PV Fuse-Links –Superior Protection of Valuable Photovoltaic Modules

Fuses have been used for electric circuit protection since late 19th century. However, new technologies like photovoltaic (PV) power systems have been evolving with new equipment, new wiring procedures, and new installation rules requiring specific fuses and application guidance. Increasing demand for alternative energy and strong financial support by some governments has boosted the installation of PV power systems faster than commonly accepted rules and international standards could be developed. Many terms, definitions and test procedures are still undefined and used in different ways. This article is thought to give some guidance to properly select fuses for PV systems without claiming to represent a fully recognized state of the art. PV module and fuse technology are still developing and ongoing investigations and field experience may lead to different results.

Local wiring and installation rules generally require overcurrent protection whenever a risk of fire exists by overheating of conductors. Additionally, overcurrent protective devices, e.g. fuses, when properly selected and applied, are able to save valuable equipment in the event of electric faults.

Special fuses have been developed for the protection of PV systems and standardization work is in progress to meet the very challenging requirements of d.c. circuits typical to PV generators. One has, however, to keep in mind that even these special fuses cannot provide fire protection under all potential fault conditions, e.g. in the event of an arc fault. Fuses may therefore need to be accompanied by other protection means.

The first part of this article is meant for application and service engineers who have to select fuses for PV system design or to replace operated fuse-links. Those who wish first to understand the rational behind fuse application rules may go straight to the appendix.

PV Fuse application guide for fast readers

-see Appendix for detailed technical explanations

PV modules are current-limited devices that are able to withstand any load currents including their rated short-circuit current I_{SC_STC} and occasional overcurrents due to higher than standard irradiation. Indeed, enhanced irradiation may temporarily boost operating currents to a level of 1,4 to 1,6 I_{SC_STC}. [1].

Partial shadowing of cells in a string of modules may cause local hotspots and do severe damage to modules. As overheating is caused by increased voltage at normal operating currents, fuses cannot help. By-pass diodes are the preferred solution to prevent hotspots.

Properly designed PV generators require therefore no overcurrent protection in faultless condition.

In faulted circuits, however, PV modules may be damaged by reverse overcurrents exceeding the reverse current withstand of the modules $I_{MOD\_REVERSE}$. The effects of fault currents may range from permanent damage to PV modules and reduced efficiency to broken conductors resulting in electric arcs and fire. Dangerous fault currents originate from external sources, e.g. from modules or strings of modules that are connected in parallel to the faulted string, from storage batteries in the system or from backfeeding through grid-interactive inverters.

Properly rated PV string fuses are able to protect PV modules or strings and internal wiring against dangerous reverse overcurrents.

The following guidance for the selection of PV string fuses applies primarily to PV generators without external power sources i.e., systems with no storage battery and with inverters that

[1] STC (standard test conditions): 25 °C, 1.000 W/m^2, air mass factor 1,5

cannot feed back from the grid. Additional battery fuses, PV array or PV sub-array fuses may be required in other PV systems.

NOTE - *Fault currents in PV generators depend heavily on the actual irradiation and may be much below I_{SC_STC}. Dangerous sustained electric arcs may exist with currents that would not trip an overcurrent protective device.*

Selection of PV string fuse-links

a) The number of strings connected in parallel decides on the need for fuse protection

The selection of string fuses is governed by the reverse current withstand value $I_{MOD\_REVERSE}$ of the PV modules and the string wiring. PV module manufacturers publish related values or maximum fuse ratings.

No fault current protection is generally required in PV systems consisting of only one or two strings in parallel i.e., if the fault current cannot exceed the reverse current withstand of the PV modules. For systems with greater numbers of strings in parallel, fuse protection is recommended depending on the reverse current withstand capability $I_{MOD\_REVERSE}$ of the modules (figure 1).

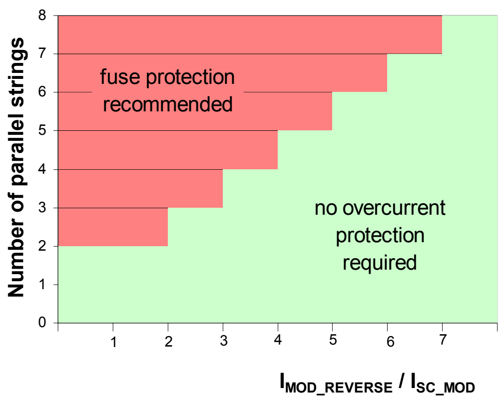

Fig. 1 - Application of string fuses

b) Designated "PV" fuses shall only be used

The use of improper fuses in PV systems may rather be a cause of damage than provide damage protection. Until a specific standard for PV fuses will exist, only fuse-links labelled "PV" or specified by the manufacturer for the protection of PV systems shall be used.

