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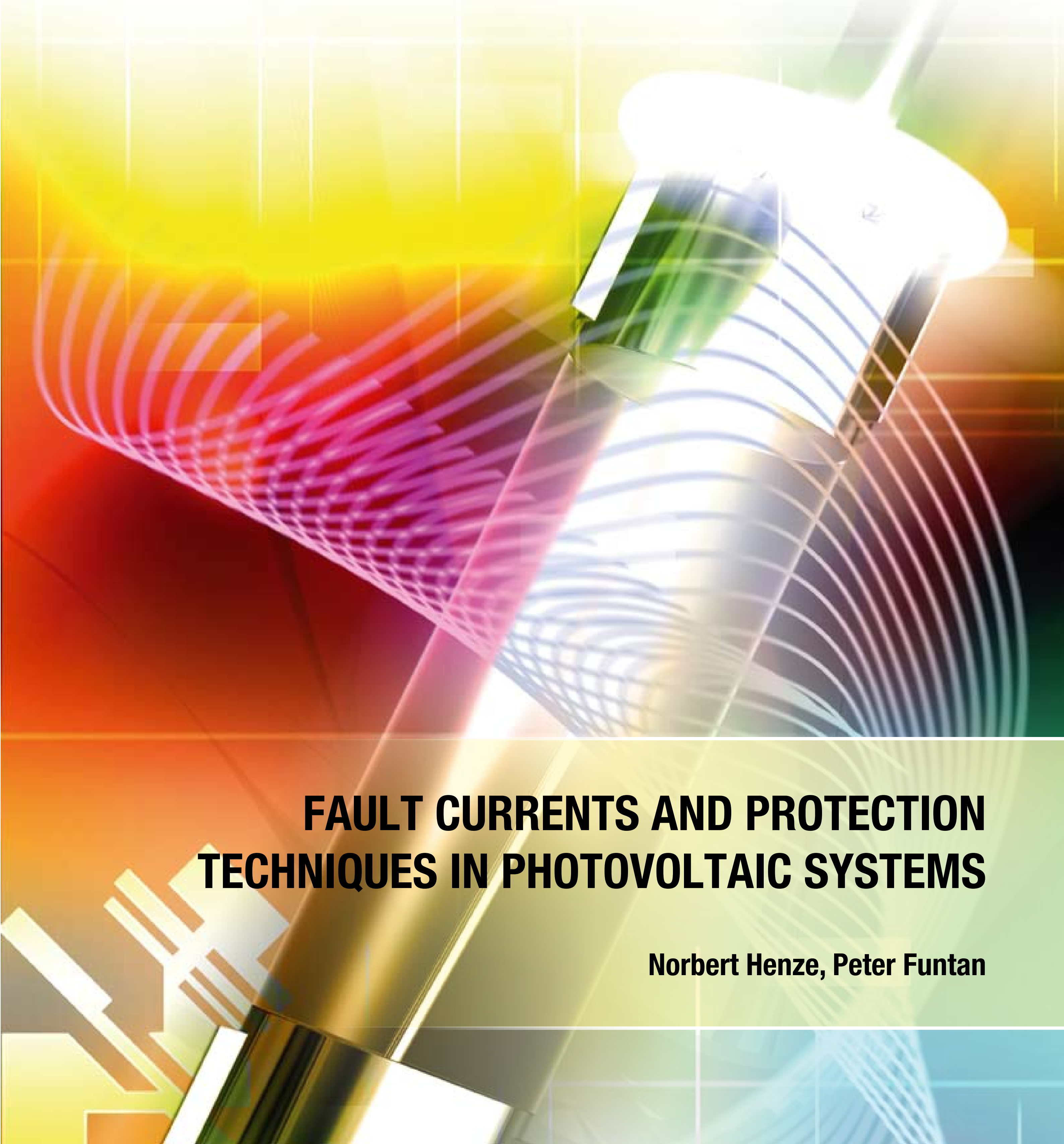

