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Experimental installations with high-concentration PV modules using III-V solar cells

V.D.Rumyantsev, V.M.Andreev, N.A.Sadchikov, A. W. Bett*, F. Dimroth*, G. Lange*

Ioffe Physico-Technical Institute, 26 Polytechnicheskaya, St.Petersburg, Russia
Phone: 7-812-2479394, fax: 7-812-2471017, E-mail: rumyan@scell.ioffe.rssi.ru

*Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany

ABSTRACT: This paper describes the main principles of design and operation parameters of experimental installations, which may be regarded as practical prototypes of high-concentration (500x and more) PV systems using III-V solar cells. Tracking aspects including mechanical supporting structure, sun sensors and electronic circuits using a close-loop tracking strategy are under development with respect to the installations for nominal output of 0.2, 1 and 5 kWp.
Keywords: Concentrator Cells, Supporting Structures, Tracking.

1 INTRODUCTION

Concentrator photovoltaics (PV) is known to be a lower cost alternative to the "flat" arrays. In order to optimize a concentrator system all the features and parameters of the different components have to be regarded and specifically optimized. General design of such a system is a complicated task. That is why only a few PV concentrator systems exist on the market whereas one would expect at least two-fold reduction in cost for generated electricity in such systems in comparison with "flat" arrays.

The Fraunhofer ISE (Freiburg, Germany) and the Ioffe-Institute (St.-Petersburg, Russia) have been involved in the development of high-efficiency high-concentration terrestrial photovoltaic systems based on the following concepts: multi-junction III-V solar cells; small-aperture and short focal length concentrator Fresnel lenses in submodules; lens panels made as a composite (glass – silicone) structure; "all-glass" module design; automatic sun-tracking mechanisms managed by analog sensors. This type of module are named FLATCON-modules, an abbreviation for Fresnel lens all-glass tandem cell concentrator modules

Photovoltaic conversion efficiencies as high as 31 % have been achieved using GaInP/GaInAs dual-junction cells grown by MOVPE technique [1]. Moreover, 3-junction III-V solar cells are under development for further increase of efficiency [2].

The concept of small-aperture concentrator sub-modules had been proposed in order to reduce the ohmic and heat dissipation losses in the cells of smaller size [3]. Furthermore, if small-size cells (2 mm in photoactive diameter for our case) are used, automatic mounting techniques can be applied for the PV module fabrication as it takes place at fabrication of the non-integrated electronic components.

The small aperture area Fresnel lenses (4 x 4 cm^2) are united in the panels forming a composite structure. A thin transparent silicone rubber profile is polymerized directly on silicate glass plates serving as the superstrates [4,5]. The modules with 4 x 12 lens panels (the full-size modules with external dimensions of 50 x18 x 8 cm^3) and modules of the reduced sizes had been fabricated and tested. Module efficiencies as high as 24.8% (3x4 lens panel; 120x concentration ratio) [6] and 21.3% (4x12 lens panel; 500x concentration ratio) were measured under outdoor illumination conditions [7].

The "all-glass" module design implies that all parts of a PV module cabinet are made of silicate glass plates: the front side with the lens panel, the rear side whereon the cells are mounted, and the side walls. The thermally matched housing is hermetically sealed with structural silicone [8].

Concentration ratios as high as 500x and more, which are necessary for economically effective application of the III-V solar cells, require a high accuracy of tracking to the sun. Tracking accuracy much better than the sun angle size (~ 32') has to be achieved around both axis. In order to develop complete practical concentrator systems different prototypes of the stand-alone photovoltaic/battery-powered tracking systems were designed and fabricated by us. Experimental tracking systems for total capacity of 0.2, 1 and 5 kWp of the installed "all-glass" concentrator PV modules were built up. The present paper describes the main principles of design and operation parameters of the developed installations.

2 CONCEPTUAL DESIGN

The conceptual design of the installations is very similar to that realized in the Ioffe Institute at early stage of the concentrator photovoltaics [9].

Each tracker consists of two main moving parts: a base platform moving around vertical axis, and a suspended platform with PV modules moving around horizontal axis. Figure 1a represents the main features of such a design with respect to the 0.2kW and 1kW installations.

