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Static and Dynamic Analysis of Seasonal Tilt Solar Module Mounting Structure

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Abstract: *This paper highlights the concept of a ground-mounted solar PV plant. It deals with the ground-mounted solar photovoltaic design, and development using numerical analysis under static and dynamic conditions. Ground-mounted solar components are made up of steel shows superior performance and is cost-effective. CFD analysis is executed on the structure of the study for flow and assessment of wind pressure on the developed model using Indian environmental conditions. The CFD results have been compared and validated h the analytical calculations obtained through IS 875 codes part 3 for wind pressure. Structural FE analysis is carried out to ensure structural stability for the given hazardous environmental conditions like wind load. Also, modal analysis is carried out to study the effect of dynamic loading.*

Keywords: Ground-mounted Solar PV Plant, steel structure, FEA analysis, CFD Simulation, IS 875-part 3, Dynamic check, Modal analysis

I. Introduction

This paper focuses on the failure of large-scale solar photovoltaic structures and the dynamic effects of wind on it. Solar power reduces dependence on conventional energies, which are a significant source of pollution and global warming. In solar farms, PV panels are usually mounted on the ground, which is helpful for large-scale solar energy production. While PV systems with a large scale and ground mount can use for central inverter systems, this is uncommon in rooftop arrays.

In recent decades, the solar cell industry has grown significantly. India today is the fastest-growing market for renewable energy in the world. The country boasts of an ambitious renewable energy target of 227 GW by 2022, of which solar comprises 175 GW [11]. As the solar industry grows in size and deployment, this number would rise while reducing costs. Developing design specifications for solar module mounting structure (MMS) is still in its early stages, and there are no specific construction guidelines. Indeed, there are no code guidelines available yet, that can support the evaluation of design wind loads for solar panels on around. The designer may calculate the loads roughly, either with overestimation or underestimation. The former puts obstacles in the path of a technology that is supposed to be cost-effective, and the later causes failure.

Many codes and standards for wind loading define slender structures with a fundamental frequency below 1 Hz as flexible structures [1]. This paper demonstrates that this is not an adequate threshold for small structures such as ground-mounted arrays of PV panels. These small structures can be excited and buffet from high-frequency panels at frequencies higher than this, both during serviceability and design wind events. This work addresses specifically Seasonal tilt Module Mounting Structure (SMS) design subjected to dynamic loads, vibrations, and gravitational loads.

- **Solar photovoltaic module** (PV module) mainly helpful in generating electricity. The module is available in landscape or portrait for fixing on solar MMS.
- **Seasonal tilt solar MMS**: PV MMS usually have a series beam, fixed ground column, and seasonal variation tilt link provided with the south-facing solar module in north latitude. Most seasonal variation PV MMS have a tilt angle from 5degree to 30degree angle for maximum benefits of sun radiations.

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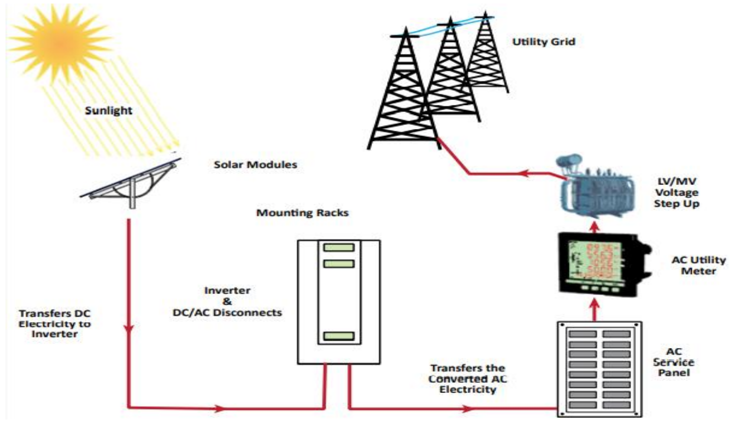

Figure 1: Work of ground-mounted solar plant

II. Literature Review

Joseph H. Cain, P.E., Principal Civil Engineer [1], showed that threshold of 1 Hz fundamental frequency is not suitable for small structures like ground-mounted arrays of photovoltaic panels. The small structure can experience both self-exciting and buffeting effect at an upwind-Natural frequency of 2 Hz. The corresponding frequency of ground-mounted systems with 4 m chord is 4 or 5 Hz. The gust effect factor G in ASCE 7.

D. Ghosha et al.[4] have shown the wind action on solar array investigated using Computational Fluid Dynamics (CFD). CSIR-CBRI, Roorkee has been installed with roof-mounted solar arrays on a power generation system with a capacity of 100 kW. The wind effects on a single solar array situated centrally or at the edge of the roof are considered in this study, CBRI building compared to solar array located at the edge (-0.6 to -5.6). Results of the CFD simulation are presented in the paper and compared with IS 875 part 3 code provisions. It may be used as an approximate estimate of wind load on a solar array. ANSYS FLUENT is used for the simulation of wind flow. The findings show that the solar array is subjected to significant suction wind load, which could lift the array if it is not built properly.

