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Harmonic stability analysis of multi-paralleled 3-phase PV inverters tied to grid

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ABSTRACT

In this paper the harmonic stability is investigated for multi paralleled three-phase photovoltaic inverters connected to grid. The causes to harmonically stabilize/destabilize the multi-paralleled PV inverters when tied to the grid is analysed by the impedance-based stability criterion (IBSC). In this paper stability of the system is investigated by varying the grid inductance with constant grid resistance and also by varying load impedance while maintaining grid inductance constant. Stability of the multiple three phase inverters tied to the grid with different grid impedance, inductance value in particular are analyzed. Overall system is stable up to grid inductance of 5mH even though there is change in load admittance. It is concluded that system stability depends only on grid impedance. It is verified with MATLAB Simulations.

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1. INTRODUCTION

Proliferation of renewable energy sources is the current scenario to the meet the increasing load demand. When these sources are connected to the grid there is interaction between the LCL filter, grid impedance, and inner current loop of the inverters. Thereby, it causes the harmonic instability [1], [2]. Which further leads to amplification of resonance over the range of frequencies. This sometimes leads to unwanted withdrawal of the PV inverters from the grid [3], [4]. The interaction of the admittances of multiple inverters causes two issues one is amplification of Resonance and seconed one harmonic instability. These two issues are analyzed and answered by means of IBSC analysis. IBSC was applied to design the output filter in chopper circuits [5], [6]. The conversion method for harmonic transfer function-based model for a Voltage source converter into a simple and efficient Single Input Single Output model [7]. Stability characteristics were obtained with the frequency coupling effect. In [8], Impedance model in dq-frame was developed for offshore wind power plant to study the effect of inverters and transmission cables. The analyzed the harmonic stability in modular multilevel based DC systems. It was verified with hardware experimentation as well as simulation. DC impedance model of the system was developed by considering the capacitor voltage fluctuation, harmonic responses [9].

In this work, IBSC tool is used in the multi-inverters tied to grid to examine the harmonic stability. The system stability is evaluated by graphical analysis using minor loop gain of the overall system. If the system obeys the nyquiest stability criteria than the system is stable otherwise it is unstable. The concept of passivity-based stability analysis has recently gained attention in control system [10] and from this stability analysis each subsystem has a phase margin lies between -90° to 90°. Then the system is stable otherwise system is unstable.

In this paper, Section 2 deals with the Mathematicall modeling of the PV system, in Section 3, the calculation of the Output Impedance of inverter and the modeling of the PR current controller. In Section.4. simulation results of the two case studies are discussed.

2. MATHEMATICALL MODELING OF PV SYSTEM

2.1. Modeling of PV array

In this study PV array provides the DC voltage to boost converter. Single diode model of a PV Cell is depicated in Figure 1. It represents simple modeling where resistances are neglected [11]-[16]. The parameters of the PV module are shown in Table.1. These are used to simulate the PV array in matlab simulation. two modules are connected in series to give the voltage of 700 V and the PV current supplied is 40A. The PV power supplied by the inverter is 2KW even though it is designed for the 14KW. The PV array voltage, current and power wave forms are depicted in Figure 2 to Figure 4.

2.2. Maximum power point tracking (MPPT)

PV panel output is highly depending on climatic conditions, extracted maximum power from PV panels. Different MPPT techniques are proposed in literature. For simple implementation, P&O technique is implemented in this paper [17], [18].

Table 1. Specifications of the PV module

Parameter	Variable	Value
Current at P_{Max}	I_m	8.30A
Voltage at P_{Max}	V_m	30.2V
O.C Voltage	V_{oc}	37.3V
S.C Current	I_{sc}	8.71A
Series Resistance	R_s	0.217ohm
Ref. Solar Radiation	S_{ref}	1000W/m^2
Ref. Temperature	T_{ref}	300k

