Performance Analysis and Comparison of a Solar Tree with Stand-Alone System

Saurabh Chaudhary, Vinaya Rana, and Nidhi Singh

Abstract In this paper, the design and performance analysis of a 50 W solar tree with a cost-effective installation is analyzed at Basti, Uttar Pradesh, India. The energy demand is increasing day by day and the fossil fuels are decreasing. So, an alternative option is required to fulfill the energy demand. The renewable energy-based source is best option to fulfill the energy scarcity. Solar tree is designed in a way that there is no effect of shading on the panel, also panels are rearranged according to azimuth angle. The technical and economical assessment of PV solar tree results a future adoptive technology for highly populated area. Solar PV systems are highly cost-effective and helps in the reduction of greenhouse gases. Five PV panels of 10 W are used to form the solar tree and compered with a single 50 W stand-alone PV panel. The maximum power and efficiency of the solar tree is more as compared to stand-alone PV panel with all same conditions, i.e., irradiation level temperature.

Keywords Solar PV system · Solar tree · Renewable energy · Stand-alone system

1 Introduction

Energy consumption is increasing day by day. The rising demand puts pressure on natural resources that leading to global warming. The reduction in electricity generation has forced the adoption of alternative and sustainable electricity generation all over the world. Renewable energy (RE) technologies are one of the best and sustainable sources of energy. The total renewable energy generation capacity in the country is estimated at 105,854 MW as of February 2022, which includes solar power, wind power, small hydro, biomass power and power from oil mills and waste. Energy consumption is currently highest in urban areas [1].

Nowadays, the RE trend is increasing with the initiatives and policies offered by the Indian government. The solar PV system can be designed as either a stand-alone grid-connected system or both [3–6]. In stand-alone PV system, a battery storage

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system is required to fulfill the energy demand day and night. The average lifespan of solar PV panel is around 20–25 years and the payback period are estimated to be 9 years. In the grid-connected solar PV system, the system directly connected to the grid so that the extra energy can be transferred into gird through net metering [2–5]. India a highly populated country that ranks 2nd in world population. Since population density is high in metro cites, which consist of high-rise buildings, land area required for a traditional stand-alone system is scarce, hence, installation of solar trees is the appropriate option as it requires significantly lesser area than the stand-alone system.

2 Design of Solar Tree

In this paper, analysis of 50 W solar tree with stand-alone system has been done. A solar tree is constructed using following components:

(a) Solar panel
(b) Long pole
(c) LEDs (for load)
(d) Small pole (for branches of tree).

A five feet long solar tree is design and installed on the rooftop with 5 branches. Each branch consists of 10 W panel and all panels are connected in parallel to fulfill the load demand. The performance of the solar tree is analyzed on the basis irradiation level change in real time.

2.1 Solar Tree Stem and Branches

The support structure for the solar panel in the solar PV tree can be similar to the stem design of a natural tree. The leaves of solar tree are arranged in a “phyllotaxy” pattern. The solar tree stem is fixed at one place then branches of the tree are welded in it properly. After that the solar panel is installed on each branch of the tree at the same azimuth angle 23° so that the maximum sun intensity is achieved on the solar tree [6, 7]. The solar tree consists of 5 branches, four of which are project outwards in 4 directions and one is in the center of the pole. The load is connected with 8 LED bulbs with the rating of 7 W and 12 V DC each. The component required in solar tree is given in Table 1.

Table 1 Components rating for solar tree

S. No.	Component name	Quantity	Rating
1	Solar PV panel	5	10 W, 12 V each
2	LEDs bulb	8	7 W, 12 V each
3	Inferred thermometer	1	−50 to 550 °C
4	Multimeter	2	0–10 A DC, 0–1000 V DC
5	Lux meter	1	0–200,000 lx

Table 2 Rating of solar panel of solar tree and stand-alone system

S. No.	Parameter	Solar tree	Stand-alone
1	Model no.	12 V/10 W	12 V/50 W
2	Power max (P_m)	10 Wp	50 W
3	Open-circuit voltage (V_{oc})	21.65 V	21.56 V
4	Voltage at P_m (V_m)	17.5 V	17.6 V
5	Short-circuit current (I_{sc})	0.61 A	3.11 A
6	Current at P_m (I_m)	0.57 A	2.89 A
7	Fuse rating	2 A	6 A
8	Panel cell area	812.5 cm^2	3898.68 cm^2
9	Quantity of panel	5 panel	1 panel
10	Total cell area	0.406 m^2	0.3898 m^2

2.2 *Stand-Alone System*

A 50 W solar panel is used for this analysis. The azimuth angle is 23°. The solar module is installed on the rooftop adjacent to the solar tree with same irradiation level and same temperature (Table 2).

3 Modeling of Solar PV Panel

The various PV cells connected in series and parallel to produce specified output power in a solar PV panel. The equivalent diagram of a cell is shown in Fig. 1 as:

The output current and voltage of the PV cell are expressed [7, 8] in (1), (2) and (3), respectively.

