Measurement of Damages at Bypass Diodes by Induced Voltages and Currents in PV Modules Caused by Nearby Lightning Currents with Standard Waveform

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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 can easily destroy bypass diodes. Due to increasing cell dimensions and 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 only at considerably higher peak induced voltages than the reverse voltage rating of the Schottky diode. In [5] and [7] the problem was analysed theoretically and the results of some first tests with short impulse currents (about 8µs/20µs) were shown. In this paper, the theoretical analysis is extended and results of many measurements performed in 2007 and 2008 with impulse current waveforms of about 6µs/350µs ($di/dt_{max} \leq 30kA/\mu s$) at different modules and with different diode types are presented.

KEYWORDS: Lightning protection, PV modules, bypass diodes.

1. Principal Analysis of 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], [7].

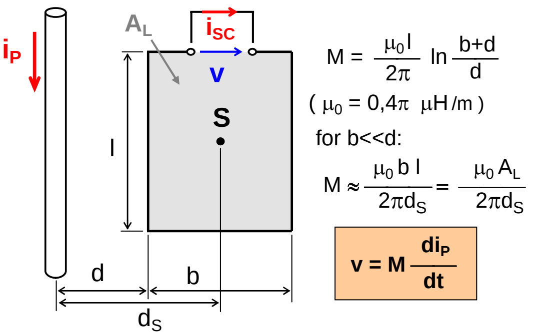

Fig. 1:
Calculation of mutual induction M between a loop and a conductor carrying a (partial) lightning current $i_P = k_C \cdot i$ (i = full lightning current according to standards).

Usually the solar cells are contacted with two (in some cases even three) metal contact strips on the front side. For such arrangements an equivalent radius r_o can be determined. Typically the strips are about 0.02·b wide and 0.48·b apart [5]. Modelling the (very thin) metal strip with a conductor with circular cross section and using the same formula as for the equivalent radius of high voltage overhead lines with two conductors in parallel, an equivalent radius of about 0.05·b is obtained [5]. This radius r_o is used to determine the loop inductance L_L (needed to calculate the resulting current in the loop) and to indicate a somewhat more accurate formula for the mutual inductance M between i_P and the bypass diode loop.

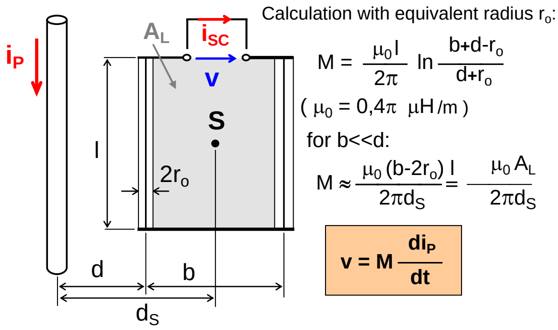

Fig. 2:
More accurate method for calculation of mutual induction M between a bypass diode loop in a module and a conductor carrying a (partial) lightning current $i_P = k_C \cdot i$ (i = full lightning current according to standards). If the module has a metallic frame, the effective value of M is further reduced by a frame reduction factor R_F [1], [5]. Usually R_F is between 2 and 6.

More accurate value for mutual inductance M for bypass diode loops for crystalline modules (parallel position, long side of loop parallel to i_P, worst case):

$$M = 0{,}2 \cdot l \cdot \ln \frac{b+d-r_o}{d+r_o} \qquad (1)$$

where

M = mutual induction of the bypass diode loop in µH between a bypass diode loop in a module and a conductor carrying a (partial) lightning current i_P

l = length of bypass diode loop in m

d = distance from axis of the conductor carrying i_P to the centres of the solar cells in m

b = distance of the centres of the solar cells in the loop in m

r_o = equivalent radius (typical 0.05·b) in m

By using formula (1) a somewhat better match to the values determined from measurements of the maximum induced open loop voltage V_{OCmax} and the maximum value of di/dt is possible ($M = V_{OCmax} / di_P/dt_{max}$).

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. 3 and 4).

- 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.

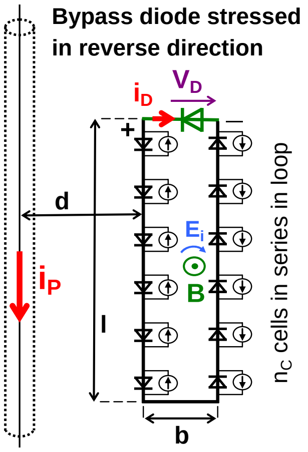

Fig. 3:
Bypass diode and solar cell diodes stressed in reverse direction in front of i_P. If the voltage is higher than the breakdown voltage, they can operate for a short time in avalanche mode, if the current is not too high. Due to the high inverse voltage the current decreases fast.

In the reverse direction, solar cells exhibit a parallel capacity 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!). Good bypass diodes survive avalanche currents up to a few 100 A for some microseconds.

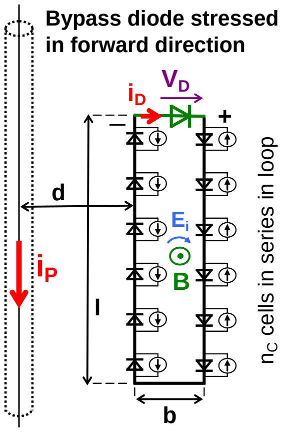

Fig. 4:
Bypass diode and solar cell diodes stressed in forward direction in front of i_P. At all diodes the forward voltage drop is low. If the maximum allowable impulse current is exceeded, the bypass diode is destroyed. As the inverse voltage is low, the current decreases slower.

In the 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 go close to the theoretical maximum, the short circuit current i_{SC} according to formula (8). This current can easily reach 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. However, according to tests performed in the high-voltage laboratory, good bypass diodes can survive forward surge currents up to a few kA (shape 8μs/20μs).

If the module has a metal frame, the effective value of M and therefore the induced voltages and currents are reduced by a frame reduction factor R_F [1], [5], [7] which is typically between about 2 and 6, see formula (4).

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 ($k_C \leq 1$, i = full lightning current, see fig. 1 and fig. 2):

Induced voltage by partial lightning current i_P:

$$v = M\frac{di_P}{dt} = M \cdot k_C \frac{di}{dt} = M_i \frac{di}{dt} \qquad (2)$$

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 bypass diode loop according to fig. 2 and a conductor with a partial lightning current i_P can be calculated as follows:

Mutual induction at loops not containing the lightning carrying conductor:

$$M = 0.2 \cdot l \cdot \ln\frac{b+d-r_o}{d+r_o} \approx 0.2 \cdot l \cdot \ln\left(1+\frac{0.9 \cdot b}{d+0.05 \cdot b}\right) \qquad (3)$$

M is the mutual inductance in μH, if all distances l, b, d and r_o are indicated in meters [m]. For more details about symbols used see explanations under (1).

If the loop is a bypass diode loop in a module with a *metal frame*, the induced voltage and therefore also the effective mutual inductance M_i is further reduced. Therefore with M according to (3) it can be defined:

Mutual induction for bypass diode loops in modules:

$$M_i = \frac{k_C \cdot M}{R_F} \qquad (4)$$

R_F = frame reduction factor: R_F = 2 – 6 for modules with metallic frame, R_F = 1 for other modules. $k_C = i_P/i \leq 1$.

In order to calculate the current, also loop inductance L_L is necessary. For a rectangular wire loop with length l, width b and wire radius r_o loop inductance L_L is:

$$L_L \approx 0.4 \cdot (l+b) \cdot \ln\frac{b-r_o}{r_o} - 0.55 \cdot b \qquad (5)$$

L_L is the loop inductance in μH, if all values (length l, width b, wire radius r_o) are indicated in m. The formula is valid with sufficient accuracy for l > b [5].

As already mentioned, for bypass diode loops with conventional crystalline cells r_o is about 0.05·b. Therefore the value of ln in formula (5) is about 3. Often the bypass diodes are placed in the connector box in the middle of the module, i.e. an additional conductor length of 0.5b and 1.5b in modules with 4 cell rows has to be considered. There is also some internal wiring in the connector box and some lead length of the diodes. This increases the inductance L_L of the bypass diode loop. For modules with more rows this additional length can be even higher for some loops, resulting in an even higher L_L. With higher L_L the resulting loop current $i_L = i_D$ and the stress on the bypass diodes and solar cells are lower, therefore the worst case is that with the lowest L_L.

For the *inductance of a bypass diode loop in a conventional PV module with crystalline cell*s and the bypass diodes in the connector box, a good estimate can be indicated as [5]:

Inductance of bypass diode loops in PV modules (diodes placed in connector boxes):

$$L_L \approx 1.2 \cdot (l + 2 \cdot b) + 0.05 \qquad (6)$$

L_L is the inductance of the bypass diode loop in µH, if the distances l and b are indicated in meters [m]. For more details about symbols used see explanations under (1).

There are also modules with small bypass diodes directly integrated into the module across the bypass diode loop (e.g. BP 7175). In this case there are no additional conductors between the loop and the connector box, no internal wiring in the connector box and negligible lead length of the bypass diode. Therefore in this case L_L is lower:

Inductance of bypass diode loops in PV modules (diodes directly integrated in module across loop):

$$L_L \approx 1.2 \cdot l + 0.7 \cdot b \qquad (7)$$

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: These formulas (6) and (7) are only valid for bypass diode loops in PV modules with conventional crystalline cells.