FAULT CURRENTS AND PROTECTION TECHNIQUES IN PHOTOVOLTAIC SYSTEMS

Norbert Henze, Peter Funtan

Fault Currents and Protection Techniques in Photovoltaic Systems

Theoretical Considerations of the Use of Fuses in Photovoltaic Systems

Norbert Henze, Peter Funtan

Fraunhofer Institute for Wind Energy and Energy System Technology IWES, Area: Systems Engineering and Grid Integration, Königstor 59, D-34119 Kassel, norbert.henze@iwes.fraunhofer.de,
peter.funtan@iwes.fraunhofer.de

Abstract

The use of fuses in photovoltaic systems is being controversially discussed among experts. On the one hand, the proper operation of the system is not supposed to require the use of fuses and in addition is considered a possible source of error. On the other hand, there is the insecurity that inadmissibly high currents may flow through the strings concerned even in regular operating conditions, e.g. in case of shading and partial snow cover [1]. Non-compliance with quality standards regarding modules and conductions or inadequately implemented installations are proven to be additional sources of error which have to be included in the considerations. Furthermore, discussions on deviating reverse current behaviour of different module technologies, missing information about securing the strings on the part of the module manufacturers or the necessity to apply the fuses only in case of certain converter concepts, contribute to the uncertainty. Missing regulations for dimensioning and not yet existing standards for solar fuses complete the present confuse situation.

Keywords: PV fuses, reverse current potential, regular operation, faulty operation, earthing fault.

1. Present situation regarding the application of fuses in photovoltaic systems

Due to improved general conditions for the supply of electricity from photovoltaic systems, an extremely dynamic market has developed in recent years. Germany took a pioneering role; countries like Spain, France, USA, Italy and Greece followed the German example by taking the appropriate steps. Worldwide it is assumed that approx. more than 40 GW in photovoltaic power was installed at the end of 2010. Presently the market can be divided into three essential segments that are characterised by typical power classes. At the end of 2008, 5.3 GW of photovoltaics were installed in Germany. About 40% of the systems were installed in private homes in the power range under 10 kWp. 50% of the grid-connected systems can be assigned to the market segment of agricultural, commercial and public buildings. Only 10% are set up as open-field installations. In Spain, for example, a completely different image emerges. Here, approx. 95% of the installed PV power of 3.317 GW was set up in form of open field installations [2].

Utilisations in medium and large power range have to be considered as main areas of application. It is difficult to evaluate the exact potential regarding the market share of PV installations in which fuses might be utilised due to the fact that many large-scale plants are also realised with string converters where usually no fuses are applied.

2. Technical aspects of the application of fuses

In order to optimally lay out a solar generator, it has to be adapted to the selected converter. Thereby an important criterion is the dimensioning of the voltage range. It will be realised by serially wiring solar modules to one string. Correspondingly, the number of modules shall be adapted in such a way that the maximum voltage of the converter is not exceeded at any time to avoid its destruction. To achieve higher performance, several strings with the same number of modules are connected in parallel. Now, at the latest, the engineer shall decide whether to apply string fuses. If several module strings are commonly operated in parallel in a solar generator, the reverse current capacity of the utilised modules has to be taken into account. This is defined by a maximum amperage with which the module can be operated in forward direction without causing any permanent damage to the module. To ensure this, two specifications are required by the manufacturers according to relevant standards. Both, the reverse current capacity of the module, and the type of the overcurrent protection shall be indicated. The necessary test specifications are described in the relevant standards. However, these specifications in the datasheets are still not being observed correspondingly. That particularly affects the type of protection. It may be assumed that the manufacturers retain a certain degree of insecurity caused by the lack of regulations regarding the dimensioning of fuses.

