FIELD TESTING OF THE PhoCUS SOLAR TRACKER BY MEANS OF A NOVEL OPTOELECTRONIC DEVICE

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ABSTRACT

The focus of the paper is to evaluate the solar tracker accuracy, installed in R.C. ENEA in Portici (NA) within the PhoCUS (Photovoltaic Concentrators to Utility Scale) project, using a novel optoelectronic device (OED) designed and patented by ENEA [1]. In this work a detailed analysis of the misalignments causes, considering the influence of the different factors (mechanical and thermal deformations, set-up errors, inefficiency of feedback, etc.), has been performed by the authors. On the basis of the experimental data, collected in absence of feedback, an accurate improvement of the feedback algorithm has been obtained. After, several outdoor tests in presence of feedback sensor have been carried out. The results have been shown an high increase of the tracking accuracy.

INTRODUCTION

The main purpose of the PhoCUS project is to develop a photovoltaic concentrators technology (C-technology) in order to demonstrate the technical feasibility of this application in Italy and to assess its greater potentials to drive a reduction of the PV system investment costs [2].

The $5kW_p$ PhoCUS standard unit is equipped with the following components (Figure 1):

- double axis solar tracker with ≤ ±0,2° tracking accuracy;
- C-modules with a geometric concentration ratio 200X .

Fig. 1. The $5kW_p$ PhoCUS standard unit

THE SOLAR TRACKER

The technical specifications of the tracking structure were defined to reach the following goals: low investment and O&M costs (free maintenance and low energy consumption); modularity to reduce the transportation and the installation cost; reliability and accuracy to minimize the operating losses; tracking accuracy of ±0.2°; normal operation up to a wind mean speed of 40km/h.

The system is based on a pedestal, supporting on its top a network structure of about $35m^2$ (see Fig. 1).

The driving system is the alt-azimuthal type one. Particularly the network structure can rotates around its horizontal axis by means of a linear actuator (altitude motion) and around the vertical axis of the pedestal by means of two epicycloids reduction gears series mechanically connected, positioned inside the pole (azimuth motion). Its main features are the following: reduction ratio is 1:7839,73; torsional stiffness $1{,}48x10^6$ Nm/rad; mechanical clearance ± 4 arcmin; maximum torque supportable 29500Nm.

The elevation motion group is connected to the output shaft of the azimuth reduction gear by means of a bolted flange. It is composed (Fig.2) of a continuous screw (1) which, rotating inside a sliding block (2), moves a mechanical lever (3) connected to the horizontal shaft of the network structure (4).

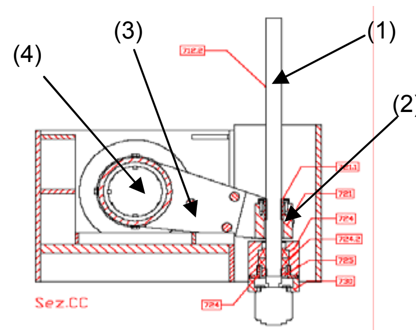

Fig. 2. Schematic section of the altitude group

The overall elevation reduction ratio is variable and it depends on the geometry of the system. Particularly it changes from 1:5570 (vertical position) to 1:8540 (horizontal position). The main features of this group are: torsional stiffness 1,85x107Nm/rad; mechanical clearances ± 1 arcmin. The driving (both for elevation and azimuth motion system) is obtained by means of two stepper motors [3].

THE CONTROL SYSTEM

The structure is equipped with a control system based on open/closed loop logic. The first one is based on a continuous computation of the sun position while the second one is obtained by means of a CCD (Charge Coupled Device) sun sensor.

The control system is based on the Magellan 8 system by ATEC Robotics Magellan Astronomy Software Controller line, used for sun trackers, telescopes, radar and large antennas for radio astronomy. The system is composed by a server that takes care of the tracker control pointing/tracking and emergencies. The block scheme of the control system is shown in Fig. 3.

The system is provided with many functions necessary to test and evaluate the solar modules performance and characteristics. At the same time other functions and peculiarities have been introduced to evaluate the structure performance on the field, namely validate the structural design and to define the function and related characteristics of the controller functions.