c) Fuse protection in both poles

Unearthed (floating) PV systems, as very common in Europe, require disconnecting and overcurrent protection devices in both poles of PV strings. When PV string fuses are required for reverse overcurrent protection, the use of fuse-disconnectors (fuse-combination units) is recommended for safe fuse-link replacement.

d) Rated breaking capacity

PV string fuses shall be d.c. rated and have a rated breaking capacity of greater than or equal to the maximum fault current of the PV system. A minimum breaking capacity of d.c. 25 kA is recommended with respect to fault currents from power storage units or grid back-feed currents. The time constant of the circuit is assumed less than 2 ms, i.e. fuse-links may be assigned a higher breaking capacity in PV systems than in systems having greater time constants.

e) Breaking range

PV string fuses shall be of the full range breaking type ("g" type), i.e. they shall be able to safely interrupt any currents from minimum melting current to its breaking capacity. Commonly available PV string fuse-links are of "gR" or "gS" type according to IEC 60269-4. A new standard for "PV" type fuses is presently being worked out and expected to be future IEC 60269-6. "PV" fuse-links referred to in this article, follow the draft standard requirements with respect to conventional fusing and non-fusing currents.

Note - *Partial range breaking capacity ("a" type) fuse-links must not be used as they may cause dangerous arcing when operated above melting current but below the minimum breaking current.*

f) Rated voltage

The fuse rated voltage U_n shall be equal or greater than the maximum open circuit voltage U_{OC} of the PV array or generator:

$U_n \geq 1{,}2\ U_{OC\_STC}$)

(Factor 1,2 accounts for increased open circuit voltage at low ambient temperatures and may be increased for cold climate conditions).

g) Minimum fuse-link rated current of PV string fuses

The fuse-link shall not operate nor deteriorate under normal operating conditions in order to avoid nuisance tripping. The ability to carry currents without deterioration is closely related to the temperature rise of fuse-elements. Operating currents above fuse-link rated current shall therefore be avoided. This is an even more vital requirement for fuses subjected to temperature cycles by repeatedly fluctuating currents as typical in PV systems.

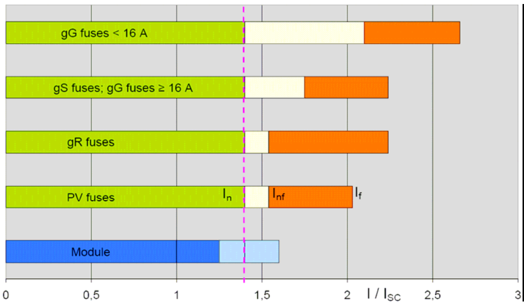

Fig. 2 - Breaking range of different fuse types
I_n - fuse rated current
I_{nf} - non-fusing current; I_f - fusing current

The rated current I_n of string fuses shall therefore be greater than the maximum operating string current, which ranges from 1,25 I_{SC_MOD} to 1,6 I_{SC_MOD} depending on local climatic conditions, including an allowance for enhanced irradiation. A reasonable application rule appears to be

$$I_n \geq 1{,}4\ I_{SC\_MOD}$$

NOTE - *Fuse-link manufacturers may apply deratings for conditions of use, e.g. high ambient temperatures or densely packed fuse-inks in enclosures with restricted heat dissipation (see below).*

As illustrated in figure 2, special “PV” fuse-links provide superior protection to standard fuse-links because of their lower fusing current rating I_f.

h) Maximum fuse-link rated current

The fusing current I_f of the fuse-link shall be equal or smaller than the no-damage reverse current (“overcurrent protection rating”) of the module. Which rule results to

$$I_n \leq 0{,}9\ I_{MOD\_REVERSE} \text{ for “PV” fuse-links}$$

(see appendix for details and for other fuse types).

NOTES - *In any case, the maximum fuse-link rated current as given by the module manufacturer must not be exceeded.*

For high values of $I_{MOD\_REVERSE}$ / I_{SC_MOD} and a great number of strings in parallel it has to be double-checked that string cable protection is still given.

i) Power dissipation and ambient temperature

PV fuse-links exhibit very low power dissipation compared with other protective devices or blocking diodes. However, array junction boxes may be exposed to high ambient temperatures and contain a greater number of fuse-links and other electric devices, e.g. blocking diodes, generating a significant temperature rise inside the enclosure. Unlike with distribution boxes acc. to IEC 60439-1, reduced load factors for greater number of circuits are not applicable. Temperature rise calculations and tests have to be based on maximum load currents in all circuits. Derating factors for high ambient temperatures as published by PV fuse manufacturers may apply.

j) Fluctuating load

PV fuse-links are subjected to frequently fluctuating load currents and shall therefore not deteriorate under the influence of permanently changing temperatures. A derating factor may apply to the fuse-link rated current according to manufacturer's literature and advice.

k) Fuse-link monitoring

The operation of one PV string fuse-link in an array or generator of multiple strings may not be easily detected. Electronic fuse monitoring is therefore recommended to report fuse operation and to enable immediate investigation and repair of the faulted string in order to minimize the loss of power supplied.

