Challenges and solutions for ensuring the long-term health of solar power plants

EPC best practice | Later this year, a new set of industry guidelines will for the first time codify a set of best practices for EPC contractors. Ahead of publication, members of Solar Power Europe's O&M task force look at some of the critical areas of PV system integration where high-quality EPC work can most effectively influence a project's lifetime performance

Solar PV is a reliable and stable technology, with innovation in modules only increasing its life expectancy. While PV modules generally receive most of the attention in the solar sector, there are a variety of technologies and services that are essential to the success of any PV installation; many of these come under the umbrella of EPC – engineering, procurement and construction – encompassing end-to-end solar services, from system design and procuring components to installing the project.

After the success of SolarPower Europe's Operations and Maintenance (O&M) Best Practice Guidelines – now in its fourth version – and its first edition of guidelines related to Asset Management (published in December 2019), the task force behind the two documents is now developing its first-ever EPC Best Practice Guidelines, which will aim to help the industry standardise and optimise the EPC segment. The document, which will be published later this year, is not only targeted towards EPC providers, but all relevant stakeholders, including investors, financiers, monitoring solution providers, asset managers and even O&M contractors. An important element of the EPC guidelines will be to benefit from the long-term experience that the European solar industry has in the operational phase and create a feedback loop and dialogue with all providers.

This article aims to introduce some of the core elements of EPC: inverters, trackers, junction boxes, and monitoring technology. These are the technologies that ensure the long-term success and efficiency of solar installations, and, if appropriate attention is given to them, can end up saving developers significant resources over the course of the solar PV system's lifecycle.

Inverters: the heart of PV plants

Inverters and their associated technologies are central components in all solar PV systems. Inverters ensure downstream that the power generated by the PV array can be fed into the grid, used by connected AC consumers or temporarily stored in conjunction with storage systems.

EPC contractors have a key role to play in ensuring the long-term health of PV power plants

Upstream, they perform important safety functions, such as earth fault detection, arc detection and anti-islanding. Due to the continuously increasing share of PV in the energy mix, inverters must perform more and more tasks, also related to grid stabilisation; as grids become smarter, inverters must also take over more grid-related services. In order to perform these services at all times, an increasing number of PV power plants will be combined with energy storage systems. The inverter can thus be described as the heart of any PV power plant – its failure therefore leads to serious problems with the larger system components.

Topology

The topology of a PV power plant usually follows three different concepts: (1) large parts of the plant can operate via a central inverter; (2) the inverter can be used at string level, combining single or multiple strings; or (3) it can be operated on a module level, via module-level power electronics (MLPE). With regard to ease of

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maintenance and availability of the plant, it should be noted that central inverters are easy to maintain, and in the best-case scenario can be repaired on site, therefore offering a high overall lifetime of 20 years or more. However, in the event of a problem, large parts of the power plant are separated from the feed-in. MLPEs as well as string inverters cannot usually be repaired on site and should not be touched until environmental influences have been eliminated. In the event of their failure, only smaller system parts or even only one PV module is affected. Such inverters usually have a lifetime that is shorter than the plant's operation time, so they need to be replaced during the life of the system.

In addition, the specific number of failures for less accessible components increases with the number of electronic components used in the system. Market analyses in relation to the frequency of the use of different topologies in industrial and utility plants show an even distribution of string inverter and central inverter designs, and a growing number of MLPE-based plants (although on a much lower level). Availability also plays a major role in the selection of the appropriate design or provider. In the event of a defect, short-term availability of replacements is crucial to keep yield losses to a minimum.

Inverters play a central role in the overall reliability of a PV system

Credit: SMA Solar

Planning and commissioning

The importance of planning when it comes to PV installations cannot be emphasised enough. In addition to the quality and reliability of the components used, it is at this stage that the quality of the system's subsequent performance is determined. Besides standard-compliant planning, the environmental conditions and working windows recommended by the manufacturer must be observed. Non-observance of these requirements usually leads to increased failure rates during operation. It is therefore recommended to have each system of relevant size inspected by an independent party before and after commissioning, and to have any deviations corrected. The documents of the IEC 62446 series, for example, provide guidance on the appropriate procedures.

