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Performance Evaluation & Simulation of Solar Power System

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Abstract: Major challenges faced in implementing solar photovoltaic electric power generation are high initial cost, low conversion efficiency of solar modules & unpredictability of solar insolation fluctuations. Before erecting a PV plant of any capacity in any location, it is best to evaluate the performance of the plant for over a period of time well before the plant is actually installed. This can be accomplished with help of computer simulation. In this work, the performance of a 1.155kW solar pv roof top plant has been evaluated by creating a simulation model using MATLAB-SIMULINK. Simulation model is evaluated for different days' insolation values without MPPT & with buck-boost converter & cuk converter, with distributed MPPT. Shadow analysis has been performed on the same module & its performance for different shading conditions. Simulation outputs for different days' data were compared with the practical outputs of the plant & were found to match accurately.

Keywords: Solar Photovoltaics, Photovoltaic (PV), Solar Insolation, Maximum Power Point Tracking (MPPT), Voltage Ripple

I. INTRODUCTION

The demand for electrical energy is increasing year by year & conversely, our non-renewable energy sources (coal & oil) are depleting at a much faster rate. In addition to these two major problems, the amount of environmental pollution caused while generating power using these conventional resources has reached the critical stage & its effects on various life forms including us have been increasingly noticed all over the globe.

Because of all these reasons, interest & research in utilisation of renewable energy sources has increased at a large scale globally since the past decade. At the present situation, among all the known & existing renewable energy sources, solar & wind energies are the most promising & reliable energy for large scale electric power generation. Though using wind energy for electric power generation is efficient, harvesting solar energy for electricity generation has been proved to rule out wind energy based on many number of factors.

Because of all the above facts, India must concentrate on renewable sources of energy to cope up with the increasing power demands & environmental hazards. Among the various renewable energy resources, India possesses a very large solar energy potential. There are about 300 clear sunny days in a year in most parts of country. The solar radiation received over the Indian land area is estimated as five thousand trillion kWh/year. [1] Long-term research studies on PV solar energy applications in India started in July 1998, with the testing of a

1.2 KWp standalone PV system with battery storage, used for lighting purposes. [2]

PV arrays are used in many applications such as battery chargers, solar powered water pumping systems, grid connected PV systems, solar hybrid vehicles, & satellite power systems. In all solar power systems, efficient simulations including PV panel are required before any experimental verification. [3]

A major challenge in using a PV source is to tackle its nonlinear output characteristics. It is very important to understand & predict the PV characteristics in order to use a PV installation effectively. [4] The electronics-based modeling of a PV solar cell/module can be realized in electric/electronic circuits-based simulation softwares. The electronic components-based models of solar cells/modules are easy to interface with the power stage. [5]

To achieve high step-up & high efficiency, DC/DC converters are the major consideration in the renewable power applications due to the low voltage of PV modules. The purpose of dc-dc converter is to insure the impedance adaptation between the PV source generation & the load.

There are several different types of dc-dc converters, buck, boost, buck-boost & Cuk topologies. Higher order dc-dc converters, such as the cuk converter, have a significant advantage over other inverting topologies since they enable low voltage ripple on both the input & the output sides of the converter. [6]

II. DESIGNING SOLAR PV ARRAY IN MATLAB/SIMULINK

A. *Solar PV model without MPPT*

The module used in the roof top plant array is model BP3165, made up of 10 strings, with 12 PV cells in series in each string making a total of 72 cells. The typical electrical characteristics of the module are listed in table 1.

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TABLE 1
MODULE RATINGS

Electrical Parameter	Value
Rated Power (Pmax)	165W
Warranted minimum Power	160W
Voltage at Pmax (Vmp)	35.2V
Current at Pmax (Imp)	4.7A
Open circuit voltage (Voc)	44.2V
Short circuit current (Isc)	5.1A

To make our simulation model reflect these characteristics, we parameterize the solar cell by short circuit current & open circuit voltage, under 5 parameter consideration as listed in table 2.

TABLE 2
CELL RATINGS

Electrical Parameter	Value
Short-circuit current, I_{sc}	5.1 A
Open-circuit voltage, V_{oc}	0.62 V
Irradiance used for measurements, Ir0	1000 W/m^2
Quality factor, N	1.5
Series resistance, R_s	0.002 Ω

12 cells parameterized as above are connected in series to form a string, which is then clubbed into a single block. Six such string blocks are connected in series to form the solar PV module. And the completed model with a load resistance of 8.6666 Ω (the ratio of V_{oc} & I_{sc} is chosen) is shown in Fig.1.

