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Full-scale measurements of wind load effects in a photovoltaic single-axis tracker module rail

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SUMMARY:
The high demand of solar photovoltaic installations used for electric power generation have resulted in an extremely competitive industry. Suppliers are under pressure to reduce design margins wherever possible for projects to be feasible. Single-axis trackers have become a popular means of increasing yield and reducing the levelized cost of energy (LCOE). However, these wind sensitive structures have been known to suffer wind damage despite the use of modern design methods and codes. Wind loading on tracker arrays are typically quantified using proprietary model-scale studies in atmospheric boundary layers wind tunnels. The current study will present results from extensive full-scale field measurements performed on an experimental one-in-portrait (1P) single-axis tracker facility in the Western Cape, South Africa. The purpose of these measurements is to quantify wind load effects in an instrumented module mounting rail, or purlin. The experimental data will be compared to results from analytical and numerical methods found in literature. Experimental data will furthermore be used in cyclic loading analysis. It is expected that these results may explain observed wind damage on existing installations and inform future design efforts to ensure long-term reliability.

Keywords: Photovoltaic single-axis tracker, full-scale wind load measurements, ASCE 7-22

1. INTRODUCTION

Photovoltaic (PV) single-axis trackers (SATs) follow the sun throughout a day, rotating from east to west about a horizontal north-south aligned axis. This causes aerodynamic properties of the structure and hence static and dynamic wind loads to vary. The basic design of a 1P SAT PV system is shown in Fig. 1. Structural elements such as the module mounting rail, torque tube and pile are visible below the PV modules. This study focuses on the effects of wind loads on the module mounting rail, which Wittwer et al. (2022) identified as one of the most critical structural elements of the tracker.

The inherent large surfaces and lightweight support structures mean that wind loading considerations govern the structural design of large PV installations. This is exacerbated by the fact that PV installations are typically located in flat exposed locations associated with higher wind loads. Significant damage of single-axis trackers due to wind actions have been reported in literature (Valentín et al., 2022, Molina, 2022). According to Wittwer et al. (2022) limited guidelines and codes of practice relating to wind load effects are concerns for manufacturers and owners in the industry.

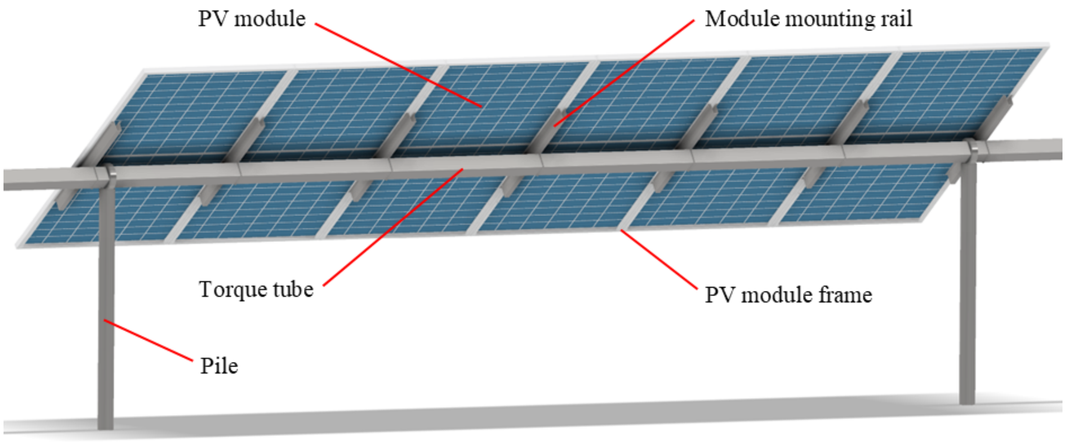

Figure 1. Design of a single-axis tracking PV system

2. LITERATURE REVIEW

PV SATs are dynamically sensitive structures. A study by Strobel and Banks (2014) supported by experimental work in an atmospheric boundary layer wind tunnel (ABLWT), showed that ground-mounted photovoltaic arrays can experience resonant response due to vortex shedding and buffeting. Significant dynamic excitation may occur at frequencies above 1 Hz, the previously assumed upper limit that defined flexible structures according to older versions of ASCE 7 (American Society of Civil Engineers, 2022b). These findings are reiterated by Cain and Banks (2015), who state that many array designs may experience dynamic effects in significant wind events. According to these researchers, dynamic amplification factors (DAF) greater than 2 have been found in low damped systems (damping ratio $< 2\%$). They furthermore propose a frequency threshold to avoid resonance due to vortex shedding.