Selection of PV fuse-links for PV sub-arrays and for PV arrays (PV generators)

Fuse-link selection for arrays or sub-arrays follows the same rules than the selection of PV string fuses with respect to minimum rated current. The fuse-link rated current has to be greater than the maximum operating current of the PV sub-array combined of n PV strings and the maximum operating current of the PV array combined of n_A PV sub-arrays respectively:

$I_n \geq 1{,}4\ I_{SC\_SUB\_ARRAY} = n\ 1{,}4\ I_{SC\_MOD}$ and

$I_n \geq 1{,}4\ I_{SC\_ARRAY} = n_A\ 1{,}4\ I_{SC\_SUB\_ARRAY}$

The maximum fuse-link rated current of PV arrays and PV sub-arrays is selected to protect the conductors of the adjacent cables and shall be equal or smaller than the current carrying capacity I_Z of the corresponding conductors:

$I_n \leq I_{Z\_ARRAY\_CABLE}$ and

$I_n \leq I_{Z\_SUB\_ARRAY\_CABLE}$ respectively

PV array cable overcurrent protection is only required for systems connected to batteries or where other sources of current may feed into the PV array under fault conditions.

Discrimination

Overcurrent protection within a PV generator shall be coordinated in such a way that, in the event of fault, the protective device on the lowest level component (string < sub-array < array) carrying the fault current operates first. Until a new PV fuse standard may establish specific discrimination rules, the time current-characteristics published by fuse manufacturers shall be used for proper coordination of fuse-links on different levels of a PV generator.

Unacceptable fuses

Only fuses having sufficient d.c. breaking capacity shall be used for the protection of PV strings, PV sub-arrays or PV arrays. Unfortunately, most fuses available in the market have to be considered unqualified though they may have same dimensions or seemingly same voltage and current ratings as qualified PV fuses. Specific care must be taken with the following likely unqualified fuses:

- Miniature fuses
- Automotive fuses
- Domestic fuses

Fuses for use by unskilled persons acc. to IEC 60269-3 (domestic fuses) are generally a.c. rated and do not qualify for PV applications, except D type fuses which are also d.c. rated as they are frequently used in industrial installations.

APPENDIX

Know the equipment to be protected

PV generators behave much different than other power generators as concerns operating currents as well as fault currents. Thorough knowledge of physical principles and operating conditions are vital for proper fuse selection and coordination. Unlike with other electrical power supplies, there is no significantly greater short-circuit current than the maximum operating current. Traditional fuse selection rules are therefore not applicable.

PV Cells

Table A1 - Cell sizes and currents (typical values of silicon cells)

Cell size		I_{SC}
4 ″	10 x 10 cm^2	3,5 A
5 ″	12,5 x 12,5 cm^2	5 A
6 ″	15,6 x 15,6 cm^2	7,5 A
8 ″	21 x 21 cm^2	14 A

PV cells, commonly referred to as solar cells, are the basic elements of PV power generation. PV cells are semi-conductor diodes having an exposed barrier junction, accessible to sunlight and generating electricity when illuminated. In the dark, PV cells behave very much like ordinary diodes (see characteristics in figure A1).

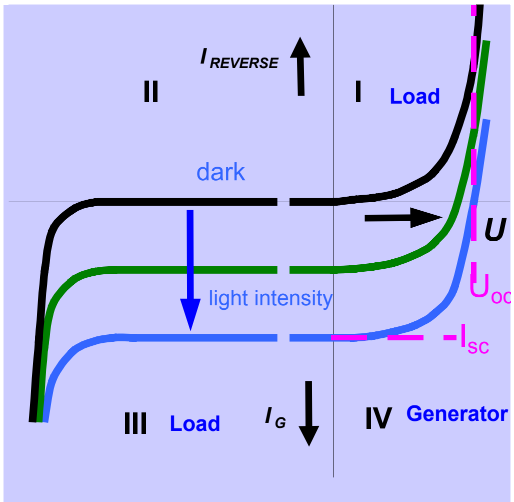

Fig. A1 – PV cell characteristics
(Load reference arrow system)

NOTE - *The load reference arrow system is used throughout this article as, in the event of overcurrents or irregular operation, all circuit components that require protection are power absorbing loads.*

PV cells represent passive loads when operating in quadrants I and III of figure A1. Electric energy is only supplied when the PV cells operate within quadrant IV. This quadrant, with the axis of current being inverted (generator diagram: axis I_G pointing to the top) is commonly used to display the characteristics of PV cells, modules and generators alike (see figure A2).

