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Performance Analysis of LCL Filter for Grid Interconnected System with Active Damping

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Abstract:
The shortage of electric power is the major problem now-a-days. As the conventional energy sources are depleting at a faster rate, there is an urgent need to investigate the alternative energy sources which help to solve the problem. The Renewable Energy Sources (RES) like wind, solar, tidal, bio mass etc., serve this purpose. But these are intermittent in nature and cannot be integrated to the present utility grid directly. Thus, to overcome the above problem power electronic converters are used. These converters should be controlled in such a way that the stability of the overall system is maintained. This paper deals with analysis & simulation of grid connected inverter with LCL filter is studied and simulated. The LCL filter is an effective solution for the interconnection of the Renewable Energy Sources to the grid but suffers from the problem of resonance. To overcome the above drawback, active and passive damping methods are proposed. And also a control strategy to reduce the lower order harmonics is proposed. The proposed control strategy is simulated in MATLAB SIMULINK environment.

Index terms:
Multi level converter, LCL filter, and Third harmonic injected PWM.

I.INTRODUCTION:

Growing demand of power and limited availability of conventional sources are the two key issues worrying researchers to think other alternatives of generating power. That's why other non-conventional sources have become popular now-a-days. Simultaneously, rising cost and complexity in existing electricity distribution systems and the inability of current systems to serve remote areas reliably has led to search for alternate distribution methods. One viable solution is use of renewable energy sources directly at point of load, which is termed as Distributed Generation (DG).These also have the advantage of cleaner energy production by reducing carbon emission, thereby being environmental friendly. But the main drawback of these RES is their intermittent nature, which causes difficulty in extracting power all the time in a day. As these are the only option left to meet the Increasing energy demand, they (RES) should be modeled in such a way to overcome this drawback.

These RES are synchronized to the grid through a dc-link and an inverter. To ensure stable operation of the grid, the voltage and frequency of the power injected by the RES should match with that of the grid. To achieve this, perfect control of the grid-side inverter is required in spite of the intermittent nature of RES. This project presents the modeling of the grid side inverter and proposes a control strategy for better synchronization of the RES to the grid.The Distributed Generations are connected to the utility grid through power electronic converter and filter. The block diagram of Grid connected Distributed generating sources shown in fig 1

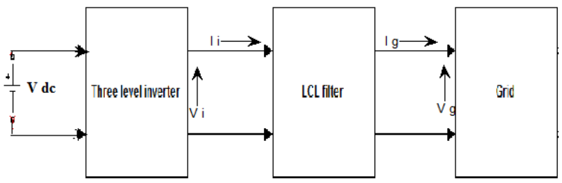

Fig1.Block diagram of grid inter connected power system

The Distributed Generation may represent wind, tidal, solar, etc. Which are Non conventional energy sources, these plants generates either AC or DC. The Generated power can be stored in batteries in the form of DC source. The main aim of converter and filter is to extract maximum power from Generated dc sources. The Converter converts the dc power to ac and feed it to the utility grid. The main aim of this converter is to keep the frequency and phase of output current same as grid voltage. The control algorithm of this converter has the following tasks- To control the active power injected into the grid. To control the reactive power transfer between the DC source and the grid. To maintain Grid Synchronization. In addition to the above main tasks, the converter also regulates local voltage and frequency, compensates the voltage harmonics and may does active filtering when required. Thus, to control the power injected into the grid, the control of converter is of utmost important. But the output current from the inverter contains harmonics. So to filter out these harmonics a filter is used at the output of the inverter.

