Normalized Representation of Energy and Power for Analysis of Performance and On-line Error Detection in PV-Systems

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ABSTRACT: In order to compare energy production and performance of PV plants of different size and at different locations, JRC at ISPRA/Italy introduced a very useful method for normalized analysis and presentation of monitoring data [1]. This method was extended and improved by ISB (especially for grid connected systems). Information contained in some diagrams can be increased by indicating additional values. Introducing new quantities for normalized power and splitting capture losses into thermal and non-thermal losses allows detailed on-line and off-line analysis of sporadic system malfunctions (e.g. MPP-tracking errors, shadowing or snow covering of the solar generator etc.).

1. Normalized Energy Yields and Losses

Definition of the normalized quantities $\mathbf{Y_r}$ (Reference Yield), $\mathbf{Y_a}$ (Array Yield), $\mathbf{Y_f}$ (Final Yield) as well as $\mathbf{L_C}$ (Capture Losses), $\mathbf{L_S}$ (System Losses) and **PR** (Performance Ratio) already allows a detailed analysis (see table 1). Annual statistics (with monthly values), monthly statistics (with daily values) and even daily statistics (with hourly values) in tabular form or by diagrams can be generated. By indicating the performance ratio on top of each bar, the information contained in bar graphs can be considerably increased. With such diagrams a direct comparison of different PV plants and a fast recognition of some malfunctions is possible.

2. Normalized Quantities for Power and normalized Daily Diagram

If the storage interval of the data is less than one hour, average values for power and irradiance (e.g. 5-minute values) can also be normalized by dividing them by the PV-generator power P_0 resp. irradiance G_0 =1kW/m^2 at STC. These new **normalized instantaneous quantities** are described with small letters ($\mathbf{y_r}$, $\mathbf{y_a}$, $\mathbf{y_f}$, $\mathbf{l_C}$, $\mathbf{l_S}$ and **pr**) analogous to the corresponding energy yields**.** With these quantities a *normalized daily diagram* can be drawn, allowing a much more detailed analysis of system performance. Such normalized instantaneous quantities are also very useful for on-line error detection by using data picked up very frequently, e.g. every second.

3. Splitting the Capture Losses

If not only electrical quantities but also solar cell temperature are measured, L_C resp. l_C can be split into

- **thermal capture losses L_{CT}** resp. $\mathbf{l_{CT}}$ (because the cell temperature is usually higher than 25°C)
- **miscellaneous capture losses L_{CM}** resp. $\mathbf{l_{CM}}$ (wiring, string diodes, low irradiance, partial shadowing, dirt accumulation, snow-covering, inhomogeneous irradiance, mismatch, maximum power tracking errors etc.)

In a grid connected PV plant a malfunction causes a remarkable rise of L_{CM} resp. l_{CM}. These quantities are very good indicators for system problems. Well planned and realized plants normally show little L_{CM}-values.

In order to calculate L_{CT} and L_{CM}, the temperature corrected reference yield $\mathbf{Y_T}$ resp. the temperature corrected irradiance $\mathbf{y_T}$ must be introduced. The power of a solar generator is temperature-dependent (the temperature coefficient is $c_T \approx 0.0044$/K with crystalline cells). An ideal solar generator with nominal power $\mathbf{P_0}$ (at STC), **solar cell temperature T_C** and **irradiance G_0 = 1 kW/m^2** operated in the maximum power point (MPP) will generate the temperature corrected nominal solar generator power

$$P_{0T} = P_0\,[1-c_T\,(T_C-T_0)] \qquad (T_0 = \text{STC-temperature} = 25°C).$$

Thus the new quantities can be calculated as

$$\mathbf{y_T = y_r * P_{0T} / P_0 = y_r\,[1-c_T\,(T_C-T_0)]}$$
$$\mathbf{l_{CT} = y_r - y_T}$$
$$\mathbf{l_{CM} = y_T - y_a}$$

By integration of these values, daily, monthly or yearly values of Y_T, L_{CT} and L_{CM} can be calculated.

