Design and Analysis of Grid-Connected Photovoltaic Systems with MPPT and Inverter Topologies Using MATLAB Simulink

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Abstract-- Grid-connected photovoltaic (GPV) systems are increasingly being explored as sustainable alternatives to fossil fuels to meet rising energy demands while reducing pollution. Solar energy, abundant, renewable, and free, has become a vital resource for electricity generation despite its intermittent nature. PV systems consist of solar cells arranged in series and parallel configurations to form modules and arrays, designed to meet specific voltage and current requirements. This study highlights the advantages of single-stage (SS) over dual-stage (DS) PV systems, including cost and space efficiency by eliminating the need for a DC-DC converter. A key challenge of PV systems—nonlinear output due to atmospheric variations—is addressed using Maximum Power Point Tracking (MPPT) techniques. A simplified inverter topology using a Feed Forward Control Loop (FFCL) is proposed for efficient grid integration of PV systems. A three-phase DS-PV system was designed and simulated in MATLAB Simulink to evaluate its performance under various loading conditions, demonstrating its potential for reliable and smooth grid connectivity.

Keywords: Grid-connected photovoltaic (GPV) systems, solar energy, renewable energy, single-stage PV system, dual-stage PV system, Maximum Power Point Tracking (MPPT), inverter topology, Feed Forward Control Loop (FFCL), grid integration, MATLAB Simulink, power quality.**1.**

I. INTRODUCTION

PVs are initially used to provide power to the regions where the grid is not usable. This kind of generation originates in the category of isolated or off grid mode. Due to the encroachment technology in solar modules, research has been carried out and is emphasize in GPV power system. Moreover, the modern research concentrated on integration, which evolves from double stage to single stage topologies. For the stability of the power system, advanced control algorithms are used.

In the future, due to the rapid growth in the global population and industries, the demand for electrical energy will increase and in turn demands for electricity generation. As per the statistics, the world's expected electricity generation was 17.5 Trillion Kilo Watt-Hours (TKWH) in 2005 and 25.4 TKWH in 2019, and the expected may reach increase upto33.3TKWH in2030.

The PV array transforms solar energy into electricity in a PV device. The appropriate power converter with a control strategy is needed to achieve I-V and P-V characteristics.

The PV system's efficiency is based on the PV array's nonlinear features, converter topology, and control strategy. In order to analyses and describe the transient responses of the PV system, detailed mathematical models must be built by which it provides nonlinear features of the PV panel, PV panels includes robust mathematical models to capture the PV system's I-V and P-V characteristics.

II. LITERATURE REVIEW

Various topologies, cascade control methods, switching control methods and MPPT methods of literature survey are presented.

Chung-Chuan Hou, et. al [11] investigated the common mode voltage mitigation by PWM techniques for 3-phase grid interconnected PV systems. Various control methods such as SVPWM, DPWM, RCMV-PWM, AZSPWM and NS-PWM techniques are discussed. The developed methods are suitable for the dc voltage with less than 1000V.

HongraeKim, et. al. [12] introduced an ovel solar converter for the application of PV battery management system. This converter named as reconfigurable solar converter.It can perform the both conversions of DC-AC and DC-DC. Precisely, huge solar PV electricity generated can be operated more efficiently by the RSCs as well as the power can be distributed quite economically due to easy of operation.

M. A. Mahmud, et. al. [13] addressed the robust feedback line a rized scheme for the stabilization of PV grid connected inverter. The mathematical model is developed by considering various uncertainties. The disturbances at PV panel including standard atmospheric and shaded conditions are considered for the validation of the proposed scheme. The proposed scheme is also validated through the fault condition of three phase fault and single phase fault at grid side.

Lin Chen, et.al.[14] focused on the 3-phase micro-inverter for solar power system in two stage conversion system. In this scheme the DC-DC conversion from PV panel to Grid connected system is used for the study. The LCL filter is implemented for mitigation of harmonics of the inverter responses.