Girma T. Bitsuamlak et al. [6] Studied different cases for various wind angles of attack on standalone ground-mounted solar panels. The solar panel experienced the highest overall wind loads for 0° degree wind angle of attack, i.e., upwind case.

Veysel Emre Uslu et al. [5] concluded that panel length significantly impacts solar panels. Also, a spacing factor is an essential factor for designing a solar farm. First-row panels are subjected to higher wind loads when panel length increases.

Mallikarjun Katkeet al. [3] studied the concept of floating solar PV plants and deals with the floating solar photovoltaic design, development using numerical analysis. CFD analysis is executed on the structure for the study of flow and assessment of wind pressure on the structure. The CFD results have been compared and validated with the analytical calculations obtained through IS 875 codes part 3 for wind pressure.

Syed Abdul Mateenet al. [7] The static structural study of a seasonal tilt photovoltaic power plant is presented in this paper. Computational fluid dynamics (flow simulation) on seasonal tilt solar PV power plants on a utility scale. Due to the different wind speeds observed in India, the highest load on the solar panel is applied. Various directions of the application of wind velocity are also considered in the analysis. The maximum wind loads acting on the module are obtained from the flow simulation using static structural analysis. The structural stability is analyzed from the static force analysis. This study helps to analyze similar types of structures under a broad range of wind speed forces.

Moreover, the authors of this paper have worked through FEM simulation of curved beam[12], cooling tower[13], containment structure[14], and PEB structure[15].

III. Geometric Model

3.1 Design Consideration

The concept of installing Solar PV modules on the ground is complex and requires proper planning, construction and hence key design factors must be takenintoaccount carefully. The factorstakeninto account were the open terrain, geographical location, and Orientation of the PV panel [2].

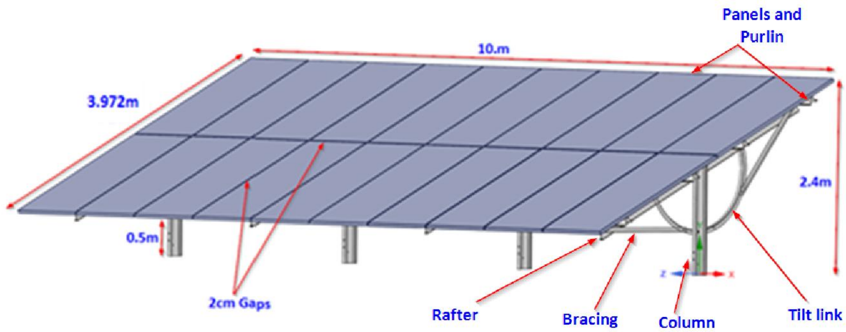

Figure 2: The geometry of a panel (composed from 20 flat PV panels)

The structural model was created in Solid-works CAD software. The structural model was restricted to the members shown in Figure 1. The dimensions of all components have been taken from reference drawings specified at the end of this report. Tilting links are provided to support the rafter and column and used to change the angle of tilt. The Purlins are supported over the rafter. Seasonal tilt MMS is supporting 20 modules. The modules are placed in portrait position over the Purlin. The rafters are light-gauge steel sections and rest on Purlin. Rafters are hinged to the column and braced by the bracing member. In industry this type of structure is called as table "2PX10" i.e. two high in portrait by 10 modules wide.

The Seasonal Mounting solar (SMS) system is a Semi-circular tilting link. It has allowing the one degree of freedom. the rotation of the elevation of the PV grid at 5°,10°,15°,20°,25° and 30°.The structure of the MMS has too many complex components to build the FE model accurately enough. Therefore, it is necessary to simplify the structure for the construction of the 3-D model. Specifically, the simplified principles should cover neglecting the small drill holes, chamfers, some fillets, and other small parts. Then the simplified solid model (a restricted number of parts to reduce calculation time) is analyzed using FEA Simulation.

As per the geographical location, the tilt angle was kept at 25 degrees Modules with a higher angle of tilt provide more shade on modules behind them. As shading impacts energy yield much more than maybe expected simply by calculating the proportion of the module shaded, a good option (other than spacing the rows more widely apart) reduces the tilt angle.

It is usually taken between 5-degree to 25-degree. As a trade-off for reducing energy yield caused by inter-row shading, it is preferable to use a lower tilt angle. It has created 300mm access routes and sufficient space between rows to allow movement for maintenance purposes.

The model designed was optimized to have minimal weight by eliminating unnecessary material and sustaining environmental conditions a dynamic effect. The installation location was Rajasthan, India and therefore, the wind speed was kept at a maximum speed of 47m/s considered. (IS875) [9].