In addition the following useful ratios can be defined:

$$\mathbf{k_T = Y_T / Y_r} \qquad \text{(temperature correction factor)}$$
$$\mathbf{k_G = Y_a / Y_T} \qquad \text{(generator correction factor)}$$

For grid connected systems:

$$\mathbf{n_I = Y_f / Y_a} \qquad \text{(inverter efficiency)}$$

Symbol	Term	Meaning / Definition	Unit	
Y_r	Reference Yield	$\mathbf{Y_r = H_I / G_0}$. Y_r is equal to the time which the sun has to shine with G_0 = 1kW/m^2 to irradiate the energy H_I onto the solar generator	$\frac{kWh/m^2}{d*1kW/m^2}$	[h/d]
L_C	Capture Losses	**Thermal capture losses L_{CT} :** - Losses caused by cell temperatures higher than 25°C. **Miscellaneous capture losses L_{CM} :** - Wiring, string diodes, low irradiance - Partial shadowing, contamination, snow covering, inhomogeneous irradiance, mismatch - Maximum power tracking errors, reduction of array power caused by inverter failures or when the accumulator is fully charged (stand alone systems) - Errors in irradiance measurements - When irradiance is measured with pyranometer: Spectral losses, losses caused by glass reflections	$\frac{kWh}{d*kWp}$	[h/d]
Y_a	Array Yield	$\mathbf{Y_a = E_A / P_0}$. Y_a is equal to the time which the PV plant has to operate with nominal solar generator power P_0 to generate array (DC-)energy E_A	$\frac{kWh}{d*kWp}$	[h/d]
L_S	System Losses	Inverter conversion losses (DC-AC), accumulator storage losses (stand alone systems).	$\frac{kWh}{d*kWp}$	[h/d]
Y_f	Final Yield	$\mathbf{Y_f = E_{use} / P_0}$. Y_f is equal to the time which the PV plant has to operate with nominal solar generator power P_0 to generate the useful output energy E_{use}. For grid connected plants: $E_{use} = E_{AC}$.	$\frac{kWh}{d*kWp}$	[h/d]
PR	Performance Ratio	$\mathbf{PR = Y_f / Y_r}$. PR corresponds to the ratio of the useful energy E_{use} to the energy which would be generated by a lossless, ideal PV plant with solar cell temperature at 25°C and the same irradiation.		[1]

$$Y_r \xrightarrow{-L_C} Y_a \xrightarrow{-L_S} Y_f \qquad\qquad Y_r \xrightarrow{-L_{CT}} Y_T \xrightarrow{-L_{CM}} Y_a \xrightarrow{-L_S} Y_f$$

Table 1: Definition and meaning of normalized yields and losses with PV plants.

4. Examples of some improved and new Diagrams

4.1 Diagrams for Energy Yields and Losses

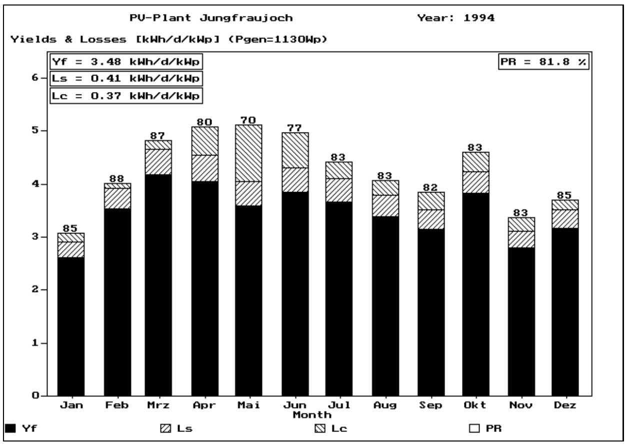

Fig. 1: Normalized yearly analysis of ISB's PV plant at Jungfraujoch (3454m) with monthly values of Y_f , L_S, L_C and PR (referred to effective solar generator power). Irradiance is measured with a reference cell. Partial snow covering of the solar generator in spring causes higher L_C and lower PR-values

