RELIABILITY ISSUES IN PV SYSTEMS – EXPERIENCE AND IMPROVEMENTS

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Abstract - A survey was conducted to collect information on faults, failures and poor performance from large PV plants a well as residential system like the ones of the »1000-Roofs-Programme«. The reason for a low energy yield in some systems was analysed. Modern modules built for a high voltage show very few failures. In one plant electrical faults affected 0.1 % of the total number of modules after two years of operation. Of these failures 90 % took place in junction boxes. Main reasons for low yield of the »1000-Roofs-Programme« systems were over-rated power of modules, partial shading of the array, soiling, faulty connections on the dc side and inverter failures. Failure analysis leads to recommendations for improved junction boxes. Modern Class II components offer the system designers more liberties. It may be appropriate to dismiss string diodes and string fuses, which results in simpler and more reliable systems.

1. INTRODUCTION

During the last 10 years Photovoltaics have seen an impressive growth in the number of fielded systems. However, the more systems are built the more difficult it gets to keep an overview and to learn from the field experience. Knowledge of system performance rests with the many small installing companies, faults and errors are rather kept confidential.
In order to evaluate these experiences Task 7 - Photovoltaics in the Built Environment of the IEA Photovoltaic Power Systems Programme specifically addresses the reliability of PV systems in one of its activities. »Reliability« is understood as the capability of a PV system to perform to its owners satisfaction. Main approach was to gather experience from operators of PV plants and to evaluate information from PV programs provided by the participating countries. Emphasis was placed on electrical integrity and energy performance. The findings are structured according to the project phases: planning and design, installation and operation. Based on the reported experiences improvements for simpler and thus more reliable systems are suggested. The recommendations are backed by a standard, which is under development at IEC.

2. DATA BASE

Experience with PV systems is mostly anecdotal. Only in few cases statistically meaningful data are available. One of these cases is the German »1000-Roofs-Programme«. Therefore its main features are presented in an overview.

2.1 The »1000-Roofs-Programme«

The German »1000-Roofs-Programme« comprised approximately 2100 PV systems built from 1991 to 1995 in Germany. They all were installed on the roofs of private residences. The programme was extensively monitored: all system owners had to

provide monthly yield data and logbook reports. Furthermore, about 100 systems were monitored in detail using remote data acquisition systems at a sampling rate of 5 min. After some years a special investigation was conducted to analyze systems which showed a poor performance. An inspection of some 200 systems gained experience on the long-term hardware behavior. The scientific work was carried out in joint co-operation by Fraunhofer ISE, FZ Rossendorf, ISFH Emmerthal, IST Energietechnik Augsburg, JRC Ispra (Italy), TÜV Rheinland, Umweltinstitut Leipzig and WIP (Becker et al., 1997, Erge et al., 1998 and Hoffmann et al., 1998).
Systems in the »1000-Roofs-Programme« were installed between 1990 and 1995. Most of the installations, 70 %, took place in 1993 and 1993. The total installed power was 5.3 MWp, average nominal power was 2.6 kW_p, and typical power values were 1.6 kWp, 1.9 kWp, 3.2 kWp and 4.8 kWp. This distribution was caused by the power rating of available inverters.
Since good data are available a Swiss residential system is included in this evaluation (Rasmussen Jet al. 1999).

2.2 Large PV Plants

Other sources of statistically meaningful data are large plants with thousands of modules. A survey was conducted asking owners of large plants, e.g. RWE Energie, Solarwasserstoff Bayern, ENEL, to share their operational experience of faults and failures affecting the electrical circuits. 13 reports were evaluated including some on large plants as Kobern-Gondorf (Germany), Neurather See (Germany), Neunburg vorm Wald (Germany), Toledo (Spain), Serre (Italy), Vulcano (Italy) (Laukamp H. et al., 1999).
Data from the large plants allow to assess the behavior of different types of modules, whereas data from the »1000-Roofs-Programme« allow to evaluate besides the components also the installation practice.

3. PLANNING AND DESIGN FLAWS

Reliability begins before the first hardware is installed. A good planning and design can boost the system performance as well as poor components can compromise it. This is illustrated by »specific yield« data from the »1000-Roofs-Programme«.