G. Ding et al. [15], In this paper, two methodologies in light of sliding mode control for controlling a solitary stage network associated three-stage sun oriented photovoltaic framework have been exhibited. The sliding mode control is hearty and has great unsettling influence dismissal as looked at to the traditional relative fundamental control. Another preferred standpoint is that input linearization isn't required for controlling nonlinear frameworks. There are two controlled factors in particular the dc-connect voltage and the q-pivot segment of the line current of the Voltage Source Converter. In the principal approach, contorting controller and first request sliding mode controller have been utilized. Super turning controller has been utilized to control both the factors in the second approach. The proposed control conspire has been reproduced to confirm the outcomes.

Varshneyet. al. [16]. This paper presents complete modeling, simulation and control of three-phase GISPV module including evaluation of various PQ issues. A detailed stepwise procedure for modeling of three-phase grid connected PV module are presented and discussed. Perturb and Observe

(P&O) method has been used for Maximum Power Point Tracking (MPPT).

Surendran, et. al. [17] The regulator boundaries impacts the performance of the closed loop system (CLS). So we need to build up at uning technique for acquiring the ideal estimations of the regulator boundaries as for a specific cycle. Regulator tuning is definitely inappropriate choice of the regulator settings may prompt to obtain the optimum values of the controller parameters with respect to a particular process.

M.C. Cavalcanti, et.al. [18]in this paper the issue of power quality(PQ)assessment in 3-phase grid connected photovoltaic (PV) system has been addressed in this paper. The author has presented comparative analysis of both the S-S and D-S power topologies. Z-source inverter (ZSI) control is designed for S-S system controlled by space vector pulse width modulation (SVPWM), and D-S is traditionally controlled using boost based voltage source inverter by sinusoidal pulse width modulation. For transient conditions the PQ of signals in both the circuits is analyzed.

O. Vodyakhoet. al.[19] In this paper, the system behavior under various abnormal conditions like unbalanced voltage or fault for a S-S PV system is studied. A control scheme is proposed for control operation of the PV system under such conditions using a fault ride-through control scheme is proposed which can support the grid by injecting reactive power. Furthermore, adjustable power quality is enabled as a Trade- off between power ripple and current harmonics.

P.-T. Cheng et. al. [20] presents a paper for a D-S PV system under the condition of low-voltage ride through (LVRT) dc-link voltage adaptive control scheme to mitigate the injection of high frequency harmonic into the grid is proposed in this paper. Under the condition of unsymmetrical grid fault the proposed control scheme can attenuate the system harmonics to operate the system within safe operation limits by shifting the double-line frequency power ripple to the front-end dc input source, which can be achieved by intentionally fluctuating the dc input power or by using dual purpose dc– dc converter depending on the input power level and voltage drop ratio.

N. Gupta et. al. [21] In this paper a dual stage topology based PV generator is designed using three level Dc-DC boost converter and Diode clamped three level inverter. A control strategy for Dc link voltage control of inverter, current harmonic injection and reactive power compensation is proposed using space vector modulation techniques.

III. OBJECTIVE OF THE STUDY

The following are objectives of the work

- To design a dual-stage PV converter to stabilize the output of the solar system under different modes of operation.
- To adopt a dual-converter topology for operating the PV system, where the DC converter regulates the DC voltage at the DC bus.
- To present a dual-stage three-phase four-wire (3P4W) grid-connected PV system with combined operation aimed at improving power quality.
- To analyze the performance of the proposed grid-tied dual-stage PV system under both constant and variable solar irradiance, with results obtained for various loading conditions.

IV. PROBLEM IDENTIFICATION

Grid integration of PV system is a difficult since the power electronic converters injects harmonics into the system and it is difficult to control the flow of real and reactive power at the point of common coupling. Here three systems namely single stage , dual stage grid tied system and PV-UPQC system for power quality assessment has been discussed.

In S-S system PV panels are directly connected to the DC to AC converters, in D-S a DC-DC converter is interlinked between PV panel and grid side inverter. In case of S-S systems, the PV array is directly connected to the dc-bus of the grid-tied inverter, which also takes care of performing MPPT in addition of achieving high efficiency and elimination of load harmonic currents. The PV-UPQC system designed has dual compensating capability first it mitigate current harmonics and smooth sine wave is injected into the system and another is at the time of unavailability of solar energy the UPQC converter tries to maintain constant voltage at the point of common coupling. The system is analysed based on the THD percentage for all the three cases and results are tabulated.

