Novel Design Of Transformerless Solar PV Farm For Increasing The Grid Transmission Limits During Day And Night

Boopathimanikandan S, Sivaraman P

Abstract: Renewable energy power generation is increased due to increasing energy demands, reducing of carbon emission and fossil fuel depletion. Form all renewable categories, Solar power generation is increased due to sun available for many hours. For transferring of highly efficient power transfer is possible now due to improved version of power converters. Compared to transformer fed grid tied solar PV system, transformerless grid tied solar PV system has high efficiency. But in night time Solar PV inverter is idle in both the cases. New control design is introduced in this paper to make use of PV inverter in night time as reactive power compensator. The output of Solar PV array is not sufficient to provide input to Inverter. Voltage of PV array is step up using Boost converter. The output of inverter is not pure sine wave to connect directly into Grid/Load. Generally, LCL with Damping Resistor filter is widely used to filter out the distortion due to small size and reduced resonant peak. In this paper, Transformerless Solar PV Farm was simulated for 3 modes of operation in PSIM Simulation tool. Stability Analysis of controllers are done by using pole zero plot and Bode plot.

Index Terms: Grid tied Inverter, LCL Filter design, Stability Analysis of Grid Tied Inverter, Transformerless PV system.

1 INTRODUCTION

THE power transfer of Solar PV farm is increased by reducing the number of power conversion stages. Even though solar PV array is reliable, efficiency of solar Photovoltaics is around 15-20%. Solar PV should be operated in maximum power region at every instant [1]. Two types of tracking's are used. i) Mechanically tracking and ii) Electrically tracking. Mostly Electrical tracking are used due to low cost, simple and high efficiency. Boost converter is used in electrical tracking by adjusting the PWM pulses to make converter resistance equals to Load Resistance. To make galvanic isolation between PV inverter to grid/load by interconnecting Low Frequency transformer. This method is called as transformer connected PV system. But in transformerless solar PV system, there is no galvanic isolation between grid and PV inverter and but isolation is provided with help of high frequency transformer used in DC-DC converter [2][3]. The power conversion process in transformerless PV system is only two stages i) DC-DC conversion ii) DC-AC conversion. So efficiency of transformerless PV system is high due to reduced power conversion stages. In Day time, PV Inverter is used for real power generation and act as reactive power compensation. In night time, entire inverter is in idle condition will be disconnected from grid. Idle inverter can be used as power factor regulator as STATCOM, by charging DC link Capacitor [4]. New control techniques are designed in this paper to make use inverter in all instant. Voltage source Inverter becomes most familiar for conversion of DC to AC Conversion process. The output of Inverter is modulated Sinusoidal wave which produces distorted currents with THD of 31%. To filter out distortion, LCL filter is used due to small size and high efficiency of active power transfer but LCL makes system unstable because of generation of resonance peaks. Passive damping technique is preferred to eliminate resonance peaks [5-7]. By designing suitable controller design, performances of grid tied Solar PV system can be improved. Multi loop controllers are designed in this research. In multi loop controller, the inner loop is for current controller that controls the grid current harmonics and reactive power injected to the grid, while outer loop controller the DC-link Voltage variations caused by input disturbances. The resonant problem developed by LCL filter is controlled by designing the suitable PI controller values with synchronous reference frame concepts. During night time, DC converter gets open only DC link Capacitor is connected as input of inverter. By absorbing small real power from grid, inverter is able to transfer reactive power to grid as like conventional power factor controller. This makes the inverter efficiency and also Grid transmission limits are increased in night without any additional circuits.

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2 GRID TIED INVERTER

2.1 DC-DC Converter

The Boost Converter with Solar PV array is shown in Fig. 1. It contains Solar PV array as Input DC source, Boost converter and MPPT controller.