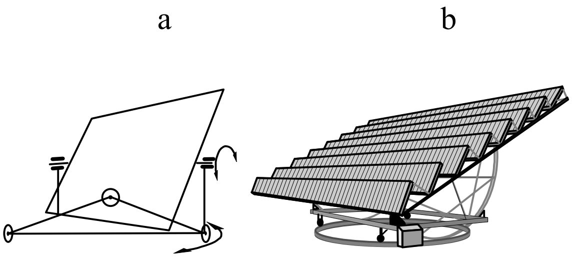

Figure 1: a – Mechanical diagram of the 0.2kWp and 1kWp solar trackers; b – modified mechanical structure for the 5kWp tracker.

In these installations the base platform is equipped with three wheels one of which is connected with an azimuth drive. In this case only a flat ground territory is necessary for the tracker operation. The suspended platform is a three-dimensional frame. The concentrator modules are installed within this frame so that a balance is achieved around the horizontal axis. The frame can rotate from vertical position (sunrise/sunset) up to horizontal position (if the sun is in zenith).

Figure 1b represents the modified mechanical structure designed for the 5kW tracker. The base platform is equipped with four ball-bearings rolling along a steel ring arranged on the ground. The suspended platform is modified in such a way that it has only a virtual horizontal axis of rotation. Two semicircular arcs support a frame placed somewhat over the virtual axis of rotation. The concentrator modules are installed as the steps of a stair. A balance is achieved between the moment of the frame with modules and that of the arcs with reinforcement parts in respect to the virtual horizontal axis. The arcs move is performed by four small-size ball-bearings situated at the corners of the base platform. The position of the arcs can vary in the range of ±45° symmetrically about a horizontal plane ensuring alignment of the modules in elevation.

Geared motor drives powered by 12 V DC are used in the installations. In each case the long parts of the platforms, or even the longest ones, may be regarded as the parts of the driving mechanisms in final step of the gearing down. In particular, the base platform is driven by one of the wheels moving along a circle of a large radius, and, consequently, it has only a small lost motion under wind load. If motors are switched in use continuously, rotation velocity of the platforms is near to 2 rotations per hour, i.e. much faster, than it is necessary for a normal tracking. Continuos operation of the motors is used for returning the trackers from "sunset" to "sunrise" position and for fast "searching" the sun after cloudy periods. At normal tracking the motors are switched on periodically, after each 8-10 seconds, to compensate arising misalignments in respect to the sun position. Such a "pulsed" regime of the drives is characterized by a duty cycle of about 30.

Tracking mechanisms are fully automatic managed by analog sun sensors. Each PV installation is equipped with a main (accurate) sensor and an additional one (see below). The main sensor can align the tracker with the sun to within 0.05 degree accuracy with acceptance angles ±70° in both horizontal and vertical directions. The additional sensor makes wider the "East/West" turning angle (up to 270°, if necessary).

3 SUN SENSORS

A close loop tracking strategy is realized in the trackers with help of the developed sensors. Such an approach excludes necessity in permanent knowledge of the tracker platforms positions and eliminates the accuracy requirements at mounting the installations in the field. Also, electronic circuits are the simplest in this case.

The main sun sensor is mounted on the suspended platform and has an ordinary configuration. It consists of four PV cells (two for azimuth, and two for elevation) placed on a flat plate protected from environments by a flat silicate glass window sealed in contour with a structural hermetic. At a distance of 10-15 cm in front of the plate with cells, another square plate is situated. It shadows in part all the cells being directed to the sun. Two differential signals are generated in the main sensor corresponding to misalignments in azimuth and elevation channels.

The additional sun sensor consists of two PV cells identical to those used in the main sensor. The cells are situated on the opposite sides of a special plate. This plate has to be orientated by its edges always from South to North (with low enough accuracy) independently of the tracker orientation. Besides, the additional sensor is equipped with a shadowing element moving in accordance with movement of the suspended platform along azimuth direction. The latter may be a part of the main sensor, as it is depicted in Figure 2. Differential output of the additional sensor is connected in parallel with that of the azimuth channel in the main sensor.

