Pilot Operation Experience of a Photovoltaic System with Simple Tracking Mechanism

Gerhard Krost and Peter Swemers

***Abstract* – In this paper a simple and robust mechanism for solar tracking of photovoltaic plants is presented. The principle is based on customary materials, thus leading to easy mounting at low cost. Comprehensive measurements proved that the expectations of energy harvest increment by solar tracking were fully satisfied, and gave further insight into the performance of a photovoltaic pilot plant.**

***Index Terms* -- Measurement campaign, pilot plant, photovoltaic, simple tracking mechanism.**

I. Introduction

It is well known that, by means of solar tracking, the energy harvest of photovoltaic (PV) plants can be considerably augmented, especially in regions with high portion of direct insolation (i.e. few clouds). On the other hand, a tracking mechanism as usually accomplished leads to significantly increased installation and maintenance costs. In contrast, the simple, cost-effective but solid mechanical tracking mechanism proposed and investigated here allows for making use of the advantages of solar tracking without rising extensive additional costs, and thus supports the economic efficiency of photovoltaic systems: The mounting of module carriers combines both azimuthal and inclination motion by leverage; one central rope based drive moves many module carriers in common and keeps the operating power as well as the maintenance effort negligibly low. The simple tracking construction is based on customary and low cost materials, and thus it is especially well suited for remote regions or developing countries with high solar irradiation.

A detailed measurement campaign over one complete year was performed at a 12 kW open land PV pilot installation, located in the western part of Germany. The evaluation of the measured data gave clear evidence of the advantages of the proposed tracking system: the expected harvest increment of approximately 25 % for the test site was definitely achieved, and the construction safely resisted the given climatic conditions (especially regarding wind resistance) of the test location all year round.

II. Construction und Configuration of the Pilot Plant

The substructure of the PV module carriers, arranged on a simple concrete foundation, consists of four jointed structural elements made of zinc coated steel, see Figure 1.

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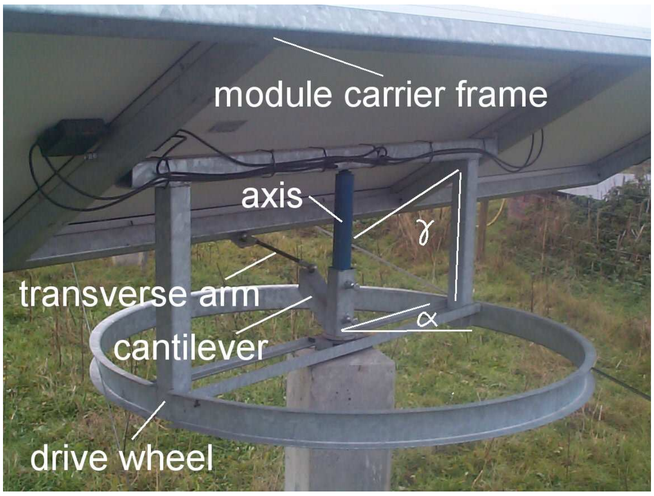

Fig. 1. Substructure of tracking mechanism.

The two-directional motion (azimuthal angle α and inclination angle γ) is achieved by junction of cantilever and module carrier frame by a transverse arm. Rotation of the construction around the axis disposes the fixed cantilever to induce a rotation angle (α) dependent inclination (γ) of the module carrier frame by means of the transverse arm the length of which is seasonally adjusted. A rack and pinion drive, slightly moved by an induction motor every 10 minutes – Figure 2 –, induces synchronous two-directional tracking of many PV panels by one common rope wound around the drive wheels of all module carriers at the site.


Fig. 2. Rack and pinion drive of tracking mechanism.

The power of the induction motor installed (140 W) would suffice to move at least 100 module carriers equipped with 600 W_{peak} each (i.e. 60 kW installed PV power) as to be seen in Figure 2; the daily energy consumption of the drive (total daily motor operation time is approximately 12 minutes) is negligible compared with the energy harvest increment achieved by solar tracking.