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

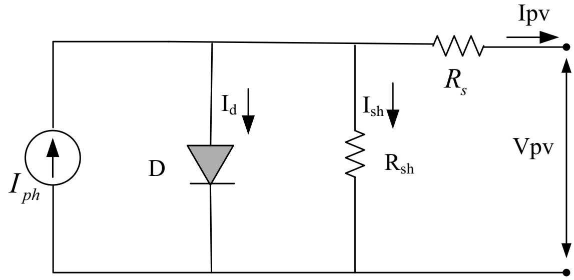

Fig. 1 Equivalent circuit of a solar cell

$$I_{pv} = I_{ph} - I_0\left[\exp\left(\frac{q\left(V_c + R_s I_{pv}\right)}{AkT_c}\right) - 1\right] - \left(\frac{V_{pv} + R_s I_{pv}}{R_{sh}}\right) \tag{2}$$

$$V_{pv} = \frac{AkT_c}{q}\left(\frac{I_{ph} + I_0 - I_{pv}}{I_0}\right) - R_s I_c \tag{3}$$

The short-circuit current and open-circuit voltages of a PV cell are in (4) and (5) as,

$$I_{sc} = I_{ph} - I_0\left[\exp\left(\frac{qR_s I_{sc}}{AkT_c}\right) - 1\right] - \left(\frac{R_s I_{sc}}{R_{sh}}\right) \tag{4}$$

$$V_{oc} = \frac{AkT_c}{q}\ln\left(\frac{I_{ph} + I_0}{R_{sh}}\right) \tag{5}$$

where T_c—temperature (K), q—electron charge (1.602×10^{-19} C), I_d—diode current (A), I_o—reverse saturation current of diode (A), I_{sc}—short-circuit current, I_{ph}—photo current (A), k-Boltzmann constant (1.38×10^{-23} J/K) and A is ideality factor (1.2).

$$\text{Fill factor} = \frac{V_m \times I_m}{V_{oc} \times I_{sc}} \tag{6}$$

$$\text{Input Power } (P_{in}) = \text{Irr.} \times \text{solar cell area} \tag{7}$$

$$\text{Efficiency } \eta\ (\%) = \frac{P_m}{P_{in}} \tag{8}$$

4 Results and Discussion

The power output of the solar tree is fed to the LED load for analyzing the overall performance of the solar tree and compared it with a stand-alone (50 W) solar panel. The complete designed of the proposed solar tree and stand-alone PV panel is shown in Fig. 2. The various parameters (V_{oc}, I_{sc} and P_m) are calculated for analysis and comparison purpose.

In Fig. 3a, the current in the I-V curve increases and reaches a peak at 2.3 A along with increase in voltage then it starts decreasing continuously and reaches down to 0.38 A as voltage is increases. When the current reaches to its maximum value, then it is known as the maximum current (I_m) along the maximum voltage (V_m). In Fig. 3b, the power in P–V curve of the solar tree increases and voltage increases and reaches to maximum power, i.e., 32 W and then decreases as the voltage increases. When the power reaches to its maximum value, then the point is known as maximum power point (P_m).

Fig. 2 Real time diagram of solar tree and a solar stand-alone PV module

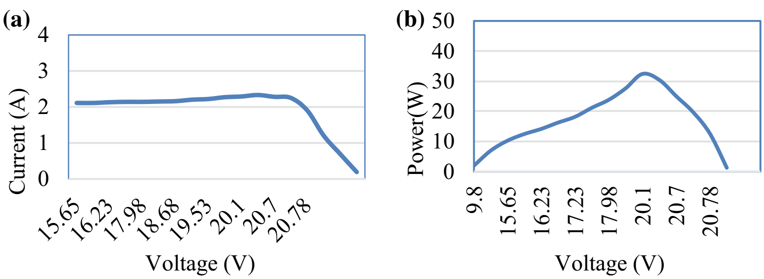

Fig. 3 **a** I-V graph of the solar tree. **b** P–V graph of the solar tree

The LED bulbs are parallel connected to the load, and initially, 2 bulbs are connected and measured the voltage and current of the solar tree. Then increasing the LEDs bulb up to 8 bulbs, and measured the voltage and current of the solar tree. Now, the P_{max} efficiency and fill factor (FF) of the solar tree are calculated with the help of V_{oc}, I_{sc}, V_m and I_m. The proposed system is then compared with a 50W stand-alone PV panel. The FF and η of the solar tree is calculated on every time interval. Initially, the FF and η of the solar tree is 0.67 and 8.10%, respectively. As the irradiation level changes, the output power of the solar tree changes accordingly as shown in Table 3.

The analysis of a stand-alone module has been done from different time scale, i.e., 10:00 A.M. to 5:00 P.M. with one-hour time interval. The FF and η of the panel is calculated on every time interval. Initially, the FF and η of the panel is 0.60 and 7.72%, respectively. As the irradiation level increases or decreases, the output power of the solar stand-alone system increases or decreases, respectively, as given in Table 4.