A. WHY LCL-FILTER?

There are different types of filter configurations in the literature like- L, LC, LCL. The characteristics and the application of each type of filter are as follows-

B. L-Filter:

The L-filter is a first order filter having -20dB/decade attenuation over the whole frequency range. So this type of filter has its application with converters having high switching frequency where the attenuation is sufficient. The L-filter topology is as shown in Fig. 2.2 and the transfer function of the L-filter is- $F(S) = \frac{1}{LS}$ (1)

C. LC Filter:

The LC Filter is a second order filter giving -40db/decade attenuation. And it has better damping characters than L filter. This LC- filter is suited to configurations where the load impedance across capacitor is relatively high at and above the switching frequency. The cost and reactive power consumption of the LC filter are more than to the L filter because of the addition of the shunt element. But this filter suffers from the problem of infinite gain at resonant frequency. The transfer function of the LC-filter is-

$$F(s) = \frac{SC}{LCS^2-1} \qquad (2)$$

D. LCL-Filter:

This is a third order filter with an attenuation of -60dB/decade above resonant frequency. So it can be used for converters with low switching frequency. It can achieve reduced levels of harmonic distortion with small value of inductance. Thus, this filter suits better for the interconnection of RES with utility grid. On the other hand LCL filter may cause both dynamic and steady state input current distortion due to resonance.

II. MODELING OF GRID-CONNECTED MULTI LEVEL INVERTER

A new topology has mentioned, three level T- type neutral point clamped (3L-TNPC). The benefit of 3L-TNPC is the three level output voltage waveform while there are no restrictions to the switching scheme as in three level NPC. A three level TNPC phase leg consists of only 8 semiconductors: 4 IGBTs and 4 anti parallel freewheeling diodes. In this 3L TNPC topology semiconductors with different breakdown voltages are used. T1 and T4 need to withstand the full dc link voltage.

The inner switches connect AC to neutral and must be able to block half of the DC link voltage. In 3L TNPC topology the conduction paths are either through one higher blocking semiconductors or two lower blocking devices in series. Numbering semiconductors are shown in figure 2. Inherits the advantage that the exact same switching pattern can be used for both 3L NPC and 3L TNPC topology. The mathematical model of the grid-connected Distributed Generation is necessary in order to simulate and study the performance of the system at different operating conditions.

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There are certain assumptions based on which the mathematical model is derived. They are as follows- Three phase grid voltage is symmetrical, and stable. Three phase loop resistance and inductance are of the same value in all phases. Switching loss and on-state voltage drop are neglected. Effect of distributed parameters are neglected. Switching frequency of the converter is high enough. The circuit diagram of grid-connected inverter with LCL-filter is shown in Fig.

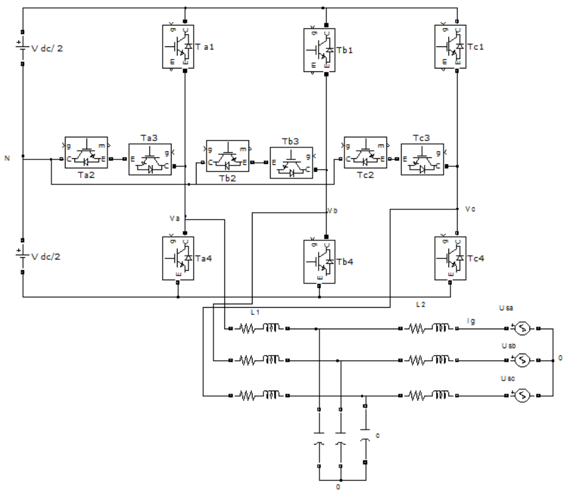

Fig 2. The circuit diagram of grid-connected inverter with LCL-filter

The parameters of the Fig.2 are as follows:

L_I is the inverter side filter inductor

L_G is the grid side filter inductor

C is the filter capacitance

V_A, V_B, V_C are the inverter side output voltages

U_{SA}, U_{SB}, U_{SC} are the grid side output voltages

I_G is the current entering the grid

V_{DC} is the voltage across dc-link capacitor

Park's Transformation:

Transformation from a,b,c to α β.

