

Analysis of Grid Inverter System Using LCL Filter Based on Active and Passive Damping Methods

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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 way that the stability of the overall system is maintained. In this project, the control of grid connected inverter with LCL filter is studied. The LCL filter is an effective solution for the interconnection of the RES 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.

KEYWORDS : LCL filter, active and passive damping methods, shunt and series connected LCL filter, reducing low order harmonics.

I. INTRODUCTION

At present, there is an exponential rise in the power demand and to meet this demand the existing energy resources are not sufficient. And also these resources are depleting day- by-day. So there is an urgent need to develop the power generation from Renewable Energy Sources (RES) which provide a reliable alternative for the conventional energy sources. 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 Renewable Energy Sources are connected to the utility grid through a power electronic converter and a filter.

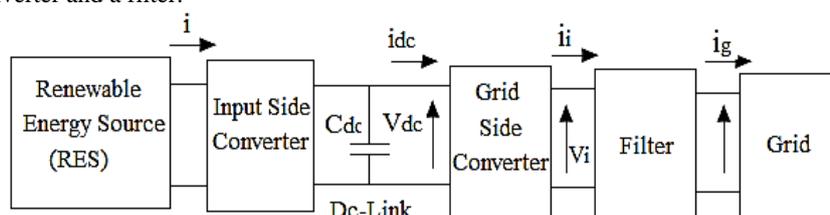


Fig.1 Block Diagram of Grid Connected System

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In Fig. 1 the RES may represent wind or solar panel, which generate either ac or dc. Its main aim is to extract maximum power from the RES. It may contain a boost converter to boost the voltage levels to match with that of the utility grid values. The control algorithms of input side converter include MPPT techniques to extract maximum power from RES at every point of time. The DC-link is used for providing constant dc input voltage to the grid-side converter. It contains a capacitor, C_{dc} for this purpose. The Grid-side Converter converts the dc power to ac and feed it to the utility grid. The main aim of this converter is to maintain constant dc-link voltage to keep the frequency and phase of output current same as grid voltage. In addition to the above main tasks, the grid-side 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 grid-side 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.

II. MODELLING OF GRID CONNECTED INVERTER

The mathematical model of the grid-connected RES is necessary in order to simulate and study the performance of the system at different operating conditions. The assumptions are (a) Three phase grid voltage is symmetrical, stable and internal resistance is zero, (b) Three phase loop resistance and inductance are of the same value in all phases, (c) Switching loss and on-state voltage drop are Neglected, (d) Effect of distributed parameters are neglected, (e) Switching frequency of the rectifier is high enough. The circuit diagram of grid-connected inverter with LCL-filter is shown in Fig. 2.1

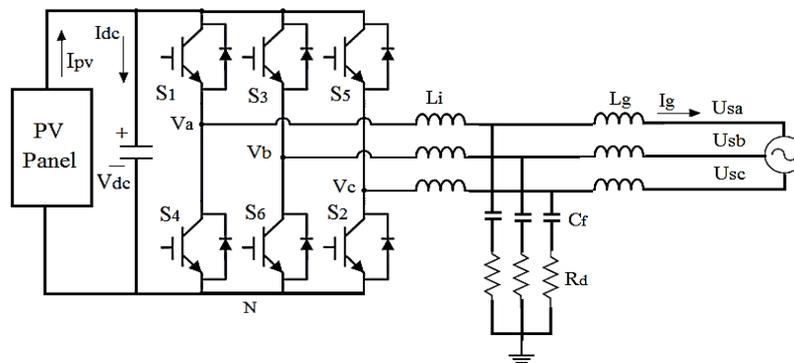


Fig.2.1 Circuit-Diagram of Grid-Connected Inverter

The parameters of the Fig. 2.1 are as follows

TABLE-1. SYSTEM PARAMETERS

Symbol	Parameter
Li	Inverter side filter inductor
Lg	Grid side filter inductor
Cf	Filter capacitance
Rd	Small damping resistance in series with the filter capacitance
Va , Vb , Vc	Inverter side output voltages
Usa , Usb , Usc	The grid side output voltages
Cdc	Dc-link capacitance
Ipv	Current from the PV-panel
Idc	Current through dc-link capacitor
Ii	Current from the inverter
Ig	The current entering the grid
Vdc	Voltage across dc-link capacitor