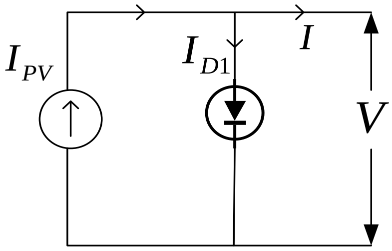

Figure 1. PV cell equivalent circuit

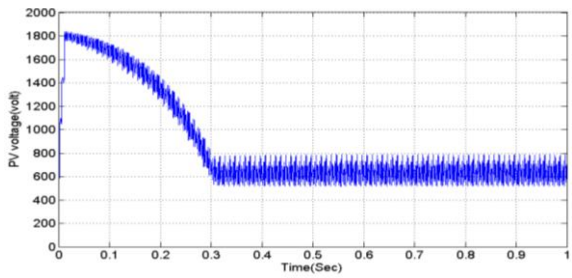

Figure 2. PV voltage (in volts)

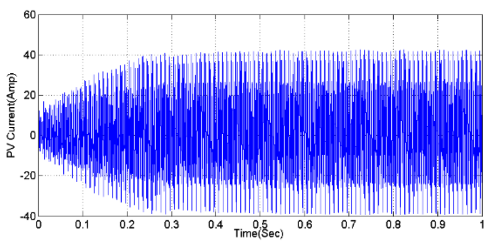

Figure 3. PV current (in amps)

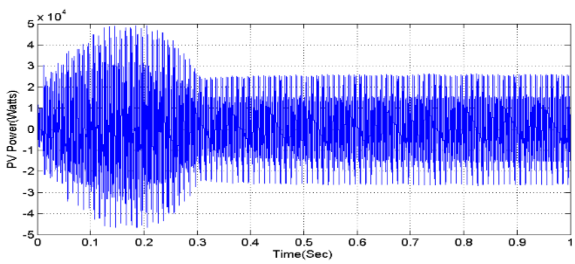

Figure 4. PV power (in watts)

3. MODELING OF INVERTER OUTPUT ADMITTANCE
3.1. Calculation of inverter output admittance

The small signal modeling of grid connected inverter is shown in Figure 5. in that PV inverter is tied to the grid, for filtering purpose LCL filter is used. The overall system is represented in block diagrame in Figure 6. In this work PR current controller is taken as current controller [19], [20].

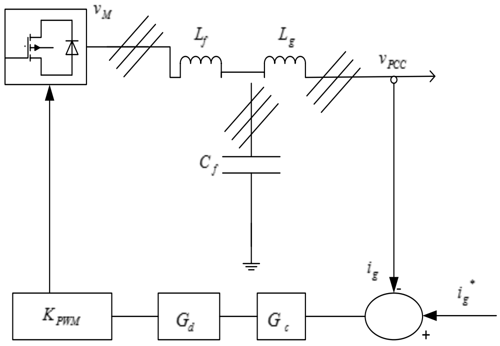

Figure 5. 1-Ph. depication of system

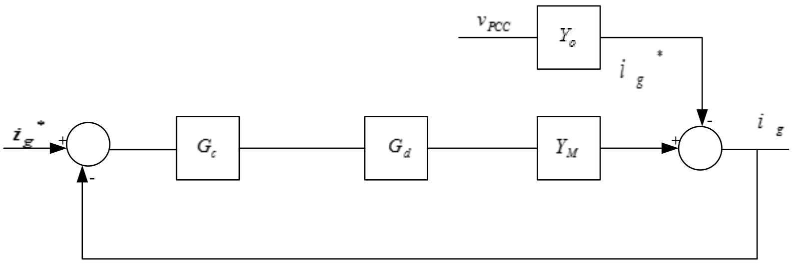

Figure 6. Block diagrame of the system

Where (G_c) Current controller, (G_d) delay gain and (K_{PWM}) PWM gain are defined as [21], [22]:

$$G_C(s) = K_1,\ G_d(s) = e^{-1.5T_S s}\ ,\ K_{PWM} = 1 \tag{1}$$

The converter output admittance is defined as $Y_C(s) = \dfrac{Y_0}{1 + G_C\, G_d\, Y_M}$ (2)

The output admittance of LCL filter is given by

$$Y_o(s) = \left.\frac{-i_g}{v_{PCC}}\right|_{v_M=0} = \frac{s^2 C_f L_f + 1}{s(s^2 C_f L_f L_g + L_f + L_g)} \tag{3}$$