B. Evaluation of Solar PV model without MPPT

The data of solar insolation in W/m^2, DC current output, DC voltage output, & output power of the roof top plant were taken for thirty days, from 8:00 am to 5:00 pm, at an interval of 15 minutes between each consecutive readings. It is to be noted that in this work's simulation, only the insolation

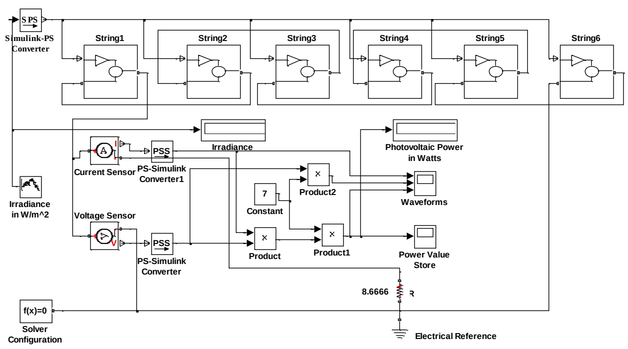

Fig. 1 1.155 kW Solar PV system model without MPPT

Parameter is considered to be the varying factor with temperature being fixed at a constant temperature. All further evaluations were done with the presumption of clear sky, with no dust & no shadow over the array.

The graph in the Fig. 2 compares the practical output power with the simulated output power & the variation of two with the variation in insolation level over the time of the day.

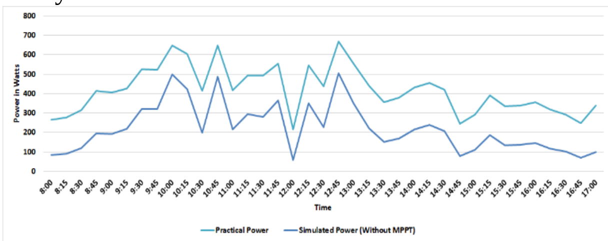

Fig. 2 Comparison of practical & simulation output power

There is a huge difference in the practical & simulated output power values.To rectify the mismatch & make our model more accurate, we add MPPT technique to our model.

III.DESIGNING SOLAR PV ARRAY WITH MPPT

A. Solar PV model with Buck-Boost converter

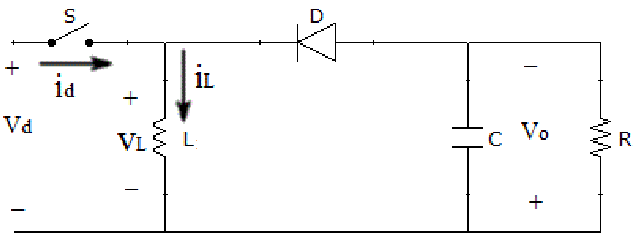

Fig. 3 Buck-Boost converter

Fig. 3 shows the circuit diagram of a simplest buck-boost converter. A buck-boost converter is obtained by the cascade connection of the two basic converters. In steady-state, the output to input voltage conversion ratio is the product of the conversion ratios of the two converters in cascade (assuming that switches in both converters have the same duty ratio):

$$\frac{Vo}{Vd} = \frac{D}{1-D} \qquad \text{..........} \quad (1)$$

This allows the output voltage to be higher or lower than the input voltage, based on the duty ratio D.

Operation: When the switch is closed, the input provides energy to the inductor & the diode is reverse biased. When the switch is open, the energy stored in the inductor is transferred to the output. No energy is supplied by the input during this interval. The output capacitor is chosen to be large enough to achieve constant output voltage.

B. Design of Buck-Boost converter

The design of the Buck-boost converter is done with the presumptions of necessary parameters of the power stage, as follows,

Minimum input voltage, V_{inmin} = 30.2 V
Maximum input voltage, V_{inmax} = 38.2 V
Desired output voltage, V_{out} = 35.2 V
Desired output current, I_{out} = 4.7 A

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Calculation of Duty ratio: The minimum duty cycle for buck mode & maximum duty cycle for boost mode have to be calculated first because, at these duty cycles the converter will be operating at the extremes of its operating range. The duty cycle is always positive & less than 1.

Let % η = 95%.

$$D_{buck} = \frac{Vout\ X\ \%\eta}{Vinmax} = 0.88 \qquad \text{.......... (2)}$$

$$D_{boost} = 1 - \frac{Vinmin\ \ X\ \%\eta}{Vout} = 0.19 \qquad \text{.......... (3)}$$

Where

D_{buck} = minimum duty cycle for buck mode.

