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Modeling and Analysis of a Maximum Power Point Tracking Control for Double Stage Solar Photovoltaic Grid-Connected Systems

Shilpa C[1], Jayakumar N[2], Nagaraja Rao[3]

[1]PG Scholar, Dept. of Electrical and Electronics Engineering, TOCE, Karnataka, India.
[2]Associate Professor, Dept. of Electrical and Electronics Engineering, TOCE, Karnataka, India.
[3]Associate Professor, ECE, Shri Madhwa Institute of Technology, Karnataka, India.

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Abstract - *The control scheme for maximum power point tracking of a photovoltaic system, to supply power to the grid by means of Boost converter and an inverter, which is controlled by PWM(Pulse Width Modulation) is introduced in this paper. The mathematical model for the Boost converter is derived in detail, the inductor and capacitor values of the Boost converter are estimated for continuous conduction mode, so as to maintain the output voltage of the controller constant. To adjust the duty cycle of the boost converter and to increase the efficiency of the photovoltaic panel, Perturb and Observe Method(P&O), Incremental Conductance(IC) and Fuzzy Logic Control(FLC) techniques for the Maximum Power Point Tracking(MPPT) is introduced, modeled and compared using MATLAB/Simulink.*

Key Words: **Solar Photovoltaic system, Maximum Power Point Tracking, Perturb and Observe Method, Incremental Conductance, Fuzzy Logic Control.**

1.INTRODUCTION

The desire for electricity is rising with the highest tempo of all the energy utilized worldwide. This continuous growing energy demand has led the human race a huge challenge as a result of socioeconomic development. The extinct of fossil fuels and its massive use to fight the existing industrial revolution deviates us on the heights of use of fossil fuel. Irreconcilable of non renewable resources to attain this unfathomable demand for energy, energy reliability and shoot up hike of fossil fuel prices has led to invent reconcilable options[1]. To overcome these demands the universal convenience of renewable energies such as solar and wind power provides a impressive resolution. Never ending research has shown an growth in efficiency in conversion and transmission of the renewable energy sources. Among the renewable energy sources the Solar Photovoltaic(SPV) generation is forefront as the propitious future energy technology[2].

Sunlight is converted to DC form of electricity. Based on the applications, SPV systems are of three types, grid connected SPV system, stand alone SPV system and hybrid SPV systems. The skilful extraction insists attainments of certain remarkable challenges like instability in power, extremely large investment, efficiency of energy conversion is low and power cost. Since SPV system requires very less maintenance, reducing power cost is a big issue. Thus, the only cost saving is to increase the efficiency of SPV system. Recent writings unveil that Maximum Power Point Tracking (MPPT) techniques are employed to enhance the output power of the module. Thus MPPT techniques becomes essential for a grid connected system. An power electronic circuitry utilized to equalize the behavior of module apropos the maximum power point is called MPPT. The block diagram for a typical grid connected system is illustrated in Fig 1.

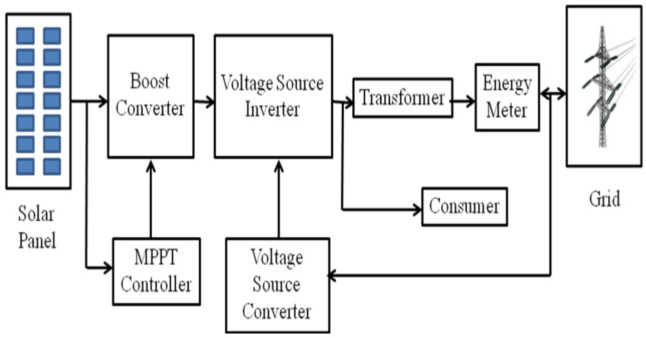

Fig -1: Block Diagram of a Grid connected SPV system.

SPV system comprises of a solar array, made up of solar cells of series and parallel combination, DC-DC boost converter, Maximum Power Point Tracking(MPPT) controls, Inverters and grid connected system. In double stage grid coupled SPV system, the DC side is controlled by the MPPT technique and the power factor correction is synchronized by voltage source converter. Nevertheless, the quality of the power, system reliability and synchronization to grid becomes essential in grid connected SPV system. Furthermore, the inoculation of reactive power to the grid creates evolution of control algorithm.