V. METHODOLOGY ADOPTED

Although PV systems are emerging as power solution to meet the increased demand of electricity, but the reliability and robustness of the PV panel is always question able. We are designing a dual stage PV converter to stabilize the output of solar system at various modes of operation. A dual stage topology is adopted to operate the PV system, where the parallel converter is controlled to act as a sinusoidal voltage source, while the series converter is controlled to operate as a sinusoidal current source.

The DC/AC converter is controlled through FFCL in order to suppress load harmonic currents and compensating reactive power. Furthermore, regulated, balanced, and harmonic-free output voltages are provided to the load. The proposed system is shown in Fig-.1.

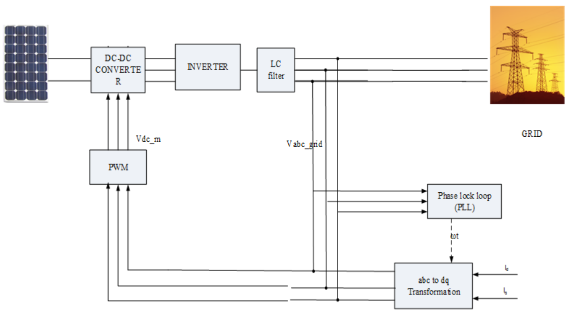


Fig 1: Proposed system for dual stage grid tied PV system

In the paper D-S 3P4W grid-connected PV system with combined operation involving DC-DC regulator and DC-AC conversion with power conditioner is presented. The performance analysis of the proposed PV-connected grid system under following two operating mode has been carried out;

- Ideal PV system connected to the grid with for static resistive load (OPM-1).
- For unbalanced RLC loading (OPM-2).
- PV system connected to the grid with dynamic loading (OPM-3).

Comparative results have been presented for single stage and dual stage grid tied system.

5.1 Modeling and Simulation

The scope of the research is to develop a coordinated controlled harmonic free grid connected solar system. The simulation model for solar system is developed in MATLAB Simulink version 2013a. The system description for such a system is presented in next section.

5.2 Simulation Model of Solar Panel.

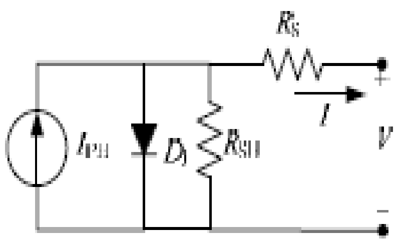


Fig 2: Generalized solar cell single diode module

A simulation model for generalized single diode solar cell is developed for the circuit shown in Fig-2

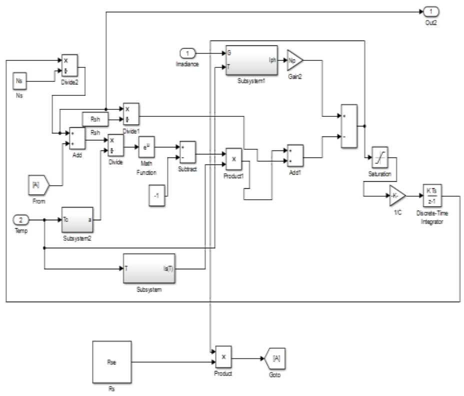
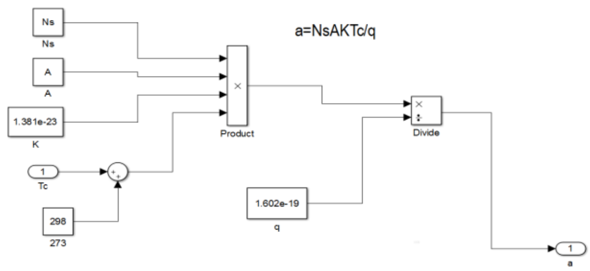
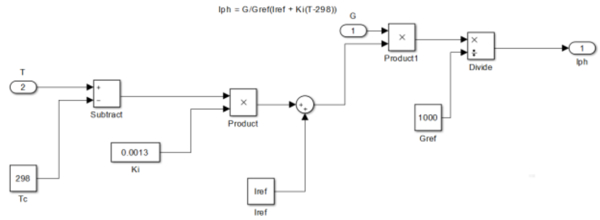


