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Grid Stability Analysis with LCL Filter using 1-phase Inverter

D V V V CH Mouli, M.Suneel Kumar, P.Kalpana

Abstract**: *The demand for power generation is increased day to day due to increase of industrial loads as well as domestic loads like machines, air conditioners,etc.This will lead to increase of utilization of natural resources. Whenever natural resources with solid state devices interfaced with grid, the stability of the grid will become an important issue. So the additional use of LCL filter will lead to protect the stability of the grid along with its closed loop dynamic control. In this paper the grid stability is analyzed using LCL filter with 1-phase inverter in open loop as well as closed loop. Different LCL configurations along with transfer function analysis are also proposed in this paper. Interfacing of renewable sources with solid state non linear switching devices cause the harmonics and other disturbances on the grid. The LCL filter will reduce these harmonics and increase the quality of the grid. The application of LCL filter for weak grids is very significant in the sense of stability..***

Keywords : LCL filter, PI control, bode diagram, resonance, grid, block diagram, signal flow graph

I INTRODUCTION

Grid stability is depending up on the parameters like voltage swings, frequency swings, harmonics, etc. To maintain the voltage stiffness Grid interfacings are used with LCL filter. In 3-phase system feedback control is used by taking the voltage and current parameter with PLL and abc-dq-abc transformation. In this paper the 1-phase system is analyzed. With the help of grid voltage parameter , the feedback control is adopted with PI control to vary the modulation index for inverter as well as for one of the inductor to vary the inductance value. Normally Non conventional sources are interfaced with grid using solid state power converters and firing controllers whether their generation type is either DC or AC .Grid stability maintenance is very important when solid state switching devices are interfaced to it. The LCL circuit is used with grid to improve its stability. Grid voltage stiffness will depend up on the inverter modulation index MI. In addition to the inverter MI , the values of LCL parameters of the filter and type of LCL configuration will also influence the grid voltage stiffness and stability.

Various transfer function's [1-3] stability analysis will help to design LCL circuit for improving grid stability. In this paper different transfer functions at LCL open loop and at closed loop PI control is developed and analyzed for stability with using bode plots. Switching and steady loads are connected at grid point to observe the voltage patterns of the grid using simulation. The total resistance for damping can be identified using resonance . condition. The block diagram representation with line graph will provide the transfer function and its frequency analysis identifies its stability region. In case of 3-phase inverter used ,then obviously the LCL filter is also used in all 3-phases to improve the voltage stability further even though less harmonics in 3-phase system.

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II GRID VOLTAGE AT VARIOUS MI

A. Methodology & Experimentation :

The given below fig. 1 in block diagram indicates the LCL filter connected between 1-phase inverter and Grid

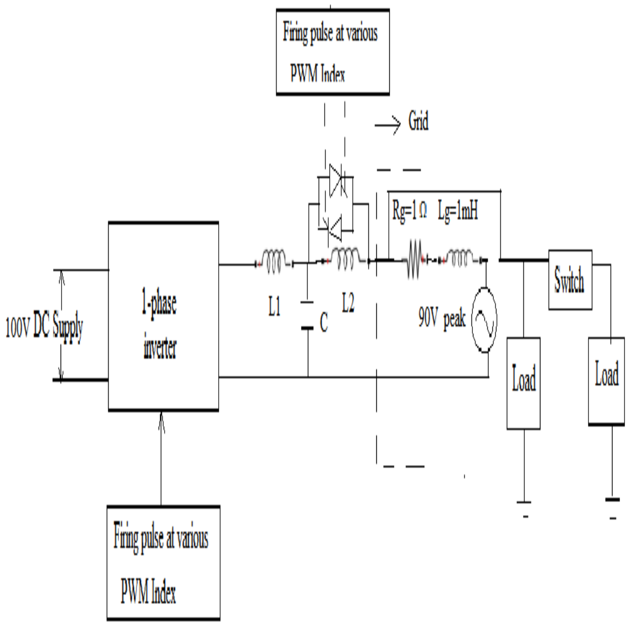

Fig.1. Grid connected with Inverter through LCL filter

at different modulation index of inverter and of l2 ,the grid voltage patterns are observed .These observations are made without pi and feedback control. The grid voltage pattern without lcl filter and with lcl filter is shown in fig. 2 and fig.3 respectively.

