Simulation Studies on Photovoltaic Systems

G D Anbarasi Jebaselvi, S Paramasivam

Abstract— **Fast improving technologies motivates every researcher to take bold steps towards power optimization and hence innovative efforts in each field have started budding and one such is in the area of hybridization of renewable energy sources. The power quality aspects, controller design, development of dynamic model, optimum power retrieval are comparatively analyzed in view of obtaining a beneficial record over the past years and to acquire better future in power management. The modeling and simulation of photovoltaic generator is obtained here for various load conditions at different environmental circumstances.**

***Index Terms*—inverter, irradiance, buck-boost converter, photovoltaic array, Maximum Power Point Tracker**

I. INTRODUCTION

EVERYONE around the world is talking about renewable portfolio standards and the global movement threatening everywhere. To have greener environment efforts are being taken using renewable sources to produce power since landfills are more quickly increasing than ever. For many, integrating renewable into an existing system is a new challenge but for a few it is an inevitable fixture. In addition, the scarcity of electric power goes day by day increasing, it is essential to set a supreme hybrid power system which could meet the unbalanced power demand might be a best combination of wind, solar and diesel sources.

Apart from solar-diesel system, a wind-diesel integrated control system is also coming up in recent years and each of the diesel units has to be equipped with an automatic voltage regulator and a governor system. Diesel plant is used as a additional resource with automatic controller which supervises the overall wind-diesel network operation without affecting the synchronization of unit, load sharing, and control of loads.

Also the wind farm controller performs automatic control and protection of the wind power plant including start-up of the wind turbines when the wind speed rises above 4 m/s (14.4km/h), and shutdown of the turbines for wind speed beyond 22 m/s (79.2 km/h).The simulation and modeling of the complete hybrid power system have been viewed seriously and much number of techniques with different algorithms is adopted in several papers in order to improve the power salvage.

This paper is divided into five sections begins with the introduction, Section II deals with the comparative study on simulation results, modeling, control methods, storage and dispatch strategies of hybrid power system to investigate the behavior of the complete hybrid system for a step change in load. Section III summarizes the design and implementation of photovoltaic system using Matlab/Simulink supported by a suitable source coding in Matlab. Section IV explains how optimum power can be retrieved in photovoltaic system using MPPT algorithm. Section V concludes with assurance that the renewables could be the best option in the near future to meet the biggest challenges shaking the humanity worldwide, the climate change and global warming.

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G D Anbarasi Jebaselvi is with Sathyabama University, Rajiv Gandhi Salai, Jeppiar Nagar,Chennai,Tamil Nadu,India (phone:044-22771419; She has been working as an Assistant Professor for the past 15 years and pursuing research in renewable energy sources.(e-mail:anbarasi.jebaselvi@gmail.com).
S. Paramasivam is with ESAB Engineering Service Limited, Chennai, Tamil Nadu, India. He has been acting as an Assistant General Manager in Research and Development section for several years. (e-mail: paramsathya@yahoo.com). He is sparing his time as reviewer for reputed journals and IEEE transactions as well.

II.COMPARATIVE STUDY

A comparative study has been done on hybrid system comprising major energy sources like wind energy, solar energy, diesel generator, battery with novergy TC701A CD, the energy optimizer specially designed for rural telecom sites where grid supply is unreliable, to enable the use and integration of renewable energy resources as depicted in Fig.1

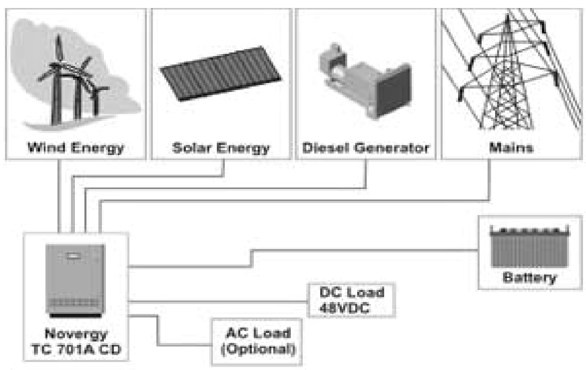

Fig.1.Schematic of hybrid power system

Since most of the thickly populated countries are blessed with abundant solar radiation with a mean daily solar radiation in the range of 5–7 kWh/m2 and have more than 275 sunny days in a year [1,2], it is best suitable to choose sun energy as the first alternative to replace the conventional fuels. To start with the photovoltaic system, to create, test and validate the overall model of solar photovoltaic array, maximum power point tracker, battery, charger, DC/DC converter and load, Simulink is used. It is an interactive tool for modeling, simulating and analyzing dynamic systems, including controls, signal processing, communications and other complex systems. Separate block diagrams are drawn to denote the mathematical systems, subsystems and specific M-files are used to call back blocks as well.

