



Improving the stability of a Grid Connected Inverter Configuration by reducing the Total Harmonic Distortion (THD) of the Grid Currents Using a LCL filter

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Abstract: This Paper presents the stability of a grid connected inverter configuration using MATLAB. The renewable energy sources generate electrical energy which is DC in nature. This DC supply is converted into 3 phase AC via a voltage source inverter (VSI) and it is linked with a grid. Due to the presence of harmonics in the inverter output there are severe oscillations in the grid current which affects the stability of this inverter connected grid configuration. In order to tackle this problem we use a LCL filter between the inverter and the grid. By doing so the total harmonic distortion (THD) of the grid current reduces and the stability of the system improves. MATLAB Simulink results are generated to verify the claims as mentioned above.

Keywords: MATLAB; Stability of grid connected system; LCL filter; Total Harmonic Distortion.

I. INTRODUCTION

The demand of electrical energy is increasing at an exponential rate in the modern world. Today, the capacity of load is increasing every year so as a result there is a lot of stress on the non-renewable sources of energy (Coal, Diesel, Various chemical processes to generate energy like battery) to generate electricity. Due to the increasing environmental hazard like pollution, chemical waste being dumped and many more, the promotion of renewable sources of energy to generate electricity (Solar panels to utilize solar energy, Wind mills to utilize wind energy, Potential energy from ocean waves in the form of Tidal energy) is the need of the hour.

The linkage of Electrical energy sources with the grid is a challenging task as it has to fulfil many objectives. An inverter is used as a common link between the renewable energy source and the grid. The nature of electrical energy which is generated from various renewable energy sources is DC. The DC voltage is converted into three phase AC supply via an Inverter. The three phase AC supply is now sent to the grid for utilisation after modification of certain parameters. The key points which are to be kept in mind before synchronising the inverter supply with the grid are as follows. The nature of AC supply should be a sinusoid. Sinusoidal three phase AC supply is desired as it has numerous advantages like sinusoids lend themselves to phasors, Sinusoidal AC waveform generates revolving magnetic field.

The other important parameter is frequency to be altered is frequency because if the frequency of the incoming supply is not same as that of the grid it can lead to instability of the whole system.

In the configuration mentioned above a LCL filter is also used between the inverter and the grid. This configuration is widely accepted as it has lots of perks. The role of LCL filter here is that it act as a low pass filter which is used to reduce the high frequency inverter current harmonics in the system. The rating of the inductor is also small thereby decreasing the overall cost of the LCL filter. Apart from these perks the issue in using the LCL filter in this configuration is that it reduces the stability of the system by introducing a pair of poles which are equal in magnitude and opposite in sign. Another issue is the problem of resonance which has to be damped either by a passive element like a resistor or we can also use the virtual resistor concept to damp the oscillations.

Hence, in this paper we try and ensure the total stability of the system and also remove the harmonics from the grid currents by using an altered Lyapunov method instead of the direct conventional method. In order to do so a capacitor is added in the feedback path of the closed loop configuration in the form of LCL filter. As a result the Total Harmonic Distortion (THD) of the grid currents also gets reduced as the Harmonics from the currents gets suppressed to a minimum. MATLAB Simulink results are presented in this paper to validate the claims made above.

II. MATHEMATICAL MODEL OF THREE-PHASE GRID CONNECTED VSI

The leftmost part is the voltage source inverter (VSI) and it is connected to the inductor L_a . The inductor L_b is connected to the grid. In between the two inductors L_a and L_b we have the capacitor C_f for all the three phases.

Inverter consists of six Insulated Gate Bipolar Transistor (IGBT). They are operated in the order of $Z_a, \bar{Z}_c, Z_b, \bar{Z}_a, Z_c, \bar{Z}_b$ to generate the three phase sinusoidal AC supply.

The differential equation of the inverter written according to the KVL and KCL are as follows:

$$L_a \frac{di_{1n}}{dt} + r_a i_{1n} = u_n v_{dc} - v_{cfn} \quad (1)$$

$$L_b \frac{di_{2n}}{dt} + r_b i_{2n} = v_{cfn} - v_{gn} \quad (2)$$

$$C_f \frac{dv_{cn}}{dt} = i_{1n} - i_{2n} \quad (3)$$

The equation of grid voltage is $v_{gn} = v_g \cos(\rho t + \theta)$ where the value of θ is taken as 0, -120degree and -240 degree. We need to convert the value of θ from degree to radians before substituting it into the grid voltage equation. For all the three phase R, Y and B respectively.