The torsional forces occurring in case of storms are born by the large drive wheel, and transferred to the rope. The track of the rope is designed in such a way that during normal operation as well as during storms no frictional forces impact on the axis of the module carrier on drive wheel level, which admits usage of a rubber bearing; this kind of bearing effects minimization of forces in case of storms by the flexibility of rubber. Tracking motion of the module carriers effects only short shadowing phases of a certain ground area. Furthermore, the module carriers are founded on concrete basements of low cross-section surface. Thus, detrimental impact on soil and plant cover is minimized, Figure 3.

Fig. 3. Pilot photovoltaic plant with simple solar tracking.

The described construction principles can be realized with elementary means and materials; in consequence of resulting low costs the approach is especially suited for remote regions or developing countries with high solar irradiation.

The 12 kW demonstration plant [1] is coupled with the public LV power grid by five inverters (at first Sunny Boy 2000, later after change Sunny Boy 2100 TL). Each inverter is fed by 12 poly-crystalline 200 W_{peak} PV modules IBC 200, mounted on 4 module carriers, Figure 4; the total installed power of PV modules is 12 kW_{peak}, the rated power of inverters 10 kW and 10.5 kW after intermittent change, respectively.

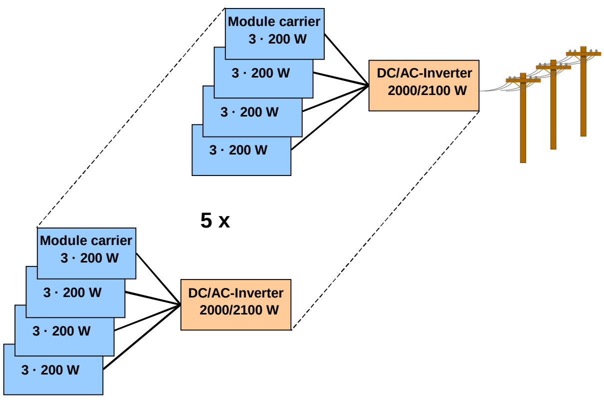

Fig. 4. DC/AC inverters and PV module groups.

III. Measurement Campaign

At the pilot plant a continuous and detailed measurement campaign was conducted over one complete year. For comparison reasons, during this campaign four out of 20 module carriers (corresponding to the complete feed of one of the five inverters) were fixed to exact south direction with an inclination angle of 30°, while the tracking mechanism of all other modules was released in bi-directional mode. Furthermore, for a certain period of time, inclinational tracking of another module group (the modules which are feeding a second out of the five inverters) was blocked but azimuthal tracking was released in order to provide further comparison possibilities (see results).

Actual power of each of the inverters as well as other parameters of the plant were sampled and stored with 30 seconds sampling rate; in particular, the following data were recorded over a complete year:

- $U_{PV\text{-}act}$ - current voltage [V]
- $U_{PV\text{-}rat}$ - rated grid voltage [V]
- P_{AC} - electric power on AC side [W]
- I_{PV} - DC current of PV plant [A]
- E_{total} - total harvested energy [kWh]
- serial numbers of inverters for clear identification of measurements
- status messages
- fault indications

Furthermore, via existing analog interfaces the module temperatures – measured by a PT 100 sensor – and the solar irradiance – collected by a reference sensor type Solarwatt Aem 02 Ra 100 t – were recorded. All measurements and status indications were daily saved in a special format on PC hard disc and later converted into Excel files for further analysis; some fundamental results will be presented in the following.

IV. Analysis of Measurement Results

A. *Global Energy Harvest*

The overall energy harvest of the 12 kW_{peak} plant during the sample year was 15 938 kWh; with 1 328 kWh per kW of installed PV peak capacity the average of fixed installations in the same geographic region (860 kW per kW_{peak}) during the same period of time was significantly exceeded.