Secondly the wind conversion system is taken for study under hybridization but the main pitfall in it is the reactive power compensation. Normally real and reactive powers on a transmission line in an integrated network are governed by line impedance, voltage magnitudes, and the angle difference between the line ends. Reactive power compensation or control is very necessary in power system to minimize power transmission losses, to maximize power transmission capability, and to maintain the supply voltage. Formerly synchronous condensers, mechanically switched capacitors and inductors, and saturated reactors have been used to control the system voltage. Later thyristor controlled reactors (TCR) either with fixed capacitors FC or thyristor switched capacitors (TSC) have been used to inject or absorb reactive power into the system.

After that, controllable series compensator such as thyristor controlled series compensation (TCSC) has been developed to change the apparent impedance of a power line by either inductive or capacitive compensation, apart from controlling active power transfer. The conduction period of reactor is regulated by thyristors to vary the effective impedance of the circuit. Though TCSC is primarily used for regulating the power flow by changing its effective reactance inserted in series with the transmission line, it may also be used for voltage stabilization.

It is desirable to have converter transformers to complement the function of the power electronic switches such as to aid system VAR compensation and to connect these devices to high voltage bus. Again the converter supplies reactive power to the network by increasing the inverter output voltage.

For small hydro-power plant or wind power plant in some remote locations, the connected large power grid is hard to provide enough reactive power, or the excess reactive power may result in a serious voltage drop and large line losses. Installing a SVC [3, 4] at the connection point can efficiently stabilize the voltage at the connection point to an acceptable level and maximally prevent the harmful impact caused by faults in the power grid. Even a small capacitor can be employed to provide the required reference voltage level to the inverter instead of capacitor banks. The capacitor/filter banks can supply sufficient capacitive reactive power to power grid and filter the harmful harmonics.

TABLE 1. Comparative results on different parameters of hybrid power system

Sources used	**Simulationresults/Software used for simulation**	**Modeling/ Control Methods**	**Storage/ dispatch strategies**	**Efficiency of the overall system**	**Overall cost**
Photovoltaic cell with inverter alone	Matlab/Version 6.5	ANN model	Thermal Energy Storage with phase change material	Increased efficiency	Increased PV module costs
Photovoltaic cell with diesel generator	Matlab/Simulink	IGBT inverter,MOSFETs	Battery as a back-up	High efficiency	Moderate capital costs
Wind convertor,Doubly Fed Induction Generator	Saber,DIgSILENT, HAWC,TurbSim, AeroDyn	IGBTS/BJTS;Hysteresis space vector PWM,sinusoidal PWM	Battery as a back-up	Good	Economical; Installation cost is high
Wind-diesel integrated system	PSCAD/EMTDC/ FAST	Automatic Reactive Power Control/SVC	Grid/Capacitor banks/SG	Optimum gain setting	Cost effective compared to the above one
Wind,solar,diesel and battery	Matlab/Simulink/ HOMER/GA	Sliding Mode Power control-Variable speed, Rotor slot harmonics and the rotational speed estimation-Model Reference Adaptive System (MRAS)	Lead acid battery	Moderate	Increased capital costs and O&M cost

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In order to apply large-scale reactive power compensation, new SVC systems with a low switching frequency PWM operation have been chosen. A series connections of existing GTO thyristors have been essential in realizing high voltage of about 4 kV and so multilevel level inverter topology have been introduced newly. The complete comparison has been drawn in Table.1

III. ANALYSIS OF PHOTOVOLTAIC SYSTEM

The design and simulation of a photovoltaic system using MATLAB/Simulink is projected here. It includes models for a solar photovoltaic array, maximum power point tracker (MPPT), battery, charger, DC/DC converter and load. The complete model is simulated under various testing conditions including sunny and cloudy periods for constant and varying loads can be combined effectively and every system is integrated to get a complete simulated model.