$$I_a = I_m \cos(\omega t) \quad (3)$$

$$I_b = I_m \cos(\omega t - 120^\circ) \quad (4)$$

$$I_c = I_m \cos(\omega t - 240^\circ) \quad (5)$$

$$I_\alpha = I_m \cos(\omega t) \quad (6)$$

$$I_\beta = I_m \cos(\omega t - 90^\circ) \quad (7)$$

$$I_\alpha = \frac{3}{2} I_a \quad (8)$$

$$I_\beta = \frac{\sqrt{3}}{2}(I_b - I_c) \quad (9)$$

Transformation from α β frame to d q frame

$$I_d = I_\alpha \cos\theta + I_\beta \sin\theta \quad (10)$$

$$I_q = -I_\alpha \sin\theta + I_\beta \cos\theta \quad (11)$$

From the circuit diagram by using Kirchhoff Law, the voltage and current equations in Stationary frame can be written as follows-

$$V_{conv} = V_c + L_i \frac{dIi}{dt} \quad (12)$$

$$V_{conv} = V_g + L_g \frac{dIg}{dt} + L_i \frac{dIi}{dt} \quad (13)$$

Conversion a,b,c frame to α, β frame

$$V_{\alpha conv} = V_{\alpha g} + L_i \frac{dIi\alpha}{dt} + L_g \frac{dIg\alpha}{dt} \quad (14)$$

$$V_{\beta conv} = V_{\beta g} + L_i \frac{dIi\beta}{dt} + L_g \frac{dIg\beta}{dt} \quad (15)$$

Conversion from α, β frame to d,q frame

$$V_d = V_\alpha \cos\theta + V_\beta \sin\theta \quad (16)$$

$$V_q = -V_\alpha \sin\theta + V_\beta \cos\theta \quad (17)$$

$$V_{dconv} = \left(V_{\alpha g} + L_i \frac{dIi\alpha}{dt} + L_g \frac{dIg\alpha}{dt}\right)\cos\theta + \left(V_{\beta g} + L_i \frac{dIi\beta}{dt} + L_g \frac{dIg\beta}{dt}\right)\sin\theta \quad (18)$$

By solving the above equation we get

$$V_{dconv} = V_{dg} + L_i \frac{dIid}{dt} + L_g \frac{dIgd}{dt} - \omega L_i I_{iq} - \omega L_g I_{gq} \quad (19)$$

$$V_{qconv} = V_{qg} + L_i \frac{dIiq}{dt} + L_g \frac{dIgq}{dt} + \omega L_i I_{id} + \omega L_g I_{gd} \quad (20)$$

Reverse transformation from d,q frame to α, β frame

$$V_\alpha = V_d \cos\theta - V_q \sin\theta \quad (21)$$

$$V_\beta = V_d \sin\theta + V_q \cos\theta \quad (22)$$

Transformation from α, β frame to a,b,c frame

$$V_a = \frac{2}{3} V_\alpha \qquad (23)$$

$$V_b = \frac{V_\beta}{\sqrt{3}} - \frac{V_\alpha}{3} \qquad (24)$$

$$V_c = -(v_a + V_b) \qquad (25)$$

III. ACTIVE AND PASSIVE DAMPING METHODS:

The LCL-filter has many advantages and suits best for grid interconnection of RES. But it may cause resonance with the grid impedance and may affect the stability of the system. In order to ensure stable operation of the utility grid, the filter resonance should be damped out effectively. This chapter explains active and passive damping methods for mitigating the resonance problem.

A. Different passive damping topologies:

a. Solution 1

The LCL filter transfer function of line side current & inverter input voltage in grid-connected mode of operation is given below.

$$\frac{I_{L2}}{U_{INV}} = \frac{\frac{1}{(L_1+L_2)}}{S(1+S^2(L_1 \| L_2.C)} \qquad (26)$$

From the transfer function it is clear that, at this frequency 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 is most responsible for resonance in LCL filter.

$$\frac{I_C}{U_{INV}} = \frac{L_1}{L_1+L_2} \cdot \frac{SC}{(1+S^2(L_1 \| L_2).C)} \qquad (27)$$

It is also clear from the frequency response of capacitor current. It carries basically resonant component & very less fundamental as well as switching component.