D_{boost} = maximum duty cycle for boost mode.

Calculation of Inductor rating:

For Buck-boost converter an inductor that satisfies buck & boost mode conditions must be chosen. The higher the inductor value, the higher will be the maximum output current because of the reduced ripple current. Equations 4 & 5 are solved & the largest result value among the two should be chosen.

Buck mode:

$$L > \frac{Vout\ \ X\ (Vinmax\ -Vout\ )}{Kind\ \ X\ FswX\ \ Vinmax\ \ X\ Iout} = 39.21\ \mu H \qquad \text{.......... (4)}$$

Where F_{sw} = the switching frequency of the converter.
L = Inductor value.
K_{ind} is the estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current. A good estimation for the inductor ripple current is 20% to 40% of the output current. i.e. $0.2 < K_{ind} < 0.4$.
Let, $K_{ind} = 0.3$ & $F_{sw} = 50000$ Hz.

Boost mode:

$$L > \frac{(Vinmin\ \ )\string^2\ X\ (Vout\ -Vinmin\ \ )}{Kind\ \ X\ FswX\ \ Iout\ \ X\ (Vout\ )\string^2} = 52.20\mu H \qquad \text{.......... (5)}$$

Hence, L = 53 μH

Calculation of Maximum switch current:

The maximum switch currents for buck & boost mode are calculated & the greater of the two values is considered.

Buck mode:

$$Iswmax = \frac{\Delta\ Imax}{2} + Iout \qquad \text{.......... (6)}$$

Where, Iswmax = maximum switch current.
Δ Imax = maximum ripple current through the inductor.

$$\Delta\ Imax = \frac{(Vinmax\ \ -Vout\ )\ X\ Dbuck}{Fsw\ \ X\ L} = \cong 1.0\ A \qquad \text{.......... (7)}$$

$$Iswmax = \frac{1}{2} + 4.7 = 5.2\ A$$

Boost mode:

$$Iswmax = \frac{\Delta\ Imax}{2} + \frac{Iout}{1-Dboost} \qquad \text{.......... (8)}$$

$$\Delta\ Imax = \frac{VinminX\ \ Dboost}{Fsw\ \ X\ L} \qquad \text{.......... (9)}$$

$$\Delta\ Imax = \frac{30.2\ X\ 0.19}{50K\ X\ 53u} = 2.17\ A$$

$$Iswmax = \frac{2.17}{2} + \frac{4.7}{1-0.19} = 6.887\ A$$

Calculation of Capacitor rating:

For Buck-boost converter a capacitor that satisfies buck & boost mode conditions must be chosen. Equations 10 & 12 are solved to calculate the minimum output capacitance for both buck & boost modes of operation. The selected capacitor must be larger than the minimum required output capacitance for both buck & boost modes of operation.

Buck mode:

$$Coutmin = \frac{Kind\ \ X\ Iout}{8\ X\ Fsw\ \ X\ Voutripple} \qquad \text{.......... (10)}$$

Where,

Coutmin = minimum output capacitance required.

Fsw = switching frequency of the converter.

Voutripple = desired output voltage ripple.

Iout = desired maximum output current.

Kind = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

The Equivalent series resistance (ESR) of the output capacitor adds ripple, which can be calculated using equation 22.

$$\Delta Voutesr = ESR\ X\ Kind\ X\ Iout \qquad \text{.......... (11)}$$

Where,

ΔVoutesr = output voltage ripple due to capacitor ESR.

ESR = equivalent series resistance of the used output capacitor.

$$\Delta Voutesr = 1\ X\ 0.3\ X\ 4.7 = 1.41$$

$$Coutmin = \frac{0.3\ X\ 4.7}{8\ X\ 50K\ X\ 1.41} = 2.5\ \mu F$$

Boost mode:

$$Coutmin = \frac{Iout\ \ X\ Dboost}{Fsw\ \ X\ \Delta Vout} \qquad \text{.......... (12)}$$

$$\Delta Voutesr = ESR\ X\ \left(\frac{Iout}{1-Dboost} + \frac{Kind\ \ X\ Iout\ \ X\ Vout}{2\ X\ Vin}\right) \qquad \text{........ (13)}$$

$$= 6.6242$$

$$Coutmin = \frac{4.7\ X\ 0.19}{50K\ X\ 6.6242} = 2.7\ \mu F$$

Hence, C = 3 μF

C. Maximum Power Point Tracking using Perturb & Observe Algorithm

Maximum power point tracking is the technique of matching the source's impedance (i.e. voltage to current ratio) with the load's impedance to maximize the efficiency of the PV system to the best possible extent. Though there are numerous algorithms that are used for this purpose, we concentrate only on perturb and observe algorithm due to its simplicity and accurate functioning. The flowchart depicting the embedded matlab function code used for MPPT is shown in Fig. 4. The final circuit model including the MPPT control and the buck-boost