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From the circuit diagram by using Kirchoff Law, the voltage and current equations in stationary frame can be written as follows [6]-

$$V_{(\alpha,\beta)} = L_i \frac{di_{i(\alpha,\beta)}}{dt} + V_{Cf(\alpha,\beta)} \quad (1)$$

$$V_{cf(\alpha,\beta)} = L_g \frac{di_{g(\alpha,\beta)}}{dt} + U_{s(\alpha,\beta)} \quad (2)$$

$$C_f \frac{dV_{cf(\alpha,\beta)}}{dt} = i_{i(\alpha,\beta)} - i_{g(\alpha,\beta)} \quad (3)$$

Let the switching function of the inverter switches be defined as- $S_K = 1$, if upper switch conducts and lower switch blocks and $S_k = 0$, if lower switch conducts and upper switch blocks Where $K=a, b, c$ From Fig. 1.2 on the dc-side,

$$I_{pv} = I_{dcg} + I_{conv} \quad (4)$$

$$I_{conv} = S_a i_{sa} + S_b i_{sb} + S_c i_{sc} \quad (5)$$

$$I_{dc} = C_{dc} i_{sa} \frac{dv_{dc}}{dt} \quad (6)$$

Where i_{sa}, i_{sb}, i_{sc} are the currents in phases-a,b,c respectively coming out of the inverter . If the switching frequency is much higher than the grid voltage frequency, then the switching function, S_k can be substituted by duty cycle, d_k [1]. Thus, from equation (6)

$$C_{dc} i_{sa} \frac{dv_{dc}}{dt} = I_{pv} - (d_a i_{sa} + d_b i_{sb} + d_c i_{sc}) \quad (7)$$

Converting the above equation in a-b-c reference frame to stationary reference frame ($\alpha\beta$) using the Park's transformation matrix, the new equation obtained is-

$$C_{dc} i_{sa} \frac{dv_{dc}}{dt} = I_{pv} - \frac{3}{2} (d_{\alpha} i_{\alpha} + d_{\beta} i_{\beta}) \quad (8)$$

Where d_{α}, d_{β} are the duty ratios of the inverter switches in α - β plane and i_{α}, i_{β} are the inverter output currents in α - β plane.

A. Proportional-Integral (PI) Controller

It contains a proportional gain K_p and an integrator with gain K_I . The integral component helps in eliminating the steady state error. The transfer function of the PI controller is-

$$G_{PI}(S) = K_p + \frac{K_I}{s} \quad (9)$$

The proportional and integral gain values are calculated by Symmetrical Optimum Method [4]. Even though the current error turns to zero in steady state, it may appear in transient condition. This controller is mainly used in d-q reference frame where the grid voltage and currents are dc variables. In d-q reference frame, the current equations are given as [1].

$$L_s i_{sa} \frac{di_d}{dt} = \omega L_s i_q = V_{dc} d_d - U_m \quad (10)$$

$$L_s \frac{di_q}{dt} = \omega L_s i_d = V_{dc} d_q \quad (11)$$

Where L_s is the grid-inductance and U_m is the maximum value of grid voltage. From above equations it is clear that the system is strongly coupled and the design complexity Increases. So to reduce the complexity, the control is done in stationary reference frame (α - β). In stationary reference control the advantage is that the number of control variables is reduced. But in stationary reference frame control, the control variables are sinusoidal in nature. So PI controllers fail in

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removing the steady state error. As a consequence employment of other type of controllers is necessary. Due this drawback a new controller known as proportional resonant (PR) controller gains large popularity in current regulation for grid connected inverter system.