3.1 Simple PVA Model and Governing Equations

When sunlight falls on solar cells, a voltage is generated across its terminal and every solar cell acts like a charged battery. Generally 36 solar cells are connected together to get minimum of 12 volt from a single solar panel and 18 cells to 6 volt output. On average silicon solar PV module of one square feet gives peak output power of 10 to 12 Watt. The output current from the PV cell can be found using the equation (1)

$$I = I_{sc} - I_d \tag{1}$$

where,

Isc – short circuit current

Id –shunted current through intrinsic diode

And also the diode current is given by the Shockley's diode equation as

$$I_d = I_o*(e^{q*Vd/(k*T)} - 1) \tag{2}$$

where,

Io-Reverse saturation current of the diode.

q-electron charge ($1.602*10^{-23}$C)

Vd-Voltage across the diode (V)

K-Boltzmann's constant ($1.381*10^{-23}$ J/K)

T-junction temperature in Kelvin (K)

Combining equation (1) & (2)

$$I = I_{sc} - I_o*(e^{q*V/(k*T)} - 1) \tag{3}$$

where

V-voltage across the PV cell

I-output current

The more accurate model in Fig.2 includes an extra diode D2 along with series and parallel resistances.

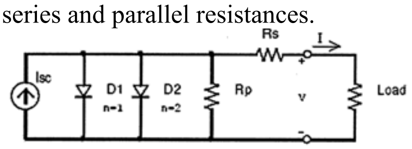

Fig.2.Accurate model of PV cell

The two diodes can be combined giving the equation

$$I = I_{sc} - I_o*(e^{q*(V+I*Rs)/(n*k*T)}-1) - (V+I*Rs)/Rp \tag{4}$$

while n-ideality factor, takes a value between 0 and 1

In the practical PV cell, series resistance accounts for any resistance in the current path through semiconductor material, the metal grid, contacts, and current collecting bus while the effect is less negligible by shunt resistance. These resistive losses are lumped together and its effect becomes very noticeable in a PV module that consists of many series-connected cells, and the value of total resistance is calculated by multiplying it with the number of cells.

3.2 Model of individual systems in Simulink

The entire network is drawn with Simulink as in Fig.3 combining various blocks adding storage devices like batteries DC-DC converter, controlling switches, and loads etc.,

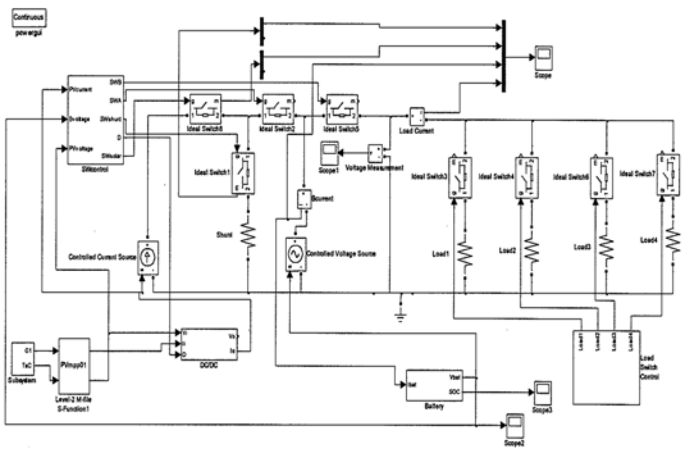

Fig.3. Complete block diagram of the Photovoltaic system

Among these battery with maximum storage capacity such as to contribute supply for four to five days in case of kdown or particularly unfavorable environmental conditions [5], is presented here as simulink model in Fig.4. It is in charging mode if the current is higher and in discharging if it is lower and has the input parameters such as initial state of charge, SOC (%), maximum state of charge, SOCm (Wh), the maximum battery capacity. The battery capacity depends on the charge or discharge rate, number of series cells n, charge/discharge battery efficiency K and battery self-discharge rate D(h^{-1}).In this battery model, the corresponding battery current and battery voltage with the state of charge has been obtained.

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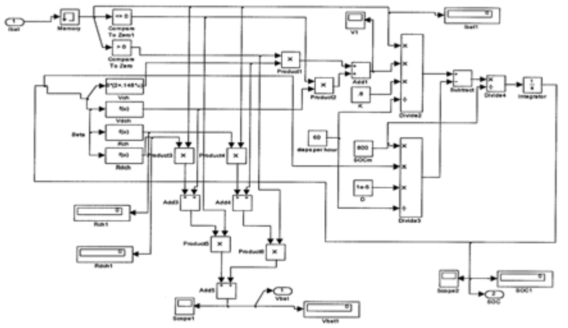

Fig.4. Simulink model of battery

The battery voltage is passed through several 'compare to constant' blocks, and checks that the value obtained with few constants say for example 12.95,12.25,12.2 and 11.6 and gives the value 1 if the condition is true and 0 if it is false. Those values are then entered in the truth table with previous condition of the switch (1 for closed and 0 for open) to set the switch position thus preventing the PV array from draining battery power after the sunset. Finally, the duty cycle of the DC/DC converter is found by passing the ratio of battery voltage to PV module voltage through the 'u/ (u+1)' block.