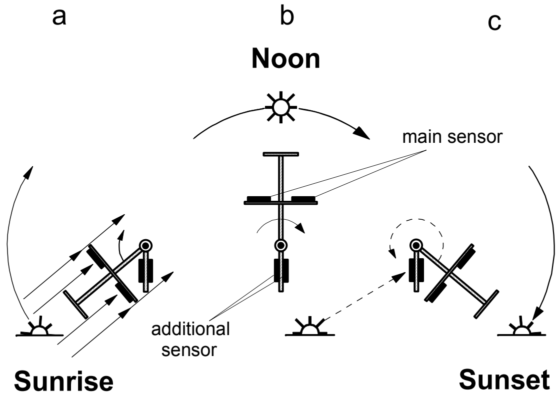

Figure 2: Relative azimuth position of the main sensor and additional sensor at sunrise (a), noon (b) and sunset (c). Also, next day sunrise is shown in sunset position.

Let us consider joint operation by both sensors (see Figure 2). If one assumes that the initial position of a tracker at sunrise is similar to that shown in Figure 2a, then only the main sensor is in operation and the additional one is shadowed. The same situation remains during a whole sunny day, for example, at noon (Figure 2b) and at sunset (Figure 2c). "Sleeping" position of the tracker during night is the sunset position. Next day sun illumination activates left cell in the additional sensor, which generates a signal with sign corresponding to anti-clockwise rotation of the tracker. Rotating in such a way, the tracker turns the main sensor up to a position where sunlight can activate the azimuth cell responsible for anti-clockwise adjustment. After this, the left cell of the additional sensor is shadowed, but the rotation goes on up to position aligned with the sun. A normal tracking is starting.

It is clear from Figure 2 that combined (main + additional) analog sensor is characterized by very wide acceptance angle. "East/West" operation sector may be extended up to 270° what is important, for example, for the case of regions situated at higher latitudes. Moreover, such a sensor ensures the motion and fast alignment of the tracking system with the sun in both clockwise and anti-clockwise directions only within allowed sector and independently of the starting position, in particular, after nights and any cloudy periods.

4 ELECTRONIC CIRCUIT

High-concentration PV systems can convert only direct sunlight. To reduce power consumption for tracking, no motions have to be in the trackers, if direct sunlight is absent. As a rule, the cells in analog sensors analyze and compare the light intensities by means of generation of photocurrent integrated within a whole photosensitivity spectrum. We propose to use in such sensors multijunction cells optimized to the direct sunlight spectrum, i.e. in the same way as it takes place for the solar cells in concentrator PV modules. In this case the photocurrent value depends not only on integral illumination intensity, but also on relation of the intensities within different spectral regions accepted in different subcells of the monolithic multijunction structure. Therefore, a sensor equipped with multijunction cells should "prefer" direct sunlight being less sensitive to diffused light characterized by "deformed" spectrum. In the sensors developed by us the dual-junction GaInP/GaInAs cells have been employed. It is noteworthy, that the dual-junction cells generate a higher voltage in comparison with ordinary (single-junction) ones, what is beneficial for the design of the final-control electronic circuits.

Figure 3 represents a practical circuit design for the azimuth channel. Summarized signal of the combined sensor depends on illumination disbalance arising due to misalignment with the sun. Voltage magnitudes around 2 V are generated in dual-junction cells even at low illumination intensities. It is enough for activation of one of the light-emitting diodes in optotransistors OP1 or OP2, depending on the sign of the generated voltage. Corresponding optotransistor becomes opened giving rise to current flow across relay P_1 or P_2. The contact pair of the relay leads current to a commutating transistor and to one of branches of a transistors bridge loaded with motor.

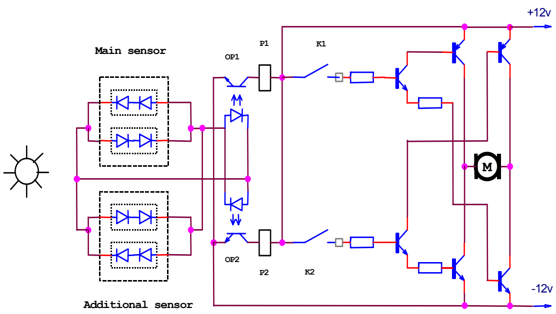

Figure 3: Practical electronic circuit for azimuth channel.