B. Proportional-Resonant (PR) Controller

To overcome the drawback of the PI controller, PR controllers are proposed. The advantage of PR controller is the possibility of implementing harmonic compensator without affecting the controller dynamics [3]. The transfer function of an ideal PR controller is

$$G_{PR}(s) = K_p + \frac{2K_{is}}{s^2 + 2Gw_c s + w^2} \quad (12)$$

But this has an infinite gain at the frequency ω rad/s. So a cut-off frequency ω_c is introduced to obtain finite gain and also to reduce sensitivity towards utility grid frequency variations by adjusting the band-width. Thus, the transfer function of non-ideal PR controller is

$$G_{PR}(s) = K_p + \frac{2K_{is}w_c s}{s^2 + 2Gw_c s + w^2} \quad (13)$$

With the flexibility of tuning the resonant frequency, the PR controller can be used for selectively compensating the low-order harmonics. The gain values are calculated by using the formulae give in [4].

C. Control Strategy

The main aim of the control strategy is to obtain unity power factor operation and to reduce the harmonics in the current injected into the grid. To achieve these objectives, the grid voltage is aligned along the d-axis of the 2- ϕ rotating coordinates. So $V_d = V_g$ and $V_q = 0$ The grid voltage and current when expressed in d-q reference frame can be written as

$$V_g = V_d + jV_q \quad (14)$$

$$I_g = I_d + jI_q \quad (15)$$

Three-phase complex power injected to the grid is given as

$$S = V \cdot I \quad (16)$$

Thus, the complex power in d-q reference frame is given as

$$S = V_d I_d - jV_d I_q \quad (17)$$

This shows that active power injected to the grid depend on 'Id' and reactive power depends on 'Iq'. Thus, the active and reactive powers are controlled independently. To make the reactive power exchange to zero, the reference value I_q^* is set to zero. The current Id is controlled to meet the active power demand.

$$I_d = \frac{P^*}{V_d} = \frac{P^*}{V_g} \quad (18)$$

III. SIMULATION AND RESULTS

The overall control strategy of grid-interfaced inverter with active and passive damping. Methods for LCL-type filter configuration is studied and analyzed using MATLAB Simulink environment. The system parameters considered for this study are given in Table-2. The obtained results during steady state and transient conditions are discussed in this section.