It is undisputed that a parallel connection of strings in a solar generator might cause reverse power flows. However, the operating conditions leading to a reverse flow have to be known. In general, a distinction has to be made whether it is a regular operating condition or a faulty operation [3]. To be in a position to judge whether fuses are necessary at all to protect modules and cables, all possible general conditions under which a solar generator is operated must be taken into account. Thereby the most important aspects are the number of strings available in parallel, the reason regarding type and intensity leading to the reverse flow, the earthing concept of the solar generator, the converter topology and, not at least, the technical data of the modules and their technology itself. For the dimensioning of the fuses the rated values for voltage and current must be taken into account. Basically, these values arise from the module data, the operating conditions expected at the location as well as from the system design of the planner.

Those currents capable to trigger fuses in the solar generator can only result from a total current of the rest generator. The most unfavourable case would be if a rest generator could feed back into a single string. However, this is only possible if the string concerned has a lower voltage level compared with the rest generator.

2.1. Theoretical considerations regarding the probability of reverse current

For a better understanding please see the following example describing the case of energy recovery of a solar generator into a single string. The characteristic line K1 can be assigned to a solar generator with 25 strings. The characteristic line K2 represents an electrically reduced single string as it would result in case of a fault (e.g. short circuit affecting the modules). If this string is operated parallel to the solar generator with the characteristic line K1, it can be considered as a connected load. For this reason the characteristic line K2 is depicted as load curve K2* (reflection at neutral axis). This parallel connection originates a new characteristic line K3. The open circuit voltage U_{oc} of the resulting characteristic line can be derived from the intersection (S1) of the characteristic lines K1 and K2*. For all characteristic lines the MPP points (MPP1, MPP2, MPP3) are sketched in.

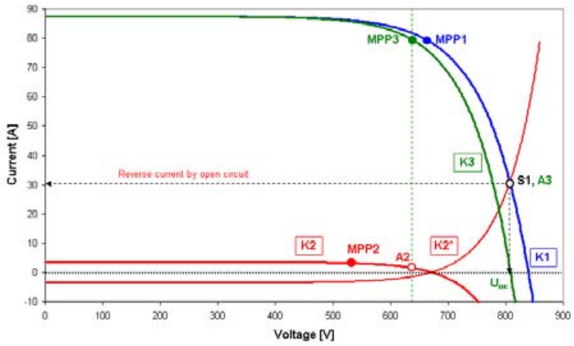

Fig. 2.1: Circumstances in case of reverse current load of a defect module string

Operating this constellation, for example, at a converter in MPP (point MPP3), the operating point A2 of the defect string will be shifted from its MPP point (MPP2). A reverse current would not flow. It appears more critical if the solar generator is in open-circuit mode, i.e., the converter is switched off or separated from the solar generator. In this case a significantly higher reverse current appears (operating point A3). The larger partial generator is on an open-circuit voltage level and feeds into the defect single string with a high reverse current. In this case, the reverse current will cause damage if no precautions are taken.

3. Operating conditions with reverse current potential

The volume of reverse current and possibly its distribution basically depends on the relation between feeding part and reverting part of the solar generator. Dimensions and general conditions to be considered here exceed the module-specific electric parameters and characteristics. Considerations must also include operating conditions, converter conceptions or earthing conceptions as well as possible errors caused by external influences or faulty installations. As a rule, there must be generally distinguished between regular and faulty-based operating conditions in the photovoltaic system.

Basically, regular operating conditions are determined by external influences. This includes partial shading, snow coating or temperature differences of the modules. Production-related tolerances or operating conditions influencing the PV system (MPP operation, open-circuit operation) must also be taken into consideration. Faulty operating conditions include, e.g., interruptions, earth faults, defect bypass diodes and installation errors. Here, too, all possible operating conditions of the PV plant have to be taken into account. Likewise, planning errors can lead to irregular operating conditions.

3.1. Reverse current situations during regular operation of the photovoltaic system

The regular case is that all solar modules are installed at the same angle and identical orientation. All modules are operated under nearly the same surrounding conditions. That means that all possible influencing factors like irradiation intensity, module temperature, mode of installation, orientation and wind influence have the same effect on all modules. If these conditions are given, it can be assumed that there are no reverse currents. In practice, however, diverse situations are possible that do not comply with the normal prerequisites mentioned before. In the view of some theoretical considerations these cases shall be examined to that effect if there exists any reverse current potential.

