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Pv layout optimization: String tiling using a multi-objective genetic algorithm

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Abstract

Urban environments present new challenges to the integration of photovoltaic systems onto the building envelope. This study describes a multi-objective genetic algorithm developed for the maximization of the PV electrical production and minimization of relevant system costs, such as wiring, modules and inverter costs. Two case studies are analyzed, featuring a partially shaded rooftop and a vertical facade. The PV layouts suggested by the genetic algorithm outperform the conventional configurations by reducing the cost of produced electricity between 6% and 18%. The optimization results also show that layouts with more but shorter PV strings achieve higher energy yields. However, when compared with longer clustered strings in the most sunlit areas of the surfaces, this results in the doubling of costs.

Keywords: Photovoltaic; Partial shading; Genetic algorithm; Multi-objective optimization

1. Introduction

There are many methodologies available to plan a PV system, typically using averages of solar radiation and temperature and considering representative module parameters, and software-based sizing approaches. However, while the process is quite straightforward for systems deployed in areas with no horizon obstructions (typically non-urban plants), the scenario becomes more challenging when dealing with surfaces with intricate shadowing events (decentralized urban PV generation). In those situations, the incident solar radiation varies along the surface on an hourly basis, requiring a different approach to the system sizing: as the connection between modules is done in series (PV strings), a partial shadow on one of the modules significantly impacts the production of the string. Moreover, due to different sun-paths throughout the year, the shadow patterns on surfaces are constantly evolving, making this a very complex problem of systems optimization. AC modules with micro inverters are also an alternative to conventional string based systems (Kurokawa et al., 1997). They hold the advantage of being immune to output power drop when a module is shaded and are also immune to mismatch losses. On the other hand, their installed power cost is higher and maintenance can be costly and hard to perform in facade environments since the micro inverters are spread all over the facade. This study will not consider AC modules with micro inverters.

Continuous and complex optimization problems, which cannot be fully represented and solved through well-defined mathematical expressions, may be addressed

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through evolutionary strategies. When a problem has neither a unique and obvious solution or the search space is overly large, or even if the problem has more than one objective, Evolutionary Algorithms (Bäck et al., 1993) or Genetic Algorithms (GA) (Goldberg, 1989) are numerical modeling procedures that can be employed. In an effort to replicate the behavior of natural evolution of species in nature, these algorithms create populations of individuals which are then subject to selection, recombination and mutation operators (or only mutation in the case of evolutionary algorithms). A performance comparison between both strategies is out of the scope of this paper and as such the reader is invited to Fonseca's work whereby a review and analytical investigation was undertaken to compare both (Fonseca, 1995).

Some studies regarding the optimization of some features of PV systems using evolutionary strategies have been reported in literature. For example, in (Kornelakis and Koutroulis, 2009) a sizing optimization scheme was developed for Grid Connected PV systems using a GA to maximize the total net profit of the systems. However, the study does not include losses associated to temperature or inverter-to-array sizing ratio. Moreover, the proposed technique is only suitable for flat rooftops and where supporting structures are used that allow for tilt angle adjustment (which is an optimization process variable). Sulaiman et al. (2012) presents an algorithm through evolutionary programming to optimize the usage of available area with the prerequisite of maximizing the technical or economic performance. The optimization is based on a pre-defined sets of inverters and PV modules that would optimize technically or economically the performance of a fixed system. Despite overcoming the limitations of previous approaches, the sizing results are not feasible, as they point to a unique PV string with numerous modules. Although not done in the study, it would also be interesting, using a Pareto ranking algorithm, to perform a multi-objective optimization with both objectives being evaluated simultaneously. On the other hand, Gómez-Lorente et al. (2012) address the optimization of PV plants with solar tracking in terms of reducing electrical losses. Different evolutionary algorithms were employed and statistically compared, revealing that the scheme with random mutation outperformed the rest due to faster convergence whilst remaining equally accurate. Another use of a GA is presented in Shirzadi et al. (2014) to minimize the mismatch losses in PV arrays. However, it is a purely theoretical study; the module parameters were statistically obtained from the technical specifications of a PV module and the radiation set to be uniformly distributed (i.e. with no shadowing effects). Nevertheless, the approach can be applied to a real system for arranging PV modules with known measured parameters.

The goal of the present assessment is to address two different surfaces to test a multi-objective GA aiming at maximizing the PV production of the system and minimizing system costs, i.e. giving the best PV strings sizing and tiling configuration. The relevant losses to the system are considered together with solar radiation changes caused by shadow events. The solutions obtained are compared with the conventional tiling.

2. Methodology

Input data used is described in the first subsections, along with the expressions employed to compute PV production and relevant systems costs. The optimization strategy and the implemented GA mechanisms are then presented.

2.1. Solar radiation model

In order to estimate the PV production of a system, solar radiation data is required. Long-term solar radiation measurements in the horizontal plane are somewhat common but measurements on the tilted plane are rare. As such, a solar radiation model using horizontal plane data is employed to calculate the incident radiation on non-horizontal surface. Since there are few models are able to perform this type of calculations in a three-dimensional urban space (Freitas et al., 2015), the SOL model was used in the present work. SOL is a 3D solar radiation model developed for the assessment of solar potential in the urban environment. The model's inputs consist on a geo-referenced $1 \times 1\ m^2$ Digital Surface Model (DSM) and a local typical meteorological year (TMY) data set. The model outputs hourly irradiation values for any point of an urban landscape regardless of location (i.e. on a roof, ground or facade) and takes into account mutual shading between buildings and other urban features. For a more detailed description of SOL model see (Redweik et al., 2013).

The irradiation levels for a $4 \times 8\ m^2$ rooftop case-study, the one circled in Fig. 1, were computed from a synthetic DSM assuming the latitude for the city of Lisbon. The tilted roofs are south facing and are represented with colors according to their heights.

The adjacent buildings cast very well defined and predictable shadows patterns: in the morning the building to the right is responsible for casting a shadow on the middle rooftop while the left one obstructs most of the sunlight in the later hours of the day. In Fig. 2, the partial shading events on the rooftop are represented. The original rooftop model has a defined area of $4 \times 8\ m^2$ but the edges of the roof were excluded as these represent the limiting areas of the rooftop where PV modules are not usually installed.

The installation of PV systems in the rooftops of buildings in the urban environment represents a primary option. However, due to limitations on the available area, building facades are gaining interest. Despite vertically mounted solar panels receiving less solar radiation than roofs, particularly in the summer months, facades feature higher areas. For example, for high-rise buildings this can result in the tripling annual electricity production. Also, since