Design and Analysis of Dual Axes Tracking System for Solar Photovoltaic Modules

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***Abstract* - solar energy has a large potential to become the fuel of the future. The challenge however remains to effectively capture the available solar energy and efficiently convert the captured solar energy into electrical energy. The project is a definitive attempt to explore the opportunities in effectively capturing the solar energy by designing a mechanical system and support structure to rotate a set of photo voltaic modules which are capable of generating 1 kWh electricity. Large scale solar power generation is the broad framework of the current problem statement. Literature review reveals that tracking the sun in both the directions can improve the power output by 25 to 30 percent. This improvement can play a vital role in adapting the solar power as the major power generating source, as it opens the scenario of large scale grid connected power generation. Within this framework, the present study aims to design a solar tracking system and its support structure that can allow the photovoltaic solar panels, which are capable of generating 1 kWh electrical energy to efficiently absorb solar radiation, thereby improving the electric output from the structure. The system has to track the sun in both directions, withstand the dynamic loads viz. wind loads, remain safe in most adverse conditions and possess the ease of assembly and manufacturability.**

***Index Terms* - Renewable Energy, Solar Photo Voltaic Modules, Dual Axes Solar Tracking, Slew Bearing**

I. INTRODUCTION

A secure, sufficient and accessible supply of energy is very crucial for the sustainability of modern societies. Most predictions provide for the energy consumption growth of developed nations compounding at around 1% a year; however, for developing nations, consumption presently compound at over 5% a year [1].The recent decades have seen the increase in demand for reliable and clean form of electricity derived from renewable energy sources. One such promising example is solar power. Solar energy has a large potential to become the fuel of the future. It is abundant, free of pollution and is void of any risk factors as present in the nuclear fuel technology or the hydrogen fuel cell technology. Electricity generation from solar energy is assuming increasing importance in the context of large negative environmental externalities caused by electricity generation due to the predominance of fossil fuels in the generation mix. Further it has a great advantage of production at different capacities. There can be a series of large solar units that can supply power to the national grid and at the same time, there can small solar modules used for domestic purpose. This ability of applicability at domestic level makes it an important source for those who do not have access to the conventional power lines. Therefore exploring the opportunities in tapping the solar energy has a great impact on the development of mankind at large.

The effective methods of capturing the full potential are critically analyzed and studied. A solar tracking system was designed with active tracking systems in both directions viz. east to west, north to south. The design was critically examined from various parameters and a comprehensive design analysis was performed. This was followed by a parametric analysis with an objective of enhancing the scalability of the design by identifying the variables that affect the design and predicting their values so as to estimate the efficiency of the scaled up system. Various factors such as manufacturing & assembly considerations, maintenance & repair considerations, material selection etc., have been considered.

Apart from the design process, focus was also laid on studying the impact of the loads on the structures, particularly the effect of wind loads that significantly factor the safety of the tracking system. FEA tool was used to simulate the conditions of wind flow from different directions and the effect of it on the solar structure was observed. Throughout the design process standard practices and methodologies were adopted to ensure standards compliance. Along with all the successful steps in the design process, an insight into the parametric analysis was also included with an aim that the information would be useful to those who are pursuing further research in the same domain. It was assumed that the slew bearing drives would be employed to facilitate the tracking in both the directions. These results carry equal weight alongside the successful results as they can save the time of future researchers.

II. INCIDENT SOLAR RADIATION

The combined effect of the elliptical orbit and the tilt of the axis causes seasons in the Earth's atmosphere. Among all the key variables that affect the amount of solar energy reaching the surface of the Earth, two key variables were identified to be critical for the current design.

a) Sun rays inclination at the specific geographical point; and
b) Thickness of the atmosphere between the specific point and the sun.

In a single day, the thickness of atmosphere through which the sun rays have to pass varies quite significantly from sunrise to sunset. At any place between the two tropics, there are moments where the sun can be at an angle of 90° at noon (right over our heads), and also at an angle of 0° at sunset. In places other than the mentioned earth's piece of surface, the Sun’s angle never reaches 90 degrees but it has a maximum angle which depends on the latitude. The greater the thickness of the earth's atmosphere, the greater is the solar radiation that is getting dispersed in the atmosphere without reaching the earth’s surface.