3.2 Design of Unit Structures and Formation of the Solar Farm

The length of all the members is kept within an assortment for ease in handling and maintenance. The Ground-mounted PV generation system consists of several arrays as per the desired power output. Each panel has a capacity of 330W. The panels are arranged in rows and columns with the dimension of 1956×992 mm from Vikram Eldora grand 330 wp Module datasheet. The total plant capacity depends on the space and panel arrangement. The solar farm formed by an array of solar panels is as per the layout of location and supported by the pile foundation system, which retains the position of the structure when subjected to any Lateral load.

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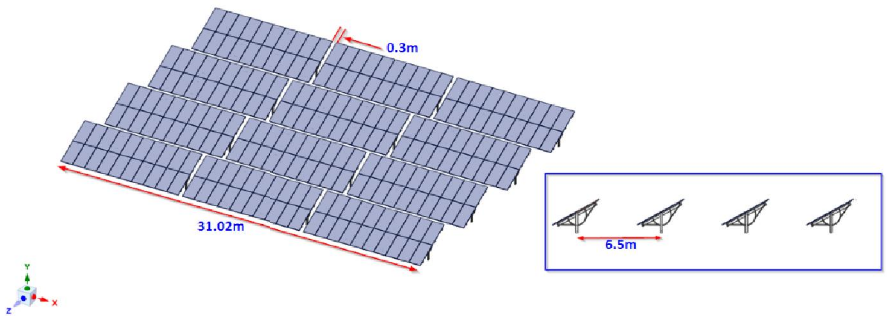

Figure 3: Unit Structure displaying Main and Walkway

The joint connection usually has a bolt/pin connection which Allows for thermal expansion using expansion joints was necessary for long sections so that modules do not become unduly stressed. The Pile foundation system and solar MMS system are firm enough to maintain the steadiness of assembly for the subjected wind speed and seismic load. Significant weight attracts a large amount of seismic load. The solar structure is lightweight; hence wind load is predominant. The anchoring structure design needs to take care of corrosion resistance.

IV. CFD Analysis

A 3D CFD model interpreting the solar PV system is developed. A grid dependency test was carried out, and we selected a mesh size of 50292 cells. The mesh type was the cut cell method. The generated mesh is shown in fig 3.

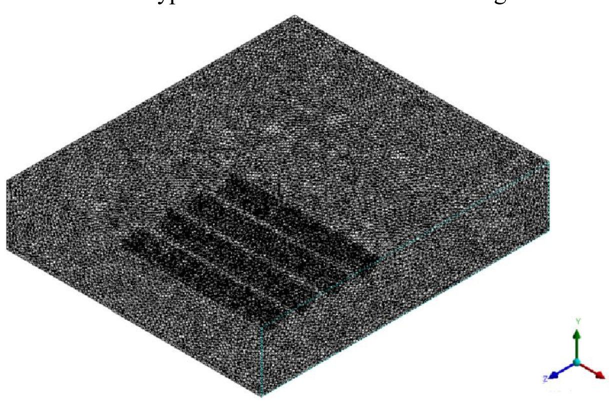

Figure 4: Meshed model for CFD analysis

As the system is subjected to wind load, the forces acting on the panels are computed by CFD analysis. CFD methodology is used in the mentioned analysis to figure out the force and pressure developed by the wind on the Solar panels to wind incident angles of 0°, 90°, and 180° for wind flow. Solar panels at 25° angle of orientation are studied at 47 m/s wind speed. The CFD model is developed with a fixed wind speed under steady-state conditions. The information of input data is given in Tables 1 and 2.

Table 1: CFD Data

Analysis Type	External
Gravity	9.8 m/s^2
Basic Wind Speed	47 m/s
Fluid	Air
Flow type	Laminar and Turbulent
Environmental Pressure	101325 Pa
Temperature	293.2 K
Turbulence intensity	5 %

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Table 2: Air Properties

Specific heat ratio(Cp/Cv)	1.399
Molecular mass	0.02896 kg/mol
Dynamic viscosity	1.85e-05 Pa.s (at 293.2 K)
Density	1.225 kg/m^3

4.1 Load Combinations

Following three load cases have been considered for design for serviceability:

1. WINDWARD- 0°
2. LEEWARD-180°
3. SIDEWIND-90°

The modeling process first involves taking fluid geometry from the real world and replicating it in the virtual environment. From here, a mesh is created to divide the fluid volume into discrete sections. In this CFD Domain, anything that does not have a flow condition applied to the volume is excluded, i.e., cavities without flow are excluded. Boundary conditions are then entered into the model to term parameters such as the type of fluids to be modeled or the details of any solid edges or flow inlets/outlets.