Now we define the transition function for Inverters (u_n) :

$$u_n = \begin{cases} 1 & Z_n \text{ closed} \\ -1 & \bar{Z}_n \text{ closed} \end{cases}, \quad n = a, b, c \quad (4)$$

Z_n (Upper limb IGBT devices of VSI)

$\bar{Z}_n$ (Lower limb IGBT devices of VSI)

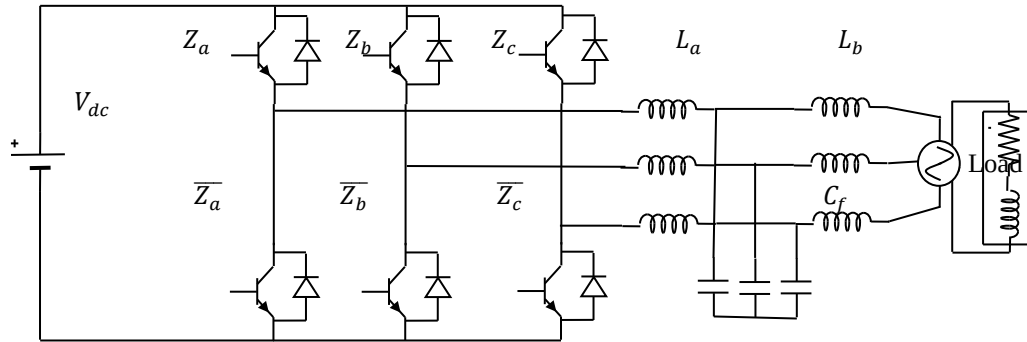


Figure 1. Renewable energy source connected with grid via three legged VSI and LCL filter

Now we change all the variables from equation (1) - (3) into Dc variables by changing it into the d-q frame. Here we have used x-y variables instead of d-q frame in all the equations.

$$L_a \frac{di_{1x}}{dt} + r_a i_{1x} = 0.5 u_x v_{dc} - v_{cfx} + \rho L_a i_{1y} \quad (5)$$

$$L_a \frac{di_{1y}}{dt} + r_a i_{1y} = 0.5 u_y v_{dc} - v_{cfy} - \rho L_a i_{1x} \quad (6)$$

$$L_b \frac{di_{2x}}{dt} + r_b i_{2x} = v_{cfx} - v_{gx} + \rho L_b i_{2y} \quad (7)$$

$$L_b \frac{di_{2y}}{dt} + r_b i_{2y} = v_{cfy} - v_{gy} - \rho L_b i_{2x} \quad (8)$$

$$C_f \frac{dv_{cfx}}{dt} = i_{1x} - i_{2x} + \rho C_f v_{cfy} \quad (9)$$

$$C_f \frac{dv_{cfy}}{dt} = i_{1y} - i_{2y} - \rho C_f v_{cfx} \quad (10)$$

On defining the state variables, we get

$$x_a = i_{1x} - i_{1x}^*$$

(11)

$$x_b = i_{1y} - i_{1y}^* \quad (12)$$

$$x_c = i_{2x} - i_{2x}^* \quad (13)$$

$$x_d = i_{2y} - i_{2y}^* \quad (14)$$

$$x_e = v_{cfx} - v_{cfx}^* \quad (15)$$

$$x_f = v_{cfy} - v_{cfy}^* \quad (16)$$

The symbol (*) is used to signify the reference or base values. Hence, if such a symbol is used to with currents it will signify the reference or base currents.

