Gradual Reduction of PV Generator Yield due to Pollution

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Abstract: Since spring 1994 the PV-laboratory of HTA Burgdorf has operated a new test center for PV-systems with a solar generator of 60 kWp on top of the new building of the department of electrical engineering. In course of time, a development of a *permanent* pollution strip was observed which caused a gradual reduction of energy yield of up to 10% until the end of 1997. The most important external source of unusual pollution at this location is a *main railway line* (Berne-Zurich) at a distance of only about 50m. Pollution by *iron dust from railway lines* seems to favor development of permanent pollution strips at the edges of framed modules. As soon as *pioneer plants* begin to grow, this effect is enhanced, as they retain all kinds of dust arriving on the modules. Under such conditions a *periodical cleaning of a PV generator* seems to be necessary. To cure this problem, artifical cleaning in June 1998 became necessary. Measurements of IV-curves before and after cleaning have proved that most of the power loss is reversible.
KEYWORDS: PV Array – 1: Performance – 2 : Pollution - 3.

1. Introduction

Since spring 1994, the PV-Laboratory of HTA Burgdorf has operated a new test center for PV-systems with a solar generator of 60 kWp. Besides intensive tests of many different inverters [1, 2, 3] , continuous analytical monitoring of two inverters of 20kW and two inverters of 3.3kW has been performed for more than three years. The main solar generator consists of 1056 framed modules Siemens M55HO mounted in summer 1993 with a tilt angle of 30^o and the long side in horizontal position. In course of time, a *gradual reduction of array yield (up to 10 %)* until spring 1998 was registered. In this period of time, artificial cleaning was performed only on the irradiance sensors used for monitoring purposes, but not on the modules of the solar generator. Pollution problems affecting energy yield of PV generators have been reported already in [4].

2. Location and environment

The solar generator is on top of the new building of the department of electrical engineering of HTA Burgdorf about 10m over ground in a town of about 15000 inhabitants. In the region surrounding this town with some light industry, there are also forests and some farms, causing biological pollution (with pollen) especially in spring.

Fig. 1: View of the building of the department of Electrical Engineering of HTA Burgdorf with a PV generator of 60kWp on top of the roof.
A main railway line passes about 10m behind the point where the picture was taken.

The most important external source of unusual pollution is a main railway line (Berne-Zurich) at a distance of only about 50m. As the railway station of Burgdorf, where many trains stop, is less than 1 km away, many trains are braking or accelerating when they pass the building. The region is pretty humid, natural rainfall is more than 1000 liters per m^2 a year and is distributed sufficiently over the whole year, thus natural cleaning of the array was considered to be sufficient before installation of the plant.

3. Pollution after 4 years of operation

While in the years 1994 till 1996 only in spring a clearly visible pollution was observed, in course of 1997 with a rather dry and sunny period from the end of July until the beginning of November, a development of a *permanent* pollution strip (compact pollution up to 1 cm, followed by a strip of visible, but not compact pollution) close to the lower edge of the module frame was registered. The influence of this polluting strip on array perfomance was especially severe on the modules of the main generator (with the long side in horizontal position), because the distance between cells and frame is very small there (1-2 mm).

Fig. 2: View of a part of the PV array with visible pollution. The modules at the left side are cleaned, whereas the others show the pollution accumulated from summer 1993 to fall 1997.

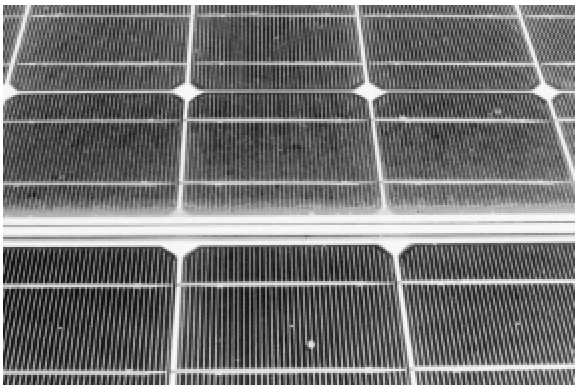

Fig. 3: Strip of pollution at lower edge of framed modules M55 (long side mounted in horizontal position, tilt angle 30°) causing partial shading.

