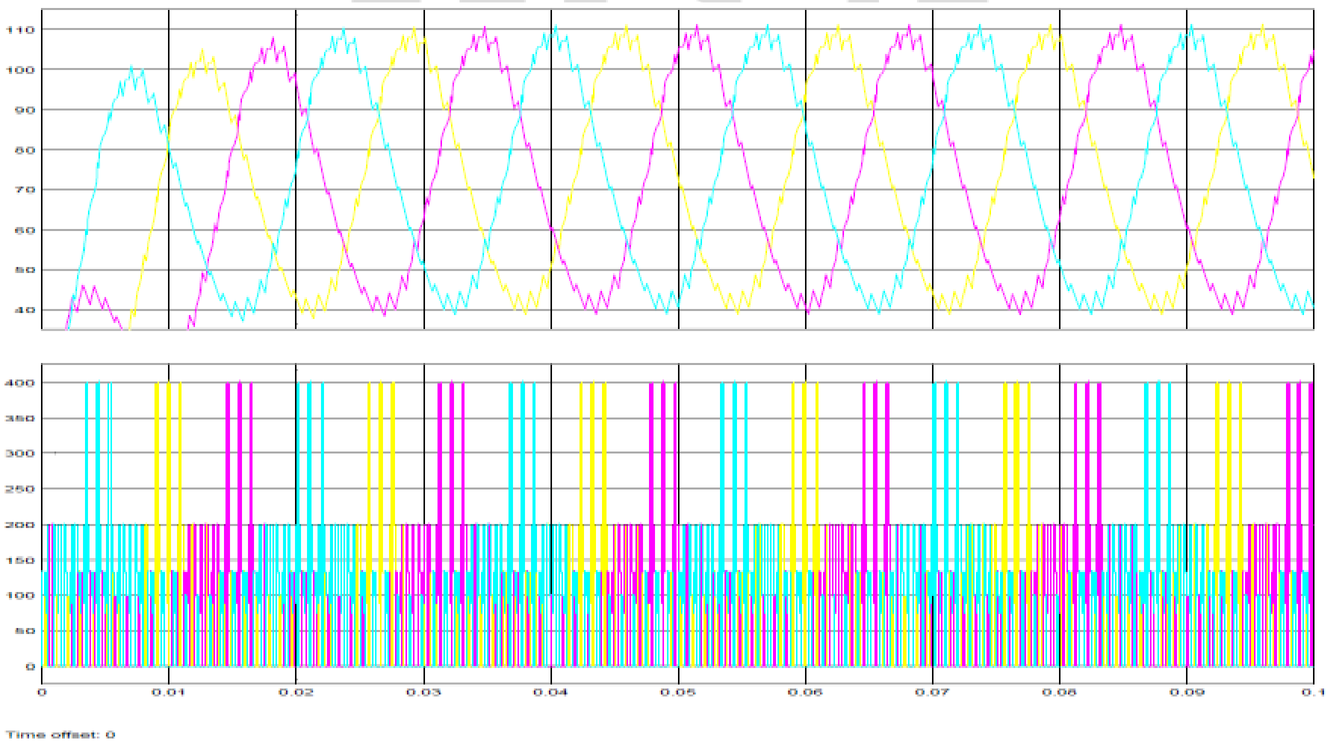

Figure 12 DC to AC Convertor

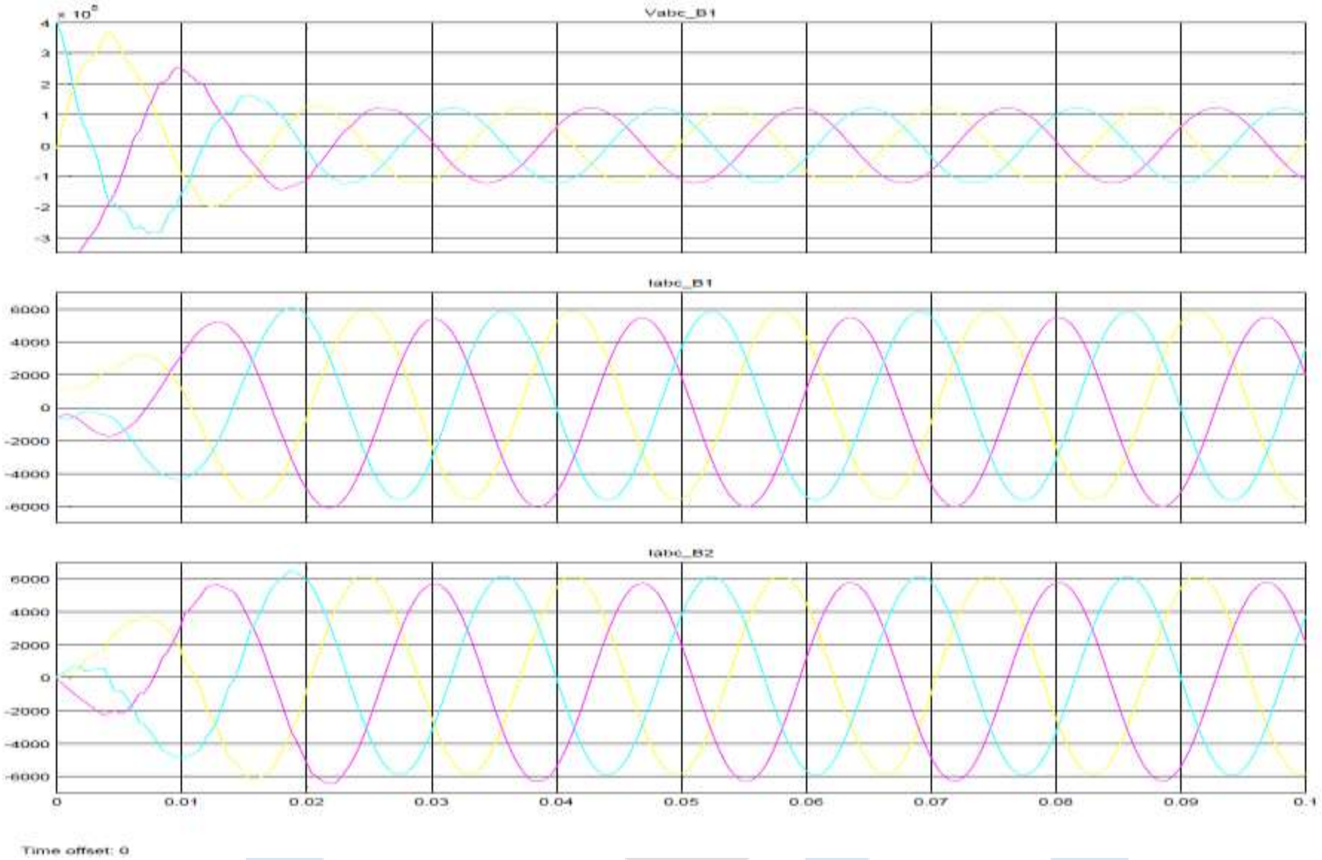

Figure 13 Filtered 3-Phase output

In figure 13 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.

Work	**Maximum Attenuation**
L	15 db
LC	18 db
LCL	20 db
TRAP	20 db
LCL with passive Resistance	37 db
LCL-LC [1]	60 db
