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Dynamic simulation and modelling of stand-alone PV systems by using state equations and numerical integration methods

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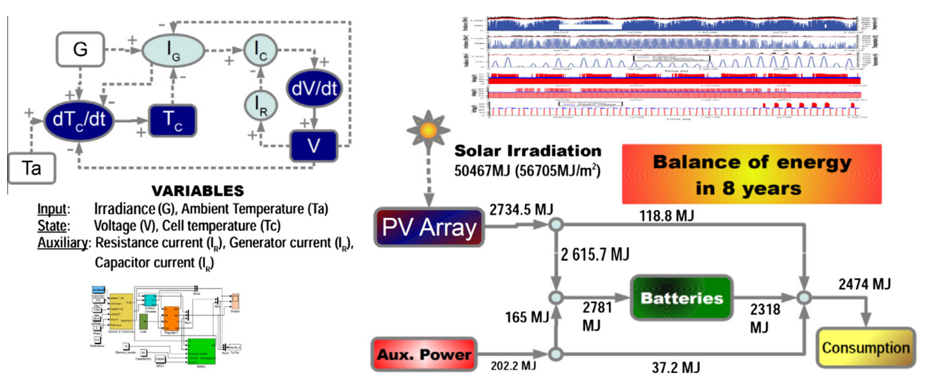
HIGHLIGHTS

- New state equation model that permits dynamic simulation of stand-alone PV systems.
- A double-diode model that uses the IEC-60981 standard has been developed.
- Parameters are extracted from *I–V* experimental data by multiple linear regression analysis.
- Energy balance and efficiencies were obtained of a long-term simulation.

GRAPHICAL ABSTRACT



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ABSTRACT

It is known that simulation of PV systems permits to study their performance helping engineers to design them. This paper deals with the dynamic simulation and modelling of stand-alone PV systems by using state variables and numerical integration methods. Two PV systems have been modelled and simulated: a PV array directly connected to a resistive load and a PV array with batteries also connected to a resistive load. A double exponential model, together with the procedure 1 for temperature and irradiance corrections of the IEC 60891 standard, has been used to model the PV array and considering the general battery model of Coppety with some modifications, the system with batteries was simulated. The obtained results from the simulations and experimental tests have been analysed and have shown that this methodology is a good option to simulate these systems.

1. Introduction

The dynamic simulation of photovoltaic systems permits to study their performance and to analyse the effects of changes in their design parameters. In simulation of photovoltaic systems several approaches have been adopted, some of them are briefly commented below.

One of these approaches is the PC software tool DASTPVPS that simulates photovoltaic pumping systems by calculating the steady-state working point in every time step [1]. This quasi-static simulation method allows studying of PV system performance and their design.

One of the best-known simulation programs in solar systems is TRNSYS that was developed by "The Solar Energy Laboratory" of