III. STEADY-STATE ANALYSIS

On taking equation (5)-(10) we can write them as:

$$L_a \frac{di_{1x}^*}{dt} + r_a i_{1x}^* = 0.5 U_x V_{dc} - v_{cfx}^* + \rho L_a i_{1y}^* \quad (17)$$

$$L_a \frac{di_{1y}^*}{dt} + r_a i_{1y}^* = 0.5 U_y V_{dc} - v_{cfy}^* - \rho L_a i_{1x}^* \quad (18)$$

$$L_b \frac{di_{2x}^*}{dt} + r_b i_{2x}^* = v_{cfx}^* - v_g + \rho L_b i_{2y}^* \quad (19)$$

$$L_b \frac{di_{2y}^*}{dt} + r_b i_{2y}^* = v_{cfy}^* - \rho L_b i_{2x}^* \quad (20)$$

$$C_f \frac{dv_{cfx}^*}{dt} = i_{1x}^* - i_{2x}^* + \rho C_f v_{cfy}^* \quad (21)$$

$$C_f \frac{dv_{cfy}^*}{dt} = i_{1y}^* - i_{2y}^* - \rho C_f v_{cfx}^* \quad (22)$$

Where U_x and U_y denote the x and y components of the transition function in the steady-state.

IV. MODIFIED LYAPUNOV-FUNCTION BASED CONTROL STRATEGY

The conventional stability method proposed by Lyapunov is amongst the most widely used scheme to test the asymptotic stability of the system. The whole point of this research paper is to ensure the total stability of the grid connected inverter system.

The energy delivered by the source (V_{dc}) is represented by P_{in} . This energy is not totally delivered to the grid, some part of this energy is dissipated in the form of heat losses. A major part is lost in the resistive part of the two inductive parts of the filter (R_a and R_b). We denote this energy by P_{Ra} and P_{Rb} . The energy dissipated by the IGBT devices which are used in the inverter is denoted by P_{ig} . Hence, the energy which is left after all these losses is delivered to the grid.

As we know that inductor and capacitor are active element so they do not dissipate energy. So, the energy P_{in} is exchanged from the stored energy of the inductor and capacitor in order to attain the equilibrium state of the inverter. The equilibrium points are ($x_a = 0, x_b = 0, x_c = 0, x_d = 0, x_e = 0, x_f = 0$). We denote this bidirectional energy exchange as $\Delta P_{La}, \Delta P_{Lb}, \Delta P_{cf}$. The prime aim as mentioned above was to determine the total stability, behaviour and performance of the system. In order to do so we use Lyapunov's conventional stability theorem for which we have to define a function $P(q)$ which is a scalar quantity. We can assure the stability only if the system obeys the below given conditions.

- i. $P(0) = 0$
- ii. $P(q) > 0$ for all $q \neq 0$
- iii. $P(q) \rightarrow \infty$ as $\|q\| \rightarrow \infty$
- iv. $P(\dot{q}) < 0$ for all $q \neq 0$

Now on substituting;

$$u_x = U_x + \Delta u_x \quad \text{and} \quad u_y = U_y + \Delta u_y \quad \text{And also (11) – (16) in (5) to (10)}$$

On solving we get,

$$L_a \dot{x}_a + r_a x_a = 0.5 \Delta u_x V_{dc} - x_e + \rho L_a x_b \quad (24)$$

$$L_a \dot{x}_b + r_a x_b = 0.5 \Delta u_y V_{dc} - x_f - \rho L_a x_a \quad (25)$$

$$L_b \dot{x}_c + r_b x_c = x_e + \rho L_b x_d \quad (26)$$

$$L_b \dot{x}_d + r_b x_d = x_f - \rho L_b x_c \quad (27)$$

$$C_f \dot{x}_e = x_a - x_c + \rho C_f x_f \quad (28)$$

$$C_f \dot{x}_f = x_b - x_d - \rho C_f x_e \quad (29)$$

Let us define the Lyapunov function in terms of energy stored in inductor and capacitor as follows

$$P(q) = \frac{3}{2} L_a x_a^2 + \frac{3}{2} L_a x_b^2 + \frac{3}{2} L_b x_c^2 + \frac{3}{2} L_b x_d^2 + \frac{3}{2} C_f x_e^2 + \frac{3}{2} C_f x_f^2 \quad (30)$$

On differentiating (30), we get

$$P(\dot{q}) = 3x_a L_a \dot{x}_a + 3x_b L_a \dot{x}_b + 3x_c L_b \dot{x}_c + 3x_d L_b \dot{x}_d + 3x_e C_f \dot{x}_e + 3x_f C_f \dot{x}_f \quad (31)$$

