Damages at Bypass Diodes by Induced Voltages and Currents in PV Modules Caused by Nearby Lightning Currents

H. Haeberlin
Berne University of Applied Sciences (BFH-TI), Division of Electrical- and Communication Engineering,
Laboratory for Photovoltaics, Jlcoweg 1, CH-3400 Burgdorf, Switzerland
Phone: +41 34 426 68 11, Fax: +41 34 426 68 13, e-Mail: heinrich.haeberlin@bfh.ch, Internet: www.pvtest.ch

ABSTRACT:
In 1990 – 1993 and during an EU project in 1998 – 2000, the PV laboratory of BFH-TI has carried out tests about sensitivity of PV modules against lightning currents flowing in or close to the frame of a PV module [1], [2], [3]. For these tests, impulse currents with $i_{max} \leq 120kA$ and $di/dt_{max} \leq 40kA/\mu s$ were used. It could be shown that even at moderate distances the voltages induced in a module by such lightning currents may go up to several thousand volts. Such voltages could easily destroy bypass diodes. Due to increasing cell dimensions and therefore increasing currents, more and more Schottky diodes are used as bypass diodes, which have only quite low reverse voltage ratings between 40 V and 100 V. In practical operation, such damages actually occur, but usually (and fortunately!) only at considerably higher peak induced voltages than the reverse voltage rating of the Schottky diode. First tests with such bypass diodes and simple wire loop models were performed in Dec. 2006 [4]. In this paper, this problem is analysed more thoroughly, a model to calculate a rough estimate of the voltages and currents stressing the bypass diodes is introduced and some results of practical measurements at bypass diodes in real modules are given [5].

KEYWORDS: Lightning protection, PV modules, bypass diodes, surge protection.

1. Approach to the Problem

A good approach for lightning protection is to catch the lightning current i with an air termination system (e.g. lightning capturing rods), to split it into several down conductors carrying only a fraction $i_P = k_C \cdot i$ of the whole current ($k_C < 1$) and to place the exposed installation (e.g. the PV array) in the protected area of the air termination system at a sufficient separation distance d from the conductors carrying a (partial) lightning current i_P (see fig. 1). Usually d is between about 0.3 m and 3 m or more. Very often only one conductor is relevant for the induced voltage and current in a module, therefore mainly this case must be examined [1], [5].

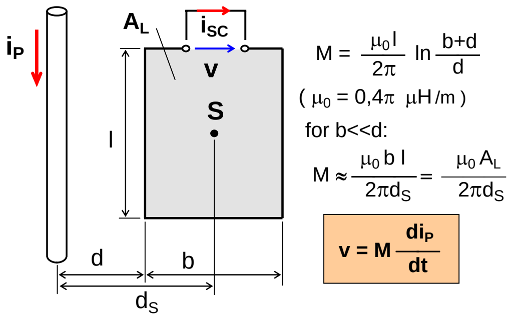

Fig. 1:
Calculation of mutual induction M between a loop (e.g. a bypass diode loop in a module) and a conductor carrying a (partial) lightning current $i_P = k_C \cdot i$ (i = full lightning current according to standards). If the module has a metallic frame, the effective value of M is further reduced by a frame reduction factor R_F [1], [5].

Depending on the mutual orientation of the bypass diode loop in the module concerned and the polarity of the lightning current, two cases must be distinguished, when considering the voltage in the front oft the lightning current (see fig. 2 and 3).

- Bypass diodes and solar cells reverse biased (and possibly in avalanche mode) during front of lightning current.
- Bypass diodes and solar cells forward biased (and conducting) during the front of the lightning current.

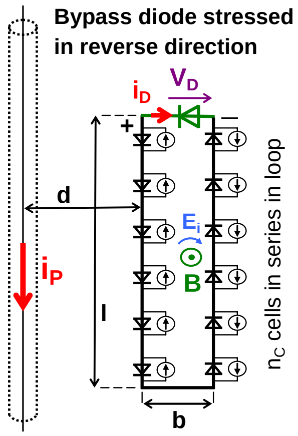

Fig. 2:
Bypass diode and solar cell diodes stressed in reverse direction in front of lightning current i_P. If the voltage is higher than the breakdown voltage, they can operate short time in avalanche mode, if the current is not too high. Due to the high inverse voltage the current decreases fast.