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converter is shown in Fig. 5. The o/p capacitor of the buck-boost converter is chosen with an ESR of 1Ω as specified in the design.

D. Evaluation of Solar PV Model with Buck-Boost converter

Using the same previous insolation data, solar PV model with buck-boost converter was evaluated. The graph in Fig. 6 shows that the results of the solar PV model with buck-boost converter are in better match with the practical power values. Although, the output voltage waveform was of much oscillating nature and in turn the resultant power waveform was also of similar oscillation which makes it to be of poor quality when compared to a steady straight line waveform of a DC.

In order to minimize all these issues and make the output of the solar PV array to be of more optimum quality, we substitute the buck-boost converter with a cuk converter and see if it serves the intention.

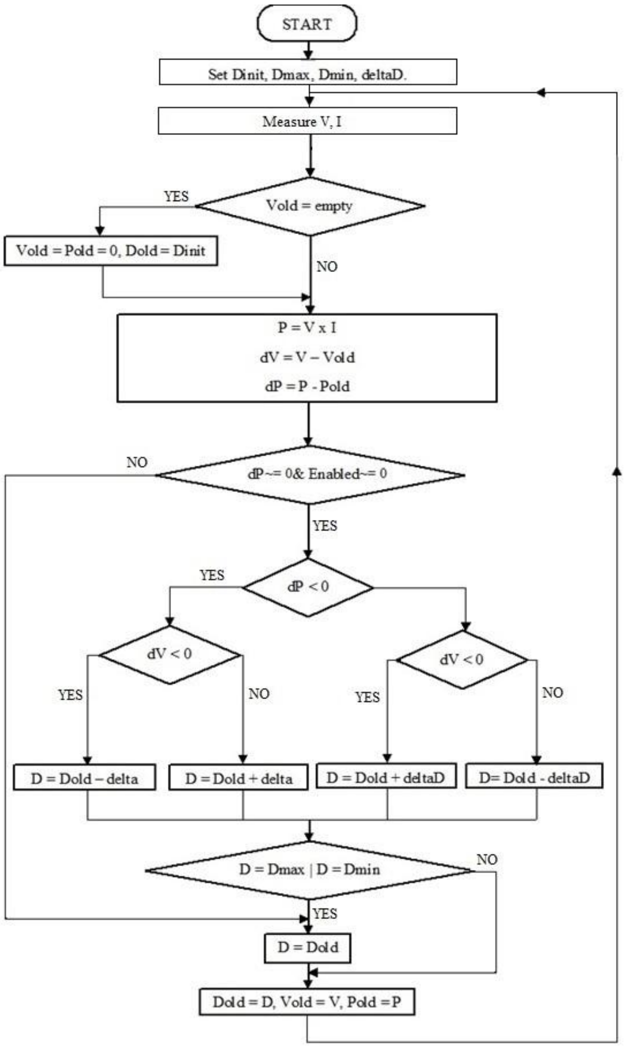

Fig. 4 Flow chart of P & O algorithm

In the flow chart Dinit is initial duty ratio. Dmax is maximum duty ratio. Dmin is minimum duty ratio. DeltaD is perturbation step size. Vold, Pold & Dold are previous values of voltage, power & duty ratio. V, P & I are present values of voltage, power & current. dV,dP are difference in voltage & Power.