Substituting (24) - (29) in Equation (31), we get

$$P(\dot{q}) = \frac{3}{2} x_a v_{dc} \Delta u_x + \frac{3}{2} x_b v_{dc} \Delta u_y - 3r_a (x_a^2 + x_b^2) - 3r_b (x_c^2 + x_d^2) \quad (32)$$

Clearly $P(\dot{q}) < 0$ as per the given conditions of the Lyapunov function if Δu_x and Δu_y are selected as

$$\Delta u_x = K_x x_a v_{dc}, \quad K_x < 0$$

$$\Delta u_y = K_y x_b v_{dc}, \quad K_y < 0$$

From (17) and (18), the steady state transition function of x and y can be defined as

$$U_x = \frac{2}{v_{dc}} (r_a i_{1x}^* + v_{cfx}^* - \rho L_a i_{1y}^*) \quad (33)$$

$$U_y = \frac{2}{v_{dc}} (r_a i_{1y}^* + v_{cfy}^* + \rho L_a i_{1x}^*) \quad (34)$$

Where,

$$i_{1x}^* = i_{2x}^* - \rho C_f v_{cfy}^* = i_{2x}^* (1 - \rho^2 L_b C_f) \quad (35)$$

$$i_{1y}^* = \rho C_f v_{cfx}^* = \rho C_f (r_b i_{2x}^* + V_g) \quad (36)$$

$$v_{cx}^* = r_b i_{2x}^* + V_g \quad (37)$$

$$v_{cy}^* = \rho L_b i_{2x}^* \quad (38)$$

By observing equation (35)-(38) one can conclude that, we can easily evaluate all the unknown parameters mentioned in (35)-(38) if we know the value of reference x components of the grid current (i_{2x}^*).

On applying the control variables to the system, $u_x = U_x + \Delta u_x$ and $u_y = U_y + \Delta u_y$ we cannot damp the oscillations that occur due to the resonance of the LCL filter. In order to do so we have to use capacitor in the feedback path of this system in the closed loop configuration to remove the fluctuations from the grid current. The new modified equations are as follows

$$u_x = \frac{2}{V_{dc}} (r_a i_{1x}^* + v_{cfx}^* - \rho L_a i_{1y}^*) + K_x x_a V_{dc} + K_{cx} (v_{cfx}^* - v_{cfx}) \quad (39)$$

$$u_y = \frac{2}{V_{dc}} (r_a i_{1y}^* + v_{cfy}^* + \rho L_a i_{1x}^*) + K_y x_b V_{dc} + K_{cy} (v_{cfy}^* - v_{cfy}) \quad (40)$$

By changing the value of K_{cx} and K_{cy} we can adjust the level of damping. The value of gain K_{cx} and K_{cy} must always be positive.

V. MATLAB Simulation Results

The control method based on Lyapunov for the grid connected system is done here by using MATLAB. The Simulink results are generated to validate the proposed objective to ensure the stability of the system. The specifications of parameters used in the MATLAB model are given in appendix.

Figure 2 Shows the start-up response and the DC voltage obtained from the Lyapunov based stability scheme without capacitor voltage feedback. From figure 2 it is understood that there exist oscillation in the grid current which are damped very slowly.

