Evaluation of the Different Losses Involved in Two Photovoltaics Systems

SCHAUB, Patrick, MERMOUD, André, GUISAN, Olivier

Abstract

The nominal efficiency of PV-modules is around 12%. The overall efficiency of PV systems lies typically around 8-9%. The purpose of this work is to understand and explain such a difference and, consequently, identify actions which can be significant in the design and the optimization of PV systems. We have monitored in great detail, two PV systems located in the city of Geneva. One of 7.5 kW is connected through three inverters to the three phases of the grid. The other one of 2.2 kW is directly connected to trolleybus lines at a DC voltage of 600 V. All losses involved in such systems depend on local conditions and are closely correlated. It may be difficult to evaluate each one separately. Nevertheless, by appropriate selections of data and by testing components in separate experiments, we have evaluated the different losses affecting the performances of the systems under study. These are distributed in several contributions of comparable significance; for example, in the former system: PV-modules characteristics lower than expected, MPPT efficiency decrease with solar radiation, ohmic losses in wiring, temperature [...]

Reference


Available at:
http://archive-ouverte.unige.ch/unige:120905

Disclaimer: layout of this document may differ from the published version.
Evaluation of the Different Losses Involved in Two Photovoltaics Systems

P. Schaub, A. Mermoud, O. Guisan
Group of Applied Physics, University of Geneva,
4, chemin de Conches, CH 1221 Conches-Geneva, Switzerland
Tel (22) - 789 13 11, FAX (22) - 347 86 49

ABSTRACT - The nominal efficiency of PV-modules is around 12%. The overall efficiency of PV systems lies typically around 8-9%. The purpose of this work is to understand and explain such a difference and, consequently, identify actions which can be significant in the design and the optimization of PV systems. We have monitored, in great detail, two PV systems located in the city of Geneva. One of 7.5 kW is connected through three inverters to the three phases of the grid. The other one of 2.2 kW is directly connected to trolleybus lines at a DC voltage of 600V.

All losses involved in such systems depend on local conditions and are closely correlated. It may be difficult to evaluate each one separately. Nevertheless, by appropriate selections of data and by testing components in separate experiments, we have evaluated the different losses affecting the performances of the systems under study. These are distributed in several contributions of comparable significance; for example, in the former system: PV-modules characteristics lower than expected, MPPT efficiency decrease with solar radiation, ohmic losses in wiring, temperature effects, incidence angle effects through glass, poor inverter efficiency during operation, inverter startup near threshold, little shadowing due to a security fence. Spectral effects are significant, but not quantifiable in this frame. Altogether, the nominal efficiency of 12.4% is reduced to 7.8%, i.e. an overall loss factor of 37% over the rated energy.

1. - Introduction

Two photovoltaic systems, located in the city of Geneva, were monitored in great detail (a quarter of hour step time) during more than one year. On both systems, the PV-panels are arranged in sheds on flat roofs, with free air circulation all around.

The first one is a pilot installation, equipped with 42 modules in series (2.2 kW nominal, 17.9 sqm), which are directly connected to the overhead lines of a trolleybus network (TPG, public transports of Geneva), at a nominal voltage of 600V DC. Half of the panels are of the model M55 from Arco/Siemens (monocrystalline cells), and half are an equivalent product, consisting of Arco cells encapsulated by the Swiss firm Atlantis Energie AG. We measured there essentially the global irradiation in the collector plane, voltage and current at the terminals of the system, the voltage at the middle point between the two kinds of modules, the ambient temperature and the temperature of two irradiated cells at the midpoints of panels. This system is extremely simplified since there is no necessity of power conditioning. The number of panels was adjusted to fit the voltage requirement by higher temperatures in summer.

The second system is owned by the SIG (Services Industriels de Genève, the public utility of Geneva), and measured by our team at the university of Geneva. The field, consisting of 126 panels Arco M55 and 16 of Atlantis, has a nominal power of 7.5 kW (at standard conditions) for an area of 61.2 sqm. It is divided into three subfields, with 16 modules of three panels in series each, and connected to the three phases of the AC grid through three SI3000 inverters. These inverters operate at the maximum power point, at a relatively low nominal voltage of 50-60V, resulting in high currents and therefore high ohmic losses.

Meteorological measurements at this second system were more complete: we recorded irradiation in both the horizontal and the panel planes, the diffuse horizontal component (pyranometers CM11), ambient temperature and wind speed. Electrical measurements included voltage and current on both the DC and AC sides of each phase; DC power was calculated and accumulated at each measurement sample (every 2 seconds), when AC powers were given by specialized devices performing true \( U^* I \) calculation in real-time. The total energy was cross-checked by usual energy-counters; overall electrical measurement accuracy's are estimated to be better than 0.5%.

Cells' temperature were measured continuously at the back side of two panels, but one cannot expect accuracies better than a few degrees Celsius (3 to 6°) from such measurements; moreover, their representativity over the whole field, with different exposures to wind, is very difficult to estimate.

Measurements and results are detailed in the final reports of each project ([1] and [2]).

