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A new approach to estimate the performance and energy productivity of photovoltaic modules in real operating conditions

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Abstract

In this study, a new theoretical approach offering a good prediction of the performance of photovoltaic modules/strings/arrays was developed. The approach implemented in the Matlab/Simulink environment, is based on Levenberg Marquardt (LM) algorithm and was used to estimate the parameters of five electrical models selected among the most used ones. First the problem of initial guess is considered. For parameters initial values, an analysis of six was performed and lead to the choice of the group which offers the best trade-off between accuracy and speed of calculation. To validate the effectiveness of the proposed approach, the five-parameter model (L5P) is used for a comparison with both a deterministic method and two heuristics methods. The results clearly show that, the accuracy achieved with LM method is comparable to the deterministic one, but higher than that of the heuristics methods. Furthermore, the five selected electrical models have been evaluated on four different PV modules technologies. The *I–V* characteristic curves obtained under Standard Test Conditions (STC) by each of them, are compared to the manufacturer data. It was shown that, when the LM algorithm is used, the fives electrical models predict the behavior of the photovoltaic silicon modules with close accuracy. The best trade-off is achieved with L5P model. This result is confirmed by the theoretical estimation of solar energy production performed for three real power plants by using the fives models. The maximum difference between calculated and measured energy is around 14%.

Keywords: Levenberg Marquardt algorithm; Photovoltaic module; Energy productivity; Modeling; Outdoor conditions

1. Introduction

This last decade, the enthusiasm of developing countries for renewable energies and especially for the photovoltaic (PV) energy has been strongly increased because of the energy crisis they are facing. In Africa, numerous projects are implemented for both large scale PV plants and stand-alone PV systems. For example, thanks to the recently energy policy adopted in Cape Verde, several PV plants have been installed, the largest one has a power of 5 MWp. In Burkina Faso, a very advanced project is underway for a PV system of approximately 30 MWp. Individual kits are mostly developed for rural population as the rural electrification rate is very low, about 18% according to the International Energy Agency (AIE, 2013). However, as PV modules sold on the market are not tested in natural environmental conditions very often, the performance of these latters is much less than those measured under standard test conditions (STC) and given by the manufacturer (Merten et al., 2008).

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Nomenclature

DeltaE	relative error *of* the estimated energy
E_g, $E_{g_{ref}}$	gap of the semi-conductor material in the real and reference conditions respectively (eV)
E_{th}, E_{meas}	monthly energy of PV field estimated and measured respectively (kW h)
ErPmax	relative error on the maximum power of the module
$f(p)$	modulus of the vector $r(p)$
G, *Gref*	solar irradiation in real and reference operating conditions respectively (W/m^2)
H	Hessian of the function *f*
I_o, $I_{0_{ref}}$	saturation current in real and reference operating conditions respectively (A)
I_i, Ith_i	measured and estimated currents (A)
I_{ph}, $I_{ph_{ref}}$	photocurrent in real and reference operating conditions respectively (A)
$J(p)$	Jacobian of the vector $r(p)$
K	constant of Boltzmann (1.38×10^{-23} J K^{-1})
LM	Levenberg Marquardt algorithm
L3P	three parameters electrical model
L4P	four parameters electrical model
L5P	five parameters electrical model
2M7P	seven parameters electrical model
m	number of points of the IV curve measured under reference conditions
M1DR	single diode electrical model with recombination current in the intrinsic layer *i*
M2DR	two diodes electrical model with recombination current in the intrinsic layer *i*
n	ideality factor
NRMSE	normalized root mean square error
NMBE	normalized mean bias *error*
$N_{modules}$	number of identical modules of the PV field,
p	vector of electrical parameters
$Pmax_{th}$	estimated value of the maximum power of PV module (kWp)
$Pmax_{measure}$	measured value of the maximum power of PV module (kW p)
R_s, Rs_{ref}	series resistance in real and reference operating conditions respectively (Ω)
R_{sh}, $R_{sh_{ref}}$	shunt resistance in real and reference operating conditions respectively (Ω)
SD	Standard deviation
T, T_{ref}	solar cells temperature in real and reference condition (K)
T_a	ambient temperature (K)
T_{NOCT}	nominal temperature of the PV cells (K)
$\alpha_{I_{SC}}$	temperature coefficient of the short-circuit current
β_{Voc}	temperature coefficient on the open circuit voltage

Moreover, the energy production is sometimes quite different for module of different technologies of same maximum power is measured under STC. In fact, the module performances are closely related to its intrinsic characteristics such as the absorption, the resistance and the manufacturing process. These latters are greatly influenced (but not in the same way) by the environmental conditions, the temperature and the sun irradiation (solar power and spectrum) (Merten et al., 2008). For example, a high level of irradiation would be beneficial to crystalline technologies whereas amorphous silicon and chalcopyrite based modules have current and voltage mismatch due to material metastable phenomenon (Cañete et al., 2014). It is therefore difficult, but essential to know how to choose, for a given site, the technology that provides the best trade-off between cost and the real performance of the module in a natural environment. One of the major challenges in this choice lies in the mathematical model to be used, in order to precisely predict the performance of photovoltaic modules under real operating conditions.

Many scientists have focused their studies on the modeling of photovoltaic modules and have developed several electric models with different level of complexity. These models differ mainly by the number of diodes, the shunt resistor (finite or infinite), the ideality factor (fixed or variable) and the numerical methods used to determine the unknown parameters (Saloux et al., 2011; Lun et al., 2013; Kulaksiz, 2013; Siddiqui and Abido, 2013; Ma et al., 2014). So far, the results of studies conducted in order to compare different models are still subject of many debates in the scientific community. Then, the key issue to be addressed is "which model can better reproduce the electrical behavior of a given PV module under real environmental conditions?"

The aim of this paper is to propose a new approach based on Levenberg Marquardt (LM) algorithm, which can help choosing the suitable electrical model for a given PV technology. The most used five electrical models are implemented with the same method (LM method). Once the PV module parameters are determined for each model, its energy productivity can be estimated by using the electrical parameters obtained with the best model. The choice of the preferred model is guided by the analysis of statistical errors of each electrical parameters, and by the accuracy of the model. This approach can then be used as a quick and accurate decision tool, not only for the choice of the best electrical model to estimate the energy productivity of a given PV technology, but also for the choice of the best PV technology suitable to climatic and environmental characteristics for a given site.