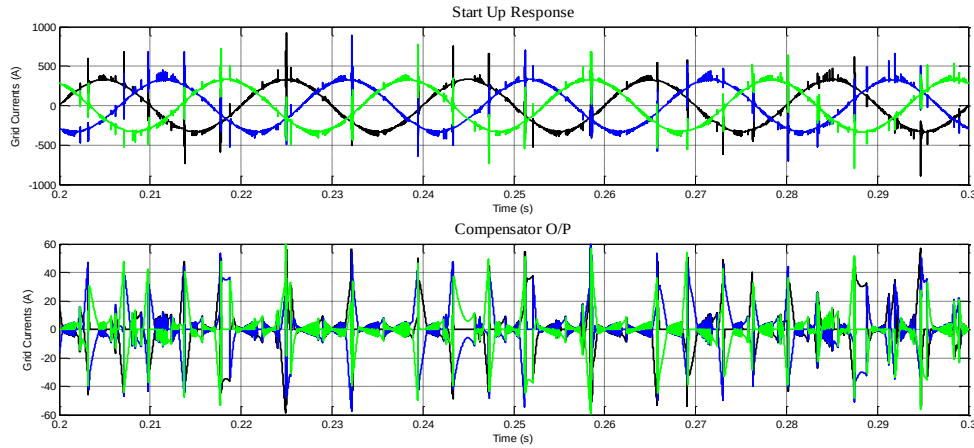


Figure 2: Start-up response without capacitor voltage feedback

In figure 3 we can observe that by using the capacitor in the closed loop configuration of the proposed system the fluctuations or harmonics on the grid current gets damped much effectively improving the overall stability of the system. The harmonic waveforms of phase(R) grid currents obtained by Lyapunov based stability scheme with and without capacitor voltage feedback is given in Figure 4. In figure 4 the Total Harmonic Distortion (THD) of the grid currents without capacitor voltage feedback is coming out to be 30.62% and the fundamental frequency is 52.66Hz. Similarly, the THD of the grid currents with capacitor voltage is coming out to be 3.81% and the fundamental frequency is 51.26Hz.