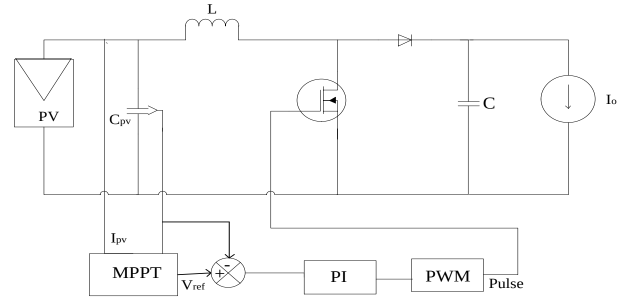


***Fig. 1**. Boost Converter with Solar Module*

Solar PV array used in the simulation is 2000Watts with 240 Volts. 60 series panel with Open Circuit Voltage of 37.6V, short circuit current of 8.9A and maximum power of 250W of each are connected to obtain 240V and 2000W. The Maximum Power voltage and maximum power current is 30.3V and 9A respectively. The PV and IV characteristics of solar array were obtained for various irradiance values at constant temperature of 25˚C as shown in Fig. 2.

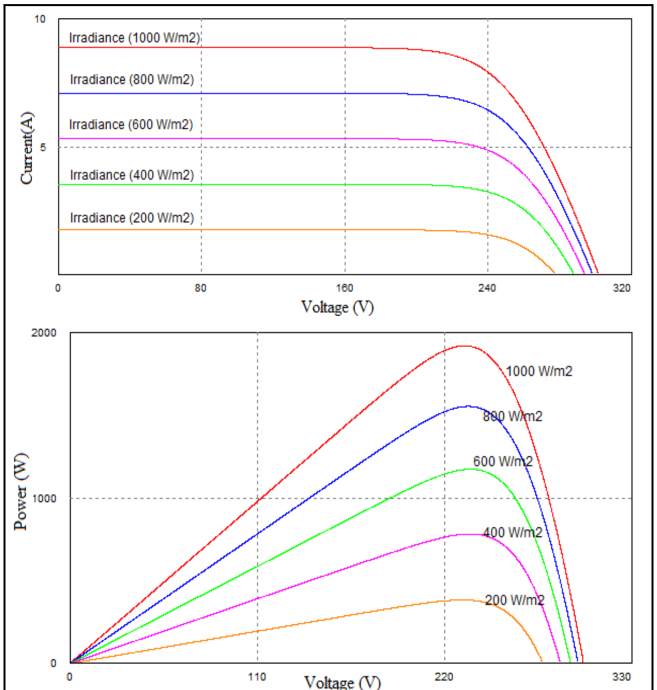


***Fig. 2**. Solar panel IV and PV characteristics*

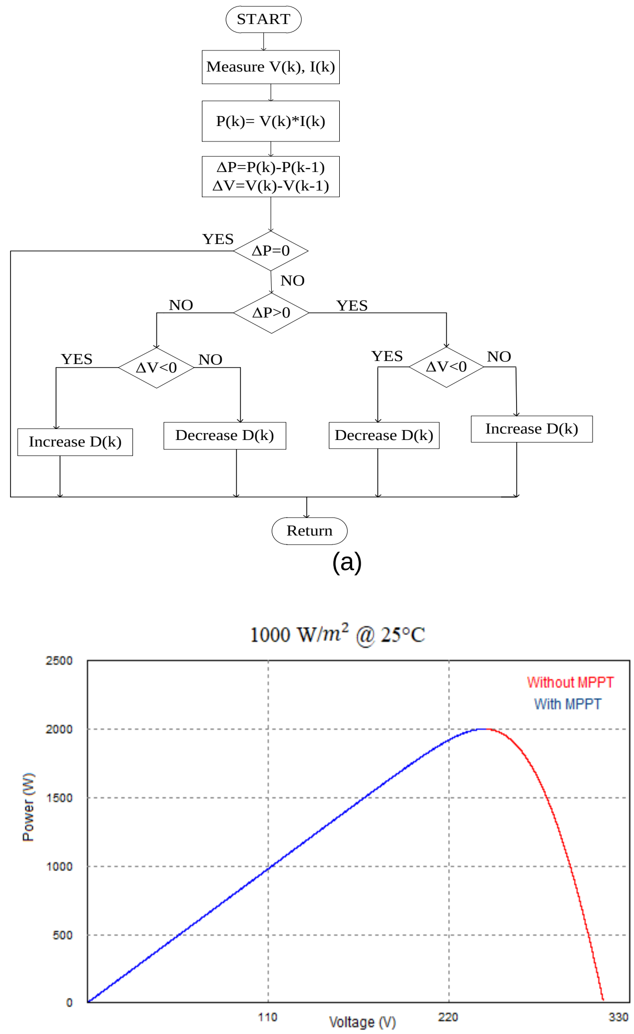
The Boost converter is designed for 400V(output) with 240V (Input Voltage). The various parameters of Boost converter are calculated and listed in the Table 1.