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):

$$i_{SC} \approx \frac{M}{L_L \cdot R_F} i_P = \frac{M}{L_L \cdot R_F} k_C \cdot i = \frac{M_i}{L_L} i \qquad (8)$$

Due to the impedance and the voltage drop at the solar cells and the bypass diodes needed for conduction, occurring currents in bypass diode loops must always be lower than the values calculated with (8).

With the bypass diode stressed in reverse direction according to the situation in fig. 3 for first lightning strokes, where $V_{OCmax} = M_i \cdot di/dt_{max}$ is often not considerably higher than the resulting sum of the necessary voltage drops at the solar cells and the bypass diode, the peak current i_{BRmax} is much lower than the peak values calculated with (8). If $V_{OCmax} = M_i \cdot di/dt_{max}$ is low (smaller than the sum of the necessary voltage drops), i_{BRmax} is very low or even nearly 0.

However, for reverse mode stress by negative subsequent short strokes and for forward mode stress according to fig. 4, the induced open loop voltage $V_{OCmax} = M_i \cdot di/dt_{max}$ is usually much higher than the sum of the necessary voltage drops at the solar cells and the bypass diode.

In this case, the resulting peak current in the bypass diode $i_{Dmax} = i_{BRmax}$ in reverse mode and $i_{Dmax} = i_{BFmax}$ in the forward mode is usually only a little lower than the values calculated with (8):

$$i_{Dmax} \approx k_D \frac{M}{L_L \cdot R_F} i_{P\max} = k_D \frac{M_i}{L_L} i_{\max} \qquad (9)$$

Typical values for k_D are between 0.6 and 1.

Although the voltage drop at the solar cells and the bypass diode in forward mode is low, the duration of the forward currents i_{BF} is still considerably lower than the duration of the primary lightning currents i. In practical experiments performed in the HV laboratory, usually less than 20µs were needed for the current i_{BF} to drop below 50% of its peak value, therefore a comparison with surge current specifications of 8/20µs (for forward mode, if available) of the bypass diodes used would make sense.

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

With two separate linear models for the reverse (fig. 5) and the forward direction (fig. 6) 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.

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

$$i(t) = I\left(e^{-\sigma_1 t} - e^{-\sigma_2 t}\right) \qquad (\sigma_2 >> \sigma_1) \qquad (10)$$

In the simulations performed for fig. 7 to fig. 15, the following values for I, σ_1 and σ_2 were used [5]:

First stroke lightning currents with i_{max} = 100kA (10/350µs):
I = 106.5 kA, $\sigma_1 = 2150\ s^{-1}$ and $\sigma_2 = 189900 s^{-1}$.

Negative subsequent short stroke lightning currents with i_{max} = 25 kA (0.25/100µs):
I = 25.2 kA, $\sigma_1 = 6931\ s^{-1}$ and $\sigma_2 = 3975000 s^{-1}$.

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

$$i_D(t) = \frac{M_i \cdot I}{L_L}\left[\frac{\sigma_1 \cdot e^{-\sigma_1 \cdot t}}{(\sigma_1 - \sigma_3)} + \frac{\sigma_2 \cdot e^{-\sigma_2 \cdot t}}{(\sigma_3 - \sigma_2)} + \frac{\sigma_3 \cdot (\sigma_1 - \sigma_2) \cdot e^{-\sigma_3 \cdot t}}{(\sigma_1 - \sigma_3)(\sigma_2 - \sigma_3)}\right] - \frac{V_{tot}(1 - e^{-\sigma_3 \cdot t})}{L_L \cdot \sigma_3} \qquad (11)$$

where $V_{tot} = V_{AV} = n_C \cdot V_{CA} + V_{BA}$ for fig. 5 and $V_{tot} = V_F = n_C \cdot V_{CF} + V_{BF}$ for fig. 6 (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 5 or fig. 6)

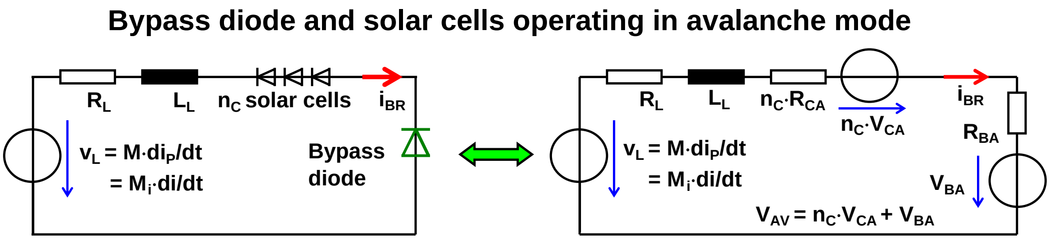

Fig. 5:
Linearised equivalent circuit diagram for an approximate calculation of the reverse current $i_D = i_{BR}$ in the bypass diode (avalanche mode), if the diode is stressed in reverse direction according to fig. 3 (at left original circuit, at right linearised form for operation in avalanche mode).

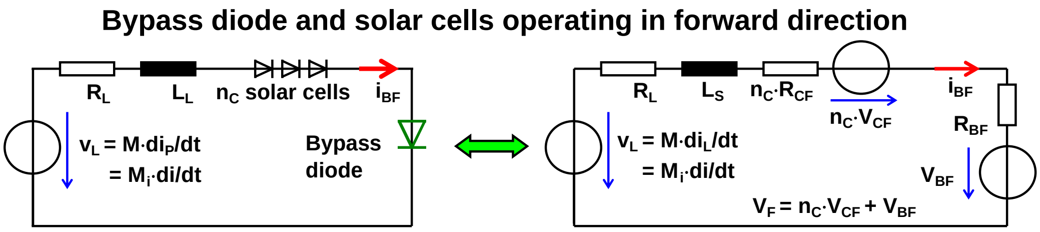

Fig. 6:
Linearised equivalent circuit diagram for an approximate calculation of the forward current $i_D = i_{BF}$ in the bypass diode, if the diode is stressed in forward direction according to fig. 4 (at left original circuit, at right linearised form). For a more precise modelling of the high current mode, a little higher forward voltage drops than usual have to be assumed.

3.1 Calculated examples for reverse operation of solar cells and bypass diode

As an example, a typical bypass diode loop with $n_C = 18$ solar cells and a loop inductance of $L_L = 2\ \mu H$ and $R_L \approx 0$ is examined [5]. For operation in the avalanche mode, for each of the solar cells a breakdown voltage $V_{CA} = 20$ V and a resistor $R_{CA} = 5\ m\Omega$ can be used. For the Schottky bypass diode a breakdown voltage $V_{BA} = 70$ V and a resistor $R_{BA} = 50\ m\Omega$ can be assumed. Thus a total $V_{AV} = 430$ V in fig. 5 is obtained. Fig. 7 and fig. 8 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.

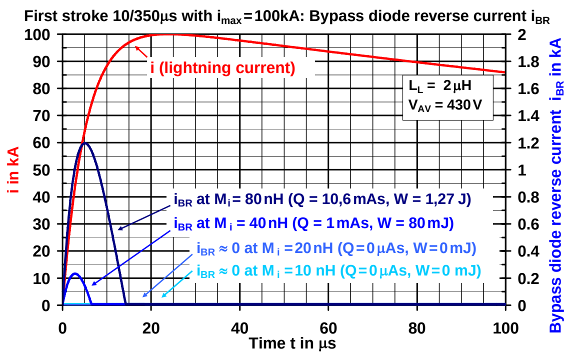

Fig. 7:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with $n_C = 18$ solar cells with $V_{CA} = 20$ V and a Schottky bypass diode with $V_{BA} = 70$ V at different typical values of effective mutual induction M_i and $L_L = 2\ \mu H$, calculated for a first lightning stroke with $i_{max} = 100$ kA.
In this case, maximum bypass diode avalanche currents are considerably lower than the range calculated with (9). For small M_i i_{BR} is ≈ 0 [5].

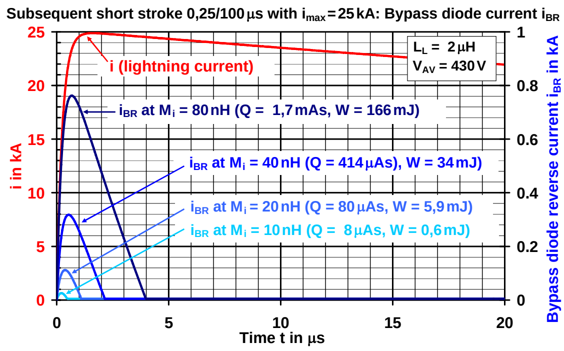

Fig. 8:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with $n_C = 18$ solar cells with $V_{CA} = 20$ V and a Schottky bypass diode with $V_{BA} = 70$ V at different typical values of effective mutual induction M_i and $L_L = 2\ \mu H$, calculated for a negative subsequent short lightning stroke with $i_{max} = 25$ kA [5].
In this case, for higher M_i maximum bypass diode avalanche currents are in the range calculated with (9).