3.1 Low yield analysis in the »1000-Roofs-Programme«

Looking at the annual yield of the systems shows an astonishing broad distribution (figure 1). This cannot be explained by the slightly uneven irradiation over Germany.
To understand the phenomenon a special investigation was conducted. A significant fraction of the poor performance was caused by prolonged inverter failures. Accounting for these systems still left some 100 systems with too low yield. Nearly all were inspected and 17 were analyzed in detail (Hoffmann V.U. et al., 1998, Erge Th., et al., 1998).

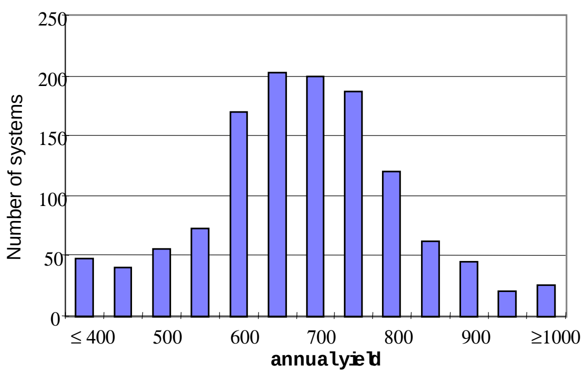

Fig. 1: Distribution of annual specific yield in 1996 (data from 1243 PV systems).

Four main reasons for poor performance were identified:

- inverter failures
- real power of a module below its name plate power
- partial shading of the generator by trees, other buildings and protruding building parts
- defects in the dc installation causing interrupted strings

The inverter failures were mostly attributed to an immature state-of-the-art. The other effects were assessed with respect to their energy yield (table I).

Table I: annual energy losses for 17 low yield systems

fault type	peak loss in %	average loss in %
module over rating	>20	ca. 10
partial shading by nearby trees	25	ca. 10
string interruptions	>20	15

The determination of generator power at STC frequently revealed power deficits of 10 to 20 % compared with the datasheet values given by the module manufacturers. Nominal STC power was reached only by two module manufacturers: Siemens and GPV (Hoffmann et al., 1998).
After some five years of operation inspections of selected systems were carried out by TÜV Rheinland, Forschungszentrum Rossendorf and IST. 200 PV systems were inspected by the end of 1997. Table II shows, which design flaws were noted.

Table II: PV system defects and deficiencies found by inspections of 200 »1000-Roofs-Programme« systems

planning and design problems	systems affected
(partial) shading of the solar generator	41 %
unsuitable string fuses and overvoltage protection devices	15 %
unsuitable isolation switches between PV array and inverter	56 %

To be fair it must be noted that the system installer runs a business and wants to satisfy his client, even if the site is not optimally suited. Homeowners sometimes order a PV system regardless of shading problems.
Rasmussen et al. (1999) report an interesting interaction of degradation, poor component specification and system design. An eleven years old system consists of strings of six modules ARCO M55 in series was retrofitted with a new inverter. The modules are degraded with reduced Voc (fig. 2).

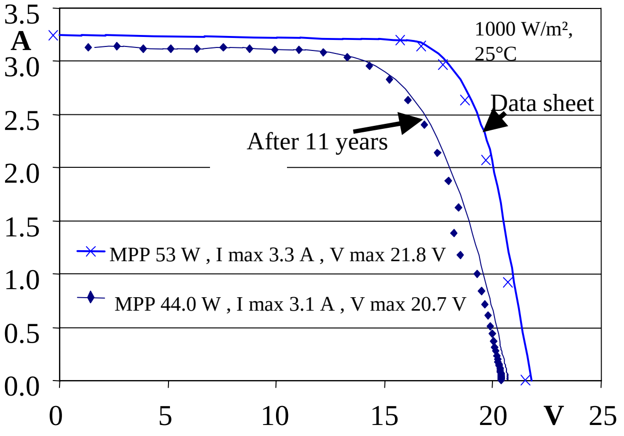

Fig. 2: I-V curve of a degraded module after 11 years.

When the system was started with the new inverter a power drop at higher irradiance levels was noted. The analysis revealed that the inverter did not reach its specified minimum input voltage of 72 V but limited the input voltage at 85 V. Thus, the inverter was not able to track the MPP under the conditions of elevated module temperature and degraded Voc. System designers should allow for plenty of margin to account for such combined effects.