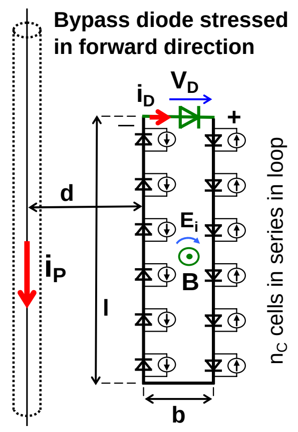

Fig. 3:
Bypass diode and solar cell diodes stressed in forward direction in front of lightning current i_P. At all diodes the forward voltage drop is rather low. If the maximum allowable impulse current is exceeded, the bypass diode is destroyed. As the inverse voltage is low, the current decreases slower.

In the reverse direction, solar cells exhibit a parallel capacity (up to a few μF at 0 V, decreasing with increasing reverse voltage) in parallel with a reverse biased diode that has a breakdown voltage between about 10 V and 30 V. Schottky diodes usually have a breakdown voltage of about 1.5 to 2 times of the rated reverse voltage and are often specified for an avalanche energy of 10 mJ to 100 mJ. As a bypass diode loop consists of about 12 – 24 cells in series, an induced voltage of up to a few hundred volts can be tolerated in such a loop before high avalanche currents are induced that destroy the bypass diode (and if they are too high even the solar cells!).

In the forward direction, the solar cells and the bypass diodes are both conducting and have a forward voltage drop in the order of about 1 V. Therefore a significant forward current can flow, which can reach a maximum value close to $(M/L_L)\cdot i_P$, where M is the Mutual inductance between the conductor carrying the (partial) lightning current i_P and the bypass diode loop and L_L is the inductance of the bypass diode loop. This current can easily reach a few 100 A to a few kA and can destroy the bypass diodes and damage the solar cells, if it is too high. In the data sheets of bypass diodes usually a peak current value I_{FSM} for a sine half wave (8.3ms or 10ms) of a few 100 A is indicated, and it can be expected that the diode can at least withstand to an induced peak current of this size.

If the module has a metallic frame, the effective value of M and therefore the induced voltage and current are reduced by a frame reduction factor R_F [1], [5], which is typically between about 2.5 and 6.

2. Calculation of induced voltage and short circuit currents in module loops

The voltage induced by a partial lightning current $i_P = k_C \cdot i$ in a loop is ($k_C \le 1$, i = full lightning current, fig. 1):

Induced voltage by partial lightning current i_P:

$$v = M\frac{di_P}{dt} = M\cdot k_C\frac{di}{dt} = M_i\frac{di}{dt} \qquad (1)$$

M_i can be called the *effective mutual inductance* between the full lightning current i and the loop considered.

Resulting mutual induction M between a loop accoriding to fig. 1 and a conductor with a partial lightning current i_P can be calculated as follows:

Mutual induction at loops not containing lightning carrying conductor:

$$M = 0{,}2\cdot l\cdot \ln\frac{b+d}{d} \qquad (2)$$

M is the mutual inductance in μH, if all distances l, b, d are indicated in meters [m].

If the loop is a bypass diode loop in a module with metallic frame, the induced voltage and therefore also the effective mutual inductance M_i is reduced. Therefore with M according to (2) it can be defined:

Mutual induction for bypass diode loops in modules:

$$M_i = \frac{k_C\cdot M}{R_F} \qquad (3)$$

R_F = frame reduction factor: R_F = 2.5 –6 for modules with metallic frame, R_F = 1 for other modules. $k_C = i_P/i \le 1$.

In order to calculate the current, also loop inductance is necessary. For the *inductance of a bypass diode loop in a conventional PV module with crystalline cells*, a good estimate can be indicated as:

Inductance of bypass diode loops in modules:

$$L_L \approx 1.2\cdot l + 0.7\cdot b + 0.05 \qquad (4)$$

L_L is the inductance of the bypass diode loop in μH, if the distances l and b are indicated in meters [m]. Typical values for L_L are between 1 μH and 3 μH [5].

Note: This formula is only valid for bypass diode loops in conventional PV modules!