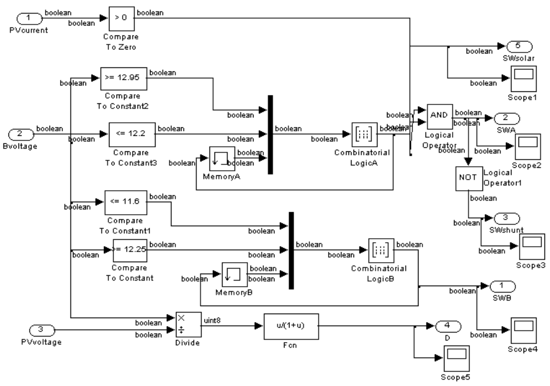

Fig.5.Simulink model of controlling switches

The compare to zero blocks used in controlling switches Fig.5 decides the switch position such that only one value for R1 (Rch or Rdch) and V1 (Vch or Vdch) is passed through depending on whether the battery is charging or discharging. The memory block receives an input and then outputs that value the next time step. The equations for the voltage and resistance of the battery during charging and discharging is

Charge Mode

$V1=V_{ch}= [2+0.148*u]*6$ (5.1)

$R1=R_{ch}= (0.758+0.1309/[1.06-u]*6)/800$ (5.2)

Discharge Mode

V1=Vdch= [1.926+0.124*u]*6 (6.1)

R1=Rdch= (0.19+0.1037/[u-0.14]*6)/800 (6.2)

In order to save battery's life, a charger is necessary with controlling switches and Table 2 shows the various conditions of output voltage with 0 or 1 values.

TABLE.2.Switching conditions and values

CONDITION	A'	A
$V \geq 12.95$	0	0
$V \geq 12.95$	1	0
$12.2 < V < 12.95$	0	0
$12.2 < V < 12.95$	1	1
$V \leq 12.2$	0	1
$V \leq 12.2$	1	1

CONDITION	B'	B
$V \leq 11.6$	0	0
$V \leq 11.6$	1	0
$11.6 < V \leq 12.25$	0	0
$11.6 < V < 12.25$	1	1
$V \geq 12.25$	0	1
$V \geq 12.25$	1	1

It is very essential to note down the switching positions of A and B such as to connect battery either to PV module or to the load. Each switch has its own operating conditions to decide which state it should be ON. A charger along with a switch-mode DC/DC converter, the heart of MPPT hardware [6] is used to convert an unregulated DC input into a controlled DC output at a desired voltage level and to regulate the input voltage at PV MPP. When the MPP goes below the maximum charge of the battery under a low-irradiance and high-temperature condition, additional voltage is boosted to slightly increase the overall efficiency.

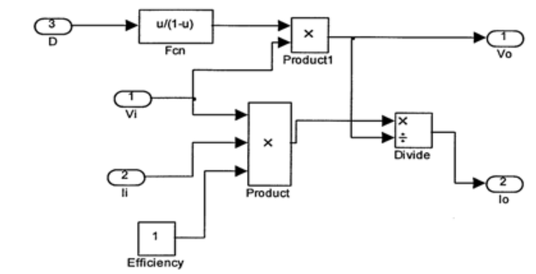

Fig.6.Duty cycle of DC –DC converter

$$\frac{V_o}{V_s} = \frac{D}{1-D} \quad (7)$$

The DC/DC converter block in Fig.6 has its inputs 'D', 'Vi' and 'Ii' and 'Io' as an output is used to control the output current of PV cell. The 'Fcn' block inputs 'D', and outputs, D/(1-D)'.That output is then multiplied by 'Vi' to provide'Vo'.The signal 'D' is the duty cycle of the converter and is found in the 'SWcontrol' block.

