Power losses in PV arrays due to variations in the I-V characteristics of PV modules

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Abstract—It is well known that variations in the I-V characteristics of photovoltaic modules can lead to power losses when the modules are connected in parallel or in series. The main task of this work was to get a general view of the mismatch losses under non-standard conditions. I-V characteristics of the 36 individual modules of a PV generator at the University of Oldenburg were measured and recorded. The parameter of the two diode model were determined for each module. The measurements were the basis for the calculations of the mismatch losses due to series and parallel connection of PV modules. The calculations for a PV string (20 modules in series) pointed out that the losses are less than 4.5%. The results for a 5.3 kW_p PV array have shown that the losses vary between 1.3% and 1.9%. The losses due to parallel connection are negligible.

1 Introduction

Variations in the I-V characteristics due to manufacturing process can lead to significant power losses in a PV array. There is some work dealing with these mismatch losses, but most of them only examine the losses under Standard Test Conditions (STC -irradiance: 1000 W/m^2, AM 1.5 spectrum; module temperature: 25 °C) [1,2,6]. The results of these studies show that the losses are less than 9%. There is a lack of work dealing with the losses under non-standard conditions. The results of Janoch [5] show that the mismatch losses decrease with increasing irradiance.

This paper shall point out the measurements, the calculation of the parameters of the two diode model and the calculation of the mismatch losses under non-standard conditions.

2 Measurement of the variations in the I-V characteristics of PV modules

The explored 1.9 kW_p PV generator at the University of Oldenburg is composed of 36 single crystalline PV modules with a MPP power of 53 W under Standard Test Conditions. The field is divided into two parallel strings each of 18 modules connected in series.

Portable measuring equipment was used to record the I-V characteristics for each of the 36 individual modules. Simultaneously the parameters irradiance and module temperature were measured and recorded. This was done for instantaneous value and one minute averages.

The irradiance was measured with an photovoltaic sensor (ESTI) and a thermal pyranometer (Kipp and Zonen). Pt-100 and IR sensors were used to record the module temperature. Since measurements have to be carried out under steady state, they were done under clear sky conditions. For each module an ensemble of I-V characteristics was recorded for irradiance values between 600 W/m^2 and 1000 W/m^2. The time required to record an I-V characteristic of a PV module was less than 20 ms, so that variations of the external parameters irradiance and module temperature could be neglected during the measurements.

For the second step a computer program—developed at the University of Oldenburg—was used to fit the parameters of the two diode model to the measured I-V characteristic [3]. The two diode model describes quantitatively the I-V characteristic of a PV module. With the individual parameter set and the utilization of the standard test conditions the standard I-V characteristic can be determined for each module. The results for one module are shown in figure 2.1. The results of the measurements point out that the variations in the I-V characteristics of PV modules due to manufacturing process can be measured and determined.
The distribution of the MPP power of the 36 modules (figure 2.2) leads to an average value of 52.6 W and a standard deviation of 0.53 W. Only one module has merely a MPP power of 47.9 W (-8.9%). According to the manufacturers data specification the MPP power is 53 W.

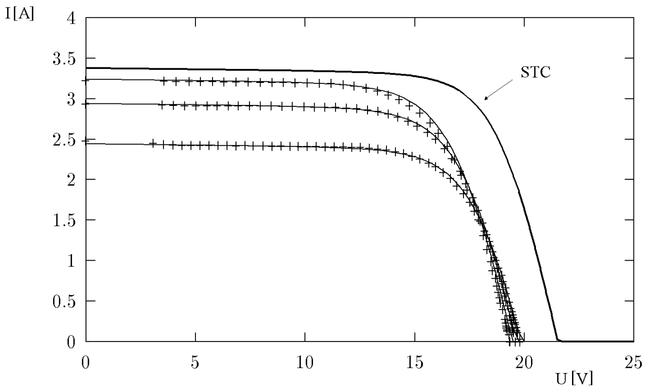


Fig. 2.1. *Measured I-V characteristic (+), results of the parameter fit for the two diode model (-) and the calculated I-V characteristic under STC derived from the parameter fits.*