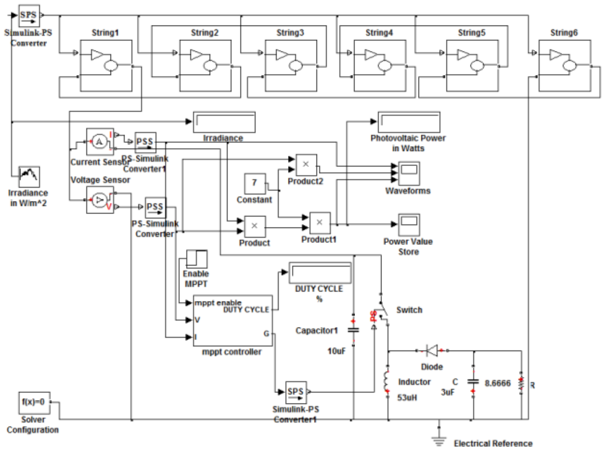

Fig. 5 Solar PV model with MPPT & Buck-boost converter

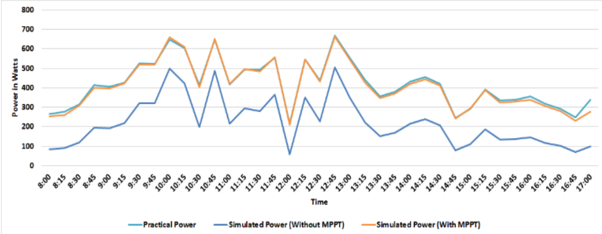

Fig. 6 Comparison of practical & simulation output (with & without Buck-Boost converter)

E. Solar PV model with Cuk converter

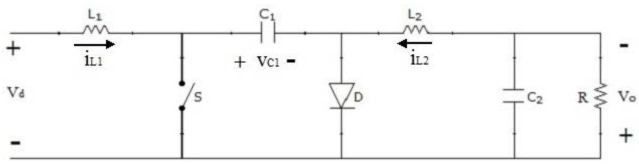

Fig. 7 Cuk converter

Fig. 7 shows the circuit diagram of a simplest cuk converter. Like the buck-boost converter, cuk converter also provides a negative polarity regulated output voltage with respect to the common terminal of the input voltage. The capacitor C_1 acts as the primary means of storing and transferring energy from the input to the output. In steady-state, the output to input voltage conversion ratio of the converter is same as that for the buck-boost converter.

Operation: When the switch is off, the inductor currents i_{L1} and i_{L2} flow through the diode. Capacitor C_1 is charged through the diode by energy from both the input and L_1. Current i_{L1} decreases, because V_{C1} is larger than V_d. Energy stored in L_2 feeds the output. Therefor i_{L2} also decreases.

When the switch is on, V_{C1} reverse biases the diode. The inductor currents i_{L1} and i_{L2} flow through the switch. Since $V_{C1} > V_o$, C_1 discharges through the switch, transferring energy to the output and L_2. Therefore i_{L2} increases. The input feeds energy to L_1 causing i_{L1} to increase.

In a buck converter, energy goes to the load when switch is closed. In a boost converter, energy goes to the load when switch is open. The advantage of cuk converter is that the energy is transferred to the load both when the switch is open as well as when the switch is closed. In general, buck-boost converter the output is much of pulsed output current which increases the output voltage ripple. Whereas in the case of cuk converter the output current is

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more of continuous current apparently reducing the output voltage ripple of the converter, which is a major advantage. The type of converter used alters the output of the solar PV array and we make use of this point to optimize our solar output.

F. Design of Cuk converter

The design of the Cuk converter is done with the presumptions of necessary parameters as follows,
Minimum insolation = 100 W
Maximum insolation = 1010 W
Minimum input voltage, V_{inmin} = 30.2 V
Maximum input voltage, V_{inmax} = 38.2 V
Desired output voltage, V_{out} = 35.2 V
Switching frequency, f = 50 kHz
Duty ratio = D
Here, both the minimum and maximum input voltages are considered as the two different cases and for each case the values for the different components for the converter are found out and the greater value among the two are chosen for the component.
Case 1: V_{in} = 30.2 V, V_{out} = 35.2 V.

$$\text{w.k.t,}\quad \frac{Vo}{Vd} = \frac{D}{1-D} = 0.59$$

$$L1 = \frac{((1-D)^2)\,X\,R}{2\,X\,D\,X\,f} = 28.5\,\mu H \qquad \text{.......... (14)}$$

$$L2 = \frac{(1-D)\,X\,R}{2\,X\,f} = 36\,\mu H \qquad \text{.......... (15)}$$

$$C_1 = \frac{D}{2\,X\,f\,X\,R} = 681nF \qquad \text{.......... (16)}$$

$$C_2 = \frac{1}{8\,X\,f\,X\,R} = 289nF \qquad \text{.......... (17)}$$

Case 2: V_{in} = 38.2 V, V_{out} = 35.2 V

D = 0.48

Using the equations from 14 to 17, following values were obtained.

