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Cell string layout in solar photovoltaic collectors

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ABSTRACT

This work aims at describing a simulation model that studies the influence of the cell string layout on the performance of solar panels taking into account the environmental conditions. Several solar cell string configurations in the photovoltaic modules are simulated using a simulation program for integrated circuits, looking for a mitigation of the effects of shading and/or non-uniform illumination of the solar panel. The simulation model is validated using data provided by Solarus,[1] as well as results obtained experimentally in Sweden concerning outdoor tests or using a lab solar simulator with similar collectors. The model is simple and flexible enough to be easily matched to various string layout configurations and, unlike several maximum power point tracking procedures, it allows the correct assessment of the maximum power in situations presenting multiple maxima in the power *versus* voltage stationary characteristic of the solar panel. The simulated and experimental average electrical efficiency in December in Gavle (Sweden) for flat collectors manufactured by Solarus with strings of 38 solar cells connected in series is around 20%. Modifications in the solar modules currently manufactured in Solarus are proposed, together with the identification of the contexts in which they represent a reasonable added value. Examples of module configurations with overlapped bypass diodes show an increase of almost 100% in the short circuit current. The methodology used in this work for the design of the solar cell configuration is a valid contribution to the analysis of stationary roof/ground grid-tied or off-grid small installations and it represents undoubtedly an important tool for the enterprises in the manufacturing process.

1. Introduction

The imperative necessity of changing from a fossil fuel paradigm to renewable sources is today very well established. Special issues on related subjects show that this is undoubtedly a theme of current interest [1]. The renewable energy directive in the European Union (EU)[2] establishes an overall policy for the production and promotion of energy from *renewable* sources. As far as solar energy is concerned, special attention to the photovoltaic and thermal (PVT) technology has been done since the 1970s. It shall be emphasized that this is a matter that remains quite current, taking into account the advancements in recent years and the future work required for the progress of the innumerous applications in this important domain [2].

1.1. Present state of the art

In the context of the sustainability of the earth's energy supply chain, renewable energy sources (RES) - wind, hydro, solar, geothermal, bio, - play an important role.[3]

In 2014, global wind generation was 706 terawatt-hours or 3% of the world's total electricity. In 2015, hydropower generated 16.6% of the world's total electricity and 70% of all renewable electricity. In spite of biomass combustion being an important contributor for pollution, biofuels provided 2.7% of the world's transport fuel in 2010.

Solar energy has the advantages of being environmental friendly and having unlimited availability. The price of solar power has been continuously decreasing in the last decades ($96 per watt

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URL: http://www.solarus.se (J. Gomes).

[1] Swedish SME that manufactures concentrating hybrid photovoltaic and thermal solar panels (http://www.bcorporation.net/community/solarus-sunpower-sweden-ab) and (www.solarus.se).

[2] In July 2009, the leaders of EU and G8 announced an objective to reduce greenhouse gas emissions by at least 80% below the 1990 levels by 2050. (From Roadmap 2050).

[3] https://en.wikipedia.org/wiki/Renewable_energy.

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Nomenclature

A_{aper}	aperture area of the collector (m^2)
A_{cell}	solar cell active area (m^2)
A_r	receiver area (m^2)
C	reflector concentration ratio (–)
C_0	sensitivity of photocurrent with irradiance (A m^2/W)
C_1	thermal sensitivity of photocurrent (A/K)
f	useful fraction of the diffuse radiation (–)
G	solar irradiance (W/m^2)
G_b	beam solar irradiance (W/m^2)
G_{dif}	diffuse irradiance (W/m^2)
G_{ref}	solar irradiance at STC (W/m^2)
I	load current (A)
I_{sc}	short circuit current (A)
I_D	diode ideal current (A)
I_{mp}	current at MPP (A)
I_{pv}	photovoltaic generated current (A)
I_{Rp}	current in the shunt resistor (A)
I_S	dark saturation current (A)
$J_{sc,ref}$	short circuit current density at STC (A/m^2)
K	Boltzmann constant, $1.38064852 \times 10^{-23}$ (J/K)
L_{aper}	aperture length (m)
L_r	receiver length (m)
L_{tr}	collector length along the trough axis (m)
M	number of bridged cells per BP diode (–)
N	number of solar cells per string (–)
P_{conc}	power in the concentrated (bottom) side of the receiver (W)
$P_{conc\text{-}beam}$	power in the bottom side due to beam radiation (W)
P_{conc_dif}	power in the bottom side of the receiver radiation (W)
P_{flat}	power in the flat (upper) side of the receiver (W)
P_{mp}	peak power or power at MPP (W)
q	modulus of electronic charge, 1.6×10^{-19} (C)
r	reflector factor of the glass (–)
R_p	parallel, leakage or shunt resistor (Ω)
R_s	series resistor (Ω)
T	absolute temperature (K)
V	load voltage (V)
V_{cell}	voltage across the illuminated cells in the string (V)
V_C	reverse breakdown voltage (V)
V_F	forward diode voltage (V)
V_{mp}	voltage at MPP (V)
V_{oc}	open circuit voltage (V)