Proposed	74 db

Table 1: Comparative results

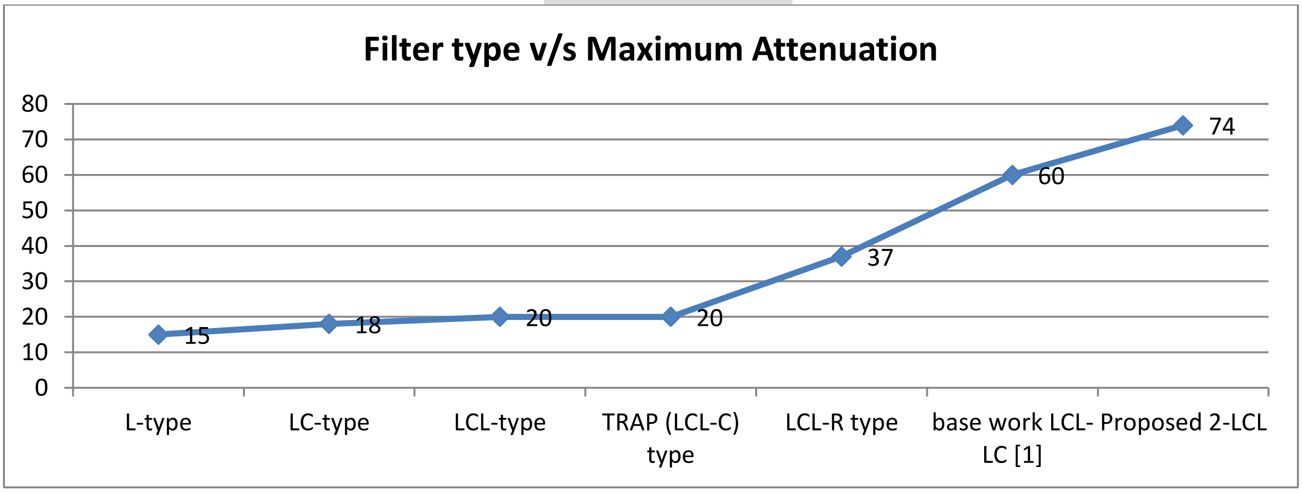

Figure 14 the attenuation observation and comparison

Table 1 and figure 14 shows the comparative results between the proposed work and other standard filters and base paper also. It can be seen tha proposed work has highest attenuation among available methods.