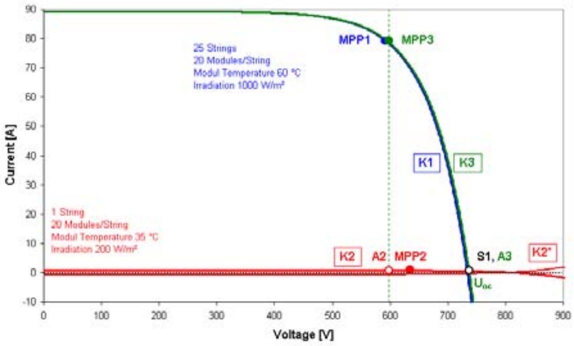

Fig. 3.1: Operating conditions of the solar generator in case of homogeneous shading

Example: Differing irradiation intensities – Due to different distribution of irradiance, a partial generator or string manifests a reduced module temperature by 25 °C, resulting in a higher voltage depending on the technology. For example, a mutual shading between modules of the lowest row in case of tracking systems or divergent orientation of partial generators situated on rooftops. The individual string is no longer operated in the MPP (shifting of the operating point A2 to the left, image 3.1). In the open-circuit mode there is also no reverse current relevance.

Example: Snow coverage – A situation that only small areas of a solar generator are covered by snow occurs if part of the snow slides from the generator surface with beginning thaw. In this operational event it is assumed that the solar generator covered by snow only receives a homogeneous irradiance of 10 W/m². The module temperature of the area covered by snow is 0°C.

Fig. 3.2: Solar generator partially covered by snow

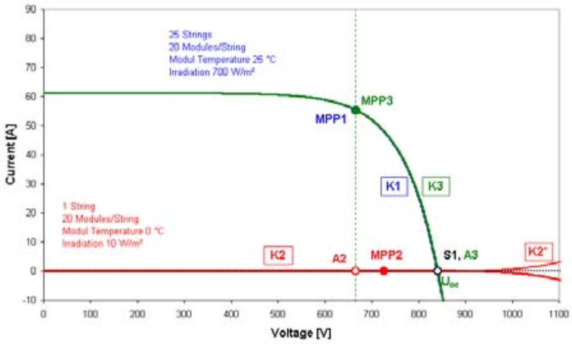

Fig. 3.3: Operating conditions of the solar generator partially covered by snow

A realistic temperature of the modules in wintertime is 25°C at an irradiation intensity of 700 W/m² and surrounding temperatures around the freezing point. The characteristic lines K1 and K3 are nearly congruent. Reverse currents into the snow-covered string are not possible.

Example: Large temperature differences – In certain situations it may occur that an individual string is operated at higher module temperatures compared with the rest generator. This might be conceivable in case of a building-integrated system where building segments obtain little back ventilation or even constructed with insulation techniques. Assuming that individual façade elements have additional thermal insulation, over temperatures between 40°C and 50°C are possible. Then the maximum module temperature would achieve values of up to 80°C. For the shadowed generator part a module temperature corresponding to the ambient temperature of 30°C is assumed. The irradiance only amounts to 300 W/m².

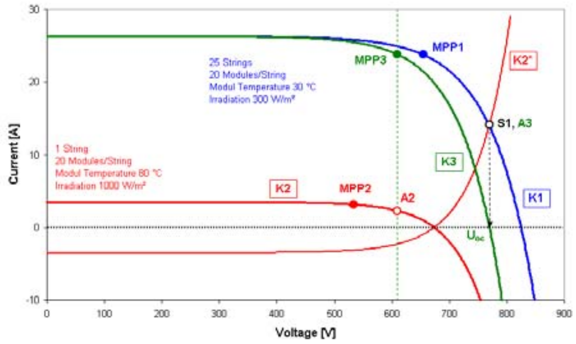

Fig. 3.4: Reverse current conditions at a large temperature difference

If this theoretical case occurred – which is considered to be unlikely – in an open circuit situation would flow a reverse current of approx. 15 A. The MPP of the affected string would be left in direction of the open circuit voltage (A2).

