WHITE PAPER

SINGLE-AXIS SOLAR TRACKER STOWING STRATEGIES: WHAT WILL BEST PROTECT YOUR INVESTMENT FROM EXTREME WIND EVENTS

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ABOUT THE AUTHORS

Nathalie Kermelk is head of engineering and product management at Ideematec Deutschland GmbH. With more than 13 years experience in solar industry, gained through leading solar manufacturers, such as Solarworld, she is now responsible for international projects design and new product development in a leading engineering position at Ideematec Deutschland GmbH. Her main skills are the structural integration and structural improvement of solar tracking systems with respect to wind static and dynamic stability.

Dr. Thorsten Kray led the Institute of Industrial Aerodynamics Solar Group at I.F.I. Aachen for 8 years and has recently been promoted to Head of Building Aerodynamics. He has overseen wind tunnel studies on hundreds of different solar roof and ground mount systems and has been involved in solar projects all over the world. Besides wind tunnel data based ballast layouts for solar arrays mounted on flat roofs, his key skills are static and dynamic loads on ground mount solar fixed tilt and tracking systems.
INTRODUCTION

The installation of utility scale PV tracking systems represents a significant investment for owners. The focus should not only be on the upfront cost, but also on the quality and durability of the whole PV power plant over a 25- to 30-year lifetime. Owners and other project stakeholders expect their investment to be long-lasting and durable. Obviously, a key component of any solar power plant is the tracking system itself and, thus, the focus lies on the tracker’s stability, resilience and technical matureness with regard to wind actions. This calls for sophisticated and quality-oriented engineering and profound knowledge of the parameters that contribute most to the structural integrity and stability of any tracking system.

Of these parameters, the natural wind and its related effects certainly pose the greatest challenge and threat to solar trackers and drive the design. For the past several years, the vast majority of utility-scale PV failures have happened due to adverse wind and weather conditions. Following major wind events such as hurricanes and extratropical cyclones, there is usually a rise in social media posts showing damaged solar power plants and failures related to solar installations. Not only does any damage to a power plant represent a serious loss of capital and revenue, but even worse, published photos and video footage of wind-related failures significantly affect the trust in the solar industry as a whole. In order to correctly account for wind effects on single-axis tracking systems, reliable wind and structural engineering are needed.

For the past several years, the vast majority of utility-scale PV failures have happened due to adverse wind and weather conditions.
Once the solar tracker is in operation, it has to be ensured that it can withstand operational and design wind speeds. The usual approach taken here is that the tracker remains in operation up to a certain wind speed threshold and goes into a safe stow position if wind speed rises above that threshold. The most important choice needs to be made between two fundamentally distinct philosophies: stowing flat vs. stowing at high tilt angles. While the first one has the advantage of low equivalent-static wind loads, it is extremely prone to aeroelastic instabilities if no appropriate counter measures are undertaken. Stowing at high tilts, on the other hand, reduces the risk of instabilities, but comes at the cost of significantly higher design wind loads.

The details surrounding wind mitigation of single-axis tracking systems is not always made available to the public. Despite this lack of information, we have attempted a review of stowing policies of single-axis tracking systems of the top 12 global PV tracker suppliers in terms of annual shipments in the market. Almost all suppliers rely on an active stowing approach, i.e. sensors indicate when wind speed exceeds a threshold and motors will actively put the trackers into their designated stow positions.

With regard to stow position, we found that more than 50% of the manufacturers stow at 0° tilt with the remainder of the tracker suppliers stowing at tilt angles of 30° or higher. Generally speaking, both stow strategies are applied to 1P/2H and 3H/2P/4H configurations.

Despite the higher susceptibility to aeroelastic instabilities such as torsional galloping, flutter or vortex lock-in, most 2P/3H/4H trackers stow at 0°. Some tracker suppliers address this issue by reducing the tracker row length, thereby effectively increasing the eigenfrequency. However, this approach does have the disadvantage that more drives are needed which in turn increase cost and require additional maintenance with associated downtime.

A more cost-effective approach is the use of torsional locking devices which fix the tracker at 0° tilt angle when in stow mode, effectively making it comparable to and as stable as a fixed-tilt system. However, to the best of our knowledge, among the top 12 SAT manufacturers which supply 93% of worldwide shipments, only the pioneering Ideematec safeTrack SAT system and two others have adopted this approach. The concept of high transmission ratio and torsional locking devices is explained in detail from page 13 of the present Whitepaper.
As opposed to systems stowing flat, tracker suppliers who opt for a stow position of e.g. either -30° or +30° face the challenge that their systems are designed for wind approaching only from one 180° wind sector, where negative tilts denote the leading edge of the tracker moved towards the ground (nose down). Negative tilts are more commonly seen in the market due to lower torsional response compared with positive tilts.