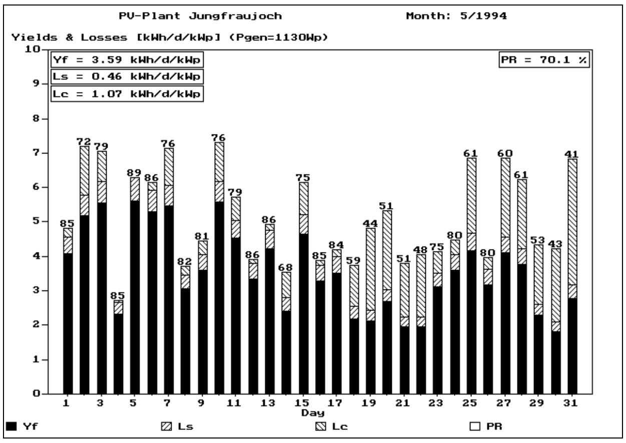

Fig. 2: Normalized monthly analysis for PV-plant Jungfraujoch for May 1994. Due to the very large snow quantity in spring 1994, one of the two PV generators was covered with snow for a few days. Therefore on these days L_C values are higher and PR values are lower than on other days without snow coverage

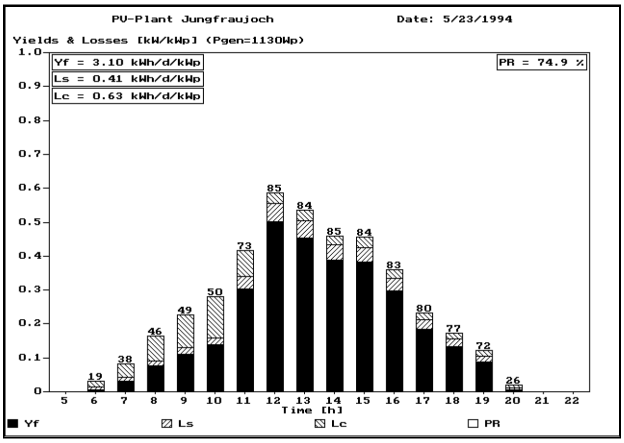

Fig. 3: Normalized daily analysis for May 23, 1994 with hourly values of Y_f , L_S, L_C and PR. Hourly values of yields and losses are indicated as kW/kWp resp. without dimension. In early morning, part of the PV generator was covered by snow. Then, after 10:00, the snow was removed, causing a characteristic rise of PR.

4.2 Diagrams for normalized Power Yields and Losses

Using the normalized instantaneous quantities defined in chapter 2 and 3, very useful normalized daily diagrams can be generated. These diagrams clearly indicate operational problems of a PV-system, even if these problems are only sporadic.

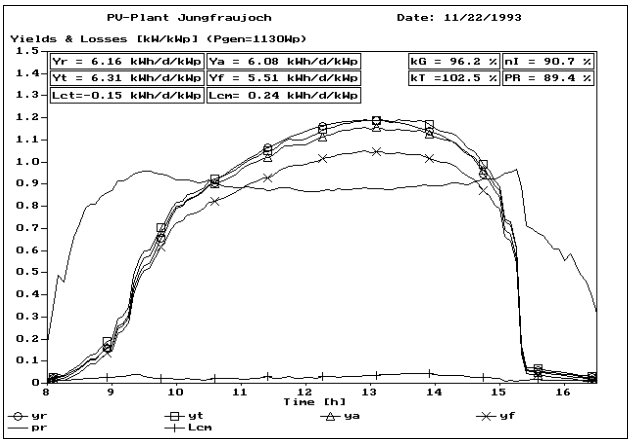

Fig. 4: Normalized daily diagram for November 22, 1993 with instantaneous values of y_r, y_T, y_a, y_f, l_{CM} and pr. This day was a clear and cold winter day without any problems, so l_{CM} is very small and pr reaches a maximum value of more than 0.95.

