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Loss-of-load probability model for stand-alone photovoltaic systems in Europe

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Abstract

Sizing of stand-alone photovoltaic systems (SAPVS) requires knowledge of their reliability. Because of primary influence of the solar irradiance and meteorological conditions, simulations are the best way to compute an accurate reliability for a given location and fixed sizing parameters. These studies have been developed for more than two decades, but have had a narrow geographical applicability.

In this paper, we perform a complete (in time and space) simulation of a standard SAPVS in Europe using 23 year radiation data corresponding to almost 2300 geographical points. At each point, the tilt angle that maximizes the energy reaching the PV array in December is estimated and the relation among sizing parameters and reliability is computed for wide ranges of values. Finally, multilayer perceptrons are trained for both computations, allowing (after their training) simple and fast estimations of the sizing parameters of this type of plants for any location in Europe.

The procedure presented in this paper, although focused particularly in Europe, can be easily extended to almost any other region in the world.

Keywords: Stand-alone PV systems (SAPVS); Loss-of-load probability (LLP); Multilayer perceptron (MLP)

1. Introduction

Autonomous or stand-alone photovoltaic systems (SAPVS) are installations with photovoltaic modules and batteries designed to fit some load without any connection to the electric grid. Even in Europe, those systems are interesting for powering stations, plants or houses in rural areas, where the grid is distant or is not very reliable. Additional benefits of this kind of systems are independence and its energy-saving and environmentally friendly character.

A SAPVS is characterized by two dimensionless parameters: C_S, related to the capacity of the storage system, and $C_A(\beta)$, the mean or minimum capacity of the PV panels array, defined:

$$C_U \stackrel{\text{def}}{=} N_B V_B C_B \text{DOD}, \tag{1a}$$

$$C_S \stackrel{\text{def}}{=} \frac{C_U}{L}, \quad \text{and} \tag{1b}$$

$$C_A(\beta) \stackrel{\text{def}}{=} \frac{\eta A \widehat{G}_d(\beta)}{L}, \tag{1c}$$

where N_B is the number of batteries (supposed all equal), V_B the nominal voltage of one battery (in V), C_B the nominal or rated capacity of each battery (charge dimension, in C = As), DOD the maximum allowable depth of discharge of each battery (dimensionless), C_U the maximum useful capacity of the batteries (energy dimension, in J), L the mean daily energy load (in J), η is the average whole energy transmission efficiency of the PV system from the PV array to the load, A the array area (in m^2), and $\widehat{G}_d(\beta)$ is a

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Nomenclature

$a,\ b$	parameters in Liu–Jordan correlation
A	total area of PVA, m^2
AG	auxiliary generator
ANN	artificial neural network
b	bias of a neuron
B	beam irradiation, J/m^2
$B_d(0)$	daily beam irradiation on horizontal plane, J/m^2
$B_d(\beta)$	daily beam irradiation on tilted plane, J/m^2
$B_{e,d}(0)$	e.t. daily solar irradiation, horizontal plane, J/m^2
$\overline{B}^{\perp}_{e,h}$	average e.t. hourly solar irradiation, normal incidence, J/m^2
$B_h(0)$	hourly beam irradiation on horizontal plane, J/m^2
$B_h(\beta)$	hourly beam irradiation on tilted plane, J/m^2
BS	batteries system
$C_A(0)$	capacity of the PVA (horizontal) relative to the load
$C_A(\beta)$	capacity of the PVA relative to the load
C_B	nominal or rated capacity of each battery, $C = \mathrm{A\ s}$
C_S	capacity of the BS (C_U) relative to the load (L)
C_U	maximum useful (energy) capacity of the BS, J
D	diffuse irradiation, J/m^2
$D_d(0)$	daily diffuse irradiation on horizontal plane, J/m^2
$D_d(\beta)$	daily diffuse irradiation on tilted plane, J/m^2
$D_h(0)$	hourly diffuse irradiation on horizontal plane, J/m^2
$D_h(\beta)$	hourly diffuse irradiation on tilted plane, J/m^2
DOD	maximum allowable depth of discharge of each battery
E_{aux}	daily energy provided (if any) by AG to BS, J
$E_{aux,T}$	total energy provided by AG to BS, J
e.t.	extraterrestrial (outside the atmosphere)
ET	equation of time, h
f	parameter in isoLLP model, Eq. (16)
$f_1,\ f_2$	parameters in Eq. (5)
G	global (total) irradiation, J/m^2
$G_d(0)$	daily global irradiation on horizontal plane, J/m^2
$G_d(\beta)$	daily global irradiation on tilted plane, J/m^2
$\widehat{G}_d(0)$	representative daily insolation on the horizontal plane, J/m^2
$\widehat{G}_d(\beta)$	representative daily insolation on the PVA plane, J/m^2
$\overline{G}_{d,Dec}(0)$	average of December-daily global irrad. horizontal plane, J/m^2
$\overline{G}_{d,m}(\beta)$	monthly average daily global irradiation on tilted plane, J/m^2
$G_h(0)$	hourly global irradiation on horizontal plane, J/m^2
$G_h(\beta)$	hourly global irradiation on tilted plane, J/m^2
h	hour index in the day ($h = 1, \ldots, 24$)
H	number of neurons in the hidden layer of the MLP
j	day index in simulation ($j = 1, \ldots, N_{days}$)
k_1	parameter in Klucher's model
K_{Dd}	daily fraction of diffuse to global irradiation
K_{Td}	daily clearness index
$\overline{K}_{Td}$	average of daily clearness index
$\overline{K}_{Td,y}$	yearly average of daily clearness index
L	load (physical system)
L	energy load (mathematical variable), J
LLP	loss of load probability of plant
LLPt	target value of LLP in that algorithm
M	number of neurons in the output layer of the MLP
MLP	multilayer perceptron
n	day index in the year (1st January is $n = 1$)
$\boldsymbol{n}$	unit vector normal to the PVA plane
N	number of inputs in the MLP
N_B	number of batteries in BS
N_{days}	total number of days in the simulation
N_{points}	number of selected points in Europe (2280)
P	number of patterns in MLP training
PV	photovoltaic
PVA	photovoltaic panels array
$r_D,\ r_G$	parameters in Liu–Jordan correlation
R	albedo irradiation, J/m^2
$R_h(\beta)$	hourly albedo irradiation on tilt plane, J/m^2
SAPVS	stand-alone photovoltaic systems
SOC	state of charge of BS
SOC_j	state of charge of BS at the end of day j (post-load)
SOC'_j	state of charge of BS at sunset of day j (pre-load)
u	parameter in isoLLP model, Eq. (16)
$u_1,\ u_2$	parameters in Eq. (5)
V_B	nominal voltage of each battery in BS, V
w_i	weight i in neuron
x_i	input i in neuron/MLP
y	output in neuron
y_i	output i in MLP
α	PVA azimuth angle (supposed null in this work), rad
$\beta,\ \beta_g$	PVA tilt angle ($0 \leqslant \beta \leqslant \frac{\pi}{2}$), rad, °
β_{opt}	β value that maximises $\sum_{j \in \mathrm{Dec}} G_{d,j}(\beta)$, rad
Γ	day angle, rad
δ	declination, rad
Δ^{+}_{SOC}	(positive) increment in SOC due to solar energy income
ϵ_0	squared ratio of mean-to-actual Sun–Earth distance
η	global efficiency of PVA
θ_s	Sun's zenith relative to PVA plane, rad
θ_{zs}	Sun's zenith, rad