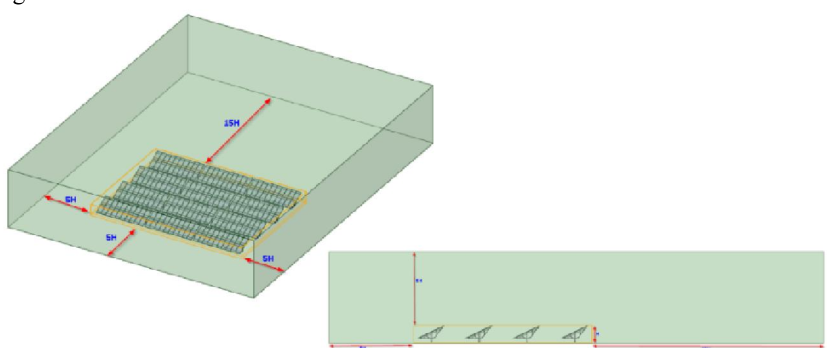

Figure 5: The numerical modeled domain

The Domain for CFD simulation is shaped to develop a high flow on stationary surfaces. The free exposure of structure with panels to the wind is studied. Domain Size is 55X 68X13m^3 for all conditions. The CFD simulation computed the forces on various panel surfaces, and wind pressure was evaluated from the forces. As a result, maximum pressure is considered for steady-state analysis. As computed, the maximum lift force generated due to windward condition is 37114 N, and the leeward condition is 1527 N; analysis for the same load condition needs to carry out for respective load conditions. It is clear enough from CFD analysis that high pressure is observed for upwind conditions due to high variation inflow. Hence, a certainty factor should be taken into account to calculate design wind Pressure.

V. CFD Result

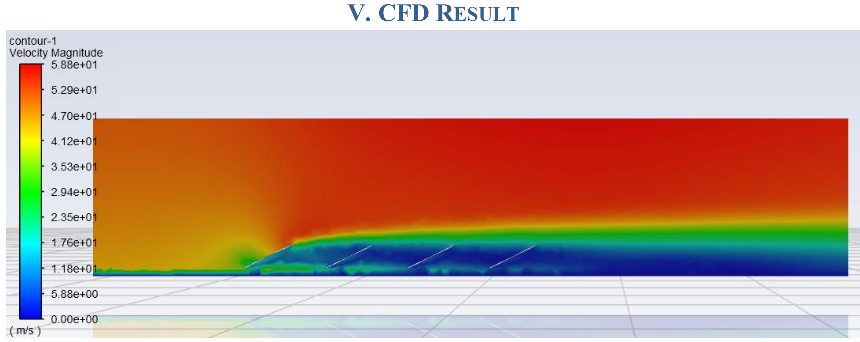

Figure 6: The wind velocity distribution.

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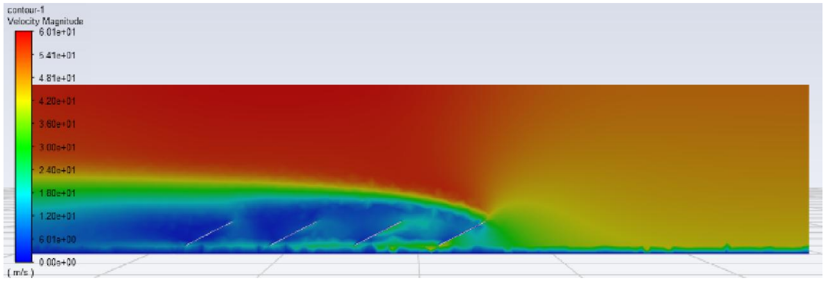

Figure 7: The wind velocity distribution Backside.

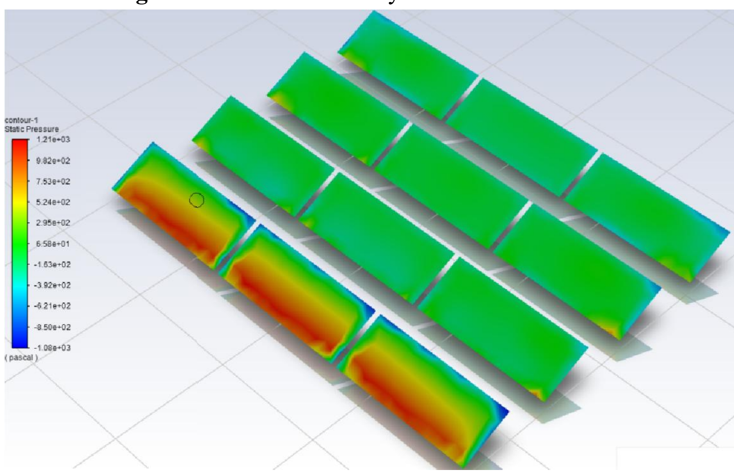

Figure 8: Pressure distribution on panels.

The maximum force has been computed through CFD analysis and is used to evaluate Wind Pressure for the worst load condition, as shown below.

