WIND LOADS ACTING ON PV PANELS AND SUPPORT STRUCTURES WITH VARIOUS LAYOUTS

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ABSTRACT

This study investigates the wind loads acting on ground mounted photovoltaic panels and the support structures thereof with wind tunnel experiments. As a result, observed at the northernmost panel is the minimum wind force coefficient to which the corresponding wind load exceeds the wind load specified in IEC 61215. On the other hands, the maximum and minimum wind force coefficients for the support structures have almost same values in various layouts of PV arrays. This means that the design wind loads for support structures can be determined independent on the array arrangements.

Keywords: PV Panel, Support Structure, Wind Force Coefficient

Introduction

In Japan, nuclear power facilities were damaged by Tohoku Earthquake March 11, 2011. Accordingly, the natural energy electric generation systems attract attentions, and a lot of photovoltaic (PV) plant has been constructed in Japan. Some PV plant may be vulnerable to wind hazard, therefore the information of wind loads is essential to the design of PV panels and support structures thereof. With the recent increased construction of PV plant, several experimental studies have been carried out on wind loading on PV panels, for example by [Chun et al. (2008)], [Kopp et al. (2012)] and [Ruscheweyh et al.(2013)]. Ruscheweyh showed that numerous parameters affect the wind load for PV panels mounted on the ground. One of them is geometry of the module field arrangement. At some PV plant, PV arrays which may consist of six or more panels will be arranged in the irregular shape of the site. In such case, it is not necessary to align the eastern and western edges of the arrays and they can be arranged in staggered arrangement. However, most of the information on wind loads is based on the aligned layout.

This study investigates the wind loads acting on PV panels and support structures thereof arranged in aligned and staggered arrangement. The case of the arrangement including a passageway among the arrays for maintenance work is also studied. The values of wind loads for the PV panels are different from those for support structures, as the tributary areas are different to each other. Those wind loads would be given separately.

Experimental Setup

Wind tunnel experiments were conducted in the boundary layer wind tunnel of Obayashi Institute of which test section has the height of 3m and the width of 3m. The boundary layer flow simulated as an open country terrain was applied in this study. The turbulent boundary layer flow was generated by means of spires and uniformly placed
roughness blocks. The velocity and turbulence intensity profiles are shown in Fig.1. The profile of velocity corresponded to the power law with exponent alpha ($\alpha$) is 0.15 and the turbulence intensity at the height of array was approximately 20%. The mean wind velocity at the height of 50mm (5m in full scale) above the wind tunnel floor was set to 11m/s. Fig.2 shows the power spectral density distribution of the wind velocity component at the height of array together with the Karman’s spectrum. The Karman’s spectrum is calculated from the Karman interpolation formula using longitudinal length scale $L_u=1$m. The spectrum of the simulated flow agreed considerably better with the Karman’s spectrum, except the high reduced frequency region.

The panel models have two different slopes, i.e. $\theta=10^\circ$ and $30^\circ$, as shown in Fig.3 (a). The models consist of ten rows of array with total length of 100m, which are scaled to 1/100. The array layout patterns are shown in Fig.3 (b). The locations of pressure taps and the wind direction are defined in this figure. The pressure taps were installed on both surfaces of the panels. Pattern A is the basic layout, and Pattern B has a passageway, which is formed as a vacant space after rejecting one low of array.

Wind pressures were measured at increments of 5° for wind directions between $0^\circ$ and $180^\circ$. Wind pressures were measured with the sampling frequency of 1,000Hz and sampling period of 20 seconds, corresponding to 33.3Hz and 10 minutes in full scale respectively. Each test case was sampled at 6 runs, and peak wind force coefficients were calculated as the average value of 6 peaks.

