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Measurements of power transfer efficiency in CPV cell-array models using individual DC–DC converters

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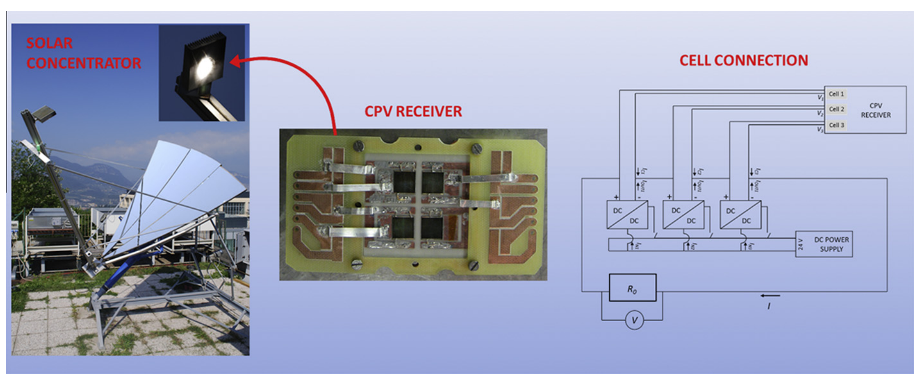
HIGHLIGHTS

- Non-uniform illumination is a major problem in parabolic dish CPV systems.
- A connection fitting each cell of the array with a DC–DC converter is used.
- The possibility of choosing the working point of each cell is the key advantage.
- An array using diodes is shown to increase the efficiency of this connection.
- Another experiment, using real solar cells, confirms the benefits.

GRAPHICAL ABSTRACT

Illumination non-homogeneity is the main problem which affects dense-array CPV systems. In a previous work we theoretically showed that connecting each cell in the array to a DC–DC converter module, leads to an increase of the power transfer efficiency with respect to classical series connection. This finding is here confirmed by two experiments making use of a cells' array, one for a certain combination of shirt circuit currents and another for a typical illumination distribution produced by a parabolic reflector. Encouraging gains in the order of 10% are found.



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ABSTRACT

The high degree of non-uniformity in the irradiance distribution over series-connected solar cells is the main obstacle to the development of concentration photovoltaic (CPV) systems using parabolic dishes. In order to overcome the power loss resulting from the current mismatch due to illumination inhomogeneity, we propose a new cell connection with individual DC–DC converters. The aim of this work is to present an experimental procedure to implement this new approach and to demonstrate its advantages with a basic CPV array prototype. Two separate experiments are carried out respectively with real and equivalent-circuit solar cells in order to study the *I–V* behavior of the connection under different irradiance distributions. The cells working points which yield the highest net power are determined by maximizing the array efficiency by means of a calculation algorithm. The effectiveness of the system is then proved by comparing the output power obtained by field measurement, with the maximum power that could be delivered by the cells array connected in series. In this study, a possible path towards the development of a more effective CPV receiver prototype is outlined.

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1. Introduction

Current mismatch among series-connected solar cells has very serious implications on the performance of concentrator photovoltaic (CPV) systems. Given that all cells carry the same current, the current delivered by a series connected array is constrained by the lowest current element, which is typically the cell receiving the lowest average irradiance. Mismatch problem affects most of CPV system types, including single lens-single optics modules due to soiling effects [1], optical misalignments [2] and resistance effects [3]. The low output current from the array results in a significant loss in the overall output power and average conversion efficiency. In regard to densely packed CPV cells array, the current mismatch is generally higher due to the intrinsic irradiance non-uniformities caused by the concentrating optics [4,5]. This issue particularly concerns parabolic dish systems, which produce Gaussian illumination profiles and expose the cell-array to very high irradiance gradients [6–8].

The high cell-to-cell current mismatch leads to degradation in power performance as well as danger of cells damage due to reverse-bias operation [9]. A common method to protect the cells from reverse biasing is to connect a bypass diode in parallel to each cell, in the same way as for single cell-single optic systems (see for example the CPV receiver developed by Emcore [10]). Bypass diodes successfully prevent damage to the cells but do not give back the power lost due to current mismatch. The most adopted solutions to the mismatch problem aim to enhance the light uniformity at the receiver. Large-area dish concentrators often use planar or curved facet mirrors mounted on a parabolic dish frame, individually oriented to provide a more uniform irradiance at the focus. This is cost effective only for very large collectors, as for example the 135 m^2 dish by Solar System Pty Ltd [11], and still does not achieve high uniformity. Another approach is to use optical flux homogenizers [12], which effectively improve the irradiance distribution on the CPV receivers but also cause optical losses of 10% or more for typical designs [13]. Basically the higher the achieved uniformity, the higher the losses are. A totally different approach is proposed by Vivar et al. [14], where a receiver with cells radially arranged into circular sectors is proposed. This arrangement enables the CPV system to obtain a better distributed irradiance across the cells. Opposite circular sectors (cell pairs) are connected in parallel, and this helps reducing the effects of optical misalignments. In contrast, this solution requires a special cell design and adds wiring complexities.