Various literature's are published on different MPPT techniques used[3-9]. MPPT techniques differ in simplicity, sensors needed, cost, type of circuits and efficiency. Although, it is worthless to utilize complex algorithms with more cost if similar results are obtained with less cost and simpler algorithm. However in this paper, the Perturb and Observe Method (P&O), Incremental Conductance(IC) and Fuzzy Logic Control(FLC) techniques for MPPT are considered, cause of simplicity and popularity. The main aim of this paper is to design MPPT, to trace the maximum power without oscillations around the operating point for a range of specific atmospheric condition and to design properly the passive components of the boost converter, so that it works in continuous conduction mode and extracts maximum power from the solar panel.

2. MATHEMATICAL MODELING OF PV MODULE

To study the behavior of the solar cell, the equivalent model is illustrated in Fig 2, with a diode in parallel with a current source and the series and parallel resistors, as considered in [10].

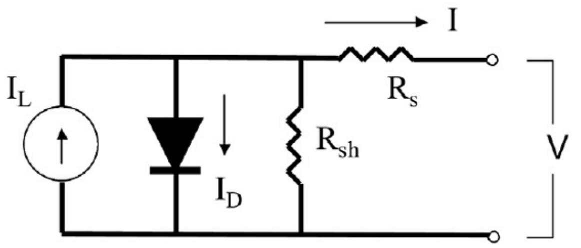

Fig -2: Equivalent Model of a Solar Cell.

I - is the current produced by the SPV module.
V - is the voltage produced by the SPV module.
R_s - Series resistor, it is the resistance provided by the metal contacts and the semiconductor of the solar cell. For ideal operation it is assumed as zero.
R_{sh} - Shunt resistor, it is the resistance due to non ideal mature of the semiconductor and the impurities present. For ideal operation it is assumed as infinite.

By considering Kirchhoff's voltage law to the equivalent model, the current produced is obtained as,

$$I = I_L - I_0(e^{(qV+I_{RS}/AKT_C)} - 1) - ((V - IR_s)/R_{sh}) \quad (1)$$

I_L - is the photo current, produced by sunlight.
A - is the ideality factor.
q - is the magnitude of the charge(=1.6×10^{-19}C).
I_0 - is the saturation current in diode.
T_c - is the working temperature of the cell.
K - is the Boltzmann's constant(= 1.38×10^{-23} W/m^{2}K).

Photo current depends on the radiation of the sunlight and working temperature of the cell and is given by

$$I_L = G(I_{SC} + K_t(T_C - T_{ref})) \quad (2)$$

I_{sc} - is the short circuit current at STC (standard test condition that is, at a radiation of 1000W/m^2 and a working temperature of 25ºC).
G - is the solar radiation in KW/m^2.
T_{ref} - is the reference temperature.
K_t - is the temperature co-efficient.
The saturation current is given by

$$I_0 = I_{RS}(T_c / T_{ref})^3 e^{(qE_G(\frac{1}{T_{ref}} - \frac{1}{T_c})/KA)} \quad (3)$$

E_G - is the energy gap of the semiconductor.
I_{RS} - is the reverse saturation current of the diode at STC.

In this paper the SPV array module utilized is Sun Power SPR-305-WHT to deliver the power of 10kW. PV array comprises of 74/9 strings of modules associated in parallel, each string comprising of 4 modules associated in series. Module specifications under STC is given in Table 1.

Table -1: PV array specifications.

STC Power Rating	305W
STC Power Rating unit of area	187W/m^2
Number of cells per module	96
Short circuit current	5.96 A
current at maximum power point	5.58 A
Open circuit Voltage	64.2 V
voltage at maximum power point	54.70 V
Peak Efficiency	18.7%

3. DESIGNING OF BOOST CONVERTER

To decrease the losses in the energy transfer to the grid, it is required to increase the PV voltage. In this project the DC-DC converter used is a Boost converter, to boost the voltage. The Boost converter is regulated by varying the duty cycle D
The output voltage and the input voltage is related as explained in [11], and is given by

$$V_o = V_s /(1 - D) \quad (4)$$

V_0 - is the output voltage.
V_s - is the input voltage, in this case it is the PV voltage.