With M_i and L_L the resulting short circuit current i_{SC} in a lossless bypass diode loop can be calculated:

Induced short circuit current in bypass diode loop (R_L=0):

$$i_{SC} \approx \frac{M}{L_L\cdot R_F}i_P = \frac{M}{L_L\cdot R_F}k_C\cdot i = \frac{M_i}{L_L}i \qquad (5)$$

3. Models for estimation of induced voltages and currents in module loops with bypass diodes

With two separate linear models for the reverse (fig. 4) and the forward direction (fig. 5) and the Laplace transform, it is possible to determine the currents flowing through the bypass diode and the solar cells in case of a nearby lightning stroke. They are treated more in detail in [5]. The principal correctness of these models and calculations could be demonstrated by laboratory experiments with the high impulse current generator in the high voltage laboratory of BFH-TI. Unfortunately at present the fall time of the simulated lightning currents is still much lower than that of a real lightning current according to relevant standards. Therefore, after a stress in one direction, the diode is exhibited immediately after to a (milder) stress in the other direction. Thus with the present equipment the total stress is a little higher than in reality. Currently work for upgrading the high impulse current generator is under way. Standard test impulses 100 kA/ 10 μs/350 μs should be available by the end of 2007.

Bypass diode and solar cells operating in avalanche mode

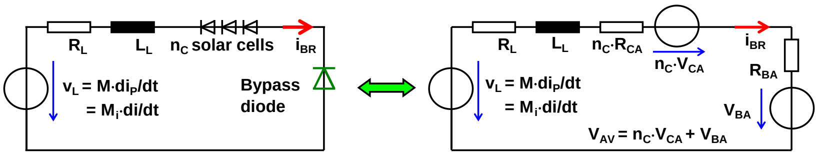

Fig. 4:
Linearised equivalent circuit diagram for an approximate calculation of the reverse current $i_D = i_{BR}$ in the bypass diode (avalanche mode), if the diode is stressed in reverse direction according to fig. 2 (at left original circuit, at right linearised form for operation in avalanche mode).

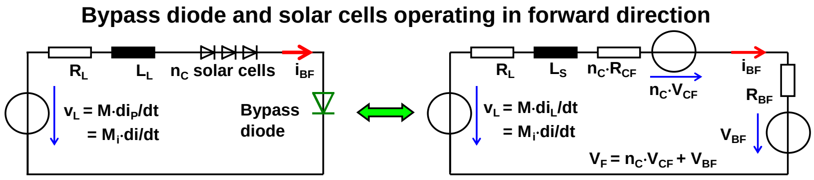

Fig. 5:
Linearised equivalent circuit diagram for an approximate calculation of the forward current $i_D = i_{BF}$ in the bypass diode, if the diode is stressed in forward direction according to fig. 3 (at left original circuit, at right linearised form). For a more precise modelling of the high current mode, a little higher forward voltage drops than usual have to be assumed.

For the lightning current i the following mathematical representation can be chosen:

$$i(t) = I\left(e^{-\sigma_1 t} - e^{-\sigma_2 t}\right) \qquad (\sigma_2 >> \sigma_1) \qquad (6)$$

Then by means of the Laplace transform it can be obtained (exact calculations see [5]):

$$i_D(t) = \frac{M_i \cdot I}{L_L}\left[\frac{\sigma_1 \cdot e^{-\sigma_1 t}}{(\sigma_1-\sigma_3)} + \frac{\sigma_2 \cdot e^{-\sigma_2 t}}{(\sigma_3-\sigma_2)} + \frac{\sigma_3 \cdot (\sigma_1-\sigma_2)\cdot e^{-\sigma_3 t}}{(\sigma_1-\sigma_3)(\sigma_2-\sigma_3)}\right] - \frac{V_{tot}(1-e^{-\sigma_3 t})}{L_L \cdot \sigma_3} \qquad (7)$$

where $V_{tot} = V_{AV}$ for fig. 4 and $V_{tot} = V_F$ for fig. 5 (sum of all constant voltages in each circuit), and

$$\sigma_3 = \frac{R_{tot}}{L_L}$$

(R_{tot} = sum of all resistors in the bypass diode loop with the inductance L_L in fig 4 or fig. 5)

As an example, a bypass diode loop with n_C = 18 solar cells and a loop inductance of L_L = 2 µH is examined. For operation in the avalanche mode, for each of the solar cells a breakdown voltage V_{CA} = 20 V and a resistor R_{CA} = 5 mΩ can be used. For the Schottky bypass diode a breakdown voltage V_{BA} = 70 V and a resistor R_{BA} = 50 mΩ can be assumed. Thus a total V_{AV} = 430 V in fig. 4 is obtained. Fig. 6 and fig. 7 show the resulting (avalanche) reverse currents i_{BR} through the bypass diode and the solar cells under a reverse voltage stress in the front of the lightning current for typical values M_i of 10 nH, 20 nH, 40 nH and 80 nH.