The same calculations were also performed for a bypass diode loop with fewer solar cells and the diodes directly integrated in the module. In this case, L_L is lower, which increases the current under otherwise similar conditions. With the same values of $V_{CA} = 20$ V, $R_{CA} = 5\ m\Omega$, $V_{BA} = 70$ V and $R_{BA} = 50\ m\Omega$ as in fig. 7 and 8 the resulting (avalanche) reverse currents are shown in Fig. 9 and 10 for typical values M_i of 10 nH, 20 nH, 40 nH and 80 nH for $n_C = 12$, $L_L = 1\ \mu H$ and $R_L \approx 0$ (e.g. in a module BP7175).

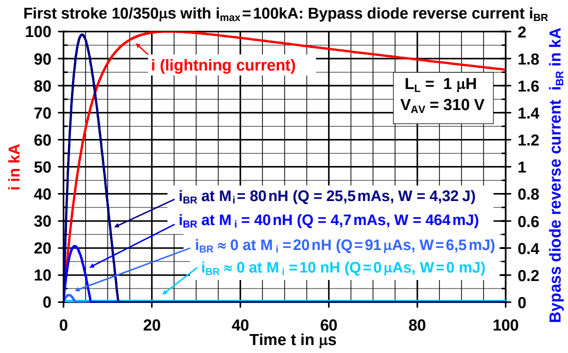

Fig. 9:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with n_C = 12 solar cells with V_{CA} = 20 V and a Schottky bypass diode with V_{BA} = 70 V at different typical values of effective mutual induction M_i and L_L = 1 µH, calculated for a first lightning stroke with i_{max} = 100 kA. Due to the lower L_L for the same M_i the values for i_{BR} are nearly twice the values in fig. 7. Moreover, due to lower V_{AV} i_{BR} is also >0 for M_i = 20nH. In this case, maximum bypass diode avalanche currents are considerably lower than the range calculated with (9). For small M_i i_{BR} is ≈ 0.

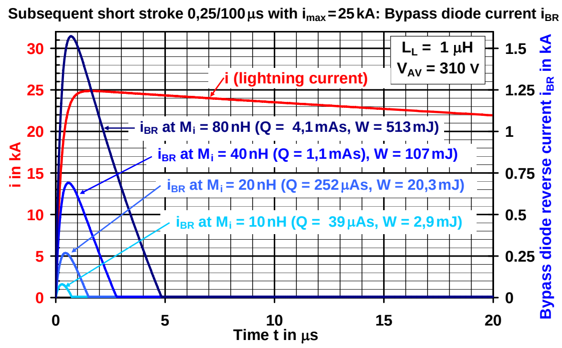

Fig. 10:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with n_C = 12 solar cells with V_{CA} = 20 V and a Schottky bypass diode with V_{BA} = 70 V at different typical values of effective mutual induction M_i and L_L = 1 µH, calculated for a negative subsequent short lightning stroke with i_{max} = 25 kA. Also in this case due to the lower L_L for the same M_i the values for i_{BR} are about twice the values in fig. 8.
In this case, for higher M_i maximum bypass diode avalanche currents are in the range calculated with (9).

If standard silicon diodes with high reverse breakdown voltage are used, no reverse current can flow until the induced voltage v = M_i·di/dt exceeds the relatively high V_{AV} in the loop. However, such diodes usually have no avalanche specification and are easily destroyed if their V_{RRM} is exceeded and there is only a small reverse current i_{BR}.

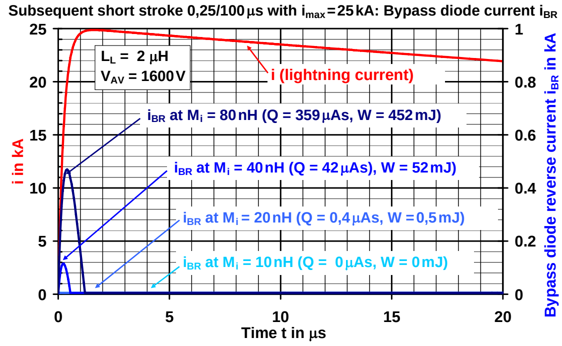

Fig. 11:
Bypass diode reverse (avalanche) currents i_{BR} in a module loop with n_C = 18 solar cells with V_{CA} = 20 V and a standard high voltage silicon diode as a bypass diode with V_{BA} = 1240 V at different typical values of effective mutual induction M_i and L_L = 2 µH, calculated for a negative subsequent short lightning stroke with i_{max} = 25 kA. For small M_i-values i_{BR} is ≈ 0 [5].

The values chosen in the examples for the resistors R_{CA} and R_{BA} were relatively low. It can be assumed that often the real values will be higher. Therefore the results obtained can be considered as worst case conditions.

3.2 Calculated examples for forward operation of solar cells and bypass diode

For operation in the forward mode, for each of the solar cells a voltage V_{CF} = 0.95 V and a resistor R_{CF} = 4 mΩ can be used. For the Schottky bypass diode a voltage V_{BF} = 0.9 V and a resistor R_{BF} = 3 mΩ can be assumed. Thus for a module with n_C = 18 a much lower total voltage V_F = 18 V in fig. 6 is obtained. Fig. 12 and 13 show 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.

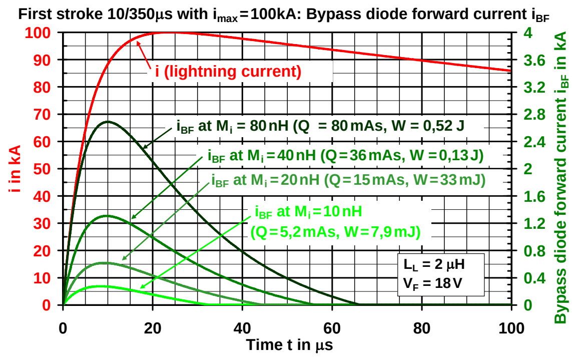

Fig. 12:
Bypass diode forward currents i_{BF} in a module loop with n_C = 18 solar cells with V_{CF} = 0.95 V and a Schottky bypass diode with V_{BF} = 0.9 V at different typical values of effective mutual induction M_i, calculated for a first lightning stroke with i_{max} = 100 kA [5].

The same calculations were also performed for a bypass diode loop with fewer solar cells and the diodes directly integrated in the module. In this case, L_L is lower, which increases the current under otherwise similar conditions.

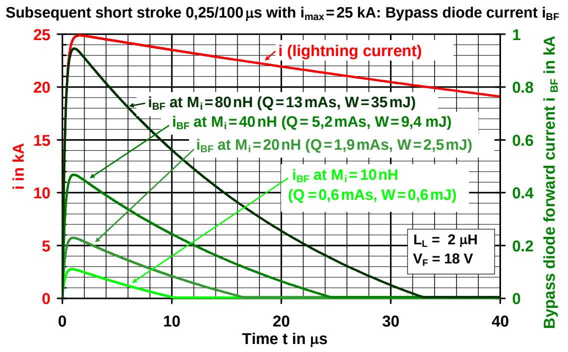

Fig. 13:
Bypass diode forward currents i_{BF} in a module loop with n_C = 18 solar cells with V_{CF} = 0.95 V and a Schottky bypass diode with V_{BF} = 0.9 V at different typical values of effective mutual induction M_i and L_L = 2 µH, calculated for a subsequent short stroke of i_{max} = 25 kA [5].

With the same values of V_{CF} = 0.95 V, R_{CF} = 4 mΩ, V_{BF} = 0.9 V and R_{BF} = 3 mΩ as in fig. 12 and 13 the resulting forward currents are shown in Fig. 14 and 15 for typical values M_i of 10 nH, 20 nH, 40 nH and 80 nH for n_C = 12 and L_L = 1µH (e.g. in a module BP7175).

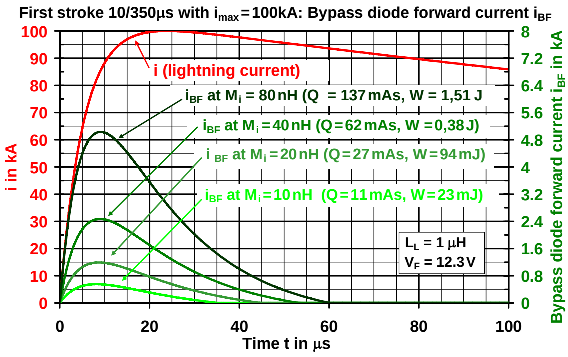

Fig. 14:
Bypass diode forward currents i_{BF} in a module loop with n_C = 12 solar cells with V_{CF} = 0.95 V and a Schottky bypass diode with V_{BF} = 0.9 V at different typical values of effective mutual induction M_i and L_L = 1 µH, calculated for a first lightning stroke with i_{max} = 100 kA. Due to the lower L_L for the same M_i the values for i_{BF} are nearly twice the values in fig. 12.