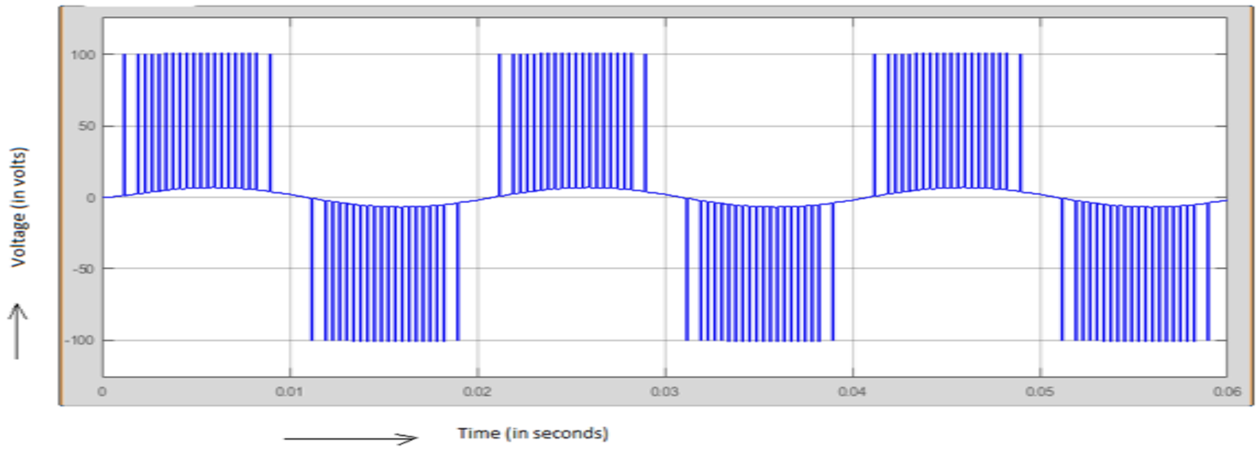

Fig.2 Grid Voltage Without LCL Filter

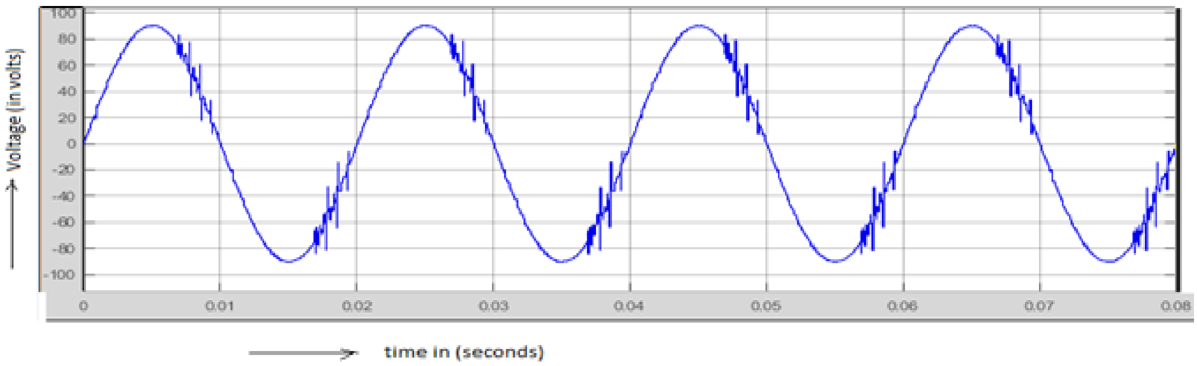

Fig.3. Grid Voltage using LCL filter for MI of 1 at Inverter and L2

At the modulation index of 0.2 for inverter as well as for the inductor L_2 ,the grid voltage showing oscillations at positive and negative peaks as shown in Fig.4 .