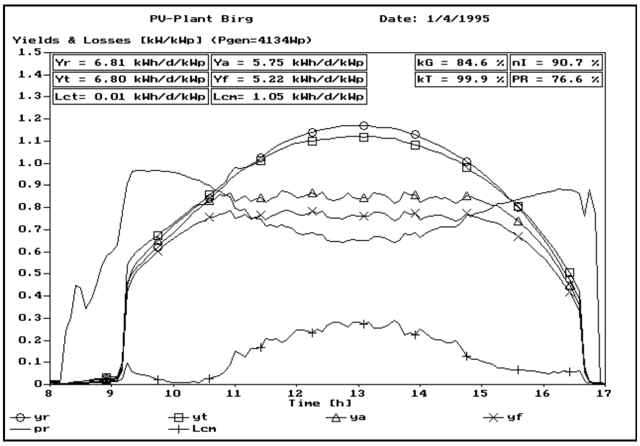

Fig. 5: Normalized daily diagram for PV plant Birg/Schilthorn (2670m.) on Jan. 4, 1995. As the PV generator (P_0 =4134Wp) is slightly oversized compared to nominal inverter power, DC power is limited to 3.5kW between 10:00 and 15:00. In normalized representation, y_a is limited to 0.85. As y_T reaches a maximum of 1.13 around noon, l_{CM} rises at higher irradiance levels up to a maximum of 0.28. The daily value of PR is considerably lower than in fig. 4.

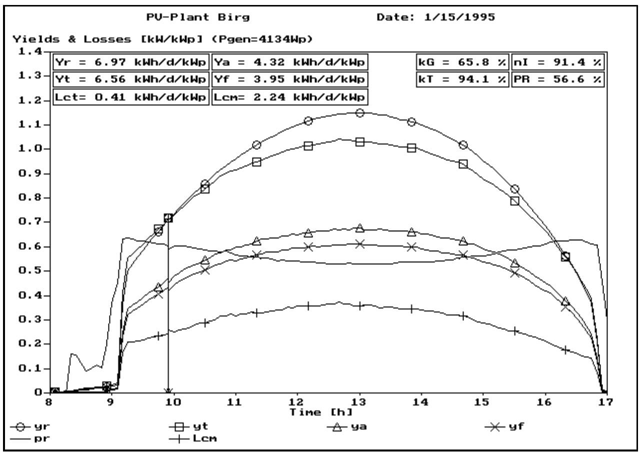

Fig. 6: Normalized daily diagram of PV plant Birg on January 15, 1994. Because of heavy snowfalls part of the generator is covered by snow. After sunrise l_{CM} is already 0.2 and rises to 0.37 around noon. Energy production is reduced considerably, k_G is only 66% and PR only 57%. Around 9:55 a short inverter shutdown occurred, probably caused by a voltage transient on the AC side.

A similar daily diagram could be observed after a fault in some strings of the PV generator (e.g. defects in diodes, fuses etc.).

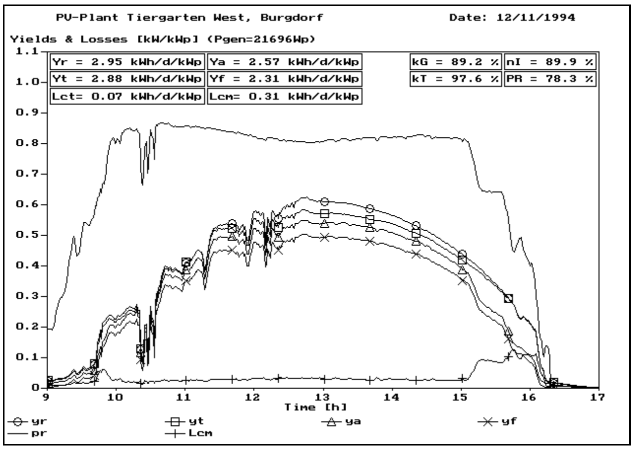

Fig. 7: Normalized daily diagram on December 11, 1994 of the PV plant (20kWp) on the western part of ISB's building for the department of electrical engineering. After 15:00 l_{CM} rises slowly owing to shadows creeping up from the lower to the higher module rows. Thus l_{CM} is also a good indicator for partial shadowing of the PV generator.