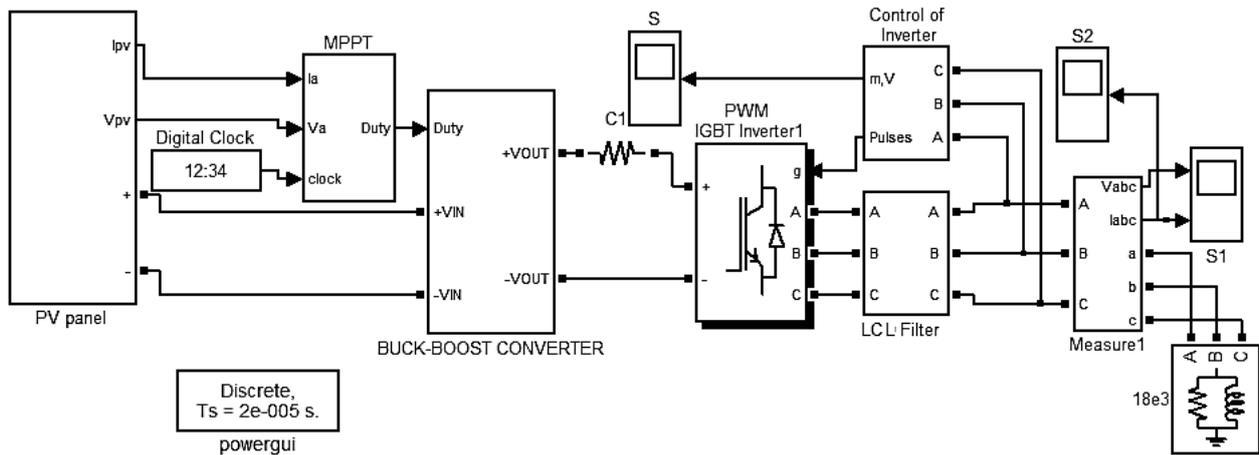


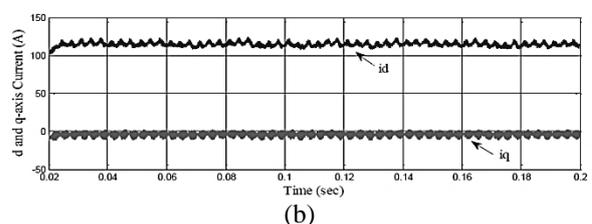
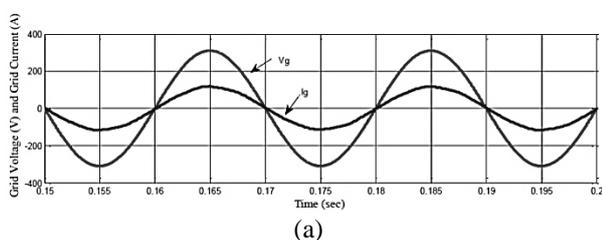
Fig.3.1 Simulation for active and damping method

TABLE-2. SYSTEM PARAMETERS

Symbol	Parameter	Value
P_{pv}	System power	100 kW
V_{dc}	Dc-Link Voltage	600 V
U_g	Grid Voltage	300 V (Line to Line)
C_{dc}	Dc- Link Capacitance	13400 μ F
F_s	Switching Frequency	4.5 kHz
L_i	Inverter Side Inductance	2 mH
L_g	Grid Side Inductance	1.8 mH
C_f	Filter Capacitance	4.7 μ F
R_d	Damping Resistance	2.2 Ω
C_1	Damping Capacitor	4.7 μ F

D. During Steady State Conditions

The simulation results under steady-state condition for active and passive damping methods are illustrated in Fig. 3.1 and Fig. 3.2 respectively. Fig.3.1 (a) shows the three phase grid voltage and grid current waveforms under steady state conditions using active damping method and they are almost close to sinusoidal waveforms. Fig.3.1 (b) depicts d and q-axis grid current components and q-axis component is almost zero. And it implies that there is no reactive power injected into the grid and it ensures unity power factor operation of the grid. The corresponding grid active and reactive power response is shown in Fig.3.1 (c). Also the dc-link voltage is maintained constant at 600 V which is illustrated in Fig.3.1 (d). With the help of active damping method, PWM VSI with LCL filter injects sinusoidal current into the grid. As a result, THD of grid current is largely reduced (1.66%) and it is shown in Fig.3.1 (e). The corresponding steady state response of passive damping method for LCL-type filter for grid-connected PMW VSI is shown Fig3.2.



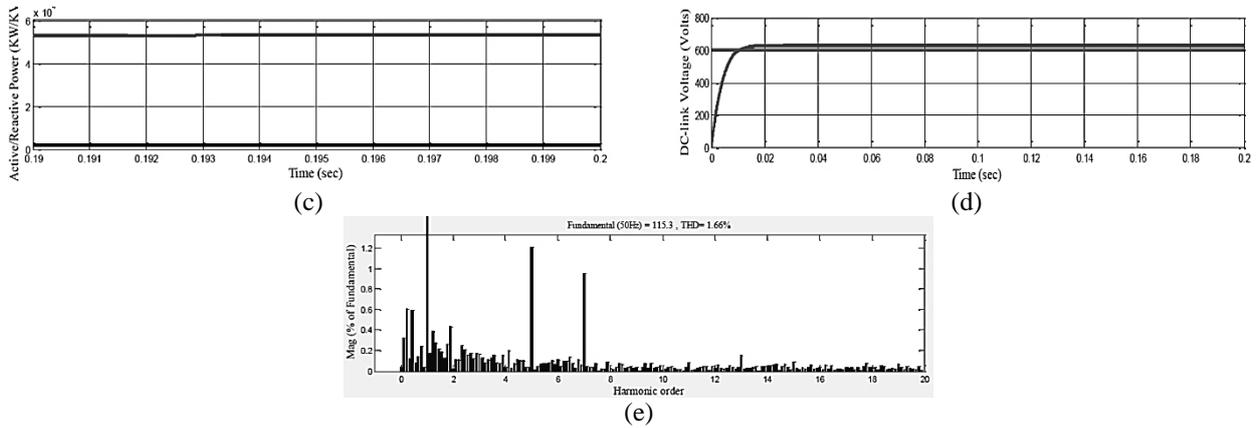


Fig.3.1 Simulation results for active damping method under steady state condition (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) Response of active and reactive Power (d) Response of dc-link voltage (e) THD of grid current.