Downtimes of PV systems are often caused by inverters [1]. However, many of the interruptions underlying these evaluations are ultimately due to problems with other system components. Here, ground-fault problems and, if a corresponding detection is available, actual or incorrectly detected arc-faults play a role. In addition to the plant design, the quality of the components used is of decisive importance. However, a plant designer or installer has only limited possibilities to comprehensively assess quality without being able to rely on field data and other empirical values. The conformity of the inverters to qualifying standards is mandatory but does not allow a detailed statement about their durability in the field. This can only be determined by a long lifetime test, in connection with simulations based on inverter lifetime models.


Ensuring the structural integrity of trackers involves multiple stakeholders

Credit: Array Technologies

Maintenance

According to the data available, the error rate for inverters is 300–500 times higher than for PV modules [1]. Even if one considers that the number of installed modules is similarly higher than the number of inverters, this value shows the importance of inverters for reliably high yield values of PV systems. The reliability of inverters depends largely on the reliability of the components installed in them, such as IGBT power bridges, capacitors and others. The lifespan of each of these components can be assessed accurately on the basis of extensive modelling. The inverter, however, consists of a large number of such components which are complexly interwoven and where a reduced function of most of these components results in a standstill of the entire inverter. Because of this, the prognosis of the lifetime of such systems is complex and not always accurate.

A decisive factor that determines the lifespan of inverters, besides the design, is their maintenance during operation. While not all the topologies described above can be maintained in the same way – MLPEs are maintenance-free in principle and string inverters can hardly be maintained – it is often sufficient to protect against environmental influences and contamination during maintenance. In addition, especially for large plants, the creation of a maintenance concept consisting of the three most important components – preventive maintenance, corrective maintenance and predictive maintenance – is a good idea. Details on the creation of such comprehensive concepts are described elsewhere [2, 3]. It is expected that future innovations to inverters will improve their lifespan; however, early research indicates that an extended provision of grid-related services, such as reactive power supply, will have a negative effect on the lifespan of inverters [1].

Energy storage

Large-scale energy storage systems are still a relatively new technology, and there is only limited data as to performance and lifespan. It can be assumed that energy storage systems, at least with regard to electronic components such as semiconductors and capacitors, exhibit similar failure rate behaviour to those in classic system configurations. The core of the energy storage devices – the battery cells – exhibit a different behaviour. In addition to so-called 'calendar ageing', they exhibit load-dependent ageing. Depending on the application – rare grid support or daily complete cycling – they have to be replaced at a certain point, but usually before the inverter has reached the end of its lifespan. Further topology-dependent considerations are described elsewhere [4].

The reliable and continuous operation of inverters is of central importance for long-term high energy yields of PV power plants. A good system design that allows for standard-compliant operation under the conditions specified by the manufacturer is of central importance. However, this should be checked in the course of a detailed plant acceptance test in order to be able to address deviations. A plant-specific maintenance concept helps to detect and eliminate early failures in time. It also ensures that many environmental influences are reduced over the years to the level envisaged in the plant design.

Trackers

As it stands, there is no specific standard for the structural calculation of trackers in a solar PV fixed structure. Therefore, the calculation is based on civil codes for building like ASCE or Eurocode. There is a deficit in standardisation, which could lead to problems. Moreover, applicable tracker certification for IEC 62817 or UL 3703/UL2703 do not cover structural issues but rather potential failures or health and safety issues. With that said, civil construction codes have typically been applied to trackers with insufficient attention to the structural dynamics. Structural dynamics refers to a type of structural analysis that relates to the behaviour of structures subjected to dynamic loading (i.e. wind, wave, traffic, earthquakes, impacts, etc).