The trans admittance of the LCL filter is given by

$$Y_M(s) = \left.\frac{i_g}{v_M}\right|_{v_{PCC}=0} = \frac{1}{s(s^2 C_f L_f L_g + L_f + L_g)} \tag{4}$$

Finally, the converter admittance is given by

$$Y_C(s) = \frac{i_g}{v_{PCC}}\bigg|_{i_g^*=0} = \frac{Y_O}{1+G_c G_d Y_M} = \frac{s^2 C_f L_f + 1}{s^3 C_f L_f L_g + s(L_f + L_g) + Ke^{-1.5T_S s}} \tag{5}$$

Here K_1 -Gain of controller, T_s - sampling time, i_g -Grid current, V_M, V_{PCC} -converter output voltage, PCC voltages, L_f, Lg - filter inductance value inverter side and grid side.

3.2. Proportional resonant current controller:

A proportional resonant (PR) controller exhibits a better steady state and dynamic performance. Input- output relation of an ideal PR controller is expressed by (6) [22], [23]. In the same way, for a non-ideal PR Controller it is given by (7) [24]:

Ideal proportional resonant controller: $$G_{PR}(s) = K_P + \frac{2K_r s}{s^2 + \omega^2} \tag{6}$$

Non- ideal PR controller: $$G_{PR}(s) = K_P + \frac{2K_r \omega_c s}{s^2 + 2\omega_c s + \omega^2} \tag{7}$$

3.3. Harmonic stability analysis of multilevel inverters tied to the grid

The block diagram of overall system is shown in Figure 8 and its corresponding Matlab-Simulink diagram is presented in Figure 9. A capacitor bank of 12μF is connected parallel at PCC. Grid specifications are taken as 400V, 50Hz and impedance $Zg = (0.1 + j400)\ \Omega$. A PR controller is used to drive the inverter and an LCL filter is used to improve the quality of grid current [25]-[28]. PWM technique is implemented to produce switching pulses to converter. Specifications and parameters of the five inverters are stated in Table 2.