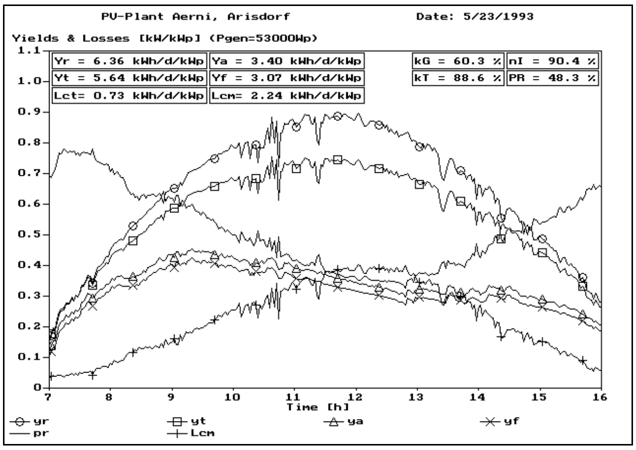

Fig. 8: PV plant Aerni/Arisdorf (53kWp) on May 23, 1993. The inverter obviously had a serious problem with maximum power point tracking. During the day l_{CM} rises very high and pr drops. The daily value of PR is very low, too.

5. Methodical analysis of a malfunction by means of normalized diagrams:

(Example with a 8.9kWp grid connected PV plant at Interlaken)

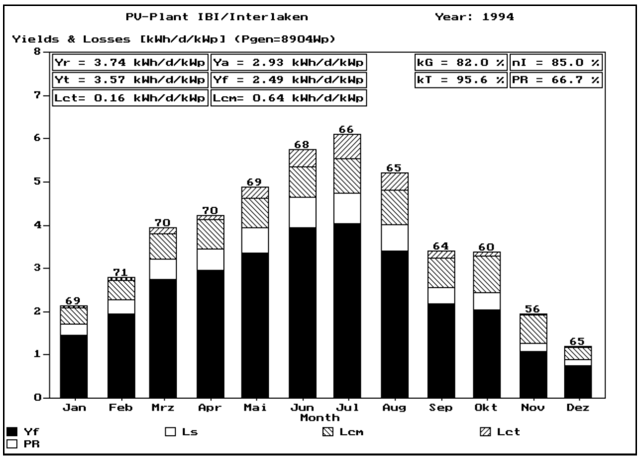

Fig. 9: Normalized yearly analysis 1994 for PV plant IBI/Interlaken (with 4 inverters in master-slave configuration). In October, L_{CM} is too high compared to other months, therefore there must be a problem.

With normalized diagrams, an approach to the problems encountered is quite easy by successive reduction of the time interval for which the diagram is generated:

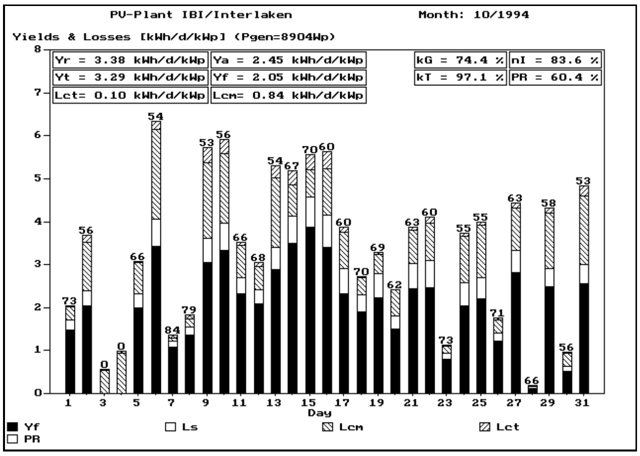

Fig. 10: Normalized monthly analysis for October 1994. During October 2, a problem occurred. As a consequence, the plant was out of order for two days. On October 5, the plant was switched on with reduced power (2 instead of 4 inverters).