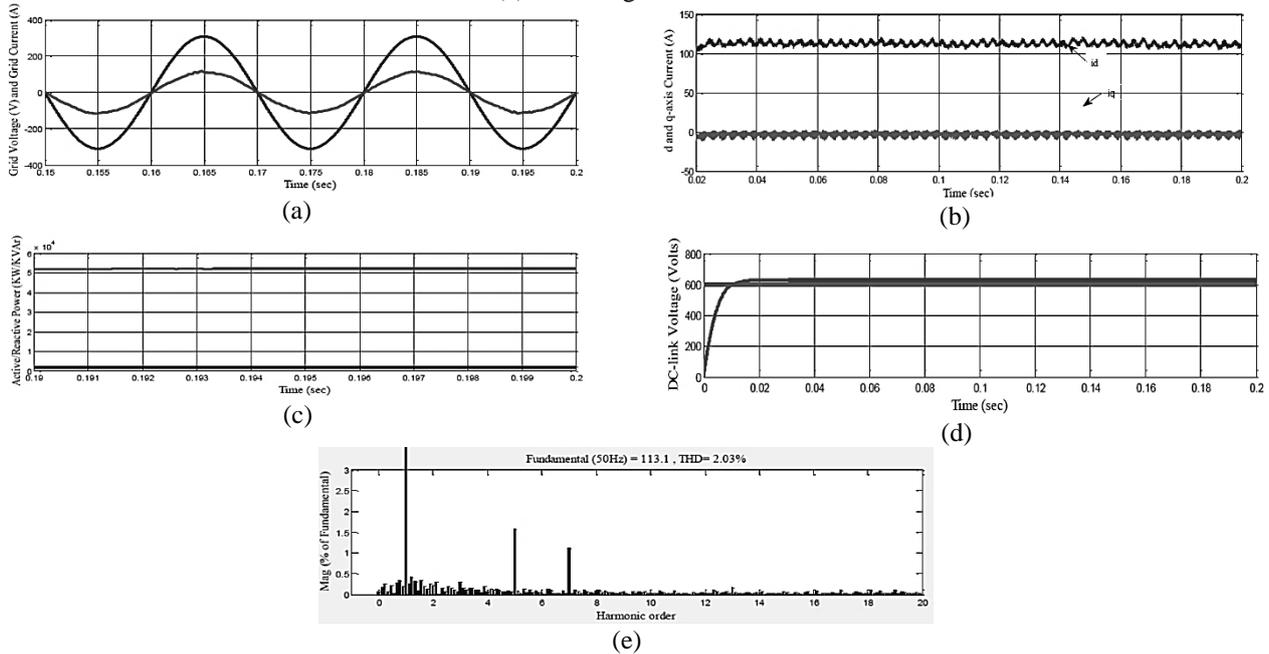


Fig.3.2 Simulation results for passive damping method under steady state condition (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) Response of active and reactive Power (d) Response of dc-link voltage (e) THD of grid current.

E. During Step Change in the Input PV power

In order to simulate the operation of the proposed control strategy and to analyze the transient response of both active and passive damping method of LCL-type filter, a step changes in the extracted PV power whose amplitude reduced from 100 kW to 70 kW at 0.08 sec is applied and the related simulation results are shown in Fig.3.3 and Fig.3.4 respectively. Due to step change in the PV power input at 0.08 sec, d-axis grid current component is changed at 0.08 sec and it reaches the steady state at 0.1 sec which is clearly shown in Fig.3.3 (b). However, q-axis grid component is still zero because of the proposed control strategy and it ensures unity power factor operation of the grid. This figure shows that after a small transient time, the output inverter current reaches its steady state

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value of 100 A, which is exactly equal to the reference value. This proves that the current loop controller along with active damping method in the LCL-type filter is effective such that measured currents track their references with constant dc-link voltage of 600 V (from the Fig.3.3 (c)). Moreover, its dynamic behavior is satisfactory. In addition, the active damping method with LCL-type filter injects sinusoidal current into the grid with lesser THD (1.85% from the Fig.3.3 (d)). The corresponding response of passive damping method with LCL-type filter for grid-connected PWM VSI is illustrated in Fig.3.4.

