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# "PC Simulation and Sizing of PV Systems"

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# PC SIMULATION AND SIZING OF PV SYSTEMS

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Abstract

The scope of this work is to offer a software tool capable of describing stand-alone and grid-connected PV systems over an yearly run with hourly time-step. The data bases of PV components include devices tested at GENEC facilities and can be easily updated to include new items. Meteorological input data are both TMY files and reduced sets of several year's observations. Load profiles are user defined hourly sequences of power demand values, on seasonal basis. The sizing procedure of stand-alone systems lead to the optimal energy matching between modules array and battery bank. Simulation output data (monthly and yearly balances of energy flows in the different branches of the PV system) are presented in graphical and tabular format ; they are also recorded in ASCII files for subsequent interpretation.

## 1. Introduction

Current trends in solar energy systems are leading towards a *warranty of results* concept, in order to increase the end-user confidence in the performances of the system. The correct sizing is therefore a key point to design a PV system properly tailored on the customer's needs. The very well known rules of thumb *[1]* are not enough refined to allow the design of a system capable of supplying a prescribed Load Coverage Rate (LCR).

Neither the simple computer programs using monthly radiation averages and one representative day/month can describe the behaviour of a system intrinsically non linear. We have therefore developed a PC software tool that allows an easy definition of PV system architecture and a choice of components by means of an user-friendly interface.

The simulation is run with 1 hour time-step in order to follow precisely the evolution of the system and especially the occurrence of array/load disconnections, crucial phenomena that can't be described using monthly averages.

Models used for the simulation are quite simple in order to require few input parameters. Comparisons with experimental data have shown the accuracy of the calculation results within the scope of this program (i.e. the overall description of a PV system and not its diagnosis or fault detection).

## 2. Software description

The computer code has been written in Turbo Pascal, a programming language quite flexible and suitable to organise the screen with multiple windows and to draw curves and histograms. The program structure consists of a main executable file (about 300 kB) which has several external units to perform the different calculations; program maintenance is therefore quite easy, as well as the implementation of new models or the extension to new configurations. The run-time required for a simulation is about 40 seconds with a 486 family CPU and 50 MHz clock. The design of the system architecture and the choice of components is made by means of pull-down menus. Data bases contain the parameters describing some components that have been tested at GENEC facilities ; new data can be easily entered to update the data bases. The configurations that can be simulated are stand-alone and grid-connected systems, the sizing being possible for the former only.

The simulation of grid-connected is intended to verify the correct matching between PV array and inverter power, so as to maximise its average efficiency and approach the so-called *European efficiency [2]*.Modules tilt angle choice is guided by a routine that calculates the optimal tilt for a given radiation file, both for a constant tilt and for 4 seasonal tilt angles. The user can thus verify the effects of a tilt variation on the cumulated radiation in the plane of array and on its yearly distribution. The calculation of the array working point in the IV plane is made with an iterative Newton-Raphson procedure. At each time-step it calculates the intersection between the module characteristic I(V,H,T) and the V(I) of the load (battery characteristic for stand alone system, pump characteristic for directly coupled system, fixed voltage or MPPT for grid-connected) . All variables are considered constant during the time-step and updated at the end of each step depending on the energy flows.

## 3. PV module modelling

The model that has been retained for our software is the single-diode solar cell model. Even if more accurate models can be found in the literature, it is worthless to use an extremely precise model as the spread of the characteristics of the modules constituting an array makes the reality far more inaccurate than the results obtained with the single-diode model. Moreover the few parameters required for the complete characterisation of a module follow a criterion of simplicity and allow a straightforward use of modules out of the data base. The formulation of the I(V,H,T) relation for the one-diode model is as follows :

$$I_{mod} = I_{ph}(H, T_{mod}) - I_0 \cdot \left[ \exp\left( \frac{V_{mod} + R_s \cdot I_{mod}}{V_{th}} \right) - 1 \right] - \frac{V_{mod} + R_s \cdot I_{mod}}{R_{sh}} \qquad (1)$$