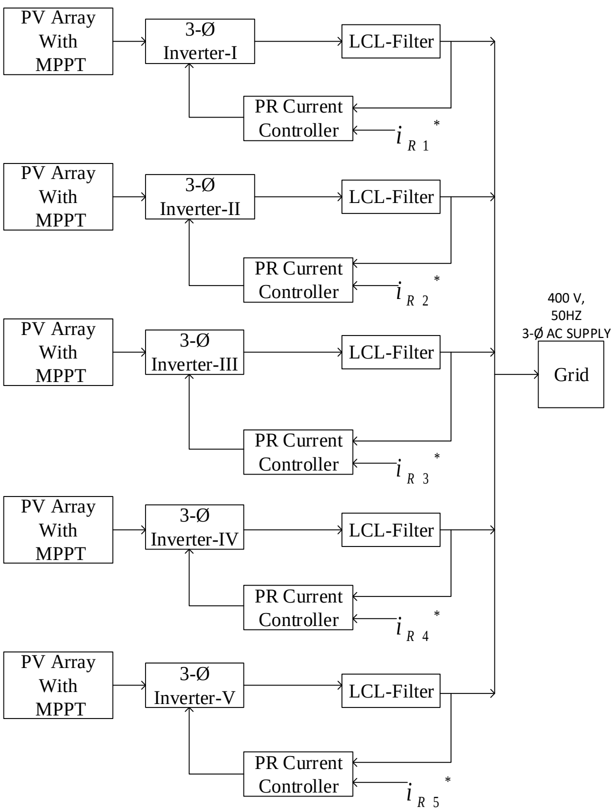

Figure 8. Five PV arrays tied to grid

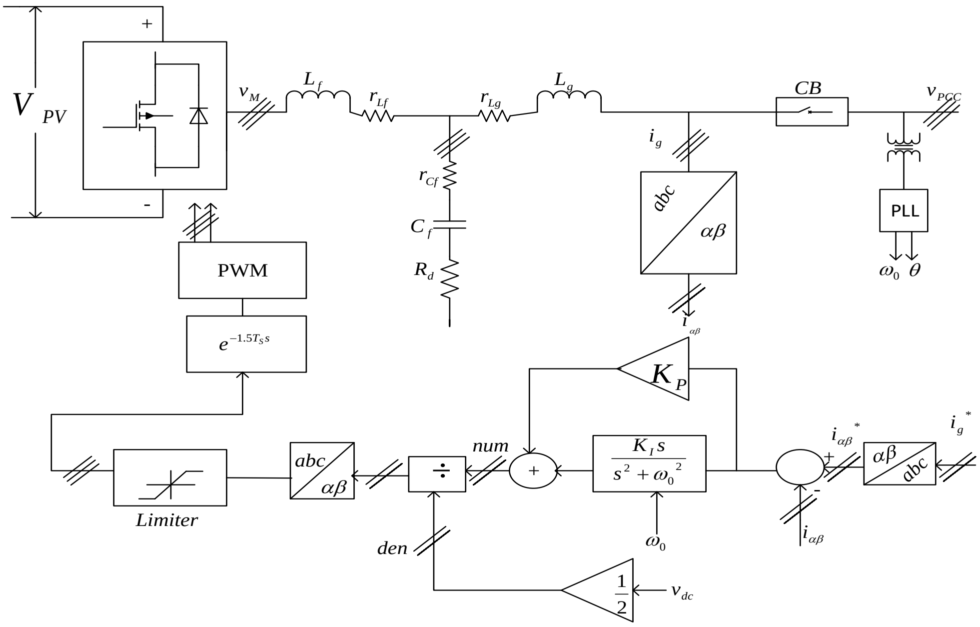

Figure 9. Single line diagram of a PV inverter tied to grid

Table 2. System specifications

Inverters	Parameters	INV.1	INV.2	INV.3	INV.4	INV.5
Rating	KVA	5.6	3.5	10.5	4.2	7
Switching frequency	KHz	10	10	15	10	
DC Voltage				600V		
	L_f [mH]	20	22	24	25	15
Filter Values	C_f[µf]/r_d	22/0.2	15/0.4	2/7	3/42	15/0.9
	L_g[mH]	0.22	0.3	1.7	1.3	0.2
	r_{Lf}[mH]	11.4	15.7	66.8	49.7	10
Parasitic Values	r_{Cf}[mf]	7.5	11	21.5	14.5	11
	r_{Lg}[mΩ]	2.9	3.9	22.3	17	2.5
Control Gain	K_p	5.6	8.05	28.8	16.6	5.6
	K_I	1000	1500	1500	1000	1000

The expression for source admittance is given in the (8).

$$Y_{SG} = \frac{1}{R_S + sL_S} \tag{8}$$

where R_S-Grid resistance, L_S-Grid inductance

The expression for source admittance is depicated in (9)

$$Y_{LG} = SY_{CPFC} + Y_{CL1} + Y_{CL2} + Y_{CL3} + Y_{CL4} + Y_{CL5} \tag{9}$$

where Y_{CPFC} denotes the admittance of capacitor CPFC, minor loop gain T_{MG} is obtained as:

$$Y_{LG} = Y_{CFPC} + \sum_1^5 Y_{CLX} \; , T_{MG} = \frac{Y_{MG}}{Y_{LG}} \tag{10}$$

The minor loop gain (T_{MG}) is highly depending on the load admittance given by (10). In this study, load impedance is assumed to be constant. It means that all 5 inverters are tied to the grid and grid inductance is varied from 1mH to 1000mH, with the grid resistance constant. If the MLG of the overall system obeys the Nyquist stability criteria for different values of grid impedance, then the system is harmonically stable, otherwise overall system is said to be unstable.

4. SIMULATION RESULTS AND DISCUSSION

Two different case studies are considered to examine the harmonic stability analysis with the above defined system parameters given in Table 2, where five PV inverters are tied to the grid. In first case study, grid impedance is variable and load impedance is constant. In the second case study, load impedance are variable and grid impedance is constant at $Zg = (0.1 + j400)\ \Omega$.