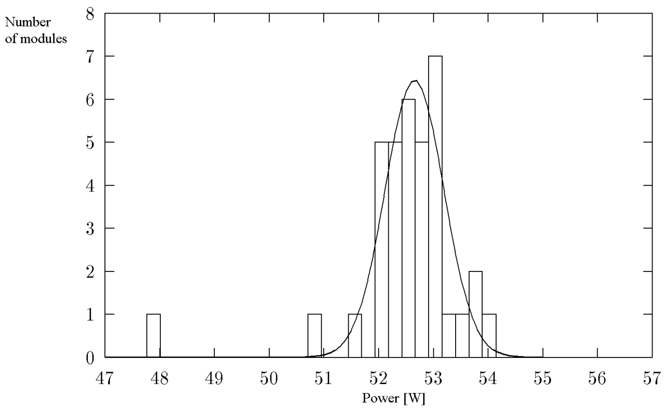


Fig. 2.2 *MPP power distribution of the 36 individual modules under Standard Test Conditions.*

3 Simulation of mismatch losses in PV arrays due to series and parallel connection of PV modules

The next step was to calculate the mismatch losses due to variations in the I-V characteristics of PV modules for different generator configurations. These calculations have been performed using the computer program INSEL [4], which is a block orientated simulation system developed at the University of Oldenburg. For the calculations eight of the 36 individual parameter sets were chosen. They represent the following power classes under STC:

Class	1	2	3	4	5	6	7	8
$P_{MPP,STC}$ [W]	47.9	51.6	52.6	52.3	53.1	53.7	53.0	54.0

Because the mismatch losses should be determined under non-standard conditions, meteorological data from Bremerhaven, Germany (Test Reference Year) and from Albuquerque/New Mexico, USA have been used for time series simulation.

3.1 Mismatch losses due to series connection

First the mismatch losses due to variations in the I-V characteristics of PV modules have been determined for a PV string consisting of 20 modules connected in series. Afterwards calculations were carried out for a PV array consisting of 5 parallel strings each having 20 modules connected in series. In both cases a PV generator with modules of identical I-V characteristics—identical parameter of the two diode model—has been used as a reference for the determination of the mismatch losses. In this case the difference between the annual energy output of any generator configuration and the reference is defined as mismatch loss.

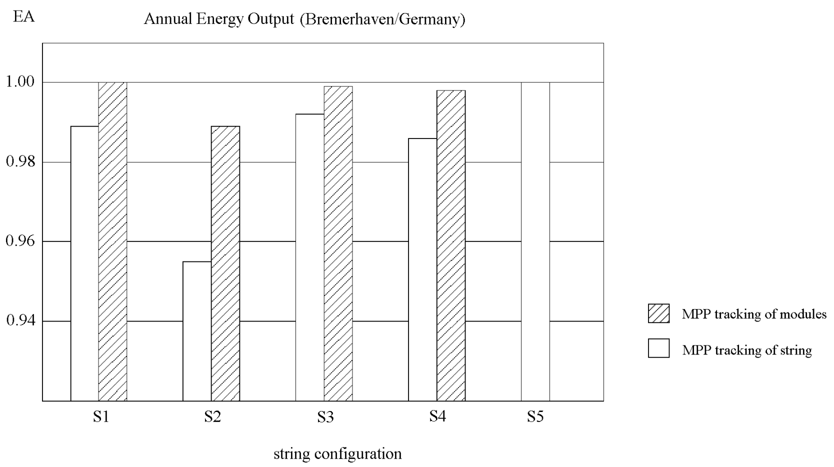
For the following five PV string configurations the annual energy output was calculated:

- S1: The classes 2-8 have nearly the same probability (class 2-7 three times, class 8 two times).
- S2: Similar to configuration S1: One module of class 8 was replaced by a module of class 1.
- S3: The distribution of the power classes follows approximately a gaussian distribution according to figure 2.2 (average value 52.6 W, standard deviation 0.53 W).
- S4: The distribution of the power classes follows a gaussian distribution including the module with a power of 47.9 W (average value 52.5 W, standard deviation 0.96 W).
- S5: The string consists of PV modules with identical I-V characteristics (20 modules of class 3). This configuration serves as the reference.