where $I_0 = \dfrac{I_{ph} - V_{oc}/R_{sh}}{\exp\left( V_{oc}/R_{sh} \right) - 1}$ $\qquad V_{th} = \dfrac{A_0 \cdot n_{cell} \cdot k \cdot T_{mod}}{q}$

$$T_{mod} = T_{air} \cdot (NOCT - 20) \cdot H/H_{800}$$

The dependence of $I_{sc}$ and $V_{oc}$ on the temperature and irradiance are assumed as in ref *[3]* :

$$I_{ph}(H,T) = I_{ph,STC} \cdot \frac{H}{H_{STC}} + \alpha \cdot I_{ph,STC} \cdot (T_{STC} - T_{mod}) \qquad (2)$$

$$V_{oc} = V_{oc,STC} + V_{th} \cdot \ln\left( H/H_{STC} \right) + \beta \cdot (T_{STC} - T_{mod}) \qquad (3)$$

In our calculation we neglect the temperature coefficient of the form factor, which involves the temperature dependence of $R_s$ and $R_{sh}$, because of the scarceness of reliable measures. The set of 5 parameters ($I_{sc}$,$V_{oc}$,$R_s$,$R_{sh}$,$A_0$) are thus calculated from measured IV points with least squares method for standard conditions (STC). We have evaluated the accuracy of this method comparing measured IV points with the calculated I(V) curve for H,T values far from STC. In fig. 1 we report the measured and calculated IV values for a module PHOTOWATT BPX 47451 at 400,600,800,1000 W/m$^2$. The deviation at $P_{max}$ is respectively -7%, -3.7%, -1.5%.

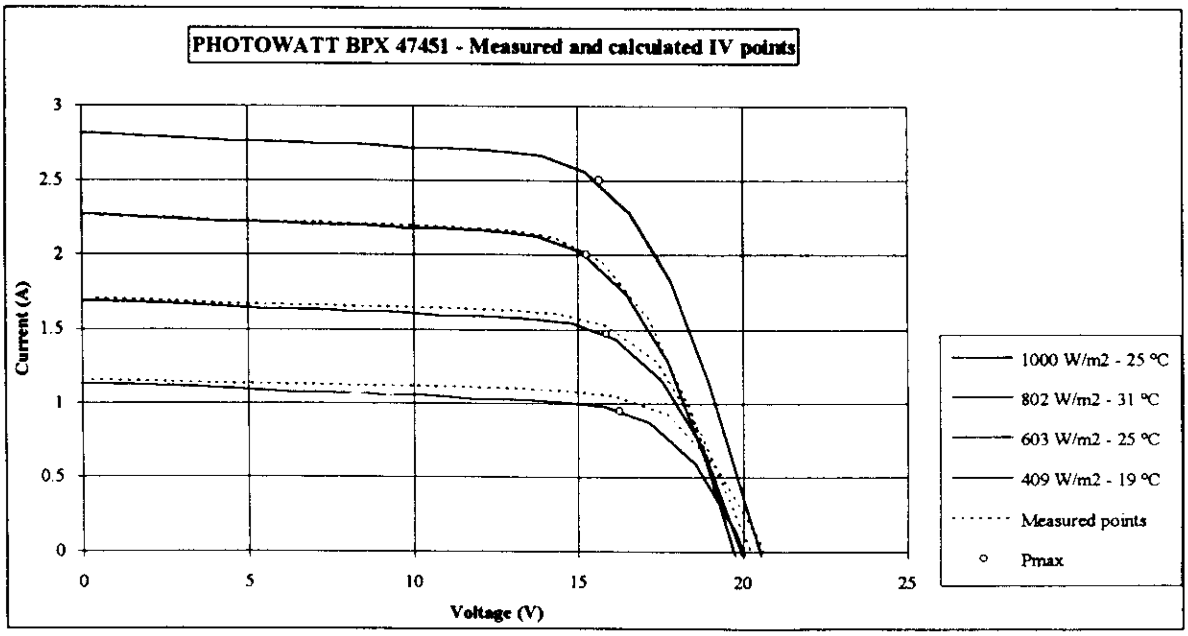


Fig. 1: Comparison between measured and calculated IV points for a module PHOTWATT BPX 47451