B. *Monthly Harvest and Comparison*

A monthly analysis allows, among other, for identification under which conditions tracking is of particular advantage, and gives the chance to compare the energy harvest with that of other PV plants in more detail.

Figure 5 shows the monthly energy harvest of the tracked module groups (inverters 1-5) in comparison with that of the fixed module group (inverter 5) – each related to the relevant installed peak power – over the complete year. Even in the month of lowest irradiation (November) the harvest increment by tracking is above 10 %, and in June it is more than 35 %, thus leading to yearly harvests of 115.04 kWh/kW_{peak} of the tracked and 91.33 kWh/kW_{peak} of the fixed modules, which results in an average yearly harvest surplus by tracking of almost 26 %.

The installed PV power related harvest of the tracked modules even exceeds the results of a reference 100 kW_{peak} PV plant with bi-directional tracking located in Bavaria (where the solar irradiation conditions usually are better) – the energy harvest of which could be monitored via the internet during the same time period – by more than 6%.

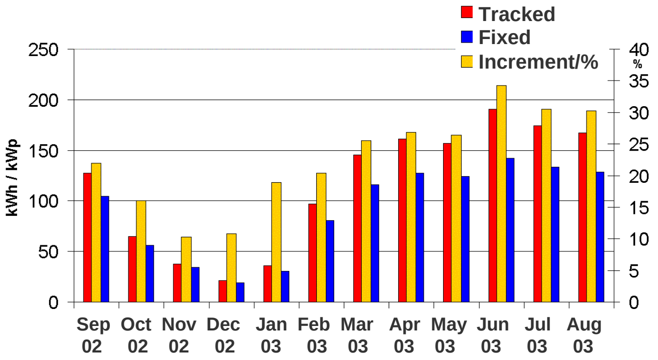

Fig. 5. Monthly energy harvest increment by solar tracking.

It should also be mentioned that, at times of highest insolation, the power limit of the inverters (10 and 10.5 kW rated power, respectively, see above) which is below the related installed power of modules (12 kW_{peak}) leads to a slight reduction of harvest, the amount of which is hard to estimate. The ratio of installed inverter/PV powers (83.3% and 87.5%, respectively) widely follows the recommendations of inverter manufacturers for fixed PV installations; in the case considered here a ratio of, e.g., 95% would be more advantageous.

For further comparison, in Figure 6 the monthly peak power related harvests of the plant under regard and the Bavarian 100 kW_{peak} plant were divided by the actual accumulated monthly solar irradiation of the relevant region.

Temporal unavailabilities of the Bavarian plant – mainly caused by failures of the fragile controls and electric drives of the single module carrier tracking mechanism applied there – are counterbalanced by the mentioned inverter-power related slight harvest decrement of the plant regarded here, which on the other hand had no failures of the tracking mechanism in consequence of its simple and robust construction.

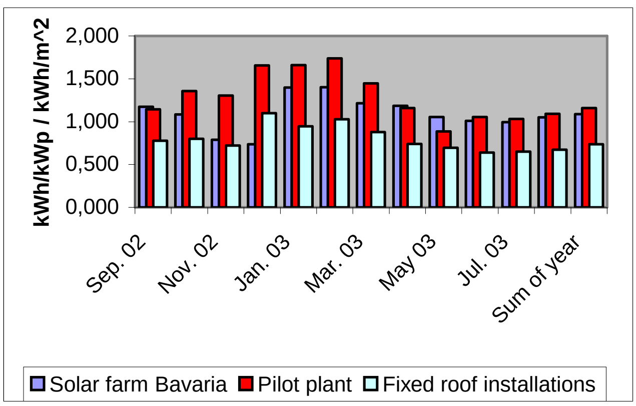

Fig. 6. Monthly harvest of different PV plants.

Figure 6 also shows the monthly harvests of several PV plants with modules fixedly mounted on roofs [6], which are located in the same region as the plant under consideration here; these are beat by up to 80% punctually and by 55% in yearly average.