The second factor that influences the effect of the solar radiation on the earth’s surface is the inclination of the sun’s rays with earth. The solar elevation angle at any point on the earth’s surface is the elevation angle of the sun. It is the angle between the (idealized) horizon and the geometric center of the sun's apparent disk. It is influenced by the hour angle, declination angle, and the local latitude.

It can be calculated, to a good approximation using the following formula [2]:

$$\sin\theta = \cos h \cos\delta \cos\varphi + \sin\delta \sin\varphi \qquad (2.1)$$

Where,

Θ is the solar elevation angle

h is the hour angle, in the local solar time

δ is the current declination

φ is the local latitude

Hour Angle (h): The angle between the local solar noon (meridian which contains the south- north line) and the horizontal projection of the Sun's rays on a horizontal plane. It is given by:

$$h = 360/24\,(12-T) \qquad (2.2)$$

Where, “T“ is the local solar time

Declination Angle (δ): Angle between the line joining the centers of sun and earth and the equatorial plane of the earth

Local latitude (φ): The angle made by the radial line joining the location to the center of the earth with the protection of the line on the equatorial plane. By convention, latitude is measured as positive for the northern hemisphere and negative for southern hemisphere. It can vary from +90 o to -90 o

III. SOLAR TRACKING SYSTEMS

A solar collector or photo-voltaic module receives the maximum solar-radiation when the Sun’s rays strike it at right angles. Tilting it from being perpendicular to the Sun will result in less solar energy collection by the collector or the module. Therefore, the optimal tilt angle for a solar energy system depends on both the site latitude and the application for which it is to be used. Many solar applications are mounted either on a fixed rack or on a tracking rack. Fixed collectors or modules producing heat or electricity throughout the year are usually installed and tilted at an angle equal to the latitude of the site in which the collector or module faces directly the Sun.. The energy collected by the solar system in both winter and summer is far less due to several reasons such as clouds in winter and temperature scattering in summer in addition to the Sun’s changing altitude. But nevertheless in such cases, it is desirable that the average yearly collection of energy is maximized (i.e. the angle position of the collector or module is adjusted to receive maximum energy).

A Sun-tracking mechanism increases the amount of solar energy that can be received by the solar collectors or photo-voltaic modules: consequently this would result in a higher daily and annual output power harnessed. The use of a tracking system is more expensive and more complex than fixed mounts: however they can become cost-effective in many cases because they provide more power output throughout the year and in many cases this increase exceeds 25% [2]. Commercially, tracking systems are available either as a single-axis or a dual-axis design. The single-axis tracker follows the Sun’s apparent east-to-west movement across the sky, while the dual-axis tracker, in addition to east–west tracking, tilts the solar collector or module to follow the Sun’s changing altitude angle.

IV. DESIGN OF DUAL AXIS SOLAR TRACKER

A Sun-tracking mechanism increases the amount of solar energy that can be received by the solar collectors or photo-voltaic modules: consequently this would result in a higher daily and annual output power harnessed. The single-axis tracker follows the Sun’s apparent east-to-west movement across the sky, while the dual-axis tracker, in addition to east–west tracking, tilts the solar collector or module to follow the Sun’s changing altitude angle.

Design Criteria for Dual Axis Tracker

Before proceeding into the design process, it is imperative to form an exhaustive list of requirements the system has to meet. The below table (Table 1) lists out all the important functions and the features that are expected out of a dual axis solar tracker while briefly describing each feature.

Table 1 Design Criteria for dual axis solar tracker

Function	Description
Scalability	The design should be scalable to be used for varying wattage so as to cater different scales and kinds of applications. This would enhance the product scope.
Dual axis Tracking	On an average day, the sun has to be tracked for approximately 12 hrs. In addition to that, North South movement of the sun over the year has to be taken care of. The solar panels. The solar panels have to rotate almost 180 degrees every day. The rpm at which the solar tracker has to rotate is approximately 0.000604 RPM.
Structural Stability	The structure has to withstand the wind loads when panels are in the inclined position. These wind loads

	may vary depending upon the geographical and climatic conditions.
Quick Return	At the end of the twelve hour regular tracking, the panels should be brought back to the initial position to start tracking for the next day. Also, this is the rest position in which the panels are parallel to the ground. This rotation can be done faster unlike the slow step by step rotation of the tacking period.