The model can thus be retained as appropriate for our calculation, even because the weight of an irradiation below 400 W/m$^2$ is quite often irrelevant (e.g. in the site of Cadarache, 44° N, the fraction of H below 400 W/m$^2$ is less then 20% of the total energy).

## 4. Power management

In our model we implement the most common technique, that is an on/off regulation driven by 2 voltage thresholds with histeresis. The voltage thresholds don't take into account the temperature dependence of the battery capacity. Future enhancements of the program will include an MPPT regulation.

## 5. Battery modelling

Existing lead acid battery models (e.g.in *[4,5,6]*) are quite refined to characterize a quasi-steady state battery but inaccurate for its dynamic behaviour. The *history* of a battery has dramatic effects on the internal resistance *[7]*, as well as transient phenomena imply subsequent relaxations that can prevent, particularly in deep SOD, the battery to give its full allowed capacity. Moreover the ageing of a battery bank induces quite soon (even less than 1 year) a modification of the parameters and a divergence between the elements of the same bank *[8]*, rendering thus the model unable to describe properly the battery characteristics.
We have therefore choosen to describe the battery by means of an average value of internal resistance as evaluated in *[8]*, and then express the battery voltage as

$$V = V_{oc} \pm R_{int} \cdot I \qquad (4) \qquad\qquad V_{oc} = a \cdot SOC + b \qquad (5)$$

This method is fairly inaccurate to describe fully charged batteries (sudden increase of $R_{int}$ due to outgassing phenomena), but this occurence is relevant only in floating operations and not in the normal working operations of a stand-alone PV system. An average faradic efficiency and self-discharge is also taken into account.

## 6.Inverter modelling

Performances of 1 to 3 kW grid-connected inverters measured with an accuracy <1% *[9]* could be fitted with 3% RMS error using current inverters models *[10]*. We have therefore proposed a new 6 parameters model *[11]* to fit the data better than 1%:

$$R = \frac{a \cdot x^2 + b \cdot x + c}{\exp(d \cdot x) + x_0} + k \qquad (6)$$

where $R$ is the inverter efficiency and $x$ the load rate (ratio between the input power and the nominal power).
In fig. 2 are reported the fitting curves of the SOLCON 3300 inverter using the Schmidt model and the 6 parameters one.
The precision thus obtained will give a better comprehension of the grid-connected systems and will lead to an optimal matching between array size and inverter power.