Dynamic behaviour is a concern for both fixed solar structures and solar trackers, however, the latter are generally more flexible and thus more susceptible to aerodynamics. The type of dynamic load of concern in solar trackers is therefore wind. Aeroelasticity is the study of the interaction between the deformation of an elastic structure in an airflow and the resulting aerodynamic force (fluid-structure interaction). This is an interdisciplinary problem: aerodynamics (a bluff body in an airflow), dynamics (effects of inertial forces), and elasticity (material behaviour of the structure).

Solar PV tracker failures are often caused by insufficient consideration to the aeroelastic effects during the design and testing phase. Often components directly attached to the torque tube have been deformed or even completely broken or ruptured, including U connections, bolts, nuts, brackets, slew drives, torque couplers, bearings, or even torque tube extensions. This demonstrates that the components receive dynamic energy when excitation happens; this phenomenon is called dynamic amplification or instability and can be mitigated by designing the structure to withstand them.

There needs to be a minimum level of study and testing required to properly address the potential aeroelastic effects of PV trackers. In addition to the mean and background components of the wind loads, which form part of a static structural analysis, the self-induced structural response of the tracker creates additional inertial loading, particularly in the modes with the lowest frequencies. How to make sure that the stiffness force is equal or above the self-excited forces plus the buffeting force, less the inertial and damping forces? One reasonable approach is looking at the instabilities to characterise them properly.

Conventional single-axis trackers rely on a central torque tube driven from a single location in the middle and are free to rotate at the ends of the row. This makes them particularly susceptible to various types of aerodynamic instabilities depending on their chord length, natural frequency, and damping ratio. These instabilities can be driven by five identified mechanisms:

1) **Torsional flutter and galloping.** Flutter is related to aerodynamic forces depending on the rotation and angular velocity of the structure itself and can lead to large amplitudes that can cause a catastrophic failure, such as the famous Tacoma Narrows Bridge in the USA. This mechanism characterises high-tilt angle behaviour. Galloping also depends on the rotation of the structure but due to variations in the aerodynamic pitching moment. The pitching moment reduces the overall structural stiffness, resulting in either unidirectional twisting or oscillatory motion. This mechanism characterises low-tilt angle behaviour.

2) **Torsional divergence.** The flexible axis of rotation can result in significant deflections at the outside edges of the row, which could result in a snowball effect of increased loads. This mechanism is most likely to occur in extreme wind events. Trackers are typically protected with a stow position protecting the structure from torsional divergence. According to UNE-EN 1991-1-4, some simplified formulae can help to determine if divergence can be a significant problem for the tracker under consideration.

3) **Buffeting.** Buffeting is the result of turbulent flow and wakes generated by windward objects. It is recommended to review EN1991-1-4 (Spanish annex) to see if this is applicable to the tracker under analysis. Wind tunnel testing – using small-scale tracker models in a simulation of the natural wind – is being used by the industry to determine the aerodynamic properties of a proposed tracker and the critical wind speeds for the onset of the unstable behaviour. This can be accomplished in at least two ways:

a) **Sectional wind tunnel and Computer Fluid Dynamics** (CFD) for buffeting. The key advantage is that it can be inexpensively and quickly produced and can be easily modified to investigate the changes to the structure layout. Sectional wind tunnels typically use mean values and some instabilities are triggered by gusts. In this case, low turbulence intensity tested does not necessarily mean a conservative approach.

b) **Full aeroelastic model testing** (3D buffeting). This is the more expensive way if the multi-row option is selected. The tested scale is smaller than the sectional wind tunnel but still representative for a tracker. The whole tracker does not twist the same (as is the case in the section model), only the free end has the full twist. Moreover, an instability in one row can trigger instability in neighbouring rows.

4) **Vortex-induced vibrations.** Vortex-shedding takes place when vortexes shed alternatively at two opposite sides. This produces an oscillating force perpendicular to the wind direction. Resonance shall occur if natural frequency match shedding frequency and deflection would be amplified on this case. It is recommended to review EN1991-1-4 (Spanish annex) to see if this is applicable to the tracker under analysis.