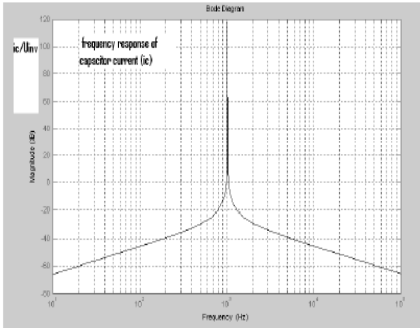

Fig 3. Frequency responses of the capacitor current in LCL filter without damping.

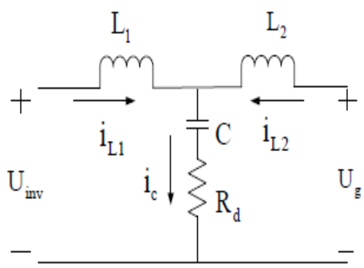

Fig4.Series damping LCL filter

Fig 4. shows the first & the simplest kind of passive damping topology. The bode-plot is given for the capacitor current vs. inverter voltage & line side current Vs inverter output voltage. It is clear from those that larger series resistance can give better damping or lower 'Q' as clear from the transfer function after damping.

$$\frac{I_C}{U_{INV}} = \frac{L_2}{L_1+L_2} \cdot \frac{SC}{(1+CR_dS+S^2(L_1 \| L_2)C)} \qquad (28)$$

$$\frac{I_{L2}}{U_{INV}} = \frac{1+SCR_D}{S^3(L_1L_2C)+S^2(L_1+L_2)CR_D+S(L_1+L_2)} \qquad (29)$$

So, here damping factor is proportional to Rd. 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 Rd 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.

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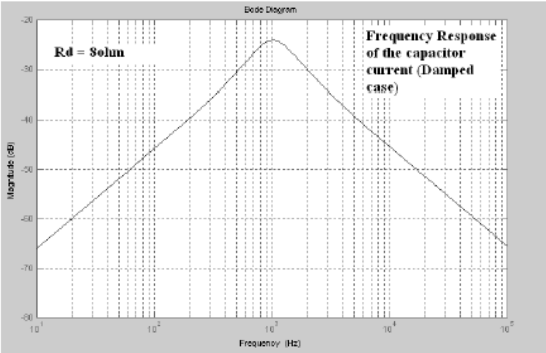

Fig. 5.Frequency response of capacitor current after damping

b. Solution 2:

Second solution is a slight modification over the first 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. Here one more inductance is inserted parallel to damping resistance. As a result current at fundamental will be by passed through Lf& loss will be considerably saved.

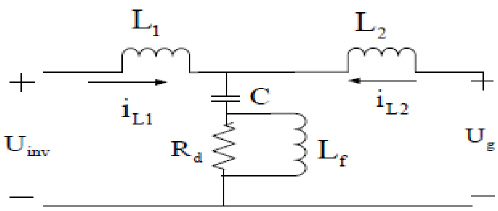

Fig 6. **By passing the damping resistance by Lf**

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.

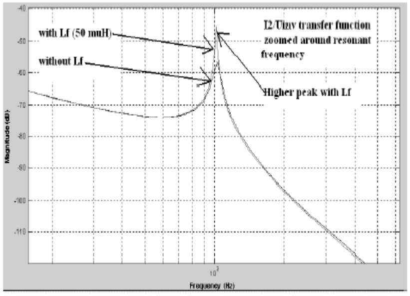

Fig 7.Frequency response with by passing inductance

c. Solution 3:

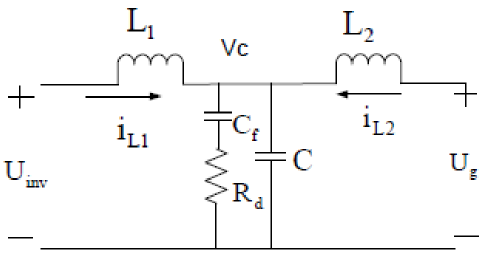

Fig 8.R-C parallel damping for the LCL filter

In this type of damping is much more preferred compared to simple series damping as here damping is not only depends on resistance but also on the ‘a’ (Cf / C) ratio .It is shown by following frequency plots: -

