Journal of Scientific & Industrial Research
Vol. 79, August 2020, pp. 740-745

Design and Development of a Solar Artifact using Structural Analysis

Atanu Maity, Ashok Kumar Prasad*, Nitish Kumar and Subrata Kumar Mandal
CSIR - Central Mechanical Engineering Research Institute, Durgapur, India

Received 11 May 2018; revised 14 July 2019; accepted 21 May 2020

The Flat or rooftop mountings of PV systems require large area of land for the generation of electricity. As per the present scenario, the availability of suitable land is a major problem in cities as well as in the villages in India. Keeping it in mind, a solar artifact has been designed and developed at our Institute. The necessary structural analysis and mechanical load has been done in reference with sustainable wind load of the structure. By taking Factor of safety as 15, the Von Mises Stress is found to be 307.948 MPa. A typical shadow analysis has also been carried out on the solar panels attached with the solar artifact to determine whether there is any overlap of solar panels and thereby to get maximum solar energy.

Keywords: Phyllotaxy pattern, PV panel, PV system, Shadow analysis

Introduction

The solar artifact or solar PV artifact is a structure of solar panels which looks like a natural tree.[1] In solar artifact, the PV is arranged in a phyllotaxy pattern instead of leaves, so that most of the cells get exposed to sunlight without any obstruction. Along with that the solar tree produces around same amount of power as compared to a conventional flat arrangement by taking only a 1% of land area.[2] Whereas, the panels for flat mounting on homes would not get sufficient sun rays since the angle of sunrays varies throughout the daytime. The solar artifacts are really a means of practical solution for urban street lighting system. There is a rapid increase in the use of PV systems in India due to continuous reduction in prices of solar cells. In this context use of PV technology for the domestic requirement in the form of the solar tree is the good alternative as compared to conventional flat or rooftop mounting.[3] It has been found that the artifact requires a very small area and hence it could be installed near or in front of a house or even on a terrace.[2–4] It has been suggested that by increasing the spread of the PV solar tree, more energy is produced due to the coverage of more angles of the incoming sunlight.[5] They also analyzed the performance of the tree at three different locations around the world by simulating six different semi-dome shape solar PV tree structures based on increasing number of layers and panels.[6] The concept of solar artifact or arrangement of solar PV cell in a phyllotaxy pattern (Fig.1a) has been used by many researchers. Such a combination of the solar PV cell can be done on trees like coconut, palm or other natural trees to reduce the cost of mounting. The efficiency can be further improved by using nanowire.[7,8] Usually, a solar artifact is having a structure similar to a tree as shown in Fig.1b. Here PV panels are mounted on the stem-like structure which is fixed on the main structure in a phyllotaxy pattern.

Problem Description and Working of the Developed Solar Artifact

The problem lies with the fact that the generation of 2 MW power by using PV module system requires approximately 10 acres of land for fixing the panels. The availability of suitable land is a major concern.[9] Based on the information, a solar power artifact has been developed at our institute. The uniqueness of the development lies in the limited use of ground for accommodating the foundation for the pole which serves as the ‘trunk’ of the Solar Power Tree. This means that ground space is freed for other purposes, while solar power absorption takes place at an elevation. This, however, is not the case with ground deployed solar panels, where much larger ground area is required for an equivalent power generation. For example, in case of the 3 KW variant of the Solar Power Tree, which uses fourteen 240 Wp Solar Photovoltaic (SPV) panels, the area needed for accommodating the foundation of the pole is of the order of 4 sq. ft. For a similar generation in a ground