In designing the boost converter, the selection of the inductor plays an important role to ensure for any duty cycle, with the considered range of atmospheric variations, the inductor current is always continuous that is it operates only in continuous conduction mode. Consider I_L , average inductor current, ΔI_L, peak ripple current and T_s (f_s=$1/Ts$) is the switching period. Ensuring continuous conduction and analysis discussed in [11],it can be concluded,

$$L_{crit} = D(1-D)^2 R_{crit} T_S / 2 \quad (5)$$

But as explained in [8], the output current is maximum at 0.334 thus,

$$L_{crit} > 0.074 R_{crit} T_S \quad (6)$$

To prevent the inductor ripple current from flowing to SPV the boost capacitor is designed as follows. The ripple component in inductor current is $2\Delta I_L$ and it flows through the capacitor and its average component I_L flows through PV. Let, ΔV_g be the allowable peak to peak ripple voltage across the capacitor and V_g is the average voltage produced by PV as in[11]. Therefore, the incremental charge on capacitor ΔQ is given by,

$$\Delta Q = C_i \Delta V_g \quad (7)$$

Also, $\Delta Q = C_i \Delta V_g = \Delta I_L T_s / 4$ (8)

During switch-ON, inductor current changes from i_{l1} to il_2 and $\Delta I_L = (i_{l2}\text{-}i_{l1})$ and voltage across inductor, which is the voltage across the PV panel can be expressed as,

$$V_g = 2\Delta I_L * L * D * T_S \quad (9)$$

Using the value ΔI_L from (8) in equation (9)

$$C_i = (DT_s / 8L)(V_g / \Delta V_g) \quad (10)$$

With radiation varying from 1000W/m² to 200W/m², to maintain the steady dc link voltage of 500V, corresponding minimum inductor values are given in Table-2. The switching frequency is chosen as f=5kHz (Ts=0.0002 second). For a value of R_{crit}, the lesser the switching time period, less is the inductance value needed.

Table -2: Inductor values for different irradiation

Irradiation (W/m²)	PV power (W)	PV Voltage (V)	PV Current (A)	Load Resistance (ohm)	Duty ratio	Inductance L (mH)
1000	10038	218.8	45.88	24.905	0.56	0.37
800	7121	184.3	38.64	35.1074	0.63	0.52
600	4041	138.8	29.11	61.865	0.72	0.92
400	1797	92.56	19.41	139.12	0.814	2
200	449.2	46.28	9.705	556.5	0.9	7.89

From the table it is clear that 8 mH is sufficient for MPPT in different operating region ensuring Continuous Conduction Mode in all duty ratio.

4. MPPT TECHNIQUES

As described earlier, the MPPT technique is essential in solar PV applications, cause with varying atmospheric conditions, the maximum power point varies. MPPT works on specific tracking algorithms and is not a mechanical tracker. The primary goal of MPPT is to extract the maximum power from solar PV module using simple logic to function at maximum efficiency.

4.1 Perturb and Observe Method

It is the most simple and common technique used because of the ease of implementation. Perturb means the system is subjected to an impact having the tendency to modify its typical or regular state. In this method the duty cycle of the boost converter is perturbed and thus the voltage between the DC-link of the boost converter and PV array is perturbed. The voltage is revised to attain the maximum power due to the perturbation introduced in the duty cycle of the boost converter.