Load Calculations

Structural design of the system is critically dependent on the amount of load it can withstand. Determination of the loads exactly is a highly important factor to ensure that the structure remains stable even in the most adverse condition. Therefore loads are calculated as per the standards of ANSI/ASCE. According to the given standards, the major types of loads are as described below.

Dead Loads

Six solar panels have been chosen to be mounted onto the structure. Each solar panel weighs 16 kg. The panels are arranged in a 3x2 matrix with 3 panels along the longest side (column) and 2 panels along the shortest side (row) as shown in the figure 5. The panels were supported using a grid type of steel structure. Each panel weighs 16kg and the grid frame along with the connected cables weighs around 14kg. Therefore the total dead load on the structure is 110 kg.

Wind Loads

While dead loads are always constant, wind loads cause a time-varying random loads on the structure. The amount of load experienced by the structure depends on the velocity of the wind, incidence angle of attack, atmospheric conditions, structural design, geographical factors and proximity to the neighborhood structures. The flow of wind over a body is a classic problem in fluid mechanics that deals with the flow of fluids over a body.

Two kinds of forces are generated in such a situation. One force is parallel to the direction of the flow and the other kind of force is perpendicular to the direction of the flow of wind. These forces are calculated for a particular wind speed for various degrees of inclination of the solar panels. The maximum values of forces are calculated. The structure is designed to withstand the highest possible loading scenarios to ensure reliability and integrity of the structure. In order to calculate the wind speeds and estimate various correction factors, the standards were based on IS875:1979.

Chennai belongs to Wind zone 5 of India. Basic wind speed is based upon the peak air speed averaged over time and corresponds to 10m height above mean sea level in open terrain. The magnitude of the wind forces are calculated as follows:

Location: IIT Madras, Chennai, India (13 degrees N, 82 degrees E)

$$\text{Normal force} = A \times P \times Cd \qquad (3.1)$$

Where,

A is the effective area

P is the wind pressure = 0.5 * density * velocity^2

Cd(Drag co-efficient) for flat plate for laminar flows is 1.05

Hence, Area = 6 * (1*0.67) = 4 m^2

Velocity (Max.) = 44 m/s

Design wind speed = V * k1 *k2 *k3= 19.4* 0.9 = 17.5 m/s

K1 is the probability factor; the existing system design duration is 25 years. Hence k1 = 1

K2 is terrain and height factor. IIT Madras belongs to Category 3, which indicates close proximity to structures. The above conditions suit Class A criteria, hence k2 = 0.9

K3 is the local topography factor viz. hill, valleys, escarpments, etc. Since the location has no such features in the vicinity, k3=1

Hence the design wind speed = Vmax * k1 * k2 *k3 = 35 m/s

Density of air = 1.1755[2]

The major loads acting upon the frame directly are listed as shown in the figure 1. However, not all the loads mentioned are of concern. The inertial loads are almost neglible since, the angular velocities and the angular accelerations experienced by the system are quite low. The major component of loading is due to the dynamic wind loads.

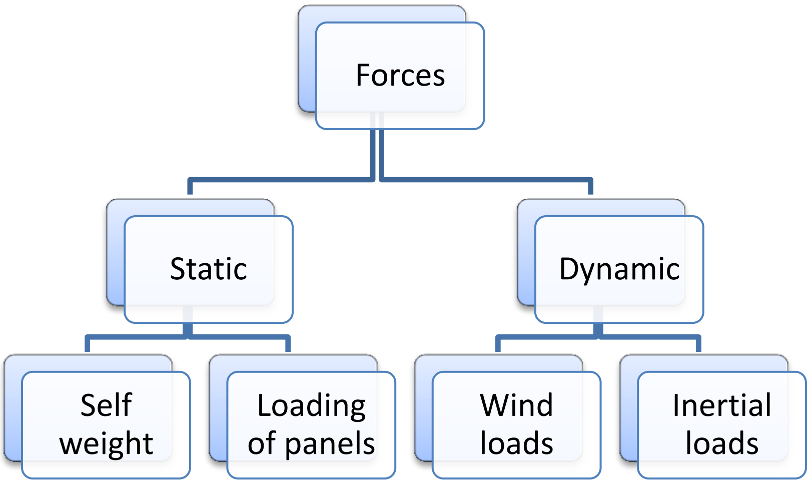


Figure 1 List of forces acting upon the structure

Among all the loads, the most important ones considered for the analysis for the dean and wind loads. Since, the loads caused by the other three are not quantifiable; they're taken care of with a sufficient factor of safety.

