Monitoring complex for concentrator photovoltaic installation with a tracking system

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Abstract. The concentrator photovoltaic modules efficiency and their power generation are strongly dependent on the accuracy of their orientation by a tracking system towards the Sun. The more the solar cell power concentration ratio, the more stringent requirements are imposed on the module’s guidance system and tracking accuracy in the direction of the Sun. Effectiveness of the proposed technical solutions for the pair “module – tracking system” is usually verified as a result of the photovoltaic installation continuous monitoring. Such solutions for the specialized complex are presented, which provide for both control over the operating modes of the turning system used for the modules orientation to the Sun and tracking accuracy continuous monitoring, as well as regular monitoring of the modules output parameters in a photovoltaic installation.

1 Introduction

At the present stage of solar power development, the concentrator photovoltaic modules (CPVM) with radiation concentrators and multi-junction solar cells (SCs) are number one efficiency converters in the world [1, 2]. The efficiency of such promising modules with the solar power concentration ratio of more than 300X has already exceeded the threshold of 40% [2]. Such modules use achromatic lenses with minimal blurring of concentrated radiation in the focus (optical efficiency up to 90%) and four-junction SCs with an efficiency of more than 46% (AM1.5D).

On the other hand, when manufacturing the full-size modules used in photovoltaic generation systems (power plants), all the positive results achieved in the development of individual laboratory prototypes can be can be noticeably degraded in combining the lenses into lens panels, and the solar cells in groups on a planar base and while assembling the module. Among the most important requirements for the lens units of photovoltaic modules are the high accuracy of maintaining the same distances between the centers of individual Fresnel lenses in the unit and the parallelism of the optical axes of all lenses in the parquet. Only if these conditions are met when assembling the module, one should expect that the centers of the focal spots of the lenses will coincide with a given accuracy with the centers of the SC, which is necessary to ensure identical I-V characteristics of all subcells and their identical change when the module is inaccurately oriented to the Sun. For the solar cell, a

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high positioning accuracy on a heat sink base should be provided (standard tolerance ~ 0.1-0.2 mm in all axes relative to design values). When assembling the module, the flatness and parallelism of the lens panel and the base with the solar cell should be maintained, as well as the structural distance of the FL-SC and the alignment of the elements in the photovoltaic cells. Any violation of design parameters and design tolerances will entail some deterioration in the output and functional characteristics of the module in comparison with those determined by the properties of the primary elements. The use of the modules with maximum permissible deviations in design parameters in tracking installations will obviously require a significant improvement in orientation accuracy indicators, which can significantly increase the cost of the tracking system.

For the pair “module – tracking system”, the adopted technical solutions effectiveness verification is usually carried out on the basis of the results of continuous monitoring of the solar photovoltaic power plant. The solutions for a tracking photovoltaic installation, which includes a specialized complex that provides control of the operating modes of the orientation of modules in the direction to the Sun, continuous monitoring of tracking accuracy and regular testing of the main photovoltaic parameters of CPVMs, are presented in this paper.

2 Tracking photovoltaic installation and its main elements

The installation design is shown in Figure 1. A dual-axis system with small backlash tolerances in the angular movement mechanisms provides for 360 and 90 degrees rotations around the vertical (azimuth) and horizontal (zenith) axes, respectively. The modules are fixed to the frame and aligned towards the Sun by means of adjusting fixture. The criterion for fine tuning the module is its maximum photocurrent recorded in the mode of active precision tracking of the installation.

![Fig. 1. Tracking photovoltaic installation: 1 - tracking platform, 2 - CPVMs under test, 3 - pyranometer, 4 - precision tracking sensor, 5 - pyrheliometer, 6 - tracking accuracy monitoring sensor.](image)

The orientation control system of the installation includes a real-time clock module, some precision tracking sensors and an actuator with the angular position sensors.

The algorithm for determining the angular position of the Sun uses the data of the current time and the geographical coordinates of the photovoltaic installation location. The actuator controls the orientation mechanisms to ensure the required rate of change in the angular position of the modules in the absence of direct solar radiation. In clear sunny periods the installation is exactly oriented via an electronic loop with sensors for precision tracking.
The sensor for precision tracking can be built according to either a balanced circuit or a circuit with hysteresis of the photodetector current. The first approach is widely used in the systems controlling over tracking installations, despite the existing drawbacks: the currents balance adjusting is rather a complexity in maintaining the required tracking precision at a given mechanical accuracy of rotation drives and the potential risks to switch to backtracking modes in conditions of rapidly changed cloudiness.