The execution of this technique is shown as a flow chart in Fig 3, unless the maximum power is reached this procedure is iterated

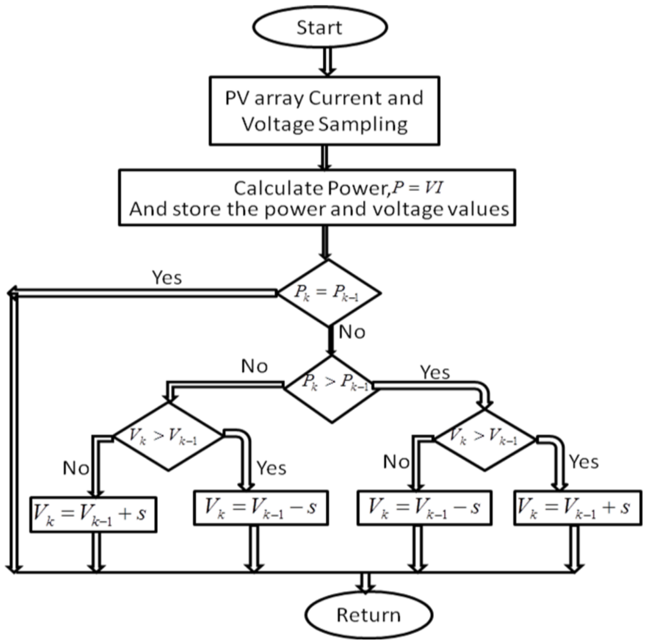

Fig -3: Flow chart of P&O Method.

4.2 Incremental Conductance

In IC method, the voltage produced by the SPV panel is constantly balanced by the voltage at MPP. The voltage produced by the SPV panel depends on the instantaneous and incremental conductance of the PV module.

At MPP the slope of the power curve of the PV array is zero and it is demonstrated in Fig 6. To the left hand side of MPP the slope is augmenting and to the right of MPP the slope is diminishing. The fundamental conditions of this strategy are as per the following.

At MPP, $$dI/dV = -I/V \quad (11)$$

Left of MPP, $$dI/dV > -I/V \quad (12)$$

Right of MPP, $$dI/dV < -I/V \quad (13)$$

Where I - is the current produced by the SPV array and V- is the voltage produced by the SPV array. The incremental conductance is presented on the left hand side of the equations and the instantaneous conductance is presented on the right hand side of the equations. In IC method, the duty cycle of the boost converter is adjusted unless the condition in equation(11) is fulfilled. The flow chart of this method is illustrated in Fig 4.

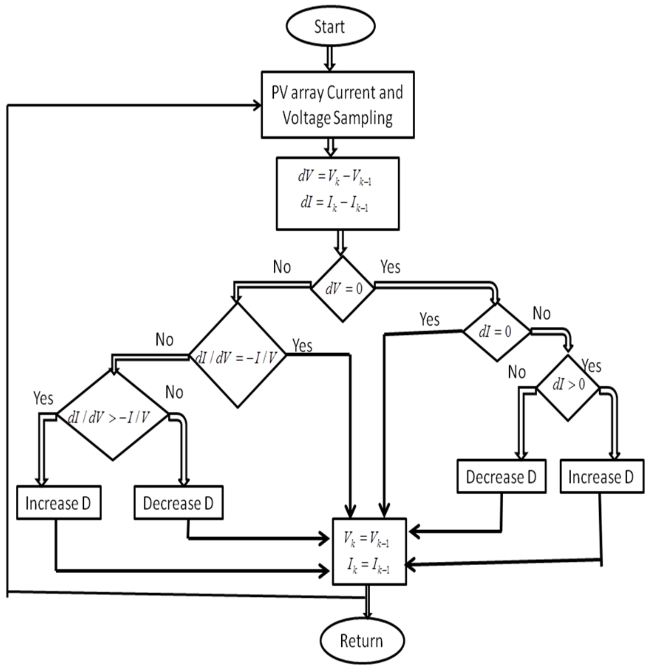

Fig -4: Flow chart of IC method

4.3 Fuzzy Logic Control

FLC is gaining importance in MPPT applications, as it is an intense strategy for reasoning and to handle non-linearity, when it is hard to express the determined conduct of the system as far as scientific model are in systematic equation and input information are uncertain. FLC consists of 3 steps: Fuzzification, Inference system and Defuzzification.

In fuzzy logic control of MPPT, the inputs are PV voltage and PV current and output is change in duty cycle. In this case 7 membership functions are utilised: Very Low(VL), Low(L), Low Medium(LM), Medium(M), Medium High(MH), High(H) and Very High(VH). The rule base table is depicted in Table 3, totally 49 rules are used. The succinct esteem assigned to change in duty cycle for different PV voltage and PV current are based on power converter and the knowledge of the programmer.