C. Influence of Tracking Directions

Measurements recorded during temporal blocking of the elevation mechanism of the PV modules feeding inverter No. 2 – i.e., these modules were temporarily moved in azimuthal direction only – prove that the energy harvest of this module group minimally differs from that of the module groups with two-dimensional tracking, see Figure 7; the reason that they are even slightly above may be caused by quality spreading of the particular modules involved. Thus, it can be stated that by abandonment of elevation tracking further significant simplification of the module carrier construction without noticeable decrement of energy harvest is possible – and applied in the meantime [1].

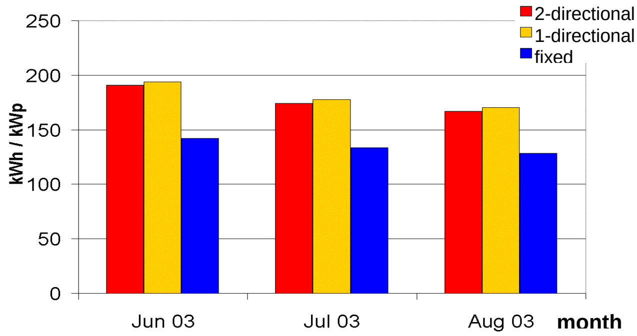

Fig. 7. Comparison of tracking ranks.

D. Daily Energy Harvest

In Figure 8 (next page) for each calendar week during the measurement period the daily average energy harvest of one of the tracked module groups of 2.4 kW_{peak} installed PV power is shown. The values entered are the arithmetic means of daily harvests over a complete week, including the minimal and maximal daily values of the actual weeks. There were few weeks where disturbances in the measurement system occurred, leading to less exact results which are entered in gray.

In connection with maps showing the yearly regional solar irradiance shapes these results allow for setting up realistic energy harvest prospects, as well as for proper dimensioning of energy storages for non grid-coupled PV plants. In the latter cases the expected daily harvest shapes have to be opposed to those of the loads to be supplied. In Figure 9 (next page) some typical ordered daily harvest shapes of the demonstration plant are shown; an analysis proved that in all seasons of the year at cloudless days the demonstration plant delivers 80% of nominal installed PV power for more than three hours, and 60% of nominal installed PV power for more than 5 hours. In contrast, in case of heavily clouded days such prospects are not possible just like that.

