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Case study of a grid connected with a battery photovoltaic system: V-trough concentration vs. single-axis tracking

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ABSTRACT

Photovoltaic systems (PVSs) combined with either some form of storage, such as a battery energy storage system (BESS), or direct load control, can play a crucial role in achieving a more economical operation of the electric utility system while enhancing its reliability with additional energy sources. At the same time, it is also important to use cost-effective PV solutions. In this context, a low-concentration PVS (CPVS) is analysed as a feasible alternative. This paper, present a case study of a complex PVS, composed of two PVSs, a storage system (BEES) and an inverter that allows the system to operate in both the island and grid-connected modes. The first PVS, is a 2.76-kWp single-axis tracking system (azimuth) with modules facing south and tilted 30°, while the second PVS is a dual-axis tracking system, rated 860 Wp, consisting of a concentrator at the flat mirrors (DoubleSun® Four). The system is installed on the roof of the main building of the "ITIS Marconi" school (Italy). A detailed description of the system is provided, and preliminary operating data are presented and discussed. The efficiencies of the PV systems are calculated and measured to evaluate the cost effectiveness of a low-concentration system.

1. Introduction

To cope with the future increasing presence of PV generation in the power grid, it is necessary to control PV generation, which, similar to conventional power sources, is non-programmable. A possible control solution is to equip the grid-connected PV systems with storage batteries, to adequately modify the daily generation profile [1]. Of course, the adopted solutions that will allow the integration of numerous non-programmable energy sources into the distribution grid, must cope with economic issues. In fact, PV plants have very low operating costs, but relatively high capital costs, mainly due to the low surface density of solar energy. One feasible way to reduce these capital costs is to incorporate optical systems (mirrors or lenses) that increase the incident radiation per m^2 of solar cells [2,3]. It is important to note that, the cost reduction obtained with the optical concentration systems, due to the reduced amount of solar cells, must be balanced by: additional optics, solar tracking systems, and the partial loss of diffuse light.

In fact, the optical concentration system only transmits the direct component and does not transmit the diffused portion, which must be deducted from the estimate of the radiation due to the extra concentration. In this regard, the possibility of concentrating solar radiation at the reflectors has been the subject of numerous studies. Significant and encouraging results were first published (for solar collectors) some decades ago [4,5], while similar prospects were announced later, also for photovoltaic (PV) systems [6].

In [7], it is affirmed that the annual energy production can increase by 10–30%, while the cost of the plant would only increase by 10%. In [8], for a system with a low-concentrator (2*X*) reflector, the PV power generation increased its value by approximately 23%. However, these results, are strongly dependent on certain factors, including: the ratio of the heights reflector/PV module, the latitude and average monthly levels of radiation at the site under consideration, and the distance between the modules when installed in an array. Evidently, before the adoption of solutions, such as "augments", careful economic evaluation must be performed on a site-by-site basis. To collect significant data on tracking and low-concentration systems, in an area of Mediterranean climate, the ITIS's (Industrial Technology Public Institute) "G. Marconi" school in Catania installed two small PV systems: a tracking azimuthal type and a low-concentration type, Doublesun® Four, patented by WS Energia [9].

The first operational data have been analysed in cooperation with the DIEEI Department of the University of Catania (Italy). The purpose of this report is two-fold. First, an overview of the operative problems affecting the energy production of the systems is provided. Second, measurements and mathematical models are

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used to provide, a preliminary evaluation of the cost effectiveness of a low-concentration system. This paper is organised as follows: Section 2 provides the optical and electrical theoretical backgrounds describing the behaviour of a PV system; Section 3 gives a detailed description of the system, the load and measurements apparatuses; Section 4 presents the efficiencies of the PV systems and provides some examples of daily profiles; and Section 5 is dedicated to the validation of the model.

2. Theoretical background

To study a tracking system with and without concentration, and compare the measured performances against a reference model, a theoretical background coverings both optical and electrical efficiency considerations is required.

2.1. Optical basics

For low concentrations, the most widely used device is the V-trough concentrator, which consists of flat mirrors on either side of the photovoltaic module (Fig. 1).

This device can achieve a geometric concentration of greater than 2*X*.

V-trough geometry is defined by two parameters: the trough angle, Σ, and the geometric concentration, *C*, which is the quotient of the trough aperture, *A*, and the absorber (PV module) width, *a*.