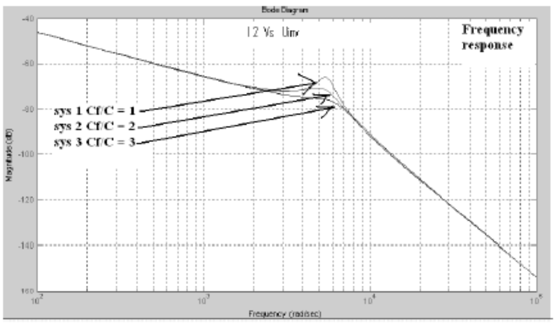

Fig 9.damping by changing Cf / C ratio

B. ACTIVE DAMPING:

a. Introduction:

In case of passive damping, damping provided by physical element like resistors. But this process is associated with losses and in the high power application with process cannot be afforded. To reduce losses and improve the performance inductors, capacitors are provided along with resistors.In case of active damping, damping is being provided by means of control algorithm, this process is not a loss process so this process is much more attractive. But there is a limitation of active damping, such as this control technique depends on the switching of power converter,so this is effective only when power converter is switching. On the other hand switching frequency of the power converter is limited hence the control BW of the active damping is also limited. There are broadly two methods of active damping can be thought one is based on traditional PI-controller and the other is based on generalized statespace approach. In this chapter we will focus on a method of active damping based on State-space (arbitrary pole placement).

b. Active damping based on traditional approach:

The traditional approach is based on different current control strategy such as conventional PI-controller based (in rotating frame) combined with lead compensator or a resonant controller as a main compensator in α-β domain. In these approaches BW of the system or settling time cannot be arbitrarily fixed as these based upon main current controller BW. In other words placement of the closed loop poles is determined by the current controller design

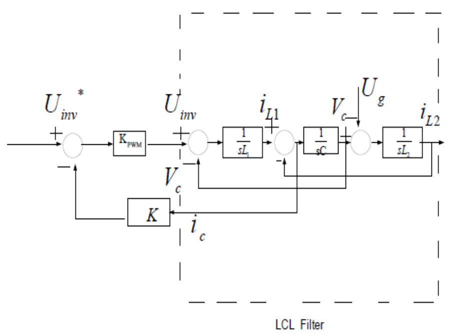

Fig 10. Active damping by weight age capacitor current feedback

c. Physical realization of Active Damping (concepts of Virtual resistance)

The concepts of active damping can be realized from the equation. After Splitting the state-space form we get,

$$C\frac{dV_c}{dt} = I_{L1} - I_{l2} \qquad (30)$$

$$L_1\frac{dI_{L1}}{dt} = -(1+K_1)V_C - K_2I_{L1} - K_3I_{L2} + U_{INV} \qquad (31)$$

$$L_2\frac{di_{L2}}{dt} = V_C - U_G \qquad (32)$$

So, if we try to give the circuit form of the above equation then it approximately looks like:-

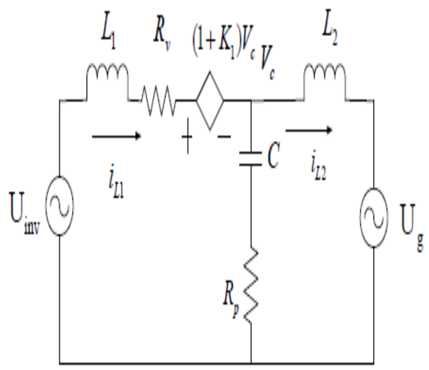

Fig 11.Approximate Circuit representation for Active damping

R_V is the series and R_p is the parallel virtual resistance. Now from circuit representation it is clear that these two resistances are providing the damping to the LCL resonance though these resistances do not exist in practical. These are coming just because of control action which is used to damp the resonance that is why these are called **"Virtual Resistances"**.