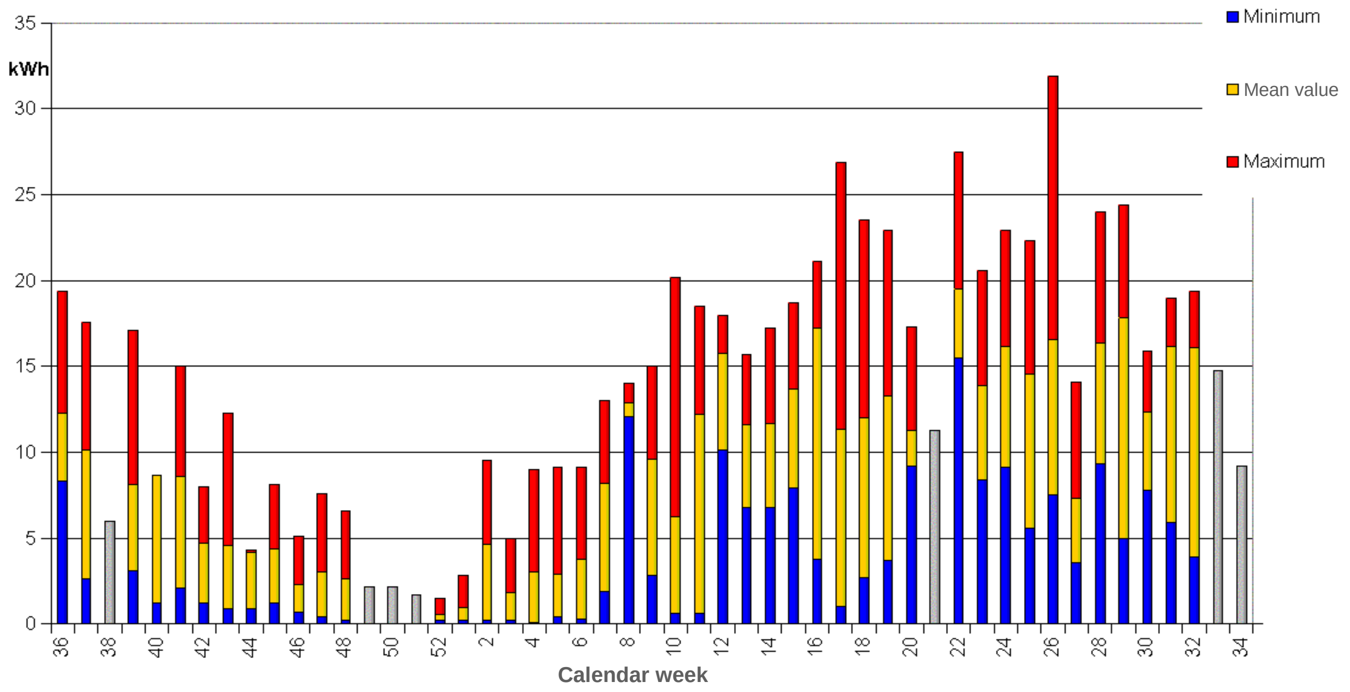

Fig. 8. Average daily energy harvest within calendar weeks.

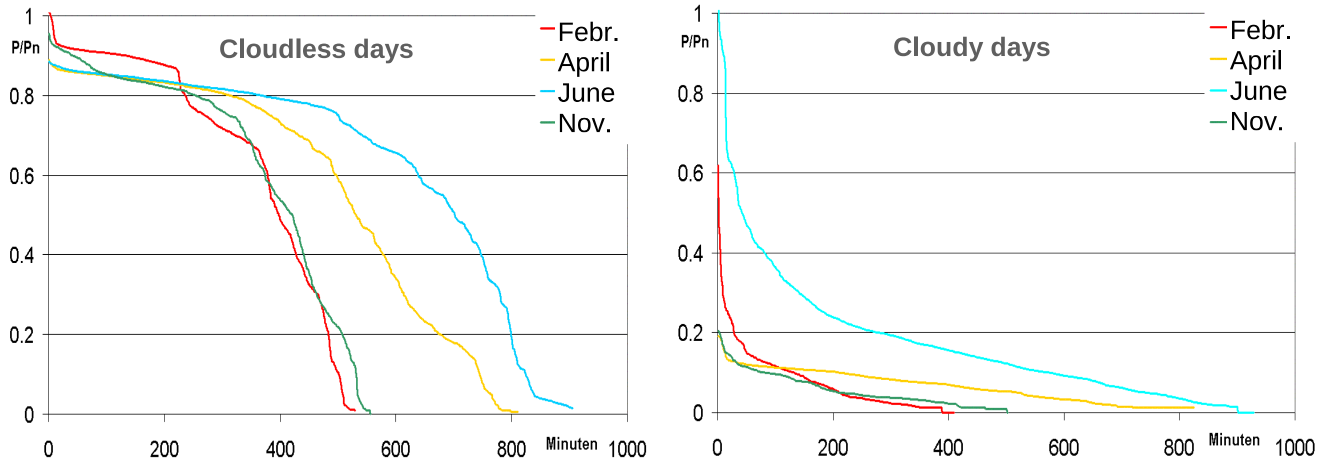

Fig. 9. Ordered energy harvest shapes of pilot plant.