Table -3: Rule Table

V/I	**VL**	**L**	**LM**	**M**	**MH**	**H**	**VH**
VL	VL	VL	VL	VL	VL	M	MH
L	VL	VL	VL	VL	M	MH	H
LM	VL	VL	VL	M	MH	H	VH
M	VL	VL	M	MH	H	VH	VH
MH	VL	M	MH	H	VH	VH	VH
H	M	MH	H	VH	VH	VH	VH
VH	MH	H	VH	VH	VH	VH	VH

5. SIMULATION AND RESULTS.

The design of boost converter is considered and the grid coupled SPV system is modelled in simulink with maximum PV power of 10000W, and a maximum PV voltage of 215V, under 25 degree Celsius is shown in Fig 8.3. The inverter is shown as 3-phase bridge which converts the output voltage of boost converter, that is 500V DC to 500V AC. The transformer steps up this 500V to 20000V and supplies it to the grid. The P-V and I-V characteristics are illustrated in Figures 6 and 7 respectively, for different irradiations.

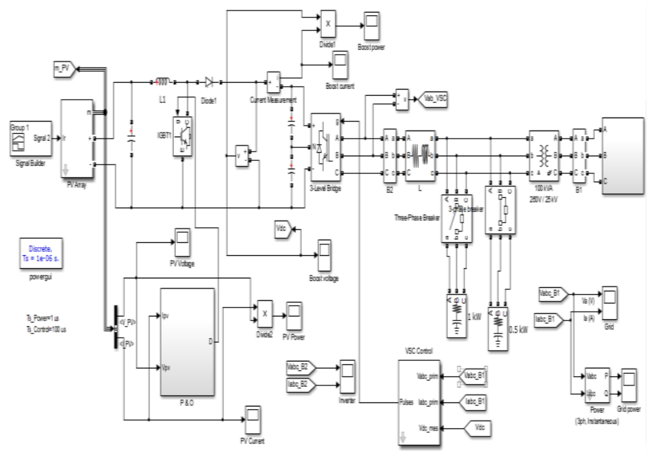

Fig -5: Simulink model of a grid connected SPV

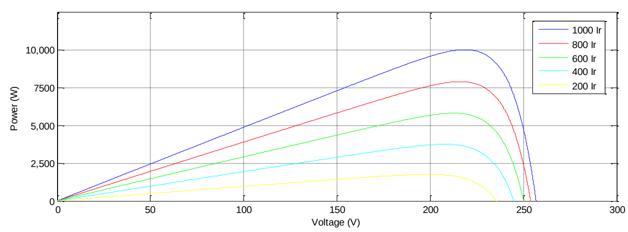

Fig -6: P-V Curve for 10000W PV array

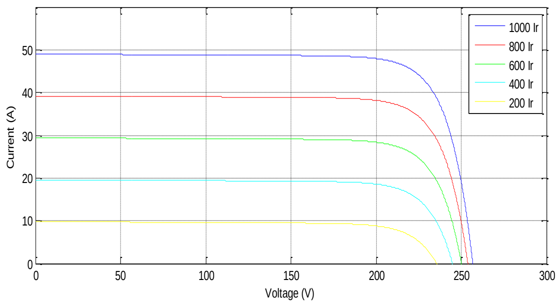

Fig -7: I-V Curve for 10000W PV array

The change in irradiance applied to the system at different intervals of time is shown in Fig 8, with minimum irradiance of 200 W/m² and maximum irradiance of 1000 W/m². This change in irradiance waveform is used as the irradiation from the sun changes throughout the day. In simulation the change in irradiance is introduced for 3 seconds.