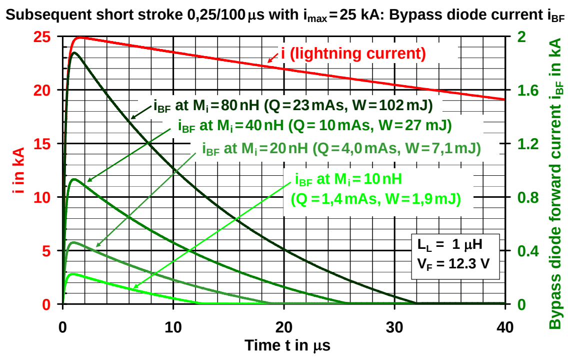

Fig. 15:
Bypass diode forward currents i_{BF} in a module loop with n_C = 12 solar cells with V_{CF} = 0.95 V and a Schottky bypass diode with V_{BF} = 0.9 V at different typical values of effective mutual induction M_i and L_L = 1 µH, calculated for a negative subsequent short stroke with i_{max} = 25 kA. Due to the lower L_L for the same M_i the values for i_{BF} are nearly twice the values in fig. 13.

Of course the linearised models used for these calculations have their limitations, as solar cells and bypass diodes are inherently non-linear. For instance in practical measurements in the reverse direction avalanche currents i_{BR} > 0 can still be measured for maximum induced open loop voltages $V_{OCmax} = M_i \cdot di/dt_{max}$ that are a little lower than the calculated V_{AV} of the linear model used in fig. 5.

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

In the first tests performed in 2007 and presented in [5] and [7], the fall time of the simulated lightning currents was still much lower than that of a real lightning current according to relevant standards. Therefore, after a stress in one direction, the diode was exposed immediately after to a (milder) stress in the other direction. Thus the total stress was a little higher than in reality. By the end of 2007 the high impulse current generator was successfully modified to produce standard test impulses of up to 110 kA with standard waveform 10 µs/350 µs.

For tests in reverse direction mainly a high di/dt is essential and the influence of back duration is negligible, as the duration of the current impulses is only a few microseconds due to the high inverse voltage at the solar cells and the bypass diode. On the other hand, for tests in forward mode, mainly the peak current and a sufficient back duration (> 200µs) is important, di/dt has a lower influence. As changes of the front and rise time of the impulse current generator are time consuming, the shape of the test current impulses was set to about 6/350µs, which have the highest possible di/dt in the front for reverse stress tests and a standard back time for forward stress tests (see fig. 16). Thus it is not necessary to make changes between reverse and forward stress tests.

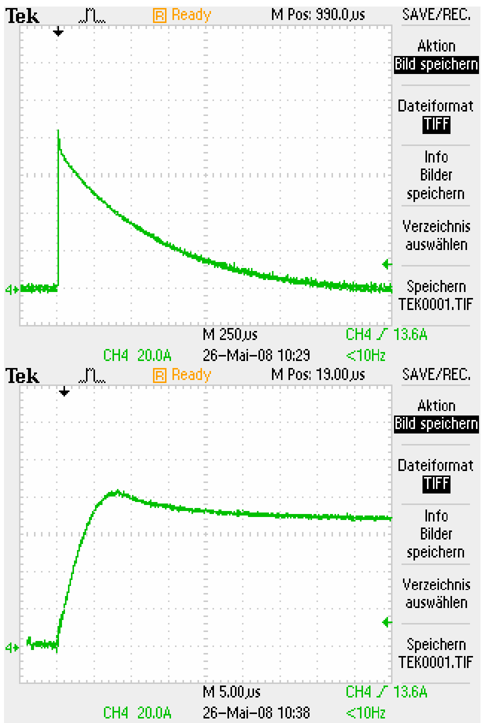

Fig. 16:
Shape of a test impulse current i with i_{max} ≈ 82 kA with a time resolution of 250µs (top) and 5µs (bottom) [9].

Stress limits for bypass diodes for tests performed at BFH's PV laboratory 1.2007 to 8.2008

Type	State (after)	F/ R	Module	n_C	d [mm]	b [mm]	i_{max} [kA]	di/dt_{max} [kA|μs]	M_b [nH]	M_i [nH]	L_L* [μH]	V_{OCmax} [V]	V_{Dmax} [V]	i_{Dmax} [A]	E_A [mJ]
80SQ045	**ok**	R	KC-60L	18	150	160	46	8	100	100	1.5	**800**	90	165	61
	def	R	KC-60L	18	150	160	54	9.2	100	100	1.5	**920**	100	350	
	ok	R	KC-60L	18	400	160	70	16.9	43.6	43.6	1.5	**737**	85	130	42
	def	R	KC-60L	18	400	160	86	21	43.6	43.6	1.5	**916**	110	360	
	ok	R	KC-60	18	250	160	98	25.2	64	32	1.5	**806**	84	185	49
	def	R	KC-60	18	250	160	106	27.1	64	32	1.5	**867**	85	280	
	ok	R	BP7175N	12	250	128	104	27	56.5	21	1.2	**567**	85	190	48
80SQ045	**ok**	F	KC-60L	18	400	160	94	24	43.6	43.6	1.5	1046		2400	
	ok	F	KC-60	18	250	160	106	26.5	64	32	1.5	848		1600	
	ok	F	BP7175N	12	250	128	100	26.4	56.5	21	1.2	554		1650	
	def	F	KC-60L	18	400	160	105	27	43.6	43.6	1.5	1177		2700	
SBM1040	**ok**	R	KC-60L	18	400	160	64	16.2	43.6	43.6	1.5	**706**	75	110	30
	def	R	KC-60L	18	400	160	67	16.8	43.6	43.6	1.5	**732**	80	160	
	ok	R	KC-60	18	250	160	86	21.9	64	32	1.5	**701**	75	120	29
	def	R	KC-60	18	250	160	92	23.7	64	32	1.5	**758**	80	150	
	ok	R	BP7175N	12	250	128	98	25.2	56.5	21	1.2	**529**	75	160	37
	def	R	BP7175N	12	250	128	104	27.2	56.5	21	1.2	**571**	75	200	
SBM1040	**ok**	F	KC-60L	18	400	160	37	9.5	43.6	43.6	1.5	414		850	
	ok	F	BP7175N	12	250	128	60	17	56.5	21	1.2	357		1000	
	def	F	KC-60L	18	400	160	52	13	43.6	43.6	1.5	567		1200	
	def	F	BP7175N	12	250	128	76	20.1	56.5	21	1.2	422		1200	
P1000M	**ok**	R	KC-60L	18	250	160	86	21	64	64	1.5	**1344**	1300	40	—
	def	R	KC-60L	18	250	160	94	22.7	64	64	1.5	**1453**	900	1080	
P1000M	**ok**	F	KC-60L	18	250	160	108	25.7	64	64	1.5	1645		4000	
LOW VF+TVS	**ok**	R	KC-60L	18	300	160	85	21.4	55.4	55.4	1.5	**1186**	280	460	440
	def	R	KC-60L	18	300	160	92	23.2	55.4	55.4	1.5	**1285**	320	540	
LOW VF+TVS	**ok**	F	KC-60L	18	250	160	108	25.7	64	64	1.5	1645		4000	
P6KE24+SB1240	**ok**	R	KC-60L	18	300	160	68	16.8	55.4	55.4	1.5	**931**	40	400	60
	def	R	KC-60L	18	300	160	86	21.5	55.4	55.4	1.5	**1191**	55	700	
P6KE24+SB1240	**ok**	F	KC-60L	18	250	160	108	25.8	64	64	1.5	1651		4000	

Table 1:
Overview and stress limits of the bypass diode tests performed at BFH's PV laboratory from Jan. 2007 to Aug. 2008. In case of a module without frame (KC-60L), effective mutual inductance M_i is about M_b, determined from the geometry between the bypass diode loop and the primary current i_P with (3). In case of a module with metal frame (KC-60 and BP7175N), M_i was determined by measuring V_{OCmax} and di/dt_{max} and calculating $M_i = V_{OCmax} / (di/dt_{max})$ in the forward direction. Due to the inductance of the connection between the bypass diode loop and the shunt used to determine the diode current i_D, L_L determined with (6) or (7) has to be increased by ≈ 250nH in order to get the effective inductance L_L*.

Table 1 gives an overview of all bypass diode tests performed so far. For most tests new diodes were used that were not exposed to other stress tests before. In order to see also beginning damage, before and after the stress exposure an I-V-curve of the bypass diode under test was determined. These tests were quite time consuming and were performed mainly during the work described in [8] and [9]. In table 1, the test condition (bypass diode type, reverse (R) or forward (F) mode, state (ok or defective) after the stress exposure, number of cells n_C in bypass diode loop, distance d from the primary impulse current, width of solar cells b, maximum current i_{max}, maximum di/dt in front of current, geometric (M_b) and effective (M_i) mutual inductance, effective loop inductance L_L during the measurement, maximum open circuit voltage $V_{OCmax} = M_i \cdot di/dt_{max}$ (mostly the reverse stress limit for a given combination of solar cells and bypass diode in a bypass diode loop), V_{Dmax} (maximum voltage across the bypass diode in reverse direction) and i_{Dmax} (maximum diode current) and in some cases also estimated avalanche energies in the diodes.

There are significant variations of the limiting values between the individual diodes. In table 1 for surviving diodes the highest value is indicated, which a diode of a certain diode type could support without any other diode that got defective at a lower stress. However, there are individual strong diodes that survived a 10% to 50% higher stress than the ok value indicated in table 1. Also for the values given for defective diodes, the lowest value that caused a defect is indicated and there are individual diodes that survived a considerable higher stress.