The strategy of opting for either a positive or a negative tilt angle, however, poses a risk to both, the stability of the tracking system due to changes of wind direction during a storm and the associated potential for higher wind loading.

To that extent, the question arises: How big is that risk? To put it in other words, what are the chances that the wind will drastically change its direction within a short period of time and how long will that period of time be? An answer to the latter can be given by looking at typical go-to-stow-times of solar tracking systems. Most manufacturers that employ an active stow strategy state that their systems can go from operation to stow within a matter of minutes. Therefore, if a tracker needs to adjust stow position during a storm when the wind speed is already way beyond its go-to-stow wind speed, it is susceptible to failure due to aeroelastic instability and/ or wind loading in excess of the design wind loading.
The latest major storm causing strong wind gusts in Europe was windstorm ‘Ciara’ (also referred to as “Sabine” in German speaking countries) in February 2020. Ciara, which classified as an extratropical cyclone hit the British Isles and later mainland Europe with 3-second wind gusts locally exceeding 36 m/s or 130 km/h (81 mph). We have taken a look at wind data as published by the Deutscher Wetterdienst (German Meteorological Service) in order to quantify the extent to which the wind changed its direction and speed over time.

Sample data from German weather stations in three German cities are presented in Figures 1 through 3. Data series start on February 9 and end on February 10. Charts show the wind speed and direction for the maximum 3-second gust within subsequent 10min intervals. Individual data points, although spaced by 10min in the diagram, may be closer together in reality as the peak gusts within the 10min intervals may have occurred at the end and at the beginning of consecutive intervals.

Figure 1: Gust wind speed over time in windstorm Ciara, Weather Station 1
One can see that on February 9, and partly on February 10, the gust wind speed was well above 20 m/s, a typical value at which trackers go to their designated stow position. Thus it is of particular interest how wind direction changed over time. As shown in the green curves, the mean wind direction changed over time as the intensity of the storm weakened. On February 9, the average wind direction at all three stations was around 200° and went to around 260° in the course of the following day. Apart from this long-term trend, however, a variation on a shorter timescale is clearly visible.

Consecutive data points show a change in wind direction of up to 40°. From the data presented it appears that wind direction is particularly volatile as wind speed decreases. However, even strong wind gusts well beyond 20 m/s featured a change of wind direction of 30° or more from one 10-min interval to another. In any case, it is obvious that the wind direction is anything but stable during a storm and that wind directions of strong gusts may vary to a great extent during the response time of a typical tracker system.

*Have you ever asked yourself, how wind direction changes during a storm event and how a direction-dependent tracker reacts to these changes?*

*If the tracker cannot react within a defined timeframe it leads to a high risk for storm damages effecting both the overall system as well as modules!*
Extracting the Cp values from Tables 1 and 2 in the appendix, the design wind pressure (wind load) is calculated from equation (1). Note, however, that this design wind pressure already takes into account the ultimate limit states concept of AS/NZS 1170.0:2002 which is why no additional safety factor is needed. Since “Uplift” governs the stresses on modules, only pressure coefficients for that particular load case will be considered in the following.

For a 0° stow position, the design wind pressure (wind load) according to equation (1) corresponds to $w_1 = 1.337 \text{kN/m}^2 (1335 \text{ Pa})$ for the outer zone and to $w_1 = 0.802 \text{kN/m}^2 (802 \text{ Pa})$ for the inner zone.

Assuming a 30° stow position, an increase in wind loads is observed. The design wind pressure according to equation (1) now corresponds to $w_1 = 2.479 \text{kN/m}^2 (2479 \text{ Pa})$ for the outer zone, whereas for the inner zone a value of $w_1 = 1.385 \text{kN/m}^2 (1385 \text{ Pa})$ is calculated.

Table 1 summarizes the design wind loads in outer and inner PV array zones assuming wind zone A.4 for sample sites in Australia.