*Author for Correspondence
E-mail: aprasad@cmeri.res.in

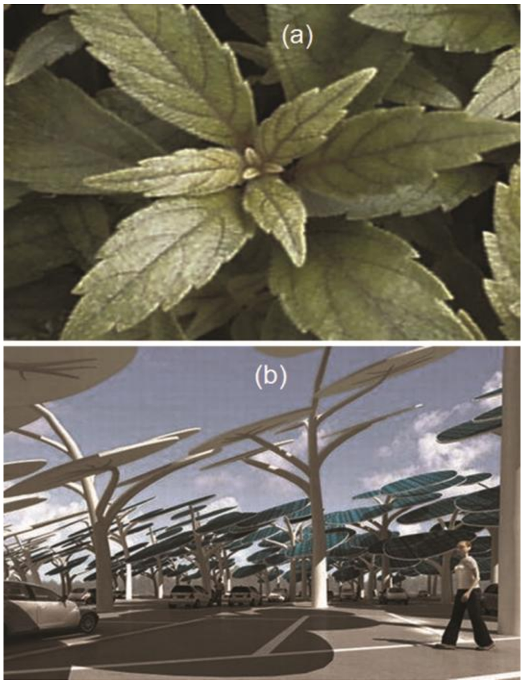

Fig.1 — (a) Phyllotaxy pattern in a plant (b) A typical structure of a solar artifact

deployed solar system, the minimum area that would be required in the simplest series configuration is about 99 sq. ft. Moreover, this area is practically lost for all other purposes, which is not the case with the Solar Power Tree. This developed tree is a tall pole-like structure and it takes only 1% (in our case it is 4%) of land area in comparison to general PV housing for generation of the same amount of power.[10,11] With due adjustment of load over the main pole structure, the solar panels can be mounted throughout following a pattern of spiraling phyllotaxy as found in the natural plants as shown in Figs 1a and 1b. Each panel can be locked to any suitable position to withstand the wind pressure due to heavy storm affecting over the main pole/ trunk. The panels are fitted, naturally facing towards the sun at an optimum angle of 0.401 rad (23°) so as to collect the maximum solar energy.

Materials and Methods

Design Methodology and Analysis of the Structure

Design

Based on the conceptual design, 3D CAD Model was prepared as shown in Fig. 2. Using this model, design calculation has been carried out and the structural analysis was also done.

The structural analysis and design analysis procedure has been done by three different steps:

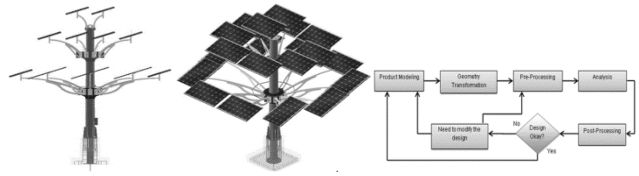

Fig. 2 — 3D CAD Model and Loop of design analysis

modeling of the solar artifact, pre-processing and analysis as shown in Fig. 2.[12] In order to analyze the design, the properties of material have been incorporated into the model along with the forces, stress, and strain. Then, the model is broken down into a large number of interconnecting elements, resulting in an appropriate meshing and each of these elements shows its individual mechanical and material properties. The resultant data thus obtained has been used to predict the resultant effect of the force at particular points on the model particularly the load bearing areas like joints, columns, truss etc.

Analysis of Panel Support` Arms

Panel Support arms are the slender parts, which originate at the pole/mast and extended outwards for support of solar panels. It may be noted that each solar panel along with their supporting bracket weighs approximately 40 kg. Structurally the arms act as a cantilever. To reduce self weight of such structures they are made up of hollow tubes and thin plates. To optimize its design several rounds of design modification and stress analysis have been carried out. Consider a case where a monkey or several monkeys are playing on the solar panels. The panel support arms are most vulnerable components of the solar tree. In addition to their self weight, each support arm has to carry extra load caused by the monkeys. Moreover, a monkey jumping on a panel is more harmful than a monkey seating idle (Fig. 3a). This will cause excessive stress on the base of the support arm. Without digging into intricate detail of such situation an extra load of 150 kg has been considered for this analysis.

Structural Analysis

Based on the analysis results of the individual support arms, the analysis was also carried out for the whole structure in static condition. The input parameters like force, materials properties and the results obtained are given in Table 1**.** The analysis results are shown in Fig. 3b, 3c.