3.2 Hot-Spots in large area modules

Bypass diodes for hot-spot protection of large area modules are sometimes left out. Protection from hot-spots is seeked by using several parallel cell strings within a module (Laukamp H. et al. 1994). This approach does not protect the modules, if regular partial shading from nearby objects occurs. A field experiment using the shadow of an open window demonstrated the occurrence of hot-spots (Laukamp H. et al. 1998). Neighboring modules that are shaded from a street lamp show cell and glass damage.

4. INSTALLATION FAULTS

Many installation faults of different severity were found in the plant inspections. Table IV gives an overview on the type of defect and the relative occurrence.

Table IV: PV system defects and deficiencies found at inspections

installation faults	fraction of inspected »1000 roofs« systems affected
solar generator cabling not mechanically fastened	24 %
lack of heat dissipation of string diodes	60 %
loose terminal connections	5 %
unsealed cable entry from top of j-box	-
broken printed circuit boards (PCB) in j-box	-

Among the rather few module failures the predominant location of faults were the module connection boxes (j-box).

To correctly appreciate the damage one has to note that in a very large PV plant out of 40 000 within a two years some 40 j-boxes were affected. Of these some 20 cases of disconnected soldered connections occurred and 12 j-boxes were damaged by arcs. However, in all cases the arc was contained in the J-box and did not cause outside damage (Laukamp et al. 1999). From the »1000 Roofs« inspection no arc incident caused by a faulty connection was reported. We assume that this can be explained by the rather low system voltages - 50 V ... 160 V - used throughout this program.

Loose or broken connections seem to be caused mostly by poor workmanship during installation. However, thermal cycling, which works the screwed connections loose with time, can also cause these defects. In a few cases broken PCBs in J-boxes were reported, which caused arcing across the fissures. Possibly, the cracks were cause by too much torque or pressure. Depending on the circumstances, mainly the operating voltage, these faults can lead to an electric arc and subsequent destruction of the module junction box.

5. OPERATIONAL EFFECTS

During operation some corrosion of contacts in j-boxes was noted. This leads occasionally to a high impedance contact and interruption of the respective string. This corrosion can be attributed to water leaking into the j-box or by accumulation of condensing moisture (Laukamp et al. 1999). Therefore, water drainage at the bottom of the j-box is recommended. Table V gives an overview which operational faults and disturbances were found.

Table V: PV system defects and deficiencies found by inspections of 200 »1000-Roofs-Programme« systems

problems during operation	**fraction of inspected »1000 roofs« systems affected**
moderate to strong soiling of the solar modules	12 %
corrosion and defects in the solar generator mounting	19 %
corroded plug/receptacle connectors	1 %
defect string diodes	< 2 %
defect string fuses	4 %
defect overvoltage protection devices	< 1 %
faulty modules (broken glass, open circuits, discoloration)	< 2 %

Soiling affected some 10 % of the »1000-Roofs « systems. The average effect on energy production is < 2 %. However, PV modules of less than 30 ° inclination and high horizontal cover profiles were found to loose 2-6 % of power. The worst soiled string gained 18 % more power by cleaning.

6. SIMPLER SYSTEM DESIGN IMPROVES RELIABILITY

As shown before poor contacts, wrong fuses, failing string diodes reduce the energy produced by PV systems. Omitting these components would benefit the overall system reliability. But are not fuses and string diodes necessary to protect the generator and its surroundings?
Not necessarily. Under certain conditions diodes and fuses may be omitted (fig. 3). This had been first appreciated in a german draft standard (Laukamp and Bopp, 1996). Currently an IEC (International Electrotechnical Commission) standard is under development using the same approach (IEC, 1999).

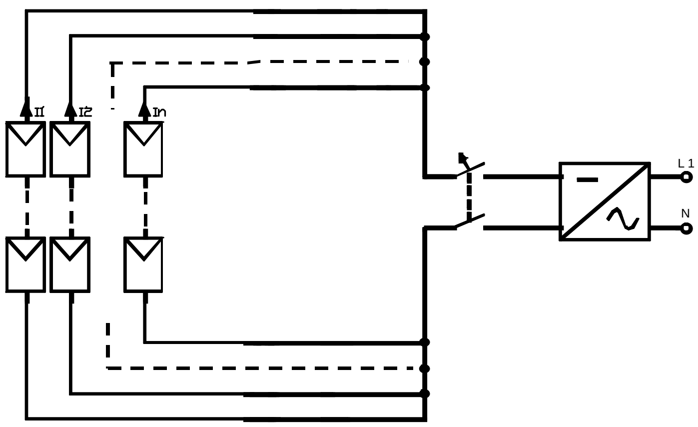

Fig. 3: Simple system design using class II equipment and double insulated wires with improved temperature rating