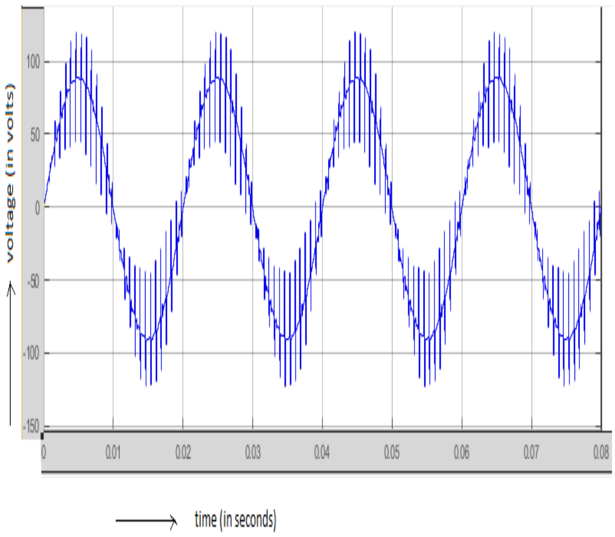

Fig.4 Grid Voltage at MI of 0.2 for Inverter and L_2

From the Fig.4 , it is observed that modulation index will also one of the factor to determine the stability of the grid. The oscillations are different in grid voltage at different modulation indices.

B. Results& Discussions :

At different modulation index , the grid voltage peak levels are also changed . Different voltage levels at various modulation index is indicated in below Table I .

Table- I: Grid Voltage at different MI

At Inverter modulation index =0.2		
S.NO.	Modulation index of Inductor L_2	Peak value of Grid Voltage (in Volts)
1	0.2	120
2	0.4	120
3	0.6	110
4	0.8	105
5	1	95
At Inverter modulation index =0.4		
1	0.2	115
2	0.4	115
3	0.6	108
4	0.8	100

5	1	90
At Inverter modulation index =0.6		
1	0.2	103
2	0.4	98
3	0.6	100
4	0.8	93
5	1	90
At Inverter modulation index =0.8		
1	0.2	94
2	0.4	92
3	0.6	92
4	0.8	88
5	1	88
At Inverter modulation index =1		
1	0.2	100
2	0.4	98
3	0.6	95
4	0.8	90
5	1	90

The voltage levels are decreasing as modulation index is raised. But the oscillations in the wave are decreased. At high index voltage drops are high due to high currents. The values L_2 at different modulation index based on the voltage and current measurements in the inductor is given in the Table II . The 3-phase grid voltage at modulation index of 0.8 and at the inductor L_2 value of 1mH is shown in Fig 5. The 3-phase grid voltage is controlled in open loop [4]. In closed loop method current and voltage feed backs are taken [5,6] . The current values are converted from abc/dq transformation [7,8] to control the firing angle[9].

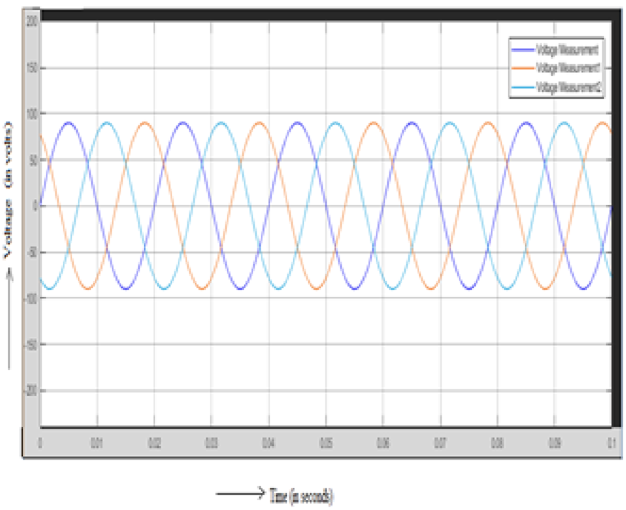

Fig.5. 3-phase grid volta

Table- II: L_2 Value at different MI

S.NO.	Modulation Index	Value of L_2 in hendry
2	0.4	0.1
3	0.6	0.085
4	0.8	0.07
5	1	0.05

III CLOSED LOOP GRID VOLTAGE CONTROL USING PI

A. Methodology with Experimentation:

In closed loop control , the pulse width modulation levels of inverter as well as inductor L2 is varied automatically by comparing rectified grid voltage with reference voltage through PI control. The total closed loop control can be represented with block diagram[1,8-11,] to analyze the stability by different means.. The closed loop control can be used either for inverter firing or for Inductor firing or for both at the same time. Fig.6 shows the Grid voltage wave form for both firing controls. The Fig. 7 shows the block diagram of closed loop control of the grid voltage with V_{ref} =100v.