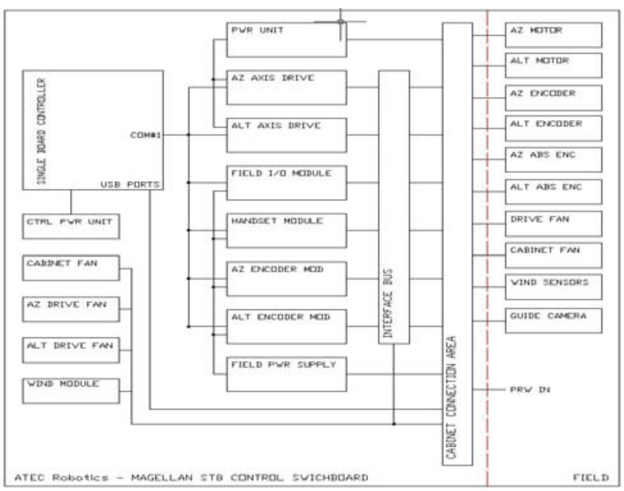

Fig. 3. The control system block scheme

The system is equipped with stepper motors that guarantees stability and durability due to the simple construction. The motors are provided with optical encoder on axis. The use of encoder on the motor axis allows, in any case, to compensate for loss of motor steps. Two more absolute encoders are placed on the output axis of the alt-azimutal gearbox. They have been introduced to optimize the homing function in terms of time spent for this task. Up to 16 absolute positions are available at the axis level. The system automatically performs the homing with the recognition of one of the absolute available data. Proximity limits and over-travel limits determines the emergency interlock chain intervention.

The system includes some wind speed and direction sensors whose informations are used for the fast pointing of the tracker in a safety position that is determined by the combination of hail and wind. The system is able to determine the minimum energy position of the tracker in respect to the wind and contemporaneously the best position in case of hail. In case of wind speed over 90km/h the tracker is positioned to zenith.

The server is provided with a graphic User Interface that can be repeated in remote control.

In the evening the tracker points to the desired position determined by the sun computed position at the dawn of next day. The emergency functions are always active and the system is protected against wind sensor faults. In case of software stack a watch-dog restarts the system in less than 30 seconds.

In order to optimize the tracker performance in terms of pointing and tracking the system itself is equipped with a guiding camera whose intervention allows to reduce the tracking and pointing error down to some arcsec RMS. Fig.4 shows the CCD camera mounted on the heliostat.

Fig. 4. The CCD camera

The camera, used for point and track optimization, represents the most reliable system. In fact the CCD gives the possibility to analyze the shape of the sun spot. The analysis of the spot guarantees the possibility to reject that spots without introducing sun position determination errors. The fuzzy control works on seven levels of analysis of the spot in order to avoid any possible error in the tracking control. The control software is provided with a real time graphic scope than allows the optimization and/or control of the system performance by reporting the sun spot position error in respect to the computed sun position.

Still the presence of the camera allows to activate two functions that are used to study and characterize both the tracker and the solar modules performance. The H-track function allows the controller to use the stepper motor in closed loop with a step partialization to better control the motor speed. The parameterization of the control loop assures tracking accuracy below the arcsec in case of moderate wind speed. The L-track function allows the controller to manage the motors in closed loops but with a duty cycle in the range 0.5-10% guaranteeing RMS tracking error of the order of 5-8 arcsec. This mode is characterized by a very low power consumption (power and thermal) in respect to the H-track function. H-track mode is used to optimize the characterization phase of the modules and of the entire tracker, while the L-track mode is used during standard utilization of the tracker as well as a standard commercial tracker.

TRACKING ACCURACY

The solar tracking accuracy is one of the main factor which influences the system energy production. The tracking accuracy is defined as the solid angle between the perpendicular to the lens parquet of the C-modules and the direction of the solar beam.

In condition of perfect alignment, the spot projected from the lens strikes perfectly the cell; when the misalignments raises, a portion of the light transmitted by the lens doesn't hit the cell, so the energy production of the system decreases remarkably. The maximum allowable misalignment for the PhoCUS system is ±0,5° and the corresponding energy losses are about of 4%.

The losses induced by the misalignments are mainly due to:

- mechanical deformations of the tracking structure due to the structure's weights and the wind too;
- thermal deformation of metallic carrying structure;
- set-up errors (C-modules and solar tracker assembly);
- inefficiency of feedback;
- mechanical clearances of the reduction gears.

A detailed analysis of the misalignments has been carried out tacking into account the mechanical stiffness of the metallic structure, the torsional stiffness of the reduction gears and their mechanical clearances. The loads coming from the wind were calculated as static-equivalent actions by means of the Peterka-Derikson method.