To avoid a drastic reduction in PV production due to the series connection of PV cells and modules, as well as hot-spot phenomena, incident irradiation must be evenly distributed over the PV surface. For an ideal concentrator that is perfectly aligned with the sun, this condition leads to the following relation for a single reflection [10]:

$$C = \frac{A}{a} = 1 + 2\cos(2\Sigma) \tag{1}$$

To maintain a uniform irradiance even when the alignment is not perfect, i.e., $\theta_i \neq 0$, real concentrators use longer mirrors (L') than those derived from Eq. (1). In this way, it is possible to give the concentrator an angular aperture, θ_u, that is the maximum angle of incidence for which the irradiation of the receptor is uniform. In other words, the incident angle, θ_i, must always be less than θ_u. This angle, referred to as the acceptance angle, depends on the tracking strategy (continuous or discontinuous).

The optical concentration, C_{opt}, is smaller than *C* because the mirror reflectivity, ρ, is less than one, thus, Eq. (1) must be modified as follows:

$$C_{opt} = 1 + 2\rho\cos(2\Sigma) \tag{2}$$

Reflectivity depends significantly on wavelength; thus, the optical concentration depends on the solar elevation angle. As solar elevation increases, air mass decreases, the solar spectrum is displaced towards ultraviolet, and the reflectivity of the silvered mirrors is decreased [11].

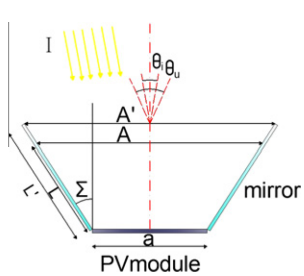

Fig. 1. Schematic geometry of V-trough concentrator.

Optical efficiency, η_{opt}, is defined as the relationship between the optical and geometric concentrations. To evaluate η_{opt} two contributions must be considered: the first contribution relates to the beam fraction of the solar radiation (F_B), which is the ratio of the beam solar radiation (I_B) over the global irradiance (I); the second contribution relates to the diffuse fraction, F_D, which is the ratio of the diffuse (I_D) solar radiation over the global irradiance (I). Therefore, η_{opt} takes the following form:

$$\eta_{opt} = (1 - F_D)\eta_B + F_D\eta_D \tag{3}$$

When the device only receives beam irradiance with an angle of incidence inside of the acceptance angle, optical efficiency is given by the following expression:

$$\eta_B = \frac{1 + 2\rho\cos(2\Sigma)}{C} \tag{4}$$

The value of η_D can be approximated from the following expressions [12]:

$$\eta_D \approx \frac{\rho^{\frac{n_d}{C}}}{C} \tag{5}$$

$$n_d \approx a + b\left(\frac{\sin^{-1}\frac{1}{C}}{\Sigma}\right) \tag{6}$$

Coefficients *a* and *b* depend on the geometric concentration and their values for *C* = 2*X* are 0.149 and 0.148, respectively [12]. In [13], a concentration coefficient is defined as follows:

$$\sigma C = 1 + (C - 1)\eta_B F_B \tag{7}$$

where η_B is the overall efficiency of the optics (determined from the mirrors' reflectivity, ρ, and the optical configuration, including the specified maximum misalignment of the tracking system), and F_B is the ratio between the direct and global irradiances. Table 6 summarises the main parameters of the CPV subsystem model. Eq. (7) assumes that only the beam component of the irradiation I_B is reflected from the mirrors onto the module. In practice, this assumption is incorrect, and it is expected that a fraction of the diffused light will also be reflected onto the module according to efficiency η_D.

2.2. Electrical efficiency

The efficiency of a solar cell is dependent on both the irradiance and cell temperature, i.e., both the open-circuit voltage and fill factor decrease substantially with temperature (as the thermally excited electrons begin to dominate the electrical properties of the semi-conductor), while the short-circuit current increases, slightly.

Thus, the net effect leads to a linear equation of the following form [14]:

$$\eta_c = \eta_{STC}[1 - \beta(T_{PV} - T_{PV,STC}) + \gamma\log_{10}I] \tag{8}$$

in which η_{STC} is the module's electrical efficiency at the standard test condition, $T_{PV,STC}$ of 25 °C, and at solar radiation flux of 1000 W/m^2. The energy performance of the PV module is a function of its operating temperature, T_{PV}, and irradiance (I). In Eq. (8) there are two parameters that depend on the technology of the PV module, i.e., the power temperature coefficient of module β and the intensity coefficient for cell efficiency γ.

The module voltage reduces with increasing temperature, and although the current increases slightly, the overall effect is a decrease in efficiency with increasing temperature (at least for Silicon crystalline technology). Based on the information available in the PV module database of PVSyst software [15], the average value of the maximum power point thermal coefficient for different PV technologies, and the average η_{STC}, have been