The results of the calculations are shown in figure 3.1. The annual energy output of the reference string (Configuration S5) serves as the reference and is normalized to one. The hatched bars show the sum of the annual energy output (EA) of the individual modules ($EA_{string} = \sum_{n=1}^{20} EA_{module,n}$). The open bars carry out the annual energy output of the string.

Class	1	2	3	4	5	6	7	8
Confg. S1	0	3	3	3	3	3	3	2
Confg. S2	1	3	3	3	3	3	3	1
Confg. S3	0	1	5	5	4	1	4	0
Confg. S4	0	2	4	4	3	2	3	2
Confg. S5	0	0	20	0	0	0	0	0

Table 3.1 Number of modules for the different string configurations.



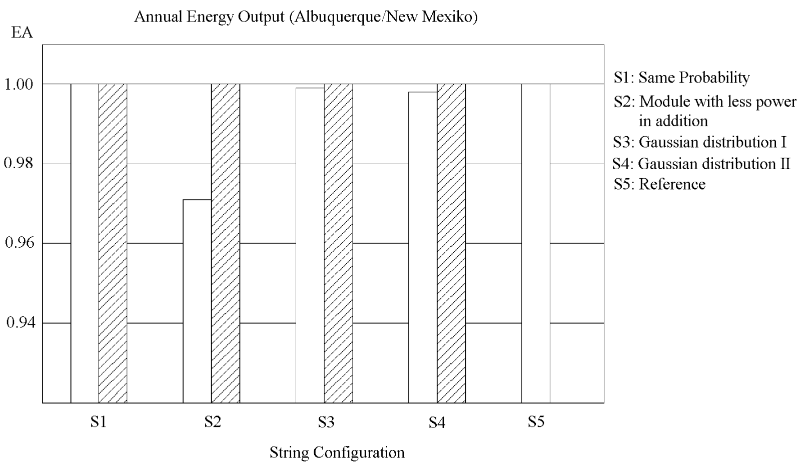


Fig. 3.1 *Results of the calculations of the mismatch losses for different string configurations. The reference string consists of 20 modules with identical I-V characteristics.*

The calculations for Bremerhaven carried out that the mismatch losses vary between 0.8% and 1.4% if no module of class one is included in the string. For configuration S1, where the classes 2-7 are connected three times and class 8 two times, the mismatch losses were calculated to 1.1%. The first gaussian distribution (configuration

3) leads to mismatch losses about 0.8%. The second gaussian distribution, which has a higher standard deviation (0.96 W) as in configuration 4 results in mismatch losses of 1.4%. The connection of a module, whose MPP power deviates -8.9% from the average value (Class 1), has a distinct influence on the mismatch losses. This was realized in configuration 2 and mismatch losses in the range of 4.5% were calculated.

For Albuquerque/New Mexico the mismatch losses are lower. The losses for configuration 1 are negligible, for the first gaussian distribution (configuration 3) they are 0.1% and for the second gaussian distribution (configuration 4) 0.2%. As for the calculations for Bremerhaven, the connection of a PV module of class 1 leads to significant power losses of 2.9%.

The lower losses for Albuquerque can be explained with figure 3.2 and figure 3.3. Figure 3.2 shows that the MPP power deviation from the reference decreases with increasing irradiance for any string configuration. The module temperature in this case was assumed as constant (25 °C). Figure 3.3 shows the distribution of the hourly irradiation values for the data used.

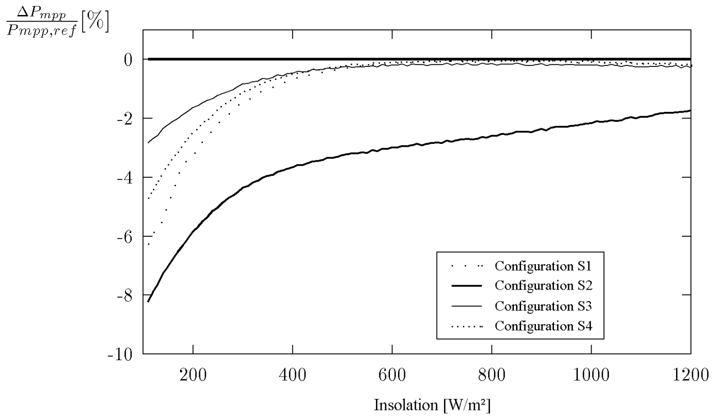


Fig. 3.2. *Relative power loss depending on the irradiance for the various string configurations exemplary for a module temperature of 25 °C. The reference is a PV string consisting of 20 modules with identical I-V characteristics.*