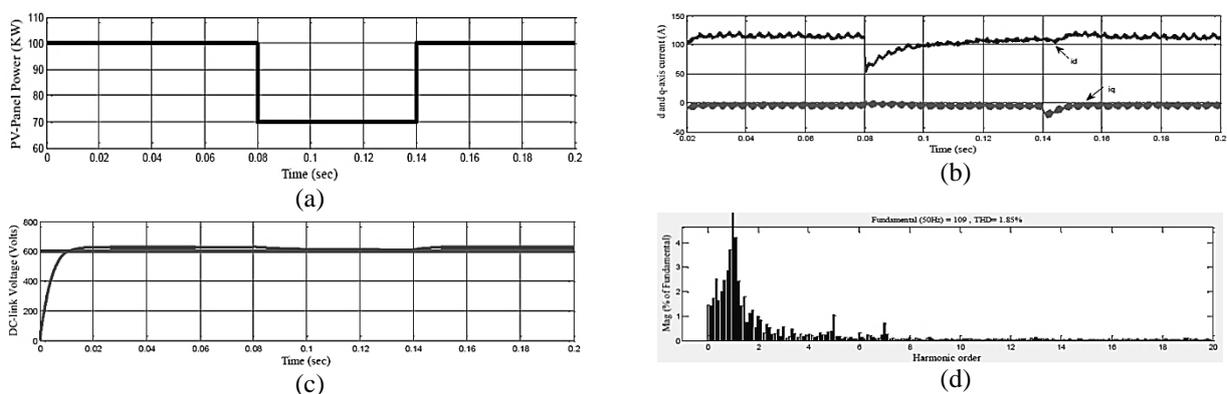


Fig.3.3 Simulation results for active damping method during step change in the input PV power (a) Step change in the input PV power (b) d and q-axis grid currents (c) Response of dc-link voltage (d) THD of grid current.

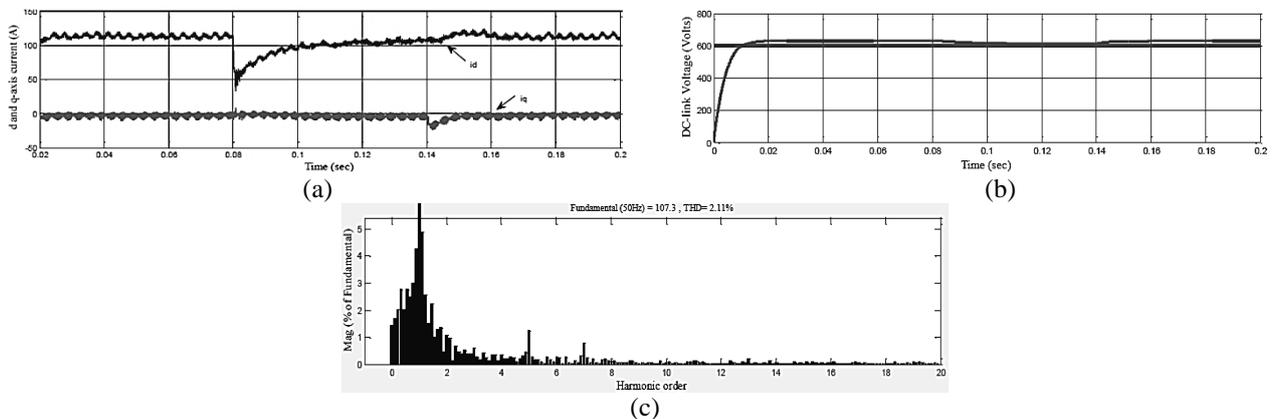


Fig 3.4 Simulation results for passive damping method during step change in the input PV power (a) d and q-axis grid currents (b) Response of dc-link voltage (c) THD of grid current.