The use of optotransistors rules out the possibility of simultaneous action of both branches in the transistor bridge. Compact low-inertia relays with hermetized contact pairs have been employed in the present circuit design. The circuit shown in Figure 3 is very simple characterized by extremely low current consumption in "sleeping" regime.

5 PRACTICAL DESIGN OF THE CONCENTRATOR PV INSTALLATIONS

The prototypes of the stand-alone automatic tracking systems have been designed, fabricated and tested with respect to tracking abilities.

5.1 The 0.2 kW tracker

This tracker (see photograph in Figure 4) is situated on the roof of the Ioffe Institute (St.-Petersburg). Suspended platform has a two-step three-dimensional structure

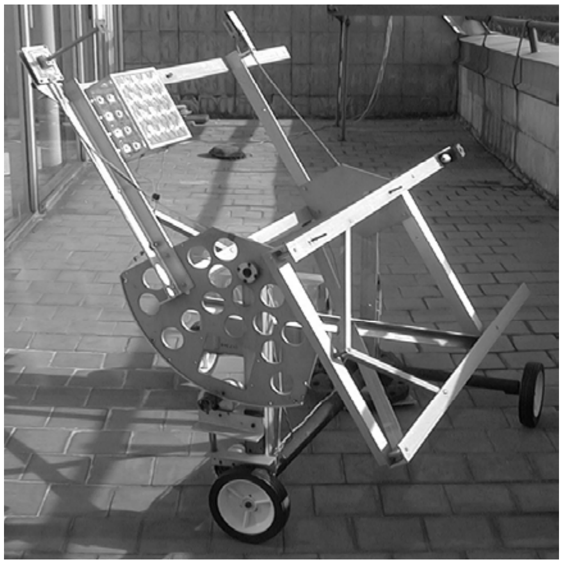

Figure 4: Photograph of the 0.2 kW tracker (Ioffe Institute, Russia).

where 12 full-size concentrator modules can be arranged. Both platforms are moved by identical drives. Each drive consists of miniature DC motor and gearbox. The azimuth gearbox is mechanically connected with one of the wheels moving along the ground. The elevation gearbox is equipped with small roll connected with a quadrant attached to the suspended frame.

Figure 5: Main sun sensor (on the left) and additional one (on the right) mounted on the 0.2 kW tracker.

As an azimuth axis, a short vertical rod fastened in the ground is placed at crossing point of the three wheels axes. This rod prevents a “drift” of the tracker after many rotations in azimuth. Also, a flexible steel wire is connected co-axially with this rod by one end. This wire serves for stabilizing the position of additional sensor with respect to the ground.

Besides sensors (see photograph in Figure 5) and electronic circuits described above, the tracker is equipped with a portable 12 V Ni-Cd battery and overcharge controller. The battery is charged from a concentrator PV module based on 16 series connected single-junction GaAs solar cells. At tracker development the different approaches to sensors and circuits design had been tried at initial stages. Now it is used for current testing the experimental “flat” and concentrator solar cells, submodules and modules, but, being equipped with necessary quantity of the full-size concentrator modules, it may be considered as a prototype of practical PV installation.

5.2 The 1 kW tracker

The tracker is shown in photograph Figure 6. It was installed on the roof of the Fraunhofer ISE in August 2000 and is in continues operation providing a long-term outdoor test of the concentrator modules based on III-V solar cells. The suspended platform structure was designed with aim to obtain a balance between the modules mounted on the front side of the frame and those