Work	Maximum Damping at Resonant Freq.
L	0 db
LC	2 db
LCL	0 db
TRAP	10 db
LCL with passive Resistance	100 db
LCL-LC [1]	6 db
Proposed	1.3 db

Table 2: Comparison and analysis of results observed for different work

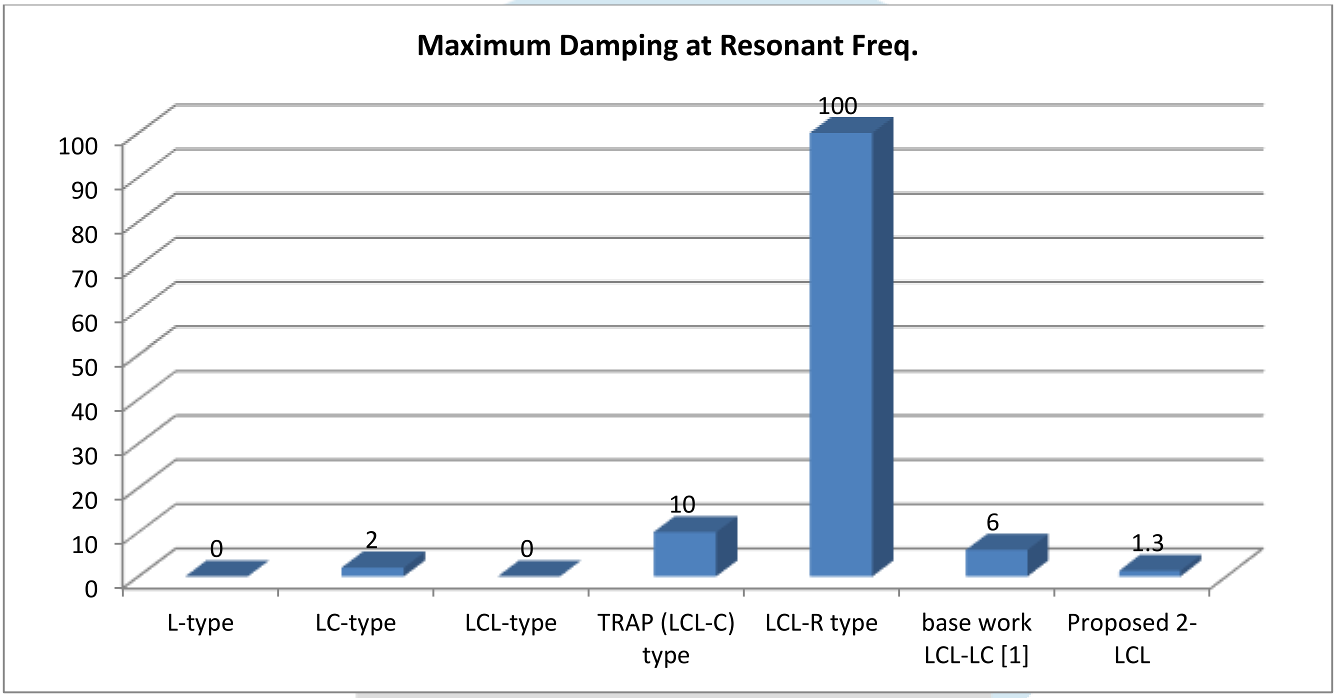

Figure 15: Damping Comparison with various works

From figure 15 and table 2 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.

IV-Conclusion

The work is been completed with designing of grid array DC/DC convertor and DC/AC convertor and proposed 2-LCL power filter. A detailed simulation model of the PhotoVoltaic Array with a new Active Power Filter is implemented in MATLAB / SIMULINK using SIMPOWER Systems library is proposed in this thesis, control system for combined operation of new power filter with PV generation system in 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.

In grid connected PV array system buck convertor are responsible for generation of harmonics and many filters are been developed previously to enhance the attenuation and reduce the damping, our proposed filter is showing higher attenuation than all previous work but on cost of small damping at resonance or at fundamental frequency. Proposed 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 than our maximum attenuation of 74 db. Frequency limit that we have observed is 20 Khz maximum after this proposed filter attenuation starts decreasing this can 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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