L_1 = 49 µH, L_2 = 45 µH, C_1 = 554 nF

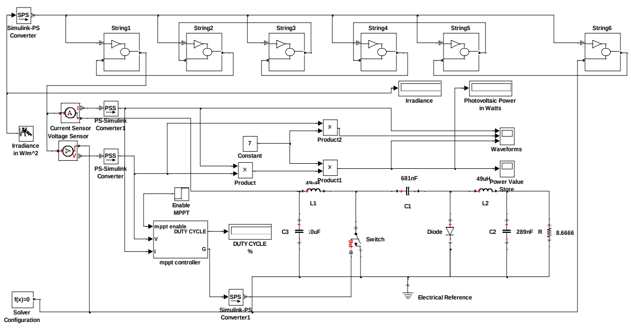

Fig. 8 Solar PV model with MPPT & Cuk converter

G. Evaluation of Solar PV model with Cuk converter

The solar PV array with cuk converter was simulated using the same insolation data and the Fig. 9 shows that the obtained results are much better than the previous results. The simulation output with cuk converter was very much close to the practical output.

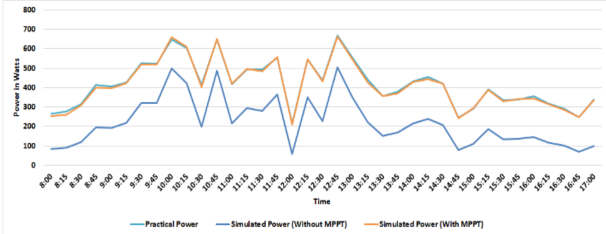

Fig. 9 Comparison of practical & simulation output (with & without cuk converter)

H. Shadow Analysis

Shadow is considered to be an important criteria in PV systems because, a partial shadow can drastically put down the output of the system. Shading a single module in an array will make the entire array to fall down to the level of shaded module and the net impact on the performance is too high. Now, we will take a PV module and simulate it with different percentages of shadow and try to evaluate the module's performance, which can also reflect the effect of shadow on an array level too. In the solar PV module BP 3165, there are 3 strings of cells connected in series, with 24 cells in each string. The module consists of 3 bypass diodes, each of it being shared between 24 cells, as shown in Fig. 10

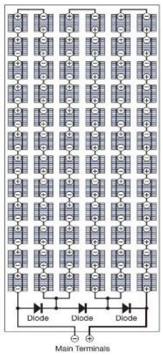

Fig. 10 Bypass diodes in 72 cells module

Case 1: When all the cells are equally insolated, all the bypass diodes are reverse biased and there won't be any problem and the operation of the module is normal. Consider that, randomly, a single cell is shaded and all other cells are getting equal insolation. This drops the current generation of the shaded cell, and pulls cells connected in series to it, in its own string, to pass the same lower current resulting in higher voltage build across the unshaded cells of the string, finally resulting in forward biasing of the bypass diode connected to the string. Irrespective of the number of cells shaded in a string, (i.e. whether one cell of the string or two cells of the string or all cells of the string) the bypass diode makes the current to go around the string without entering into it. So, even if a single cell is shaded, its entire string is cut off and won't participate in generation until the shade disappears.
In the simulation model, the bypass diodes have a forward knee voltage of 0.5 V and on state resistance of 0.2 Ω. At no shadow operation, the voltage across the bypass diode varied from a minimum of -11.85 V to a maximum of -11 V, with zero current flowing through them (except the reverse leakage current, which is negligible). A single cell in the last string was shaded by giving 0 input for insolation, and the model was simulated with insolation

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data of 1st Feb 2013. The voltage across the bypass diode connected to the shaded string varied from 0.7 V to 1.03 V, with the module current flowing through it. The graph in Fig. 11 shows the results.

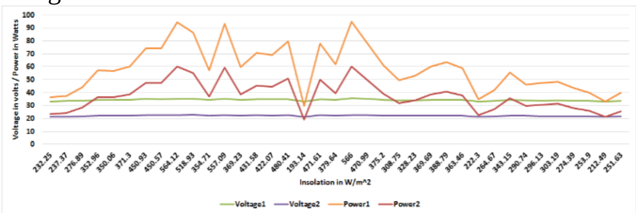
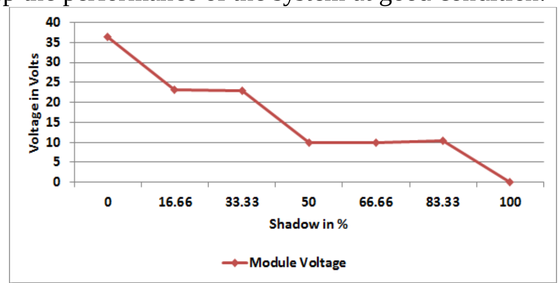