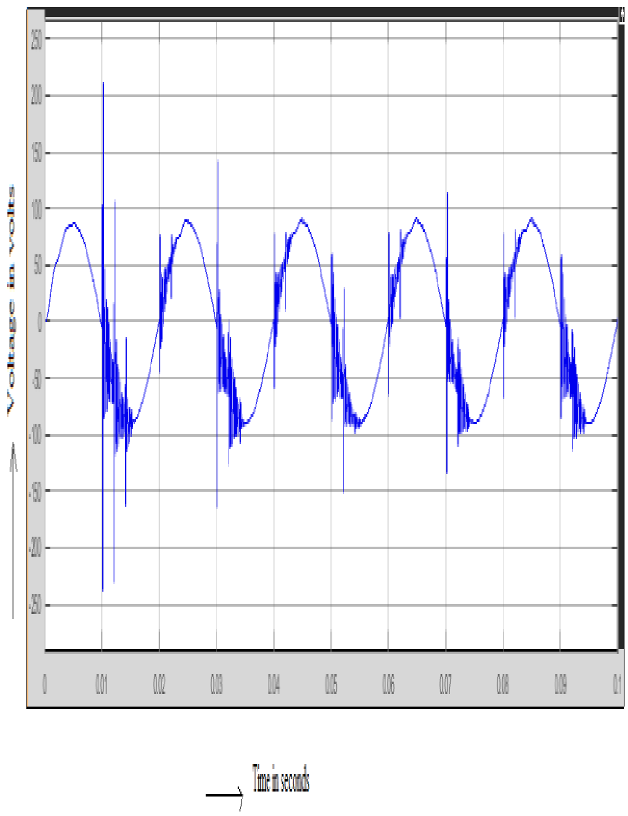

Fig 6. Grid Voltage in closed loop control with both Inductor and Inverter firings