NOTE - *Currents in forward direction of the diode are defined as "reverse currents" $I_{REVERSE}$ with respect to PV generator operating currents.*

The maximum short-circuit current I_{SC} supplied by a PV cell is limited by the cell size (see table A1) and proportional to the irradiance intensity (figure A1). The voltage generated by a PV cell corresponds to the threshold value of the diode and is close to 0,5 V for a silicon diode. The open circuit voltage U_{OC} of commercially available silicone PV cells ranges typically between 0,5 V and 0,7 V at 25 °C operating cell temperature. For commercial applications, a number of PV cells will therefore be interconnected in series and in parallel to achieve the desired output power. Series interconnection gives added output voltage while parallel interconnection gives added currents (see figure A2).

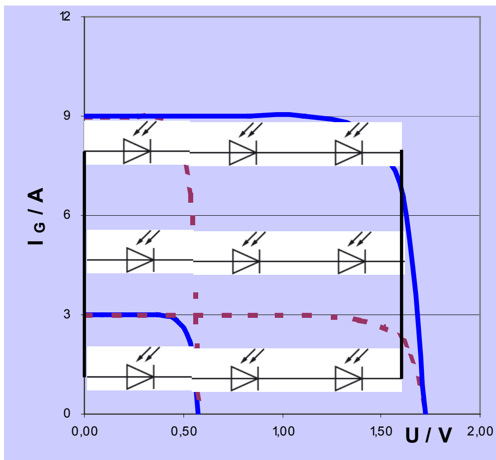

Fig. A2 - Generator characteristics of PV cells connected in parallel and in series

For testing and rating of PV cells and PV modules, a standard set of reference conditions has been defined in IEC 61215. These standard test conditions marked with the index "STC" are:

- Cell temperature T_{STC} = 25 °C
- Irradiance intensity G_{STC} = 1.000 W/m^2
- Light spectrum (relative optical air mass) AM = 1,5

NOTE - *Standard Test Conditions represent an approximation of the environmental conditions in Central Europe. Local and temporary climatic conditions may deviate significantly.*

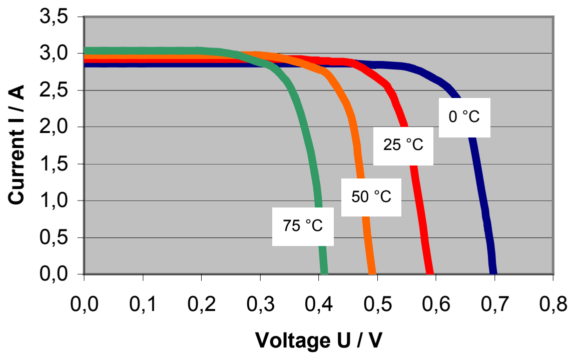

Fig. A3 - Cell characteristics at various temperatures

While the PV cell temperature does not significantly influence the maximum PV cell current, the cell open circuit voltage and consequently the power supplied, drop substantially at high temperatures as shown in figure A3. Low ambient and PV cell temperatures raise the PV system voltage and the energy yield.

PV Cell characteristics are reflected in PV module, PV string and PV array characteristics at different scale of voltage and current.

PV modules

PV cells are fragile items and require mechanical and environmental protection for better handling and outdoor installation. Besides, the power supplied by single PV cells is hardly of any practical use because of their limited output voltage of about 0,5 V. A greater number of cells, typically 36 up to 120, is therefore interconnected in series to achieve the desired output voltage and assembled and environmentally protected in PV modules. Usually, PV cells are not interconnected in parallel within a PV module, i.e. the PV cell current and PV module current are identical.