IV. OPTIMUM POWER IN PV MODULES

A controller that tracks the locus of the maximum power in PV array is known as the MPPT. A single PV cell produces an output voltage less than 1 V, about 0.6V for crystalline silicon (Si) cells, thus a number of PV cells are connected in series to get a desired output voltage. BP SX 150S PV module is chosen for investigating the behavior of photovoltaic system by simulation in MATLAB/Simulink.

4.1 MPPT Algorithm

The maximum power transfer occurs only when the input impedance of converter matches with optimal impedance of PV module. The location of the maximum power point in the I–V plane is not known beforehand and changes according to the variations in irradiance and temperature of the sun. The tracking algorithms searches the point where maximum power could be got and in the most commonly used perturb & observe algorithm, the operating voltage of PV module is perturbed by a small increment, and the resulting change in power, ΔP, is observed. If the ΔP is positive, then it is understood that it has moved the operating point closer to the MPP and hence further voltage perturbations in the same direction could move the operating point still near MPP.

On converse, if the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP. Though this method reduces the overall efficiency, it is oscillatory in fixing the operating point after each cycle, but used because of its easy handling and low-cost.The fluctuations in fitting the maximum power point can be reduced by the introduction of a bypass loop which skips the perturbation when the ΔP is very small near MPP. A momentary pause in perturbations is observed if the direction of perturbation is reversed several times in a row, indicating that the MPP has been reached. P&O technique applies perturbation to the buck-boost DC-DC controller by increasing or decreasing the pulse width modulator duty cycle, subsequently observes the effect on the PV output power [7]

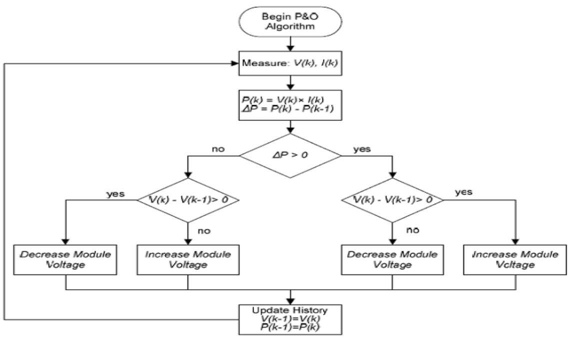

Fig.7.Flowchart depicting P& O algorithm

The flowchart as given in Fig.7 below explains the operation of this algorithm. It starts with measuring the present values of voltage and current of PV module and then calculates the incremental changes, *dI* and *dV* respectively. If the condition satisfies the inequality

$$I + (V*dI/dV) < 0 \qquad (8)$$

it is assumed that the operating point is at the left side of the MPP, and then it must be moved to the right by increasing the module voltage. Similarly, if the condition satisfies the inequality

$$(dI/dV) < (-I/V) \qquad (9)$$

it is assumed that the operating point is at the right side of the MPP, and hence must be moved to the left by decreasing the module voltage. Lastly when the operating point reaches MPP, the condition satisfies the equation

$$(dI/dV) = (-I/V) \qquad (10)$$

and the algorithm ignores the voltage adjustment. At the end of each cycle, it updates the history by storing the voltage and current data that would be used as previous values in the next cycle. While designing the MPPT controller another key point to note whether MPPT is still operating at the same MPP or not even after the atmospheric conditions frequently varies. If the condition dV = 0, and the irradiation not changed and also at dI = 0, it takes no action. If the irradiation has increased, condition dI > 0, it raises the MPP voltage and hence the algorithm will increase the operating voltage to track the MPP. Similarly, if the irradiation has decreased, condition: $dI < 0$, it lowers the MPP voltage and ultimately would decrease the operating voltage.

The Fig.8 shows the block diagram for the implementation of MPPT algorithm by drawing subsystems in simulink holding two inputs irradiance G and Temperature T to activate the block called Level-2 M-file S-Function. The corresponding M-file calls back the block for further operation.

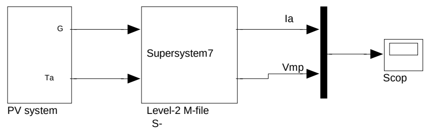

Fig.8. in Simulink model for MPPT

An example series of input irradiance with corresponding values of temperature for particular months say March and May has been taken for simulation study. A sequence of 47 such values for a whole day (24th March and 20th May) starting from 1P.M up to midnight 12'o clock in ½ an hour gap is taken and interpolated using the specified lookup table (i.e) The irradiance data in the lookup table blocks GMarch24 and GMay20 and the temperature data within TMarch20 and TMay20 are taken for simulation purpose.