A better solution is a hybrid circuit for the tracking sensor with hysteresis of the photodetector current. The sensor consists of four photodetectors (two each for the vertical and horizontal tracking axes), which are equally illuminated with precise orientation. When tracking for a pair of photodetectors located on both sides of the shading screen, the currents are recorded and the ratio of the obtained values is estimated. Depending on the photocurrent value, the controller decides to change the tracking mode from the sensor to the real time clock and vice versa.

When working with a tracking sensor, the ratio of the photodetector currents will indicate the magnitude of the angular deviation of the installation from the precise direction to the Sun. The moment of the turning mechanisms actuation and the duration of their operation are set by threshold values of photocurrents (which is set by the controller): the bigger the photocurrents ratio unit deviation, the coarser tracking mode is realized, i.e. the longer the time intervals during which the installation does not track the Sun. Accordingly, the smaller the preset unit deviation, the shorter the rest periods of the installation and the more precise the tracking will be.

To control the limiting misalignment angles, to which the platform with the modules will deviate in the active movement mode, a tracking accuracy monitoring sensor is provided [4]. This sensor is an optical sight, in which the “sunbeam” from the entrance aperture falls on the position-sensitive (CMOP) matrix with a semitransparent screen. The position of the light spot determines the angle of deviation of the platform from precise aiming: at a distance of 0.5 meters from the aperture to the screen, the precision of angular readings is 6 angular min.

Requirements for tracking accuracy are determined by the maximum admissible misalignment angle, within which the maximum cumulative power efficiency of photovoltaic modules is provided. Obviously, this angle will be slightly less than the limiting designed misalignment angle of a separate module due to the existing differences, both between the modules themselves and due to technical errors in their relative position on the swing frame.

The maximum allowable installation-modules misalignment angle is usually carried out according to the criterion of 10% decrease in photocurrent or power at the point of the optimal load (maximum power point tracking – MPPT) relative to the maximum value.

For the considered version of the tracking system, the entire set of preparatory and experimental procedures consisted of the following (the tuning procedures were carried out on a clear, windless day):
- the turntable was positioned with a plane for positioning the modules perpendicular to the flow of solar radiation (the position is controlled by an optical sight);
- for the photodetectors of the tracking sensor, the minimum current ratio is set, which sets the maximum precision tracking mode with almost continuous operation of the rotary mechanisms;
- experimental modules are installed on the turntable, and their independent alignment in the direction to the Sun is performed;
- at the stepwise coarsening of the tracking sensor sensitivity (increase in the current hysteresis), the maximum permissible misalignment angles are found, at which the module current drops by no more than 10%. At the same time, the deviation angles are monitored using the tracking accuracy monitoring sensor.
The system for monitoring the photovoltaic characteristics of the modules is based on an electronic recorder that collects data on the amount of electricity generated, on the air temperature on the surface of the modules, the ambient temperature, and the level of solar irradiance. The control computer and the program ensure the coordinated operation of all elements and systems of the photovoltaic installation, the collection of data on time dependences for the power generation and tracking accuracy, tracking modes, and the solar radiation. A simplified diagram of a specialized complex is shown in Fig. 2.

**Fig. 2.** A simplified diagram of a specialized complex for controlling the operating modes of the tracking system of modules, continuous monitoring of tracking accuracy and solar irradiance parameters, recording the main photovoltaic parameters of CPVMs.

### 3 Experimental results

Experimental assessments of the power efficiency of the modules were carried out in outdoor conditions (St. Petersburg) using a tracking system, which provided the following modes in terms of the maximum deviation of tracking in respect to the exact direction Sun: +/- 0.05 /0.09 /0.13 /0.17 angular degrees (ang.deg.), respectively (Fig. 3). The sensitivity of the tracking sensor was automatically stepping down, which corresponds to the tracking time intervals T1 (+/- 0.05 ang.deg.), T2 (+/- 0.09 ang.deg.), T3 (+/- 0.13 ang.deg.) and T4 (+/- 0.17 ang.deg.). At the same time, continuous monitoring of the power generation of two modules was carried out. The modules under test were manufactured using the same technology and they are different only due to geometric deviations of the structure within the technological tolerances. The experiment was carried out on a clear sunny day with a direct solar insolation level of at least 850 W/m² (July 2020, St. Petersburg).