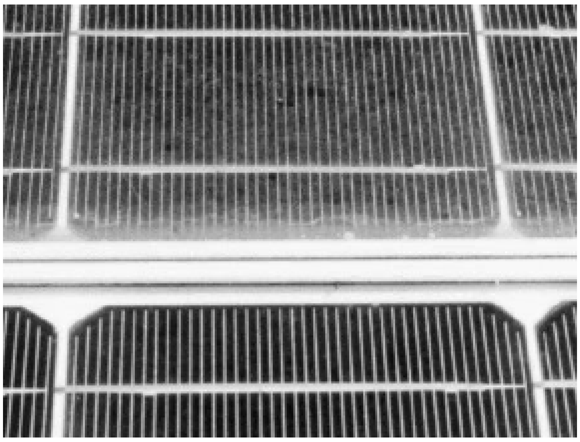

Fig. 4: Close look to the relatively compact strip of pollution about 1 cm wide (detail of fig. 3).

Similar visible pollution strips could also be observed at some modules M55 mounted the other way (short edge in horizontal position) at a tilt angle of 65° and oriented with a 60° deviation from south to east. As the distance between the lower edge and the cells is more than 1 cm in this case, the influence on module performance is usually less important. However, when the strip is large enough, a power reduction is also possible (see fig. 5).

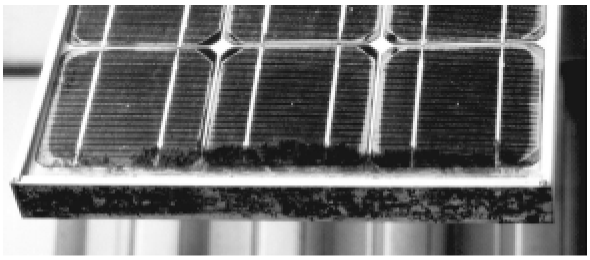

Fig. 5: Large strip of pollution at lower edge of framed modules M55 (short side mounted in horizontal position.

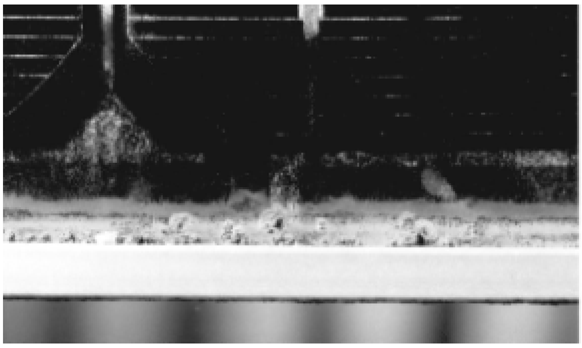

Fig. 6: Close look to a place where lichens are developing (detail of fig. 5).

4. I-V-curves and MPP power of polluted and cleaned modules

With the I-V curve analyser for PV generators of HTA Burgdorf, the I-V curves of the solar generators for the different inverters under test were determined and converted to STC.

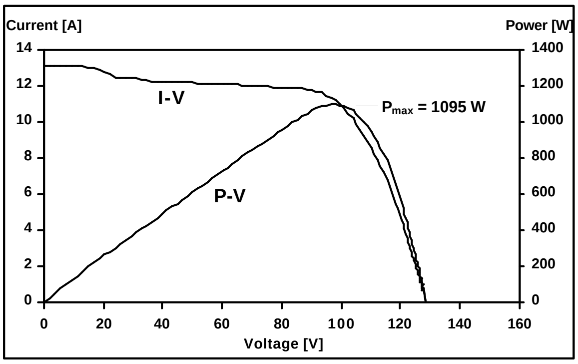

Fig. 7: I-V-curves, P-V-curves and MPP power of an uncleaned array (4 parallel strings of 6 modules M55 in series) after 5 years of operation (measured in June 1998).