5) **Aeroelastic deflection.** If under a design wind event, the tracker deflects significantly, it is likely that the tracker is susceptible to dynamic effects, such as aeroelastic deflection. This means that the wind loads will change because of the varying shape of the tracker. Aeroelastic deflection closely relates to torsional divergence, but the difference may be that they are associated to non-stationary and stationary causes and consequences, harmonic loading, and instability, respectively. This instability can be estimated with iterative methodology.

The aforementioned instabilities are studied in different ways in the industry. A consensus has yet to be reached on the corresponding uncertainties associated with the methodologies used. However, any common approach should consider the three main disciplines working on the study of the above issues: (1) rigid-body dynamics, (2) fluid mechanics, and (3) structural mechanics.

The lack of consensus is also explained by the variety of results reported by the wind tunnel experts. It appears that there is not a single curve fitting all trackers because damping ratios, modal frequencies, stiffness, mass, and geometry are slightly different from one manufacturer to the other; full-scale testing on trackers to quantify the natural frequencies and damping ratios for each mode should be conducted with several site-specific factors that are typically experienced in the field, such as different soil conditions, pile spacing, pile dimensions, or torque tube thickness.

Several tracker failures that have occurred in the last few years have made it clear that construction, installation and commissioning issues may be involved in the tracker failures, not only the presence of any of the aeroelastic instabilities above mentioned. In a PV plant in Spain, a torqueing check revealed that almost two-thirds of the checking points showed torques below the minimum requirement by the manufacturer in their installation guideline. A wind event caused damages in the trackers, but who is responsible for those damages? It is true that the lack of torque was one issue, but the wind conditions did not justify the level of damage unless the aeroelastic effects were behind the failures.

Today's market is dynamic, and the tracker industry is moving fast. Therefore, situations where the civil work constructor, the installer and the tracker manufacturer are not willing to accept any responsibility on the tracker damages should be avoided in the future for the sake of the reputation of the solar industry. Any standardisation in the tracker industry regarding structural calculations and aeroelasticity should also consider the impact of the design, manufacturing, construction, installation, and commissioning on the final stability of the trackers for the site conditions.

Monitoring

The general trend in the solar industry is a reduction of on-site monitoring, leading to a situation where monitoring involves too much data and too little information. Solar PV plants show 5-10 incidents per year on average; this includes a number of false positives and issues with the communication infrastructure. Incidents may result in unnecessary engineer visits to PV plants to rectify the various issues. Reducing the number of unnecessary visits from engineers can reduce overall O&M costs for a plant.

Monitoring is often seen as an avoidable cost, as it does not contribute to the money-earning part of PV system operation, thus there is a lot of value engineering. This leads to a number of problems. First, there is no redundancy planned into monitoring systems, resulting in unnecessary call-outs from engineers. Further, monitoring is critical in identifying potential warranty cases, so saving too much on monitoring means that critical trends may be missed, and faults may develop in a way that the remedy ends up being more expensive than it would have been otherwise. Not monitoring appropriately means that optimisation potential is missed. There are diverging views, but on average, well-monitored and optimised systems have an increased yield of 3-5%. In case of selling or purchasing a system, the data is critical in establishing the value of the asset. Issues in the monitoring can devalue the asset significantly.

Typical faults in monitoring include:

- **Communication errors:** To remedy this potential error, use two independent methods of communication;
- **Sensor issues:** This refers to device failures, idiosyncratic measurements, or even birds sitting on top of an irradiance sensor. Here redundancy helps as well as automatic failure detection algorithms in the database;
- **Incorrect mounting:** Here, module temperature sensors can drop off and measure ambient temperature. Module temperature is often not done, but is actually critical if one encounters issues in the field and seeks to investigate them based on monitoring data;
- **Incorrect calibration or units:** This can involve mixing Fahrenheit or Celsius, using different standards when defining UV irradiance, or simply having value engineered the costs of calibration by using non-accredited suppliers or extending the stability date being set;
- **Soiling of irradiance sensors:** This can also mask issues relevant for potential quality issues.