Figure 4 shows the graph between power and time. It is observed that P_m of solar tree (P_m-ST) is 32 W and P_m of stand-alone solar module (P_m_Sa) is 29.7 W at noon time. Figure 5 shows the graph between efficiency and time. Maximum efficiency of

Table 3 Performance analysis of solar tree (50 W)

Time	Irr. (W/m^2)	Temp (°C)	P (W)	P_m (W)	FF	η (%)
10:00	724	39.50	35.60	23.84	0.67	8.11
11:00	841	40.00	42.36	27.64	0.65	8.10
12:00	993	43.50	47.83	32.42	0.68	8.04
13:00	952	46.00	47.64	30.44	0.63	7.88
14:00	950	41.30	43.47	25.04	0.58	6.49
15:00	651	35.60	29.05	19.76	0.68	7.47
16:00	436	24.90	18.70	12.64	0.68	7.13
17:00	188	19.40	7.9	4.68	0.59	6.13

Table 4 Analysis of stand-alone solar module (50 W)

Time	Irr. (W/m^2)	Temp (°C)	P (W)	P_m (W)	FF	η (%)
10:00	724	38.50	36.23	21.78	0.60	7.72
11:00	841	39.80	41.77	25.97	0.62	7.93
12:00	993	43.90	45.24	29.79	0.66	7.70
13:00	952	46.20	45.16	27.81	0.61	7.50
14:00	950	41.50	34.34	22.25	0.65	6.01
15:00	651	35.90	24.36	14.85	0.61	5.85
16:00	436	25.10	16.26	11.52	0.71	6.77
17:00	188	20.30	6.92	4.34	0.63	5.92

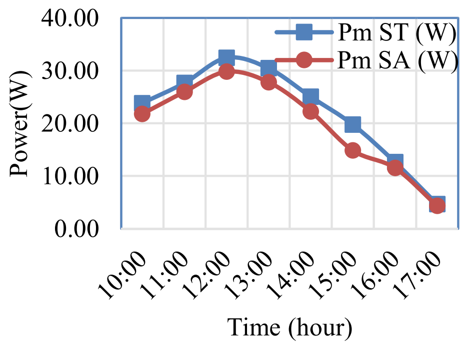

Fig. 4 Output power variation in solar tree and stand-alone solar module

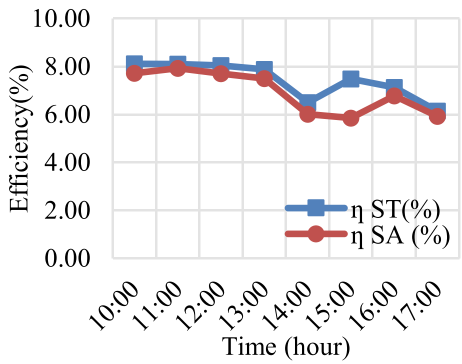

Fig. 5 Efficiency variation in solar tree and stand-alone solar module

solar tree (η_St) is 8% approximately, while efficiency of stand-alone solar module (η_Sa) is approx.7.9%.

From Table 5, it is observed that power shows an increase from 10 A.M. to 12 P.M. and starts decreasing and is significantly lower at 5 P.M. in both stand-alone and solar tree systems, however, overall value of power is higher in solar tree as compared to stand-alone system. Efficiency does not show a constantly decreasing pattern; however, there is an overall decrease from 10 A.M. to 5 P.M.

5 Conclusion

In this paper, a solar tree of 50 W has been designed and compared with a stand-alone solar module of 50 W. The performance parameter is calculated on the basis of temperature and irradiation on different time scale. The V_{oc}, I_{sc} and P_m are 17.98 V, 1.98 A and 23.84 W, when the irradiance is 724 W/m^2 and temperature of panel is 39.5 °C. As temperature and irradiation level increase/decrease, the output power of solar tree increases/decreases, respectively. At the same time, the P_m, V_{oc} and I_{sc} of stand-alone PV module are 17.85 V, 2.03 A and 21.78 W. The output power and

Table 5 Time versus solar tree (P_{max} and η) and stand-alone system (P_{max} and η)

Time	Solar tree			Stand-alone		
	P_m (W)	FF	η (%)	P_m (W)	FF	η (%)
10:00	23.84	0.67	8.11	21.78	0.60	7.72
11:00	27.64	0.65	8.10	25.97	0.62	7.93
12:00	32.42	0.68	8.04	29.79	0.66	7.70
13:00	30.44	0.63	7.88	27.81	0.61	7.50
14:00	25.04	0.58	6.49	22.25	0.65	6.01
15:00	19.76	0.68	7.47	14.85	0.61	5.85
16:00	12.64	0.68	7.13	11.52	0.71	6.77
17:00	4.68	0.59	6.13	4.34	0.63	5.92

efficiency of solar tree are more as compared to stand-alone PV panel, i.e., 23.84 W, 8.1% of solar tree and 21.78 W, 7.72% stand-alone. So, the solar tree power and efficiency is more and the installation area of solar tree is less as compared to stand-alone PV system.

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