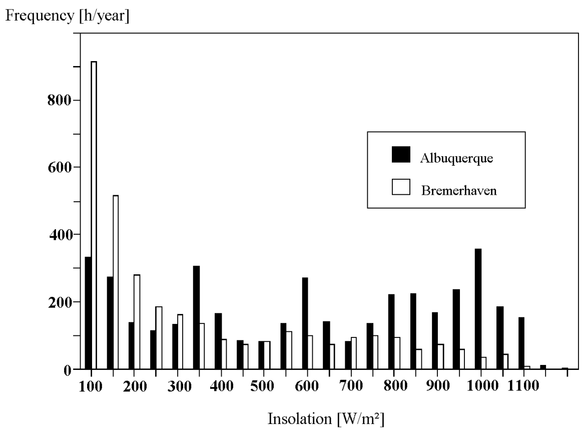


Fig. 3.3. *Frequency distribution of hourly irradiation values for the data sets used.*

3.2 Mismatch losses in a PV array

To get information about the mismatch losses due to parallel connection the PV generator was extended to 5.3 kW$_p$. It consists of 5 parallel strings each with 20 modules in series.
For these calculations it was assumed that the distribution of the MPP power of the individual modules follows the first gaussian distribution shown in figure 2.2.

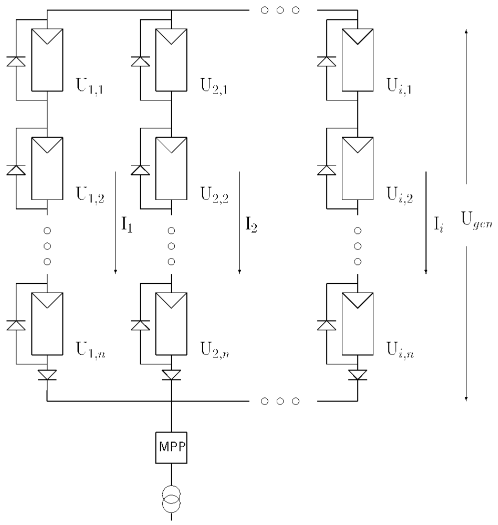


Fig. 3.4. *PV array used for the calculations.*

In addition two modules of class 1 were included in the array. Calculations were made for the following configurations:

A1: The MPP voltage of each string is, before connecting the whole array, under STC nearly identical.
A2: The modules are sorted with respect to the MPP power. Modules with the lowest MPP power are sorted in the first string, modules with a higher MPP power in the second string and etc. $P_{String1}^{MPP,STC} < P_{String2}^{MPP,STC} < \dots P_{String5}^{MPP,STC}$
A3: The modules were distributed by chance.
A4: Only one kind of module (power class 3) is used in the array. This configuration serves as the reference.

Figure 3.5 shows the results of the calculations for Bremerhaven (above) and Albuquerque (below). A PV array consisting of 100 modules with identical I-V characteristic serves as the reference and its annual energy output is normalized to one. The difference between the annual energy output of any generator configuration and the reference is defined as mismatch loss. The black bar gives the annual energy output of the whole generator, the white ones the sum of the annual energy output of the individual strings and the hatched ones represent the sum of the energy output of the modules.

If the MPP voltage deviation of the strings—before connecting in the array—is less than 0.2% under STC (Configuration A1 and A2) the mismatch losses in the case of Bremerhaven are 1.9% respectively 1.6%. 10 distributions by chance (Configuration

A3) lead to an average value of 1.75% ±0.05%. The calculations for Albuquerque lead to an average value of 0.99% ±0.05%. The mismatch losses for the other configuration are for Albuquerque 1.2% (configuration 1) and 0.8% (configuration 2).