A realistic case can occur if part of a façade (e.g. the balustrade area) is accomplished as insulated PV element while another part is realised as a curtain façade.

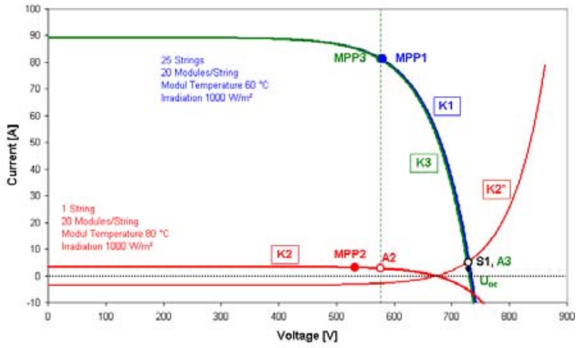

Fig. 3.5: Reverse current conditions at temperature difference and high irradiance

In comparison with the conditions assumed above, the irradiation intensity is the same on the solar generator and the thermally insulated string. This assumption is based on a temperature difference of 20°C. In this case, too, there would be no reverse current in the MPP operation of the converter. In the open-circuit mode a reverse current of approx. 5.5 A appears, i.e. about 1.5 times the short-circuit current of the module. The module should cope with reverse currents of this magnitude at any time.

Example: Reverse current characteristic dependent on technology – In comparison with crystalline modules, thin-firm modules show a flatter characteristic of the I-V curve. However, this circumstance has a positive effect in relation to the reverse current problematic. The following chart compares the two technologies. The assumed operating parameters of both module types were chosen identically. The assumption in both cases is based on an individual string reduced to 16 modules, not corresponding to a regular operation mode. The flatter curve of the characteristic line of the thin-film modules results in a lower reverse current. Due to clarity reasons the resulting characteristic lines have been omitted.

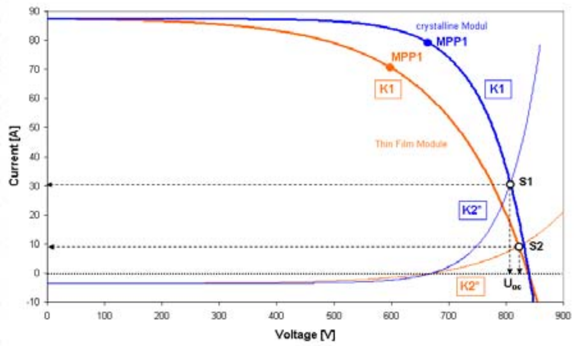

Fig. 3.6: Reverse current characteristic dependent on technology

Thin-film modules are less vulnerable to reverse currents than crystalline modules due to the flatter curve of the characteristic line. However, manufacturers are more reserved with regard to the reverse current carrying capacity of these modules.

3.2 Reverse current situations during faulty operation of the photovoltaic system

A photovoltaic system is comprised of diverse components ensuring the functional of the entire installation. During the whole life cycle of the system, solar generator and module cables are exposed to weather conditions. In the most unfavourable case this also applies to generator terminal boxes, DC circuit-breakers and converters. In view of the reverse current problematic, the errors in the installation of the modules, mounting systems and cabling are particularly significant. Special attention has to be paid to earth faults, defect bypass diodes or installation errors. Due to existing experiences, earth faults are assumed to be the most probable error source. However, detailed statistics regarding the cause of damage are not available. Those insurers offering at least rudimentary statistics register these errors under "technical failures" or attribute them to deficiently realised installations.

Case of failure: Defect bypass diodes – Bypass diodes are integrated in the connection box of a solar module. Their task is to minimise the losses within the module in case of shading. The probability is considered low that a bypass suffers a defect. Up to now there have only been occasional reports of damages. The most frequent cause of damage may be the impact of inductive overvoltage caused by indirect lightning effect. Here it can be that several diodes in several modules are affected.