TABLE 1

BOOST CONVERTER SPECIFICATIONS

Parameters	Values
Input Voltage / Output Voltage	240 V/400 V
Switching Frequency	20 kHz
Duty Cycle	0.4
Boost Inductance (L)	21 mH
Output Capacitance (C)	220 µF
MOSFET – IRF740	400 V, 10 A & 0.48 Ω

MPPT algorithm used in this design to extract maximum power is dP P&O algorithm. The flowchart for dP P&O algorithm was shown in Fig. 3(a)[8]. In P&O algorithm, at every instant change in power and change in voltage is calculated and estimate correct tracking direction by performing an additional measurement in the middle of the MPPT sampling period. Fig. 3(b) shows PV characteristics obtained for 1000W/m^2 at 25ºC with and without MPPT algorithm.



(b)

***Fig. 3**. (a) Flowchart for MPPT P&O algorithm, (b) MPPT Tracking Curve.*

2.2 Grid tied Inverter

Fig. 4 shows Grid tied inverter with LCL filter along with controller. Generally, MOSFET Switches are used in inverter circuit having medium power operations. In this design, N channel MOSFET IRF840LC is used. The specifications of IRF840LC are V_{DS} = 500V, 0.85Ω as input resistance. Inverter can able to supply of both real and reactive power demanded by the load. By using sinusoidal pulse width modulation (SPWM) techniques, output of inverter will be controlled according to the load demand [9]. According to the phase angle generated by the reference sine wave, real and reactive power flow can be controlled. The output of inverter is modulated switching voltages with THD of 31% so can't connected directly into the Grid/Load. Filter circuit should be connected in between inverter and Grid/Load to obtain pure sine wave output. Generally, LCL Filter is used due to small size and low resonant peaks. The grid connected inverter is controlled by dual loop control where input side disturbances is controlled by DC Link control and output side (AC side control) is controlled by grid control algorithm. An AC side controller has two loops namely; inner current loop and outer power or voltage loops. The inner loop controls the high frequency current harmonics injected into the system where as outer loop controls active and reactive power flow into the grid/load by using synchronous reference frame [10] [11].

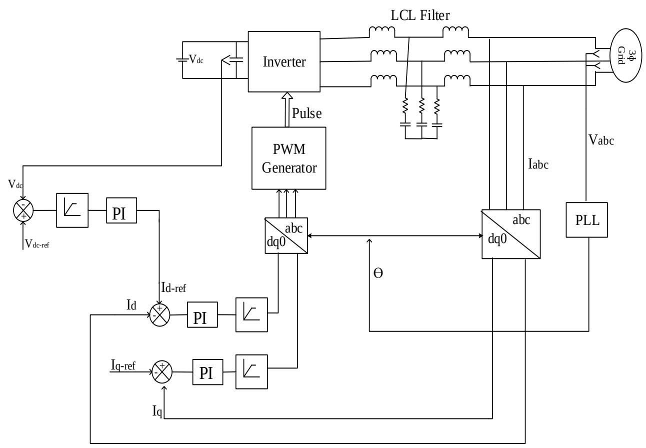


***Fig. 4**. Three Phase Inverter with LCL Filter*

2.3 Grid tied Inverter

To filter out the modulated output voltage and distorted current generated by VSI, LCL filter with damping resistor is used. Due to high efficiency of active power transfer, small size and reduced resonance peak generated. The flowchart for design LCL Filter [12] is shown in Fig. 5. LCL Filter specifications are designed with modulation index of 0.5, 20% of attenuation factor and 10% of ripple current are listed in Table 2.

TABLE 2
LCL FILTER SPECIFICATIONS

Grid Frequency	50 Hz
Switching Frequency	20 kHz
Nominal Power	2 kW
Grid Voltage	415 V
DC Link Voltage	400 V
Inverter side inductor	5.31 mH
Grid side inductor	0.217 mH
Filter capacitor	1.86 µF
Damping Resistor	3.5 Ω

3 PROPOSED ALGORITHM

The proposed algorithm transformerless Grid tied Inverter is operated in 3 modes. i) Grid Tied mode ii) Reverse power flow mode iii) Night Control mode. The flowchart for operation of inverter control is shown in Fig. 5. Controller sense the power developed by the solar PV, based upon the values of solar power, controller tunes the mode of operation.