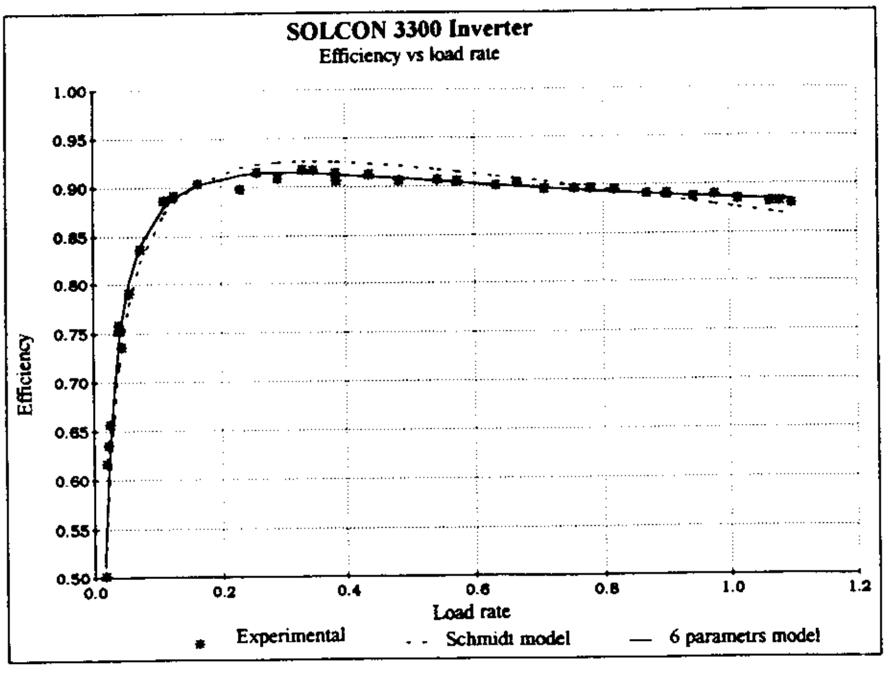


Fig. 2 : Comparison of Schmid model with the 6 parameters one for the inverter SOLCON 3300

## 7.Solar radiation data

The representativity of the solar radiation data is a relevant parameter to qualify the goodness of the simulation. If long time irradiation measures are available it's straightforward to calculate a TMY *[12]*. In the present version of PVDIM irradiation data input are sequences of real hourly measures of direct and diffuse horizontal components. For each month of the year an average month is deduced out of long time observations. A typical year is thus built as a sequence of true months. The profile so obtained is representative of a typical year, rather then being an year really occurred *[13]*.

It's also possible the use of true meteorological data files, provided the proper format (global horizontal, direct and air temperature). Since long time observation on hourly base are not commonly available we foresee to implement a synthetic data generator using autocorrelation and Markov transition matrices techniques *[14,15,16]*.

## 8. Load profile

The load profile is an user-defined sequence of hourly AC/DC power load values. The daily profile can be constant over the year or can have 4 different seasonal values. The user can thus create a library of profiles to be used for different configurations.

## 9. Simulation outputs

The simulation and sizing outputs are, as reported in fig. 3, the daily averages over the month (or over the year) and the monthly (yearly) balances of energy flows in the different parts of the PV system. The array load factor represents the fraction of the theoretical array yield that has been used; the load coverage rate is the ratio between the supplied and demanded energy. Data are presented in tabular form or can be visualized as histograms.

An economical analysis is also performed. The initial investments are reported, as well as the yearly cash flows for different lifetimes of the system and interest rates. Finally is calculated the electrical kWh cost. For grid-connected systems is also provided a comparison between the utility and the mixed utility/PV kWh costs, for the choosen load profile.

YEARLY RESULTS - ESSAI1.CFG essai

| | | | | | |
|---|---|---|---|---|---|
| PV system with battery | | | Yearly simulation | | |
| | Yearly (kWh/y) balances | | | | |
| METEO | | | BACK-UP | | |
| Glob array irradi. (/m2) | 1668.9 | kWh | Back-up production | | |
| PV ARRAY | | | Fuel consumption | | |
| Gross array yield | 1143.6 | kWh | Daytime running hours | | |
| Energy losses | 37.8 | kWh | Nighttime running hours | | |
| Net array yield | 1105.9 | kWh | GLOBAL SYSTEM | | |
| Losses for disconnections | 298.3 | kWh | Load requirements | 1758.9 | kWh |
| Used energy | 807.5 | kWh | Covered load | 807.7 | kWh |
| Array load factor | 73.6 | % | Grid injected energy | | |
| STORAGE | | | Load coverage rate | 57.5 | % |
| Stocked energy | 505.5 | kWh | Load covered with PV | 57.5 | % |
| Destocked energy | 505.7 | kWh | Loss of power hours | 3758.0 | h |
| Charge/disc. efficiency | 99.1 | % | Consecutive losses | 45.0 | h |
| Charge/disch. losses | 1.8 | kWh | | | |
| Storage balance | -2.0 | kWh | | | |
| Average SOC | 34.0 | % | | | |
| Average batt.cycling | 49.1 | % | | | |
| INVERTER | | | | | |
| Average efficiency | | | | | |

Fig. 3 : Simulation output values

## 10. Sizing procedure

Several techniques have been proposed to size analitically a PV system *[17,18,19]*. They all use monthly averages to size the array/battery bank for a prescribed loss of power probability.