Fig 3: Simulation model for solar panel

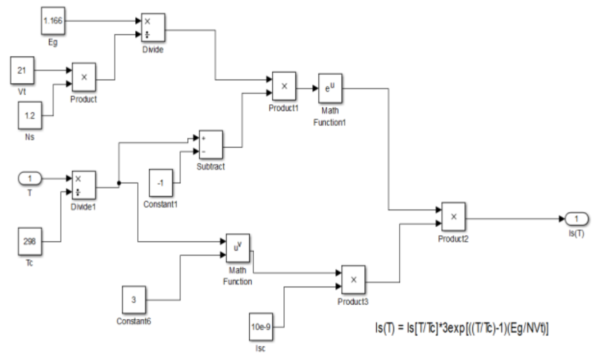


(a).Ns series module.

The simulation model for the above system is shown in Fig-3. The model was developed for standard test conditions of cells temperature at 25°C. The solar array is designed using series cell 36 and parallel module 45.The standard irradiation values of 1500, 1200, 1000, 800, 600w/m2 were taken as input parameter for the model. The subsystem of simulation model of figure 3 is obtained from equation, which are designed in MATLAB using Simulink toolkit. In eq. (4.1), A, K, Tc and q are constant values. Hence a constant function 'a' is denoted for Ns series module as shown in fig. 4(a).



(b), subsystem 1 presents the modeling of I_{ph}



(C): Simulation model for solar panel

Fig 4

In simulation model of fig. 4.4, subsystem 1 presents the modeling of I_{ph} as shown in eq. (4.2) and subsystem presents the modeling of I_S as shown in eq. (4.3). The simulation model for eq. (4.2) and (4.3) is presented in figure 4.4 (b) and (c). For the parameters selection as per the Table-1; PV and VI characteristics were drawn taking T constant at 25o and for (Fig-5).

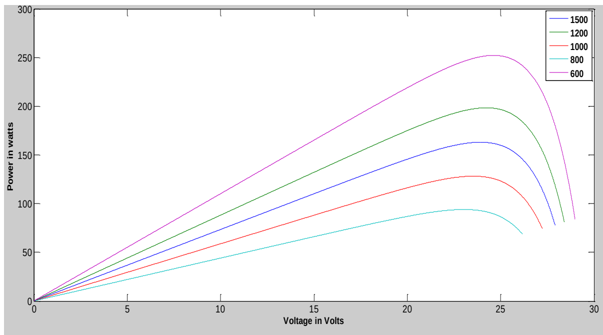


Fig 5: PV characteristics of SPV at different Irradiation

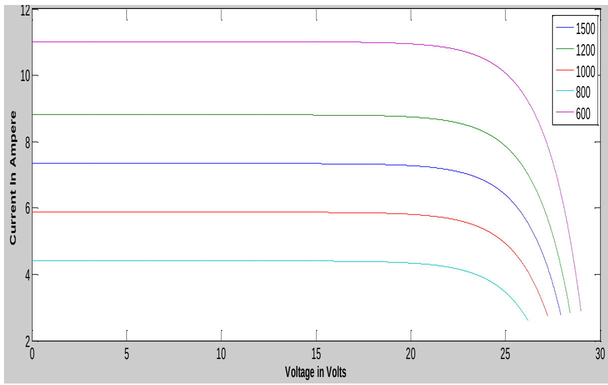


Fig 6: VI characteristics of SPV at different Irradiation

5.3 DC-DC Converter

Dc-Dc converter regulates the dc output voltage of SPV (Solar Photo voltaic), it tries to rule out harmonic from the voltage output and keep it constant, what-ever may be the output from the solar panel. Fig-7 shows the simulation model of Dc-Dc converter and table-1 gives the detailed of system components.