<table>
<thead>
<tr>
<th>Stow Position</th>
<th>Outer zone</th>
<th>Inner zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° stow</td>
<td>1337 Pa</td>
<td>802 Pa</td>
</tr>
<tr>
<td>30° stow</td>
<td>2479 Pa</td>
<td>1385 Pa</td>
</tr>
</tbody>
</table>

Table 1: Design wind load for modules in outer and inner PV array zones depending on stow position; calculation performed assuming wind zone A.4 according to AS/NZS 1170.2
Using ASCE 7-16, the code addressing “Minimum design loads and associated criteria for buildings and other structures” issued by the American Society of Civil Engineers, it becomes clear that the basic wind speed for Risk Category II buildings and other structures for most of the desert regions in the USA where SAT systems are being installed corresponds to about 115 mph or 51 m/s. The ASCE/SEI 7-16 basic wind speed is based on 3-second gust at 10 m height, 50-year return and Exposure C. Taking into account a wind directionality factor of 0.85, but setting the velocity pressure exposure coefficient, topo-graphic factor and the ground elevation factor to 1.0, a (peak) velocity pressure $q_z$ of 1.357 kN/m² is calculated.

Table 2 summarizes the design wind loads in outer and inner PV array zones based on pressure coefficients from Tables 1 and 2 of the appendix.

<table>
<thead>
<tr>
<th>Stow position</th>
<th>Outer zone</th>
<th>Inner zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$ stow</td>
<td>1493 Pa</td>
<td>896 Pa</td>
</tr>
<tr>
<td>$30^\circ$ stow</td>
<td>2769 Pa</td>
<td>1547 Pa</td>
</tr>
</tbody>
</table>

Table 2: Design wind load for modules in outer and inner PV array zones depending on stow position; calculation performed assuming a basic wind speed of 115 mph (51 m/s) according to ASCE 7-16

Note that in opposition to earlier editions of the ASCE/SEI 7 the basic wind speed maps in ASCE/SEI 7-10 and ASCE/SEI 7-16 include the importance and load factor, thus the wind load calculated according to equation (1) is directly applicable for strength design.
According to the Spanish wind loading standard, UNE-EN 1991-1-4:2018, the fundamental value of the basic wind velocity in zone B corresponds to 27 m/s, 10 minute mean at 10 m height above ground in terrain category II.

Assuming terrain category II, a (peak) velocity pressure $q_z$ of 1.072 kN/m² at 10 m height above ground (reference height for pressure coefficients) is calculated.

Since in the Eurocode the partial (safety) factor is not readily included in $q_z$, equation (1) needs to be modified as follows:

$$w_2 = C_p \times q_z \times SW$$  \hspace{1cm} (3)

where $SW$ is the partial (safety) factor; for ultimate limit states design, EN 1990 defines $SW = 1.5$

For a $0^\circ$ stow position, the design wind load according to equation (3) corresponds to $w_2 = 1.769$ kN/m² (1769 Pa) for the outer zone and to $w_2 = 1.061$ kN/m² (1061 Pa) for the inner zone.

Assuming a $30^\circ$ stow position, the design wind load according to equation (3) now corresponds to $w_2 = 3.280$ kN/m² (3280 Pa) for the outer zone, whereas for the inner zone a value of $w_2 = 1.833$ kN/m² (1833 Pa) is calculated. Table 3 summarizes the design wind loads in outer and inner PV array zones assuming wind zone B.

<table>
<thead>
<tr>
<th>Stow Position</th>
<th>Outer Zone</th>
<th>Inner Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>1769 Pa</td>
<td>1061 Pa</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>3280 Pa</td>
<td>1833 Pa</td>
</tr>
</tbody>
</table>

Table 3: Design wind load for modules in outer and inner PV array zones depending on stow position; calculation performed assuming wind zone B according to UNE-EN 1991-1-4:2018
Tables 1, 2 and 3 show that at a 30° stow position, loads on modules are higher by a factor of 1.8 compared with a 0° stow position. Another issue with high module loads is that module manufacturers often do not give their full approval for unusual fastening situations.

Generally speaking, the load bearing capacity of most modules corresponds to 2400 Pa (for Uplift) if module rails in compliance with the manufacturer’s manual are used.

However, for any deviation from the default mounting situation, e.g. if short module rails or no module rails at all are present, the load bearing capacity may reduce to a range of 1400 Pa to 1800 Pa.

Given these lower allowances for loads on PV modules, at some project sites stowing at 30° tilt may not be possible while stowing at 0° is.

Figure 1: Increasing module load with different tilt angles for Ideematec’s Horizon
A market-type tube tracker relying on modules mounted directly on top of the drive tube with no further transmission ratio has to withstand 100% of the forces acting on the table. These forces are fully transmitted to the motor and gearbox unit, see Figure 2.