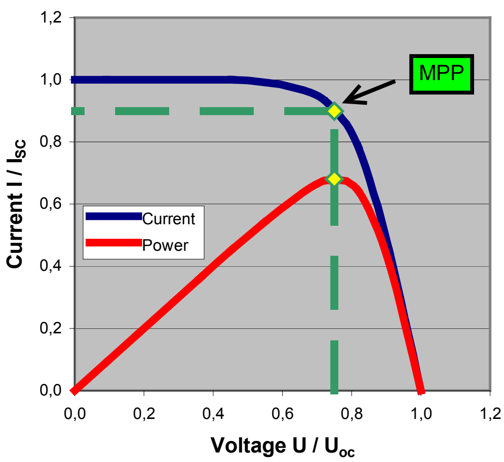

Fig. A4 - Module characteristics

PV modules include a module junction box, mounted to the back of the module, and connecting means, e.g. cables and connectors for the addition of further modules. Bypass diodes (figure A11) may be either integral parts of the module or included in the module junction box.

PV module manufacturers supply technical data, e.g. short-circuit current I_{SC}, open circuit voltage U_{OC} and the optimum operating parameters I_{MPP} and U_{MPP} defining the maximum power point MPP of the module (figure A4). For maximum utilization of solar irradiation, the PV generator needs to be operated as closely as possible to the maximum power point. A sophisticated electronic control called MPP tracker is therefore required to respond to the fluctuating environmental conditions and is usually integral part of the power conditioning system that adapts the PV generator to primary networks (figure A5).

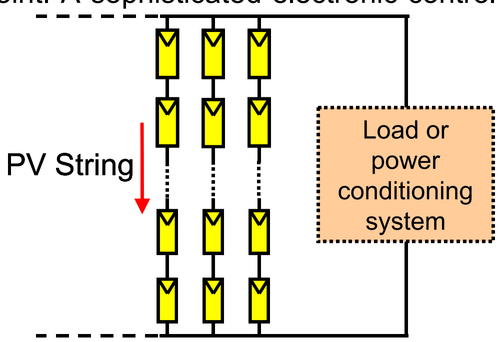

Fig. A5 - PV Generator

PV generators (PV arrays)

PV generators comprise the whole assembly of d.c. components in a PV system except energy storage devices or power conditioners or loads (figure A5). A module of 36 cells may be used to charge a 12 V battery in a stand-alone system. In this application, the single module would form a PV generator or PV array. Larger grid tied systems require a greater number of modules, interconnected in series to form PV strings (figure A5) in order to achieve the desired voltage. Greater currents may be achieved by paralleling several PV strings to form a PV array and several PV sub-arrays may be interconnected in parallel to form a PV generator. String cables of positive and negative polarity are commonly joined in array junction boxes (figure A6) that may also include overvoltage protection devices and, when required, blocking diodes.

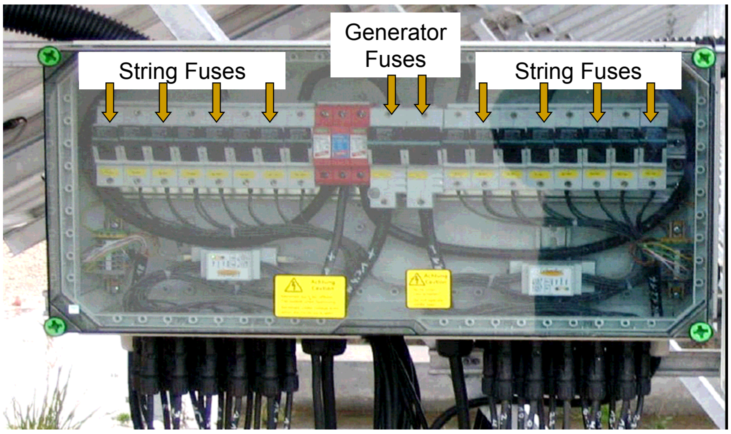

Fig. A6 - Array junction box

There is virtually no limitation to achieve huge amounts of electric power, e.g. in the order of several Megawatts, by interconnecting PV modules in series and in parallel. Specific care must be taken to interconnect only same type of modules having same characteristics within close tolerances. Marked tolerances in module characteristics or irradiation result in significant power loss and generator efficiency.

Regular and irregular operating conditions

It is well understood that regular operation of PV cells should be within quadrant IV of figure A1, i.e. electricity should be generated. Irregular operating conditions within quadrants I and III can, however, not always be avoided and may lead to overheating and even thermal destruction of PV cells. An equivalent circuit diagram consisting of a current source and a diode in parallel (see figure A7), may be helpful to approximate the electric behaviour of PV cells and to explain various operating conditions:

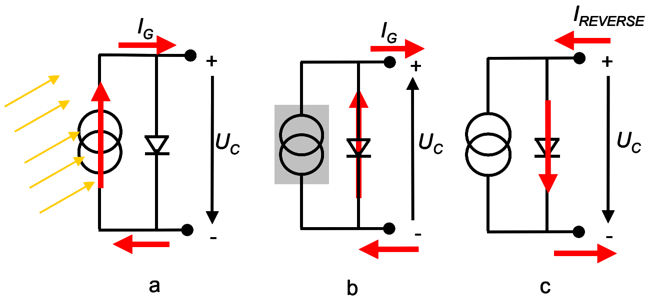

Fig. A7 - Equivalent circuit diagram of a PV cell a) irradiated b) shadowed c) reversed

- **In the sunlight**, PV cells (figure A7 a) generate a (forward) current I_G and a voltage U_C corresponding to operation in quadrant IV of the cell characteristic (figure A1). Operating currents including short-circuit currents are limited by the current source nature of PV cells and will not normally damage properly designed PV systems.
- **Partial shadowing** of one PV cell in a string of multiple PV cells will hardly influence the generator current but force the PV cell to operate in quadrant III, i.e. reverse the polarity of the cell voltage (figure A7 b) and raise it to the junction breakdown level of $U_C \approx -15$ V to -25 V (figure A9). The power absorbed by shadowed PV cells in a string is raised by more than one order of magnitude above normal operating conditions. The temperature rise involved causes hot spots (figure A8) that may permanently damage the PV module. Unfortunately, **fuses cannot protect PV modules from hot spots** as these are not caused by overcurrents, but by high reverse voltages (figure A9). Hot spots

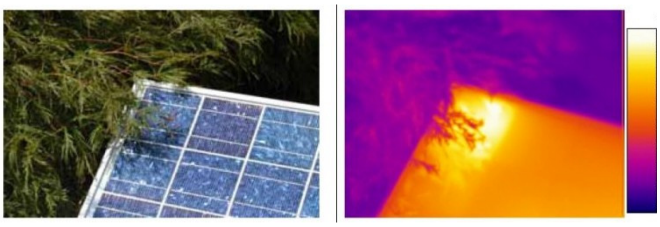
Fig. A8 - Hot spot due to partial shadowing

Photo: Photovoltaik-Systemtechnik Schlussbericht
by Luciano Borgna, Christof Geissbühler, Dr. Heinrich Häberlin, Martin Kämpfer, Urs Zwahlen
Berner Fachhochschule, Technik und Informatik, Fachbereich Elektro- und Kommunikationstechnik, Photovoltaiklabor, Jlcoweg 1, CH-3400 Burgdorf
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can widely be prevented by means of bypass diodes connected across several cells or across a module in generator (forward) current direction (figure A11). The detection of hot spots requires regular inspections by means of infrared camera.

- **Reverse currents,** as illustrated in figure A7 c, may be imposed to a shadowed module by parallel modules exposed to high radiation levels. The shadowed module represents a load and operates in quadrant I (figure A1). Under faultless conditions, the operating voltage is limited to the maximum open circuit voltage U_{oc}. Consequently, in faultless systems, the absolute values of reverse currents can hardly exceed the short-circuit current level of the module.

  In faultless circuits, reverse currents do therefore not represent dangerous loads that would require fuse protection.

  However, in faulty PV generators, the voltage applied to individual modules may exceed the normal open circuit voltage and generate substantially greater reverse currents, which may overheat the module and should be interrupted by string fuses before damage occurs (figure A9).

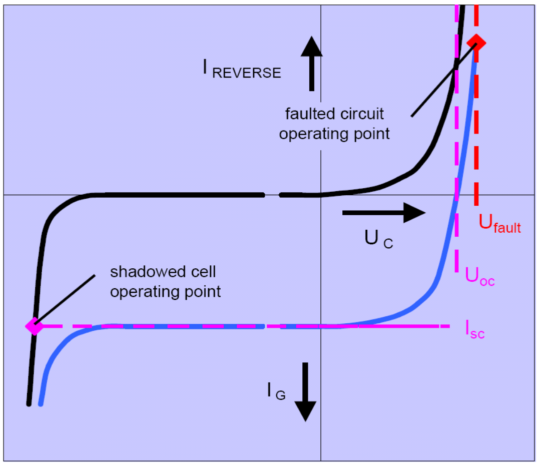

Fig.A9 - Shadowing and fault conditions

Fault currents in PV systems

Unlike with other power sources, short-circuiting of the load would not result in dangerous overcurrents in a PV system. Overcurrents may, however, result from short-circuit faults in modules, junction boxes and module wiring or from earth faults in array wiring. Though PV modules are current-limited sources, they can be subjected to reverse overcurrents supplied by either multiple parallel PV strings or from external sources (e.g. batteries) or both.