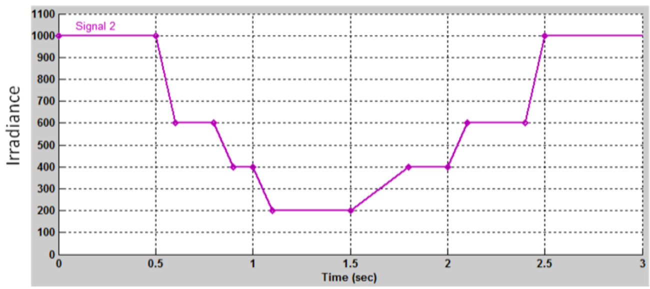

Fig -8. Different irradiation at different interval of time applied to PV panel.

The output voltage of PV panel is illustrated in Fig 9, which initially overshoots to 258V and settles by 0.1 second. It oscillates between 217V to 200V for change in irradiation from 200W/m² to 1000W/m² respectively. The current and power generated by the PV panel is shown in Figures 10 and 11 respectively, which changes with the changing irradiation.

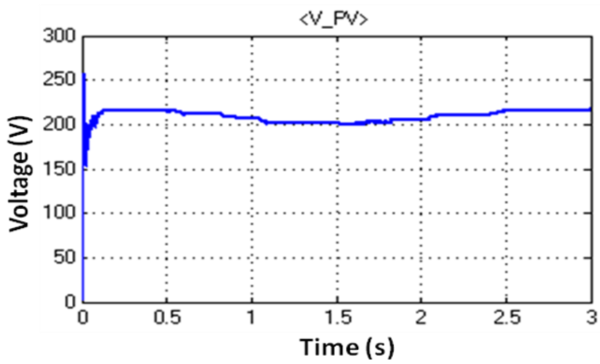

Fig -9. PV Voltage.

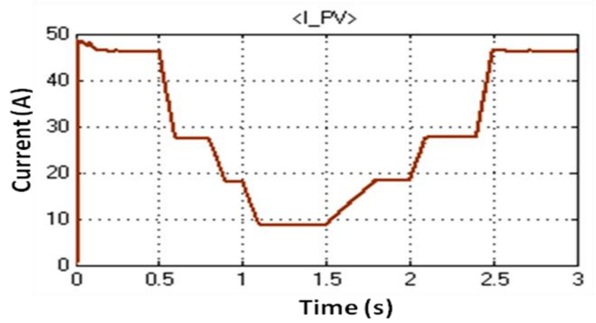

Fig -10. PV Current.

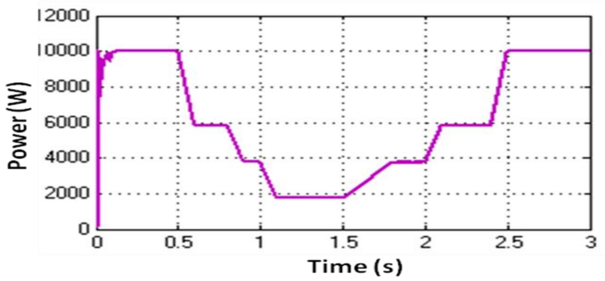

Fig -11. PV Power.

The PV output is fed as input to the boost converter. The voltage obtained at the boost converter is illustrated in Fig 12, which is maintained at 500V, initially there is a peak overshoot of 700V. The output current and power of the boost converter is shown in Figures 13 and 14 respectively, which oscillates due to changing irradiation.

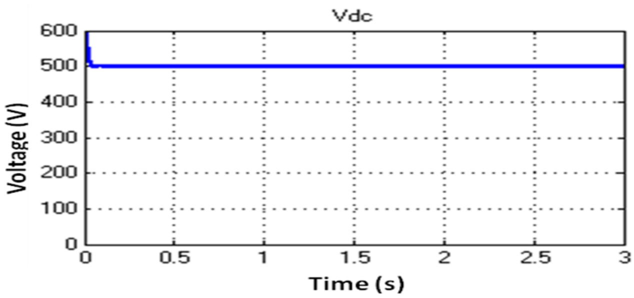

Fig -12. Voltage Obtained at the Boost Converter.