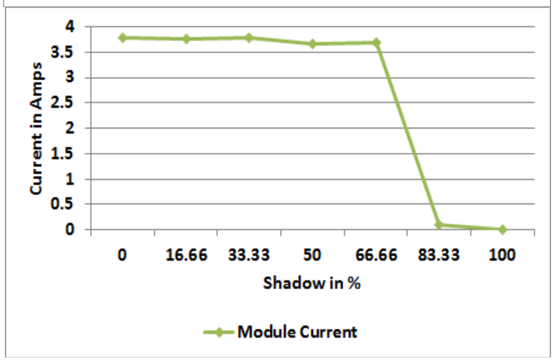
Fig. 11 Comparison of module output voltage and power without shadow (Voltage1, Power1) and with a single cell shaded (Voltage2, Power2)

Case 2: The module was shaded longitudinally in terms of percentage, with a step percentage of 16.66%, which would cover a 12 cell string with each step, and simulated with an insolation of 800 W/m^2. The fall of the module voltage, current and power with the increasing shadow resulted in following graphs in Fig. 12. The graphs show that, until the very last string is remaining without shadow, we have output. **Case 3:** When, a minimum of one cell in all strings of the module is shaded, the output is zero. This is most likely to happen when there is a latitudinal shadow over the module, covering a minimum of one cell in each string. Hence, latitudinal shadow is more affective on the module's performance and should be avoided to the maximum possible extent.

If we consider that in a large array, one or two modules are shaded as said above, the net current will flow through the bypass diodes, keeping the loss of power minimum and avoiding the damage of the system.

Keeping all these facts in view, a solar PV array should be mounted in such a position and angle, such that the surrounding elements like buildings or poles etc. should have most minimal chances of creating shadows on the modules. A mounting angle above 12° helps the modules to self-clean whenever there is rainfall. In heavily dusted locations, modules should be cleaned once in a while to keep the performance of the system at good condition.





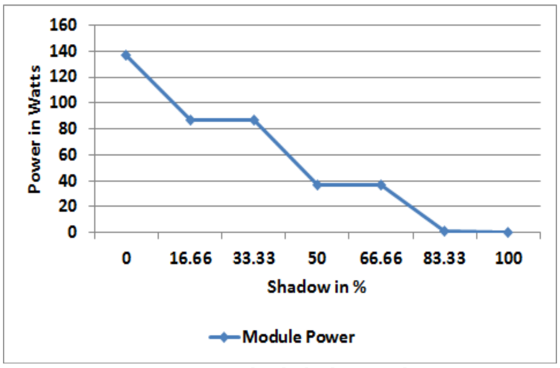


Fig. 12 Longitudinal Shadow Analysis

III. SIMULATION RESULTS

The output of the solar PV system here is not a perfect dc. It's a pulsating (oscillating) dc output with a frequency of 50 kHz (as per the switching frequency of the converter's switch). The waveforms of the output current, voltage and power of the solar PV array with Buck-Boost converter are as shown in Fig. 13.

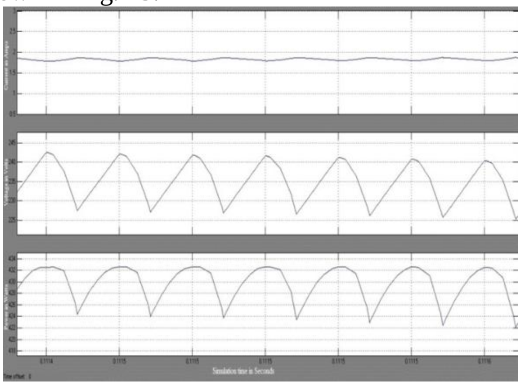


Fig. 13 Output Current, Voltage & Power Waveforms of Solar PV array with Buck-Boost converter

From a random duration of simulation, from 0.1114s to 0.1116, the waveforms are zoomed into. The fig. 5.3 shows that the current level is almost constant at 1.8 A with no much effective variation. Whereas, the voltage level is much oscillating with a higher difference from a minima of 227 V to maxima of 242 V. This means that the variation in voltage level is high and thus the resulting power waveform is also of similar oscillation which makes it to be of poor quality when compared to a steady straight line waveform of a DC. In order to minimize all these issues and make the output of the solar PV array to be of more optimum quality, we substituted the buck-boost converter with a cuk converter and the results were way better as shown in Fig. 14.