What we intend to do is to use the results of the simulation to characterize the effects of different array/battery sizes combinations on the load coverage rate (LCR) and on the SOC, given as side conditions the load profile and meteorological data. We have run several simulations for constant, day-time and night-time load profiles and we have noticed a recurrent beheaviour as reported in fig.4. For a given array size the increase of the battery size leads first to a simultaneous increase of LCR and SOC (the system goes towards the *matching point*), then the SOC starts decreasing while the LCR keeps increasing; in these conditions the bigger LCR results from a discharge of the battery and not from an energy production. Further increase of the battery size leads obviously to SOC=LCR=100% with infinite size battery.

It follows that the optimal size for a given LCR is realized by the curve (corresponding to a given number of modules) whose matching point lies at an ordinate equal to LCR; battery size is straightforward.
The sizing procedure requires iterated simulations in order to detect the matching point. The convergence step is fixed depending on the LCR value of a starting configuration and the prescribed one. Convergence occurs generally within 10 to 20 simulations.

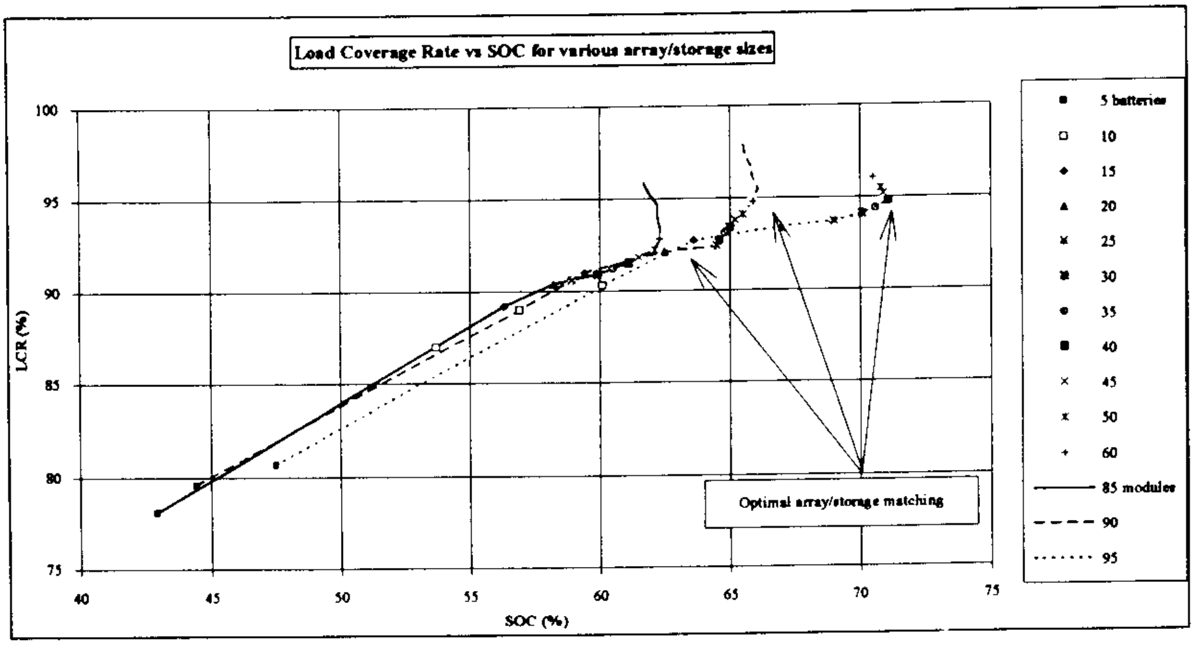


Fig.4 : Matching point for a 12 kWh/day constant load and 3 different array sizes.