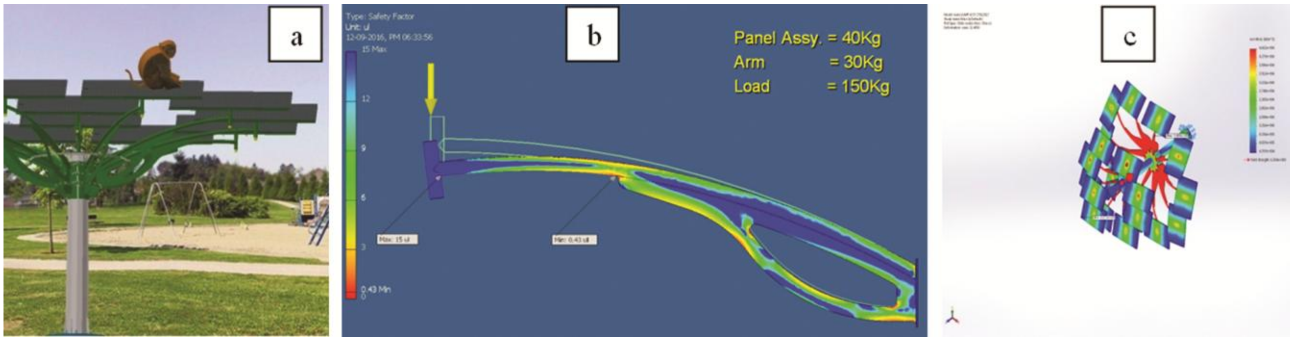

Fig. 3 — Analysis results: a, b - Panel support arm, c - Whole structure

Table1 — details of load vector, materials properties and results

A: Panel Support arms

Load Vector

Load Type	Force, N
Vector X	0.000
Vector Y	-1500.000
Vector Z	0.000

Material Properties

Name	Steel	
General	Mass Density	7.85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	210 GPa
	Poisson's Ratio	0.3 ul
	Shear Modulus	80.76 GPa

Result Summary

Name	Minimum	Maximum
Volume	3673980 mm^3	
Mass	28.8408 kg	
Von Mises Stress	0.04501 MPa	313.289 MPa
Displacement	0 mm	15.1201 mm
Safety Factor	0.428315 ul	1.5 ul

B: Whole structure of the artifact

Material properties

Name:	Alloy Steel
Model type:	Linear Elastic Isotropic
Default failure criterion:	Max von Mises Stress
Yield strength:	620.422 MPa
Tensile strength:	723.82 MPa
Elastic modulus:	2.1e+011 N/m^2
Poisson's ratio:	0.28
Mass density:	7700 kg/m^3
Shear modulus:	7.9e+010 N/m^2
Thermal expansion coefficient:	1.3e-005 /Kelvin

Model properties

Mass:21748.5 kg
Density:7700 kg/m^3
Volume:2.82448 m^3
Weight:213136 N

Results

Type	348.42 MPa
von Mises Stress	

Wind Analysis

Wind load is a serious threat to such structures. Wind load is a calculated value representing the total forces on a structure or object cause by pressure from wind moving over it. As a force, wind load is the product of pressure distributed over an area (Pa times m^2). In this case, the pressure is the "velocity pressure", governed primarily by wind speed. The area in the equation represents the projected area of the object on a plane normal to the wind direction. Further modifying these factors is the "drag coefficient", which represents the shape of the object. The model was analyzed for wind speed of 180 kmph. Subsequently the load was transferred to estimate the developed stresses at various locations, such as, at the base of the tree as well as branches.