Design of Frame

It is the key component of the structure as it directly bears the load of the panels and the wind loads. Six panels each weighing 16 kg are attached to the frame. It comprises of longitudinal members in both vertical and horizontal directions in the plane of the panels as shown in the figure 3. The members are of hollow box section which is chosen due to the advantages of symmetry and ease of availability. Also, hollow structures are more efficient in comparison to solid structures regarding the lateral load bearing capacity.

The frame design is thus developed using the above mentioned inputs. The design can be further optimized using I-beams or a truss structure, but the advantage is found not to be of much value, due to the factors such as the cost, ease of availability, ease of assembly and manufacturability.

Design of Base Column and Arms

The base column (figure 3) is the part that connects the structure to the firm ground below. Often the structure is placed on to a concrete base to ensure the integrity of the structure. The base column is divided into two parts: The bracket and the base structure. The bracket adjoins the slew bearings and the motor assembly to the base column which is bolted into the concrete slab. The base column is of a tapered truss structure which is preferred due to its low weight and ability to withstand high impact loads. The arms are the load members that convey the loads from the frame to the entire structure as shown in the figure 3.6. The cross section is hollow cylindrical structures which deviate at the ends to accommodate the loading of the panels at their ends. The major loads applied on to the structure are bending loads and axial torsional loads.

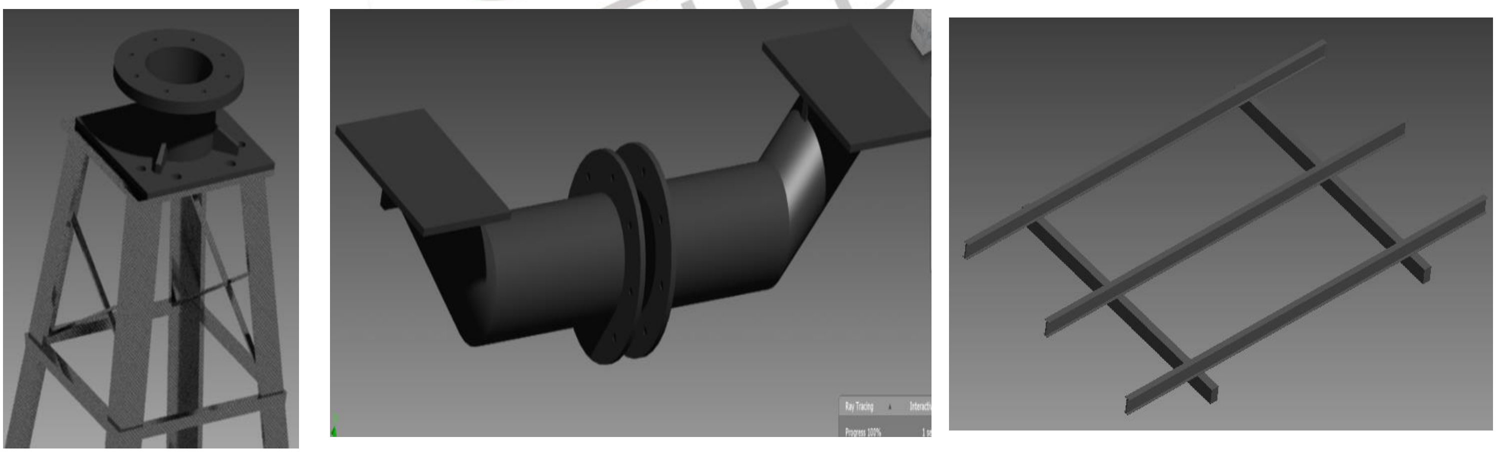


Figure 2 3d model of Base, Arms, frame of the structure

Selection of Slew Bearings

A "slewing" bearing is a rotational rolling-element bearing that typically supports a heavy but slow-turning or slow-oscillating load. The bearing derives its name from the word "slew" (means to turn without change of place). In comparison to other rolling-element bearings, slewing bearings are thin in section and are often made in diameters of a meter or more.