The choice of the connection type aims to maximize the PV power transferred to the external load. The power output of a multi-cell array depends not only on the manufacturing characteristics of the cells and on the working conditions (irradiance distribution, spectral content, humidity, temperature), but on the way the cells are interconnected, too. Cells designed for CPV application typically deliver high currents. For instance the last generation 1 cm^2 solar cells by Spectrolab generate currents of about 7 A (maximum power point current) at 50 W/cm^2 [15]. By connecting these cells in series, the overall current can be kept as low as possible, this way reducing Joule-effect losses. In general, when a CPV dense-array is large enough, solar cells are grouped in a basic module connected in parallel, and connection between basic modules is in series. The optimized array configuration, specially tailored for the flux distribution of the solar concentrator, has to be estimated by computation methods [16,17]. A promising way to improve system performance is the use of cells which can provide high voltage and low current, as they could be connected in parallel and still give a reasonably high array output voltage [18]. The working voltage of a group of parallel connected cells would be only weakly limited by the open-circuit voltage of the less-illuminated cells.

To deal with the current matching issue we proposed an array configuration in which less illuminated cells are supplied by an external power source through individual DC–DC converter modules. This electrical connection has the capability of allowing the "best" cells to work closer to their maximum power point (MPP). When the cell-array is properly set-up, this configuration provides a net power amount larger than classical series connection, as we have analytically demonstrated and numerically simulated for a 20 cell-array exposed to a Gaussian illumination profile [19]. This solution could lead to some practical advantages, too. First the homogenizing optics could be designed with fewer restrictions or even be omitted altogether without sacrificing performance. Second, impact of optical misalignments and tracking errors could be reduced. The concentrator system could then be designed with lower requirements on mechanical stiffness, tracking accuracy and cost.

Although we proved this new type of connection to be very promising by means of theoretical analysis, we did not yet investigate the complexity of software and hardware configurations for its practical realization. The present work is aimed to establish an experimental procedure to implement this connection and to show its possible advantages and weaknesses.

In the first part of the paper, the connection is described and the concept of power transfer efficiency is introduced. This figure of merit is used to assess the advantages of the connection in terms of PV output power. In Section 2 we present an experimental test of the new connection with DC–DC converters using solar cell equivalent circuits based on diodes. A 3-cells array was assembled and a procedure to optimize the electrical configuration was adopted. Given a certain mismatch condition, the array went through a computer algorithm, designed to predict the optimal working point of each cell. Next, the array was set up and the output power evaluated under some current combinations. In Section 3 we report an experiment adopting the same procedure to test an array of 3 multijunction (MJ) solar cells operating in a CPV system. From field measurements, single *I–V* data were acquired and used to determine the optimal electrical configuration of the array. Power transfer efficiencies of the new connection are compared to the maximum power transfer efficiency obtained from a series connection under the same working condition. The new cell connection in an array operating with a CPV system has shown to require some complexity to reach the expected performance; for this reason a way to improve the hardware configuration is pointed out. In the conclusions, the overall remarks of the work are reported.

1.1. Cell connection with DC–DC converters

The aim of this new type of connection, extensively described in [19], is to have a non-zero number of degrees of freedom in the circuit, unlike classical parallel and series connections. Choosing the electrical working points of each cell so that all cells could operate close to their MPP, the array would be enabled to deliver more power to the external load. A possible way to fulfill this condition is to connect each cell in the array to an individual DC–DC converter. The operation of DC–DC module, power supplied by an external source (see Fig. 1) is described by the equations

$$\left\{\begin{array}{lll} \eta_A(V_{IN}, I_{IN}, V_{OUT}, I_{OUT}) \cdot P_{IN} = P_{OUT} & if & P_{OUT} > 0 \\ P_{IN} = K(V_{IN}, I_{IN}) & if & P_{OUT} = 0 \end{array}\right\}. \quad (1)$$

where η_A is the DC–DC converter module efficiency, *I*, *V* and *P* are the DC–DC current, voltage and power, respectively, and subscripts *IN* and *OUT* refer to input and output values. In Eq. (1), *K* takes account of the power dissipated by the DC–DC converter when it is supplied with P_{IN} and its output is zero. The term *K* may be