In the reverse direction, for a given combination of solar cells and bypass diode in a bypass diode loop, the critical quantity is the theoretical maximum open circuit voltage $V_{OCmax} = M_i \cdot di/dt_{max}$. If it is lower or close to the necessary voltage drop at the solar cells and the bypass diodes to drive them in the avalanche mode, the diode current is low, but it increases very much if V_{OCmax} rises significantly above this value. Permissible avalanche reverse currents for bypass diodes are much lower than permissible forward currents (typically about a factor of 10).

From Diotec, a German manufacturer of diodes, samples of combinations of two parallel diodes were supplied (LOW VF + TVS already mounted in one case) and two separate diodes P6KE24 and SB1240 that had to be connected in parallel for the tests. These combinations proved to be more resistant than the other bypass diodes tested, especially the version LOW VF + TVS. Standard high voltage Si-diodes P1000M also proved to be quite robust, but they have relatively poor avalanche behaviour and break down very soon after their maximum reverse voltage is exceeded.

If the number of solar cells in a bypass diode is lower (e.g. n_C = 12 instead of 18), for the same diode the permissible theoretical maximum open circuit voltage $V_{OCmax} = M_i \cdot di/dt_{max}$ is lower. On the other hand, a bypass diode with a higher avalanche voltage can survive a higher V_{OCmax} until the avalanche current rises to a critical value.

The beneficial effect of a frame can also be clearly seen in table 1. Whereas in a frameless KC-60L all diodes and diode combinations could be destroyed in the reverse mode, in modules with metallic frame this was only possible for the relatively weak diodes SBM1040 and 80SQ045.

In the forward direction, the bypass diodes and diode combinations could survive surge currents, which were typically about a factor of 10 stronger than the permissible avalanche currents.

The following figures 17 to 29 show results of actual tests carried out in the high voltage laboratory of BFH-TI. The modules were all mounted *in parallel position* (like in fig. 1 and 2, details see [5]).

4.1 Examples of measurements in reverse direction

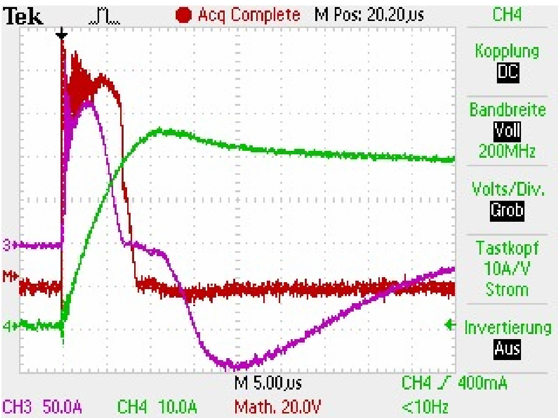

Fig. 17:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without frame) at d = 15 cm ($M_i \approx$ 100 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 46 kA and $di/dt_{max} \approx$ 8 kA/µs. The diode used was an 80SQ045 (rated V_{RRM} = 45V). In the avalanche mode the voltage (red) is limited during 6.5 µs to about 90 V, the peak reverse current (violet) is about 165 A and the avalanche energy about 61 mJ.

Fig. 17 to fig. 19 show examples of actual measurements in the reverse direction with different modules and a bypass diode 80SQ045 under reverse stress in the front of the lightning current. Due to the special shape of the test impulse current, immediately after its maximum bypass diode and solar cells are stressed somewhat in forward direction and a certain forward current is flowing. All diodes survived the stresses shown in fig. 17 to 19.

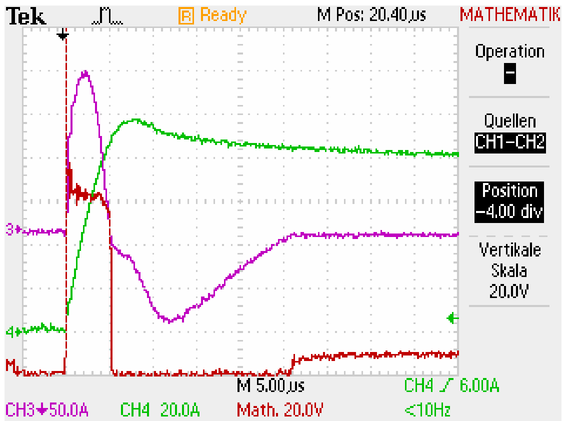

Fig. 18:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60 (*with metal frame*) at d = 25 cm ($M_i \approx$ 32 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 98 kA and $di/dt_{max} \approx$ 25.2 kA/µs. The diode used was an 80SQ045. Here the voltage (red) is limited during 5 µs to about 84 V, the peak reverse current (violet) is about 185 A and the avalanche energy about 49 mJ [9].

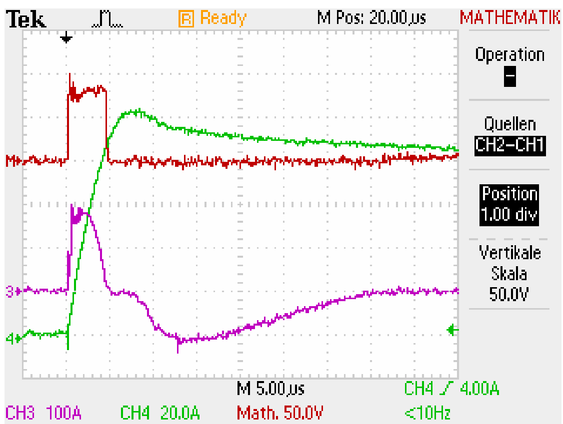

Fig. 19:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 12 solar cells in a monocrystalline module BP7175N (*with metal frame*) at d = 25 cm ($M_i \approx$ 21 nH, $L_L \approx$ 1.2 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 104 kA and $di/dt_{max} \approx$ 27 kA/µs. The diode used was an 80SQ045. Here the voltage (red) is limited during 4.5 µs to about 80 V, the peak reverse current (violet) is ≈ 190 A and the avalanche energy ≈ 48 mJ [9].

For fig. 17 and 18, the resulting V_{OCmax} is nearly identical, as the bypass diode loop is identical, whereas in fig. 19 it is considerably lower, as there is a module with other cells and only n_C = 12 instead of 18 solar cells per bypass diode loop.

Fig. 20 and fig. 21 show examples of measurements in the reverse direction with different modules and a bypass diode 80SQ045 under reverse stress in the front of the lightning current, in which the diodes were destroyed and resulted in a not perfect short circuit.

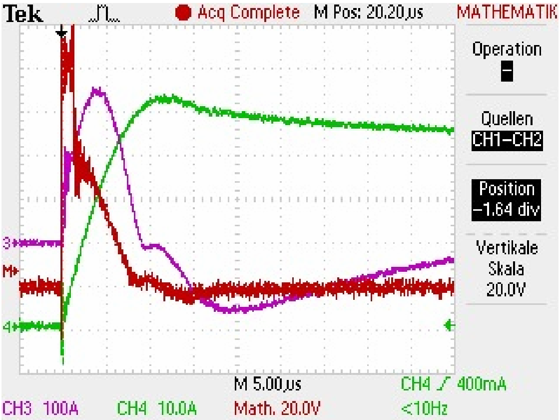

Fig. 20:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without metal frame) at d = 15 cm ($M_i \approx$ 100 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 54 kA and $di/dt_{max} \approx$ 9.2 kA/µs. The diode used was an 80SQ045 (rated V_{RRM} = 45V). The voltage at the diode (red) is limited at first during 1.5 µs to about 100 V, then the diode breaks down and the voltage decreases to 0. Here the peak reverse current (violet) is about 350 A.

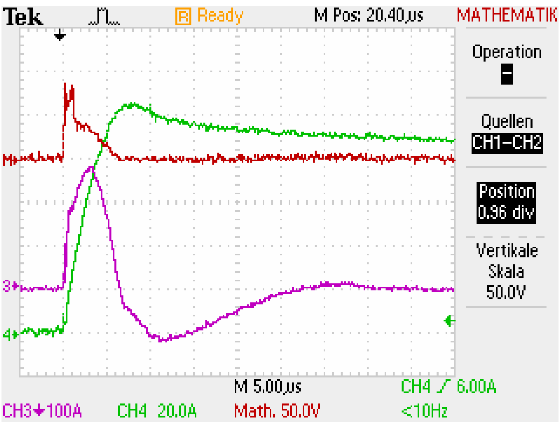

Fig. 21:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60 (*with metal frame*) at d = 25 cm ($M_i \approx$ 32 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 106 kA and $di/dt_{max} \approx$ 27.1 kA/µs. The diode used was an 80SQ045. The voltage at the diode (red) is limited at first during 1.5 µs to about 85 V, then the diode breaks down and the voltage decreases to 0. The peak reverse current (violet) is about 280 A [9].

In Fig. 20 and 21, the bypass diodes fail already after about 1.5µs. In the avalanche condition, the voltage was limited to ≈ 85 V – 100 V. 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. Again it is obvious that for the same bypass diode configuration the maximum open circuit voltage $V_{OCmax} = M_i \cdot di/dt_{max}$ in loop is the critical value. There are only minor differences between the two tests, but these small differences already cause significant differences in peak current.

Modules with bypass diodes directly integrated in the module often use the small diode SBM1040. Of course this diode is somewhat weaker and breakdown may occur already at lower avalanche current and energy. Fig. 22 shows a breakdown of a SBM1040 already at a peak avalanche current of about 150A.