4.1. Case study 1: Constant grid resistance and varying grid inductance

4.1.1. Grid inductance up to 5mH

Here grid resistance is kept constant and grid inductance is varied. The system becomes stable upto L_S = 5mH. In this case all the 5 inverters are tied to grid. The grid iducatance $LS = 5mH$, total grid current is 44A. Nyquist Plot of the minor loop gain and the simulation results of THD of grid current, grid curent wave form, individual individual inverter currents, %THD of the grid currents for the overal system are shown in Figure 10 to Figure 13. respectively.

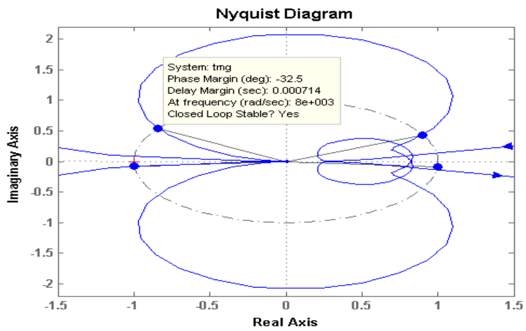

Figure 10. Nyquist plot of minor loop gain

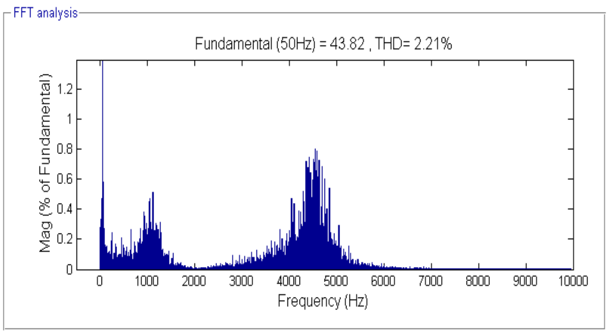

Figure 11. THD analysis of the grid current with grid inducatane upto 5mH

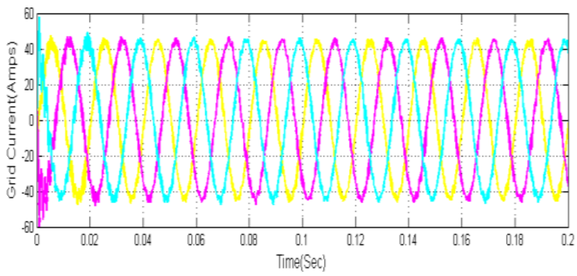

Figure 12. Grid current (in Amp)

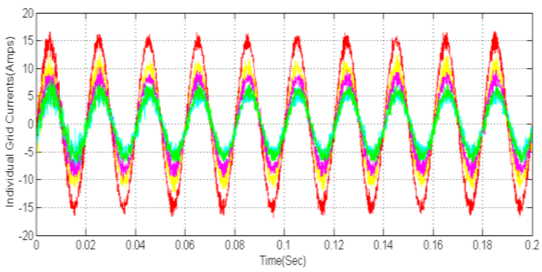

Figure 13. Individual inverter currents (in Amp)

4.1.2. Grid inductance more than 5mH

This case is used to illustrate when the grid inductance (L_S) is more than 5mH. The overall system becomes unstable. Nyquist Plot of minor loop gain with gird inductance value $LS = 6mH$ is shown in Figure 14. %THD of the grid current, Grid current and inverter currents are shown in Figure 15, 16, 17 respectively.