Some potential faults and resulting maximum fault currents (open load circuit and standard test conditions) in a PV system of n parallel strings and without external source are explained in figure A10:

a) Module short-circuit

The total output voltage of the faulted string is by the output voltage of one module less than the open circuit voltage of the healthy strings. Hence, the n-1 parallel strings feed back into the faulted string (figure 10, fault a). The reverse current in the faulted string may amount to

$I_{REVERSE} \approx (n - 1)\, I_{SC}$.

The corresponding electric power of

$P_v = U_{MODULE} \times I_{REVERSE}$

has to be dissipated by the healthy modules in the faulted string and carried by the connecting cables. The current in the conductors of the short-circuit loop is even greater and amounts to $I_{fault} \approx n\, I_{SC}$.

b) Double earth fault

In the event of simultaneous earth faults in a busbar and one string, the earth loop

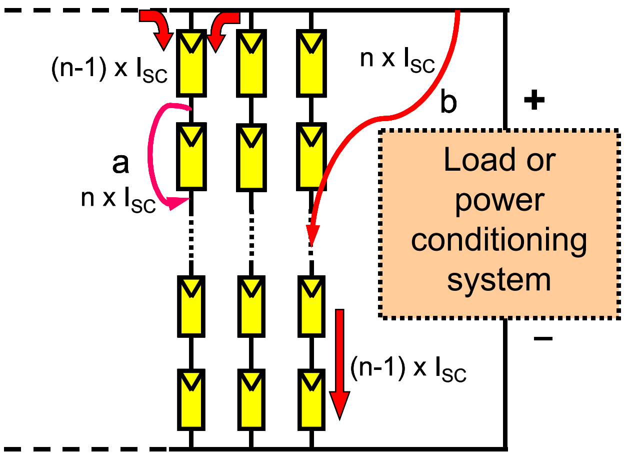

Fig. A10 - Potential faults in a floating PV array

current amounts to $I_{fault} \approx n\ I_{SC}$ and the reverse current in the string segment between fault and opposite busbar is

$I_{REVERSE} \approx (n\text{-}1)\ I_{SC}$, corresponding to a power loss of $P_v = U_{MODULE} \times I_{REVERSE}$

In both cases, overheating of modules and conductors may be expected and overcurrent protection is required depending on the number of parallel strings (see figure 1). Double earth faults can, of course, occur in opposite polarity to the one shown in figure A10. Therefore, in a floating PV system, overcurrent protective devices, if required, have to be installed in both, positive and negative string cables.

Reverse overcurrent protection by means of PV string fuses

In most large size PV generators, overcurrent protective devices are required to protect cables and PV modules from overheating in case of insulation faults. Fuses are preferably used because of their reliability, compactness, low costs and low power dissipation. As the cables are usually selected by voltage drop requirements, the required current carrying capability is almost automatically given and the major task of fuses remains to protect valuable PV modules from overheating and damage by reverse overcurrents.

Principal criterion for fuse selection is therefore the reverse current a PV module can withstand temporarily until a protective device interrupts the fault current. Typical values for $I_{REVERSE}$ of crystalline silicon PV modules may be assumed between 2 I_{SC_STC} and 3 I_{SC_STC}. (Module manufacturers, depending on cell material and module design may give greater values.)

Fault current protection is irrelevant in PV systems consisting of only one or two strings in parallel, and without storage battery, provided the PV modules are capable of withstanding a reverse current at least equal to their rated short-circuit current I_{SC_STC} (see figure 1).

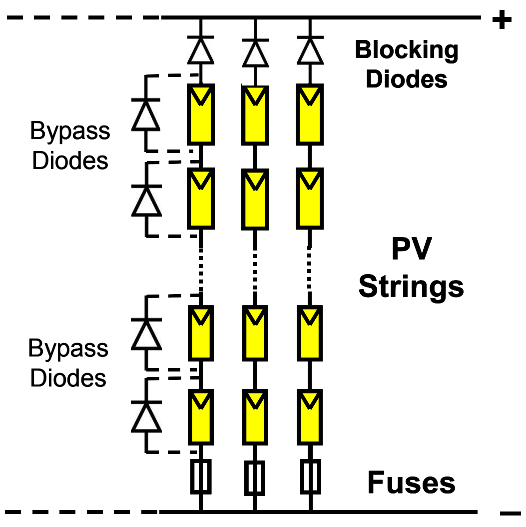

Fig. A11 - Protective devices in a PV generator

Module manufacturers may give applicable values for $I_{MOD\_REVERSE}$ depending on cell material and module design. As an alternative, a maximum rated fuse current may be given, which is, however, not very meaningful without precise fuse specification.