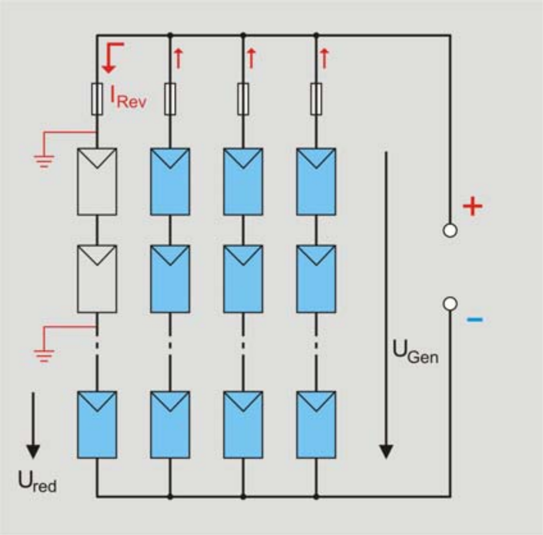

Fig. 3.7: Reverse current at conducting defect bypass diodes

If there is a failure of the bypass diodes, two different cases shall be distinguished. An interruption has no consequences for the reverse currents. However, if the diode has a conducting defect the corresponding module part will be short-circuited. This means that the affected string is operated with the rest generator at reduced voltage. But damaging reverse currents can only flow if several bypass diodes have conducting defects at the same time. The probability can be considered low that this defect appears.

Case of failure: Earth fault – There are numerous reasons for earth faults. In most cases, the solar module itself and the complete DC installation can be assumed to produce the failure. Breakage of glass, damaged back side foil or reduced insulation resistance are the most common faults on the side of the module. In view of the installation, frequent reasons for an earth fault are material fatigue, animal chewing damage or improper installation of cables. Reports from insurers and appraisers show that technically accepted rules of engineering are frequently not respected when installing the system.

The considerations must include the converter concept and the earthing conditions on the DC side. Reverse currents in case of an earth fault can only occur when parts of a string or solar generator are short-circuited by one or several earth faults. The proportion of the bridged modules has a direct influence on the magnitude of the occurring reverse current.

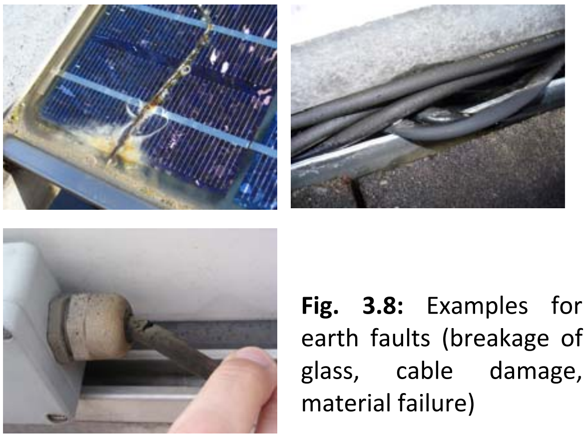

Fig. 3.8: Examples for earth faults (breakage of glass, cable damage, material failure)

Systems with unearthed solar generator

If converters with galvanic isolation are used in a PV system, the solar generator shows no definite voltage conditions regarding the earth potential. It is assumed that this type of installation concept can be found most frequently in the segment of the lower and medium capacity range. Manufacturing the solar modules in accordance with protection class II as well as installing the cabling in an earth fault and short-circuit proof way, it is assumed that an overload on the DC side is protected according to a normative interpretation of IEC 60364-712 (DIN VDE 0100-712). Due to the lack of earth potential, a single earth fault puts nobody at risk or causes reverse currents in any part of the solar generator. It is assumed that the fault can be detected and removed within a reasonable time.