F. Comparative Analysis

A comparative study between active and passive damping methods for LCL-type filter is discussed here. With reference to Table-3 it is found that, the active damping method is superior over passive damping method and it ensures almost sinusoidal current injection into the grid with reduced THD. Also the loss befalling in the passive damping method are more with the introduction of extra physical components, which further reduces the overall efficiency of grid-connected inverter system.

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TABLE-3 THD OF GRID CURRENT COMPARISON

Type of Damping	Steady-State Condition	Source Dynamics Condition
Active Damping	1.66%	1.85%
Passive Damping	2.03%	2.11%

IV. SIMULATION RESULTS FOR SHUNT CONNECTED LCL FILTER

The proposed control strategy is simulated in MATLAB SIMULINK environment and the results are discussed in this section. The parameter values of the shunt connected LCL filter are given in Table-4

TABLE-4 SYSTEM PARAMETERS

Symbol	Parameter	Value
P _{pv}	System power	100 kW
V _{dc}	Dc-Link Voltage	600 V
U _g	Grid Voltage	300 V (Line to Line)
C _{dc}	Dc- link capacitance	13400 μF
F _s	Switching frequency	4.5 kHz
L ₁	LCL Filter Inductance	1.2 mH
L ₂	LCL Filter Inductance	1.1 mH
L _g	Grid Side Inductance	1.8 mH
C _f	Filter capacitance	4.7 μF
R _d	Damping resistance	2.2 Ω
C ₁	Damping capacitor	4.7 μF

A. During Steady State Conditions

The simulation results under steady-state condition are illustrated in Fig. 4.1. Fig.4.2 (a) shows the three-phase grid voltage and grid current waveforms under steady state conditions and they are almost close to sinusoidal waveforms. Fig.4.1 (b) depicts d and q-axis grid current components and q-axis component is almost zero. And it implies that there is no reactive power injected into the grid and it ensures unity power factor operation of the grid. Also the dc-link voltage is maintained constant at 600 V which is illustrated in Fig.4.2 (c). The THD of grid current is largely reduced (1.27%) when compared with series connected LCL-filter and it is shown in Fig.4.3 (d). Thus, the fundamental component of the current injected to the grid has been increased, increasing the active power supplied by the RES to the utility grid.

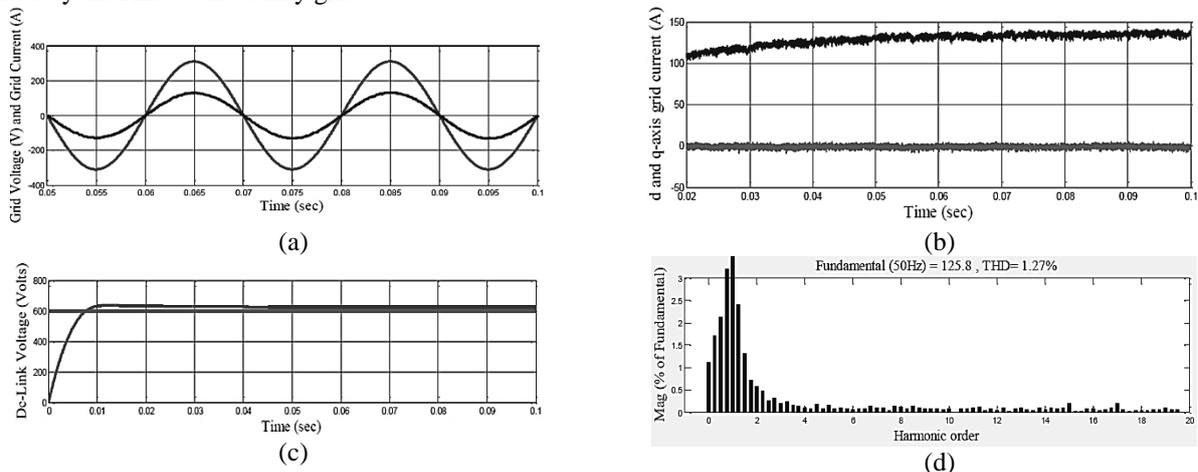


Fig.4.1 Simulation results under steady state condition (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) Response of DC-link voltage (d) THD of grid current.