Table-1: Parameters description for DC converter

Parameter	Values
Input voltage	77.1 volts
Output voltage	127 volts
R1	0.001 ohm
Rload	20 ohm
Ldc	45e-3
Cdc	350e-6 F

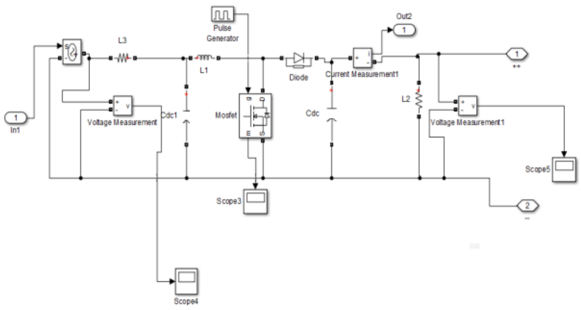


Fig 7: simulation model for DC converter

5.4 Inverter

Inverter converts the dc output into equivalent three phase ac output. The components for designing the inverter are; abc to dqo transform, phase lock loop (PLL), discrete controller, three phase three arm universal bridge triggered by 3 level-12 pulse carrier based pulse generator with switching frequency 5 KHz. The simulation model of the inverter is shown in Fig-5.7. LC filter is connected to filter out harmonics with L= 35 mH and C= 165 micro farad.

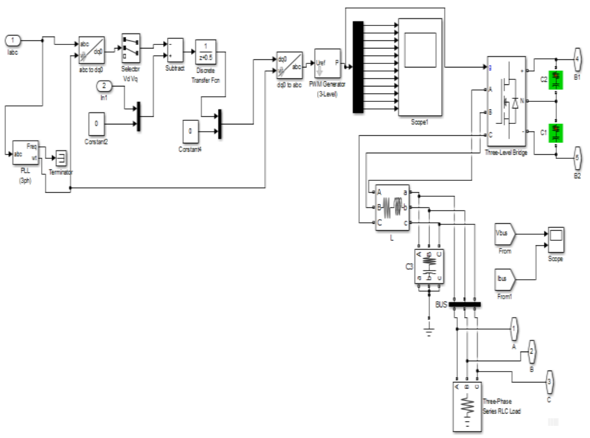


Fig 8: Three phase bridge inverter.

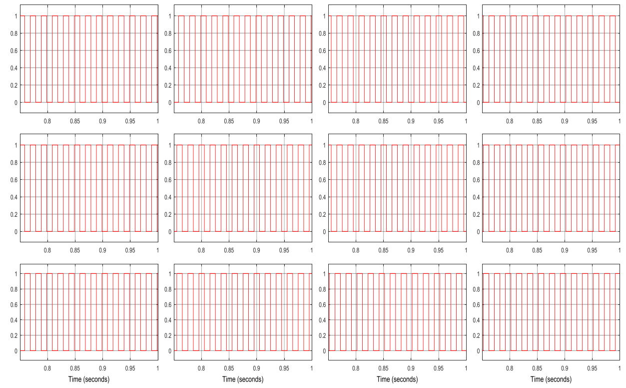


Fig 9: Output pulse generated from PWM generator to trigger the switches of inverter.

The abc to dqo transform is used to convert three-phase system into its equivalent 2-phase system to obtain only positive sequent component in order to simplify the system. PLL is used to synchronize the PV-inverter with the grid hence grid three-phase voltage is used as reference signal. Discrete control helps in rectifying the error between the generated three-phase values and the reference signal. The pulse output of 3-level PWM is presented in figure 9.

6. Simulation Model and Result Discussion

Although PV systems are emerging as power solution to meet the increased demand of electricity, but the reliability and robustness of the PV panel is always questionable.

We are designing a dual stage PV converter to stabilize the output of solar system at various modes of operation. A dual converter topology is adopted to operate the PV system, where DC converter controls DC voltage at DC-bus, while the AC converter is controlled to operate as a sinusoidal current source to synchronize the DS-PV with grid. In the work D-S 3P4W grid-connected PV system with combined operation to improve power quality is presented. The performance analysis of the designed system is carried out under various loading;

1. Dual stage PV system grid tied with resistive load of 500 W (OPM-1).
2. Dual stage PV system grid tied with unbalanced RLC load (OPM-2).
3. Dual stage PV system grid tied with dynamic three phase variable loading. (OPM-3)

Comparative results have been presented for single stage and dual stage grid tied system. The system parameters are shown in Table 2.

Table 2: System parameters.