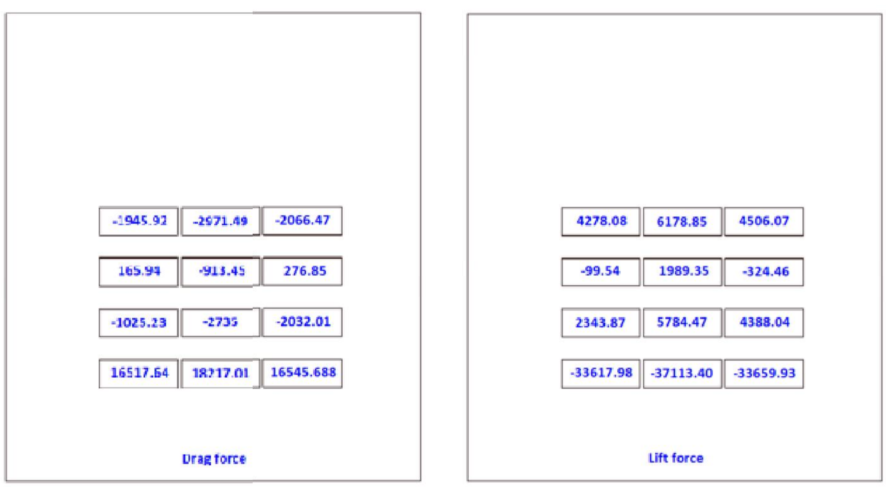

Figure 9: Drag and Lift force on panels.

Using the formula and data from CFD analysis 25^o of tilting angle, the following formula shall determine the coefficient of pressure Cp [2] from net average force.

$$C_P = \left[\frac{(F_D)}{\frac{1}{2}\delta V^{2`} A}\right]$$

Net Average Force	38034	-75347
Coefficient of pressure	0.68	-1.35

Wind loading acting on solar panels for upwind is calculated as follows. The two most prominent factors for evaluating wind pressure are the tilt angle of the panel and the wind speed. Accordingly, the design wind pressure is calculated as per IS code 875 part 3

- Wind Speed = 47 m/s
- Tilt angle =25° (solar panel tilt)

The above two factors govern the evaluation of wind pressure in the respective direction. As per IS875 code, for the above conditions.

Design wind speed

$$Vz = Vb \times k1 \times k2 \times k3 \times k4 = 38.49\ m/s$$

Wind pressure at height z

$$Pz = 0.6 \times V^2 = 889.02\ Pascal$$

Table 3: Describes various factors as shown below

Factors	**Used to account**	**Value**	**Code reference [9]**
k1	Probability factor for basic wind speed	0.9	6.3.1
k2	Terrain roughness and height factor	0.91	6.3.2
k3	Topography factor	1	6.3.3
k4	Importance factor for cyclonic Region	1	6.3.4
Ka	Area averaging factor	0.9	7.2.2
Kc	Combination factor	0.98	7.3.3.13
Kd	Wind Directionality Factor	1	7.2.1

Design wind pressure

$$Pd = kd \times ka \times kc \times Pz = 634.46 Pascal$$

Maximum pressure coefficient Cpd=1

Minimum pressure coefficient Cpu= -1.6

Design Wind Pressure for upwind= $Cpu \times Pd$ = 812. 11Pa.

Design Wind Pressure for downwind= $Cpd \times Pd$ = 685.21 Pa.

VI. Result Summary

Table 4: Wind pressure comparison

Description	**IS CODE**	**CFD RESULT**
C_{Pi}	1	0.68
C_{pe}	-1.6	-1.35
Design wind Pressure	634.4626	634.4626
Upwind	812.1121	685.2196
Downwind	507.5701	345.1477
Total Deformation for upwind case (mm)	15.94	13.522

The result is approximately 18 % Less than the analytical value.

VII. Static Structural Analysis for Upwind

To examine the magnitude of induced stresses arising from various design loads, a design-by analysis approach using finite element methods has been necessary because of the absence of suitable design-by-rule methods for the design features requiring assessment. To get wind pressures through CFD simulation on a 5Cx4R Ground-mounted solar farm

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was done, which is then used in following FEA to check the strength and stability of the component. The site location is India, with a basic wind speed of 47m/s.

7.1 Boundary Condition and Loads for Static Structural Analysis

The analysis aims to verify structural stability considering dead load, wind, and wave loads for the Ground-mounted solar farm utilizing the structural FE analysis. The system, which constitutes a photovoltaic array(s) is designed to withstand the extreme fair wind (positive pressure) and adverse wind (negative pressure) on the design tilt angle of the solar photovoltaic array (s).