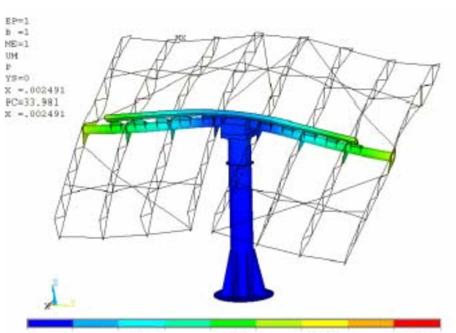

Fig. 5. Deformations of the PhoCUS structure

The stress-strain analysis has been performed using ANSYS Professional. The configuration based on a PV generator elevation angle of 60° and wind direction of 60° *vs.* modules normal has been considered as case study (Fig. 5).

The results shown that in the peripheral areas the deformations are greater than those calculated near to the pedestal. On the basis of this analysis, it has been possible to calculate the misalignments of each modules on the supporting structure.

In Fig. 6 the average value of the module misalignments *vs*. the wind speed is reported.

The deformations, in absence of wind, are due to the mechanical clearance of the reduction gears.

The nominal features, in terms of tracking accuracy, are the followings:

- ≤ ±0,2° with a wind velocity less than 40 Km/h;
- ≤ ±0,3° with a wind velocity from 40 to 60 Km/h;
- ≤ ±0,7° with a wind velocity from 60 to 90 Km/h;

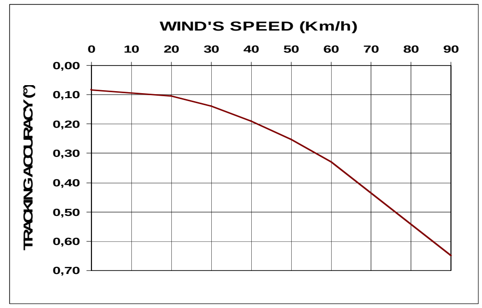

Fig. 6. Module misalignments vs. wind velocity

THE OPTOELECTRONIC DEVICE

An optical electronic device, to verify the solar tracker accuracy, were designed and patented by ENEA (Fig. 7). This device is composed of the following components:

- a PSD (Position Sensitive Detector) sensor, which is based on lateral effect photodiode technology [4];
- a high temperature stability and low noise analog amplifier to fit the PSD output signal to the A/D input signal;
- a microcontroller equipped with an internal and additional external memory unit to save the data;
- a display showing the measured values.

Fig. 7. The OED prototype

The duolateral PSD consists of N-type silicon substrate with two resistive layers separated by a PN junction: the front side has an ion-implanted P-type resistive layer with ohmic contacts on two sides; and the backside has an ion-implanted N-type resistive layer with two contacts at opposite ends placed orthogonally to the contacts on the front side. Because the position signal is divided only into two parts, the duolateral PSD has the highest position detecting ability of all the sensor types.

The resistivity of the ion-implanted layers is extremely uniform, so the photocurrent for each electrode pair is inversely proportional to the distance between the incident spot of light and electrodes (see Fig. 8). The duolateral PSD generates photocurrents proportional to the position and intensity of the centroid of light on the active area.

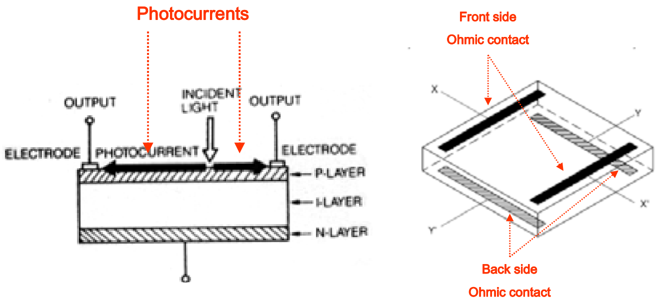

Fig. 8. The duolateral PSD sensor

The right position (zero misalignments) is reached when the solar beam hits the centre of the PSD sensor (Figure 9a); on the contrary the PSD sensor monitors a misalignment value proportional to the distance between its centre and the solar beam incidence on the PSD (Figure 9b).

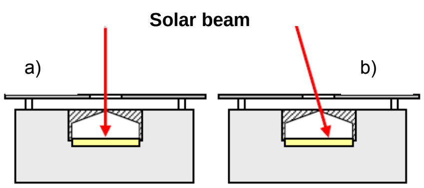

Fig. 9. The OED working scheme

An accurate calibration by means of indoor and outdoor tests has been carried out by the application software. The calibration is necessary to minimize the influence of the following factors: non-linearity of the PSD; structural tolerance of the OED; measurements errors.

The main OED features are the following: sensitivity 0.005° and accuracy 0.75% of measured value.