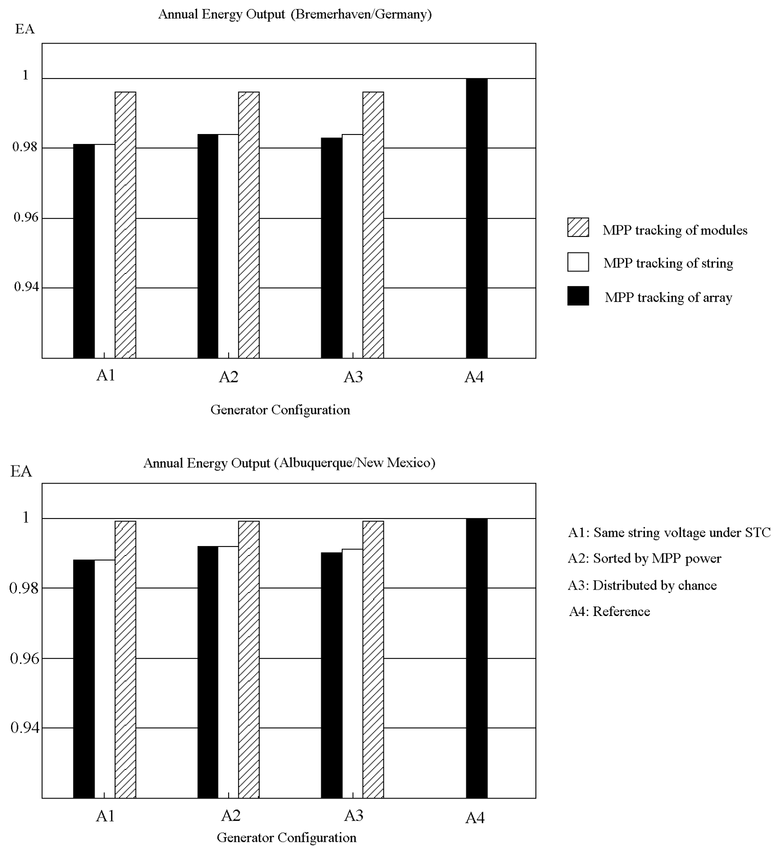


Fig. 3.5. *Results of the calculations of the mismatch losses for different generator configurations. The reference generator consists of 100 modules with identical I-V characteristics.*

The calculations show that the losses due to parallel connection are negligible. The difference between the annual energy output of the whole array (black bars) and the sum of the strings (white bars) can be considered as mismatch loss due to parallel connection.

Analogue to the calculations for a PV string consisting of 20 modules connected in series (see above), the calculations for a PV array pointed out that the power losses decrease with increasing irradiance (figure 3.6) The module temperature in this case was assumed to be constant (25 °C).

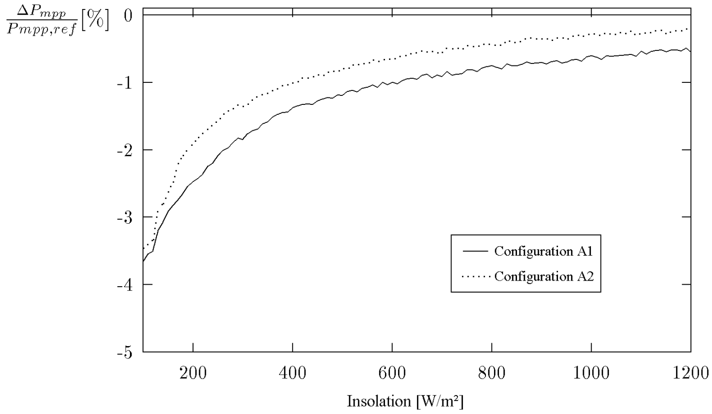


Fig. 3.6. *Power losses in a 5.3 kW$_p$ PV array for different irradiance values. The module temperature is assumed to be constant 25 °C.*

4 Conclusions

- Variations in the I-V characteristics of PV modules due to manufacturing process can be measured and determined with the developed measuring equipment.
- The parameters of the two diode model can be determined with a computer program and be used for the calculation of the mismatch-losses.
- Mismatch losses are a result of series connection of PV modules. The losses due to parallel connection can be neglected.
- Power losses in PV arrays and PV strings due to variations in the I-V characteristics of PV modules increase with decreasing irradiance.

References

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