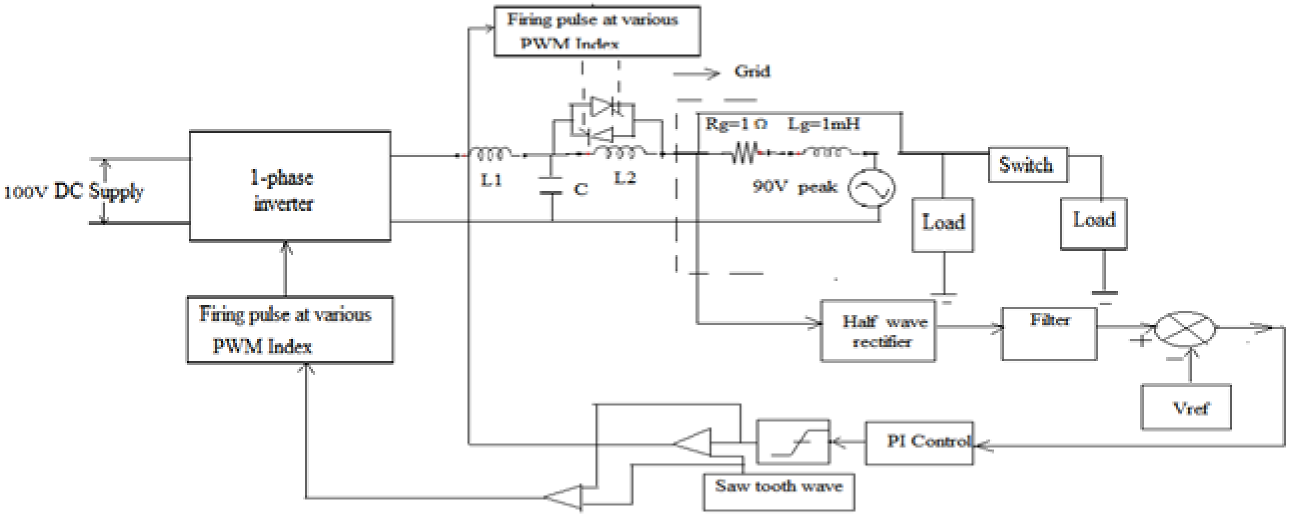

Fig .7. Closed loop Grid Voltage control with LCL Filter

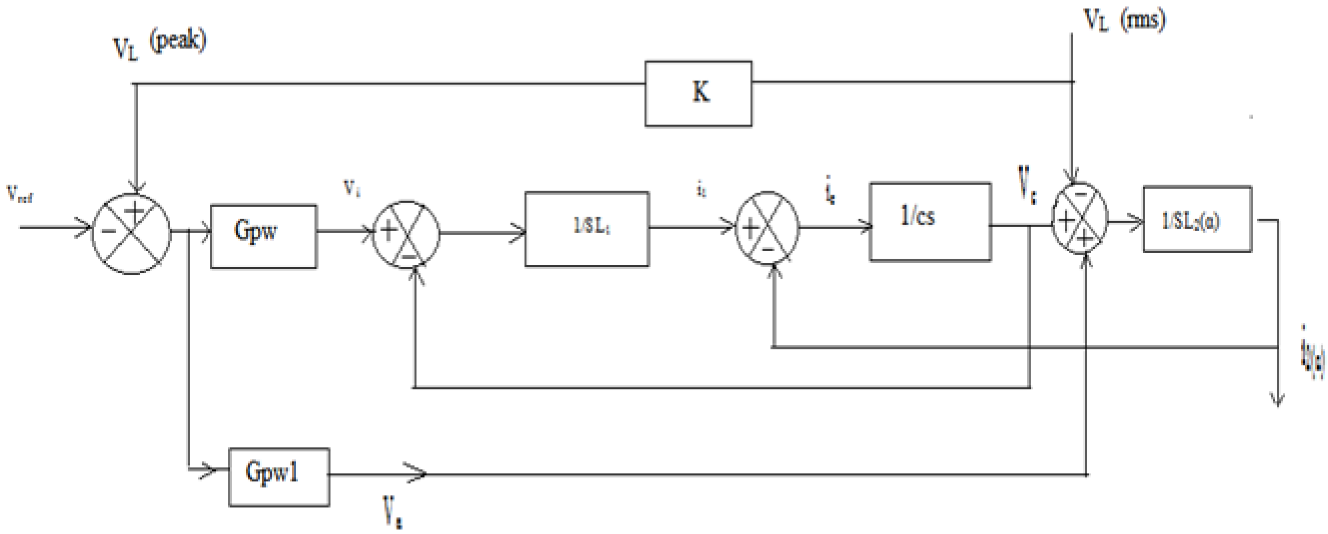

Fig. 8 Block diagram representation of closed loop control

The closed loop control represented in block diagram mode and it is shown in Fig. 8. Gpw is the transfer function of whole inverter control and Gpw1 is the transfer function of inductor L_2 controller. The only LCL filter block diagram [12] is represented in a simpler manner as shown in Fig. 9.

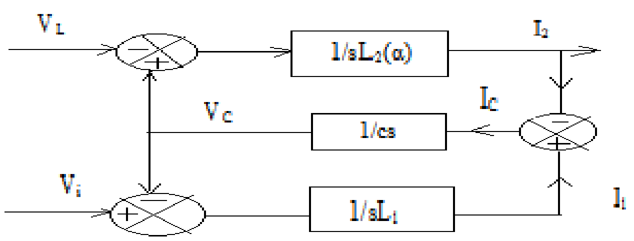

Fig. 9. Block diagram representation of LCL filter

At resonance condition [13-17] of LCL filter ,the frequency will be obtained by using the following equations

i) If Resistance R_g is neglected

$$x_{L1} = \frac{x_{L2g} * x_c}{(x_{L2g} - x_c)} \quad (1)$$

Where $x_{L2g} = x_{L2} + x_g$ (2)

The Resonance frequency ω_r= 4461.05 rad/sec

ii) If Resistance R_g is consider the resonant condition is given as

$$x_{L1} = \left(\left(x_{L2g} - x_c\right)\left(x_{L2g} * x_c\right) + R_g^{\,2} * x_c\right) \div \left(R_g^{\,2} + \left(x_{L2g} - x_c\right)^2\right) \quad (3)$$

The resonant frequency can be identified by solving higher order polynomial with using (3). The transfer function $[i_1(s) / V_i(s)]$ at $i_2 = 0$ is [18-20]

$$\left(\frac{i_1}{V_i}\right) = \frac{s}{L_1\left(s^2 + \frac{1}{L_1 c}\right)} \quad (4)$$

By substituting the values of L_1 , c the transfer function is obtained as

$$\frac{i_1}{V_i} = (10)\left[\frac{1 - z^{-1}\cos(10^7)^{\frac{1}{2}}T}{1 - 2z^{-1}\cos(10^7)^{\frac{1}{2}}T + z^{-2}}\right] \quad (5)$$