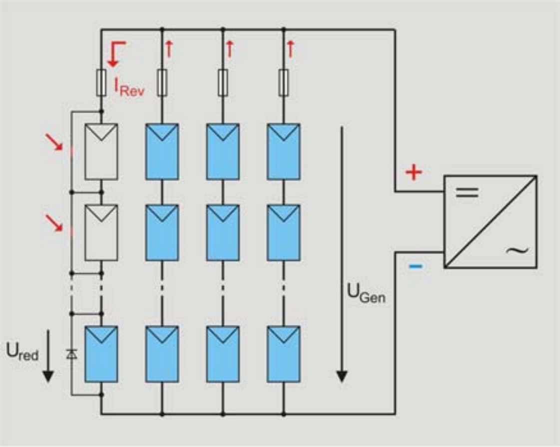

Fig. 3.9: Double earth fault of a solar generator without earth potential

Only if there is a second earth fault, parts of the string can be short-circuited, for example via the utilised frame system. Then the connection to the earth potential will be established by using the usually earthed frame system. Due to the fact that the frame system is considered a reference potential, it is comprehensible that in case of two earth faults in different strings larger parts of the solar generator are short-circuited.

Systems with earthing of active parts

If there is a galvanic isolation between the DC and AC side it is permitted to earth an active conductor of the DC system. Optionally, it is also possible to realise a midpoint earthing.

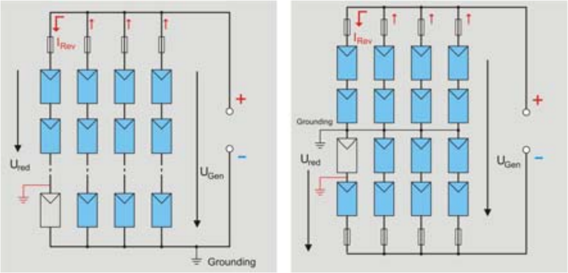

Fig. 3.10: Simple earth fault in systems with earthing of active parts of the solar generator

With respect to the voltage conditions in the solar generator, such systems present clearly defined conditions. However, it is a disadvantage that high earth currents can already flow when a single earth fault occurs, which – in the most unfavourable case – reach the short-circuit current of the entire solar generator. The distribution of this system is relatively rare.

Systems without single galvanic isolation

According to DIN VDE 0100-712, section 712-413.1.1.1.2, a fault current protection switch is compulsory for systems without a single galvanic isolation between the DC and AC side. As a result, the poles of the solar generator are alternately directly connected to the neutral conductor of the mains. This again is connected to the neutral point of the power transformer, which in turn is earthed. This means that there is a direct connection to the earth potential. The consequences are similar to those of systems with earthing of an active part of the solar generator. In case of a single earth fault, a fault current against earth would happen and consequently trigger the fault current protection switch immediately, putting out of operation the system (solar generator in open-circuit mode).

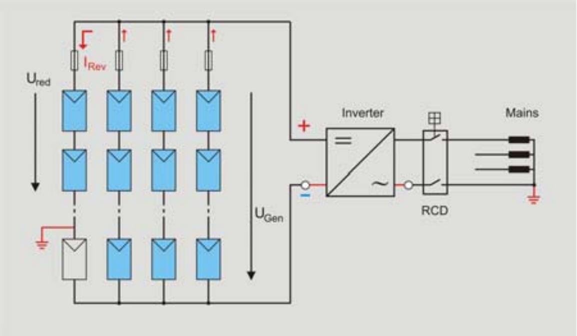

Fig. 3.11: Simple earth fault of solar generators without simple separation

Again, the probability of reverse currents is higher than in systems with galvanic isolation between DC and AC side.

Case of failure: Installation error

In case of subsequent connection of cables and connectors on the roof, it can happen that the plugs are connected incorrectly. This should not be a problem as long as module strings are always installed following the same pattern of installation. When changing the installation pattern – e.g. roofs on different levels where string formation is only possible by using two generator levels – wrong polarity within one string can cause that the voltage of the incorrectly connected module is no longer available. In case of reverse current, the bypass diodes of the affected module will become conductive. Depending on the number of incorrectly connected modules, there can be a considerable reverse current flow.