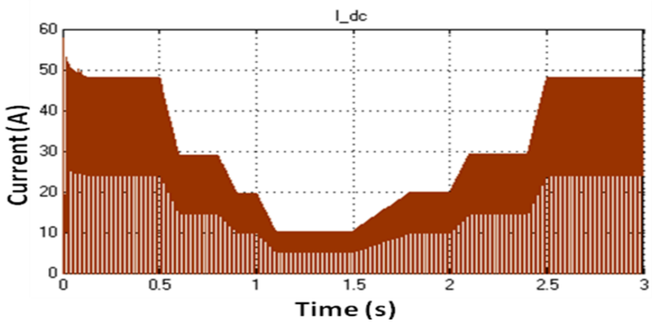

Fig -13. Current Obtained at the Boost Converter.

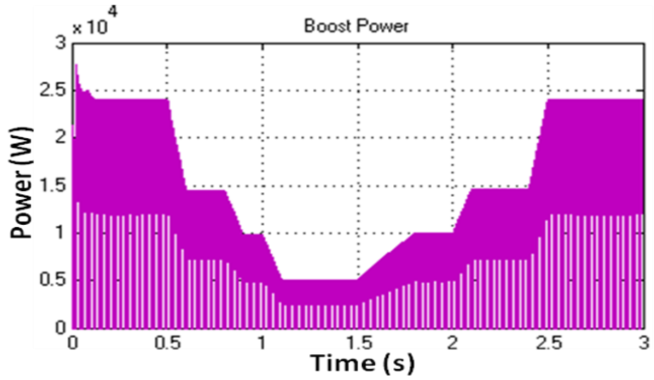

Fig -14. Power Obtained at the Boost Converter.

The input to the three phase inverter is fed by the boost converter, the output voltage and current waveforms obtained at the inverter are illustrated in Fig 15. The output voltage is 500V AC. The output current is about 60A for 10000W/m² and 50A for 200W/m².

The inverter output is stepped up using the transformer and is supplied to the grid. The voltage and current waveforms supplied to the grid is illustrated in Fig 16. The voltage is stepped up to 20KV. The current is about 0.35A.

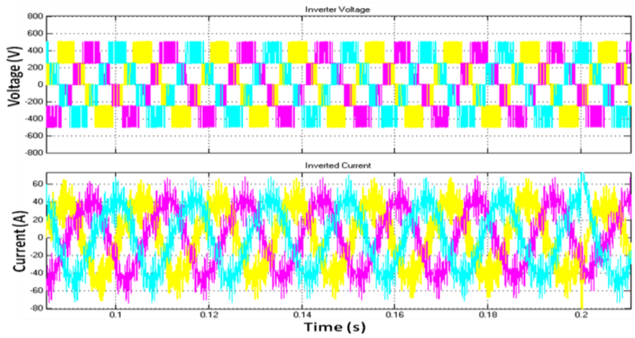

Fig -15. Voltage and Current Waveforms Obtained at the Inverter.

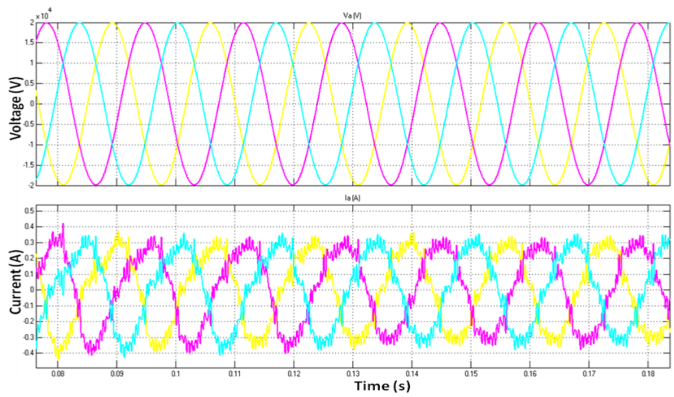

Fig 9 -16. Voltage and Current Waveforms Supplied to the Grid.

6. COMPARISON OF RESULTS.

The variations in the voltage and current at PV panel, boost converter, inverter and the grid are summarized for different MPPT techniques, that is P&O, IC and fuzzy logic control, in tables 4,5, and 6 respectively.

Table -4: Variations in the Output at Different Levels With P&O MPPT for a Grid Coupled SPV System.