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Nomenclature

A	PV array area (m^2)
A_1	ideality factor of the diffusion current exponential
A_2	ideality factor of the recombination current exponential
C	electrical capacity (F)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
G	global irradiance on the tilted plane ($W\,m^{-2}$)
G_1	global irradiance on the tilted plane at reference test conditions ($W\,m^{-2}$)
G_{ref}	reference irradiance ($W\,m^{-2}$)
I_0	reverse maximum current or saturation current in the PV array (A)
I_{01}	PV array saturation current of the first exponential term (A)
I_{02}	PV array saturation current of the second exponential term (A)
I_b	in series inductance current of the battery model (A)
I_c	shunt capacitor current (A)
I_G	PV array current (A)
I_{G1}	PV array current at reference test conditions (A)
I_{mp}	current in the peak power point (A)
I_R	current through a load resistance (A)
I_s	PV array photocurrent at reference test conditions (A)
I_{sc}	short circuit current (A)
K	Boltzmann constant ($J\,K^{-1}$)
K_1	correction factor of the PV characteristic curve.
L	self-inductance (H)
m	PV array mass (kg)
Ns	number of in series cells
q	electron charge (C)
Q	discharge of batteries (Ah)
Q_g	accumulated charge (Ah) from the gassing process beginning
R	load resistance.
R_b	additional in series resistance in the battery circuit (Ω)
R_p	shunt resistance of the PV array (Ω)
R_s	in series resistance of the PV array (Ω)
T_a	absolute ambient temperature (K)
T_c	absolute cell temperature (K)
T_b	battery temperature (K)
T_{c1}	absolute cell temperature at reference test conditions (K)
T_{ref}	reference temperature (K)
U	heat loss coefficient ($W\,m^{-2}\,K^{-1}$)
V	PV array voltage (V)
V_1	PV array voltage at reference test conditions (V)
V_c	battery voltage (V)
V_{ec}	final voltage in the battery charge (V)
V_g	start voltage of the gassing process (V)
V_{mp}	voltage in the peak power point (V)
V_{oc}	open circuit voltage (V)
α	I_{sc} thermal coefficient (AK^{-1})
α'	absorption coefficient of PV panels
β	V_{oc} thermal coefficient (VK^{-1})
τ	time constant of the gassing process (h)
τ_c	cover transmittance of PV panels

the University of Wisconsin. TRNSYS has a modular structure of FORTRAN subroutines for modelling physical devices. Eckstein [2] developed a number of models to apply this program to photovoltaic systems where an iterative algorithm solved the involved characteristic equations to determine the working point (*I–V*). TRNSYS use an iterative process, called successive substitution, for solving the algebraic and differential equation system.

In other cases, the different system components may be modelled by using an analogy to electric components, for example, in computer tools such as Saber [3], PSPICE [4] or Virtual Test Bed (VTB) [5]. In each time step, PSPICE fits linear models to non-linear devices and solves the resultant system of nodal equations for the operating point.

State equations may be used to determine the working point and to study of the photovoltaic system performance. In this methodology, the system state is characterized each time by the values of state variables that, together with the inputs values, determine the rates of change in these state variables. Their values are calculated by numeric integration. This methodology is usually used in "System Dynamics".

A model with state equations [6] was used to study of the performance of a permanent magnet brush-less motor powered by a PV array and simulated with the well-known Runge Kutta integration method. In addition, non-linear models may be linearized around a steady operating point and they may be analysed with matrix calculus [7].

Adjakou et al. [8] used linear state equations models to study micro-fluctuations in the operation parameters of photovoltaic systems as a function of external perturbations. They identified two operating areas in the *I–V* characteristic curve of photovoltaic arrays that could be represented in a simplified way by two straight lines.

The use of linear models has the advantage of permitting to obtain an analytical solution of the differential equation system in order to study their stability properties. This has a special relevance in control systems.

I–V characteristic curve of a photovoltaic array is non-linear, especially in the nearness of peak power point. As a consequence, the use of non-linear relations and numerical methods of integration are a good option in simulation studies, making possible the study of the transient states. These methods used in the simulation of continuous systems are easily implemented with tools such as Simulink of Matlab.

Some PV systems have different operation stages and are more exactly represented by using several models than by a single model. The change among models will depend on certain events happening. Discrete event and differential equations specified system formalism (DEV&DESS) [9] can be an appropriate method to implement these multi models systems.

Differential equations models may be also approximated by quantized systems, which can be exactly simulated by discrete event coupled models by using discrete event system specification (DEVS). This last formalism represents other possible style to make PV system models that has advantages in parallel and distributed simulations. In this sense, PowerDevs [10] is a tool for DEVS modelling that may be used to simulate PV systems.

This paper is focused to the application of state equations models to stand-alone PV systems. A double diode model has been used to modelling the PV array. The double-diode model includes an *I–V* equation with two exponential terms, one with an ideality factor (A_1, equal to unity) that takes account of the diffusion current in the neutral zone and another with a different ideality factor (A_2, theoretically equal to two) that computes the recombination current in the depletion zone.