- Wind force on the panel due to wind loading is applied on the Panel face as normal force. Wind pressure for load due to proper wind direction on the design tilt angle of the panel, load due to adverse wind direction on the design tilt angle of the panel, and load on a side face of components are considered. All the values are obtained as per CFD see Section III.
- Self-weights are directly taken by FEA software from given densities.
- Since Geometry and loading is symmetrical, it is convenient to solve the problem by considering Symmetry in FEA. Thus, in figures, all the models are shown in halves because of the Symmetric boundary condition.

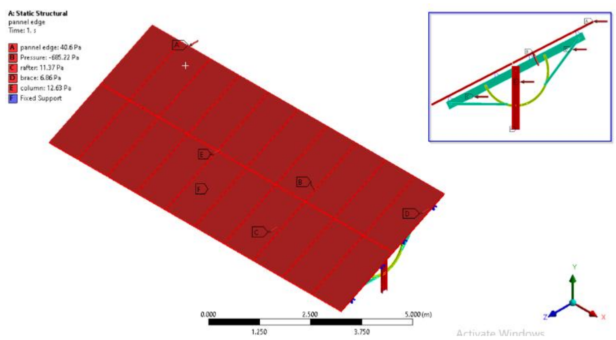

Figure 10: Boundary conditions and load for upwind

7.2 Structural Analysis Assumptions and Simplifications

1. Stiffening-effect due to Wind load (w), Snow loads (St), Self-restraining loads (T), and any other loads are not considered.
2. Structural members are considered homogenous and assumed that they do not contain defects.
3. Member connections are assumed Bonded.
4. Panel density is 1850 kg m^-3 and stiffness is 2.1e+07 N/m^2.

7.3 Result

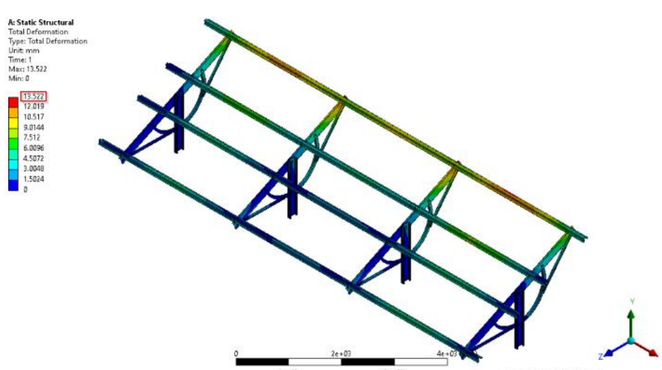

Figure 11: Total Deformation plot for upwind.

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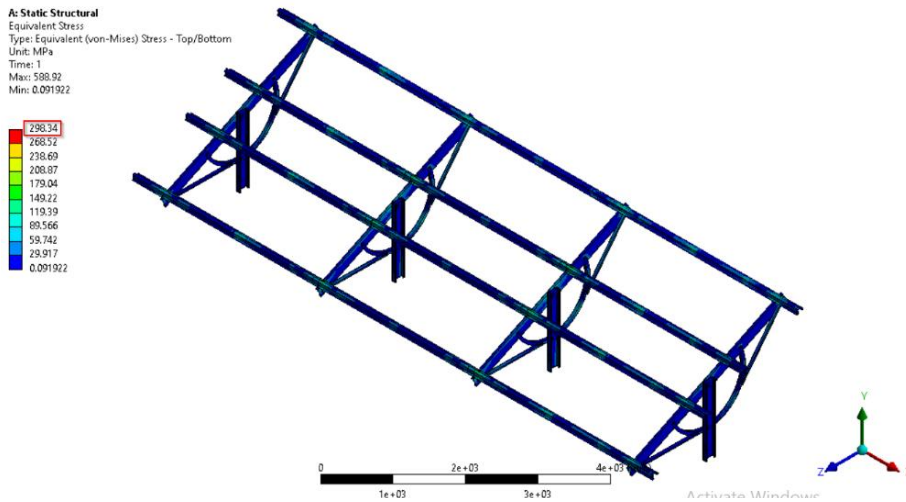

Figure 12: Equivalent Stress plot for upwind.

As per the above analysis, the induced stress in all the components is within the permissible limit. Hence, the designed components for the given material with required additives are safe for the given load condition.

VIII. Dynamic Analysis

The dynamic structural analysis of a 2P×10 MMS system is carried out with six different tilt angles based on its modal parameters (natural frequencies, modal shapes, and modal damping ratios) and dynamic performance indices (Modal participation factors, forcing frequencies, and mechanical quality factors) employing the Finite Element Analysis (FEA).

8.1 Analysis Details

Table 5: Analysis Details

Analysis type	Modal (Natural frequency)
Unit System	SI system
Site Location	India
Tilt angle	Variable (5 to 30 deg)

8.2 Analytical Methodology

A design-by-analysis approach using finite element methods has been necessary because of the absence of suitable design-by-rule methods for the design features requiring assessment and the need to investigate the magnitude of the frequency of vibrations carefully. The overall process of using Modal Analysis Simulation for carrying out FEA consists of three main steps: pre-processing, analysis, and post-processing. Key entities that constitute an FEA model include a geometric model of the structure created in SOLIDWORKS, a finite element mesh, material properties, loads, and boundary conditions.