Wind Load Analysis As Per IS 875 - 1987 (Part-3)

Wind forces acting on a given surface is equal to the wind pressures multiplied by the effective projected area as shown in Eq. 1.

$$F = P \times A \times C_d \qquad \dots (1)$$

Where: F = wind load, N; P = wind pressure, Pa; A = projected area, m^2; C_d = drag coefficient

Design wind speed is given by the Eq. 2 as

$$V_z = V_b \times K_1 \times K_2 \times K_3 \qquad \dots (2)$$

Where V_z= Design wind velocity, m/s; V_b= Basic wind speed, m/s ; K_1 = Risk Coefficient; K_2 = Terrain, height and structure size factor; K_3 = Topography factor

As per the clauses, $\boldsymbol{K_1}$ = 1.0 (clauses 5.3.1 of the above IS)

$\boldsymbol{K_2}$ = 1.0 (clauses 5.3.2.2 of the above IS)

$\boldsymbol{K_3}$= 1.0 (clauses 5.3.3.1 of the above IS)

Now, the design wind pressure as $\boldsymbol{P_z = 0.6\, V_z^2}$ … (3)

Where, $\boldsymbol{V_z}$ = design wind speed in m/s; In our case $\boldsymbol{V_z = V_b = 50\ m/s}$ (Based on clause 5.2, Durgapur area) $\boldsymbol{= 50 \times 1 \times 1 \times 1\ m/s = 50\ m/s}$
So, $P_z = 0.6\ V_z^2 = 0.6\ (50)^2\ N/m^2 = 1500\ N/m^2$

From Eq. 1, we may write, $F = P_d \times A \times C_d$ Where, $P_d = P$

Our design pressure P_d=P_z

Hence, Eq. 1 can be re-written as
$F = P_z \times A \times C_d$ … (4)

Here, P_z= 1500 N/m^2, A = 12 m^2, C_d= 2

By using Eq. 4, we get $F = 1500 \times 12 \times 2 = 36000\ N$.

With the calculated pressure and force, simulation was done. The input parameters taken for the Flow Simulation analysis are given in the Table 2. The results are shown in Fig. 4.

Shadow Analysis and Its Methodology

The shadow analysis calculation stands on a basic principle that the light travels in a straight line. In Eq. 5 the direction vector of the solar radiation when the sun is inclined at a solar azimuth angle of φ_s and an altitude angle of α is given. Also, this shadow prediction depends on declining angle and angle of incidence.[13]

$$cosS = cos\varphi_s cos\alpha + sin\varphi_s cos\alpha + sin\alpha \qquad \ldots (5)$$

The detailed methodology of the shadow analysis is provided below:

The angle of the Sun is called solar azimuth angle and the value is always positive. Hence, the angle is less than π/2.

$$sin\varphi_s = -(\sinh \cos\delta)/cos\varphi_s \qquad \ldots (6)$$

$$cos\varphi_s = (sin\varphi sin\theta_s - sin\delta)/(cos\varphi cos\theta_s)cos\varphi_s \qquad \ldots (7)$$

Where, h is the present time hour angle, δ is the current declination angle of the Sun, θ_s is the solar

Table 2 — Input parameters taken for the Flow Simulation analysis

Technical parameters

Name	Minimum	Maximum
Density (Fluid) [kg/m^3]	1.17	1.50
Pressure [Pa]	0.0235	1500
Wind load [N]	0	36000
Temperature (Fluid) [K]	290.15	294.85
Velocity [m/s]	0	61.640
Mach Number	0	0.18
Shear Stress [Pa]	0	21.03
Bottleneck Number	0	1.0000000
Heat Transfer Coefficient [W/m^2/K]	0	0

Ambient Conditions

Thermo-dynamic parameters	Static Pressure: 101325.00 Pa Temperature: 293.20 K
Velocity parameters	Velocity vector X direction: 0 m/s Y direction: -50.000 m/s Z direction: 0 m/s