Figure 10 shows the break down cost of the OED prototype. The PSD sensor is the more expensive component (75% of the total OED cost which is about of 2500€).

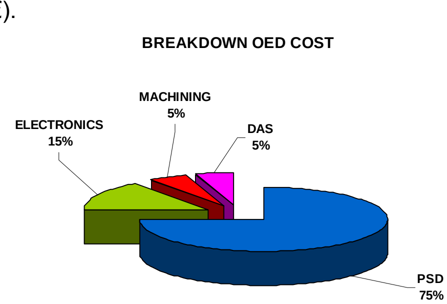

Fig. 10. The breakdown OED cost

The improvements of the OED regards the following aspects:

- the signal conditioning electronics with the use of both a 24 bit A/D converter and an ultra stable temperature analog amplifier;
- development of a wireless a/o web DTS (data transfer system) for to a on line remote control.

THE EXPERIMENTAL TESTS

Many experimental tests to measure the tracking accuracy of the PhoCUS heliostat have been carried out.

The OED has been mounted on the supporting structure in place of a C-module. The electrical supply has been provided by a flat photovoltaic module; so that the device can record continuously the measured values.

The outdoor measurements conditions are: data acquisition period of 6 months (December 2005-June 2006); measurement and acquisition time of 0,5s (120 points/minute); maximum, minimum and average values recorded on each minute; solar irradiation threshold acquisition value of 100W/m^2. The global misalignment is calculated as the addition of the misalignments vectors and the balancing threshold of the PSD photo currents is 0.004°: below this value the measured values are not considered. Figure 11 shows both altitude and azimuth misalignments in absence of feedback sensor.

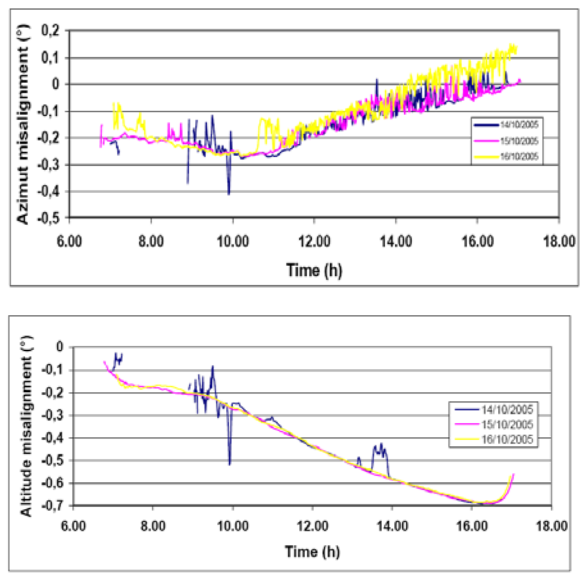

Fig. 11. The alt-azimuth misalignments in absence of feedback

The high measured values (~0,4° for azimuth and ~0,6° for altitude axis) are due to feedback absence. Particulary it possible to notate that the fluctuations amplitude of the azimuth motion respect to its average value is due to the mechanical clearances (about of 0,1°) in presence of wind gust. On the contrary the altitude motion is characterised by a lower value of mechanical clearance; so the misalignment trend is more regular.

Several outdoor tests in presence of feedback sensor have been carried out. In the Fig. 12 the global misalignement angle vs. the direct normal radiation (D.N.I.) is reported (red points). The number of measurements *vs*. D.N.I. is depicted by the yellow chart.

With regard to the system working conditions, it is possible to do the followings remarks:

- in any solar irradiance condition the global

misalignment is less than 0,1°;
- for irradiance value less than 400 W/m^2 and greater than 900 W/m^2, the tracking accuracy measurements are not repetitive;
- for D.N.I. values included between 700 and 900 W/m^2, the misalignments are higest

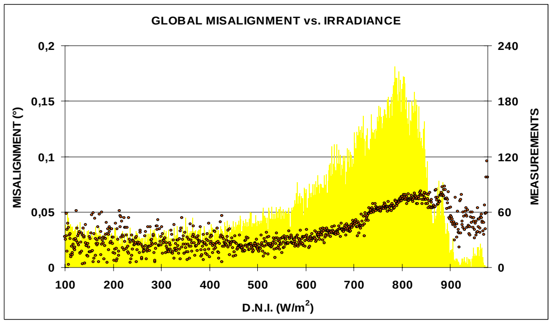

Fig. 12 The global misalignment vs. D.N.I.