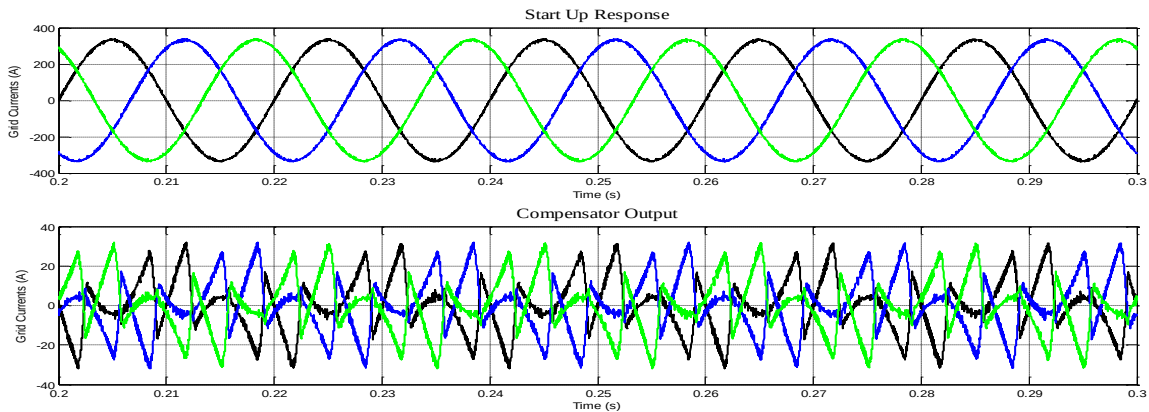


Figure 3: Start-up response with capacitor voltage feedback

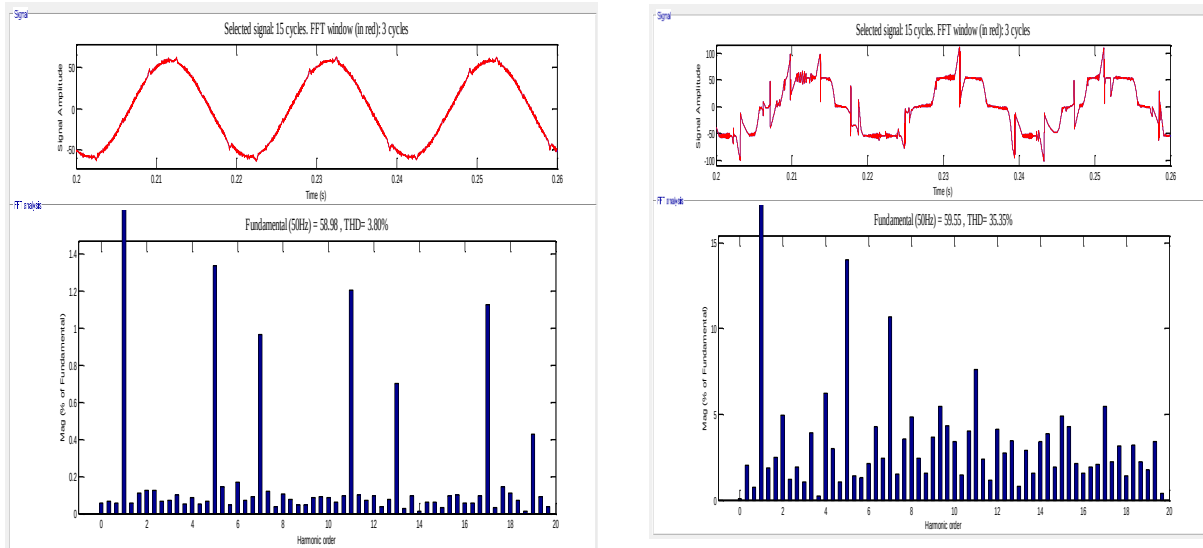


Figure 4: Total harmonic distortion with and without capacitor voltage feedback

Now, we will analyse the waveform of the voltage and current coming out from the inverter (i.e. V_{sa} and I_{sa}) and also the voltage and current going into the non-linear RL load (i.e. V_{La} and I_{La}) which we have connected to the grid. Figure 5(b) shows the results of the voltage and current without capacitor voltage feedback. Hence, from figure 5(b) we can observe that without using LCL filter there is lot of harmonics in the output voltage and current waveforms of the inverter and also of the grid.

Now, we will analyse the waveform of the voltage and current coming out from the inverter (i.e. V_{sa} and I_{sa}) and also the voltage and current going to the non-linear load (i.e. V_{La} and I_{La}) which we have connected to the grid after we have used the capacitor in the feedback path of the closed loop configuration.

From figure 5(a) we can observe that with using LCL filter the harmonics are filtered in the output voltage and current waveform of the inverter and the grid respectively.

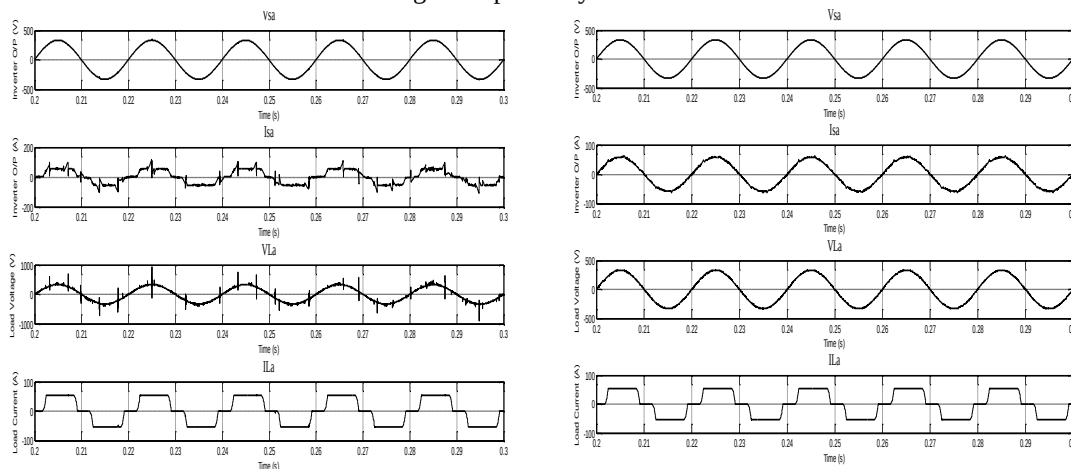


Figure 5: Voltage and Current waveform with and without capacitor voltage feedback

VI. CONCLUSION

A simulation study of an inverter connected grid configuration has been done using MATLAB. A capacitor is connected in the feedback path of the system in the form of a LCL filter. It filters the harmonics from the grid currents. The Total Harmonic Distortion (THD) of the grid currents also decreases from 35.35% to 3.80% thereby improving the stability of the system.

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APPENDIX

SYMBOL	VALUE
DC Source Voltage (V_{dc})	400V
Inductor connected on the side of the Inverter (L_a)	2.33mH
Capacitor used in the LCL filter (C_f) Y/Δ	15/5 μ f
Inductor used on the side of the Grid(L_b)	0.045mH
Resistance of Inductor (R_a)	0.55 Ω
Resistance of inductor (R_b)	1.65 Ω
RMS value of grid voltage (V_{rms})	230V
Peak value of grid voltage (V_p)	230 $\sqrt{2}$ V
Grid Frequency (V_g)	50Hz