Abstract: The performance of a PV system can be characterised by the Performance Ratio. The performance ratio can be measured by means of global monitoring and is based on only a few measured variables. The meaning of this indicator is limited to a global impression of the performance, as there is no way to identify improperly functioning components. This paper describes a method to characterise the performance of the PV system in more detail. It is based on analytical monitoring and makes distinction between different types of losses. Low irradiance losses, resistance losses, inverter losses, shading losses and temperature losses etc. can be determined with suitable software. Lost energy due to improperly functioning components can be charted in an easy way.

Keywords: Performance - 1: monitoring - 2: evaluation - 3

1. INTRODUCTION

The performance of a grid connected PV system can be characterised by a single number, the performance ratio, PR. The performance ratio of a PV system during a certain period is defined as the ratio of the measured system efficiency and the nominal efficiency of the PV modules. The performance ratio is influenced by:

- the mean intensity of the solar irradiance, as the average efficiency of the PV panel is a function of the irradiance;
- the system size, as the power efficiency of the inverter depends normally on the size;
- the system layout, high voltage arrays involve low currents, which lead to increasing mismatch, increasing inverter efficiency and decreasing resistance losses.

2. WHY A STUDY ON PV LOSSES

The Netherlands Energy Research Foundation (ECN) is involved in research in PV cells and PV systems. With respect to PV grid-connected systems our activities lie in the field of PV systems monitoring [4] and inverter research. During the last five years a number of PV systems were extensively monitored and the measured data were analysed in-depth. During the determination of standard parameters as normalised yield, performance ratio, system efficiencies, inverter characteristics several unexpected problems were encountered, for example:

- sinewave "DC-input current" of inverter;
- malfunctioning Maximum Power Point Trackers;
- power reduction because of a too high ambient temperature near the inverter/grid voltage;
- malfunctioning cascade controllers.

Although the performance ratio gives a global idea of the system behaviour, its practical use for the identification of mal functioning components is limited. The Performance Ratio for a particular system during a certain period is not a suitable quantity to indicate in which way the PV system can be improved:

- PR gives no insight in different component losses;
- presentation of PR without presentation of specific system parameters is insufficient for further analysis;
- there is no way to identify improperly functioning components.

To improve the performance of a PV system one has to identify problems with components. ECN has ample experience with analytical monitoring based on 10-minutes averaged values. In this way problems with MPPT-tracking, cascade control of parallel connected inverters and overload protection devices has been studied and solved.

3. PV SYSTEM DESCRIPTIONS

Two PV systems were selected for this study.

The PV system in De Wijk (NL) [1] is placed on the roof of an elderly people’s home. It consists of 168 R&S PV modules (7.5 kWp) and 4 inverters (SMA PVWR 1800 S). The inverter inputs are connected in parallel to the DC bus, while the 4 single phase outputs are distributed over the phases L1, L2 and L3. To reduce the inverter losses they are switched on and off by means of a master/slave controller depending on the load. The 168 PV modules (R&S IRS45) are grouped in 28 strings of 6 modules in series.

The performance ratio measured over two years is about 0.61. This relative low value is caused by a number of facts:

- the master slave controller functions improperly;
- the array voltage did not correspond to the optimum value (faulty Maximum Power Point Tracking);
- the averaged conversion efficiency of the inverter was only 82.5 %;
- partial shading because of the building geometry;
- power limiting due to high inverter temperatures.

In Zandvoort (NL) a roof integrated PV system placed on a private “zero energy” house. It consists of 64 R&S PV modules (3.3 kWp) and two inverters (Mastervolt Sunmaster 1800). Each inverter is connected to eight strings of four PV modules (R&S IRS30LA). The performance ratio is about 0.73. This based on the irradiance as indicated by the reference cell, the AC energy yield and the nominal power of the modules as given by the manufacturer. The PV system seemed to operate very well without faults. When the monthly DC efficiency curves are critically examined the following remarks can be made:

- subarray 2 produces 7 % less energy then subarray 1,
- recently string I-V curves were measured and it was discovered that a circuit blocking diode in one PV module was shorted;
• in the summer months array 1 is shaded by a tree at the
east of the living, see figure 5;
• after exchange of the MPPT control strategy the DC
efficiency was increased at low irradiance levels. In the
range between 50 and 200 W/m² the array voltage is
increased, the yearly energy yield will increase 1 %, see
figure 1.
• the DC-efficiency curve of the array shows a maximum
of 13.6% while manufacturers flash tests on modules
give 14.3%.