S. No.	Parameter	Symbol	Value
1	Nominal utility voltages (rms)	V	127.27
2	Nominal Frequency	ω	50Hz

3	Inverter inductance	*L*	45 mH
4	Filter Capacitance	C	165 µF
5	Filter Inductance	L_f	35 mH
6	Nominal Load 1	P_{Load1}	40 ohms
7	Load 2	RL(phase a) RL(phase b) RC(phase c)	6Ω , 15.6 mH 8Ω , 24.2 mH 53Ω ,470 μF

6.1 Simulation Model for Opm-1 with Results

In this case system is operated under constant irradiance of 1000w/m^2 and constant temperature of 25 ^{0}C. The simulation model for this case is presented in fig. 10. Solar panel is designed for single diode model as shown in fig 11. The input for temperature and irradiance is given using signal builder. The DC-DC convert boost the PV voltage of 77 V to 127 V. Inverter converts the DC output of PV into sinusoidal AC output. Under linear resistive load the output voltage is constant and synchronized with grid.

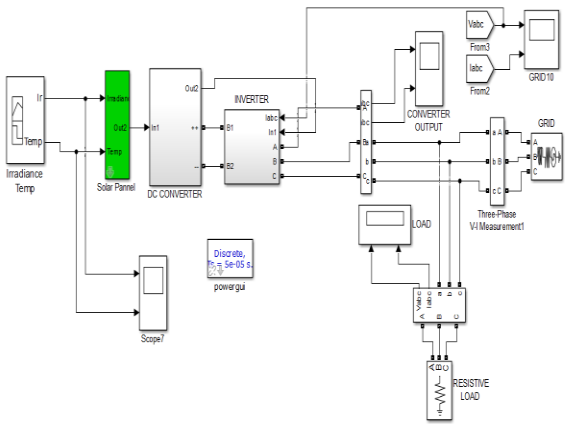


Fig 10: Simulation Model for OPM-1 with proposed topology

6.2 Simulation Model for Opm-2 with Results

In this case system is operated under variable irradiance of 600-1000w/m2 and temperature of 25-50 ^{0}C. The simulation model for this case is presented in fig. 11.

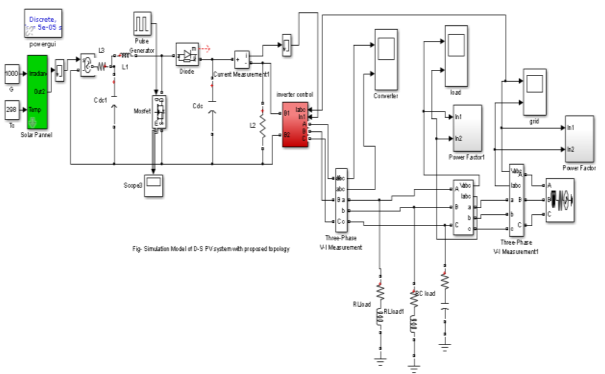


Fig 11: Simulation model for OPM-2

An unbalanced three phase load of 500 W with 50 VAr inductive as well as capacitive power demand is connected between inverter and PCC. The simulation results for output waveforms at grid side and load side are presented in Fig 12 respectively.

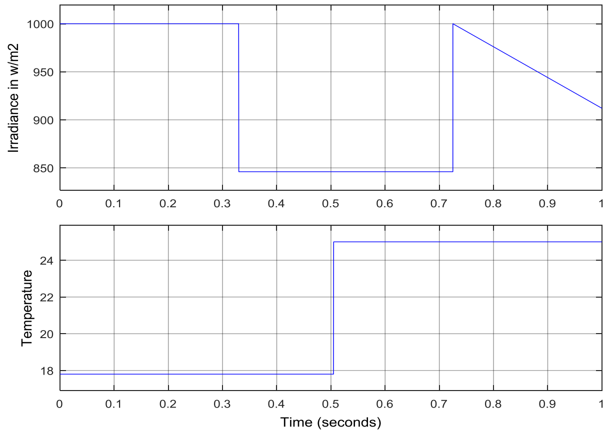


Fig 12: Graph of Variable irradiance and temperature

6.3 Simulation Model for Opm-3 with Results

In his case dynamic type of loading is connected. In dynamic loading both active and reactive power varies continuously with time. This type of loading helps in understanding the behavior of the DS-PV with grid connection under variable load pattern.The simulation model for this case is presented in fig. 13.