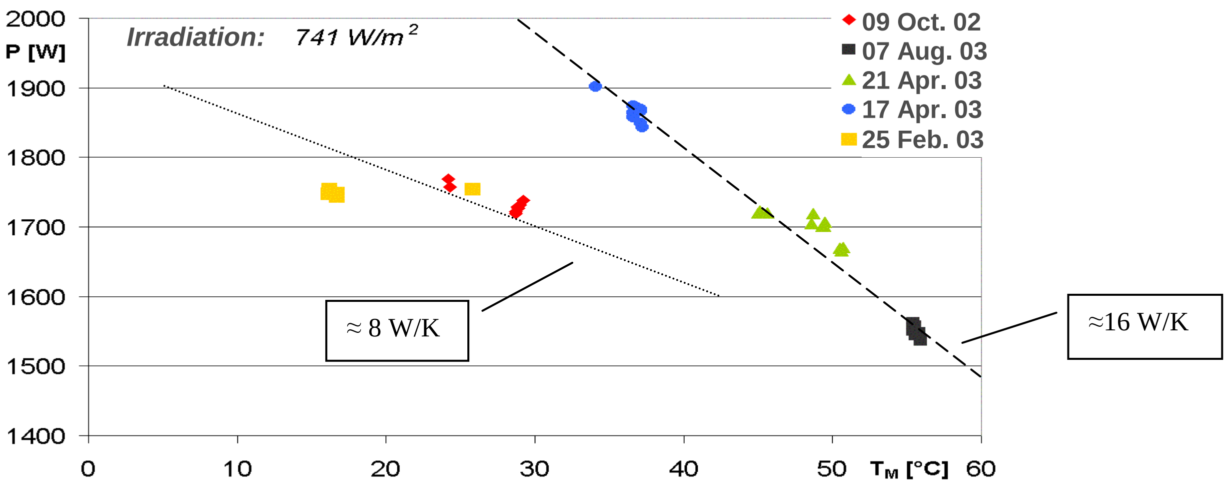

Fig. 10. Thermal dependence of PV power at given solar irradiance.

E. Temperature Dependency

Theoretically, for given solar irradiance the electric power of PV cells decreases with higher cell temperatures. Analysis of the measurement results does not clearly confirm this statement if measurements recorded at different days are considered, as it can be seen from Figure 10; on the other hand, estimation of the gradients $\Delta P/\Delta\theta$ of measurements taken at different times of one and the same day procures plausible values of 8…16 W/K (-0.33…-0.66 % of installed PV peak power/K) for the investigated module group [2].

V. Summary

The bi-directional PV tracking system presented here provides

- simple construction und handling
- low construction and maintenance costs
- high mechanical stability (wind forces in cases of storms)
- low effort and energy demand for manufacturing
- low electric auxiliary demand
- minimal sealing of soil
- good alignment to landscape
- high reliability

and fully satisfies the expectations with regard to energy harvest increment (> 25%) compared to plants with fixed module mounting.

Abandonment of elevation tracking has minimal impact on energy harvest and would further reduce construction effort and cost. Thus, the general tracking principle presented is favorably suitable for remote regions or developing countries with high solar irradiation.

VI. References

[1] http://www.sonnenstraelen.de/2/

[2] E. Skoplakia and J.A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency / power correlations", *Solar Energy*, vol. 83, Issue 5, pp. 614-624, May 2009.

VII. Biographies

Gerhard Krost (M’1999), born in 1953, received the diploma degree in power systems engineering from Darmstadt Technical University in 1978. Working at Erlangen University from 1978 until 1985 in the field of power system harmonics calculation and measurement he received his doctoral degree in 1983. Since 1985 he is with the University of Duisburg-Essen, engaged in analysis, measurement, simulation and control of bulk and decentralized power systems. In 1998 he was appointed as a professor. Gerhard Krost is a member of IEE, IEEE, VDE and CIGRE. e-mail: gerhard.krost@uni-due.de

Peter Swemers has been erecting and mounting photovoltaic plants since 1999, operating this business together with his sons as a familiy enterprise. In the context of constructing mountings for open land PV installations they developed the tracking system presented here and operate the pilot plant since the year 2000. e-mail: info@sonnenstraelen.de