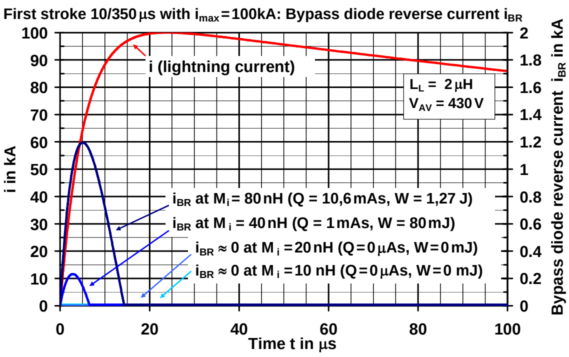

Fig. 6:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with n_C = 18 solar cells with V_{CA} = 20 V and a Schottky bypass diode with V_{BA} = 70 V at different typical values of effective mutual induction M_i, calculated for a first lightning stroke with i_{max} = 100 kA. For small M_i i_{BR} is ≈ 0.

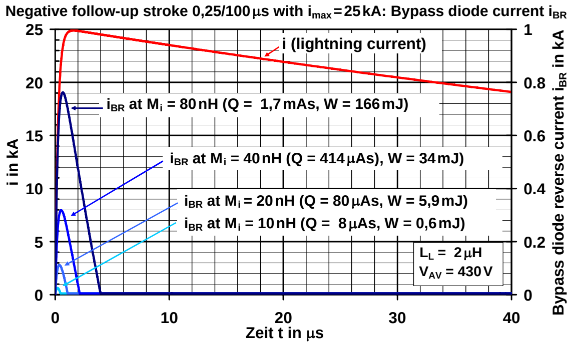

Fig. 7:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with n_C = 18 solar cells with V_{CA} = 20 V and a Schottky bypass diode with V_{BA} = 70 V at different typical values of effective mutual induction M_i calculated for a negative follow-up lightning stroke with i_{max} = 25 kA

In the same example, for operation in the forward mode, the low forward voltages of the bypass and cell diodes (values in fig. 8 and 9) result in a much lower value of V_F = 18 V (in fig. 5). With R_{CF} = 4 mΩ and R_{BF} = 3 mΩ, the resulting forward currents through the bypass diode and the solar cells for typical values M_i of 10 nH, 20 nH, 40 nH and 80 nH are obtained (see fig. 8 and fig. 9).

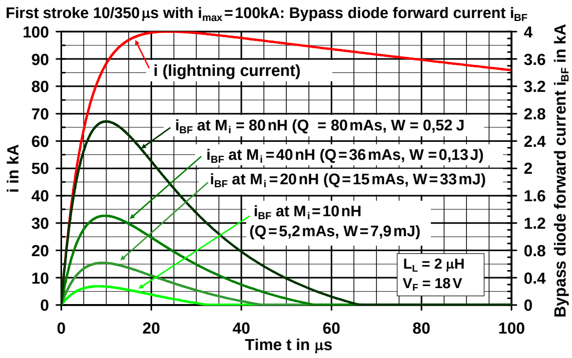

Fig. 8:
Bypass diode forward currents i_{BF} in a module loop with n_C = 18 solar cells with V_{CF} = 0.95 V and a Schottky bypass diode with V_{BF} = 0.9 V at different typical values of effective mutual induction M_i, calculated for a first lightning stroke with i_{max} = 100 kA.

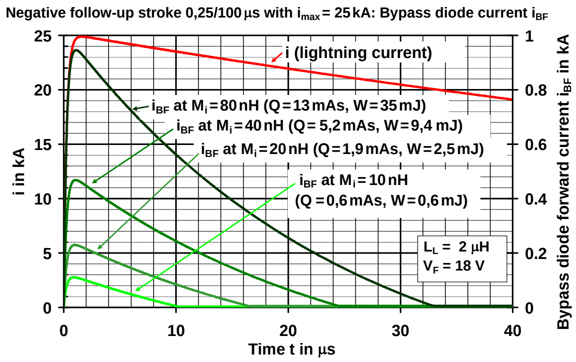

Fig. 9:
Bypass diode forward currents i_{BF} in a module loop with n_C = 18 solar cells with V_{CA} = 0.95 V and a Schottky bypass diode with V_{BF} = 0.9 V at different typical values of effective mutual induction M_i, calculated for a negative follow-up lightning stroke with i_{max} = 25 kA.