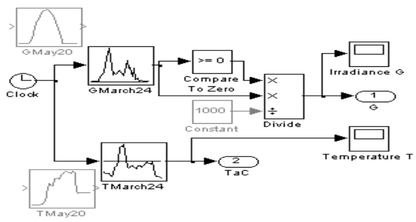

Fig.9. Lookup table with irradiance and temperature

The lookup table in Fig.9 accepts an input from the digital clock, which counts sample periods for one simulation time and provides an appropriate output with respect to the input value. The compare to zero block outputs either 0 or 1 depending on whether the condition within the block is true or false. When that value is multiplied with the irradiance data, it allows only positive irradiance or a zero value to pass through. The irradiance data is divided by 1000 because the input to the MPPT block that corresponds to G1 is measured in kW/m^2.

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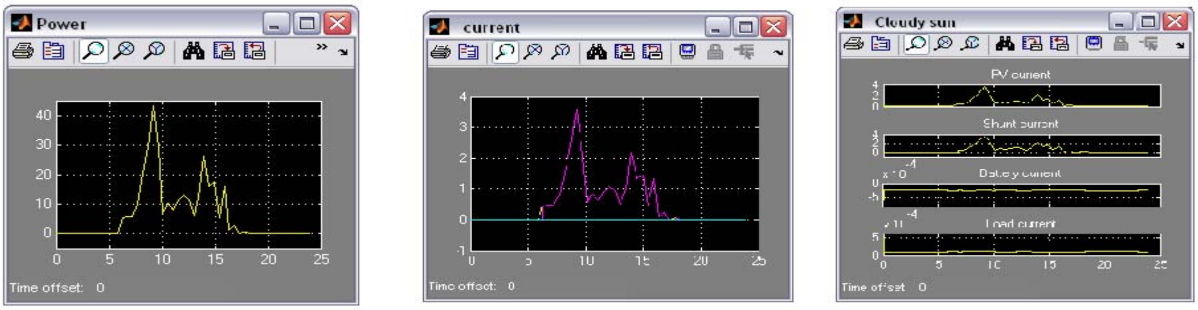

Fig.10.Significant data obtained for a cloudy Sun

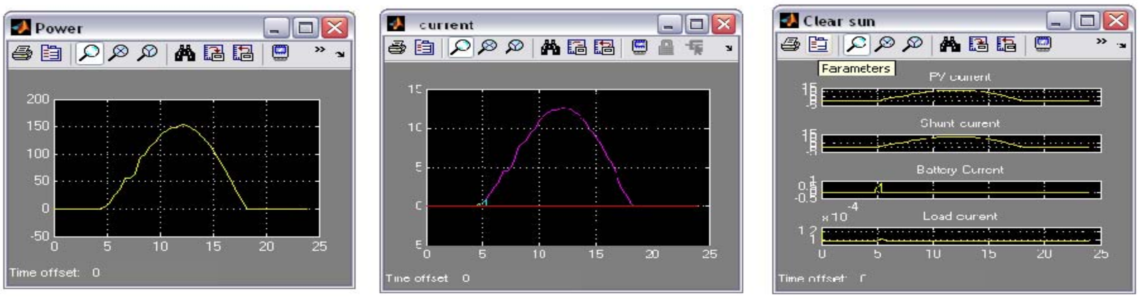

Fig.11.Significant data obtained for a clear sun

4.2 Simulation results

According to varying intensity of sun at least two conditions namely cloudy sun or clear sun, the various outputs has been obtained. The overall power and short circuit current, the maximum value of current of PV cell with the corresponding scopes are shown in Fig.10 and Fig.11.From the simulation results it is well understood that the power obtained in the clear sun is around 154 Watts, reaches almost the power rating of particular PV cell, and thus guarantees the PV model used here provides good matching with the real PV Module. Using actual irradiance data in the two different weather conditions, even a small improvement of efficiency could bring large savings if the proposed system is large.

V.CONCLUSION

Based on the outputs obtained in simulation, it can be concluded that maximum power using MPPT is done by tracking MPP faster even in sudden changes of solar irradiance. MPPT tracker has the capability to reduce the perturbed voltage as soon as the maximum power has been recognized. This action preserves more stable output power and hence more savings in energy, challenging for a better future, economically cheaper and environmentally clear. The idiom ‘harness the nature for a green future’ becomes true. ..

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