3.1 Grid Connected Mode of Operation

This mode of operation is mostly used for reactive power compensation for grid. Solar will generate the power demanded by the load. Controller senses the reactive power required by the grid to maintain unity power factor and tries to tune the inverter controller to generate amount of reactive power required by the grid by set reactive current component Iq=0. If the Solar power generated is enormous, remaining power is transferred as real power to the grid after compensating the reactive power required by the Grid.

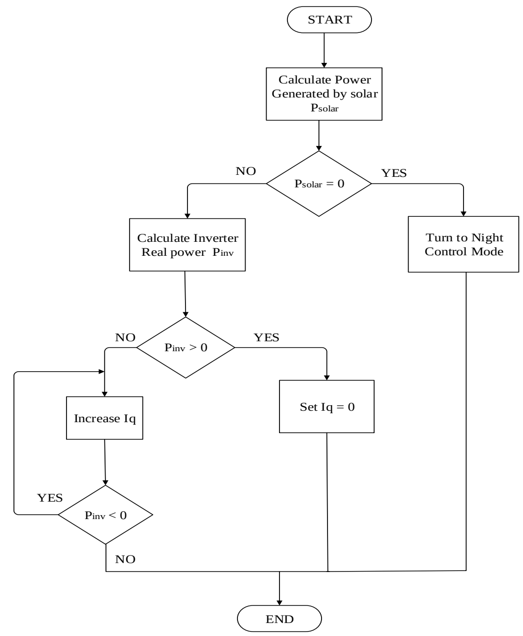


***Fig. 5**. Controller Algorithm*

3.2 Reverse Power Flow Mode

Based upon the irradiance power generated by the solar gets changed. If the power generated solar is equals or less than reactive power required by the Grid, Inverter tries to compensate the reactive power by absorbing real power from grid. So, this is called reverse power flow mode. If it happens current flow from grid will increases than normal operating level. So, this should be avoided by reducing the reactive power flow from inverter to Grid. If real power flow from inverter is in negative, decreases reactive power flow by increasing Iq value (increasing the reactive power flow in grid) until real power of inverter gets zero.

3.3 Night control Mode

Night Control Mode is turned on, whenever power developed by the solar is zero. DC Converter gets opened and Solar PV system is isolated from Inverter. In this mode, inverter acts as a power factor regulator. Small real power is absorbed by the inverter to charge the DC link Capacitor, tries to deliver reactive power to the grid to compensate the reactive power required by the Grid. In this mode, Inverter is efficiently used in night time for improving the power transmission in night time without any additional cost.

4 CONTROLLER DESIGN

4.1 DC Link Controller

The Block Diagram of DC link controller was shown in Fig. 6. DC Link Controller is designed to maintain the solar PV array in Maximum Power extraction region. Controller senses the output voltage from solar PV array and compares with reference voltage generated at MPPT block. Low pass filter (PI) is used to regulate error to generate pattern voltage to generate pulses.

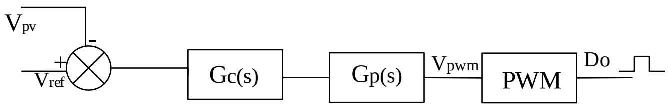
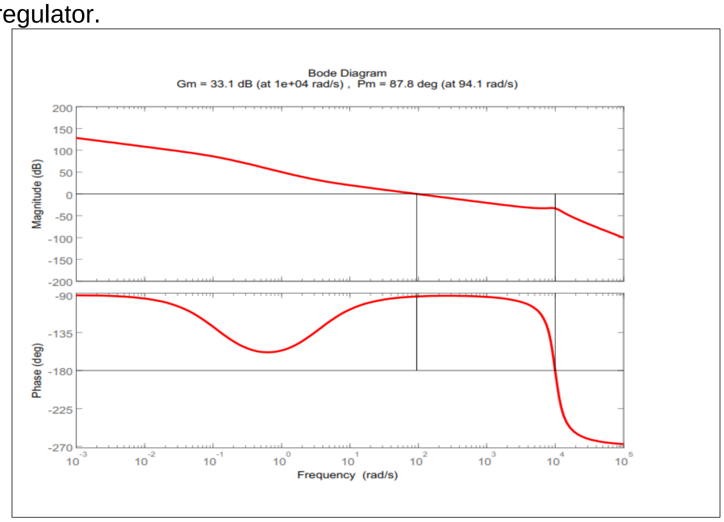