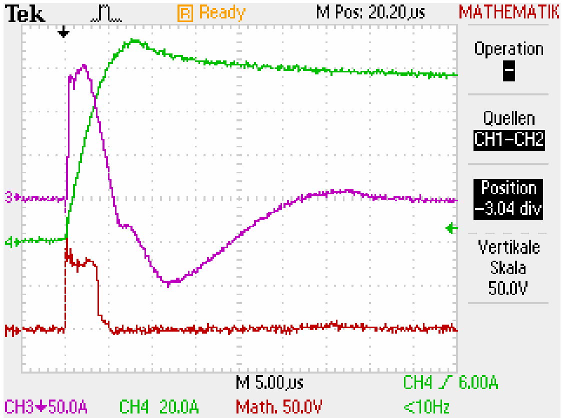

Fig. 22:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60 (*with metal frame*) at d = 25 cm ($M_i \approx$ 32 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 92 kA and $di/dt_{max} \approx$ 23.7 kA/µs. The diode used was an SBM1040. The voltage at the diode (red) is limited at first during 3.5 µs to about 80 V, then the diode breaks down and the voltage decreases to 0. The peak reverse current (violet) is about 150 A [9].

Although the modules had a metal frame in fig. 21 and 22, the reduction of M_i owing to the frame reduction factor R_F was just not sufficient to protect the bypass diodes at higher values of primary current and di/dt.

As in most cases the stress in the reverse direction is critical for survival of the bypass diodes, an interesting idea is to form teams of two diodes in parallel, one diode specialised for a low voltage drop in forward direction and another diode (e.g. transient suppressor diode) to handle the avalanche current peaks in the reverse direction. Preferably these diodes would be in one common case only to keep assembly costs low. Samples of such two-diode combinations were provided by the German diode manufacturer Diotec.

The version LOW VF+TVS was already integrated in a single case, the other team consisted of a P6KE24 and a SB1240 that had to be connected in parallel externally. As expected, these combinations survived higher avalanche currents up to 480 A and 400 A respectively.

The version LOW VF+TVS has a relatively high avalanche voltage, therefore the permissible V_{OCmax} in the bypass diode loop is also higher, but the forward voltage drop is also quite high and not much better than for an ordinary Silicon diode.

The combination P6KE24 and a SB1240 has a similar forward voltage drop like an ordinary Schottky diode, which is certainly better for larger solar cells with high currents. Fig. 23 and fig. 24 show the conditions under reverse stress that were survived by these two diode combinations.

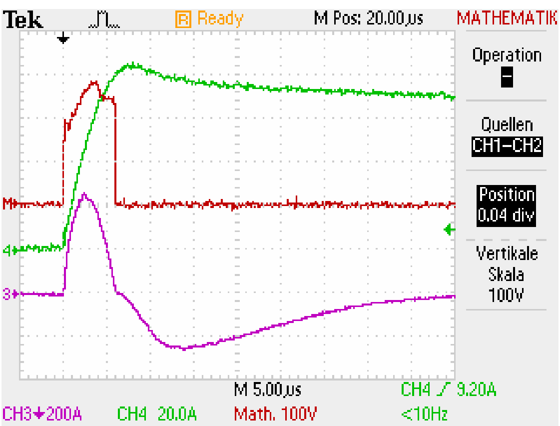

Fig. 23:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without frame) at d = 30 cm ($M_i \approx$ 55.4 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 86 kA and $di/dt_{max} \approx$ 21.4 kA/µs. The diode used was a combination LOW VF+TVS. In the avalanche mode the voltage (red) is limited during 6 µs to an average value of about 250 V, the peak reverse current (violet) is about 460 A and the avalanche energy about 440 mJ [9].

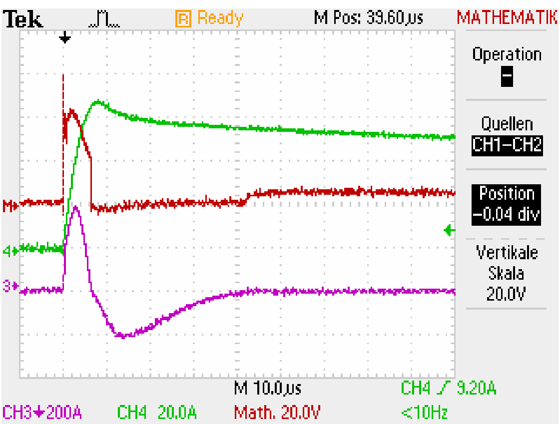

Fig. 24:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without frame) at d = 30 cm ($M_i \approx$ 55.4 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 68 kA and $di/dt_{max} \approx$ 16.8 kA/µs. The bypass diode used was a parallel combination P6KE24 and SB1240. In the avalanche mode the voltage (red) is limited during 6 µs to only about 40 V, the peak reverse current (violet) is about 400 A and the avalanche energy about 60 mJ [9].

In the tests performed, the standard high voltage Si-diode P1000M survived the highest theoretical open circuit voltages V_{OCmax} up to about 1350V in a KC60L. This was even a little higher than the values registered for the two diode combinations tested. Fig. 25 shows a P1000M that was not damaged by an induced reverse voltage of 1200 V.

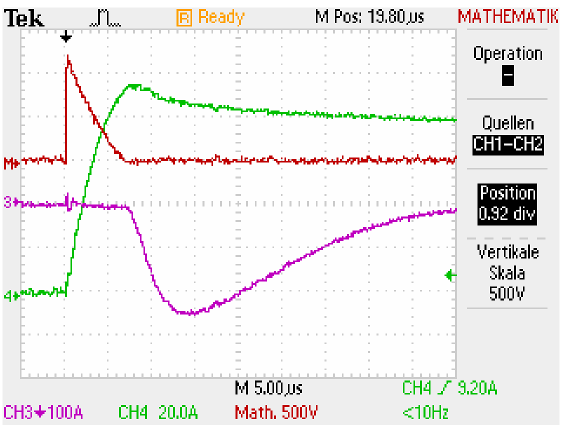

Fig. 25:
Bypass diode reverse (avalanche) current i_{BR} in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without metal frame) at d = 30 cm ($M_i \approx$ 55.4 nH, $L_L \approx$ 1.5 µH) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 94 kA and $di/dt_{max} \approx$ 23.9 kA/µs. The diode used was an P1000M. Under these conditions, in the front of the lightning current i_{BR} (violet) is ≈ 0. The voltage at the diode (red) reaches a peak value of 1200 V close to the open circuit voltage V_{OCmax} induced in the bypass diode loop [9].

4.2 Examples of measurements in forward direction

In the forward direction, bypass diodes can usually support at least ten times the avalanche reverse current. Therefore in most cases the reverse stress is the critical situation. In fig. 26 it can be seen, that even the weakest diode, a SBM1040, can survive a forward impulse current of about 1000 A.

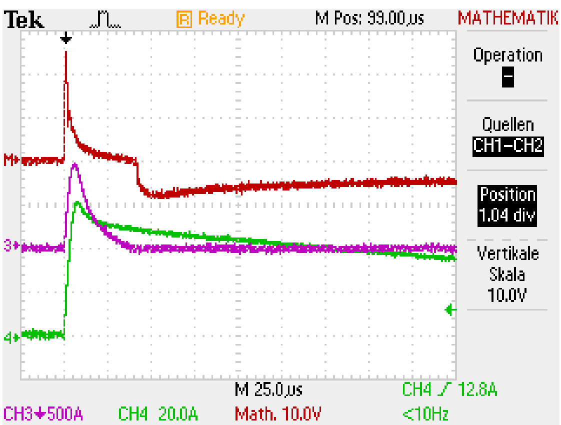

Fig. 26:
Bypass diode forward current i_{BF} (violet) in a module loop with n_C = 12 solar cells in a monocrystalline module BP7175N (*with metal frame*) at d = 25 cm ($M_i \approx$ 21 nH, $L_L \approx$ 1.2 µH, bypass diode SBM1040) induced by an impulse current (green, in kA instead of A!) with $i_{max} \approx$ 60 kA and $di/dt_{max} \approx$ 17 kA/µs. The peak current in the bypass diode is about 1 kA [9].

In the example shown in fig. 26, the bypass diode just about survived. In the forward mode, the voltage over the bypass diode (red) is limited to a few volts (except for a additional induced voltage due to a very small parasitic mutual induced voltage in the front of the impulse current). The current (violet), which has a similar form to the impulse current in the beginning, reaches a peak value of about 1 kA. Shortly after the peak of the impulse current, due to the temporarily higher negative di/dt of the lightning current (a minor deficiency of the impulse current generator used), the current in the bypass diode loop decreases somewhat faster than calculated according to the simulations in chapter 3. After the current has dropped to 0, still at the back of the lightning current, due to the slightly negative di/dt of the lightning current, the bypass diode is blocking, the bypass diode voltage is < 0.

