RELIABILITY TESTING OF GRID CONNECTED PV INVERTERS

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ABSTRACT: Large numbers of grid-connected PV systems are being installed throughout the world. In a PV system where PV modules have expected lifetimes of up to 20 years it is desirable that the other system components have a comparable expected lifetime, or at least a predictable lifetime. The PV inverter is a key component with regard to reliability and lifetime. Procedures to test PV inverters for reliability are discussed in the paper and results from tests in the laboratory and the field are presented.

Keywords: Grid-connected – 1 : Reliability – 2 : Inverters – 3

1 INTRODUCTION

Concerning PV modules a vast body of data and experience has been built up in the past years and is available to the PV community. This has resulted in an internationally accepted standardisation of test procedures for PV modules. In these tests, e.g. IEC1215, the electrical, thermal and optical properties of modules are determined and experience has shown that these tests can give an indication of the expected lifetime.

With the growth of the annually installed volume of grid-connected PV systems there is a concern for the reliability of the Balance-of-Systems components, especially the PV inverter as a key component. As the financial investment is relatively large, the consumer understandably prefers to purchase a PV system where the components have comparable expected lifetimes. At this moment no international norms for design qualification or type approval of inverters exist. At national levels various requirements on various aspects have to be met by inverters. For the Dutch normalisation institute the Netherlands Energy Research Foundation ECN has developed a guideline for the design qualification and type approval for PV inverters, [1].

The types of PV inverters and the circumstances for which they are designed to operate vary widely. For small PV systems (< 10 kWp) until recently inverters were mainly housed indoors under mild temperature and humidity conditions. The development of AC modules, where the small inverter is coupled directly to a single PV module and mounted on the rear side, introduces new operating conditions. At the back of a roof-integrated PV system the temperatures range from well below zero Celsius up to 80 °C, with the entire range of humidity conditions. Under these conditions the electronics must be ready to operate for a period comparable to the expected lifetime of the PV module.

String inverters and the larger PV array inverters are available in special versions developed for housing in outdoor conditions.

The Netherlands Energy Research Foundation ECN is involved in various projects on the subject of reliability of inverters and on the monitoring of PV systems. In the first project two types of AC inverters have been subjected to outdoor tests and tests in climate chambers. In the second project extensive testing was performed on small inverters (i.e. power less than 300 W) in climate chambers and outdoors. A third relevant project is a noise barrier with 2160 AC modules in the Netherlands, where ECN is in charge of the monitoring of the PV system. The results are discussed in this paper.

2 Life-time testing of AC modules

2.1 Outdoor tests

As part of a research project two AC module inverters have been extensively tested. In order to determine the temperature variations under real conditions six AC modules have been placed in the outdoor test facility on a south oriented tilted roof. Three types of constructions were used: two AC modules mounted above the tiles, two AC modules with an isolated box at the rear side of the modules and two AC modules having a box with limited ventilation through the box. Temperatures of the ambient air and of the housing of the inverters were recorded for several months in the summer, see figure 1.

The housing temperature of the inverter can be described by the linear relation

$$\Delta T = k \times G_i + T_0$$

with ΔT the temperature rise of the inverter temperature in relation the temperature of the ambient, G_i is the incident irradiance and T_0 is a temperature offset. k is the temperature coefficient of the inverter, it is determined by the thermal properties of the inverter, those of the PV module and the prevailing meteorological conditions.

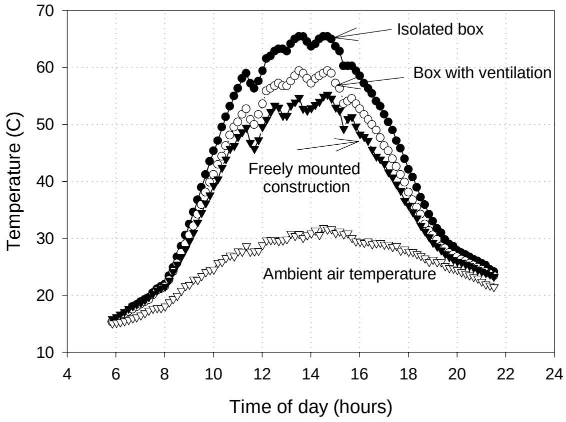

Figure 1 - Temperature distribution of ambient air and inverter housings in the three types of roof construction, as a function of time during a summer's day

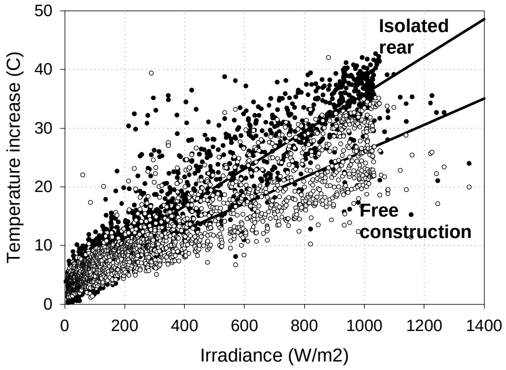

Figure 2 - Temperature increase as a function of the irradiance during a summer's month.