***Fig. 6**. Block diagram of open loop DC link controller.*

The Plant transfer function is found by control to input voltage $T(s) = \frac{D_O(s)}{V_i(s)}$. The open loop transfer function with PI Compensator is H(s)=T(s)*GPI. By proper tuning PI Controller, it can able to operate the controller in stable region. By choosing $K_p = 0.5, K_i = 0.01$ controller enter into stable operating region. The Bode plot and Pole Zero plot of DC converter with compensator is shown in Fig.7. from the plot, the positive values of Gain margin and Phase margin shows that Controller is in stable region. From the pole zero plot, All the poles are lying in RHS of S-plane and two complex poles are lying in the imaginary axis indicate output voltage have minimum ripples.

4.2 Current Controller for Grid Connected Mode

In Grid tied mode, Controller senses the grid current at PCC and regulates the grid current making in-phase with grid voltage by sending the reactive power from solar PV plant. Low pass filter (PI) with feedback mode is used as a regulator.



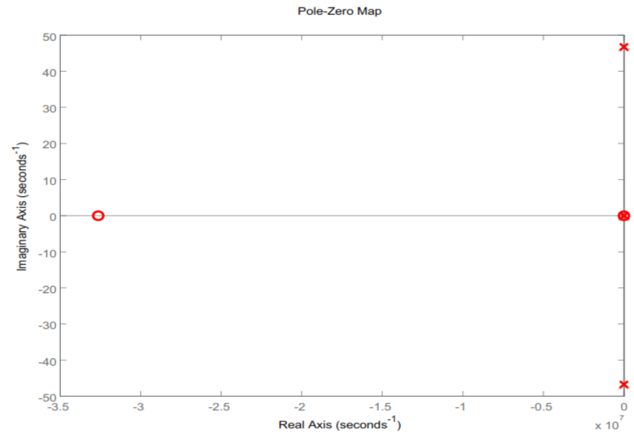


***Fig. 7**. Bode Plot and Pole Zero plot of open loop DC link controller.*

Block diagram of Closed loop current controller is shown in Fig.8. The plant transfer function is given $T(s) = \frac{I_g(s)}{V_i(s)}$ $at\ V_g(s) = 0$. The closed loop transfer function is given by $H(s) = \frac{T(s)*G_{PI}}{1+T(s)*G_{PI}}$. To make controller to operate in stable, optimized Kp and Ki values to be chosen.

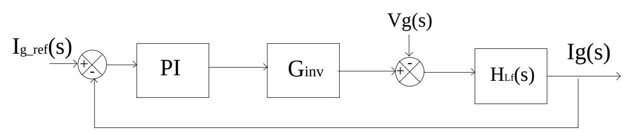
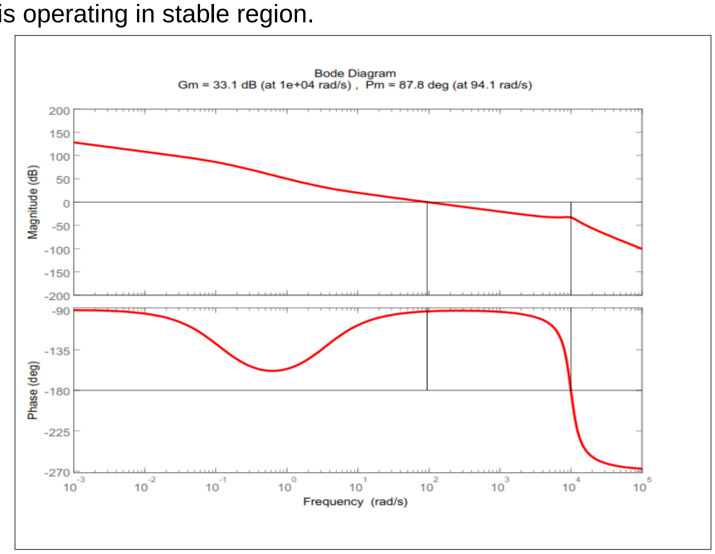


***Fig. 8:** Block diagram of closed loop current controller*

By taking $K_p = 1\ and\ K_i = 0.05$, two poles are lie nearer imaginary axis and one pole at origin so that system is marginally stable leads to generate little oscillations in output current. From Frequency response (Fig.9), the positive values of Gain Margin and phase margin shows that system is operating in stable region.