The results of energy performance monitoring clearly show that in the tight tracking mode (T1 in Fig. 3, a), steady power generation of the modules is ensured (there are practically no differences between the modules): the amount of power generation of the modules responds only to fluctuations of the direct solar insolation magnitude. Continuous operation of all mechanical drives of the tracking installation is observed, with more frequent "additional tracking" along the azimuthal axis (brown lines in Fig. 3), which corresponds to the movement of the Sun from East to West.

When the tracking accuracy becomes a "coarse" in some extend (periods T2 - T4), within certain positions of the tracking system, time intervals with reduced power generation begin to appear clearly, coinciding with the periods of rest of the installation (i.e. with periods when tracking is not performed). The modules begin to react differently to the deliverable admissible misorientation angles (0.2 and 0.3 angular degrees).
As a certain level of current ratio is reached for the photodetectors of the tracking sensor, the platform with the modules is quickly moved from the position of the time and angular “lagging behind the position of the Sun” to the position “advancing relative to the position of the Sun”. Such a transfer is characterized by the dips in energy performance, which are the larger, and the longer, the coarser tracking mode is selected. Depending on which axis the rotation was made at one time or another, the power generation profiles will also be different. An additional contribution to the range for the recorded values of the instantaneous power is made from the side of geometric mismatches in the position of the lenses and elements in the modules.

![Graph](image1)

**Fig. 3.** Time dependences of the output power of the CPVMs (Module I and Module II) at different tracking modes (T1-T4) and the dynamics of changes in the angular deviations of the tracking system in the directions “Azimuth” and “Zenith” from the exact direction to the Sun during periods of rest of the installation (time slots A-D). T1/T2/T3/T4 – are the permissible deviations from the exact orientation +/- 0.05/0.09/0.13/0.17 angular degrees. The tracking period is determined as the short time intervals of the tracking drives.
The difference between the CPVMs is most pronounced at the moments immediately after the refinement of the angle tracking drives or closer to the end during the rest periods for the tracking system. If the mode of maximally coarse tracking (T4) is considered, one can see (time intervals A-D in Fig. 3, b) that for “tracking” in the azimuth direction has a significant effect on the level of generated power by Module I. At the same time, such sensitivity is not traced in the zenith direction. Before the beginning of the period "A", the system rotates along the zenith (black lines) to an advanced (relative to the Sun) position. At the same time, Module I practically does not react to the movement of the installation, remaining within its angle of effective radiation perception. For Module II, a strong sensitivity is recorded specifically to the zenith tracking processes: immediately after tracking across the zenith angle, the significant decrease in the generated power is observed. Then, due to the superposition of azimuth and zenith misorientations, an optimal tracking mode appears for Module II (intervals B and C in Fig. 3, b). Such a mode is violated immediately after the azimuth angle is worked out (interval D, Fig. 3, b) and is restored when tracking in the zenith direction. So, frequent movement across the azimuth angle (brown lines) has a beneficial effect on the power generation of both CPVMs.

Comparison of the power generation profiles allows to conclude that Module II is more sensitive to orientation inaccuracies, i.e. that for its current design and position on the tracking platform only the maximum precision tracking mode is acceptable.

The presented results clearly demonstrate the cumulative effect of technological misalignments in modules arising both within individual cells "lens - solar cell", as well as a lens panel and a heat sink base with an array of solar cells, and errors of installing modules on the tracking platform on their energy output under the selected tracking mode.

4 Conclusions

The technical and organizational solutions for the control and monitoring of a photovoltaic installation with a tracking system and CPVMs are presented. A specialized complex has been developed that provides control of the operating modes of the tracking system with modules in the direction to the Sun, continuous monitoring of tracking accuracy, and regular testing of the main photovoltaic parameters of CPVMs. It is shown that for a photovoltaic installation with specified limiting parameters in terms of tracking accuracy, such operating modes can be selected, in which design inaccuracies in the manufacture of CPVMs and errors in their installation on the tracking platform will be largely compensated. Methods of searching for economically effective control modes for angular drives of the installation to ensure maximum power generation of CPVMs are proposed.

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