4. Results of actual measurements of induced voltages and currents in module loops with bypass diodes

Fig. 10 to fig. 13 show actual measurements with a polycrystalline module KC60 (without metal frame) and a bypass diode 80SQ45 under forward and reverse stress in the front of the lightning current carried out in the high voltage laboratory of BFH-TI.

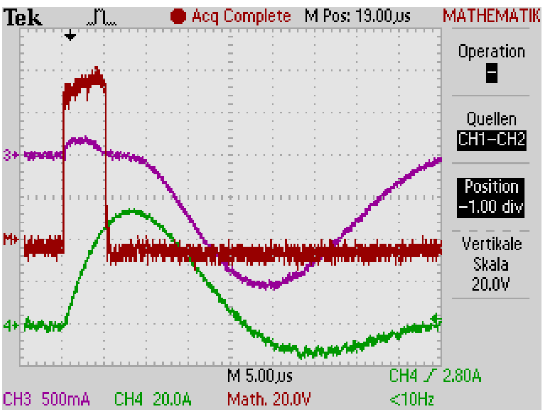

Fig. 10:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60 at d = 30 cm (M_i ≈ 55 nH) induced by an impulse current (green) with i_{max} ≈ 54 kA and di/dt_{max} ≈ 15 kA/µs. The diode used was an 80SQ045 (rated V_{RRM} = 45V). *Note: Scale for currents is 1:1000.*

In this case, the bypass diode just about survived. In the avalanche condition, the voltage (red) is limited to ≈ 75 V during 5 µs, the peak current (violet) is about 200 A and the calculated avalanche energy about 48 mJ (on data sheet: 10 mJ). As the impulse current used has a relatively high negative di/dt during the falling slope, the bypass and cell diodes are conducting in forward direction at the back of the impulse current, which would hardly be the case with a real lightning current.

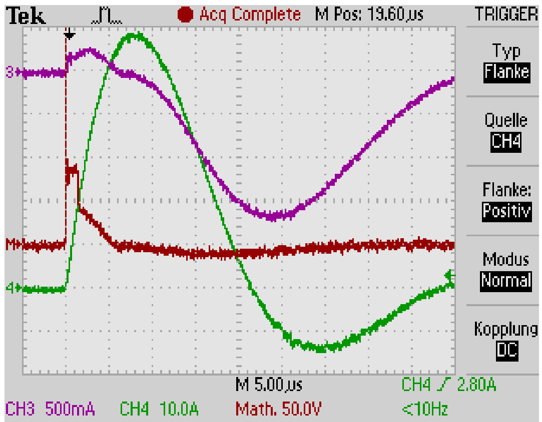

Fig. 11:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60 at d = 30 cm (M_i ≈ 55 nH) induced by an impulse current (green) with i_{max} ≈ 58 kA and di/dt_{max} ≈ 16 kA/µs. The diode used was an 80SQ045 (rated V_{RRM} = 45V). *Note: Scale for currents is 1:1000.*

In this case, the bypass diode fails already after about 1.5µs. In the avalanche condition, the voltage was limited to ≈ 80 V (red), the peak current (violet) is about 250 A. After breakdown, the bypass diode voltage decays, the diode melts through and is conducting in both directions from now on, but is not a perfect short circuit. Like in fig. 10, a strong forward current flows through the cell diodes and the bypass diodes at the back of the impulse current used for the test.