Slewing bearings are a cost-effective design and performance enhancement option for rotary devices carrying heavy loads. Slewing rings have a compact design, which facilitates more ease of use and can be manufactured without teeth, with internal or external teeth, with balls and/or with rollers. The slewing bearing drives in heavy machinery enable higher torque, speed reduction and rotational functions.

The slewing bearings are available in the market in various custom and standard types. The selection parameters are mainly: Axial Load, Tilting moment. Each bearing has its own characteristic graph which represents the operational values of the above values. The selection of the bearing depends specific to the loading scenario.

The values for the selection of the slew bearing for this particular structure are calculated and the specific type of slew bearing drive can be imported from any manufacturer. Table 2 lists out the values of the required slew bearing in this case. Further in this thesis, a chapter has been dedicated for the parametric analysis which helps in determining the slew bear for the applications of varied wattage. Table 3 summarizes the rate of change of the parameters per Kwh capacity of the system.

Table 2 Parameters for the selection of slewing bearing

	Tilting moment torque(Nm/kWh)	Axial load(kN/kWh)
East- West Bearing	600	37.87
North-South Bearing	NA	29.4

Table 3 Rate of Change of parameter per kWh of Capacity

	Tilting moment torque	Axial load
East- West Bearing	63 Nm	39.76 kN
North-South Bearing	NA	29.4 kN

Summary

The assembly has been constructed out of the parts modelled as mentioned above in the figure 3.8. The completed assembly has been as shown in the below figure. The panels have removed from the structure so as to have a clear view of the structure. The parts are assumed to be welded to their respective mating components. The fasteners that were used are of standard sizes so as to maintain the ease of assembly.

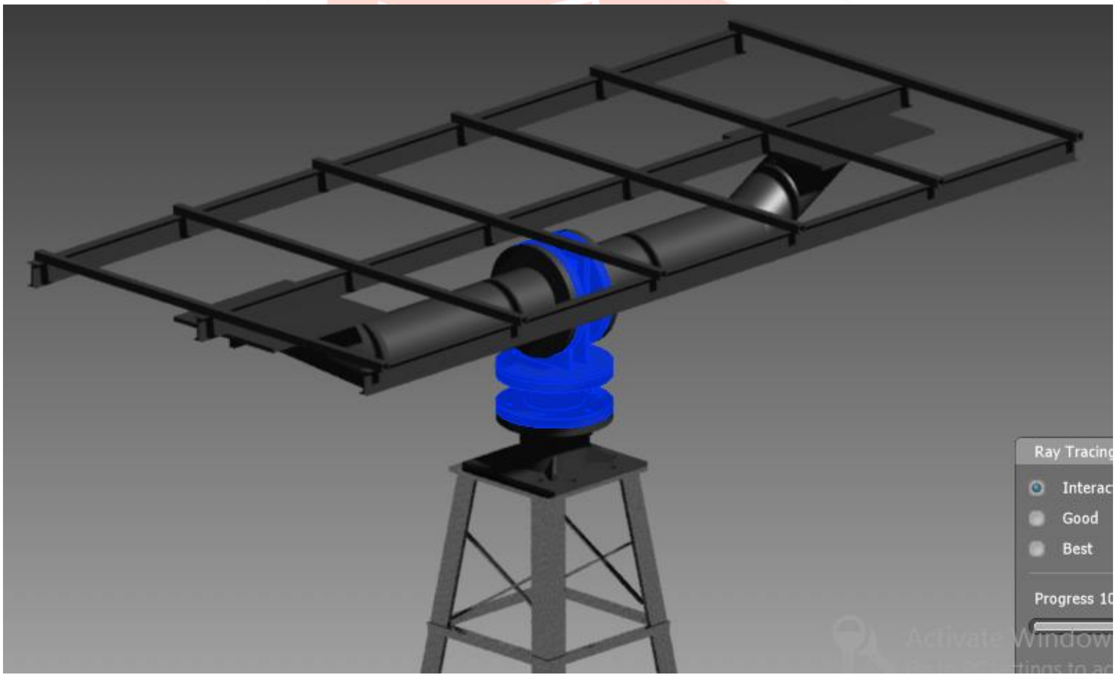


Figure IV Complete assembly of the solar tracker

V. PARAMETRIC ANALYSIS OF SLEW BEARING SELECTION

Parametric analysis refers to the description and examination of relationships between different parameters. This helps one to understand the correlation between various parameters of the system.