## 11. Experimental validation

We have compared the simulation results with data coming from a battery ageing test *[8]*.
In fig.5 we present the measured and simulated energy flows in the batteries bank The sistematic underestimation of the simulation is due to the fact that the test bench uses a fixed current load, whereas the simulation has a fixed power load.
Simulation results are therefore in good agreement with the measured data, even if further validations are required because the batteries test has almost a floating regulation whereas generally PV systems cover the full range of SOCs.

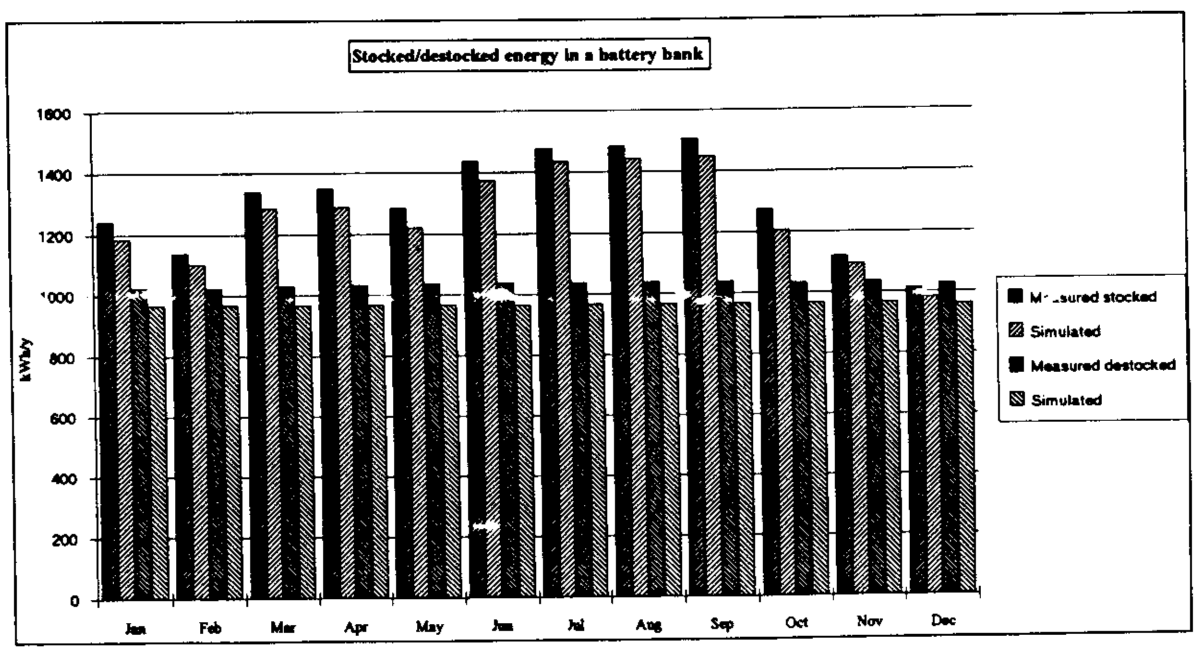


Fig.5 : Comparison of simuıaıed and measured stocked/destocked energy in battery test bench.

## 12. Future developments

As mentionned before the next step will be to include a generator of syntetic meteorological data, to extend the use of the software to sites where long time observations are not available.
As soon as data regarding the pumping systems that will be measured in the next few months at GENEC, the simulation will be extended to pumping systems directly coupled on PV array.
Finally a more refined battery model will be implemented for diagnosis and fault detection.

## 13. Conclusions

The software we present, even if it relies on very simple models requiring few parameters, is capable of performing simulation of stand-alone and grid-connected PV systems with a good accuracy.
Simulation outputs allow a complete evaluation of the PV system performances and can be of great interest both for the system designers and for the researchers.
Sizing procedure is quite accurate because based on simulation and not on overall analytical extimations.

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