Irradiation(W/m²)	**1000**	**600**	**400**	**200**
PV Voltage(V)	220	218	218	218
PV Current(A)	45	26.5	16.7	6.9
PV Power(W)	9990	5625	3650	1510
Boost Voltage(V)	500	500	500	500
Boost Current(A)	52.5	29	19	10
Boost Power(W)	26100	14600	9500	5000
Inverter Voltage(V)	500	500	500	500
Inverter Current(A)	60	55	50	40
Grid Voltage(V)	20000	20000	20000	20000
Grid Current(A)	0.35	0.2	0.15	0.1
SPV Efficiency(%)	18.6	17.9	17.09	14.1
Tracking Efficiency(%)	99.5	96.2	91.88	75.8

Table -5: Variations in the Output at Different Levels With IC Method MPPT for a Grid Coupled SPV System

Irradiation(W/m²)	**1000**	**600**	**400**	**200**
PV Voltage(V)	217.7	212.6	207.5	202.5
PV Current(A)	46.1	27.35	18.1	8.67
PV Power(W)	10035	5816	3757.7	1756
Boost Voltage(V)	500	500	500	500
Boost Current(A)	47.5	28.8	19.5	10.1
Boost Power(W)	23750	14411	9790	5070
Inverter Voltage(V)	500	500	500	500
Inverter Current(A)	60	55	50	40
Grid Voltage(V)	20000	20000	20000	20000

Grid Current(A)	0.35	0.2	0.15	0.1
SPV Efficiency(%)	18.6	18.08	17.5	16.3
Tracking Efficiency(%)	99.5	96.7	94.1	87.6

Table -6: Variations in the Output at Different Levels With FLC Method MPPT for a Grid Coupled SPV System.

Irradiation(W/m²)	**1000**	**600**	**400**	**200**
PV Voltage(V)	222.59	187.5	227.5	208.5
PV Current(A)	45	28.8	14.1	8.24
PV Power(W)	10009.73	5400	3210	1718
Boost Voltage(V)	500	500	500	500
Boost Current(A)	46.5	30	15.5	9.7
Boost Power(W)	24000	15000	7800	4875
Inverter Voltage(V)	500	500	500	500
Inverter Current(A)	60	55	50	40
Grid Voltage(V)	20000	20000	20000	20000
Grid Current(A)	0.35	0.2	0.15	0.1
SPV Efficiency(%)	18.7	17.9	14.9	16.02
Tracking Efficiency(%)	100	96.7	80	86.1

Among the three MPPT techniques discussed, the Incremental Conductance is the most desirable as the best results are obtained. In incremental conductance the results are more satisfactory, even under varying irradiations. The efficiency is about 94.5% for change in irradiation.
The perturb and observe method as an efficiency of 90.8%, but there is lot of oscillations at the maximum power point. Perturb and observe method is more simpler than incremental conductance. Because in incremental conductance division of the change in current by the change in voltage is required and then it is compared to zero, which is a bit complicated.

In fuzzy logic control the efficiencies are fine with 90.5%. However, the tracking of maximum power worsens for small gradient change in irradiation, as the controller fails to detect the changes. One more disadvantage is that the tuning is very difficult and there is no specific rules for selecting the membership functions. The efficiency of the fuzzy logic control considerably depends on the programmers skill. Moreover the design process are well defined in incremental conductance and perturb and observe method whereas in fuzzy control there are no general rules.

7. CONCLUSIONS

The PV module was modelled and analysed in this paper. The passive components of the boost converter were designed for continuous mode operation. The SIMULINK model for the double stage grid connected solar photovoltaic system was designed and tested for the three MPPT techniques. The execution of perturb and observe method, incremental conductance and fuzzy logic control MPPT techniques were observed for the double stage grid coupled PV system. The behaviour of the three MPPT techniques were compared and depending on the results, efficiency was calculated, and it was inferred that the incremental conductance was the best.

However, perturb and observe method and fuzzy logic control cannot be rejected, as perturb and observe method is more simpler and the behaviour of fuzzy logic control depends on the programmer skill.

Thus, the incremental conductance is concluded as the most appropriate MPPT technique based on the simulations and the results observed in this paper.

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