The yearly energy efficiency of the Mastervolt 1800 is
about 90.3 %.

Rough calculation of some losses could not explain the
system performance and performance ratio. For instance the
shading losses were unknown.

Figure 1 Improved MPP-tracking

4. ECN ANALYSIS METHOD

Some losses in the PV system are caused by an interaction
between the environment, the inverter and modules. In
figure 2 several types of losses are introduced in the form of
a Sankey diagram. The proposed method of analysis
consists of a clear definition of these losses on basis of
measured quantities. On the right hand side the various
losses are mentioned, where the losses [in %] are presented
against each previous measuring value. In the following
sections we describe the method in detail. Because there is
a balancing item (mismatch losses) we start with
calculating the system output, which are related to the
inverter at the bottom of the Sankey diagram. Then we
continue with the system input, i.e. irradiance
measurements at the top of the diagram and the last item to
be determined are the mismatch losses.

For a good analysis of the system behaviour and to identify
improperly functioning components we use:
• a data-acquisition system (based on a PC) with an
  average sampling period of only 10 minutes, including
  storage of the minimum, maximum and standard
deviation;
• ECN data analysis software GMP (General
  Measurements analysis Program) for the tabulated or
  graphic presentation of measured or calculated values.

To make a complete overview of the system behaviour we
compare the measured values with the expected ones. This is
done by a global characterisation of the various system
components, using system loss factors and Test Reference
Years Try’

4.1 Inverter losses - E_{inv}

The AC-energy from the inverter E_{i} (see figure 2) depends
on the array power at the terminals of the inverter (E_{a,inv})
and the E_{inv} losses. These losses can be divided in:
• standby power;
• switching and ohmic losses in semiconductors.

For accurate presentation of the inverter losses it is
necessary to calculate (or measure) the instantaneous
product of the DC voltage and DC current.

Both E_{i} and E_{inv} can be measured, so the inverter losses
E_{inv} can be calculated

4.2 Resistance/ohmic losses - E_{cu}

In small PV-systems the connection boxes are placed
mostly near the inverter, otherwise they are grouped
together nearby the PV modules. In addition to the cable
resistance there are transition resistances in terminals,
fuses and contactors/ disconnecters. In this paper we
neglect these extra transition losses. The instantaneous
ohmic power losses can be rather accurately calculated by
multiplying the cable resistance with the square of the 10
minute averaged DC-array current (P_{cu} = I_{a}²•R). The yearly
energy copper losses are equal to the sum of all power
losses during the year (E_{cu} = \Sigma I_{a}²•R•t). Mostly the real array
energy (E_{a} (array)) is not measured, because voltage sense
leads are connected to the inverter input terminals, so
E_{a} (array) = E_{a} (inv) + E_{cu}. 
4.3 Temperature losses - $E_{LT}$

A mc-Si PV module has a temperature coefficient for the Maximum Power Point of $-0.38\%/K$. The $\eta_{mc}$ (module efficiency at STC) is defined at $25^\circ C$. Depending on the wind speed and the type of mounting of the PV modules (free-standing or roof integrated) there is a temperature rise of the modules with respect to the ambient of 20 to 40°C at $1000 \text{ W/m}^2$. The array energy yield at actual irradiance, but at a simulated cell temperature of $25^\circ C$, can be calculated as follows: $E_{a_{25}} = \sum P_a \cdot \left[ 1 - \beta_{mpp} (T_m - 25) \right] \cdot t$, where $P_a$ is the actual array power, $\beta_{mpp}$ the power temperature coefficient, $T_m$ module temperature and $t$ is the measurement period. So the losses in array energy ($E_{LT}$) caused by the rise of module temperature are $E_{LT} = E_{a_{25}} - E_a$. Mark that $E_{LT}$ (temperature losses) will be positive when the effective module temperature exceeds $25^\circ C$, otherwise the losses are negative.