The k values for an inverter attached directly to the rear side of the PV module varied from 0.024 (°C/(W/m^2)), for freely mounted constructions, to 0.035 (°C/(W/m^2)) for constructions with an isolated rear side, see figure 2.

Limited ventilation shows k values close to those of the freely mounted construction 0.025 (°C/(W/m^2)). These k values for inverter housing temperatures were little above corresponding k values for the PV modules. It should be noted however, that k values show an average thermal behaviour. Under conditions of absence of wind, for example, the inverter/module temperatures can be 15 °C above the values predicted by the linear relation shown above, as shown in figure 2. The k values are used to compare ageing in accelerated lifetime tests to expected ageing under outdoor conditions.

Figure 3 shows the temperature distribution for a typical Dutch year for the ambient air and the inverter (for a specific k value of 0.035 (°C/(W/m^2)); the number of hours for a bin of 3 °C wide are shown. The inverter temperature is modelled to be higher than the ambient air temperature in proportion to the specific k value. As high temperatures correlate often with high irradiance, the inverter temperature distribution has a tail toward higher temperatures up to 70 °C.

At elevated temperatures the ageing takes place at a faster rate. For electronic components the influence of the temperature can be described by the Arrhenius rule, for the activation energy the value of 0.6 eV is taken. If we chose the temperature of 21 °C as a reference point, figure 3 also shows the effective ageing for the inverter. For this case the total number of hours of effective ageing is equal to 365x24=8760. Therefore we define 21 °C as the annual mean effective ageing temperature for continuous operation of the inverter.

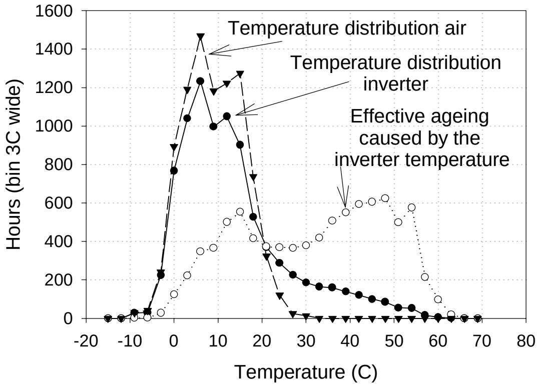

Figure 3 - Temperature distribution of the hour-average annual temperatures, for air and the inverters (for K=0.035) and ageing described by an activation energy of 0.6 eV

Temperatures of specific components in the interior of the inverters can be substantially different from the housing temperatures. Inverters, which are not directly attached to the rear surface of the module, will have lower k values than those discussed here. So, the results should be interpreted with care. The general conclusion is the inverter housing temperature can go up to 80 °C on sunny days, with even higher temperatures in the interior. Ventilation is very effective in lowering the average temperatures.

2.2 Tests in the climate chamber

In the high-temperature-test eight inverters of both types are connected to an IV simulator and delivered energy to the grid at a DC power between 70 and 90 W inside a climate chamber providing an ambient temperature of 70 °C. The power levels and the ambient temperature were chosen such that the temperatures in the interior of the inverter reached the allowed maximum temperature. Before and after these tests extensive electrical characterisation of the inverters took place. One of the most conspicuous components of the inverter is the relatively large electrolytic capacitor at the DC side of the inverter. For a single-phase inverter this capacitor is needed for energy storage and retrieval during the 50 Hz cycle. A large capacitance is beneficial for an optimal maximum power point tracking mechanism. Ageing of electrolytic capacitors can easily be quantified by measuring the Effective Series Resistance ESR of the capacitor. During the 2000 hours of testing increases of the ESR values up to 50% have been observed. The effect of this ageing on the electrical properties, such as inverter efficiency, is negligible. Continuation of these tests showed further increase of the ESR without any detectable deterioration of the inverter properties.

Ageing during 2000 hours of electrolytic capacitors under these conditions in a climate chamber can be compared to ageing that would occur under realistic outdoor conditions during 15 years. The acceleration is calculated on basis of the above defined effective ageing temperature of 21 °C. Although the capacitor is by no means the only inverter component to undergo significant ageing, it is generally thought to be a critical part with to the lifetime of the inverter. The fact that none of the sixteen inverters became defect shows that there is basis for confidence in the concept of an AC module inverter.