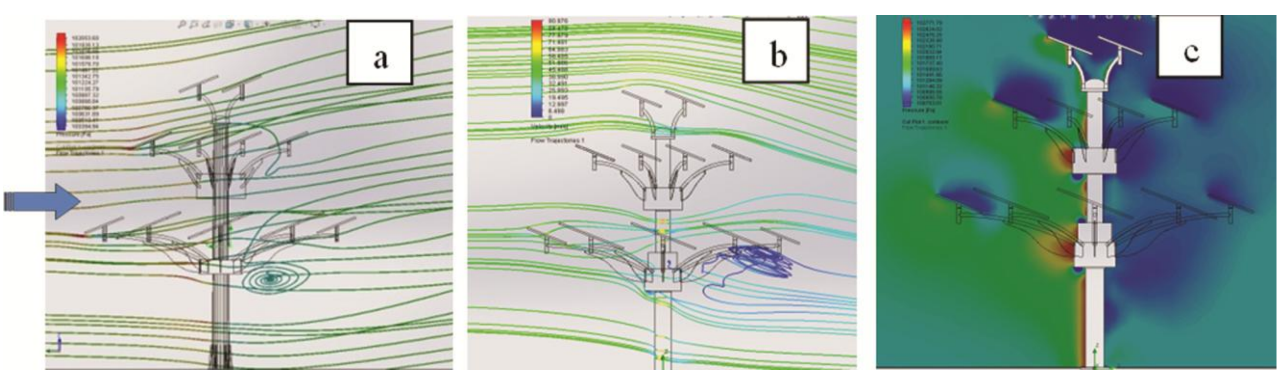

Fig. 4 — Wind Flow Analysis: a, b, c - Simulation results

elevation angle and φ is the local altitude angle.
The declination angle (δ) can be calculated in radian from Eq. 8.$23.45 \times \left(\frac{\pi}{180}\right) \times \sin\left[2\pi\left\{\frac{284+n}{365.25}\right\}\right]$ … (8)

The altitude angle can be obtained from Eq. 9.

$$sin\alpha = sin\delta sin\varphi + cos\delta cos\omega cos\varphi \quad \ldots (9)$$

The shadow analysis has been carried out to find out that all the solar panels are directly exposed to sunlight and there are no obstructions of any solar panel throughout the day. First, a concept model has been created using the Amethyst ShadowFX and using this concept model the design has been finalized. Next, the sunray is allowed to fall on the solar panel at a different angle and as per the image analysis, as shown in the Fig.5, there are limited areas of intersection of the shadow, which may be accepted. Thus the analysis results of the solar panel positioning show almost negligible shadow loss and maximum energy extraction.

Fabrication of Solar Tree

Based on the structural analysis, wind analysis and shadow analysis, the solar artifact has been fabricated. The solar PV Panels are mounted on the central main pole structure with the help of suitable supporting base. The arrangement of solar panels maintains a 'Phyllotaxy' pattern so that all the solar PV panels were directly exposed to the sunlight throughout the day without any major overlap with others. Based on the power requirement, the number of branches was selected and assembled with the main pole stems. The PV panels are mounted with the main pole structure by using hexagonal fabricated structures with nut and bolts in such a way that the structure fully balances and bears the load acting upon it even during heavy wind conditions that prevails in this geographical region. The final fabricated solar artifact has been shown in Fig. 6. The technical details of the panel of maximum energy of 250 W and other components like output cables and connectors have been given in Table 3.

Results and Discussion

From the structural analysis, we have calculated the Von mises stress as 313 MPa (Table 2) for the panel support arms. This value is much lesser than ultimate tensile strength of the selected materials. Hence, the

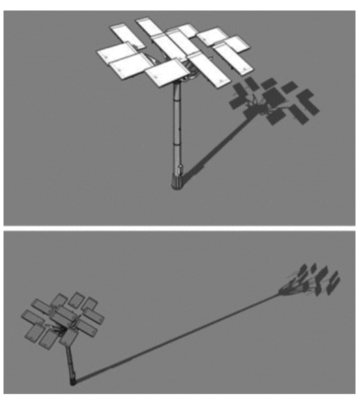

Fig. 5 — Shadow analysis

Fig.6 — Fabricated Solar artefact

Table 3 — Technical details of the developed artifact

Maximum Power (P_{max})	245 W
Voltage at P_{max} (V_{mp})	30.67 V
Current at P_{max} (I_{mp})	7.99 A
Open Circuit Voltage (V_{oc})	37.77 V
Short Circuit Current (I_{sc})	8.55 A
Temperature Coefficient of (P_{max}%/K)	-0.45 %/K
Number and Arrangement of Cells	156 mm x156 mm, multicrystalline Silicon Cells, 6x10 configuration
Dimensions (mm)	1661 x 991 x 37
Weight (kgs)	18.7
Front Glass	High transmission, low iron, tempered and textured glass, 3.2mm
Output Cables	USE-2 Solar cables, 4mm2 cross-section, asymmetric, length 800mm x 1200mm
Z Type of Connector	Low resistance, IEC/UL approved (compatible with MC4)