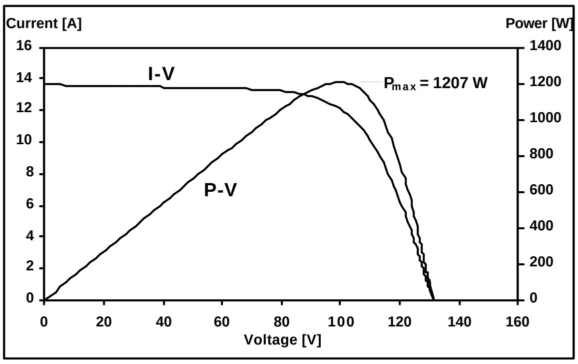

Fig. 8: I-V-curves, P-V-curves and MPP power of the array of fig. 7 after cleaning.

The result was a clearly visible deformation of the I-V curve and a reduction of MPP-power of about 8% to 10% owing to partial shading by the pollution strip. The PV generator was cleaned in June 1998 and showed an immediate increase of MPP power of 8 to 10%, thus most of the power loss proved to be reversible and can be attributed to this pollution problem.

5. Reduction of array yield versus time

Owing to the continuous precise monitoring data with irradiance values from pyranometers and reference cells (cleaned at regular intervals), it seemed feasible to determine not only the final power reduction after 4 years of operation, but also the evolution of the power reduction versus time. With the normalized representation of yield data introduced by JRC in Ispra [5] and extended by HTA Burgdorf [6], relative array performance versus time was analysed.

5.1 Short introduction into normalized representation of energy yields

Definition of the normalized quantities (see [5, 6]):

Reference yield $Y_r = H_I / G_0$

Array yield $Y_a = E_A / P_0$

Final yield $Y_f = E_{AC} / P_0$ (*grid connected* systems)

Capture losses $L_c = Y_r - Y_a$

System losses $L_s = Y_a - Y_f$

Performance ratio $PR = Y_f / Y_r$

with H_I = irradiation into array plane

G_0 = 1kW/m^2 (irradiance at STC)

P_0 = nominal PV array power at STC

E_A = DC energy produced by the array

E_{AC} = AC energy injected into grid.

These quantities already allow a detailed analysis of performance. 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. With such diagrams a direct comparison of different PV plants and a fast recognition of some malfunctions is possible.

5.1.1 Normalized quantities for power

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 (**y_r , y_a , y_f , l_c , l_s** and **pr**) analogous to the corresponding energy yields [6]. These quantities allow 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.

5.1.2 Splitting the capture losses

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

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

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

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

Thus the new quantities can be calculated as

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

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 [6]:

Temperature correction factor $k_T = Y_T / Y_r$

Generator correction factor $k_G = Y_a / Y_T$

For grid connected systems also:

Inverter efficiency $n_I = Y_f / Y_a$

5.2 Array performance versus time

To minimize influence of the seasonal pollution occuring in spring, the 3 summer months (June, July and August) of each year were chosen, because usually heavy rainfalls in May or the beginning of June clean away most of the spring's dust. As an indication of array performance, average **generator correction factor k_G** for this period was used. As the other influences contained in this factor should be nearly constant in this period of time, its variations reflect mainly the influence of increasing array pollution. In 1998, the best available month before the cleaning operation was May. The results show an annual reduction of about 1% from 1994 to 1995, 2% from 1995 to 1996, 4% from 1996 to 1997 and 1% from 1997 to 1998 (see fig. 9).