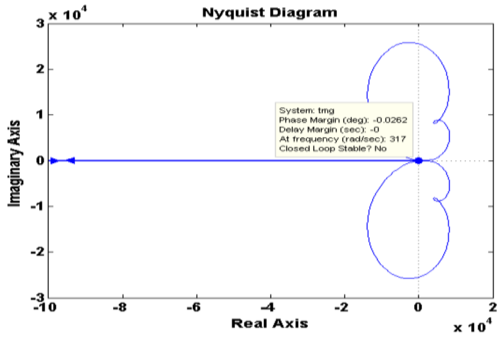

Figure 14. Nyquist plot of minor loop gain with $L_s = 6mH$

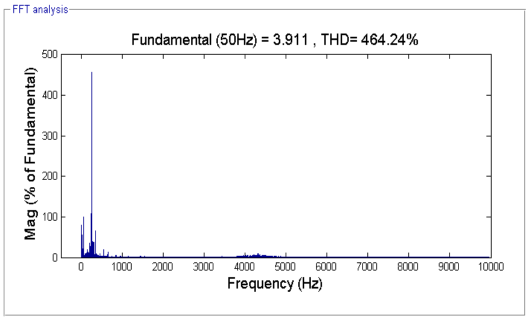

Figure 15. THD response of the grid current

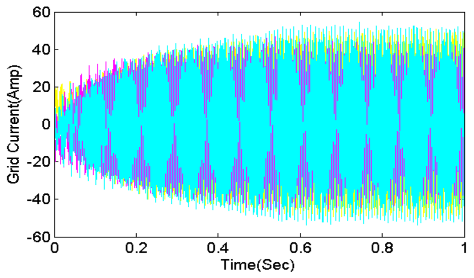

Figure 16. Grid current (Amp)

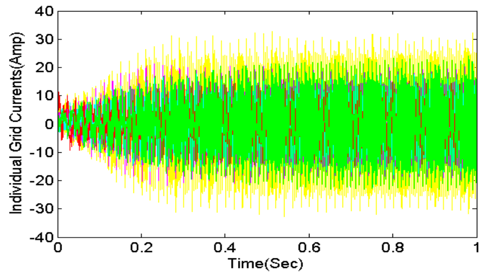

Figure 17. Individual inverter currents (Amp)

4.2. Case study 2: Constant grid impedance with varying load admittance

In in practical suitutions there is is possibility of change in load admittance will changes de to te disconnection inverter from grid. Thereby affects the overall system stability. To analyze this situation when INVs are removed from the grid, two cases are considered. In first case, INV 1 is removed and in case B INVs 1, 5 are removed. The constant grid impedance is $Zg = (0.1 + j400)$ and the reference is INV 1 given in (11).

$$Y_{SA} = Y_{CL1} \tag{11}$$

Calculation for MLG in this case is given in (13).

$$\mathrm{Y_{LA} = Y_G + Y_{CPFC} + Y_{CL2} + Y_{CL3} + Y_{CL4} + Y_{CL5}} \tag{12}$$

$$\text{Minor loop gain of the system } \mathrm{T_{MA}} = \frac{\mathrm{Y_{SA}}}{\mathrm{Y_{LA}}} \tag{13}$$

In First case, the INV 2, INV 3, INV4, and INV 5 are injecting the currents of 8A, 5A, 15A, and 6A respectively into grid. So total grid current 34A. Nyquist plot of MLG of the system is depicated in Figure 18. From IBSC, it is concluded that the system is stable. The quality of the grid current is 2.37% as illustrated in Figure 19. Total grid current and individual inverter currents are shown in Figure 20 and Figure 21 respectively.

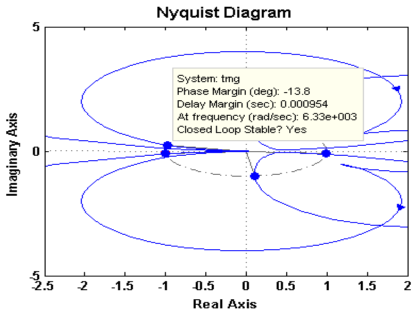

Figure 18. Nyquist plot of system INV -1 OFF

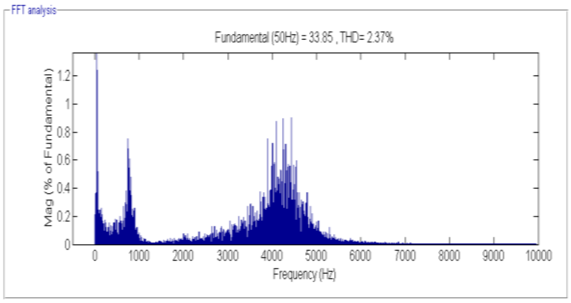

Figure 19. THD response of the grid current

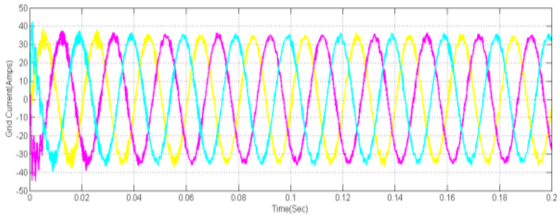

Figure 20. Grid current (Amp)