Previous versions of ASCE 7 did not make explicit provision for ground-mounted PV structures, but have been used in their design process nonetheless. Recent updates to ASCE 7 cater for fixed-tilt installations based on wind tunnel data presented in Browne et al. (2020). However, these provisions are not applicable to SAT PV installations due to the flexibility and aeroelastic effects seen in these structures. ASCE 7 recommends the consideration of wind tunnel testing in accordance with ASCE 49 (American Society of Civil Engineers, 2022a) for structures outside the scope of design codes. However, turbulence flow scale mismatches in small-scale ABLWT testing can lead to underestimated peak wind loads (Aly, 2016, Aly et al., 2013). This introduces scope for full-scale field measurements on a SAT PV installation.

Wind loads defined in ASCE 7 represent equivalent static design wind loads that a structure must be capable of withstanding. Load cycles necessary for fatigue design are not defined, but may prove significant due to the dynamic wind-structure interactions SAT structures experience. According to Holmes and Bekele (2021), the total response of a structure can be divided into three components, namely: mean, sub-resonant and resonant responses. The relative contributions of these components to the forces and moments in the module rail are of interest. With the purpose of calculating the mean response, the wind speed and measured response averaged over 10 min will be correlated. The sub-resonant component will occur due to higher frequency wind gusts causing a forced response below the fundamental natural frequency. The resonant response will be associated with natural frequencies that are activated.

The current study will also seek to statistically correlate structurally significant wind load effects with wind characteristics. Methods for calculating both narrow-band and wide-band fatigue loading under varying wind speeds are presented in Holmes and Bekele (2021). These methods make use of appropriate probability distribution functions for both response peaks and mean wind speed. Using standardised methods, suitable probability distribution functions can be calculated for statical characterisation of the measured wind speed. Similarly, suitable cycle counting methods and statistical analysis will also be used to describe the measured response. Contribution of the dynamic load effects to metallic fatigue damage can be quantified using fatigue design codes.

3. METHODOLOGY

With the aim of conducting full-scale measurements of wind load effects on an SAT PV structure, an existing SAT PV array has been instrumented. The Mariendahl experimental array is located in the Western Cape region of South Africa. The surrounding area is consistent with exposure category C and surface roughness C: open terrain with scattered obstructions less than 9.1 m in height, as defined in ASCE 7-22.

The SAT array consists of six 30 m long rows placed 5 m apart. Two Canadian Solar monofacial PV modules (model CS3W-420P HiKu) were added to the array using module mounting rails similar in design to commercial examples in a 1P configuration, as seen in Fig. 2. The central mounting rail (painted white) has an equivalent tributary area equal to one PV module and was instrumented with strain gauges to capture the effects of wind loads on this component. Additional instrumented rails and bifacial PV modules will be added to the array to increase the aspect ratio and compare the impact of different module technologies on forces in the mounting rails.

Figure 2. Experimental setup added to the existing SAT PV array

Strain gauge data from the instrumented mounting rail is captured at 128 Hz by a Lord Microstrain SG-Link and wirelessly transmitted to a base station located approximately 90 m away in a temporary building structure. Full bridge strain gauge positions were determined using finite element

(FE) analyses of the structure. Two instrumented positions allow for compilation of equivalent loads and moments similar to how they are defined in ASCE 7-22 for fixed-tilt PV installations. Three positions were instrumented to provide redundancy in the measurement system and allows for a regression fit to be applied to the data. The PV module tilt angle is logged and transmitted at 4 Hz using a Lord Microstrain G-link accelerometer.

Site-level wind data is collected at a maximum sampling rate of 32 Hz using a Gill WindMaster Pro 3-axis ultrasonic anemometer mounted on a 10 m wind mast. A Gill WindSonic 2-axis ultrasonic anemometer placed 1 m away from and at the same height as the PV modules records local wind speed and direction at 4 Hz. Data from the WindSonic is logged by Lord Microstrain V-Link and wirelessly transmitted to the same base station. This system allows for synchronous data collection between all sensors in the network.

Wind speed recorded on-site is reported as 3 second gust wind speed at a standard height of 10 m using a moving average of 3 seconds, as recommended by the World Meteorological Association (Holmes and Bekele, 2021). The 3-axis wind measurements allow incoming site-level turbulence intensities to be calculated in the longitudinal, lateral, and vertical directions. Data will be logged for several months to capture a sufficient dataset containing multiple high wind speed events with different directions.

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