Often, monitoring may appear superfluous but is in fact an essential performance assurance method. Monitoring should not be treated as an expense but instead more like an insurance policy that pays for itself. Generally speaking, the savings from reducing monitoring quality are small compared to the damage that can occur by missing issues or incorrect readings.

Junction boxes

Solar module junction box for crystalline solar modules

In general, a solar module junction box for crystalline PV modules consists of the housing cover, cover seal, housing body, terminal blocks for receiving the bypass diodes, the bypass diodes and a cable pair with plugs. For fully automated assembly the cable pair is rolled up.

TwinBox for crystalline and thin-film PV modules

A TwinBox for crystalline and thin-film PV modules is designed for fully automated assembly. It has a high dependability due to matching of components, potting compound, silicone, and adhesive foil; and it includes a compartment for electrical connection between box and panel hermetically sealed with potting compound. Further, it has a compact design due to integration of a connection technology directly into the junction box. The connection of the TwinBox is achieved by using a connector system. Depending on the choice of cables and connectors various voltage systems may be realised: IEC 1,000V-1,500V as well as UL 600V-1,000V.

Bypass diodes

During the construction of solar modules, single cells are switched in series to so-called 'strings' to achieve higher system voltages (see Figure 1, left). If one or more cells are shaded (for instance, by branches of trees or antennas), the affected solar cells no longer act like a current source, but as power consumers. Non-shaded cells deliver further current through them, generating high power losses; hot spots may occur and even cell breakdowns. To overcome this problem, bypass diodes are switched parallel to every single or some combined cells, bypassing current flow across the darkened strings (see Figure 1, right).

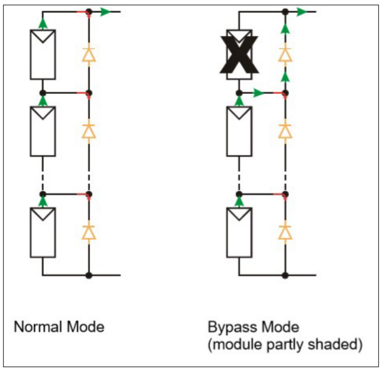

Figure 1. Function of bypass diodes (Stäubli)

Like every semiconductor device, bypass diodes have a certain leakage current, which in the normal mode of operation reduces the current supplied by the cells and therefore decreases efficiency of the solar module. Therefore, the leakage current especially at higher temperatures, should be as low as possible. Compared to this, partly shading modules is only an extreme operation mode that should be completely avoided, or at least only used during short time periods. For this mode of operation, low forward losses are desirable. Finally, the bypass diode must be protected against overvoltage spikes – such spikes may occur during assembly of the system, if current conducting cables are interrupted, or during operation, due to lightning, or other natural hazards.

Cables

Solar PV cables are halogen free and can match with most PV components, such as PV junction boxes and PV connectors, which have a rated voltage up to 1,500V DC. A fine stranded wire of tinned electrolyte copper (IEC 60228/cl.5) as well as robust materials provide a low-loss transfer even after many years. When used in accordance with instructions, the expected lifetime of this product is at least 25 years. In addition, insulating and sheath material designs provide greater resistance to abrasion and moisture. The double insulated, electron beam cross-linked cable with special compound is certified to all current standards and meets all fire safety regulations. Durable and robust materials provide increased water-repellent properties.

Conclusion

The potential of a solar PV plant is defined in the planning and design stages, by appropriate quality assurance. This article provided an overview of the main components and challenges related to EPC and is a kind of 'teaser' for SolarPower Europe's EPC Best Practice Guidelines. The guidelines will give an overview of all aspects of EPC, including handover from project developer to EPC, handover from EPC to O&M contractor, contractual recommendations, risk analysis, and mitigation recommendations. The guidelines will be launched in November at SolarPower Europe's annual event, "Solar Quality 2020". Interested companies are invited to get in touch with SolarPower Europe if they would like to be part of this initiative. ■

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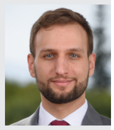

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