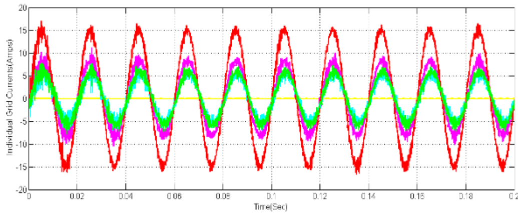

Figure 21. Individual inverter currents (Amp)

In this case INV 1 & INV5 are disconnected from grid. Nyquist plot of MLG of the system is given in Figure 22. From IBSC, the system is stable. The Quality of the grid current is given in Figure 23. Grid current and individual inverter currents are shown in Figure 24 and Figure 25 respectively.

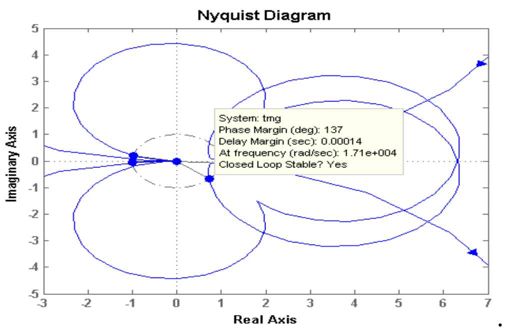

Figure 22. Nyquist plot of INV 1 & 5 are disconnected

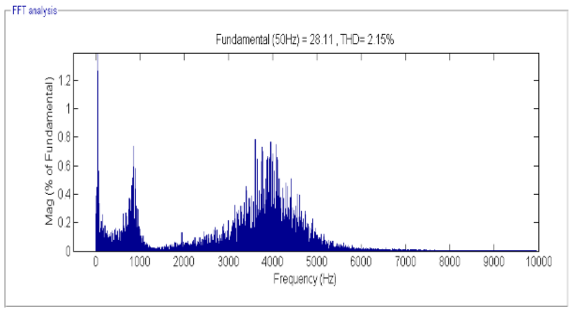

Figure 23. THD response of the grid current

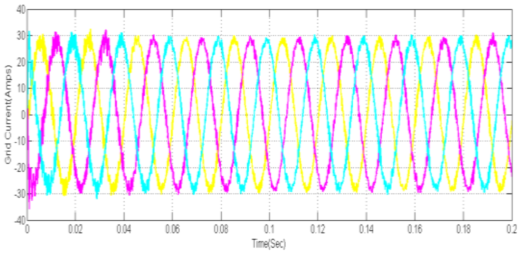

Figure 24. Grid current (Amp)

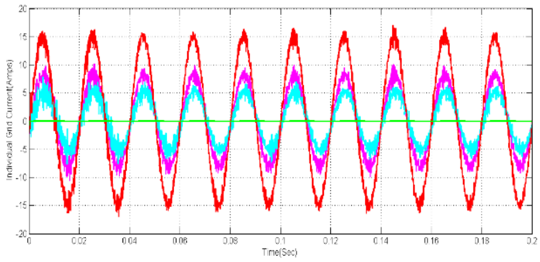

Figure 25. Individual grid current (Amp)

5. CONCLUSION

In this work, investigation of harmonic Stability of multiple PV fed 3-Ø INV is tied to grid is confirmed by new impedance based stability criterion (IBSC). Stability of the system is investigated by varying the grid inductance with constant grid resistance and also by varying load impedance and maintaining grid inductance constant. It was observed that overall system is stable up to grid inductance of 5mH and above this value, the system becomes unstable. It is also demonstrated that stability of the system depends on grid impedance only and does not depend on load impedance. It is substantiated by means of graphical analysis and Matlab Simulations.

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