4.4 Low irradiance losses - $E_{low}irr$

The shape of the module efficiency as a function of the irradiance depends on the second diode model of the module (with two diodes, an effective series and shunt resistance). At low irradiance the efficiency of the module is significantly lower than at STC. The annual low irradiance losses can be calculated as follows:

- calculate for a short time period (over the whole irradiance range) the BINNED temperature corrected DC efficiency curve at the array side: $\eta_{a_{25}} = f(Gi)$, where $Gi$ = irradiance in arrayplane, $\eta_{a_{25}}$ = temperature corrected array-efficiency (see figure 3). When the array voltage is measured at the input terminals of the inverter, make a correction for the ohmic losses: $P_{a_{(array)}} = P_{a_{(inv)}} + P_{cu}$.
- fix the maximum in this efficiency curve $\eta_{k}$ (max). Mostly the curve will be horizontal above $Gi = 600 \text{ W/m}^2$; a decreasing efficiency indicates series resistance. Calculate for each BINNED irradiance class the difference of the maximum and actual DC-efficiency: $\Delta \eta = \eta_{k}$ (max) - $\eta_k$.
- multiply above calculated difference in efficiency with the irradiation over the whole year $H_i$ (kWh/m²) within each irradiance class (W/m²), see figure 4: $E_{low irrad.}$ (per class) = $\Delta \eta H_i$ (per class).

4.5 Shading losses - $E_{shadow}$

Because mismatch losses are difficult to determine without specific I-V measurements in the field we continue the analysis for losses related to the irradiance. The mismatch losses can then be calculated as a closing item. As mentioned in section 3 the second array in Zandvoort is shaded in the summermonths by a tree on the east of the living (see picture 5). In the other months of the year is no difference observable. The reference cell which is mounted in plane with the PV array also indicates a lower irradiance than the unshaded reference cell at the top of the roof. The loss of energy ($E_{shadow}$) in kWh can be calculated by multiplying the energy ($H_i$ in kWh/m²) per irradiance class (W/m²), the array area $A$ [m²] and the difference between the expected efficiency curve and the real measured efficiency characteristic, based on an unshaded reference cell ($H_i^*-25$). So: $H_i^*-25 \cdot A = H_i^* \cdot A + E_{shadow}$ [kWh/m²]

4.6 Fundamental module losses - $E_{mod}$

At an irradiance of $1000 \text{ W/m}^2$ a module temperature of $25^\circ C$ and AM1.5, STC, a PV module has an efficiency of $\eta_{stc}$. Through various fundamental physical processes, which are partly linked to the semiconductor properties of the cell, a fraction $(1-\eta_{mc})$ will be lost.

4.7 String losses - $E_{string}$

Earlier in Zandvoort we measured a difference in energy yield between the two subarrays of 7.9%. The lower
efficiency of array 2 also can be seen at days without
shadow on the arrays. Recently we have performed I-V
measurements of the strings. Each subarray consists of 8
strings of 4 modules in series. One of this strings showed
an open circuit voltage of 65 V in stead of 75 V. It is
expected that this will cause an energy loss of about 5%.
The product of the irradiation $H_{i,25}$ [kWh/m²] (measured
with the roof integrated reference cell), the array area $A$
[m²], the nominal array efficiency $\eta_{STC}$ [%] and the bad
string losses results in $E_{a,STC}$.