arm structures are safe to withstand the required load. For the whole structural analysis, Von mises stress is 348.42 MPa which is much below the ultimate tensile strength, i.e the structure is safe from design point of view. From the wind force calculation, we have got the value of wind load as 36 kN and wind pressure as 1500 Pa. With this calculated value, it may be stated that the structure can withstand in situation like stormy weather condition (wind speed, 50 m/s) of our (Durgapur) geographical region. The shadow analysis of the panels confirms that at any position of the Sun, the shadows of the panels hardly overlap with other and all the panels are fully exposed to the sunlight. The panels are giving maximum efficiency when the PV is arranged in a phyllotaxy pattern, without occupying a large area.

Conclusions

The generation of electrical energy by utilization of solar artifact is a new concept. The structural analysis has been carried out for the developed artifact and it has been found out that the complete structure can withstand the load against high wind conditions of our geographical region. From the shadow analysis of the developed solar artifact it is observed that due to the phyllotaxy pattern of arrangement, a negligible portion of solar panels compared to the full structure get obstructed by the others from sunlight.

References

1 Dutt B & Khaiser N, Scientometric analysis of global solar cell research, *Ann Lib Inf Stu*, **63** (2016) 31–41.

2 Maity S N, Development of solar power tree – an innovation that uses up very less land and yet generates much more energy from the sun rays by SPV method", *J Env Nano Technol*, **2** (2013) 59–69.

3 Mandal S K, Maity A, Nimiety S, Solar tree – an Innovative approach for rural energy source, *Appl Sci Reports* 3 (2015).

4 Dutt B & Nikam K, Solar cell research in India: A scientometric profile, *Ann Libr Inf Stud*, **60(2)** (2013) 115–127.

5 Dutt B & Nikam K, Scientometrics of collaboration pattern in solar cell research in India, *Ann Libr Inf Stud*, **61(1)** (2014) 65–73.

6 Dutt B & Nikam K, A scientometric overview of collaboration pattern in global solar cell research, *Ann Libr Inf Stud*, **62(3)** (2015) 157–167.

7 Hyder F, Sudhakar K & Mamat R, Solar PV tree design: A review, *Renew Sust Energ Rev*, **82** (2018) 1079–1096.

8 Hyder F, Baredar P, Sudhakar K & Mamat R, Performance and land footprint analysis of a solar photovoltaic tree, *J Clean Prod*, 187 (2018) 432–448.

9 Singh I B & Park S M, Synthesis of β-MnO_2 nanowires and their electrochemical capacitive behavior, *Indian J Chem*, Sec A, **54A** (2015) 46–51.

10 Bhuvaneswari C, Rajeswari R, Kalaiarasan C & Muthukumararajaguru K M S, Idea to Design a Solar Tree Using Nanowire Solar Cells, *Int J Sci Res*, **3(12)** (2013) 2250–3153.

11 Khurana S & Bandyopadhyay T K, Patenting in Renewable Energy Sector-An Analysis, *J intellect prop rights*, **23** (2018) 44–50.

12 Maity S N, Development of Solar Power Tree – An Innovation that Uses Up Very Less Land and Yet generates much more Energy from the Sun Rays by SPV Method, *J Environ Nanotechnol*, **2** (2013) 59–69.

13 Rashid M M, Husain K N, Vitković N, Manić M, Trajanović M, Mitković M B & Mitković M M, Geometrical Model Creation Methods for Human Humerus Bone and Modified Cloverleaf Plate, J Sci Ind Res, 76 (2017) 631-639.