8.3 Model Analysis

Dynamic analyses is modal analysis, which yields the natural frequencies and corresponding mode shapes of a system under evaluation. In other words, when performing a modal analysis, we solve for the distinct deformation shapes that the vibrating system will behave at each of its oscillation frequencies.

After the fourth mode, every two consecutive modes have almost the same frequency due to the axial symmetrical structure. The vibration mode shape is also symmetrical, consistent with the mechanical structure.

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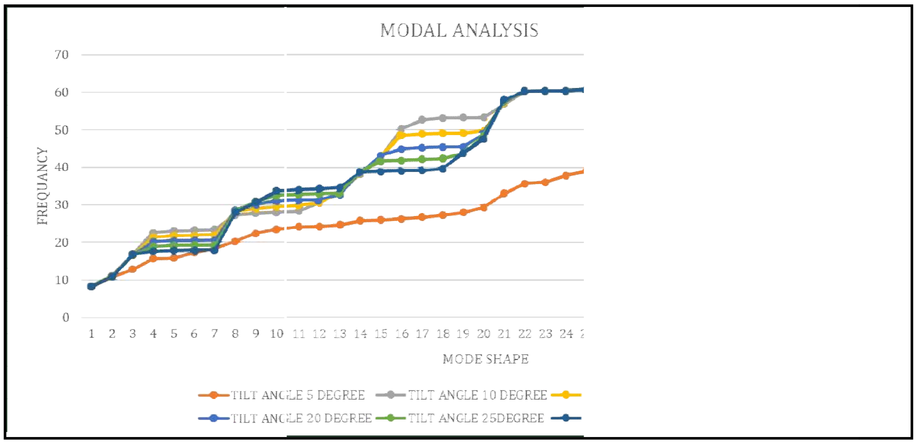

Figure 13: Frequency vs. mode shape.

IX. Vortex Shedding Frequency

Vortex shedding is a naturally occurring phenomenon. Due to the vortex shedding, dynamic loads are generated on the object, fluctuating at a specific frequency. Vortex shedding frequency described by the Strouhal number (St) [10].

St = fL/U

Where, f = frequency in Hz, U= wind speed, L = characteristic length of the body

Here L is the vertical projection of the chord length (C)

L = C * sin (θ)

θ Is the tilting angle of the solar panel

The value of Strouhal number (St) for a tilted flat plat is 0.15 [8]. The strouhal frequency is based on the highest 3-sec mean (gust) within a 1 hour observation period. As the strouhal number is fixed, the vortex shedding frequency will also get doubled if we doubled the wind speed.

St = fL/U = 0.15

U= Hourly mean speed at height(z)= V_b/k_0

V_b=Basic 3s gust wind speed

K_0 = 1.525 for wind speed 3s gust to hourly mean speed

St =0.15 Strouhal number

L= 1.75=C*sin(θ) breadth of the structure.

C=3.972 = chord length of panel

Direction	Mode (Hz)	Wind Speed, U(m/s)										
		10	15	20	25	30	35	40	45	50	55	60
X Tra	1st Mode: 8.26	2.838	4.257	5.676	7.095	8.514	9.933	11.352	12.771	14.19	15.61	17.029
Y Tra	9th Mode: 22.47	2.838	4.257	5.676	7.095	8.514	9.933	11.352	12.771	14.19	15.61	17.029
Z Tra	2nd Mode: 10.85	2.838	4.257	5.676	7.095	8.514	9.933	11.352	12.771	14.19	15.61	17.029
X Rot	2nd Mode: 10.85	2.838	4.257	5.676	7.095	8.514	9.933	11.352	12.771	14.19	15.61	17.029
Y Rot	2nd Mode: 10.85	2.838	4.257	5.676	7.095	8.514	9.933	11.352	12.771	14.19	15.61	17.029
Z Rot	9th Mode: 22.47	2.838	4.257	5.676	7.095	8.514	9.933	11.352	12.771	14.19	15.61	17.029

Table 6 : Strouhal number frequency vs. actual MMS resonant frequency

From the above table, it is observed that the actual frequency of the system is not in a close range of natural frequency for all six different directions with six different wind speeds. After the dynamic analysis, it is found that Strouhal frequency from 10m/s, 20m/s, 30m/s, 44m/s, 47m/s, 50m/s, wind speed is in close range to a natural frequency of 8.51Hz of 5-degree seasonal tilt module mount structure, which makes the structure to failure under dynamic condition. Hence our structure is not safe for the service.