Greek symbols

α_s	elevation solar angle (°)
ΔT	temperature variation from 25 °C (°C)
ν	incident angle (°)
η_{el}	electrical efficiency (–)
$\eta_{cell\_25°C}$	solar cell electric efficiency at 25 °C (–)
η_{op}	optical efficiency (–)
θ_a	acceptance angle (°)
$\theta_{a\ max}$	maximum acceptance angle (°)
$\theta_{a\ min}$	minimum acceptance angle (°)
θ_t	tilt angle of the glass cover (°)
τ	transmission coefficient through the glass (–)

Acronyms and abbreviations

BP	ByPass
CPC	Compound Parabolic Concentrator
C-PVT	Concentrating PhotoVoltaic and Thermal
EU	European Union
IST	Instituto Superior Técnico
LTSPICE	Linear Technology Simulation Program for Integrated Circuit Emphasis
MaReCo	Maximum Reflector Collector
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
O&M	Operations and Maintenance
PV	PhotoVoltaic
PVT	PhotoVoltaic and Thermal
RES	Renewable Energy Sources
STC	Standard Test Conditions
ULisboa	University of Lisbon
1M3P	Single Model with 3 Parameters
1M5P	Single Model with 5 Parameters

in the middle-1970 to less than $1 per watt in 2016). Being more predictable than wind, the operations and maintenance (O&M) procedures are easier to manage.

"By 2050, solar power is anticipated to become the world's largest source of electricity, with solar photovoltaics and concentrated solar power contributing 16 and 11 percent, respectively".[4] In the last two decades the growth of photovoltaics fitted an exponential curve and in the last year the world capacity reported was around 230,000 MW.[5]

Solar energy systems may be photovoltaic (PV), thermal or hybrid (PVT). PV system installations may be grid-tied or off-grid. Both of them may be associated to large power plants or to roof/ground mounted small installations. Obviously, the system requirements are closely related to the demands or applications. For instance, off-grid stand alone PV systems often require any electrical storage capacity.

Other aspects may be considered to distinguish PV systems, for instance, those concerning the materials used in the photo-electric conversion. Currently, silicon technologies are the most commonly. However, various alternatives have been developed recently, with special emphasis on new materials and fabrication techniques, namely those evolving organic materials. While the reported efficiencies are still low, they are promising, since they are much less expensive [3].

1.2. Literature review

Photovoltaics as a sub-domain of solar energy represents a current area of interest, as it is apparent by the amount of available literature produced by the scientific community. To choose relevant papers will be then a tremendous task, but some review papers in this large domain may be referred, namely those highlighting the following aspects:

i. *The effect of non-uniform light distribution along the receiver of the solar panel on the performance of the PV system* [4].
The sensitivity to these effects is highly dependent on the electric system configuration of the photovoltaic array.
ii. *The aging of solar PV plants ant the mitigation of their consequences.*
One of the advantages of solar PV systems is their modularity. PV modules are often considered to be the most reliable component of a PV system, with a warranty period up to

[4] https://en.wikipedia.org/wiki/Growth_of_photovoltaics.
[5] https://en.wikipedia.org/wiki/Growth_of_photovoltaics.

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