Besides through the choice of optimal electrical components the lifetime expectations of a PV inverter is determined by the reliability considerations concerning the design. Hot spots inside the inverter should be avoided by good thermal design, critical components such as the electrolytic capacitor should be positioned at a cool spot. Tests showed that the inverter should be thermally isolated as much as possible from the module surface. As the irradiance will heat the module surface to temperatures 40°C above the ambient temperature, it is preferable to provide a heat sink at a lower temperature, e.g. the module frame or the ambient air at the rear side.

For ageing of inverters, such as AC module inverters, tests developed for PV modules during which the ambient temperature and possibly the humidity is cycled from temperatures below freezing up to 85 °C have limited relevance. For PV modules these variations having ramp rates up to 200 °C per hour may test significant properties, for PV inverter it is hardly conceivable that rates like these will occur in the inverter ambient under outdoor conditions and inverters may not be designed for these circumstances. Although the inverter must be capable to operate in the entire module temperature range the rate of change in temperatures must be adapted to realistic levels, with maximum rates of e.g. 50 °C per hour. As the reliability is meant here to be measured by the period during which the inverter is operating according to its specifications, these cycling tests have more to do with the performance of the inverter than with the expected lifetime.

In a second research project on inverter reliability two further types of inverters for AC modules were tested. Several tests were carried out.

Environmental stress tests of both inverters were carried out in a climate chamber, where the inverters were submitted to a high-temperature-long-exposure test, a high-temperature-high-humidity-long-exposure test, a temperature-cycling test and a humidity-freezing test. Before during and after the tests the inverter efficiency and the electrolytic capacitors were monitored.

The first inverter passed all tests. After the two high-temperature tests two inverters failed out of eleven inverters. One inverter failed after 3720 hours and one after 6540 hours. Seven of the nine inverters, who were still operating, were tested for 6540 hours and the remaining two inverters were tested for 3910 hours. The electrolytic capacitors show an increase of ESR by a factor 4½, a decrease in capacitance by 5% while the efficiency remained stable over the 6540 hours of test time. The second inverter appeared not to be suitable for accelerated lifetime tests at increased operating temperatures. As long as the inverters were operating within specs no problems were encountered. Tests show that several protection mechanisms inhibit the inverter to operate beyond temperature limits given in the inverter's specification. Therefore no test results are available. Both inverters passed the temperature cycling test and the humidity freezing test with good results. No failures occurred during these tests.

3 FIELD EXPERIENCES

A large photovoltaic system consisting of almost 2200 AC modules has been integrated into a one-mile long noise barrier along a highway in The Netherlands [2],[3]. One of the aims of introducing AC modules to this project was to obtain statistically relevant numbers of inverters for making estimates of the reliability of the concept of AC modules. AC module inverters by two different manufacturers were installed, with a respective share of 80/20% for the total number of AC inverters.

The system has been in operation about eighteen months (April 2000). The central monitoring PC daily contacts one out of every six AC module inverters, a total of 360 inverters. The energy yield as indicated by their internal kWh-counter is stored in the PC database. During the 18-months monitoring period the PC detected 11 inverters of one of the manufacturers which indicated no further increase of their kWh counters. This can indicate defect inverters, but it cannot be ruled out that defects occur in the monitoring prints of the inverter. The possibility of eleven defect inverters out of 360 in 18 months can therefore be considered a worst case situation. Assuming a similar and constant failure rate during the lifetime of an inverter would result in an expected mean-time-to-failure of around 20 years. For the inverter of the second manufacturer the kWh counters indicate that none of the 60 inverters failed during this period.

4 CONCLUSIONS

Inverters, especially inverters at the back of PV modules and those mounted outdoors, have to operate under harsh conditions for long periods of time. Field experiences and accelerated lifetime testing have shown that the electronics can be designed and manufactured in a way that reliable operation can be guaranteed for a period comparable to the expected lifetime of the PV module. Manufacturers are clearly learning from experiences and the reliability of modern inverters is steadily improving, [4].

Besides failing through ageing, inverters can fail for a great variety of reasons, e.g. problems linked to EMI, faulty installation, or 'infant mortality', which tends to disappear with ongoing improvements of the design and manufacturing processes. These causes of failure should be identified as soon as possible in order to be able to show the customers that PV inverters can be trusted to convert the solar energy to grid-power for as long as the PV module lasts.

5 ACKNOWLEDGEMENTS

Part of this work has been funded by the Netherlands Agency for Energy and the Environment Novem under contract 146.200-109.2.

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