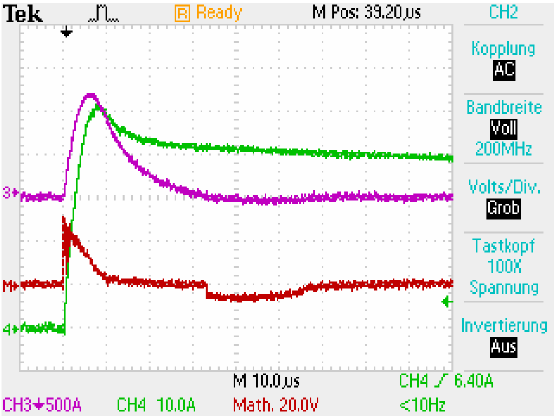

Fig. 27:
Bypass diode forward current i_{BF} (violet) in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without frame) at d = 40 cm ($M_i \approx$ 43.6 nH, $L_L \approx$ 1.5 µH, bypass diode SBM1040) induced by an impulse current (green) with $i_{max} \approx$ 52 kA and $di/dt_{max} \approx$ 13 kA/µs. The peak current is about 1.2 kA, destroying the diode [9].

In fig.27, the bypass diode failed. In the forward mode, after the small additional induced voltage in the beginning, the voltage over the diode (red) 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 1.2 kA. After the current has dropped to 0, due to the still slightly negative di/dt of the lightning current, the bypass diode is blocking for a short time, but soon it looses its blocking capability and is conducting.

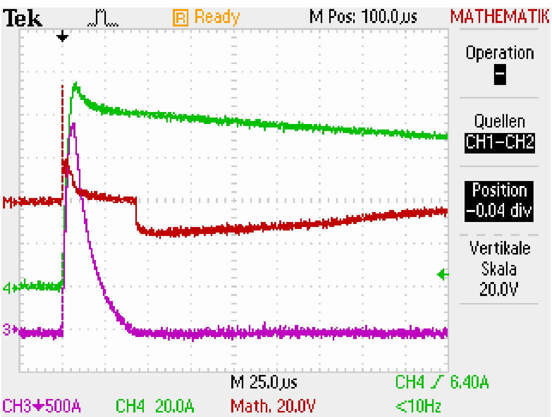

Fig. 28:
Bypass diode forward current i_{BF} (violet) in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without frame) at d = 40 cm ($M_i \approx$ 43.6 nH, $L_L \approx$ 1.5 µH, bypass diode 80SQ045) induced by an impulse current (green) with $i_{max} \approx$ 94 kA and $di/dt_{max} \approx$ 24 kA/µs. The peak current is about 2.4 kA [9].

A bypass diode 80SQ045 can survive a considerably stronger peak forward current (see fig. 28). In the forward direction, after the small additional induced voltage in the beginning, the voltage over the diode 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 2.4 kA.

Tests with stress in forward direction were also carried out with the remaining diodes and diode combinations (P1000M, LOW VF+TVS, P6KE24+SB1240). In all cases, the diodes could not be damaged, even with the highest induced currents i_{BF} (about 4 kA peak) that could be produced with our equipment and KC60L or BP7175N modules. As an example fig. 29 shows the test with a standard high voltage diode P1000M in a frameless module KC60L.

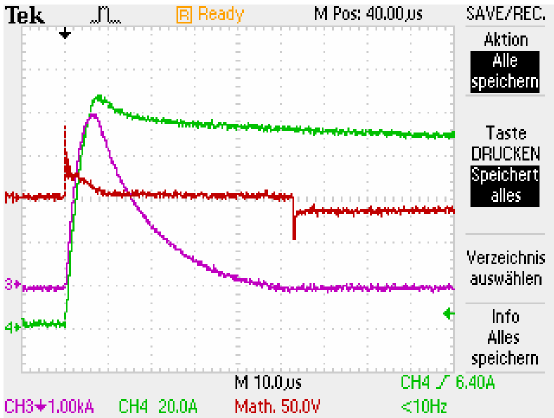

Fig. 29:
Bypass diode forward current i_{BF} (violet) in a module loop with n_C = 18 solar cells in a polycrystalline module KC60L (without frame) at d = 25 cm ($M_i \approx$ 64 nH, $L_L \approx$ 1.5 µH, bypass diode P1000M) induced by an impulse current (green) with $i_{max} \approx$ 108 kA and $di/dt_{max} \approx$ 25.7 kA/µs. The peak current is about 4 kA [9].

With the available test equipment, which can reach i_{max}, but not the high di/dt_{max} required by the standards for lightning protection class III [10] to [13], all diodes tested could be damaged in reverse direction despite the lower di/dt_{max}. However, only the two weakest diodes could be damaged in forward mode. Therefore it can be concluded that usually the reverse stress will be more dangerous than the forward stress and that the bypass diodes should primarily be designed for the reverse mode.

After the initial tests performed in 2007 and presented in [7], the German module manufacturer Alfasolar made a donation of two larger modules Alfasolar 130P6 for further tests. In a students project an attempt was made to use these larger modules to make tests with higher effecttive inductance M_i. In order to determine M_i and L_L by measurements, the open loop voltage and the short circuit current in the bypass diode loop have to be determined under defined conditions. To perform these tests correctly, the solar cell diodes must operate in forward direction. Unfortunately, by mistake in this students' project some short-circuit tests were performed with the solar cells in the reverse mode. The highest registered currents were 3 kA under these conditions. Like bypass diodes, in reverse direction solar cells can not withstand high avalanche currents similar to forward currents. Therefore they were damaged and not available for further tests.

Therefore, to assess the ruggedness of a certain solar module against nearby lightning currents, in principle not only the bypass diode, but also the *avalanche behaviour of the solar cells in the module* should be tested. If the bypass diode is too strong compared to the solar cells, the solar cells and therefore the module will be damaged instead of only the bypass diode.

Tests with modules with metal frame have shown, that it is important that the electrical contacts at the corners between the module edges are very good, as in close vicinity of (partial) lightning currents especially in large modules very high induced currents can flow in the frames (up to several 10 kA!). Therefore, if the contacts are only made by some screws in aluminium profiles and the modules are close to conductors carrying (partial) lightning currents, the contact resistance may be too high, leading to burned regions around these screws, reducing the frame reduction factor R_F and the protective effect of the frame. Such an event was observed during tests with BP7175N modules before the contacts at the corners were improved by adding additional aluminium connections.

5. Recommendations for effective mutual induction M_i and minimum separation distance d_m from lightning current i_P

The simulations performed in chapter 3 and the measurement results obtained in chapter 4 have shown that for a given value of M_i the current in the bypass diode is about inversely proportional to the number of cells n_C in the loop and to inductance L_L. Considering these results, the following first 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 (4) divided by the number of solar cells n_C in the bypass diode loop is **$M_i/n_C \leq 1$ nH/cell** and the ratio **$M_i/L_L \leq 0.01$** even for weak diodes like an SB1040.

If stronger diodes with peak permissible avalanche currents of a few 100 A are used, values for **M_i/n_C** up to **2 nH/cell** and ratios **$M_i/L_L \leq 0.02$** should be possible.

The worst case to be considered is not a single stroke, but a sequence of several strong negative subsequent short strokes (e.g. four strokes with $i_{max} \approx 25$ kA and $di/dt_{max} \approx$ 100 kA/µs within one second). The worst case is the parallel position according to fig. 1 to fig.4.

5.1 Direct calculation of M_i/cell and M_i/L_L

For practical application it would be useful to have some formulas giving directly these key values M_i/n_C and M_i/L_L. For this purpose, some dependencies between bypass diode loop length l, length of solar cells a, number of cells n_C in bypass diode loop, distance d_m from module edge closest to the lightning current i_P and distance d of centre of solar cell closest to i_P can be used (see fig. 30). Of course also the frame reduction factor R_F and k_C have to be taken into account.

Loop length l of a bypass diode loop: $l \approx 0.5 \cdot n_C \cdot a$ (12)

where

n_C = number of cells in bypass diode loop

a = cell length (in direction of l)

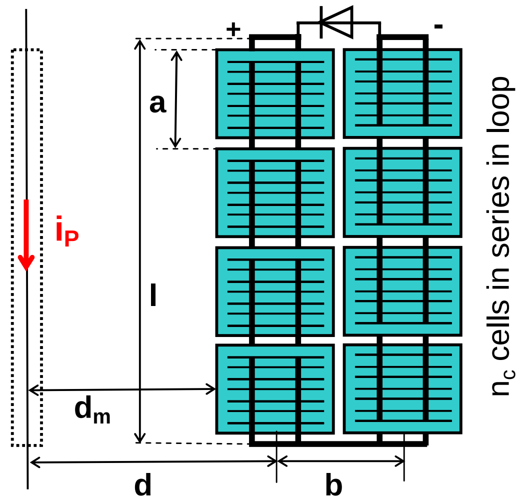

Fig. 30:
Drawing showing a module in parallel position and the dependencies between loop length l, number of solar cells n_C in bypass diode loop, cell length a (in direction of l), distance of the centres of the solar cells b, distance d of centre of closest solar cell row from i_P and d_m = distance of outer edge of closest solar cell from i_P (roughly also module distance).

Using (12) formula (3) can be modified to

$$M \approx 0.1 \cdot n_C \cdot a \cdot \ln\left(1 + \frac{0.9 \cdot b}{d + 0.05 \cdot b}\right) \qquad (13)$$

M is the mutual inductance in µH, if all distances a, b and d are indicated in meters [m]. For more details about symbols used see explanations under (1) and (3).