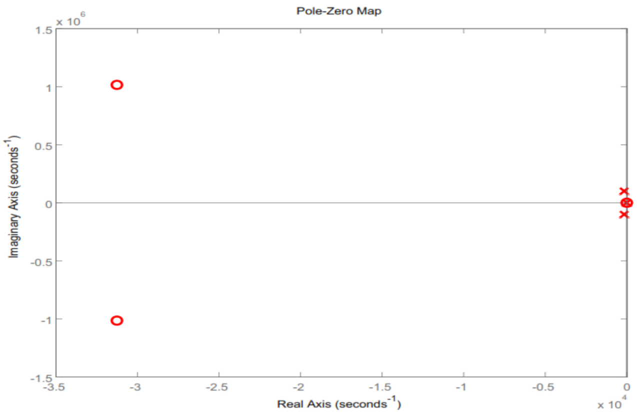


***Fig.** 8. Bode Plot and Pole Zero plot of closed loop current controller.*

5 RESULTS AND DISCUSSION

The simulations of grid connected PV System and Night mode of operations are simulated in PSIM Software with load of 2000VA at 0.7pf. The results of all the 3 modes of operations are listed in Table-3 simulated for various irradiance and temperature. In grid connected mode, solar irradiance of 1000W/m^2 at 25˚C and 800 W/m^2 at 45˚C are simulated and results are shown in Fig. 10 and Fig. 11.

At 1000 W/m^2 at 25˚C Solar power is 2000Watts. Before connecting solar PV into grid, Load consumes 3 amps from Grid at 0.7pf. After Solar PV inverter comes to operation, grid current reduces to 0.56A (RMS) with 0.97pf. Inverter supplies Real power around 1340W and Reactive power around 1350VAR. At 800 W/m^2 at 45˚C Power generated in solar PV is 1500Watts, grid supplies current of 1.1A (RMS) with 0.98pf. Inverter absorbs real Power around 375W and supplies 1392VAR of Reactive power. In this case, inverter absorbs real power for compensating reactive power flow in Grid. After sensing the Negative Real power flow, controller adjusts the reactive current component and reduces the reactive power flow to grid. By setting Iq=0.2, 800 W/m^2 at 45˚C Inverter supplies Real Power around 501W and 1307VAR of Reactive power. In this case, grid supplies current of 1.75A (RMS) with 0.9pf.

In Night mode of operation, No solar generation possible. DC Link gets open from inverter circuit. Inverter acts as a power factor regulator. By absorbing 147 watts of real power for charging the DC Link Capacitor, Inverter supplies 1427 watts of Reactive power. grid supplies current of 2.15A (RMS) with 0.99pf.

TABLE 3

PERFORMANCE ESTIMATION OF PV INVERTER UNDER VARIABLE IRRADIANCE/TEMPERATURE CONDITIONS

		Inverter			Grid		
Irradiance/ Temperature	Power Delivered by Solar	Real Power	Reactive Power	Apparent Power	Real Power	Reactive Power	Apparent Power
1000 W/25˚C	2002	1339	1350	1902	161	150	220
1000 W/50˚C	1793	805	1392	1722	450	116	465
800 W/45˚C	1410	-375	1358	1407	1875	148	1887
500 W/30˚C	1003	-856	1346	904	2356	154	2361
800 W/45˚C	1410	501	1210	1307	721	348	800
500 W/30˚C	1003	409	806	904	1091	694	1293
Night Mode	0	-147	1427	1432	1530	132	1537