IV.Control Scheme for Grid Interactive Mode With Lcl Filter

The control of the three phase inverter is required to maintain the quality of power injected into the grid, to control active and reactive power exchange between the Distributed generation and the utility grid, to

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maintain grid synchronization. Here in this chapter dq-based control strategy is adopted. The control scheme for LCL filter based system is quite different as well as complicated from those of simple L filter based grid-connected system.

A. Overview of control loop consisting of three states of System

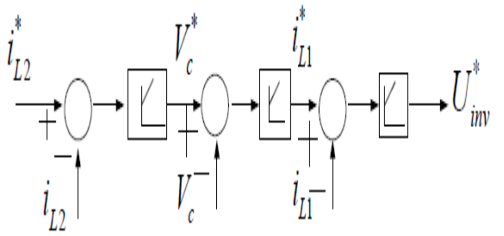

Fig 12.Conventional three loop control strategy for LCL filter

B.Reduction of Controller complexity

But here for this type of filter the capacitor voltage can be indirectly controlled so there is no need of capacitor voltage controller for LCL filter. The $I_{l1} - I_{l2} = I_c$ and the $V_c = \int \frac{1}{c} I_c$ dt, Hence if we can control I_{l1} and I_{l2} separately then that itself control the $I_c$followed by V_c.

Two Loop current control Strategy for LCL filter

Now the control loop may be reduced to following fashion:-

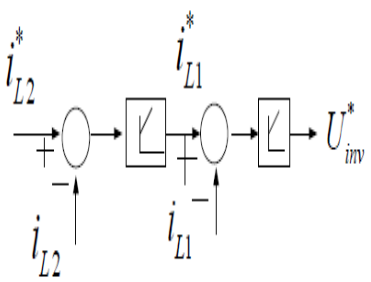

Fig 13 Two loop control strategy for LCL filter

So here the output of the line side current controller is becoming the reference of converter side current.

Now here line side current and converter side current are almost equal in magnitude and phase in fundamental as capacitor size is limited in LCL filter because of reactive power burden. Hence further more simplification is possible.The converter side current controller can also be omitted and only line side current controller is fair enough to control the current. The output of line side current controller will become inverter input reference.

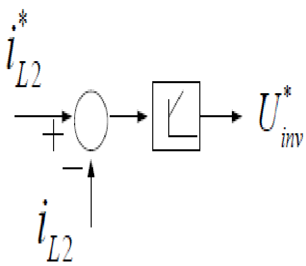

Fig 14 Single loop control strategy for LCL

Limitation of Single loop control strategy for LCL filter:

Single grid current loop controller is not sufficient for stability of the overall system. The resonance of the filter can make the system unstable as here we are only concentrating on the fundamental current where LCL filter has significant amount of resonance frequency super imposed over the fundamental. So we need to consider the resonance carefully.Higher-level control loops are required to provide fast dynamic compensation for the system disturbances and improve stability.

V. Simulation block diagram

Block diagram of Grid interconnected Distributed generation through multilevel inverter and LCL filter:

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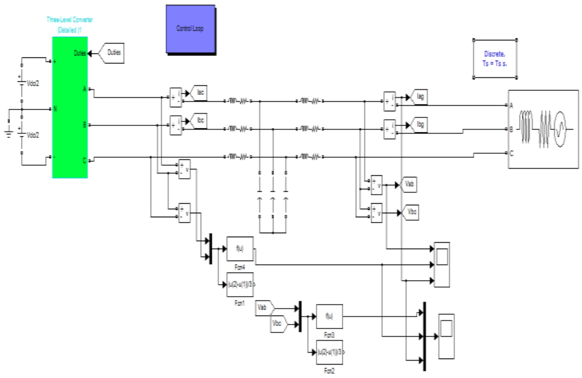

Fig 15. SimulationBlock diagram of Grid interconnected Distributed generation through multilevel inverter and LCL filter

Block diagram of control loop:

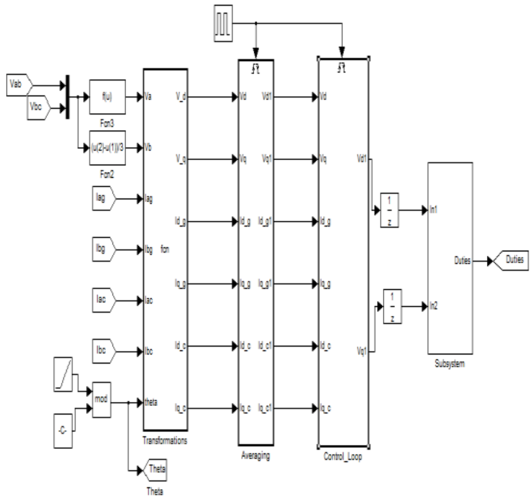

Fig 16 Simulation Block diagram of control loop

Construction of current control loop:

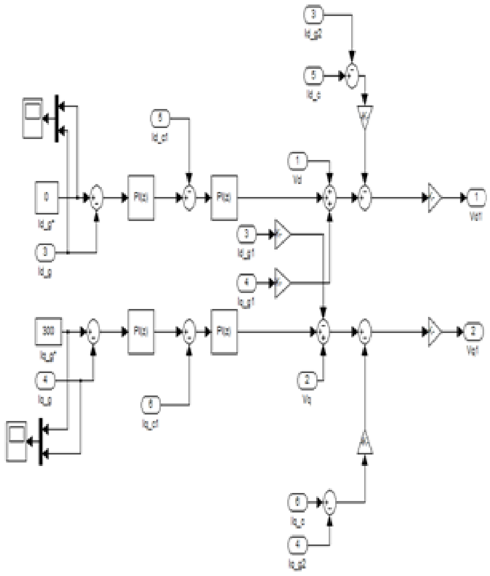

Fig 17. Simulation Construction of current control loop

VI. Simulation results:

Grid interconnection:

Simulation result shows power flow from DC source to the Grid.

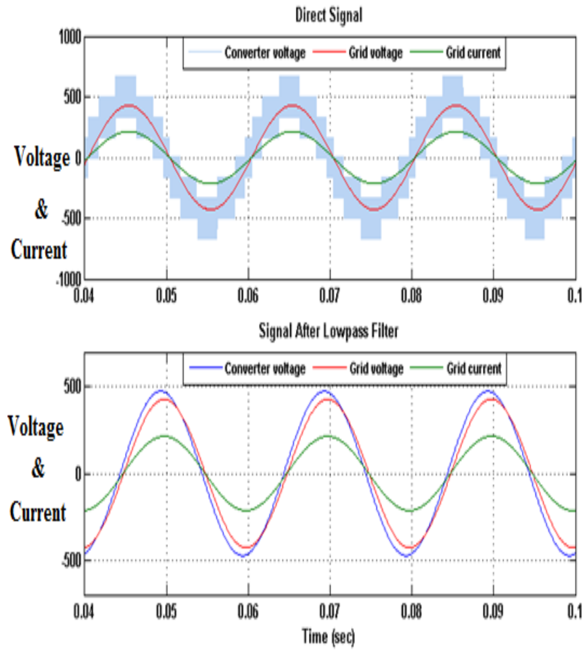

Fig18 Simulation result of power flow

Control Working:

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Simulation results shows control working to meet reference with feedback for various values of grid current.

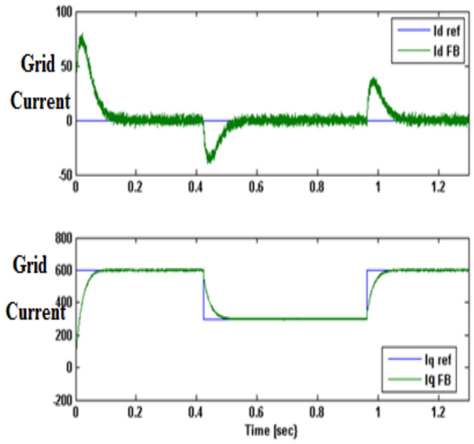

Fig19.