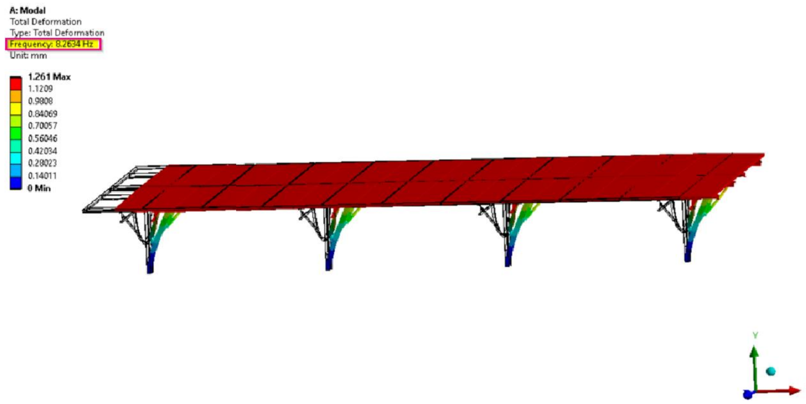

Figure 13: a) The First mode for 5-degree tilt angle solar MMS.

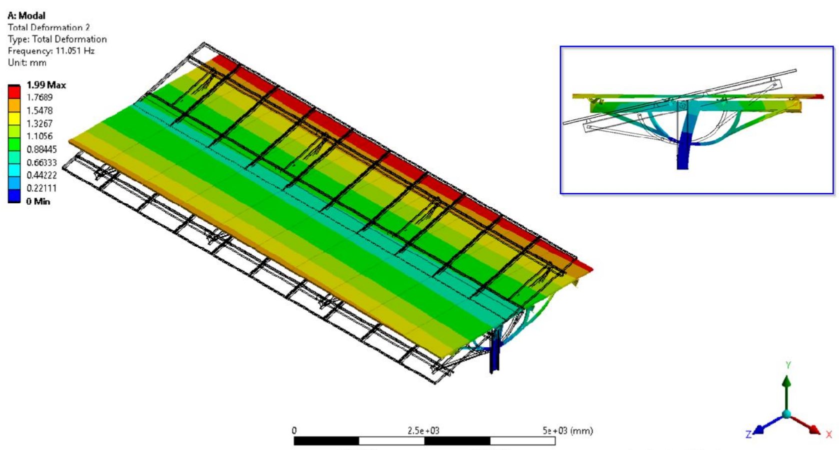

Figure 13: b) Second mode for 5-degree tilt angle solar MMS.

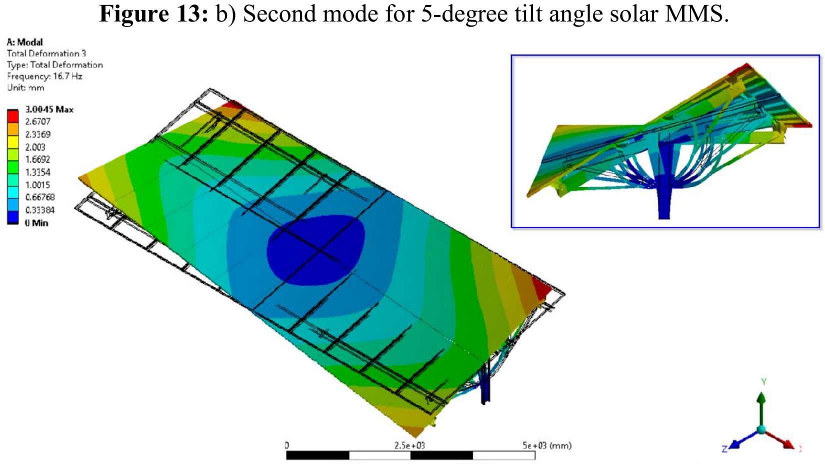

Figure 13: c) The Third mode for 5-degree tilt angle solar MMS.

The three modes of vibrations of the MMS for elevation angle at5- degree a)first b)second c) third mode. The results show that the first mode of vibration is the translation in the X-direction and the second vibration mode is bending along the Z-direction in phase or phase opposition in the XY plane. With exception of the third mode is torsional around the X-direction in the YZ plane.

X. Conclusion and Discussions

CFD simulation indicates that high wind pressure is subjected near the panel region during the upwind load condition and hence the probability of failure at this condition is high and hence accordingly maximum lift force is considered for Structural analysis. Upwind load condition should be taken as the worst case and design and analysis should be done for the same case. Pressure coefficient coming from CFD results are of less magnitude than results from IS 875 code. As IS code values are found out for the structure of height more than 10 m and at near to ground wind effect is less as compared to at of 10 m height. The structure is passing in static analysis for code requirement to stress and deformation limits. However, based on modal analysis results structure may adversely affect at 5-degree and 10-degree at 30 m/s and 40 m/s based on comparison of Strauhal Frequency and natural frequency results. This kind of behavior is found in low-frequency structures and Structure need to be strengthened.

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