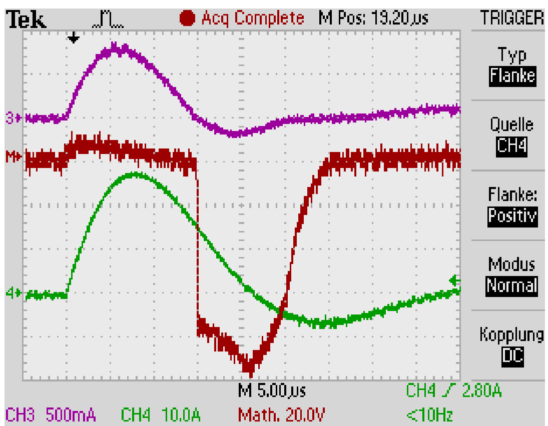

Fig. 12:
Bypass diode forward current i_{BF} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60 at d = 30 cm (M_i ≈ 55 nH) induced by an impulse current (green) with i_{max} ≈ 27 kA and di/dt_{max} ≈ 7.5 kA/µs. The diode was an 80SQ045 (rated V_{RRM} = 45V).

In this case, the bypass diode just about survived. In the forward mode, the voltage is limited to a few volts, but the current (violet), which has a similar form to the impulse current in the beginning, reaches a peak value of about 800 A. As the impulse current used has a relatively high negative di/dt at the falling slope, the bypass and cell diodes are stressed in reverse direction at the back of the impulse current, there is even an operation in the avalanche mode, but only with a smaller stress than in fig. 10. This would not be the case with a real lightning current with a realistic (much longer) back time.

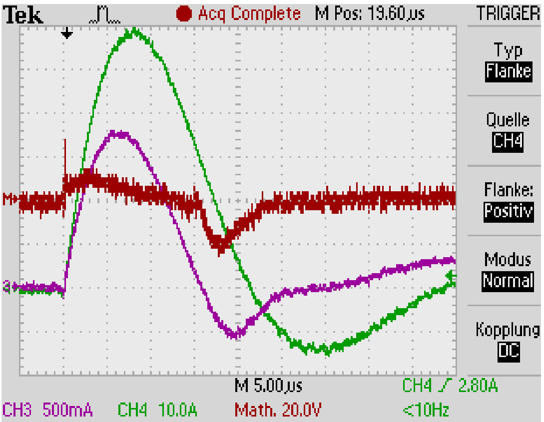

Fig. 13:
Bypass diode forward current i_{BF} in a module loop with $n_C = 18$ solar cells in a polycrystalline module KC60 at d = 30 cm ($M_i \approx 55$ nH) induced by an impulse current (green) with $i_{max} \approx 58$ kA and $di/dt_{max} \approx 16$ kA/µs. The diode was an 80SQ045 (rated $V_{RRM} = 45$V).

In this case, the bypass diode failed. In the forward mode, the voltage is limited to a few volts, but the current (violet), which has a similar form to the impulse current in the beginning, reaches a peak value of about 1750 A. As the impulse current used has a relatively high negative di/dt at the falling slope, the bypass and cell diodes are stressed in reverse direction at the back of the impulse current, but the diode has already lost its blocking capability and is conducting.

5. Preliminary recommendation for effective mutual induction M_i

Considering the simulations performed in chapter 3 and the measurement results obtained in chapter 4, a preliminary recommendation for the effective mutual induction M_i can be given:

For lightning strokes according to lightning protection class III ($i_{max} \leq 100$ kA, $di/dt \leq 100$ kA/µs, damage to bypass diodes can probably be avoided, if the mutual induction M_i calculated according to (3) is $\mathbf{M_i \leq 20}$ **nH**.

6. Conclusions

With the method presented, for the first time a rough calculation of the electrical stress (voltage and current) on bypass diodes in modules in the magnetic field of nearby lightning currents is possible.

As mentioned before, the fall time of the simulated lightning currents used for these tests was much lower than that of a real lightning current according to relevant standards and thus the stress for the diodes was somewhat higher. Therefore these tests should be repeated with impulse currents of the shape 10µs/350µs as soon as the upgrading of the impulse current will be completed. In order to further verify the model used, also tests with some other module and diode types will be performed.

Important Notice

Information contained in this paper is believed to be accurate. However, errors can never be completely excluded. Therefore any liability in a legal sense for correctness and completeness of the information or from any damage that might result from its use is formally disclaimed.

Acknowledgements

Thanks go to all the institutions that gave financial support for this project. The work described in this paper was carried out in the project "PV system technology 2003-2006" under a contract with the Swiss Federal Office of Energy (BFE). Other parts of this project were co-funded by Localnet AG Burgdorf, GMS, c/o BKW, Bern and EBL, Liestal.

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Further information about the research activities of the PV laboratory of BFH-TI (former names: ISB or HTI) can be found on the internet: **http://www.pvtest.ch.**