The transfer function $[V_c(s) / V_i(s)] = [V_L(s)/V_i(s)]$ at $i_2 = 0$ is

$$\frac{V_c(s)}{V_i(s)} = \left[\frac{\frac{1}{L_1 C}}{(s^2 + \frac{1}{L_1 C})}\right] \quad (6)$$

$$\frac{V_c}{V_i} = (10^7)^{1/2}\frac{z^{-1}\sin(10^7)^{\frac{1}{2}}T}{1 - 2z^{-1}\cos(10^7)^{\frac{1}{2}}T + z^{-2}} \quad (7)$$

The frequency analysis of (4),(6) in s-plane is shown in fig. 10a, fig.10b respectively. By observing the phase plot of the two figures, Fig.10a is showing closed loop stability and Fig.10b is not giving closed loop stability. The transfer function Gpw can be found by measuring the peak value of $V_L(s)$ and root mean square value of $V_i(s)$. The time delay for inverter is taken as $\tau = 10$ms . The PI controller [21] parameter values are taken as $K_p = 10$, $K_i = 1$. The transfer function Gpw is equal by using (8)

$$G_{pw} = \left(K_p + \frac{K_i}{s}\right)\left(k(s)\, e^{-s\tau}\right) \quad (8)$$

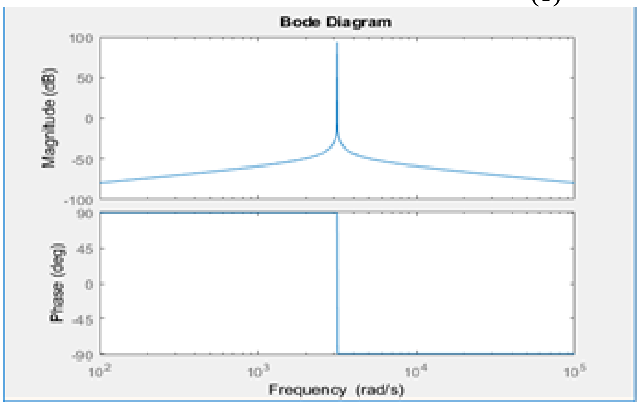

Fig10a. Bode diagram of Ii /Vi , ωr=3.17x103

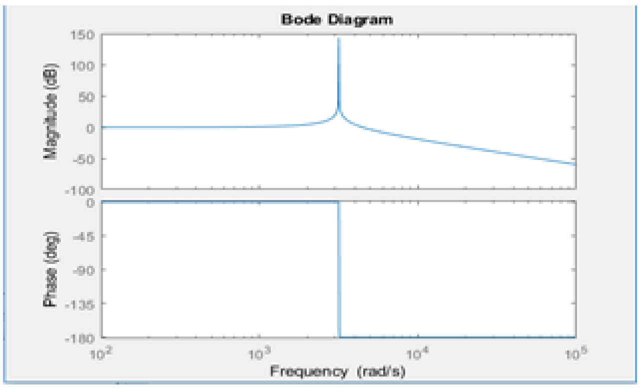

Fig10b. Bode diagram of VC /Vi , ωr=4.47x103

The G_{pw} can also be written as (9)

$$[V_L(s) - V_{ref}(s)]\, G_{pw} = V_i(s) \quad (9)$$

By taking the known parameters the K(s) is identified as

$$K(s) = \frac{(-0.592)\, s^2\, (s+100)}{(s+0.001)\,(s-j3.14)\,(s+j3.14)} \quad (10)$$

B. ***Analysis with Signal flow graph*** :

The signal graph for identifying transfer function i_2/V_L at $V_{ref} = 0$ is shown in Fig. 11

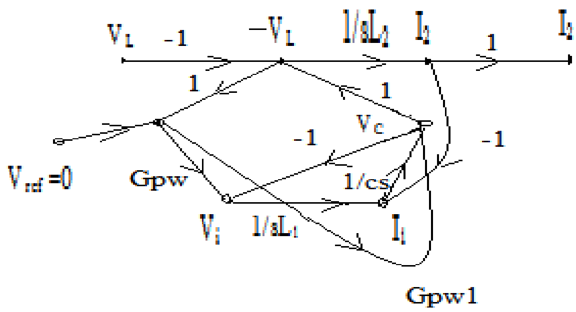

Fig. 11 Signal flow graph for i_2/V_L

Due to low value of G_{pw1}, it is approximated as zero.