NOTE - *Some module manufacturers specify a maximum reverse current about equal to the rated short-circuit current $I_{MOD\_REVERSE} \approx I_{SC\_MOD}$ and a significantly higher fuse rating, which is confusing. Seemingly, the lower rating refers to intentional application of reverse currents for de-icing or snow removal purposes, the higher value refers to fuse protection under fault conditions.*

When the module manufacturer assigns maximum fuse rated currents, the direction has to be followed and, in case of doubt, the exact fuse type clarified with the module manufacturer's customer service.

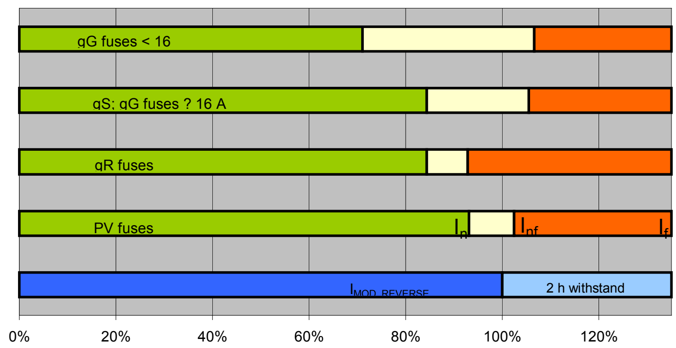

Fig. A12 - String fuse coordination
I_n - fuse-link rated current I_{nf} - non-fusing current; I_f - fusing current

When the module manufacturer specifies values for $I_{MOD\_REVERSE}$, it can be assumed that this rating has been verified according to IEC 61730 in a 2 h test at 1,35 $I_{MOD\_REVERSE}$ with no resulting damage. Hence fuse protection is given when a fuse-link assigned to the module operates prior to this no-damage test value.

Different type fuse-links, having different conventional time and fusing current ratings, require different coordination rules as listed below and illustrated in figure A12. As the conventional fusing time of commonly applied string fuse-links amounts to 1 h an is below the 2 h withstand time of the module, the following formula for string fuse selection includes a certain safety margin and gives the maximum fuse rating for a specific module:

$$\mathbf{I_f \leq 1{,}35\ \mathit{I}_{MOD\_REVERSE}}$$

For standard fuse types, the following selection criteria apply:

$I_n \leq 0{,}85\ I_{MOD\_REVERSE}$ for “gR”, “gS” or “gG” fuse-links > 10 A

$I_n \leq 0{,}7\ I_{MOD\_REVERSE}$ for “gG” fuse-links ≤ 10 A

“PV” rated fuse-links, specifically developed for PV string protection, exhibit a fusing current of $I_f = 1{,}45\ I_n$ and are selected

$I_n \leq 0{,}9\ I_{MOD\_REVERSE}$

Until a generally accepted standard exists, this application rule should be used with manufacturers' agreement.

Fuses or blocking diodes?

Some, but not all reverse currents can be blocked by means of blocking diodes in the strings (figure A11). However, blocking diodes are not considered substitute for string fuses. Blocking diodes may be indispensable items in PV systems containing storage batteries, to prevent battery discharge during night time. Their use should, however, be restricted to such applications and be avoided otherwise because they may be sources of failures and account for significant power loss.

Blocking diodes are not considered reliable reverse overcurrent protection as they often fail in short circuit mode and are susceptible to overvoltage.

In addition, the power dissipation of blocking diodes exceeds many times the one PV string fuses (figure A13), hence reducing the efficiency of the PV generator and dominating the temperature rise inside PV array junction boxes.

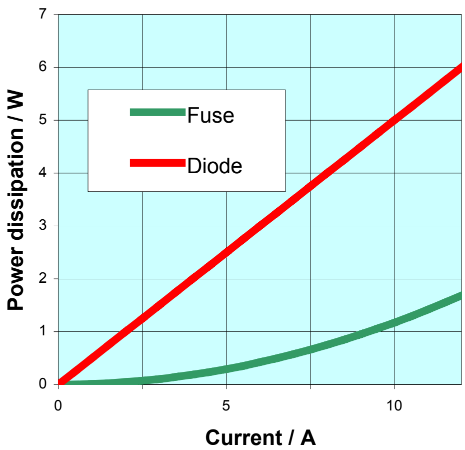

Fig. A13 - Power dissipation of blocking diodes versus PV string fuses

As PV technology including PV fuse technology are still developing, it might be a good idea from time to time, to contact your fuse specialists organized in Pro Fuse International for detailed information and advice.