The main objective of our studies is to understand why, starting from panels of 12.4% nominal efficiency specifications at standard conditions, we obtain only average annual efficiencies of 9.3% for the TPG, and 8% for the SIG installations.

This work was performed thanks to the financial support of the Swiss Federal Office of Energy (OFEN/BEW), as well as SIG and TPG contributions.

2. - SIG System Behaviour Analysis

2.1- Experimental results

Through the whole analysis, we will consider the global insolation in the panel plane as the significant and independent variable. We will then try to isolate each perturbing effect as a function of this variable.

We concentrate first on the annual results of one phase of the SIG (AC) system, eliminating the data of about 10 days because of the inverter breakdown.

As a raw result of the measurements, fig 1 shows the annual solar incident energy, and the measured DC and AC energy distributions by bins of 12 W/m². Then we plot the annual efficiency distribution by calculating, for each bin, the ratio between AC energy and incident energy, normalised to the total panels area.

These distributions depend on local climate and system conditions. Annual diffuse fraction goes up to 48% of the global irradiation in the collector plane. We notice a cut of the produced AC energy up to around 70 W/m², corresponding to the self-consumption of the inverter; and near to this region, a threshold effect which affects progressively the DC production as well as the AC one. This will be explained later on.
2.2.- Methodology

Multiple perturbing effects are closely correlated, extracting them directly from these data is not possible. Therefore we had to evaluate each of them independently by separate experiments, specific selections or physical obvious models. Then we established correction procedures and applied them sequentially to the annual distributions.

The final result is an efficiency "calculated" distribution, which should correspond to the measured one. This is an iterative process, where the final comparison of global AC efficiencies indicate the validity of our correction assumptions.

Fig 2 shows the relative loss of each studied phenomenon, as a function of the incident radiation. At each step we plot a partial efficiency factor f2, bin to bin related to the previous remaining energy. Starting energy is the nominal rated energy given by the manufacturer at standard conditions (i.e. 48 panels·53W for 1000W/m²), multiplied by the total incident energy in each bin.

2.3.- Losses analysis

Characteristics default: the first contribution taken into account is the quality of the PV-panels, put together with the mismatch of the characteristics. Characteristics of all used panels have been carefully measured in-situ [3], and are about 8.9% lower (weighted average between Arco and Atlantis used modules) than the manufacturer specifications, with a dispersion standard deviation of 2.5%. Following PV-characteristic combination simulation results of PVSYST [4], we estimated that the mean power of the field lies at a third of the standard deviation below the average. This first loss is assumed to be independent of the solar radiation.

MPP-loss: according to the one-diode modelisation of the cells [5], the nominal efficiency at MPP drops at lower insulations (it behaves roughly like the log of the incident radiation). Parametrization of the global field is calculated for the average parameters of the panels, assumed to be representative of the whole field; a parallel resistance of 200 \( \Omega \) is added to the original model. Calculated for the reference temperature of 25\(^°\)C, this \( f_2 \) loss (by respect to 1000W/m² operation) contributes by 5% to our data.

Shading: A security fence is shadowing some panels during part of the afternoon. The corresponding loss has been estimated by comparing efficiency distributions for data selected in the time intervals when no shadowing occurs, to the global annual ones. This comparison was made after ohmic losses corrections, and with energy data normalized to a panel temperature of 25\(^°\)C (through the one-diode model), since this induces strong anisotropy between morning and afternoon. The \( f_2 \) partial efficiency has no effects on high insolutions, since shadowing does not occur at noon; it shows a global annual contribution of 2%.

Ohmic losses: the resistance is calculated from the copper resistivity of the wiring as a function of the temperature \( (\rho = 1.68 \cdot 10^{-8} \, \Omega \cdot m \cdot (1 + 6.8 \cdot 10^{-3} \, T)) \). Viewed from the inverter terminals, it is of 46.2 m\(\Omega\) per 1000W/m² for each phase. The \((R \cdot f)\) loss follows a linear correction as a function of the global incident, which amounts to 2.5% annually (4% at maximum power). We may notice that this value is strongly related to the inverter voltage operation: when doubling the voltage (six panels in series), the ohmic loss would be divided by four!

Cells temperature: This contribution is estimated by a thermal correlation recorded on-site between the field efficiency and measured panel temperature, after ohmic corrections and for severe selections of data. This correlation gives a thermal power factor of -0.4 %/\(^°\)C, against about -0.5 %/\(^°\)C according to the one-diode model. Such a difference may be partially explained by the doubtful representativeness of our two measurement points as compared to the real average cells temperature. The annual field mean temperature, weighted by the incident insolations, is 35\(^°\)C. Annual field mean temperature, weighted by the incident insolations, is 19\(^°\)C. Winter operation brings a gain , but annual thermal loss is 3.4% by respect to the standard operating conditions of 25\(^°\)C.

The curious behaviour of the \( f_2 \) distribution at high insulations is explained by the fact that very high irradiations are observed mainly during transitory conditions, when sun rays are reflected on surrounding clouds, occurring under unstable weather conditions when temperature is not so high.