By substituting values for G_{pw}, by using gain formula the transfer function i_2/V_L is mentioned in (11)

$$\frac{-i_2}{V_L} = \frac{(10^{-6}s^5 + 10^{-7}s^4 + 1.098s^3 + 1040.11s^2 + 98787.93s + 9868.3)}{s(s^3 + 0.1s^2 + 98683.93s + 9868.3)} \cong \frac{(1.098s^3 + 1040.11s^2 + 98787.93s + 9868.3)}{s(s^3 + 0.1s^2 + 98683.93s + 9868.3)} \quad (11)$$

The corresponding bode plot for the given transfer function is shown in Fig. 12. The plot indicates the closed loop stability of the system. The transfer function i_2/V_i at $V_L = 0$ is given in (12)

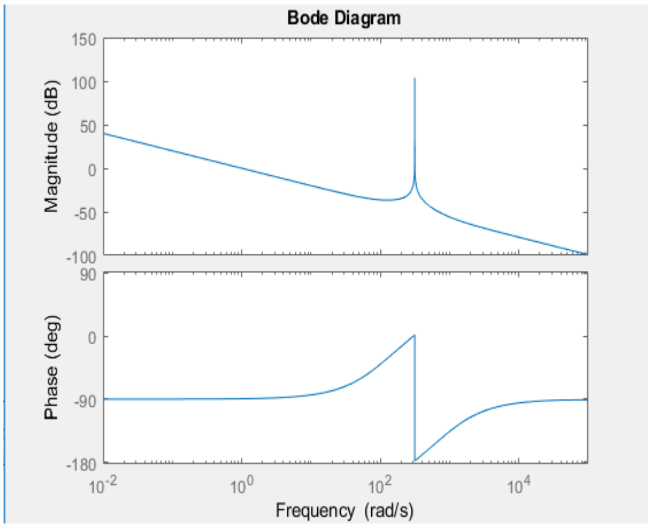

Fig.12. Bode diagram of I_2/V_L

$$\frac{i_{2(s)}}{V_{i(s)}} = \frac{cs}{1-[(L_1cs^2+1)(L_2cs^2+1)]} \qquad (12)$$

C. *Results & Discussions*

The variation of magnitude of i_2/V_i and its phase angle with variation of value L_2 is given in the Table III

Table –III : Variation of Admittance with L_2

S.NO.	Value of L_2 In hendries	Magnitude of i_2/V_i in mho	Phase angle of i_2/V_i (in radians)
1	0.05	0.02	π/2
2	0.07	0.018	π/2
3	0.085	0.017	π/2
4	0.1	0.015	π/2

Variation of i_2/V_i with L_2 at constant frequency is shown in the graph Fig 13a and Fig 13b .

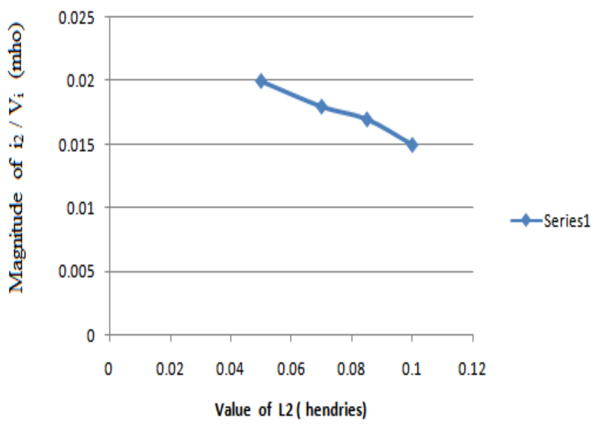

Fig.13a . Variation graph of magnitude i_2 / V_i

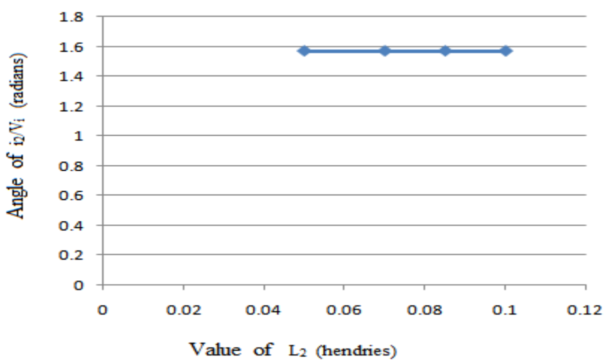

Fig 13b . Variation graph of angle of i2 / Vi

C.1 *Reconfiguration of LCL Filter:*

The Grid voltage stability depends not only in firing angle index. It also depends either in parameter values or configuration. Modified LCL filter is shown in Figure 14.