4.8 Dynamic MPP-tracking losses - $E_{dyn}$

PV modules can only generate the maximum power when
the array voltage is equal to the $U_{mpp}$ [3]. With regard to the
short term control behaviour of the inverter it should be
noted that:

- PV inverters are mostly of the single phase type. When
  the grid voltage and grid current have a sinewave
  shape, the output power time diagram shows a sin²-
  shape. Because the module output current has to be
  constant, the inverter is equipped with electrolytic
  capacitors at the input side. The limited value of this
  capacitor induces a ripple voltage on the DC side, so
  the DC voltage is not always equal to $U_{mpp}$;
- even when the irradiance has a constant level, the MPP-
  tracker is dynamically searching for a the optimum
  workpoint. The variations in the array voltage result in
  loss of energy;
- when the irradiance fluctuates the DC voltage has to be
  adjusted. Because of the delay of the MPP-tracker a
  part of the potential power is not used.

It is difficult to quantify above mentioned losses in the
field. With a PV array simulator we measured MPP-
efficiencies of about 1% in our lab for the Sunmaster
Mastervolt 1800.

4.9 Static MPP-tracking losses - $E_{stat}$

Also in steady state conditions the array voltage does not
always correspond to $U_{mpp}$. By comparison of the DC
efficiency curves $\eta_{dc}$ and $U_a = f(G_i)$ of different systems
the MPP tracking system can often be improved. In figure 1
two efficiency curves are shown, together with the
measured array voltage. Although subarray 1 is better than
subarray 2 (bad string, see par. 4.7), at low irradiance
levels the array efficiency of subarray 2 increases because
the array voltage is higher.

4.10 Mismatch losses/calibration errors - $E_{miss}$

There are two ways to determine the mismatch losses
caused by strings with different IV characteristics:

- the I-V characteristics of each string can be measured.
The behaviour of parallel strings can be modelled as an
electric network;
- The second method is to measure the real array
efficiency in the field and make corrections for the
module temperature and cable losses. When the
maximum in this characteristic is compared with the
manufacturer flash test results, the mismatch losses can
be estimated.

It is noted that the calibration of the reference cell and the
accuracy of module rating influence the results in the
approach. In our method we treat the mismatch losses as a
closing item to make the calculated Performance Ratio
equal to the measured PR.

5. RESULTS

Table 1: Various losses in PV systems

<table>
<thead>
<tr>
<th></th>
<th>De Wijk</th>
<th>Zandvoort</th>
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<tbody>
<tr>
<td></td>
<td>%</td>
<td>Remains</td>
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<tr>
<td>Shading losses</td>
<td>11.0</td>
<td>0.890</td>
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<td>Fundamental</td>
<td>12.5</td>
<td>14.3</td>
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<td>module losses</td>
<td></td>
<td></td>
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<tr>
<td>Bad string</td>
<td>2.5</td>
<td>0.975</td>
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<tr>
<td>Static losses</td>
<td>?</td>
<td>1.0</td>
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<tr>
<td>MPP-tracker</td>
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<tr>
<td>Dynamic losses</td>
<td>?</td>
<td>1.0</td>
</tr>
<tr>
<td>Mismatch losses</td>
<td>5.7</td>
<td>0.943</td>
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<td>Low radience</td>
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<td>Diode losses</td>
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<td>Resistance/ohmic</td>
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<td>losses</td>
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<td>Inverter losses</td>
<td>17.5</td>
<td>0.825</td>
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<tr>
<td>Performance ratio</td>
<td>0.612</td>
<td>0.731</td>
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</tbody>
</table>

Remark: Losses calculated against previous measuring value

When one tries to separate all parts of the losses, one can
determine the rest of each calculation step: rest = 1 -
losses/100. The product of all the rest factors yields the
performance ratio.

6. SUMMARY

Two Dutch PV-systems are analysed. System losses are
presented in a Sankey diagram. Calculated system
efficiency and performance ratio are compared to measured
values. This approach results in a more accurate prediction
of yearly energy yield with fast characterisation of the
system, system loss factors and Test Reference Year (TRY)
files.

7. ACKNOWLEDGEMENT

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for Energy and the Environment Novem.

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