A New Sensor for Measuring Tracking Accuracy, Tracker Vibration, and Structural Deflection

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Abstract. In this paper we describe the development and measurement results of a high accuracy sensor which is able to examine the precision of tracking systems in relation to the sun. Such trackers are used in many concentrator photovoltaic (CPV) applications. Tracker accuracy measurements are particularly useful for tracker and module development and power plant monitoring. Using an LED light source, the repeatability of the sensor at different temperature and irradiation levels has been examined. Based on outdoor measurements using a tracking system, a tracking accuracy measurement application is demonstrated and completed by a vibration analysis.

Keywords: Solar concentrator, photovoltaics, tracking accuracy, CPV, tracker vibration, measurement

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INTRODUCTION

Trackers are used to follow the apparent movement of the sun in many concentrator photovoltaic (CPV) applications. In a CPV system, a concentrator optics is used to concentrate the sunlight on a solar cell which is much smaller than the aperture of the optics. CPV system costs can be significantly reduced by using optical systems with high concentration factors (e.g. > 500x). At high concentration factors, the acceptance angle is reduced, which creates the need for high tracking accuracy and a rigid tracker construction. A reliable and accurate measurement of the tracking accuracy is an essential requirement for optimizing the design and the operation of tracking systems and therefore increasingly used in the CPV industry [1-3]. In this paper, we describe the development and measurement results of a high accuracy sensor which is able to examine the precision of entire tracking systems in relation to the sun. The detailed knowledge of these properties is essential to understand the performance of a CPV system. Even more importantly, it enables the tracker designer to improve the construction, the choice of components and the control strategies in order to build trackers reduced bill of materials while maintaining the same tracking accuracy.

METHODOLOGY

The tracking sensor we use is based on a silicon sensor chip coupled with a fast and ultralow-noise amplification and processing unit. The amplification unit is needed due to the fact that the output signal of the sensor chip is only in the sub-micro amp range. A lens-based optics and a filter stack are used to image the solar disc onto the sensor chip.

To measure the basic properties of the sensor such as noise and stability under changing temperature and irradiation conditions, an indoor light source has been constructed. The geometry of the light source and the distance to the sensor has been chosen to achieve the same ray divergence angles as in outdoor measurements.

To examine the linearity of the sensor, the apparent sun movement was recorded while the sensor was mounted in a fixed position.

For further outdoor tests, the sensor was installed on a CPV test tracker in Freiburg, Germany. FIGURE 1 shows an outline of the whole sensor setup mounted on a tracking system.

FIGURE 1: Outline of the tracking accuracy sensor setup mounted on a tracker system.

Short sampling intervals have been used in order to analyze not only the tracking accuracy, but at the same time also the tracker vibration. Using two or more such sensors mounted in different locations,
the deflection of the structural elements can be monitored.

MEASUREMENTS WITH AN ARTIFICIAL LIGHT SOURCE

To evaluate the sensor’s noise and temperature behavior, an artificial indoor light source based on a LED was constructed. The advantage of this approach is a very constant sensor illumination and a fixed position of the light source during the experiment. Therefore the measurement results were not influenced by the time variant behavior of the sunlight due to the apparent movement of the sun and atmospheric turbulences.

Signal Stability and Noise

FIGURE 2 shows the result of the signal stability and noise measurement that was recorded while the sensor was aligned in an orthogonal position against the light source at an ambient temperature of 25°C. In this case the light point imaged on to the sensor surface does not change its position. In the following, we refer to the x-axis of the sensor chip as “azimuth axis” and to the y-axis “elevation axis”, referring to the denotations in FIGURE 1. However this sensor is also able to measure the accuracy of tracking systems based on other tracking axes configurations.

A standard deviation of 0.01 % of full scale (abbr. F.S., the full stated measurement scale of the instrument) can be determined from this measurement. To account for variations in the electromagnetic shielding due to different cable lengths up to 20 m and housing tolerances depending on production, an error of 0.02 % F.S. applies. The signal to noise ratio (SNR) can be determined based on the root mean square (RMS) of noise and signal voltage \( U_{\text{RMS,Noise}}, U_{\text{RMS,Signal}} \) following equation (1):

\[
\text{SNR} = 20 \log \left( \frac{U_{\text{RMS,Signal}}}{U_{\text{RMS,Noise}}} \right) \quad (1)
\]

Under worst case conditions with a 20 m long signal cable connection, the minimum SNR was greater than 80 dB. According to the dynamic range, a data acquisition unit with a minimum of 14 Bit A/D conversion resolution is required. During the measurements, a data acquisition unit with 16 Bit A/D conversion resolution was used.

In outdoor measurements, this noise is mostly covered by the much higher noise caused by atmospheric turbulences.

Temperature Stability Test

During operation, the sensor is subjected to varying ambient air conditions. To examine the effects of temperature on the measurement precision, the sensor has been heated and the position change during natural cooling has been measured. FIGURE 3 shows the influences of the ambient temperature on the sensors position stability.