Simulation result of stability of control system

Simulation results shows control working to meet reference with feedback for different input DC voltage Transients.

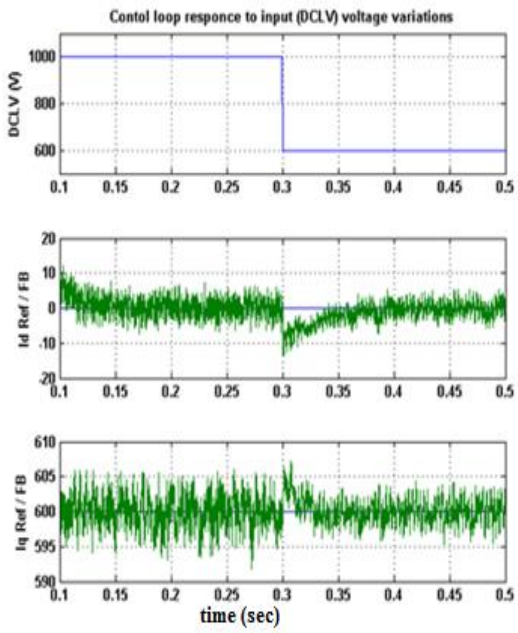

Fig 20. Simulation result for transients in DC voltages

Simulation results shows control working to meet reference with feedback for different Grid frequency Transients.

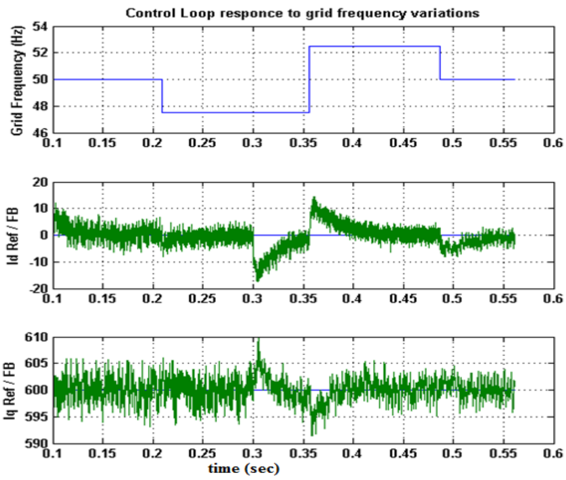

Fig 21. Simulation result for transients in grid frequency

Simulation results shows control working to meet reference with feedback for different Grid voltage Transients.

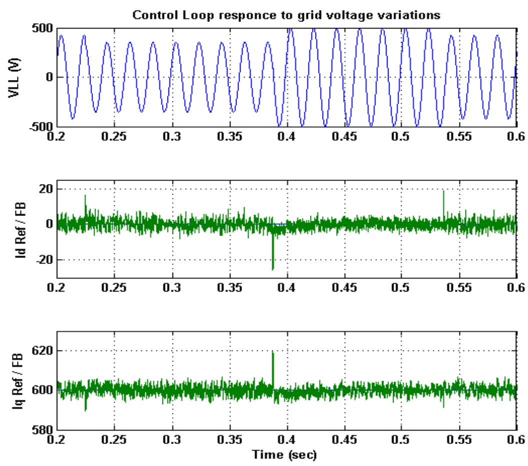

Fig 22. Simulation result for transients in grid voltage

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VII. CONCLUSION:

Performance of LCL filter for grid interconnection was studied and simulated. And found that, among different filter topologies present in the literature, the LCL filter best suits for grid interconnection application. And Active damping method of LCL filter has better response. The passive damping method of LCL filter is a low cost solution and is used where efficiency can be sacrificed slightly. Two loop current control strategy present in this project, it can achieved control over active and reactive power flow in to the grid. And ensure unity power factor operation with grid interconnection. This control strategy simulated at various transient conditions. Among different three level converter topologies, T type neutral point clamped (TNPC) obtained better performance with reduced converter switches rating, and it does not required any clamping devices, like diodes in diode clamped multilevel converter, and capacitors in flying capacitors multi level converter.

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