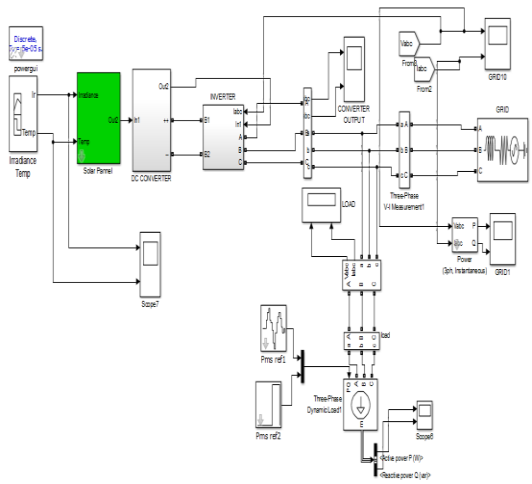


Fig 13: Simulation model for opm-3

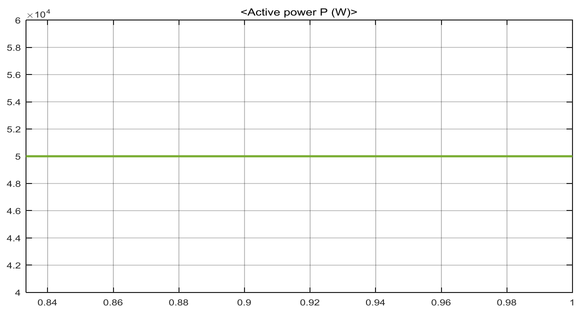


Fig 14: Active flow at load side (opm-3)

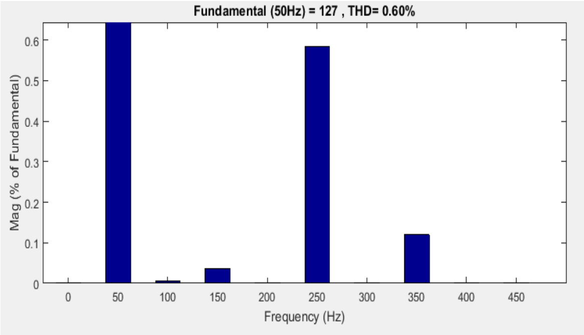


Fig 15: THD of Voltage Waveform of Grid-Tied PV System with proposed topology

From the figures 14 and 15; it can be observed that the designed inverter control reduces the harmonics and improves the power quality of the PV tied distribution system even under the condition of dynamic loading.

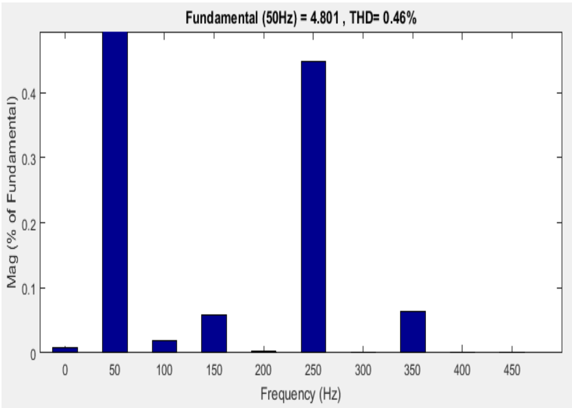


Fig 16: THD of current Waveform of Grid-Tied PV System with proposed topology

CONCLUSION

The following conclusions are made for the work done

- A dual stage grid tied PV system has been compared with single –stage grid tied system of base paper.
- A static and dynamic performance of the system has been analyzed for single phase and three phase unbalanced loading.
- THD analysis of the system converter side and grid side are determined and the percentage THD is reduced.
- The system has been analyzed with dual stage grid connected PV system to account for the harmonic mitigation strategy and also to work as a static compensator at the time when PV system is not supplying local demand due to unavailability or sudden change of solar radiations.

FUTURE SCOPE

The following are future scope for the work done

- Due to high carbon emission from conventional thermal plant electricity production from solar system has become the necessity of the time since solar energy is the green form of energy and power production through it contains almost zero carbon traces.
- The proposed system can be successfully utilized commercially for power production.
- By integrating smart grid technology the reliability of the system can be increased manifold.

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