**Peak Wind Force Coefficients for PV Panels**

Wind forces acting on the panels are calculated from the simultaneous pressures at the upper and the lower surface of panels. The wind force coefficient at a panel is estimated as:

$$C_{f,\text{panel}}(t) = \frac{C_{p,\text{upper}}(t) - C_{p,\text{lower}}(t)}{0.5\rho V_H^2}$$

where $C_p(t)$ is the instantaneous pressure coefficients on the upper or lower surface of the panel; $\rho$ is the air density; and $V_H$ is the mean wind speed at the array height. The TVL method [T. V. Lawson (1980)] is used to determine the wind load acting on a panel area from point pressure with the averaging time of 0.015s corresponding to 0.4s in full scale.

![Fig. 1 Profiles of the velocity and turbulence intensity.](image1)

![Fig. 2 Power Spectrum Density of the wind velocity at 1m height in full scale.](image2)
Distributions of the maximum and the minimum peak wind force coefficients for panels at each tap over all wind directions are shown in Fig. 4. In this paper, upward forces are expressed as negative (minus) values. The maximum peak wind forces are observed at the southernmost array and the west edge of the arrays in all layout patterns. In addition, the large positive wind forces act on the north side array of the passageway in Pattern B, and on the edges of array in the staggered arrangement, Pattern D.

For the minimum peak wind force coefficients, the unfavorable values were observed at the northern edges of all arrays, due to the separated flow. The higher negative force coefficient is recorded at the northernmost corner with panel slope $\theta = 10^\circ$, and the value is much lower than that with $\theta = 30^\circ$. The distribution of higher negative wind forces acting on the edges of array in the staggered arrangement (pattern C) was similar to that of positive wind forces acting in Pattern D.

In Pattern B, a large minimum peak wind force acts on the south side array of the passageway. For the appropriate wind resistance design, it is necessary to consider the severe wind forces acting on the arrays faced to the passageway as same as the perimeter of arrays.
The worst minimum wind force coefficient of $-4.3$ appears in Pattern C when the panel slope $\theta=30^\circ$. This minimum peak wind force is observed at the northwest corner of the northernmost array. In addition, the coefficient values of $-4.0$ or less are also observed at the corners of the other array in the case of the staggered arrangement. Both of IEC 61215 and JIS C 8990 requires that PV panels should not be damaged by wind of which velocity is 130km/h or the pressure of 2,400Pa. The minimum peak wind force coefficient of $-4.3$ observed in this study produces the pressure of 3,344Pa where the wind velocity is 130km/h. Therefore, the panels should be required to resist the wind force more than those specified in such standards.

![Image](image-url)

Fig. 4 Worst maximum and minimum peak wind force coefficients on PV panels (for all azimuths)
Peak Wind Force Coefficients for Support Structures

Design wind force coefficients specified in JIS C8955 are given as a function of a panel slope $\theta$. The design wind force coefficient is defined as only one value by panel slope. However, the wind forces are not distributed uniformly. The wind load for the shorter column of support structure may not be same as that for the longer column.

Fig. 5 shows the schematic diagram of the wind force distribution. Reaction forces at each column are calculated by using two kinds of the wind load distribution models. One of them is the uniformly wind load case and the other one is the ununiformly wind load case. Wind loads acting on the panels are calculated using the time series of the wind force coefficients obtained from the simultaneous pressure on the panel and the velocity pressure at the array height. The tributary area of one support structure has the width of 4m and the depth of 4m in full scale. Reaction forces are estimated by the equilibrium of the moments.

Reaction force changes by the position of columns. Here, the estimated result represents a typical value of reaction force for one particular arrangement. In case of the area averaging wind load, the reaction force acting on the shorter column $R_{a1}$ is equal to the reaction force acting on the longer column $R_{a2}$.

In this paper, non-dimensional reacting forces are treated as wind force coefficients for support structure. Non-dimensional reacting forces $C_R$ are defined as follows:

$$ C_R = \frac{R}{q \cdot A} \tag{2} $$

where $q$ is the velocity pressure at the array height, $A$ is the tributary area of one support structure.