FIGURE 3: Influence of the sensor temperature on the position stability. The temperature error for two positions on the sensor chip is shown at the center and the edge position of the full scale area.

FIGURE 3 shows a comparison of center and full scale position on the sensor chip. A maximum position error of -0.7 % can be determined in an operating temperature range between 28°C and 54°C.

Advanced Temperature Test

In addition to tests under normal operating conditions, the temperature tests were repeated within a temperature range of 50°C to 85°C. Although this temperature range exceeds normal operating conditions, it was chosen to include increasing dark current effects of the silicon sensor as well as amplification and linearity deviations of the analog circuit. The measurement under varying
temperatures was performed at three different positions (pos. 1, pos. 2 and pos. 3 in FIGURE 4) on the sensor chip at three different light intensities. During the measurement procedure, the light source intensity was limited by reducing the LEDs current using a linear regulated power supply. Due to the fact that the absolute light intensity was not measured (e.g. by a light intensity sensor), three approximated percentage values of 25 %, 50 % and 100 % of maximum intensity have been used. The sensor output signal amplitude at the highest value of 100 % corresponds to the signal generated at 500 W/m² direct irradiance. Only a part of the sensor area is used during normal operation, indicated by the area highlighted in FIGURE 4. The outmost positions (Pos. 2 and Pos. 3 in FIGURE 4) were chosen to indicate worst case measurements at the edge of the full measurement scale.

In FIGURE 5 the results from the entire test procedure under advanced temperature are shown represented by the standard deviation.

OUTDOOR MEASUREMENTS

Linearity Measurements

Linearity and noise measurements were done mounting the sensor in a fixed setup and aligning it towards the sun once before each measurement run. By measuring the apparent sun movement it is possible to quantify the linearity of the entire sensor. FIGURE 6 shows the results of measurements during April 10, 2012 in Munich under clear sky conditions. The linearity error is expressed by the differences between the measurement results and their linear fit (residue). The sun position refers to the position of the light spot on the sensor chip surface while the apparent sun position changes.

The maximum linearity error is 0.3 % of F.S. while the signal noise is largely dominated by the non-constant sunlight irradiance, caused by atmospheric turbulence. From the entire measurement cycle a standard deviation of 0.25 % of F.S. can be calculated. Including variations at different positions on the chip and among different sensors, a standard error of 0.70 % of F.S. has been determined.

Measurements on a CPV Tracker

To examine the accuracy measurement on a CPV tracker, the fully assembled and tested sensor was mounted on a tracking test system as outlined in FIGURE 1. The results are shown in FIGURE 7. The relation between the sensors output signal, referring to the light spot position on the sensor surface and the azimuth as well as elevation angle, is given by a calibration factor. The calibration itself routine is not discussed in this paper.

Because of the tracker drive control algorithm, a saw tooth similar signal was measured in the elevation axis.
At the position marked by “A” the tracker drives were inactive. In this case the apparent sun movement was recorded by the sensor. At the position marked by “B” the tracker drives corrected the tracker position in relation to the sun. Due to the high measurement frequency of up to 1 kHz, the sensor can also be used to measure tracker vibration. Such effects are observable in FIGURE 8, which details the area within the dashed lines of FIGURE 7.

On the left side of the graph the excitation of the tracker is shown. Following the excitation, the constantly rising elevation angle is overlaid by a low damped oscillation. Once the signal is transformed into the frequency domain by Fast Fourier Transform (FFT), the dominant frequencies can be determined. The result is shown in FIGURE 9, indicating a dominant resonance frequency of 2.3 Hz. This demonstrates the usability of the sensor for detailed structural measurements.

**SUMMARY**

In CPV power plants, accurate measurements of tracking accuracy are essential. Due to the harsh environmental conditions of outdoor measurements, the accuracy must be maintained under varying temperature and irradiation conditions.

Using an indoor test setup with a LED light source, the signal stability and noise as well as the behavior under variable light intensity and temperatures have been evaluated. In an outdoor measurement campaign, the accuracy of a CPV tracking system has been measured. Due to the high frequency capabilities of the sensor, high resolution vibration measurements were performed. The measured data was Fourier transformed to reveal the prevailing resonant frequencies. The accuracy and vibration data can be used to optimize the tracking device and therefore contribute to optimize the system performance. TABLE 1 summarizes the worst case deviations (“max”) or standard deviations (σ) normalized to F.S. for the most important measurements in this work:

**TABLE 1. Summary of measurement results.**

| Noise | result | Position stability | Linear |  |
|-------|--------|-------------------|--------|
| T<sub>ambient</sub>=25°C, LED light | max 0.02 % | T<sub>ambient</sub>=28°C…54°C (normal) | max 0.7 % |          |
| SNR  | >80 dB | T<sub>ambient</sub>=50°C…85°C (advanced) | σ=0.5 % |          |
| Linearity | Linearity within full scale (F.S.) | σ=0.7 % |        |

**REFERENCES**