The daily azimuth and altitude misalignment are reported in figure 13a) and 13b).

In particular the maximum (red points), average (blue points) and minimum (green points) misalignement values are reported for each acquisition time. Regarding the azimuth it's possible to notice that the gap between the maximum and the minimum values is due to the mechanical clearence (about of 0,1°).

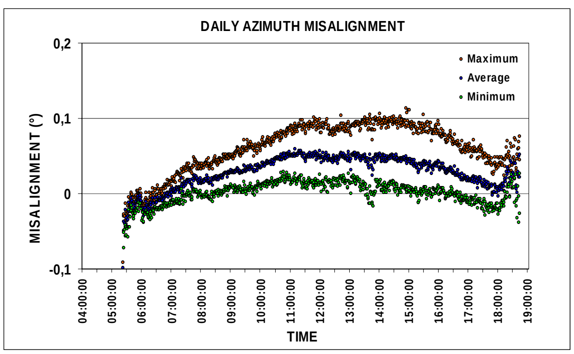

Fig. 13a). Daily azimuth misalignment

The misalignments increases during the mid-hours of the day and the average hourly misalignment is generally below 0,05°.

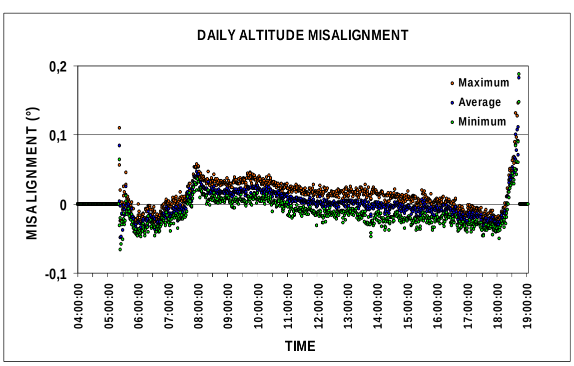

Fig. 13b). Daily altitude misalignment

As shown in figure 13b) the average daily altitude misalignment is generally below 0,03° and the oscillations due to the mechanical clearance are very low (< 0.04°).

CONCLUSIONS

The introduction of a feedback sensor bringed an high improvement of solar tracker accuracy. In fact the maximum misalignment value recorded during the data acquisition period of six months is less than 0,1°.

Respect to the CCD camera, used as feedback sensor, it has been possible to notice its performance worsening in terms of sensitivity in the range of low (<400W/m^2) and high (>900W/m^2) values of D.N.I. For this reason, the misalignment values in these operating ranges are not repetitive. But the tracking accuracy in these working conditions are however more below the design constraints (<±0.2°).

Higest misalignments have been recorded for the D.N.I. values greater than 700W/m^2. This happens because at these irradiance values the supporting structure is almost horizontal and so the gravity loads are more relevant (in terms of structure deformations) than in the case of small elevation angles (smaller D.N.I. values associated).

In any case the elevation motion group is more performing in terms of accuracy than the azimuth one.

This is due to both its greater torsional stiffness and its lower mechanical clearance.

The use of the OED, in addition to evaluate the goodness of the solar tracking, allows to:
- verify the right installation conditions of the heliostat in terms of the perfect ortoghonality of the pillar respect to the horizontal plane;
- adjust the right position of each C-module on the heliostat in terms of perpendicularity the module surface respect to the solar beam radiation.

Besides it must be underlined that the OED can be used to verify the tracking accuracy for other applications in the solar energy field. Particularly it could be very useful both in the case of the one/double axis trackers with flat PV modules and for parabolic throughs.

REFERENCE

[1]F. Pascarella, G. Leanza, A. Citarella, "Dispositivo per la Misura dell'Angolo d'Incidenza dei Raggi Solari su una Superficie Piana Mobile, in Particolare per Eliostati", Italian Patent N° RM2003A000561 - 03 December 2003.
[2] A. Sarno et al., "Design, realization and preliminary performance analysis of the PhoCUS-5 standard unit", SCC Conference, Scottsdale, Arizona 2005.
[3]Maish, A.B, "Performance of a self-aligning solar array tracking controller", Photovoltaic Specialists Conference, 1990, Conference Record of the Twenty First IEEE21, 25 May 1990, Page(s): 864-869 vol.2.
[4]Myung Kwan Shin; Hee Sun Yoon; Kyi Hwan Park; "Study on comparing the signal processing of a linear CCD with a PSD for displacement measurement", ISPACS 2004, Proceedings of 2004 International Symposium on 18-19 November 2004, Page(s): 762-766.