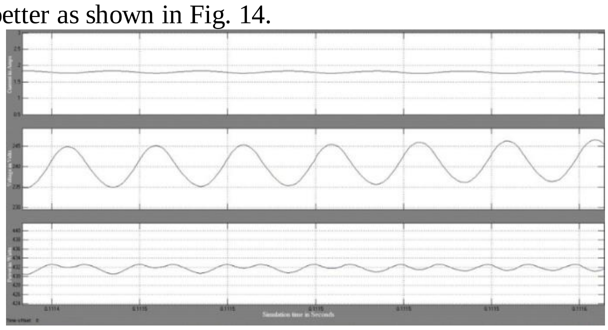


Fig. 14 Output Current, Voltage & Power Waveforms of Solar PV array with Cuk converter

As shown in Fig. 14, the output voltage waveform has much less ripple when compared to that of buck-boost converter and the shape of the waveform is much smoother. This is because, a cuk converter is actually the cascade combination of a boost and a buck converter and has the advantages of continuous input current and continuous output current, unlike the case of buck-boost converter which has pulsed input and pulsed output current. The output power waveform clearly shows that it is of much higher quality as a DC with a minima of 431 W and maxima of nearly 433 W. Hence, the oscillation in the power waveform is very minimal and thus we have obtained a best converter model for the solar PV array.
The following figures show the difference in current, voltage and power waveforms of the array with buck-boost and cuk converters for one day's insolation data.

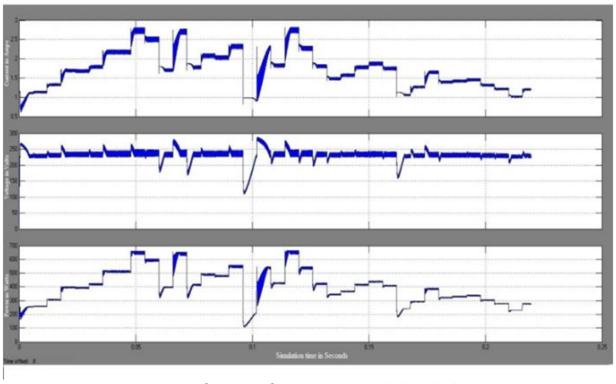


Fig. 15 Output waveforms of PV array with buck-boost converter

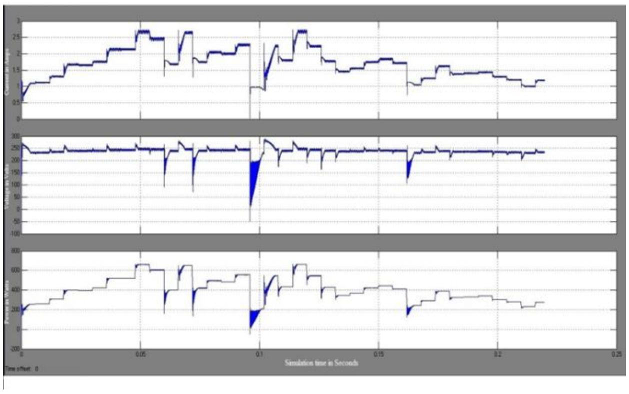


Fig. 16 Output Waveforms of PV array with Cuk converter

Since model with cuk converter was found to be better, this model was evaluated with insolation data of 30 days to check the accuracy of the model and the obtained results were accurately in match with the practical results.

IV. CONCLUSION

The results of the simulation are much accurate and the designed model can be used to forecast and predict the output of the array with the availability of insolation data. By comparing the simulation output with the practical output, it will be much easier to detect any under performance and the error/problem can be easily rectified. The main advantage of this model is that, it can be used to evaluate the performance over a period of day, or a week or even a month if we know the insolation data for that period. It is very convenient to estimate the generation of the array for longer terms of time. The model can also be used for the design and estimation of new solar PV arrays to be built and by changing the cell parameters, any company's particular model of module can be realized and the performance can be evaluated. By performing the shadow analysis, the performance of the module under shaded conditions can be evaluated and if there are chances of occurrence of shadow over the array in the given location, a different module with higher number of bypass diodes or a module with higher capacity can be chosen. Both the solar PV model and the converter models presented are proven to give most accurate results.

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