The objective of performing parametric analysis in this context is to facilitate the scaling of the structure to suit to varying demands. By providing a correlation between the wattage and the selection of slew bearing, the structure is rendered flexibility, as it is easier to estimate the costs for a scaled up model before further extensive study.

Two bearings are employed in the tracker. One for the locomotion in east-west direction and the other in north-south direction. Both bearings are subjected to different loads and hence, would require different types of bearings as in Table 4.

Table 4 Variation of slew bearing Parameters with Wattage

Power Capacity (W)	Axial Force (East-West) (N)	Tilting moment(kN-m)	Axial Force (North-South)	Tilting moment(kN-m)
1400	53018	84	41160	NA
2100 (= 2 kWh)	79527	126	61740	NA
2450= (2.5 kWh)	92781.5	147	72030	NA
2800	106036	168	82320	NA
2975(= 3 kWh)	112663.25	178.5	87465	NA

VI. ANALYSIS

The results after the Finite element analysis. Both the varying dynamic load and the static loads were analyzed and the components under the maximum amount of stresses are determined. Further, the results are discussed with respect to their impact. The loads are simulated and applied on to the 3d model developed. The analysis is performed in Autodesk Inventor and ANSYS. The results of the analysis are discussed herewith.

The panels were assumed to be inclined at various angles with respect to the ground and the vertical component (Lift) and the horizontal component (Drag) of the wind loads were calculated. In the figure above, the pressure contours for the inclination of 45 degrees is shown in Figure 5. The simulation is repeated for various degrees of inclination of the panels and the forces generated were calculated.