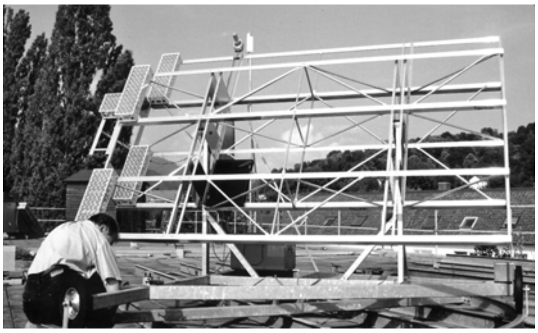

Figure 6: The 1 kW tracker with four full size-concentrator modules. One reduced-size module serves as a power supply for the tracking (Fraunhofer ISE, Germany).

mounted on the rear side (64 modules in total). The gaps between the rows of modules ensure reduction in possible wind load. Also, they provide free access to output module terminals situated on the lower sides of the module cabinets. Similar to the 0.2 kW tracker, in 1 kW tracker the azimuth movement is carried out by means of three wheels, and additional sensor is orientated by means of a flexible mechanical drive. For elevation movement a large quadrant with fastened chain is used in final step of the gearing down. A lead battery provides the tracker with electricity at searching the sun. Practical estimation of power consumption for tracking was performed covering a long period of the tracker exploitation. It was within 0.2-0.4% of output power expected of fully equipped installation.

5.3 The 5 kW tracker

The 5 kW tracker was designed with aim to use the cheapest materials and parts. In particular, cost effective cross-sectional shaped Zn-covered steel members have been employed in the frame where the modules should be installed (see photograph in Figure 7). Standard steel profiles with ready holes were cut right in the bundles. A fastened on the ground basement steel ring of 4.2 m in

Figure 7: The structure of the 5 kW tracker (Freiburg).

diameter is composed of two semicircular elements identical to the arcs supporting the “suspended” platform. The basement ring and both semicircular arcs serve as parts of the chain drives for azimuth and elevation rotations. Identical motor geared drives are used connected with chains (see photograph in Figure 8). They are situated in a protective box where a lead battery with electronic stand is placed as well. The main sun sensor is mounted on the frame together with the concentrator modules. Behind the main sensor, the additional one is placed. The South-North orientation of the additional sensor is provided by a low-power geared motor. The rotation velocity of the additional sensor is equal to that of the tracker in azimuth direction owing to necessary gearing ratio and the fact that its motor is electrically connected in parallel, but opposite in direction, with “main” azimuth motor.

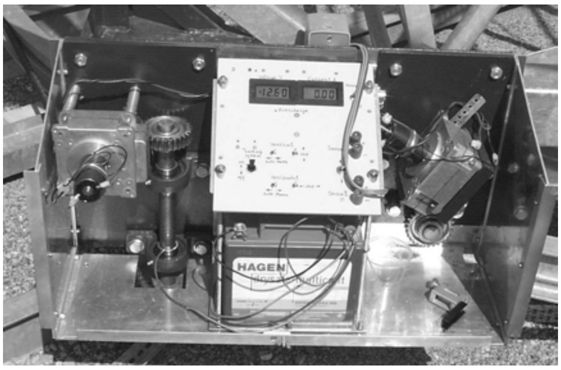

Figure 8: Arrangement of the azimuth (on the left) and elevation (on the right) motor drives in a protective box at one of corners of the 5 kW tracker base platform. A lead battery with electronic stand is situated in the center.

6 CONCLUSIONS

Intensive development of all the necessary components of the high-concentration PV systems with III-V solar cells is carried out under close co-operation between the Fraunhofer ISE and the Ioffe Institute. Besides the problems concerned with fabrication of cost-effective concentrator modules, the tracking has to be under practical development being one of the critical points for the promotion of the concentrator concept. The trackers described here may be regarded as the prototypes of practical stand-alone PV systems ranged in interval from 100 - 200 Wp to several kWp. The close-loop tracking strategy employed in the systems under development allows to simplify the structure and to reduce accuracy requirements at deployment of the systems in the field. Combined analog sun sensors with multijunction cells proposed and realized in the present work are characterized by wide acceptance angles. Together with simple electronic circuits, they ensure automatic searching and tracking to the sun with accuracy of about 0.05 degree. Low power consumption at tracking (~ 0.3% of output power of an installation) is a promising result of the present work as well.

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