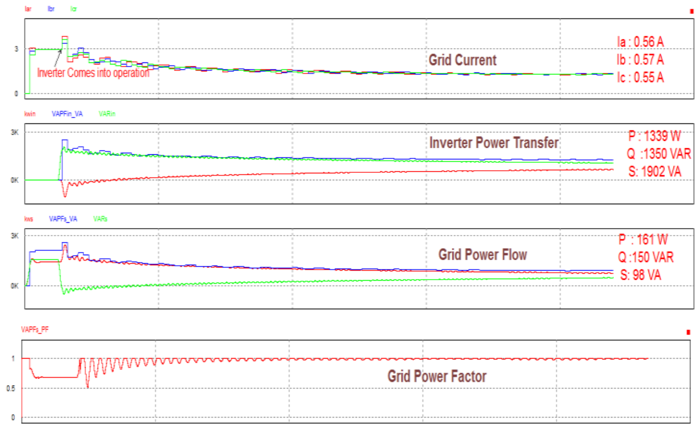


***Fig. 11**. Output waveforms of inverter at 1000 W/$\mathbf{m^2}$ at 25˚C at Grid tied mode.*

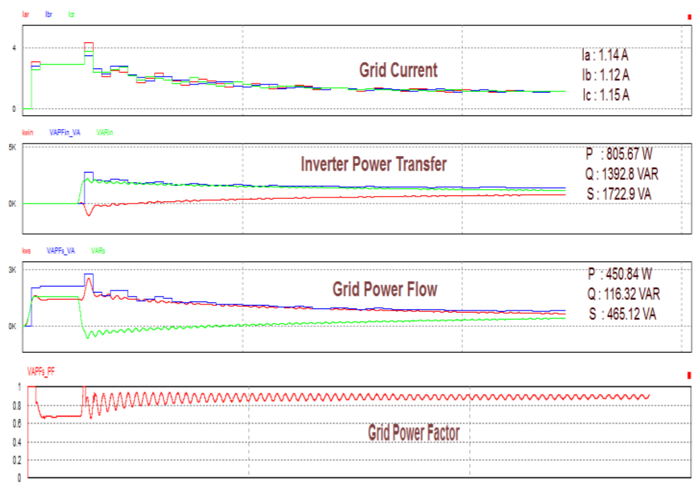


***Fig. 11**. Output waveforms of inverter at 800 W/$\mathbf{m^2}$ at 45˚C at Grid tied mode (Iq=0.2).*

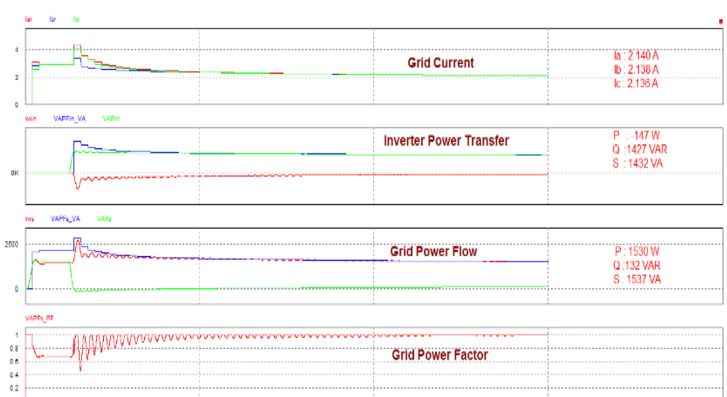


***Fig. 12**. Output waveforms of inverter at Night mode.*

6 CONCLUSION

The design and analysis of transformer-less solar PV system is done for grid tied mode of operation for day and night time and successfully simulated using PSIM simulation tool. Novel design of controller will make system work in all possible conditions based upon the solar power generated. Reverse power flow is controlled by increasing the reactive power quantity transferred by grid to load. Current control techniques can be used for both reactive power compensation techniques and PV power transfer to grid. The efficiency of transformer fed Solar PV systems is around 92-95% based upon the design. The overall efficiency of transformerless solar PV system is around 98% was achieved in this design which eliminates the losses associated in low frequency transformer. The controller stability was analysed with help of Bode plots and Pole zero plots. Controller constant (Kp and Ki) are chosen to operate the controller in stable position in all modes of operations. The current design concepts open up new opportunities for PV solar Distribution Generation system to earn revenue in daytime by sale of real power and night-time by transferring the reactive power to grid

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