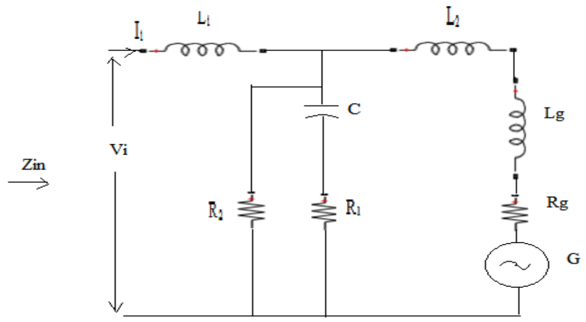

Fig 14. Modified LCL filter

The closed loop control with modified LCL filter reduces the THD level in Grid voltage. The values of R_1=1Ω and R_2=1 Ω . The extra resistances are used for damping the oscillations in the output. The THD level is reduced by 8%. In this configuration the resonance condition is obtained as given in (13)

$$\frac{x_1}{x_1'} = \frac{r_1}{r_1'} \qquad (13)$$

$$r_1 = (R_g R_{eq} - x_{L2g} x_{eq}) - x_{L1}[x_{eq} + x_{L2g}((R_1+R_2)^2 + x_c^2)] \qquad (14)$$

$$r_1' = R_{eq} + R_g((R_1+R_2)^2 + x_c^2) \qquad (15)$$

$$x_1 = x_{L1}[R_{eq} + R_g((R_1+R_2)^2 + x_c^2)] + (x_{L2g} R_{eq} + x_{eq} R_g) \qquad (16)$$

$$x_1' = x_{eq} + x_{L2g}((R_1+R_2)^2 + x_c^2) \qquad (17)$$

$$R_{eq} = (R_1 R_2)(R_1 + R_2) + x_c^2 R_2 \qquad (18)$$

$$x_{eq} = [x_c (R_1 R_2) - (x_c R_2)(R_1 + R_2)] \qquad (19)$$

In closed loop control with modified LCL filter the Grid voltage is shown in Figure 15

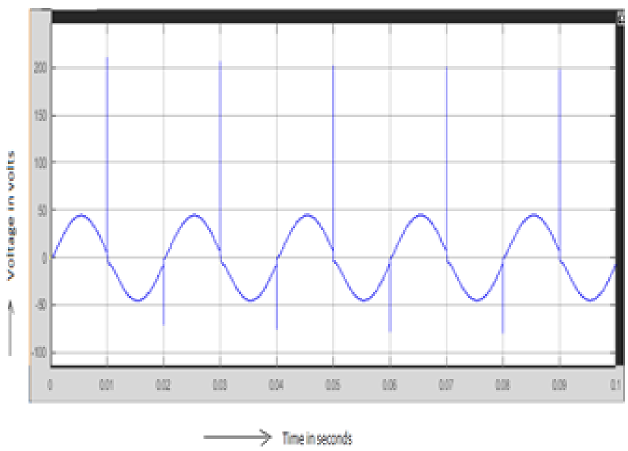

Fig 15 Grid voltage with modified filter

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IV. CONCLUSION

The importance of interfacing of renewable sources with Grid is increasing day to day. The interfacing of the Grid with solid state nonlinear switching devices used for renewable sources are causing of reduction in Grid stability. So the LCL filter analysis will enhance the Grid stability with better open and closed loop feedback control. The simulation provides theoretical analysis to implement for Grid stations. The Grid voltage gives highly sinusoidal with reduction in harmonics by using LCL filter. The stability analysis of different transfer functions will help to better design for LCL filter. Overall transfer functions can easily found with effective system block diagram representation. The importance of LCL filter for grid stability is inevitable even for 3-phase systems too.

APPENDIX

A. Circuit parameter values

L_1 = 0.1 H , c= 1x10^{-6} F , L_2 = 0.1H

Load : 10 KW, 1 KVAR inductive at $50H_z$

At half wave rectifier

R= 1000Ω , c= 1x10^{-4}F

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