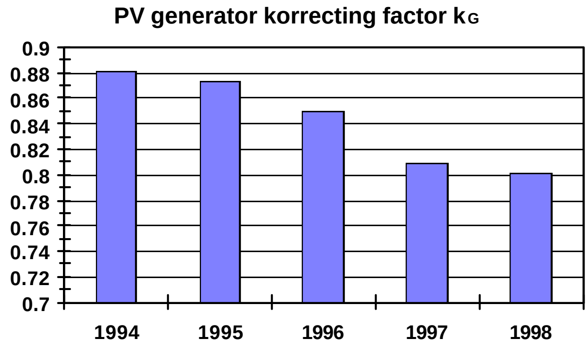

Fig. 9: Generator correction factor k_G in the 3 summer month in the years 1994 to 1997 and in May 1998.

6. Composition of the polluting material

Visual inspection of the polluting strip showed beginning biological activity by pioneer plants (moss, lichen) at some parts of the generator (see fig. 6 and fig. 11). This explains at least in part why the pollution does not increase continuously. As soon as there are pioneer plants on the polluting strip, they try to retain any dust deposited on the module. An analysis of the material composing the pollution strip showed an important part of iron particles (surrounded by iron oxide), Silicon from airborne sand from the sahara desert(!) (more than 2000 km away and different organic materials (see fig.10).

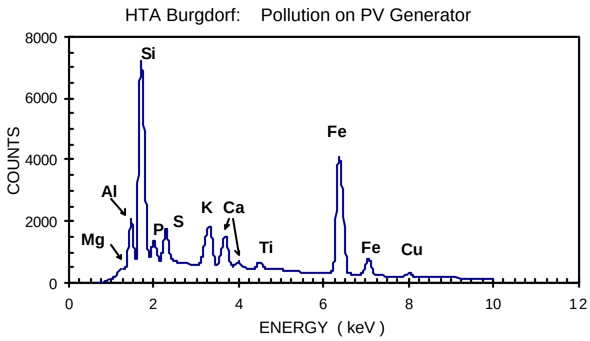

Fig. 10: Dispersive micro-X-ray analysis of the polluting material showing the most important *anorganic* components.

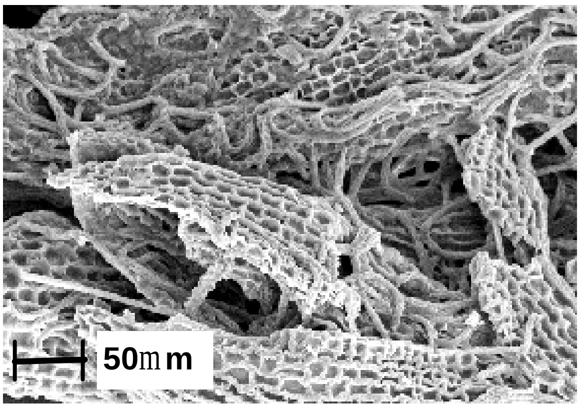

Fig. 11: Photo of lichens in pollution strip taken with an electron microscope

7. Conclusion

Pollution by iron dust from railway lines seems to favour *development of permanent pollution strips at the edges of framed modules*. As soon as pioneer plants arrive, this effect is enhanced, as they retain all kinds of dust arriving on the modules. Under such conditions a periodical cleaning of a PV generator seems to be necessary.

In September 1997 a small part of the PV generator was cleaned. It was found that most of the power loss encoutered is reversible. To clean the whole array mounted on the roof of the buildung, a removable stand had to be prepared to ensure safety of the personell involved. These preparations took much more time than planned. Therefore cleaning of the whole PV generator could be carried out only in June 1998.

Before and after cleaning I-V curves and MPP power normalized to STC were determined. Results obtained show that about 8% to 10 % of the power loss registered can be removed by cleaning the arrays (see fig. 7 and 8). It is remarkable that this figure agrees very well with the power loss that can be calculated from the loss of generator correction factor k_G in course of time. Some luck is certianly also involved, because there were some initial problems with irradiance and temperature sensors during the first months. It is quite different to make reproducable and accurate measurements of irradiance over many years.

In the future it is planned to perfom similar measurements (determination of MPP power of cleaned and uncleaned PV arrays) also at other PV plants that are not close to railway lines to see if also at such locations a permanent pollution affecting PV production occurs.

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