Incidence angle: Fresnel reflections and transmission through the glass cover are well approximated by the so-called "ASHRAE" model (cf. [5], p 309), describing the attenuation as a function of the incidence angle from one only parameter \( b_0 \). Though for one-glazing flat plate collectors, \( b_0 \) is about 0.1, analysis of the field data are more compatible with \( b_0=0.05 \) value confirmed by investigations with sun simulator on a single panel. This low effect should be due to the very different reflection conditions on the back side of the glass, which is "optically" connected through the EVA encapsulation to the anti-reflection layer of the cell. Losses are calculated separately for the direct and the diffuse components; the diffuse attenuation results of integration over the visible hemisphere, staying constant during the year. The \( f_2 \) factor looks rather linear, and becomes close to the unity at high insulations.

Inverter threshold: below an insolation threshold of 150 W/m² (i.e. 300W at the inverter input), the inverter cuts off and the field operating point stays near to the open circuit voltage. Thus the DC measured energy drops, and is no more representative of the MPP capability. The missing energy was evaluated by comparing a linear extension of the MPP values between 200 and 400 W/m². This DC-threshold loss of 3% should be included to the overall losses involved by the inverter.

Inverter AC efficiency: determined by the bin to bin ratio of AC to the remaining DC energy over the threshold, this contribution is very high (17.8%), but closely related to the inverter type. Recent models are expected to show far better performances.
2.4. - Global balances

Finally, the overall computed efficiency distribution is the product of all above T, calculated for each bin. The general shape is quite similar to the measured one, and the annual result (the weighted sum of bins) gives a resulting loss of 36.9% (of the rated energy), i.e. a system global efficiency of 7.8% (of incident energy).

Global annual losses appear on the fig. 3. The overall losses are shared into two main contributions (modules performances and inverter operation efficiency), and 6 minor ones of equivalent significance, indicating that none of them could be preferentially neglected in a proper treatment.

2.5. - Spectral effects

The little difference between these data, to be compared to the experimental 8% efficiency, may be attributed partly to the difficulties of the analysis, mainly due to the correlations between factors. Nevertheless, we did not account for spectral effects up to now.

Fig 4 shows the DC efficiency after corrections 3, 4, 5, and 6, for brackets of 20% in diffuse/global ratio. We notice that the efficiency with strong diffuse is better than the one for strong direct. We have tried to extrapolate 2 envelope-curves for 100% diffuse and 100% direct. At 300 W/m², we observe a difference of 13%, but no more visible after 700 W/m².

Therefore, we may conclude that spectral effects seem significant at low insulations, and that spectral composition may be related to the diffuse to global components. Nevertheless, the spectral content of the diffuse is not sufficiently determined to allow systematical conclusions. A proper evaluation of these effects imply detailed spectral measurements of the incident radiation, which is out of the scope of this experiment.

3. - Analysis of the TPG 2.2 kW DC-system

This system is much more simpler than the previous one, since the field is directly coupled to the DC load, without power conditioning. Identical methodology is applied.

Characteristics defaults is worst because, on one hand there are a half of Atlantis panels, and on the other hand, as all panels are connected in series, the overall mismatch effect is more pronounced. Nevertheless, the maximum power point operation is much less affected by the mismatch than the current sum at fixed voltage, and specific characteristics simulations should be performed to determine exactly where to allocate these respective contributions.

MPP-loss is slightly better, depending on the panel parametrization with the one-diode model: this sample of panels fits better with $R_{sh}=1000$ Ω than with $R_{sh}=200$ Ω.

Fixed voltage operation induces loss by respect to the MPP capability. By optimizing the number of panels, it could be reduced to about 2.5%.

Shading of neighbour lighting sheds occurs in summer, early in the morning and late in the evening, and far trees act on the direct component during some days in december and january. Nevertheless, corresponding losses are only 1.3%.

Cells temperature effect is very low since the field works at fixed voltage, relatively far from the MPP towards the current part of the characteristics.

We notice that the kind of these losses is very different from the previous ones, mainly due to the fixed voltage operation. The non-linear aspects of the fixed voltage complicate the analysis.

On the basis of these measurements, a posterior optimization indicates that using 38 ARCO panels only, the global annual system efficiency could be raised up to 10.6%.

![Fig 2. Partial efficiencies decomposition as a function of the irradiation.](image)

Loss ratios are the average annual losses referred to the previous analysis stage.
4. - Conclusions

We have identified and quantified a set of losses involved in two PV systems, which seem to explain their main operating characteristics. In the grid-connected system, panels and inverter performances are the main contributors, the other ones sharing equivalent moderate significances. In the DC system, panel performances are the dominant default, and the number of panels in series should be optimized. Moreover, as in the AC system we encountered several inverter breakdowns, the DC-system is much more reliable due to the absence of power-conditioning device. The identification of the different loss sources and their modelization were used in the elaboration of the PV-simulation tool PVSYST [4].

References