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B. During Step Changes in the Input PV power

In order to simulate the operation of the proposed control strategy and to analyze the transient response of shunt connected LCL-type filter, a step changes in the extracted PV power whose amplitude reduced from 100 kW to 70 kW at 0.08 sec is applied and the related simulation results are shown in Fig.4.2. Due to step change in the PV power input at 0.08 sec, d-axis grid current component is changed at 0.08 sec and it reaches the steady state at 0.1 sec which is clearly shown in Fig.4.2 (b). However, q-axis grid component is still zero because of the proposed control strategy and it ensures unity power factor operation of the grid. In addition, the shunt connected LCL-type filter injects sinusoidal current into the grid with lesser THD (1.89% from the Fig.4.2 (c)) even in transient conditions. As in steady state condition, the amount of current injected into the grid has been increased when compared to series connected filter.

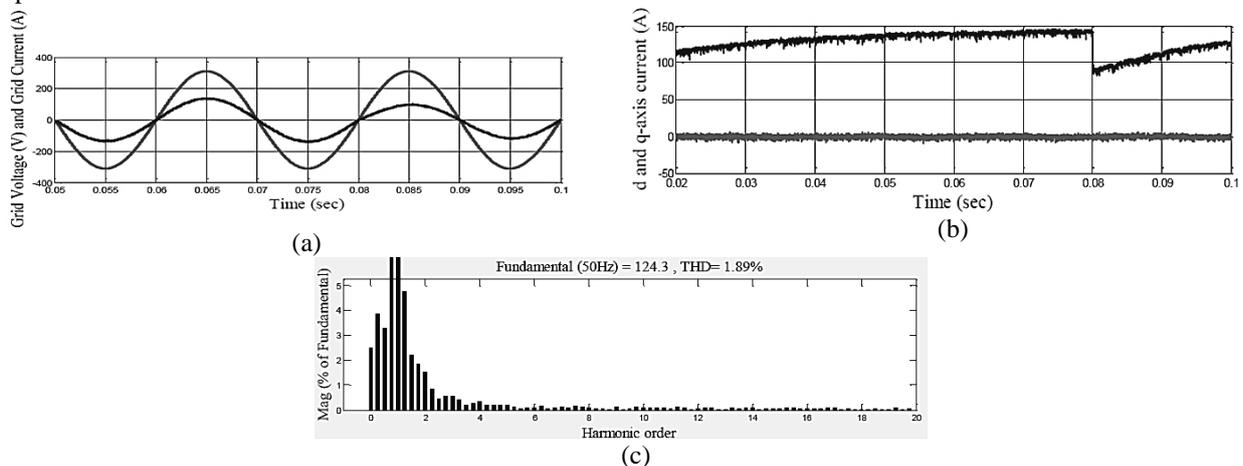


Fig. 4.2 Simulation results under step changes in input PV power (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) THD of grid current.

C. Comparative Analysis

A comparative study between series and shunt connected LCL-type filter is discussed here. With reference to Table-IV, it is found that, the shunt connected LCL filter is superior over series connected filter and it ensures almost sinusoidal current injection into the grid with reduced THD increasing the fundamental component of the injected grid current.

Table-5. Comparison of series and shunt connected LCL filter

	Steady state condition		Source dynamics condition	
	Series LCL	Shunt LCL	Series LCL	Shunt LCL
Overall THD of grid current	1.75%	1.27%	2.36%	1.89%
Fundamental grid current (A rms)	81.61%	88.97%	76.42%	87.88%

V. CONCLUSION

Now-a-days, the integration of renewable energy sources to the grid is one of the most discussed topics in power industry. There are numerous issues and challenges regarding grid interconnection. The harmonics present in the injected grid current is one of the major issues. To Overcome these problems, LCL filter can be used which filters the harmonics. But it suffers from the resonance problem. In order to overcome these problems, active and passive damping methods have been proposed in this paper. And also the control of grid connected inverter with LCL filter is studied and analyzed.

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