String diodes and fuses are not necessary, if the wires and the modules can carry the worst case fault current. The worst case current can be assumed to be 1.2 * the short circuit current at STC of the whole PV generator. Critical is the temperature dependence of the cable used (fig. 4).
There are new cables on the market with increased temperature resistance. These offer a huge advantage with respect to permissible currents at elevated temperatures. Whereas regular cables rated up to 60 °C may not at all be used in a heat-insulated facade, modern cables offer a current capacity of several 10 A. (fig 4.). The »Radox 125« is just an example, other cables with similar properties are available from other manufacturers.

In smaller systems with up to 6 parallel strings of standard modules (In ca. 3 A), a wire of 2.5 mm² cross section and extended temperature rating (> 80°C) is sufficient, as it can carry all the generator short-circuit current.

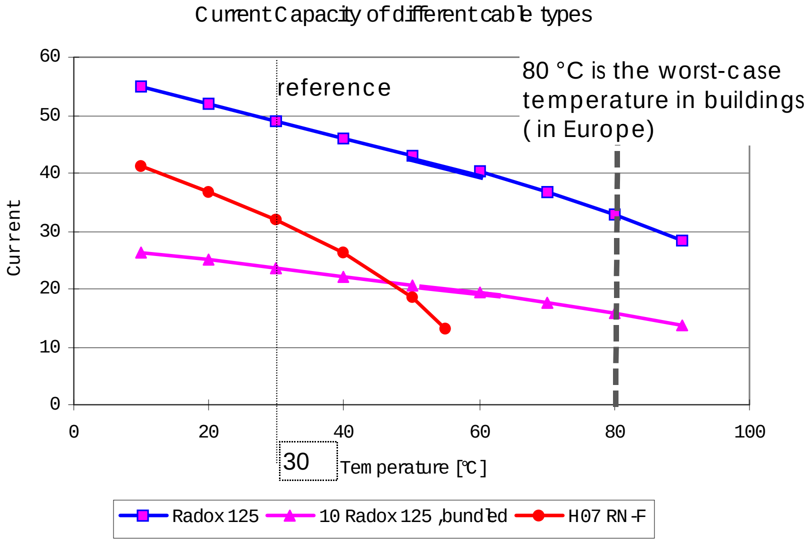

Fig. 4: Current capacity versus ambient temperature for single wires of different cable types and 10 wires of the Radox 125 type laid close together (bundling). Data were taken from DIN VDE 0298 Teil 4 and manufacturers data. For Radox 125 values below 30 °C were extrapolated. 30 °C is a standard reference temperature.

Systems with a higher number of strings, or high-current modules, should employ fuses for individual strings or groups of strings. This is a precaution against long-term degradation, the draft standard does not require it.
The exact number of strings that can be connected in parallel without protection by fuses depends on the used cable type, its cross section, the prospective maximum ambient temperature, and the spatial arrangement, as bundling of cables might cause mutual heating of wires.
If the PV modules, all connection boxes and other equipment in the dc circuit and the inverter are rated Class II and if double insulated wires of high insulation rating are used than no additional overload protection is required. This method of wiring used to be called ″earth fault- and short circuit proof “.

7. CONCLUSION

PV modules have reached a high quality standard today. Standard modules have matured over the last 20 years and show failure rates below 0.1 % per year. However, there are some brands which exhibit less than stated STC power. Critical are all new electronic components, e.g. special safety interfaces or AC/DC RCDs, which need some field experience before they work reliable.
Class II modules offer the system designers more liberty when determining the protective measure of their system. Using proper installation techniques string diodes and string fuses can be left out, which results in a simpler and more reliable system.

Based on the reported experience following recommendations can be given:

- use Class II installation equipment
- use spring loaded „cage clamp“ terminals for all field connections
- always introduce cable from the bottom side
- provide drainage opening for condensation water
- use strain relief at wire entries, e.g. by cable glands

- allow for reduced string voltage due to degradation and elevated module temperature and inverter input voltage tolerances when choosing the array voltage and the inverter

8. ACKNOWLEDGEMENT

The investigation reported here had been supported by the European Commission under the JOULE Programme and by the German Federal Ministry BMBF.

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