Ideemathec’s SafeTrack Horizon tracker counts on a decoupled drive technology where the drive tube is mounted well below the module surface. With its patented rope winch technology and unique geometry, a transmission ratio between drive tube and module table of 1:28 can be realized. In addition, the ropes are redirected at the top of the table by a pulley reducing the rope forces by 50%, see Figure 3.

These technological features enable reduction of the forces on the drive tube to only 3.6% of the forces acting on the table, compare Figure 3.

Since loads on modules are higher by a factor of 1.8 when at 30° tilt angle compared with a flat stow position, the question arises why high tilt angles are chosen by some SAT manufacturers for stow at all. One of the possible reasons is aerodynamic instability which is more likely to occur if trackers are stowed flat and if no additional countermeasures are undertaken.

Ideemathec trackers rely on 0° stow position and have a proven stability over the whole wind speed range. Let’s look into their technology in more detail.

There are three key design features of SafeTrack Horizon which ascertain its high dynamic stability:

- reduction of forces on the drive tube
- high natural frequency and
- high damping ratio.

**Figure 2: Force transmission to the drive tube of a market-type single-axis tracker and of the IDEEMATEC safeTrack Horizon tracker**
The Ideematec SafeTrack Horizon tracker comes with two dampers on every post which gives a total of eight dampers per table with a length of 30 m, see Figure 4.

Modal analysis and field vibration testing show that the natural frequency of Ideematec’s SafeTrack Horizon tracker is high compared with other tracking systems in the market. Even with a lightweight structure, a typical natural frequency is 1.7 Hz. Since the natural frequency increases with stronger structural components, it is in most cases even higher. Projects in Spain have been realized with a natural frequency of 2.4 Hz. Another important characteristic of the SafeTrack Horizon is the high damping ratio which is usually around 15%.

Proof that dynamic wind effects do not have impact on the tracker’s behavior was provided by extensive wind tunnel testing. In particular, it was shown that the onset wind speed for aerodynamic instability also referred to as torsional galloping is well above the design wind speed and thus of no concern, compare Figure 5.
The plot shows that the onset wind velocity for a very light-weighted structure of SafeTrack Horizon with 1.7 Hz natural frequency corresponds to 59 m/s. Design of such light-weight systems can only be realized where low design wind speeds are required, e.g. a 40 m/s 3-second gust wind speed. Since in such case the critical wind speed for onset of aerodynamic instability is significantly higher than the design wind speed, wind-related failure cannot occur.

If the design is made for higher equivalent-static wind loading, e.g. for a 46 m/s 3-second gust wind speed, the natural frequency of the SafeTrack Horizon system is also further increased to 2.4 Hz, ensuring a safe design at every site by excluding the risk of aerodynamic instability.

The previous comparisons show that the critical wind speed for onset of aerodynamic instability is significantly higher than the design wind speed, wind-related failure cannot occur.

Since the critical wind speed for onset of aerodynamic instability is significantly higher than the design wind speed, wind-related failure cannot occur.
In its move to continuously improve and optimize their products to satisfy the needs of the customers while complying with the increasing requirements of the market concerning bifacial modules and autonomous installation, Ideematec has an innovative Single-axis tracker development in the final test phase. This new development benefits from Ideematec’s ten-plus years of experience in the tracker market and should, in addition to the highest stability and flexibility, enable to fulfill the requirements of modern large scale powerplants in Gigawatt size.

Although the design of the new tracker system differs significantly from the SafeTrack Horizon system and despite both systems having lengths of up to 180 m per row, aerodynamic stability of the new system is provided by mechanically locking the drive tube at every post.

Ideematec’s new tracker system comes with a unique device on the drive tube which drives a sprocket wheel, initiates the table’s rotation and is able to mechanically lock the module table at every post.

The system’s characteristic is that once locked, no loading acts on the drive tube anymore, as shown in Figure 6. In addition to its special locking technology, the innovative new tracker also comes with a comparably high natural frequency of the torsional mode shape. Both features of this patented technology effectively transform the moving tracking system into a fixed-tilt system.

Since fixed-tilt systems are stable at every tilt angle, failures associated with aerodynamic instabilities such as torsional galloping or flutter are effectively eliminated.