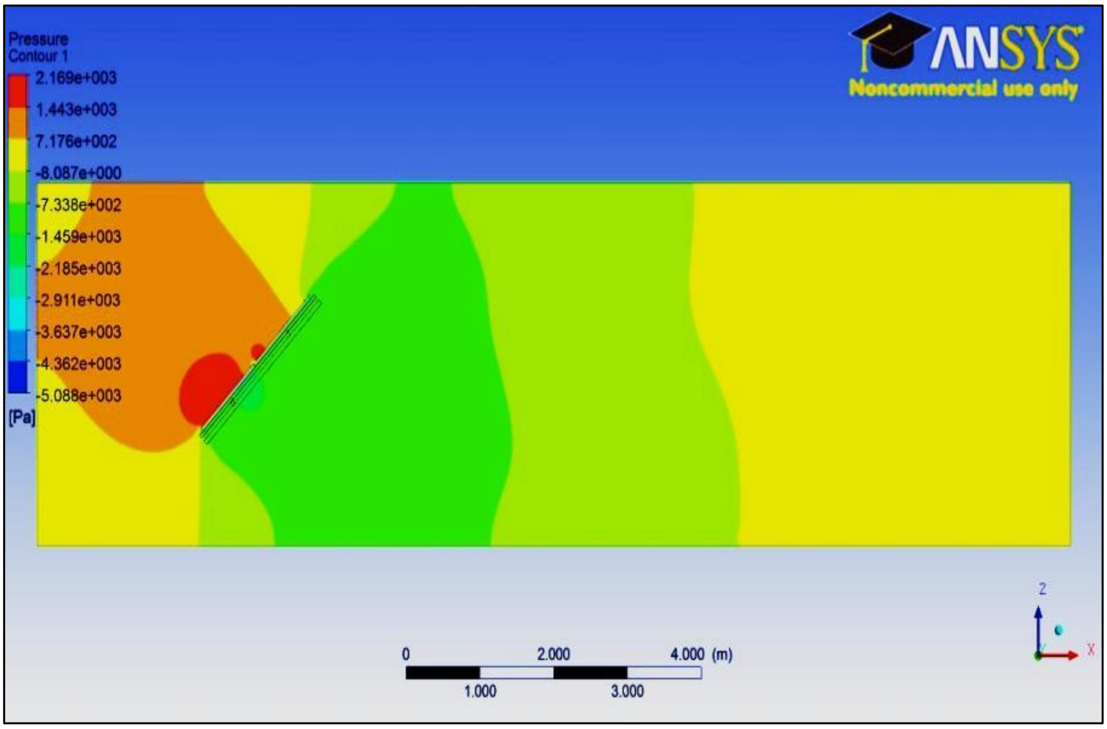


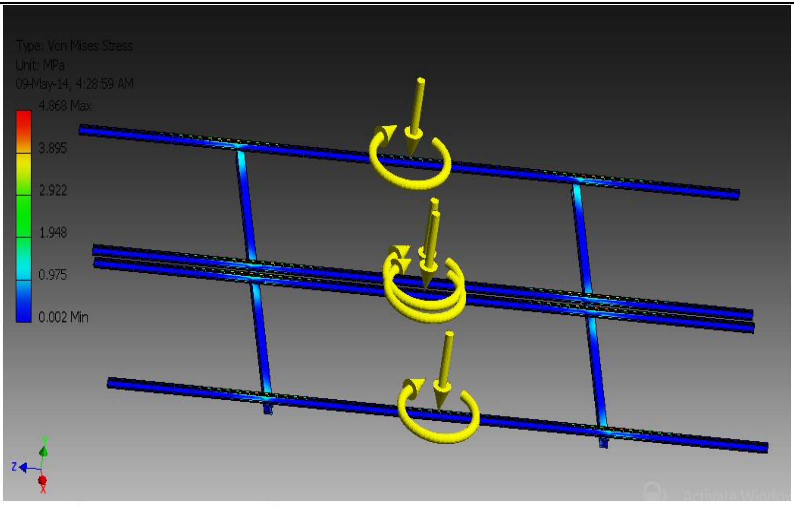
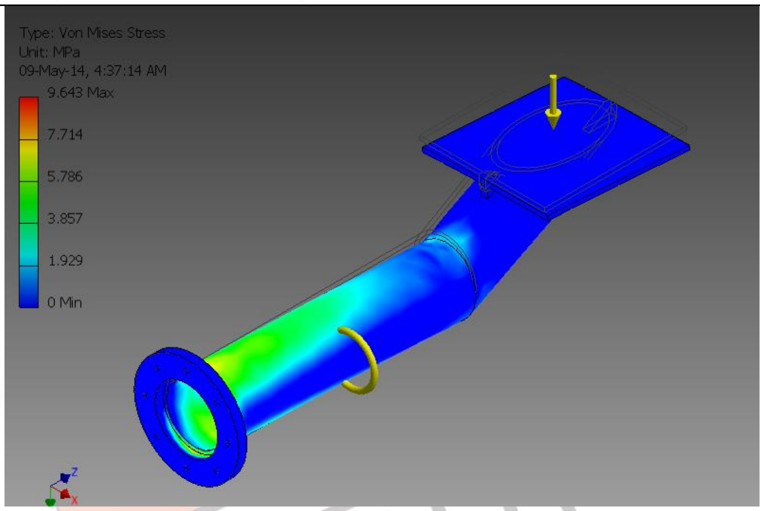
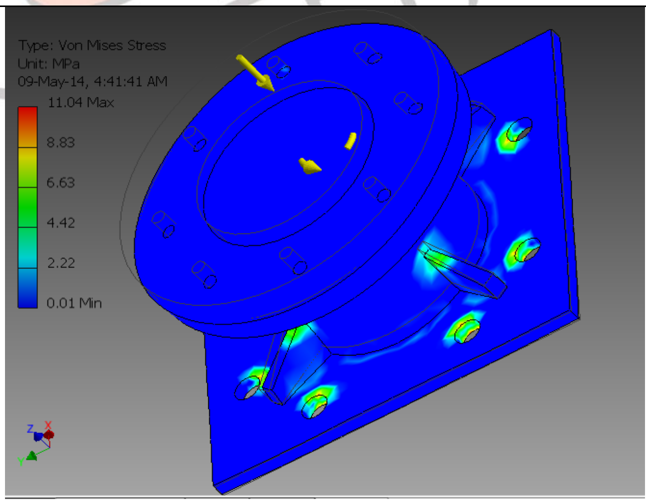
Figure 4 Pressure contours for 45 degree inclination of the panels