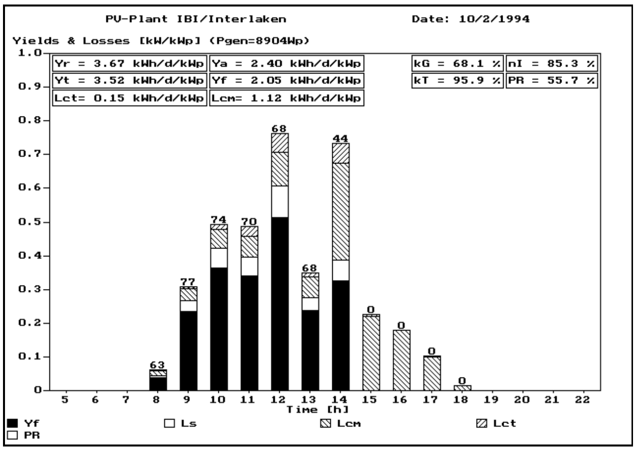

Fig. 11: Normalized daily analysis for October 2, 1994. Between 13:00 and 14:00, an inverter defect caused a shutdown of the plant. Energy production dropped to 0 for the rest of the day.

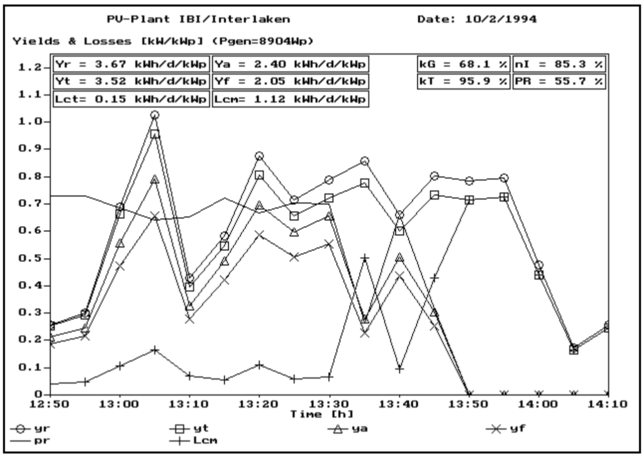

Fig. 12: Detailed analysis of the inverter failure with a expanded normalized daily diagram (5 minute average values). At 13:35 there is a maximum power point tracking problem (rise of l_{CM} and drop of pr). Around 13:42 the master inverter fails completely with a hardware defect. y_a , y_f and pr drop to 0, l_{CM} rises to y_T.

6. On-line Error Detection

Normalized power and losses can also be used for on-line error detection. If data are measured in very short intervals (e.g. every second), it is quite easy to realize a continuous plant supervision. With this supervision, detection of malfunctions is assured.

This new on-line error detection method is already realized at ISB's PV test site in Burgdorf. The following figures show two screen printouts of a data acquisition computer:

```
PV PLANT SOLAB60 (V 3.1)                                    05/03/95    10:30:00
 Normalized instantaneous values
  TOPCLASS     ( Pgen(STC) =  4176 W )

  Normalized irradiance (ref. cell)                         yr    0.501
  Normalized irradiance (pyranometer)                       yr    0.552
  Temp. corrected irradiance (ref. cell)                    yt    0.478
  Temp. corrected irradiance (pyranometer)                  yt    0.527

  All values indicated below referred to: ref. cell

  Thermic capture losses                                    lct   0.023
  Miscellaneous capture losses                              lcm   0.193
  Normalized solar generator power                          ya    0.285
  System losses                                             ls    0.022
  Normalized useful output power                            yf    0.263

  Temperature correction factor       ( kT = yt / yr )      kT    0.954
  Generator correction factor         ( kG = ya / yt )      kG    0.596
  Inverter efficiency                 ( nI = yf / ya )      nI    0.923

  Actual performance ratio  (pr = yf / yr = kT*kG*nI)       pr    0.525
SPACE Reference cell/Pyranometer  TAB Standard presentation      PV - Group ISB
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Fig. 13: Screen printout of a data acquisition computer at ISB's PV test site in Burgdorf: Normalized representation of on-line values. At this daytime (May 3rd, 1995, 10:30), the solar generator is partially shadowed by a part of the building. This partial shadowing results in a remarkable rise of l_{CM} . Due to the higher value of l_{CM} , the actual performance ratio pr is very low (0.525).