Figure 6: Detail of mechanical locking of the drive tube of the new IDEEMATEC tracker
The stow strategy is a key contributor to avoiding wind-related failure of a tracking system. At the same time, it also governs how much material must be implemented in a structure at a particular site. In the present Whitepaper it is shown that the safest tilt angle for stow is 0° if combined with intelligent load transmission or mechanical locking, high natural frequency and high damping ratio.

Moreover, the 0° stow position leads to enormous material savings in the structure and provides the best protection of photovoltaic modules against damages such as micro cracks in cells as well as back sheet and glass defects through sandblast abrasion. This is of prime importance since the modules are the highest invest of a solar plant.

Stowing flat is also easy to achieve by use of just one inclination sensor. In addition, the 0° stow position is not vulnerable to changes of wind direction as opposed to tracking systems which rely on stow at a high tilt angle without being designed for the full compass of wind directions. Another source of uncertainty of such high-tilt stow strategy may be the measurement of wind direction.

**CONCLUSION**

Last but not least, it is important to note that not every single-axis tracking system is safe at 0° stow position. Owners, EPCs and other project stakeholders should closely monitor the combination of torsional stiffness, natural frequency, and damping ratio that is to ascertain the aerodynamic stability of market-type systems at operational and design wind speeds.

We believe that modern tracking systems can unlock considerable cost savings. The excellent dynamic properties and improved locking mechanisms of our trackers will offer the opportunity to further lower the LCOE of PV systems. As our industry moves to play a bigger role in the global energy market, we’re ready to help developers and investors unlock their project’s full potential.

- Mario Eckl  
CEO, Ideematec
WIND LOADS ON PHOTOVOLTAIC MODULES

The wind load on a PV module is defined according to the equation below:

\[ w_1 = C_p \times q_z \]  

(1)

where

- \( w_1 \) [kN/m²] is the wind load acting on a PV module
- \( C_p \) [-] is a dimensionless pressure coefficient either taken from a boundary layer wind tunnel study or from the governing wind loading standard
- \( q_z \) [kN/m²] is the velocity pressure at the reference height; in most wind tunnel studies this reference height corresponds to 10 m above ground; in major wind loading codes such as EN 1991-1-1:2005 and ASCE 7-10 the velocity pressure is averaged over a duration of 3 seconds which is why it is also referred to as gust pressure

Accordingly, \( F \) [kN] is the equivalent-static force acting on a PV module

\[ F = C_p \times q_z \times A_{ref} \]  

(2)

where

- \( A_{ref} \) is the tributary area; for clip design, the tributary area corresponds to half of the module area

From the equations above, it is obvious that the \( C_p \) values largely govern the wind load acting on a PV module. Typically, pressure coefficients are determined from wind tunnel studies specific to the solar structure in question.

In order to understand why the stow position should be 0° from a structural point of view, it is necessary to learn more about \( C_p \) values.
In Tables 1 and 2, Cp values for module tilt angles of 0°, 10°, 20°, 30° and 45° are given. Furthermore, differentiation between outer and inner zones in PV arrays is made. Two load cases, Uplift and Downforce, are relevant for the design of solar PV modules. Graphical representations of Cp value over tilt angle are given in Figure 1 and in Figure 2 for the “Uplift” load case.

### Table 1: Cp values for outer zones in a solar array, typically two perimeter rows and edge tables

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Uplift</th>
<th>Downforce</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>-1.10</td>
<td>0.29</td>
</tr>
<tr>
<td>10°</td>
<td>-1.52</td>
<td>1.30</td>
</tr>
<tr>
<td>20°</td>
<td>-1.91</td>
<td>1.60</td>
</tr>
<tr>
<td>30°</td>
<td>-2.04</td>
<td>1.65</td>
</tr>
<tr>
<td>45°</td>
<td>-2.12</td>
<td>1.71</td>
</tr>
</tbody>
</table>

### Table 2: Cp values for inner zones in a solar array

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Uplift</th>
<th>Downforce</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>-0.66</td>
<td>0.14</td>
</tr>
<tr>
<td>10°</td>
<td>-0.99</td>
<td>0.50</td>
</tr>
<tr>
<td>20°</td>
<td>-1.16</td>
<td>0.63</td>
</tr>
<tr>
<td>30°</td>
<td>-1.14</td>
<td>0.65</td>
</tr>
<tr>
<td>45°</td>
<td>-0.87</td>
<td>0.70</td>
</tr>
</tbody>
</table>

It is obvious that Cp values increase with increasing module tilt angle. This leads to higher wind loads and forces on photovoltaic modules according to equations (1) and (2).