The maximum and the minimum peak wind force coefficients for support structures for all azimuths are shown in Fig. 6. The results show that there is a significant difference of the coefficients when the ununiformly wind load is taken into account. There is a little difference for the maximum peak wind force coefficients of the various layout patterns. On the other hand, the minimum peak wind coefficients are significantly different between the uniformly and the ununiformly wind load case, especially $\theta=30^\circ$. Generally speaking, the longer columns have higher upward wind load than the shorter columns. High extraction strength is required to resist large upward wind load for the longer column.

The maximum peak wind force coefficients take almost constant value at each panel slope among the various layout patterns. The minimum peak wind force coefficients have also similar tendency, except in Pattern C in $\theta=10^\circ$, which is slightly lower than those in the other layout patterns. Consequently, it can be concluded that the array arrangements does not significantly affect to the design wind force coefficients for the support structures.

**Fig. 5 Schematic diagram of wind load distribution**
Fig. 6  Peak wind force coefficients for support structures for all azimuths and for all columns

(a) Maximum wind force coefficients

(b) Minimum wind force coefficients

Fig. 7  Distributions of the ratio of peak wind force coefficient compared to the maximum/minimum peak wind force coefficients over all azimuths and in all columns
In the point of view of wind resistance design, the arrangement of PV arrays is classified into the peripheral regions and field regions. PV arrays are designed by two different level wind loads. It is important for reasonable design to clarify the peripheral regions where strong wind loads act on the arrays.

Fig. 7 shows the distributions of the ratio of peak wind force coefficient compared to the maximum / minimum peak wind force coefficients at all columns. The worst values estimated over all wind directions have been considered for each column. In the case of the steep downward wind load gradient such as Pattern D, the width of the highly loaded zone is easily defined. When the wind force variation is more gradual such as minimum wind force coefficient distributions, the width of the peripheral regions is decided as including the area that the wind loads are more than 60% of the worst value.

Fig. 8 shows the proposal peripheral regions. The width of the peripheral regions is defined to be twice the width of the array. The peak wind force coefficients of proposal peripheral regions and other regions are shown in Table 1. The peak wind force coefficients of the peripheral regions are determined as the mean value among all layout patterns of Fig. 6. The values in parentheses indicate the ratios of the field regions coefficients to the peripheral regions coefficients. The maximum wind force coefficients for the field regions significantly reduced to 50% of that for peripheral regions.

Table 1  Proposal peak wind force coefficients for support structures and ratios of the field regions coefficients to the peripheral regions coefficients

<table>
<thead>
<tr>
<th></th>
<th>$\theta = 10^\circ$</th>
<th></th>
<th>$\theta = 30^\circ$</th>
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<tbody>
<tr>
<td></td>
<td>Peripheral regions</td>
<td>Field regions</td>
<td>Peripheral regions</td>
</tr>
<tr>
<td>Long column</td>
<td>maximum</td>
<td>0.66</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>minimum</td>
<td>-2.20</td>
<td>-1.27</td>
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<tr>
<td>Short column</td>
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<td>0.45</td>
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<tr>
<td></td>
<td>minimum</td>
<td>-0.56</td>
<td>-0.33</td>
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Fig. 8 Proposal regions of the peripheral area of arrays
Conclusions

The present study focuses on the wind loads acting on PV panels and the support structures thereof. PV panels should resist the resulting wind loads, which exceed the design wind loads specified in some standards.

Distributed wind loads along the depth of the panels are used for the estimation of wind loads acting on support structures. In this case, the longer columns should resist higher upward wind load than the shorter columns. And at larger panel slope, the upward wind load becomes larger. Wind loads for support structures are independent on the array arrangements, and new wind loading zones are proposed in this paper. The definition of zones is probably the most difficult problem in the design of PV arrays. The spatial variation of wind force coefficients would be higher or lower for various locations depending on the geographical features of the site. However, the array arrangement is not significant for determination of the design wind force coefficient.

References