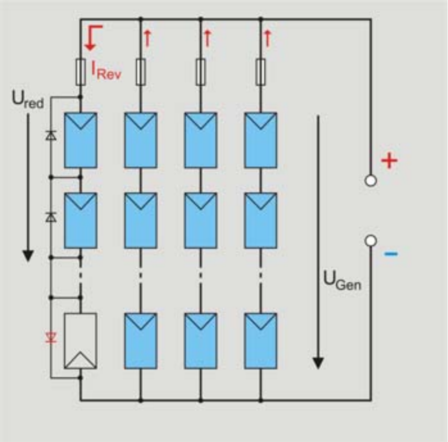

Fig. 3.12: Reverse current conditions for the case of an incorrect polarity connection

The cases of failure described above show that already at the moment a failure occurs, reverse currents with destructive potential might appear. Thereby, the magnitude of the reverse current is directly connected to the electric reduction of the damaged string. The worst case is considered to be the open-circuit mode of a crystalline solar generator.

A first evaluation of manufacturer’s data regarding the information on the reverse current capacity has shown that the double short circuit current under STC conditions can assumed to be the typical reverse current load (green line in the following graph).

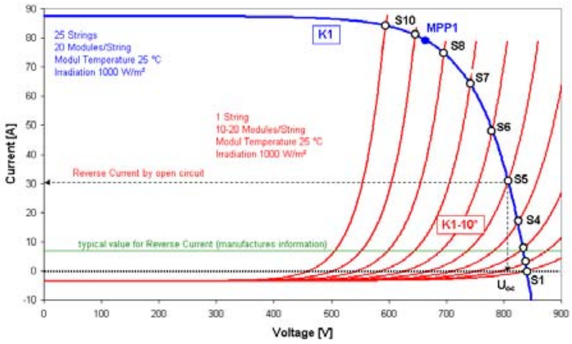

Fig. 3.12: Reverse current load of electrically reduced strings (K2 to K10)

Intersection S1 corresponds to a not electrically reduced string in comparison with the rest generator. Higher voltage differences lead to correspondingly higher reverse currents. The following image depicts a string reduced by 1 to 10 modules each (K2-10*). It can be assumed that a string which is voltage-reduced by approx. 10% is just in a position to durably carry the resulting reverse current.

4. Summary

In a medium and large power range, photovoltaics offer a large potential to apply fuses. The expert opinions differ widely whether fuses are necessary at all. The theoretical considerations clearly show that no serious reverse currents are to be expected in the regular operation of solar generators, even applying a large number of strings. This is confirmed by extreme operating conditions that hardly ever appear in a real application. Other conditions occur when the system changes over to the non-regular operating mode by reason of a failure. In this case – taking into account the earthing concept of the solar generator or the selected converter concept – it has to be determined whether fuses will be used. The currently applicable standard is based on the fact that a single fault can be controlled. However, multiple faults have not yet been taken into account but deserve to be taken as relevant. It has to be considered that a PV system represents a valuable investment asset and possibly utilised far longer than the expected useful life. No user is expected to remove a functioning system just because its fixed service life of 20 to 25 years is over. As a consequence, there will appear aging-related multiple faults caused by deterioration.

Certainly it would be wrong to restrict the fault analysis merely to the MPP operation of the converter where the risk of reverse current shows a considerably lower potential. There will always be situations in which the system changes into open-circuit operation, even under favourable irradiation conditions (maintenance, repair, power failure). Therefore, the open-circuit mode has to be considered as the critical operating condition.

It cannot be answered definitively whether the typical reverse current capacity with twice the short-circuit current at STC indicated by the manufacturers is to be evaluated too cautiously. There remain considerable uncertainties particularly regarding the new thin–film technologies. In view of the crystalline modules it may be assumed that voltage differences from up to 10% between a faulty string and the rest generator surely lead to reverse current but without causing thermal overloads.

The measurements regarding thermal behaviour of fuses under real conditions, which are still in progress, will provide important information on interpretation of fuses.

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