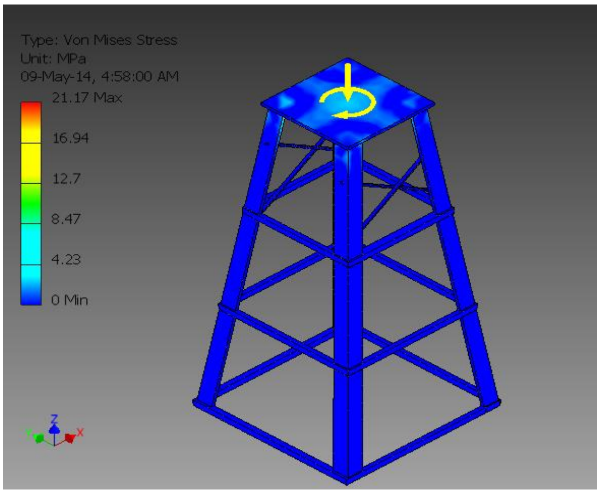
Table 5 Wind forces at various degrees of inclination

Angle	**Lift (N)**	**Drag (N)**
0 (@ 35m/s)	92.45	776.99
30	-716.8	455.8
45	-825.8	858.5
60	-662.2	1189.6
80	-248.2	1478.6

Comprehensive stress analysis has been performed on each and every component of the system. The material that was employed in the software to model the parts in ANSI 1020 Mild Steel. The loads were simulated and the geometry was modified to limit the stresses to acceptable values. The below table lists out the maximum stresses incurred in each component of the structure.

Table 6 Stress Analysis results

S.No	Component Name	Von Mises stress distribution	Maximum stress
1	Frame		48 MPa
2	Arm		96 MPa
3	Base		110 MPa

4	Base Column		21 MPa

VII. SUMMARY

The maximum stress incurred in the structure is 110 Mpa, which is in the base and is well below the yield strength value of steel i.e. 220 Mpa. Also, the total weight of structure has reduced as much as 15% in comparison [2]. It was also observed that the structure was stable when the wind loads are in the speeds of 12-25 m/s, but the device is less integral at high wind speeds exceeding 110 km/hr. However, those winds are experienced only during cyclonic conditions, hence the damage can be mitigated trough other measures.

By incorporating a tracking system, the solar panels experience higher direct solar insulation and thus generate more output when compared to fixed tilt solar panels. The power efficiency calculated for the dual axis solar tracker is calculated to be 45% more than that of the fixed mount of same PV capacity.

The current design is better in terms of the weight and scope of the product. The product is more compact than existing systems, the footprint is smaller, and panel cleaning is easier, with no manual adjustments required. The solar energy facility can be easily installed and if the need arises, can be relocated with equal ease.

VIII. CONCLUSION

The dual axis solar tracker that was developed has a capability for the better utilization of the solar energy at various levels. Dual axis rotation is capable of producing 15% higher yield than that of the single axis tracking. It was observed that the wind loads present major loading problems when compared to other loads, hence they have to be accounted accordingly.

Slew bearing drives are most aptly suited for the purpose of dual axis tracking. They are compact, widely available and have less servicing issues. Further study into the project can be oriented in trying to find the appropriate energy capacity that would be optimal for large scale power generation. Based on the mechanism developed in the current study, cost effective tracking systems can be developed for small scale photo voltaic power systems also. The forces and stresses are much smaller in magnitude for the smaller capacity structures and also the torque required to drive them is much lower. Further optimization will enhance the product by reducing weight, thus reducing loads. The projected scope of the further work in this work includes the further avenues for development viz. scalability, optimization.

Apart from developing structures that are land based, installing solar tracking systems on existing infrastructure or water bodies can also be explored. An emphasis can also be laid on the impact of large scale solar power generation plants on environment. The land covered around the footprint of the structure can also be a possible avenue to cater other chances of power generation.

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