```
PV PLANT SOLAB60 (V 3.1)                                    05/03/95    17:55:00
 Normalized instantaneous values
  TOPCLASS     ( Pgen(STC) =  4176 W )

  Normalized irradiance (ref. cell)                         yr    0.513
  Normalized irradiance (pyranometer)                       yr    0.545
  Temp. corrected irradiance (ref. cell)                    yt    0.473
  Temp. corrected irradiance (pyranometer)                  yt    0.503

  All values indicated below referred to: ref. cell

  Thermic capture losses                                    lct   0.040
  Miscellaneous capture losses                              lcm   0.041
  Normalized solar generator power                          ya    0.432
  System losses                                             ls    0.040
  Normalized useful output power                            yf    0.392

  Temperature correction factor       ( kT = yt / yr )      kT    0.922
  Generator correction factor         ( kG = ya / yt )      kG    0.913
  Inverter efficiency                 ( nI = yf / ya )      nI    0.907

  Actual performance ratio  (pr = yf / yr = kT*kG*nI)       pr    0.764
SPACE Reference cell/Pyranometer  TAB Standard presentation      PV - Group ISB
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Fig. 14: On-line values of the same plant later at the same day with nearly the same value of y_r, but without partial shadowing of the solar generator (May 3rd, 1995, 17:55). l_{CM} is very low (0.041 instead of 0.193). Because of the temperature rise of the solar generator, the value of l_{CT} is now higher than in the morning (0.040).

7. Discussion and some practical Hints

In many PV arrays there are some differences in module temperatures in the array and between modules and reference cells used for monitoring purposes. Therefore y_T (and consequently l_{CM} and l_{CT}) may be slightly influenced by such differences. As in many cases most of the capture losses L_C are caused by a temperature rise compared to STC, it is all the same reasonable to split the capture losses into the (easily explainable) thermal losses l_{CT} and the remaining miscellaneous losses l_{CM} and L_{CM} which may have different reasons, but clearly indicate system deficiencies or malfunctions. As they are difference quantities, they are also quite susceptible to measurement errors.

To reduce these practical problems as far as possible, it is essential to position **reference cell and temperature sensors** appropriately in a **average position in the middle of the array,** not at an exposed location on top of the array or even higher on a special meteo mast.

Acknowledgements

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Our thanks go also to the International Foundation Scientific Stations Jungfraujoch and Gornergrat, the owner of the research station at Jungfraujoch, who permitted the use of its building for this project. Our PV-activities in general are also supported by IBB, Burgdorf, BKW Energy AG, Berne, and EWB, Berne.

Conclusion

With normalized representation of PV system data described above, which was introduced by JRC/Ispra and improved by ISB, a very efficient analysis of PV systems of different size and at different locations is possible. Besides electrical quantities, solar cell temperature should be measured in order to split capture losses L_C into thermal and miscellaneous capture losses.

If data measured in intervals shorter than one hour are available, instantaneous values of power and irradiance can be introduced, allowing a much more detailed analysis of system performance with the normalized daily diagram or even an on-line error detection.

Due to space limitations, only a very short overview of this new method for the analysis of the performance of PV-systems could be given here. A much more detailed introduction and description is given in [2].

References:

[1] Guidelines for the Assessment of Photovoltaic Plants, Document B: Analysis and Presentation of Monitoring Data, Issue 4.1 June 1993. CEC JRC / Ispra.

[2] H. Haeberlin und Ch. Beutler: "Analyse des Betriebsverhaltens von Photovoltaikanlagen durch normierte Darstellung von Energieertrag und Leistung". SEV/VSE-Bulletin 4/95 (in German).

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[4] H. Haeberlin and Ch. Beutler: "Highest Grid connected PV Plant in the World at Jungfraujoch: Excellent Performance in the first two Years of Operation". Proc. 13th EU PV Conf., Nice 1995.

[5] H. Haeberlin, Ch. Beutler and S. Oberli: "Yield and Reliability of Grid-connected PV-Systems at different Locations in the Canton of Berne (Switzerland)". Proc. 12th EU PV Conference, Amsterdam 1994.

[6] H. Haeberlin, F. Kaeser and S. Oberli: "New PV-Inverters from 2kW to 20kW for Grid-connection: Results of Extended Tests with single- and three-phase Units". Proc. 12th EU PV Conference, Amsterdam 1994.