Considering that d is usually well > b, $d = d_m + 0.5 \cdot b$ and that $\ln(1+x) \approx x/(1+0.5x)$ for $0 < x < 1$ we obtain:

$$M \approx 0.09 \cdot n_C \cdot a \cdot \left(\frac{b}{d + 0.5 \cdot b}\right) = 0.09 \cdot \frac{n_C \cdot a \cdot b}{d_m + b} \qquad (14)$$

With $n = \frac{d_m}{b}$ (module distance in multiples of b) and including k_C and R_F according to (4) M_i becomes:

$$M_i \approx 0.09\,\mu H \cdot \frac{n_C \cdot a}{n+1} \cdot \frac{k_C}{R_F} \approx 0.18\,\mu H \cdot \frac{l}{n+1} \cdot \frac{k_C}{R_F} \qquad (15)$$

R_F = frame reduction factor: R_F = 2 – 6 for modules with metallic frame, R_F = 1 for other modules. $k_C = i_P / i \leq 1$, n_C = number of cells in loop, a = cell length in m, l = loop length in m.

For the critical quantity M_i/n_C we get:

$$\frac{M_i}{n_C} \approx 90\,nH \cdot \frac{a}{n+1} \cdot \frac{k_C}{R_F} \qquad (16)$$

The lower a, the lower k_C and the higher R_F, the lower $n = d_m/b$ can be (and the closer the module can be located to i_P) for the same value of M_i/n_C.

Formula (16) shows clearly, that in order to obtain a high ruggedness against damages caused by nearby lightning currents, *rectangular cells, whose length a is lower than their width b are better than square cells.* A good example is the module KC60 used for many tests with a ≈ 81 mm and b ≈ 160 mm where no damage was observed despite many hard tests also with strong bypass diodes.

Table 2 gives some examples of calculated values for n for different values of cell length a (for $k_C = 1$ and $R_F = 1$).

Necessary minimum factor n =d_m/b for separation distance d_m						
solar cell length a [mm]	50	80	100	125	150	200
n for M_i /n_C = 1 nH/cell	3.5	6.2	8	10.25	12.5	17
n for M_i /n_C = 2 nH/cell	1.25	2.6	3.5	4.63	5.75	8

Table 2:
Examples for values of n = d_m/b for some values of solar cell length a (in the direction of l, see fig. 30) calculated using (16) for k_C = 1 and R_F = 1.
Note: The values on the bottom line (for 2 nH/cell) are the same as for a module with 1 nH/cell and R_F=2.

The other critical quantity M_i/L_L can also be calculated as a function of n = d_m/b as follows:

Using (7) and (12) for a bypass diode loop of minimum size (worst case) we obtain:

$$L_L \approx 1.2 \cdot (0.5 \cdot n_C \cdot a) + 0.7 \cdot b = 0.6 \cdot n_C \cdot a + 0.7 \cdot b \quad (17)$$

L_L = Inductance of bypass diode loop in µH with diode integrated directly in module (a and b in m).

Combining (15) and (17) results in:

$$\frac{M_i}{L_L} \approx 0.09 \cdot \frac{n_C \cdot a}{n+1} \cdot \frac{k_C}{R_F} \cdot \frac{1}{0.6 \cdot n_C \cdot a + 0.7b} \quad \text{or reduced}$$

$$\frac{M_i}{L_L} \approx \frac{0.15}{n+1} \cdot \frac{k_C}{R_F} \cdot \frac{1}{1 + 1.17 \frac{b}{n_C \cdot a}} \quad (18)$$

where n_C = number of cells in bypass diode loop
a = length of solar cell in m (in direction of l)
b = width of solar cell in m
n = d_m/b relative distance from i_P

As b/(n_C·a) is << 1, n must be quite high to get M_i/L_L below the probably safe limits of 0.01 or 0.02 for k_C = 1 and R_F = 1. Table 3 shows the minimum values for n needed to reach these values for k_C = 1 and R_F = 1.

Necessary minimum factor n =d_m/b for separation distance d_m				
solar cells per bypass diode loop:	n_C =	12	18	24
For M_i/L_L = 0.01 and a = 0.5b:	n = d_m/b =	11.55	12.27	12.67
For M_i/L_L = 0.01 and a = b:	n = d_m/b =	12.67	13.08	13.3
For M_i/L_L = 0.02 and a = 0.5b:	n = d_m/b =	5.27	5.64	5.83
For M_i/L_L = 0.02 and a = b:	n = d_m/b =	5.83	6.04	6.15

Table 3:
Examples for calculated values of n = d_m/b for different numbers of solar cells n_C in a bypass diode loop and different ratios of a and b for M_i/L_L = 0.01 and 0.02.
Note: The values shown for M_i/L_L = 0.02 are the same as for a module with M_i/L_L= 0.01 and R_F=2.

As with the size of solar cells both mutual inductance M_i and loop inductance increase, the ratio M_i/L_L is not affected by cell size, but only slightly by the cell form (ratio a/b).

Placing the bypass diode in the connector box (instead of directly in the module) reduces M_i/L_L somewhat, therefore n = d_m/b can be a little lower. The formulas for calculations of this case are shown in (19) and (20).

Using (6) and (12) for a bypass diode loop with bypass diode in the connector box (usual case) and neglecting 0.05 in (6) we obtain:

$$L_L \approx 1.2 \cdot (0.5 \cdot n_C \cdot a) + 2.4 \cdot b = 0.6 \cdot n_C \cdot a + 2.4 \cdot b \quad (19)$$

Combining (15) and (17) results in:

$$\frac{M_i}{L_L} \approx 0.09 \cdot \frac{n_C \cdot a}{n+1} \cdot \frac{k_C}{R_F} \cdot \frac{1}{0.6 \cdot n_C \cdot a + 2.4b} \quad \text{or reduced:}$$

$$\frac{M_i}{L_L} \approx \frac{0.15}{n+1} \cdot \frac{k_C}{R_F} \cdot \frac{1}{1 + 4 \frac{b}{n_C \cdot a}} \quad (20)$$

For more details about symbols used see explanations under (17) and (18).

Due to the factor 4 in (20) instead of 1.17 in (18) for the same values of a, b, n_C and n the resulting M_i/L_L is always lower. Therefore the values calculated with (18) and shown in table 3 are worst case values. In order to obtain the correct values for bypass diodes mounted in connector boxes formula (20) should be used.

5.2 Examples for minimum separation distance d_m to (partial) lightning currents

With the formulas described in section 5.1, considering the kind of module (with / without metal frame, full or only partial lightning current to be taken into account) it should be possible to calculate the necessary separation distance d_m, if no detailed measured data about a certain module are available.

For modules with square cells (most frequent case) close to a full lightning current (k_C = 1), table 4 gives recommended values for minimum separation distance d_m for modules in parallel position (fig. 30) with and without metal frame and with weak and reinforced bypass diodes.

Necessary separation distance d_m for square cells [m]				
solar cell width b [mm]	100	125	150	200
no frame, weak bypass diode	1.3	1.6	2	3.4
no frame, reinforced bypass diode	0.6	0.75	0.9	1.6
metal frame, weak bypass diode	0.6	0.75	0.9	1.6
metal frame, reinforced bypass diode	0.25	0.32	0.38	0.7

Table 4:
Necessary minimum separation distance for different module types with and without metal frame (R_F = 2) for weak diodes (M_i/n_C= 1 nH/cell and M_i/L_L = 0.01) and for reinforced diodes (M_i/n_C = 2 nH/cell and M_i/L_L = 0.02).

Table 4 clearly shows the beneficial effect of a metal frame, which reduces the necessary value of the separation distance d_m considerably, especially if it is combined with a reinforced bypass diode or another measure to reduce M_i further. Possible additional measures for reduction are e.g. splitting the lightning current into several fractions resulting in k_C-values < 1 or mounting the modules in normal position [1], [5] with their short edge parallel to the (partial) lightning current i_P.

If stresses according to lightning protection class I or II have to be considered, in formulas (16), (18) and (20) reduced values have to be used:

For lightning protection class II with i_{max} ≤ 150 kA and di/dt ≤ 150 kA/µs) these values are M_i/n_C ≤ 0.67 nH/cell and M_i/L_L ≤ 0.0067 for weak diodes and twice these values for reinforced diodes.

For lightning protection class I with i_{max} ≤ 200 kA and di/dt ≤ 200 kA/µs) these values are M_i/n_C ≤ 0.5 nH/cell and M_i/L_L ≤ 0.005 for weak diodes and twice these values for reinforced diodes.

6. Conclusions

With the method presented, 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. Based on these results manufacturers can estimate the stress to which their components might be exposed. Therefore they could give appropriate recommendations to their customers based on the limit data of their solar cells and bypass diodes.

In order to verify the models used and the limits found so far, further tests with other module and diode types should be performed.

The models developed are based on many tests with several different module types and more than hundred bypass diodes. Reinforcing the bypass diodes can certainly improve ruggedness of solar modules against nearby lightning strokes. However, as it could be clearly demonstrated that by strong induced currents (especially in the avalanche mode) also the solar cells themselves can be damaged, it would be best to perform such tests with real modules with the bypass diodes and the solar cells actually used in a given module. Bypass diode defects mostly end up in a not perfect short circuit, which does not only reduce the performance of the module, but may cause a dangerous electrical DC arc which might even end up in a fire.

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.

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